Flood Submergence Study Using an Integrated approach of GIS and Hydrodynamic Modeling for an Indian catchment

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Abstract

Flooding has been considered as one of the most dangerous and costly disasters in terms of property damage and human casualties etc.. Flood mapping provides a better information to communities for a better flood risk management and it can help in controlling the damage by giving warning to concerned authorities. The Lower Tapi Basin (LTB) in western India having a geographical area of 2920 km^2 has been experiencing periodic floods (1978, 1979, 1990, 1994, 1998 and 2006) those frequency has increased in the recent past. Therefore, flood probability, flood predictions, flood hazard and flood risk assessment area needed to do under flood management. In this research paper, Submergence area to be identified from the flood events was carried out for different return periods (i.e. 2, 5, 10, 25, 50 and 100 years) using the GIS-based 1-D hydrodynamic model from US Army Corps of Engineering- HEC-RAS and HEC-GeoRAS. Annual peak flow data of 30 years from 1978 to 2007 has been collected at Ghala station, which is in near Surat city and examine that maximum discharge 25778m^3/s in 2006 and minimum 340.8m^3/s in 1987. This research work is also compared six flood frequency distribution methods such as Extreme value type I distribution (EVI), Generalized extreme value distribution (GEV), Log-Normal distribution parameter two/three (LN2/LN3), Parson type III distribution (P3) and Log Parson type III distribution (LP3) for Ghala station on lower Tapi river. The existing methods of flood frequency analysis produce variable outcomes, particularly at the higher return periods. Under this research effort cross-section profile, stage-discharge rating curve, river profile, flood plain and Submerged mapping have been developed for deferent return periods such as 2, 5, 10, 25, 50 and 100 years using GIS and remote sensing data integrated HEC-RAS hydraulic model for lower Tapi basin from Ukai to Hazira. Steady Flow analysis executed in HEC-RAS indicated that the discharge of 1864, 5904, 11619,25634, 44176, and 73860 m^3/s inundated 56.23, 80.51, 134.26, 234.73, 320.68 and 345 km^2 area respectively. These results provide essential information for planners, administrators and strategy maker to analyze and manage flood hazard and reduce risk.

Keywords: Flood frequency Flood modeling, GIS, HEC-RAS and Lower Tapi basin

1. Introduction

Flood is one of the most common hydrological disaster frequently experienced by the world and the flood events occur every year in various parts of the earth. Most of the countries are trying to improve their forecasting and managing systems. (Government of India, 2004) According to the government of India flood statistics, about 4,00,000 km^2 of the area is getting inundated due to floods every year. A GIS is an advance tool for supporting of hydrological and hydraulic modeling for flood management system in all over the world. In the literature, the researcher has developed several applications over the years. A GIS-based hydraulic model of a river system depends on the development of geometric and geographic data that accurately depicts the land surface to be modeled. Flood Inundation Mapping is a valuable tool for engineers, planners, and government agencies used for municipal and urban growth planning, emergency action plans, flood insurance rates and ecological studies (Marwade et al,). Hossienkhanlo et al (2013) have determined of flooding locations of some part of urban Hir water shed (Hir Chai river) and mathematical model HEC-RAS has been used for simulating river hydraulic regime, evaluating steady and unsteady floods, calculation of water level profile and finding relation with Geographical Information System (GIS). They have stated that the combination of GIS and HEC-RAS model is efficient, due to the accuracy in providing inputs and observing outputs.

Flood Frequency is the concept of the probable frequency of occurrence of a given flood (Reed et al, 2005). Flood frequency analysis is widely used in the design of the bridge, channel capacity and road bed elevation for flood plain zoning and flood protection work (Riggs 1989). An important problem in hydrology is the selecting of a frequency distribution method for fitting of extreme flood series in a region or country (Karim & Chaudhary, 1995) and for overcome this problem they have compared four flood frequency distributions method (GEV, EVI, LN and LP3) and stated that GEV distribution is suitable for flood frequency analysis in Bangladesh while EVI distribution is not. Vogel el al (1993) have evaluated consistently reveal that the LP3, GEV, and the two- and three-parameter lognormal models (LN2 and LN3) Provide a good approximation to flood-flow data in this region. Other Models such as the normal, Pearson, and EVI distributions are shown to perform poorly in the southwestern United States. GREHYS (1996) has systematically compared various regional flood estimation procedures with special emphasis on data from the two Canadian provinces. Pandey & Nguyen (1999) have examined the performance of nine different methods of estimating the parameters of the power-form model that connects the annual flood frequency as a function of the basin area. The present methods of flood frequency analysis produce widely varying results, particularly at the higher recurrence interval even where the nominal method is same (Benson, 1968).

Salimi et al (2008) have carried out to predict the flood inundation of various return intervals for Thamiraparani River Basin in Tamil Nadu (India) and recommended Log Pearson Type III distribution is a better statistical technique for flood frequency analysis for flood zoning, flood inundation, and flood plain mapping. Their methodology is following to flow values for different return periods from LP3 results are given as input into a 1-D hydraulic model, HEC-RAS to estimate the water surface profiles and flood inundation maps ware generated using HEC Geo-RAS. Timbadia et al (2011) have calibrated the 1-D hydraulic HEC-RAS model on predicting of flood for lower Tapi basin but they have been used to simulate the stages for different single roughness coefficients (Manning's 'n') for floods of the year 1998 and 2003. Urban flood plain mapping of Surat city has been done by Singh et al (2009) and found that the 84 % area of Surat city in flood zone. Joshi el al (2012) have been delineation of areas under various degrees of flood potential and analysis of results. Flood inundation map for West Zone of Surat city has been generated for flood 2006 and found that water level will rise at 12.0-meter level, 95.38 % area will be inundated. Flood inundation mapping provides flood risk maps that represents the characteristics of a hypothetical flood graphically from a synthesis of past flood events (Jeb at el, 2008). Patel et al (2015) has been prepared a DEM and TIN from the surveyed elevation data using Spatial Analyst tool. Later they have identified inundated area of North Zone of Surat city on various return period i.e. 30, 32 and 35 years and found very low water carrying capacity near this zone. Suggested to increase the carrying capacity using various measures. The aspects of various channel modification methods of river Tapi using geospatial technologies are described by Agnihotri et. al. (2011). Flood Hazard analysis has been carried out for 1998 and 2006 flood event for Surat city Mapping Using Remote Sensing and GIS (Dhruvesh et al, 2016). They found some parts of the city due to lower elevation were under water. The depth of water varies from 0.3 meters to 3.0 meters in the certain parts of area.

In the study area, researchers had the focused only urban part of the LTB but the rural area in a very large and highly vulnerable from the flood. In this research effort, the main objectives to compare flood frequency distribution methods and identified flood inundated area for different return period like 2, 5, 10, 25, 50 and 100 years using GIS and HEC-RAS hydraulic model for lower Tapi basin from Ukai to Hazira.

2. Study Area

Tapi basin covers a geographical area of 65145 km^2 and is the India's second largest westward draining inter-state river in the Arabian Sea. The origin of Tapi river is Multai (Betul district) in Madhya Pradesh (M.P.) and covers three states having an area of 51504 km^2 in Maharashtra, 9804 km^2 in Madhya Pradesh and 3837 km^2 in the Gujarat. The Tapi river basin can be classified into three zones, viz. Upper Tapi basin, Middle Tapi Basin, and Lower Tapi Basin (LTB). The area between Ukai dam to the Arabian Sea has been considered as LTB, mainly occupying Surat and Hazira twin city along with tens of small towns and villages along the river course. LTB having a geographical area of 2920km^2 has experienced periodic floods. The Surat and Hazira twin cities are almost 106km downstream of Ukai dam and were affected by recurrence floods. One among the major causes of the flood in LTB is attributed to early peak discharge from various tributaries such as Varekhadi, Anjana khadi, Serul khadi, Mau khadi and Gal khadi.

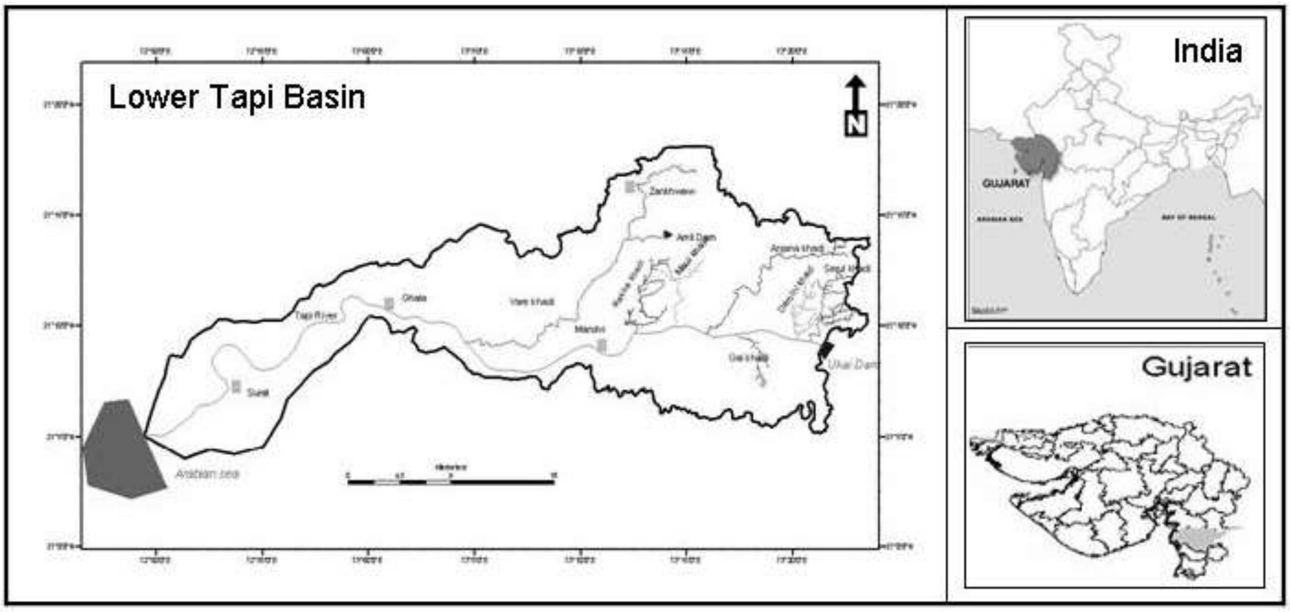


Figure 1 Study area- Lower Tapi Basin

The Study area lies between Longitude 72^{0}42' to 73^{0}40'and Latitude 21^{0}08'to21^{0}30' (refer Figure 1). LTB receive an average annual rainfall of 1376mm, and these heavy downpours result into devastating floods and water logging mainly between Ukai dam and Hazira town downstream. The major crops grown in the study area are cotton and maize followed by Soybean. The land use prevailing in the study area is mixed forest, agriculture land, rural and urban settlements. The topography of Surat is gently sloping and flat. Therefore, it can be stated that study area has multiple problems in flood formation. The Central Water Commission (CWC) of Tapi division has a good hydro-meteorological network with 18 rainfall monitoring station and 9 discharge monitoring station across the entire river basin (Dileep mawalankar, 2008). In lower Tapi basin inadequate rain gauge station and only 1 discharge station at Ghala. So, lower Tapi basin catchment can be considered as an ungauged or semi gauged catchment, resulting this historical data of the catchment is the very small amount in the quantity. Overcome this issue, need to flood estimation using hydrological modeling or simulation. Sharma et al, 2014 has estimated flooding potential for ungauged sub-watershed of lower Tapi basin using SCS CN method with integrated of GIS technology and found Varekhadi sub watershed is a very high contribution of flooding. They have established a hydro-metrological network on Varekhadi watershed for validating results. It is required to estimate flood probability, flood magnitude and flood Submergence at different return periods such as 2, 5, 10, 25, 50 and 100 years for flood design and flood management of low laying areas like Surat city.

3. Methodology

The research emphasis is, however, on the integration and the specialized data processing techniques to obtain flood information on 1) flood flow rates and discharges, 2) flooding inundating areas. The flood inundation mapping methodology is divided into three primary sets of activities: preprocessing of geometric data, hydraulic analysis, and post-processing of hydraulic results and floodplain mapping. The following methodology has been adopted for estimation of flood-inundated area (figure 2).

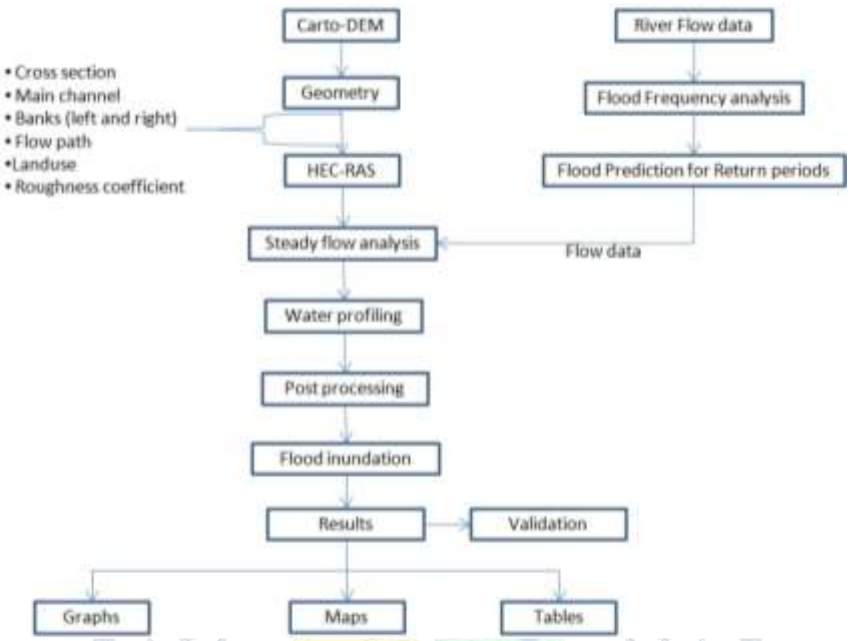


Figure 2 Methodology

3.1 River flow data

Stream flow data affect the quality of the input data in flood frequency analysis or hydrologic modeling. Flood history data can be used as an input for flood prediction and probability analysis of different return periods. It is very useful for developing stage-discharge curves and river profiling with the help of geometry data. In this research efforts, 30-year annual peak-flow data of Tapi river from 1978 to 2007 has been used at Ghala station, which is located in near Surat city and examine that maximum discharge 9,09,988 cfs in 2006 and minimum 12035 cfs in 1987 (figure 3). The study area has the experience of the flood in the year 1978, 1979, 1990, 1994, 1998 and 2006 and those frequencies have 505282, 424588, 502351, 596358, 794569 and 909988 cfs. The historical 30 years annual peak river discharge data is adequate for calculating 100-year river flow.

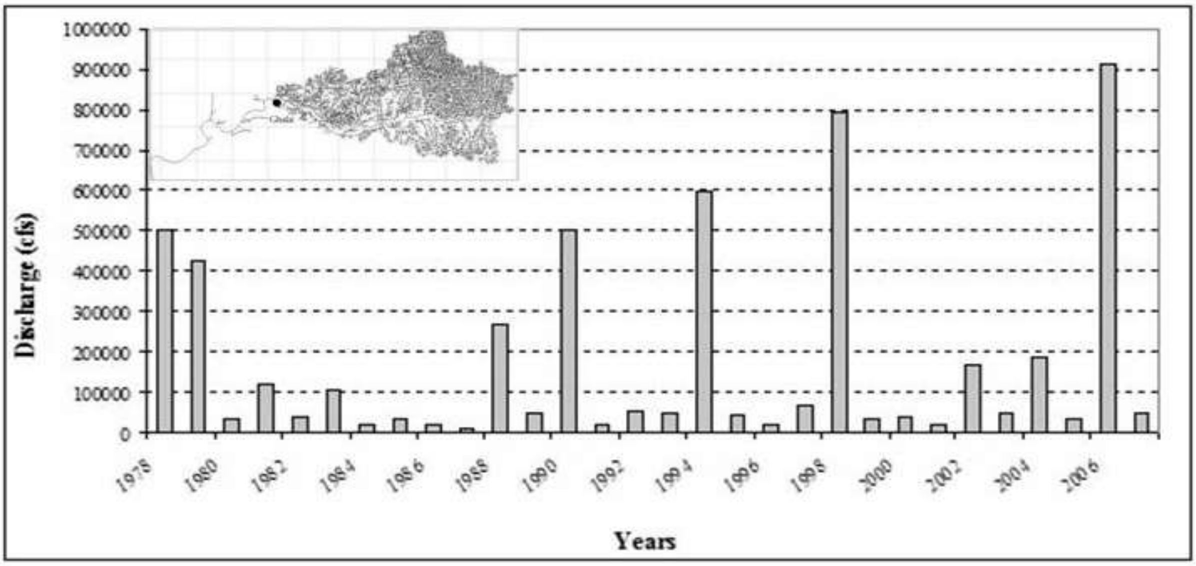


Figure 3 Flood magnitude in LTB

3.2 Flood Frequency Analysis

The annual peak flow data for 30 years are collected for flood frequency analysis and the annual peak flow values calculated for 100 successive years. There are several methods exist for the determination of maximum flood magnitudes, the historical hydrological data recorded during the past events was more reliable for the estimation of maximum probable flood. The flood discharge data is fitted to the probability distribution to define the exceedance probability beyond the range of the available data. Six flood frequency distributions methods for fitting the extreme events are tested: (1) Extreme value type I distribution (EVI), (2) Generalized extreme value distribution (GEV), (3) Log Normal distribution parameter two (LN2), (4) Log Normal distribution parameter three (LN3), (5) Parson type III distribution (P3) and (6) Log Parson type III distribution (LP3). Out of them, LP3 method was selected because it gave the largest discharge comparing to others. This method is the most widely used probability distribution function for extreme values in hydrological studies for prediction of flood peaks (Subramanya, 1994).

Distribution function: The Log-Pearson Type III distribution is a refinement to the Pearson Type III distribution. The distribution function is:

$$f(x) = \frac{(\ln x - x_0)^{\gamma-1} \exp\{\frac{-(\ln x - x_0)}{\beta}\}}{\beta^{\gamma}\Gamma(\gamma)}$$

x_o, b and g control location, scale and shape respectively. The lower bound of the distribution is exp(x_o). It is difficult to calculate exactly by hand the magnitude of the event with a return period T. The simplest approach is to estimate the T-year event from the sample mean, standard deviation and a factor K_T:

$$x_T = \bar{x} + \sigma K_T$$

The factor K_T varies with return period T and sample skewness g, and can be read from tables (US Water Resources Council (1981); Kite (1977) Table 9-2; Linsley et al. (1982) Table 13-4, for example). Sample skewness g can be calculated directly from the sample, or estimated from the parameter g using:

$$g = \frac{2}{\sqrt{\gamma}}$$

Parameters of fitted distributions for LP3-III

xo = 5.560 beta = 0.756 gamma = 2.534

3.3 Digital Elevation Model

Digital elevation models (DEMs) are readily available data sets that represent the elevation of the earth's surface at discrete points in a regular, rectangular grid. The DEM is a basic input for creating geometry such as a river, banks, flow path and cross section for the HECRAS model because DEMs consist of a matrix data structure with the topographic elevation of each pixel stored in a matrix node (Boonklong et al, 2007). DEMs are readily available and simple to use and hence have seen the widespread application to the analysis of hydrologic problems (Moore et al, 1991). The quality of DEM can be directly influenced on the accuracy of prediction of flood Submergence area and water surface elevation derived from hydraulic models. The most accurate and reliable source of DEM is remote sensing and there are many satellites launched by different countries and provide elevation information in the form of images such as LIDAR and ASTER DEM.

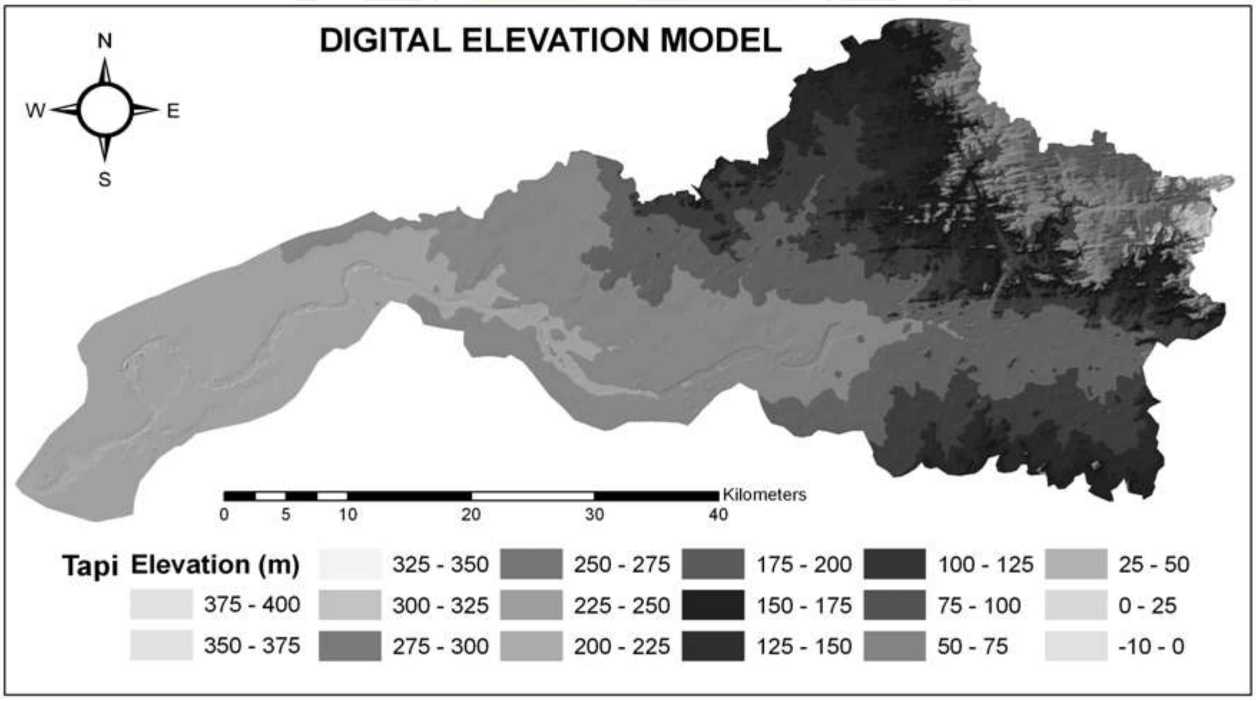


Figure 4 Digital Elevation Model of lower Tapi basin

Cartosat-1 stereo pair data with the 30m spatial resolution is providing by website Bhuvan which is managed by Indian Space Research Organization (ISRO), Department of Space, Government of India. DEM data for the study area (LTB) has been downloaded from mosdac website and cut the subset from the area of interest. Secondary data have been also collected from a survey of India topo maps and GPS survey which is required for improving the quality of DEM. The accuracy assessment carried on DEM for selected locations shows a good fit and has been in coherence with actual elevation values. The minimum elevation of the study area is -10m near Hazira and maximum elevation 350m near Ukai dam (figure 4).

3.4 Channel Geometry

The river geometry used for simulation in HEC-RAS was generated from the digitized layer covering 106 kilometers. The geometry was digitized from upstream to downstream in ArcGIS software. The bank and flow path lines were also created the same way starting with the left, channel and finally the right flow line. These geometries were then copied into the created RAS Geometry layers (centerline or river, bank lines, and flow path centerlines). The use of the Carto-DEM with 30 m resolution from the Mosdac website became apparent as it indicated a better vertical resolution to properly simulate flow than the other data. Figure 5 depicts the geometry such as cross-section, river center line, banks and flow path. There are 59 cross-sections have been created at 1.8 km interval using HEC-GeoRAS tool integrated with ArcGIS professional software.

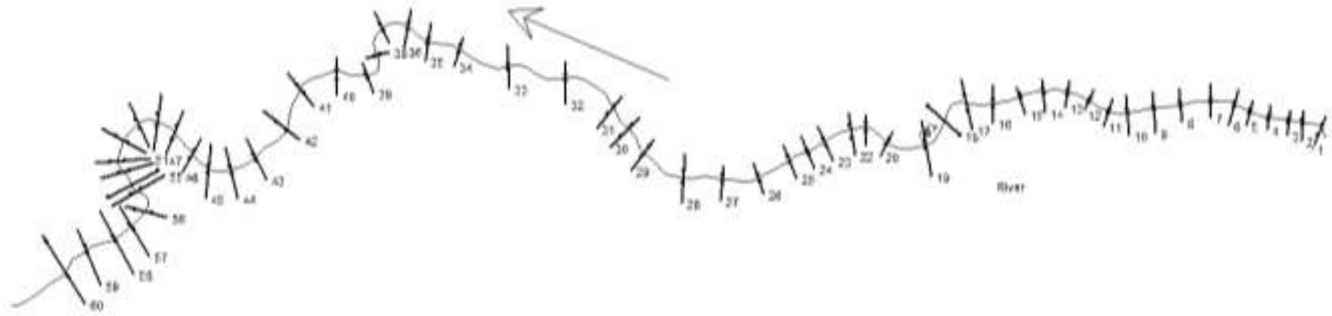


Figure 5 River geometry with cross-section

3.5 Hydraulic model

The HEC-RAS in an integrated software system for one-dimensional flow modeling is used for steady and unsteady flow calculation to determine water surface profile (USACE 2002). HEC-RAS has the capabilities for creating, store and analyze geometry data in the GIS environment and solves the full 1D St. venant equation for unsteady open channel flow. HEC-GeoRAS tool used for preprocessing or creation of geometry layers such as river banks, river center line, cross-section and other required layers integrated with ArcGIS desktop. This study uses HEC-GeoRAS to accurately extract cross section information, banks and river center line from Digital Elevation Model (DEM). In the present analysis procedure, the HEC-RAS model is used for hydraulic analyses with a set of parameters (e.g., Manning n) and input data (e.g., flows) that are obtained from the flood frequency analysis. The channel roughness, usually specified by using Manning's n, also has a significant impact on hydraulic simulations. Manning's n, which is commonly assigned by using standard look-up tables for different substrate types, can range from 0.035 to 0.065 in the main channel, and 0.080 to 0.150 in the floodplains. This study calculates six future climate scenarios 2, 5, 10, 25, 50 and 100 years return periods. The results (e.g., water surface elevations) from HEC-RAS are exported into GIS for the development of floodplain maps and estimated flood Submergence area for lower Tapi basin. Therefore, the HEC-GeoRAS tool not only increases the precision of hydraulic modeling but also fast builds the floodplain maps for the various return periods. This analysis assumes that natural channel meets uniform flow condition, it means the energy grad is approximately equal to the average channel bed slop, that water surface elevation can be obtained from a normal depth calculations.

After the completion of river hydraulic model, HEC-RAS simulation run results were exported for processing flood inundation mapping with the help of HEC-GeoRAS tool. Flood plain boundary and flood depth maps have been papered for the deferent return periods. The grid cell size 30m X 30m based on the input DEM resolution for creating various geometry layers i.e. river channel, banks, and cross-section. Hence the flood simulations have been generated over a 30m X 30m cell size under the six flood scenarios (1) T=2yr, (2) T=5yr, (3) T=10yr, (4) T= 20yr, (5) T=50yr, (6) T=100yr

4. **Result:**

This research aims to develop an integrated approach incorporating a hydrodynamic model (HEC-RAS) with a GIS to predict a flood event in both spatial and temporal contexts for future scenarios. Probability distributions for the yearly maximum discharges and calculated flood frequency analysis using six distribution methods. (1) Extreme value type I distribution (EVI), (2) Generalized extreme value distribution (GEV), (3) Log Normal distribution parameter two (LN2), (4) Log Normal distribution parameter three (LN3), (5) Parson type III distribution (P3) and (6) Log Parson type III distribution (LP3). The result of 2, 5, 10, 25, 50 and 100- years Return Period Flood Frequency Analysis based on Maximum Instantaneous flow recorded at Tapi River (Ghala Station) from the year 1978– 2007 using above six flood distribution method are summarized below in Table 1.

Table 1 Flood Magnitude at different return period

Return Period	Discharge in m^3/s					
(Years)	EV	GEV	LN2	LN3	P3	LP3
2	3799	2421	2120	2099	3096	1864
5	9986	6348	6250	6552	9478	5904
10	14083	10532	10998	11588	14086	11619
25	19259	18736	20095	21115	20109	25634
50	23099	27994	29661	31031	24662	44176

100	26910	41161	42101	43823	29233	73860

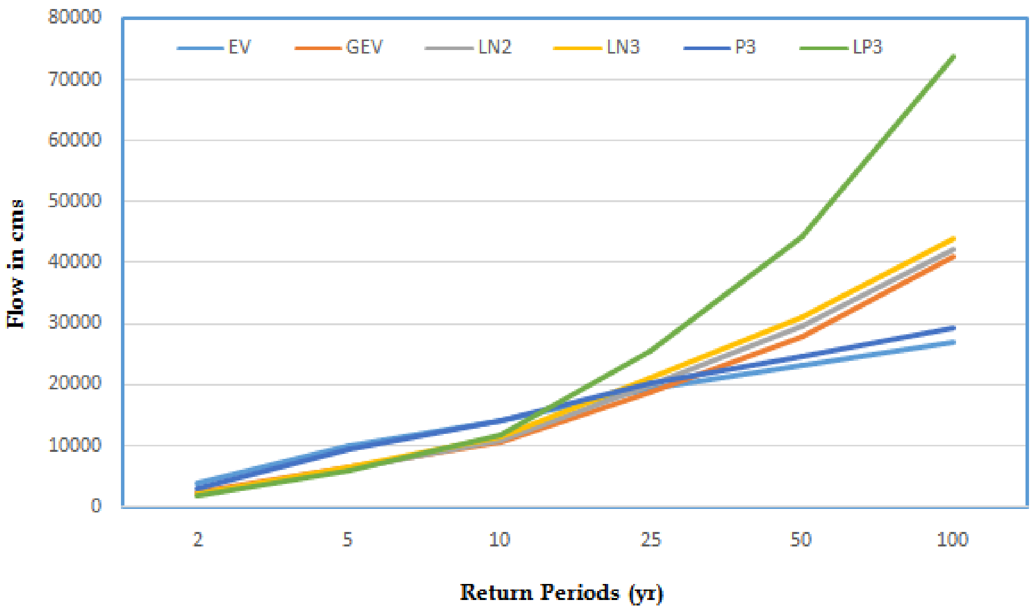
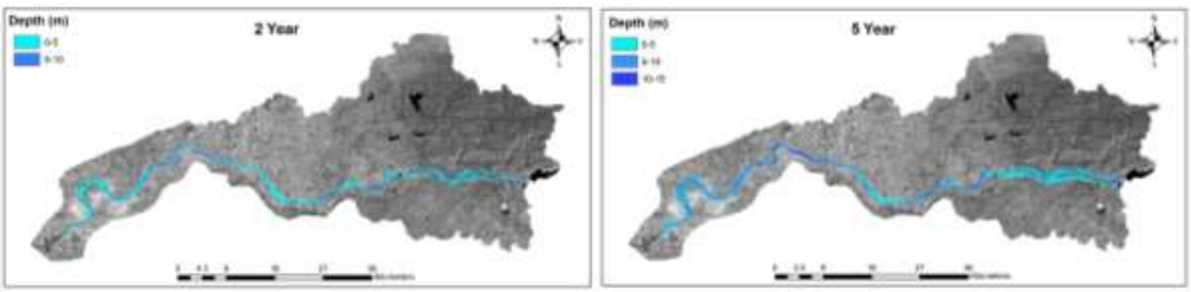


Figure 6 Comparison of Flood distribution methods

The result shows in figure 6 that the flood discharge until 25 years is nearby from each other but for higher return period results are deferred in a large amount of quantity. EV and P3 both methods are giving quite similar output and in other hand GEV, LN2 and LN3 results are matching each other but LP3 distribution method provides very high frequency of water for 100 years. The existing methods of flood frequency analysis produce variable outcomes, particularly at the higher return periods. The result from distribution method has been correlated with observed data and found the highest correlation coefficient 0.98 of LP3 distribution method. LP3 outcomes are used as an input in hydrodynamic flood Submergence for the study area. The size of the flood with a return period of 100 years or an annual exceedance probability of 1% is 2091.57 m^3/s from LP3 distribution method. Probability distribution plays a vital role in designing structure and proper management of water resources and flood disaster.



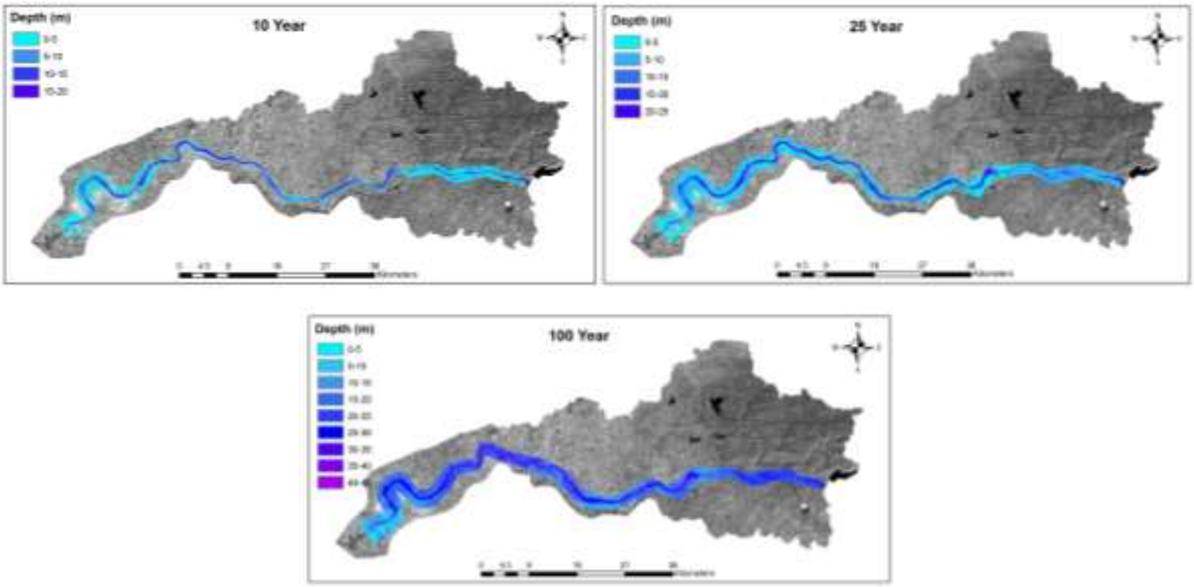
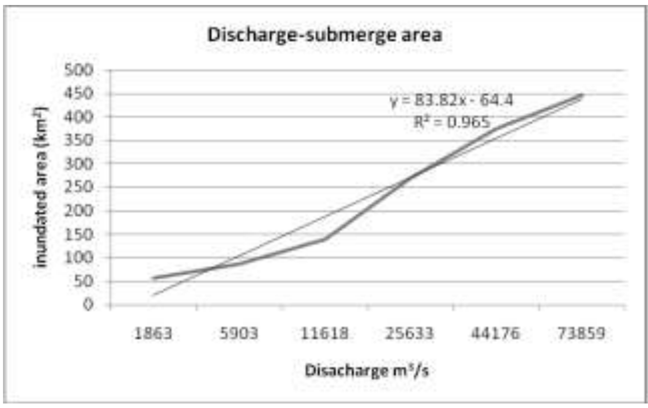


Figure 7 River Inundation maps on deferent Return periods

Submergence maps were produced, figure 7 showing the calculated flood extent at peak flow for given periods. Steady Flow analysis executed in HEC-RAS indicated that the discharge of *1864*, *5904*, *11619*, *25634*, *44176*, *and 73860* m^3/s *inundated 56.23*, *80.51*, *134.26*, *234.73*, *320.68 and 345* km^2 *area respectively*.

The relationship between simulated water depth and discharge rate for deferent return period 2,5,10,25,50 and 100 years is linear. The collection of field data in the observations to derive a reliable curve that can be used in the future. In addition, DEM accuracy and grid size may have impacts on inundation simulation, especially on the catchment boundary, routing path and inundated water volume/depth. The optimal resolution of DEM for explicitly expressed topography in the HEC-RAS model can be tested with various resolutions to improve the accuracy of the model. Currently, the finest available DEM grid size is 30 m, which is provided by MOSDAC and we are also implementing survey data collection through GPS and DGPS that can obtain finer DEM grid size of 5 m with a higher accuracy of elevation in urban areas. Thus, the cross-sections created by HEC-GeoRAS with the help of DEM have been validated with observed cross-section by leveling survey and demonstrate good fit.



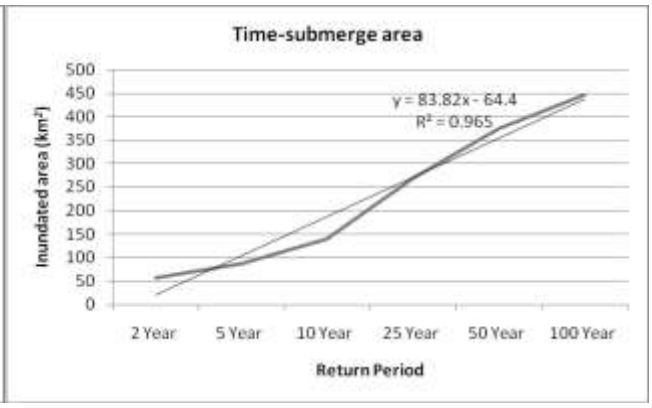


Figure 8 Relationship curves

(Figure 8) River discharge – inundation relationships fit the same criteria as discharge – stage relationships as well as Return periods relationship, all relationship controlled by river channel geometry and can thus be approximated with regression relationships. R2 error for Discharge-inundation and return period-inundation is similar 0.97, it depicts the relation between these parameters is linear. If the river depth is high resulting discharge is high and with discharge, inundation is also high. It can be concluded that the river depth is high than inundated area may be large. For discharge – inundation relationship with a series of linear equations (equation 1) with coefficients of slope (C1) and intercept (C2) which are treated as fitting parameters rather than physical features in the natural system.

Inundation area (km^2) = C1. Q+C2……………………………………………………………………. (1)

Where Q is discharged value in m^3/s

C1 and C2 are regression coefficients (C1=71.72 and C2=8.05

Inundation area (km^2) = C1. T+C2……………………………………………………………………..(2)

Where T is returned periods in year

C1 and C2 are regression coefficients (C1=64.84 and C2=31.55

Flood inundation is depended on hydraulic and hydrological parameters such as discharge, slope, river geometry, and flood plains

Table 2 Classification of flood depth with inundated area

Water Depth (m)	(Inundated Area km^2)					
	2yr	5yr	10yr	25yr	50yr	100yr
0-5	39	46	82	182	221	182
5-10	18	33	33	46	94	179
10-15		9	19	25	28	44
15-20			4	17	24	24
20-25					7	17

Total	57	88	138	270	374	446

Flood depth is the depth of water level from the ground level, which has been calculated from the HEC-RAS post processing techniques. The results show that the inundated area 56.23, 80.51, 134.26, 234.73, 320.68 and 345.91 km^2 for the periods of 2,5,10,25,50 and 100 years respectively. It contains rural and urban area such as agriculture, small villages, Surat city and deferent type of infrastructure. The inundated area fluctuates with discharge value of the river. Table 3 depicts the relationship between, times, flow value with inundated area.

Table 3Result of Submerged area

Return Periods (year)	**Discharge (m^3/s)**	**Submerged area (km^2)**	**Percentage Inundated area of LTB**
2	1863	57	3
5	5903	88	5
10	11618	139	7
25	25633	270	14
50	44176	374	19
100	73859	446	23

The result of flood frequency analysis shows that LTB has faced the flood problem in 1998 and 2006 and the discharge values are 22500 m^3/s and 25700m^3/s. For the validation purpose, flood inundation modeling has been carried out for both 1998 and 2006 food. It covers all the LTB area.

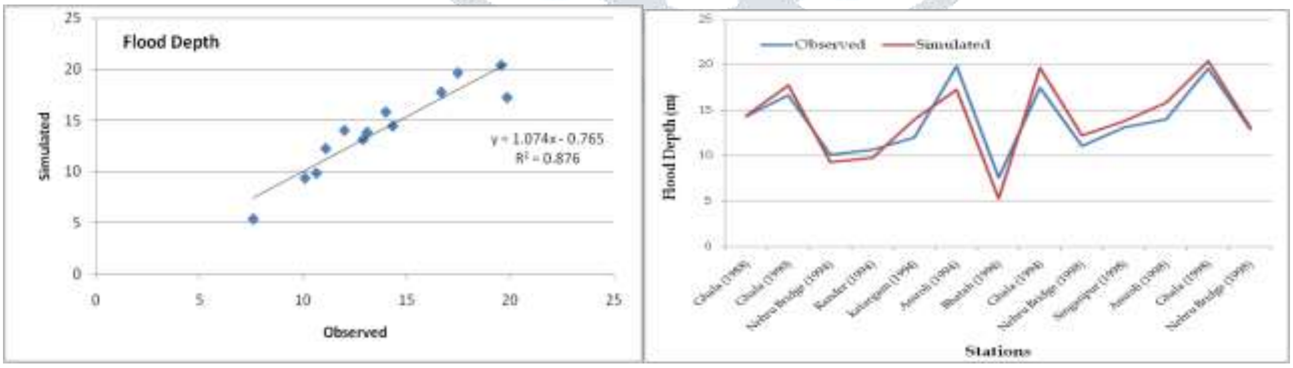


Figure 9 Relationship curves

The result found from HEC-RAS model has been verified on historical flood such as, 1998 and 2006. Total 13 stations flood depth data have been collected from the field and the irrigation department. Result validation analysis has been done and found the simulated model is quit good with a 10% error.

5. Conclusion

River discharge, river stage, and riverbank inundation data have been used to develop empirical relationships relating these three hydrologic parameters. The Simulation of flood inundated area along the main tributary under the specified flood scenarios such as 2,5,10,25,50 and 100 years was carried out. The watershed area of the Lower Tapi river basin (within Ukai dam to the Arabian Sea) has been successfully modeled, a map showing the flooded areas along the Tapi river has been delineated. The extent of flooding in the LTB will increase owing to higher peak flows caused by a large amount of rainfall in the upper catchment or high-water release from Ukai dam. Figure 6 shows the floodplain results for the same section of the LTB for the deferent return periods. HEC-GeoRAS creates the geometry of river and provides results that properly reflect the geometric characteristics in the basin. HEC-RAS Flood plain and flood extend mapping, integrated HEC-RAS with GIS is a powerful tool can simulate with appropriate parameters gives the best result comparatively another module. The flood plain contributed in some mismatch between the model results and the surveyed data collected from the field due to continuously change topographical feature. The submergence area obtained by above procedure can be used in infrastructure, agriculture, urban flood risk assessment.

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