Semi-arid River Basin Flood: Causes, Damages, and Measures

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Abstract Due to climate change, the semi-arid region received rainfall of 1 in 100 year return period which causes a flood in the region. In the present study, analysis of July 2017 flood of the semi-arid region of Banas River basin caused due to heavy rainfall has been carried out. The Dantiwada and Sipu dams on Banas River and tributary of Banas River received heavy inflows during this period. This resulted in short duration huge releases from the dams. These releases were more than carrying capacity of the river which resulted in flooding of adjoining areas. 226 numbers of villages including two major districts were inundated. 224 people lost their lives, and around 34,000 people have been evacuated. Total damages worth of Rs. 1653 crore (16.53 billion Rs.) has been reported. In the present study, reasons for flooding, damage assessment, and measures to check flooding using 1D hydrodynamic modeling have been presented. MIKE Hydro River has been used for the computation of water surface elevation along 123 km river reach. The 1D hydrodynamic model developed from cross-sections extracted from the DEM. The outcome of the present study recommends careful operation of Dantiwada and Sipu dams as well as the relocation of people living in the floodplain areas of Banas River.

Keywords Semi-arid · Flood · 1D · MIKE · DEM · Dam

1 Introduction

India has witnessed a rapid growth in its population in the past 50 years, which cause changes in land-use pattern, cropping pattern, water storage, irrigation, and drainage [1]. Due to this, hydrological cycle of semi-arid regions has been modified [2]. The impact of climate change which includes increased precipitation and storm intensity,

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particularly in semi-arid region resulted into the increased chances of flooding in the cities located on the banks of the river and in the floodplain [3, 4]. Floods are most frequently occurred natural disaster in India [5, 6]. It affects the emotional, social, as well as economic life of the peoples who are affected by it [6, 7]. Floods are mainly caused by excess rainfall [8] which generates more surface runoff [9]. But anthropogenic activities has increased the risks of flooding [10, 11], for example, by the construction of roads and bridges on the land which were previously occupied by vegetation can reduce the infiltration capacity of the land, and thus, it generates runoff more quickly [12]. Planning decisions such as the construction of houses in floodplains can also increase the risk of floods [13]. Thus, reliable hydraulic models are required to accurately predict the water level and flow at various locations along the river [14]. Generally, levels are predicted along the river, and inflows are predicted for reservoirs [15]. Apart from that, for effective management of future flooding, insurance studies, and for development of risk maps, prediction of water levels are essential. Thus, the estimation of water levels in floodplains is of prime importance. Stages in the river and its corresponding discharges and various other parameters are dependent on the channel roughness. Hence, prediction of channel roughness also plays a major role in the study of open channel flow, especially in hydraulic modeling [16]. The end-to-end flood forecasting system plays a very significant role in floodplain management. With the advancement in the computer technology, computation of river hydraulics and modeling became easier now by use of various one-dimensional, two-dimensional, and three-dimensional models, though one-dimensional (1D) models are more popular due to their simplicity for setup and calibration [17]. The prediction of stage and discharge in the river with time is considered as the flood warning parameters in any river which can be computed using St. Venant equation [18, 19]. It is very difficult to generate exact solutions of the St. Venant equation. However, approximate solutions of this equation can be obtained by using numerical methods with appropriate assumption. Methods like finite difference method (FDM), finite volume method (FVM), and finite element method (FEM) can be used to convert St. Venant equation in the form of equivalent finite difference equations, and then the solution can be generated by the different scheme [20]. Many studies have been conducted to develop various hydraulic model based on the above-mentioned method for computational river hydraulic in the past decades [21]. The different available hydraulic models like MIKE 11, HEC-RAS, etc. are using these methods for computation of flow and level of water at different grid point along the river [22, 23]. The comparative performances of these models with advantages and limitations have been investigated by many researchers [24, 25].

Studies on one-dimensional modeling for river hydraulics have certain limitations in India due to the absence of decent quality of surveyed data. The scarcity of the observed stage and flow hydrograph and limitation of surveyed cross-sections are the main reason for the restriction of studies on the river hydraulic in India [21]. The present study was carried out for the semi-arid region of Banas River basin located in the northern part of the Indian state of Gujarat which is flooded in 2017 because of change in climatic conditions. Due to less number of available surveyed river cross-section in the region, hydraulic studies have not been carried out in that zone.

In the present study, river cross-sections have been extracted from Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) of 1-arc second using MIKE Hydro River software to overcome the problem of less available surveyed river cross-sections. These cross-sections were used for development of a 1D hydrodynamic model for the Banas River using MIKE Hydro River and were calibrated for 2017 flood. The calibrated model was used to compute the water level to identify critical river reach and the highest overflowing points along the 123-km reach of the river for peak discharges corresponding to 2017 flood event for flood-control measures.

2 Study Area and Data Collection

The Banas River rises near Pindwara village in Sirohi district of Rajasthan at an elevation of 372.5 m above mean sea level. The river flows in a southwesterly direction from the origin, travels a total length of 266 km, and ends into little Rann of Kutch. The basin lies between the geographical coordinates of 71° 15′ to 73° 15′ east longitudes and 23° 30′ to 24° 55′ north latitudes. It is bounded by Luni basin in the north, Saraswati basin in the south, Aravalli hill ranges in the east, and finally the Arabian Sea in the west. The Banas River is trans-boundary river which drains an area of 8,674 km^2 out of which nearly 38% lies in Rajasthan state and the remaining 62% falls in Gujarat state. In Fig. 1, the index map of the Banas basin has been shown along with latitudes and longitudes, i.e., where the basin is located in India. It also shows the digital elevation of Banas basin and locations of the tributary, dam site, Narmada main canal, and various gauging stations. The elevation of basin changes from 1.81 to 1691.77 m with a mean elevation of 245.41 m and standard deviation of 200.02. There are two major hydraulic structures in the Banas River basin, namely Dantiwada and Sipu dams. Dantiwada dam is on Banas River at chainage of 105 km from its origin with a catchment area of 2,862 km^2. Sipu dam is on Sipu River (a tributary of Banas River) at a chainage of 60 km from its origin with a catchment of 1222 km^2. Releases from these dams are used for irrigation purpose.

The study area for the present study starts from the downstream of Dantiwada and Sipu dams. Both Banas and Sipu River meets at Bhadath village near Deesa district, i.e., around 13 km from Dantiwada and Sipu dams. From the digital elevation of the basin, it can be clearly identified that the region after the confluence of the river is almost flat with low elevation which makes this area more vulnerable to flooding. The end boundary of the study area is taken as Kamalpur gauging station which is located in Banas River near Kamalpur village, i.e., 123 km from Dantiwada dam. The 1D hydrodynamic model was calibrated for July 2017 floodwater level at Umbari gauging station which is located in Banas River near Umbari village, i.e., 53 km from Dantiwada dam.

The data for the present study was procured from dam authorities, Central Water Commission (CWC-Gandhinagar), and river gauging section offices. The present study area starts from Dantiwada and Sipu dams, and the structural details and

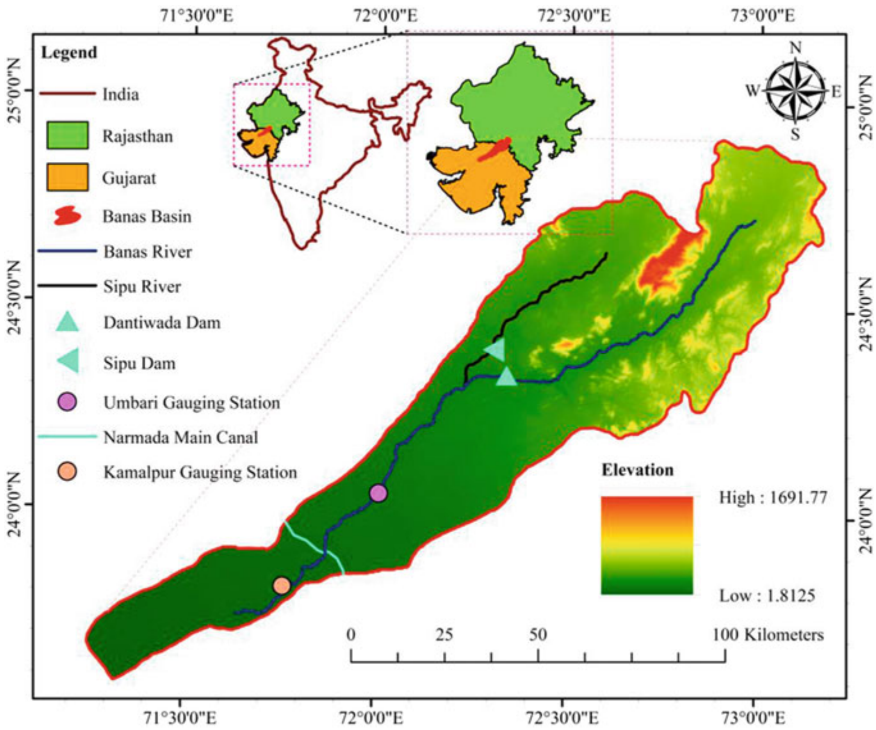

Fig. 1 Index map of Banas basin with DEM and location of structures

releases from these two dams were obtained from the respective dam authorities. The cross-sectional details and flow hydrograph for the Kamalpur gauging station were obtained from CWC while cross-sectional details and flow hydrograph for Umbari gauging station were obtained from river gauging section office, Palanpur. The SRTM DEM of the 1-arc second resolution was downloaded from the United States Geological Survey (USGS) for extraction of cross-sections. The flood damage data was obtained from different government reports and newspaper articles.

3 Methodology

The methodology includes the identification of causes of floods, development of 1D hydrodynamic model, flood damage assessment, and preventive measures. Figure 2 shows the flowchart depicting methodology. The causes of the flood have been identified firstly by means of rainfall data, topography of the region, newspaper articles, and government reports. The second step was to collect the required data for the present study which was procured from the competent authorities and public survey.

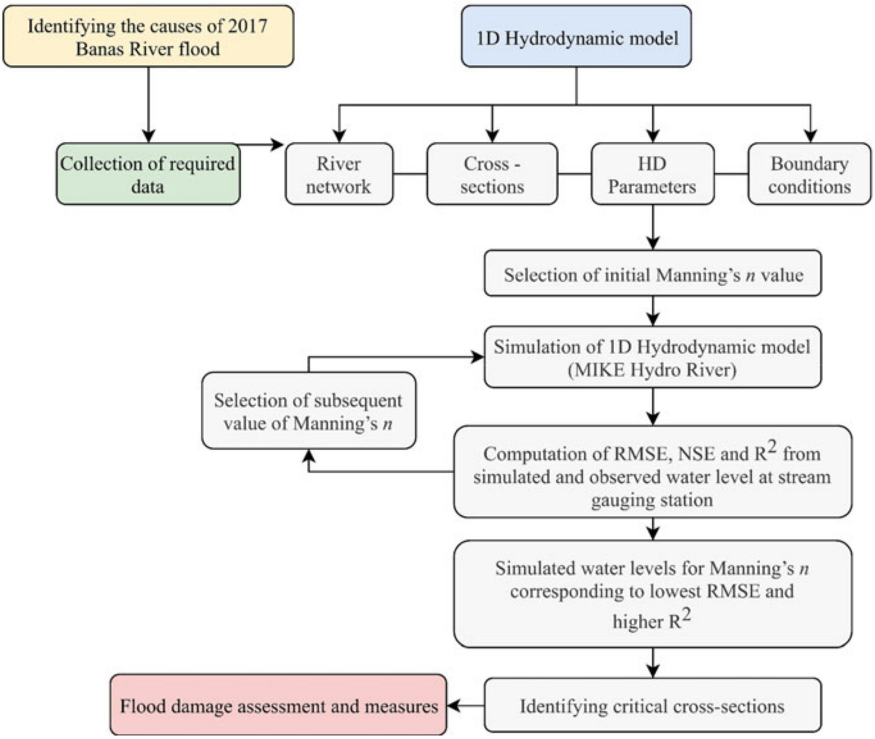

Fig. 2 Flowchart depicting methodology

The 1D hydrodynamic model has been developed for 123 km of river reach using MIKE Hydro River tool. The SRTM DEM downloaded from the United State Geological Survey was pre-processed using Spatial Analyst Tools featured in ArcGIS Desktop v10.5. This pre-processed DEM then imported in MIKE Hydro River for tracing of river reach and generation of the cross-section. Cross-sections for the model have been extracted from DEM by using "auto-generate cross-sections" tool of MIKE Hydro River. The generated cross-sections were then modified according to available surveyed cross-sectional data at some locations. The time step is taken as 10 s, and grid spacing is taken as 250 m for stability assurance. There are three open boundary conditions, and time series of releases of the Dantiwada and Sipu dams were given as upstream boundary conditions while the observed stage hydrograph at Kamalpur gauging station was given as downstream boundary condition. The initial value of Manning's n is taken as 0.03 for the simulation of the 1D hydrodynamic model. The model is calibrated for July 2017 flood period for observed stage and flow hydrograph at Umbari gauging station by changing global roughness coefficient. The range of Manning's n was taken from literature [26] for calibration of the model. The assessment of performance of the model has been carried out by calculation of performance indices, i.e., root mean square error (RMSE), Nash–Sutcliffe efficiency

(NSE), and R^2 (coefficient of determination). Finally, the critical cross-sections have been identified from the calibrated model for 2017 flood.

The flood damage assessment is comprehensively collected from government reports, newspaper articles, government authorities, and questionnaire survey to local people. The preventive measures have been identified from the 1D hydrodynamic model and field investigations.

4 Results and Result Analysis

4.1 Causes of 2017 Banas Flood

The Banas River was flooded in July 2017 due to unprecedented inflow in the river. The Mount Abu, Deesa, Banaskantha, and Dantiwada regions of the catchment received a rainfall of 1473 mm, 269 mm, 150 mm, and 490 mm respectively within 48 h, i.e., on 24/7/2017 and 25/7/2017, while the annual rainfall of the basin is 921 mm. The historical data shows that the rainfall occurred on the 23rd and 24th of July 2017 was the maximum of the past 112 years. This high rainfall was due to activation of low-pressure system in Bay of Bengal and Arabian Sea simultaneously, which is a rare phenomenon. In addition to it, Mount Abu being hilly region produced high runoff received at dam site within shorter time interval. The dam was filled up to rule level due to local rainfall. These circumstances forced the dam authorities to make a decision of sudden releases from the dams. The flow hydrograph and dam water level for Dantiwada and Sipu dams are shown in Figs. 3 and 4. Being a semi-arid region, the basin area and depth of the river are almost flat after the confluence

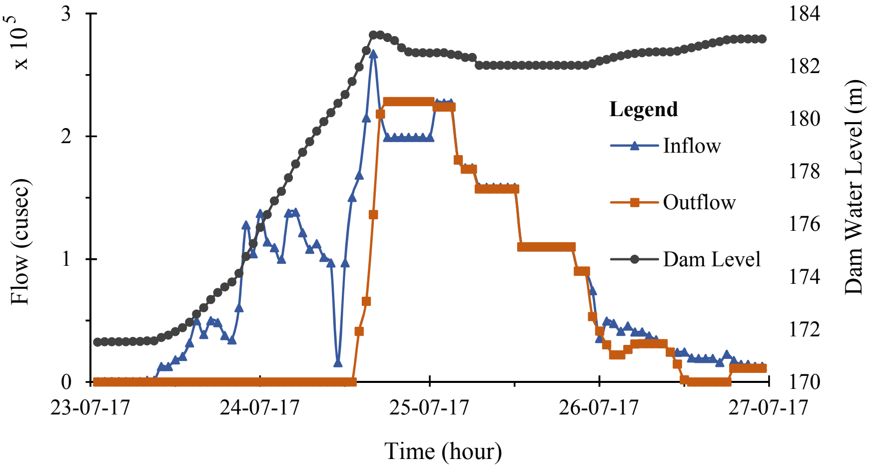

Fig. 3 Flow hydrograph and dam water level at Dantiwada dam

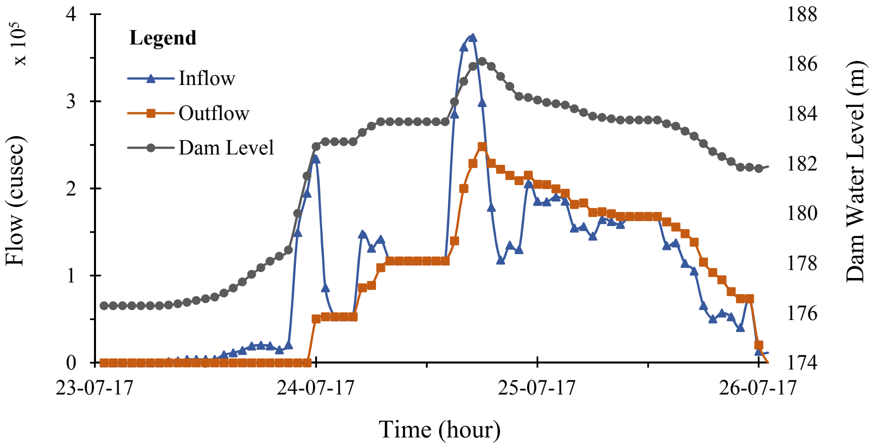

Fig. 4 Flow hydrograph and dam water level at Sipu dam

of Banas and Sipu River (can be identified from Fig. 1 also). Because of these, the carrying capacity decreases from downstream of the confluence of the river. The depth of the river near Mota Jampur and Khariya village (i.e., 78 km downstream of Dantiwada dam) is around 2–3 m, i.e., nearby villages and the bed of the river are at almost same elevation. The water in this region has a tendency to spread in the lateral direction which resulted in severe flooding. In addition to it, Narmada main canal which is having total depth of 8 m and constructed partly above and partly below the ground was also breached at various locations near Thara village. The cross-drainage works of Narmada main canal were not sufficient to pass the floodwater, which resulted in an increase of inundation of flood depth.

4.2 Results of 1D Hydrodynamic Model

The 1D hydrodynamic model has been calibrated and validated with reference to observed data for the flood period of July 2017. The maximum release from Dantiwada dam was 6465.9 m^3s^{-1}, and from Sipu dam, it was 7025.04 m^3s^{-1}. These maximum releases were at the same time, i.e., 24th July 2017 at 18:00:00 h which makes highest flow of 13,490.94 m^3s^{-1} in the river. During the calibration process, the global value of Manning's n has been changed to match the observed and simulated stage hydrograph at Umbari gauging station. Table 1 represents the results of observed and simulated stage value of Umbari gauging station with different roughness coefficient. Finally, the calibrated value of Manning's n was obtained as 0.02 with RMSE (m), NSE and R^2 value as 1.618, 0.695 and 0.891 respectively for observed and simulated stage hydrograph.

Table 1 Comparison of stage hydrograph for different Manning's *n*

Manning's *n*	0.020	0.022	0.024	0.026	0.028	0.030
RMSE (m)	1.618	1.661	1.676	1.727	1.773	1.868
NSE	0.695	0.673	0.665	0.639	0.613	0.559
R^2	0.891	0.897	0.907	0.910	0.911	0.889

Figure 5 shows the graphical representation and scattered plot of observed and simulated stage value with Manning's roughness coefficient, $n = 0.02$ at Umbari gauging station for 2017 flood. It can be observed from Fig. 5 that the simulated stage values are higher than the observed ones which may be due to the presence of Narmada main canal which is not considered in the present study. Also the bed of river is made up of fine sand which is having tendency to infiltrate the water in low discharges, and as the developed 1D hydrodynamic model does not consider the amount of infiltration, the simulated water level results are on higher side then the observed one.

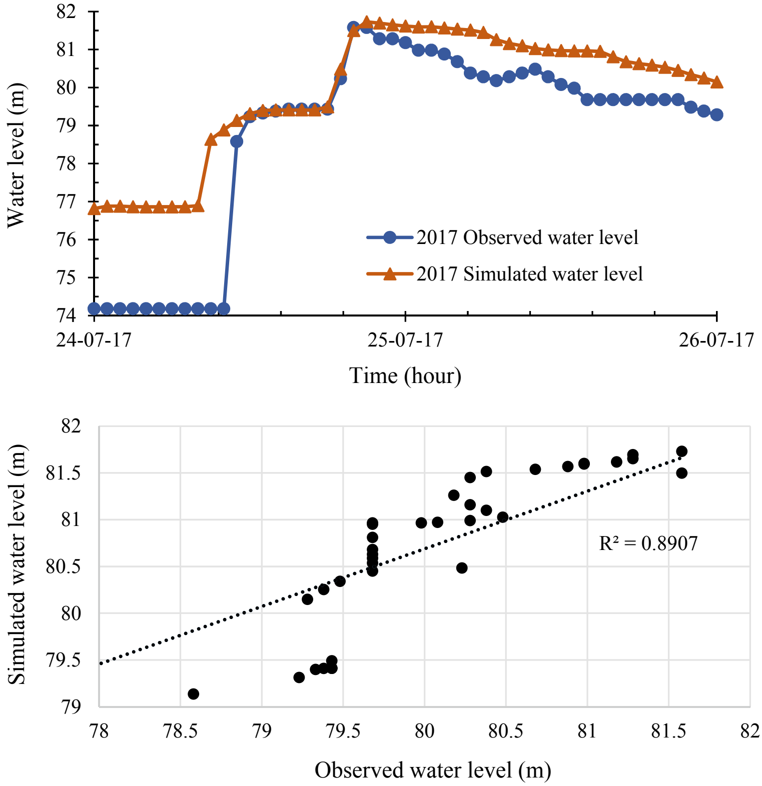

Fig. 5 Comparison and scatter plot of observed and simulated stage hydrograph

Table 2 Height of water level above river bank at all cross-sections

Cross-sectional chainage (m)	Right bank R.L. (m)	Left bank R.L. (m)	Water level (m)	Height of water level above	
				Right bank (m)	Left bank (m)
82,619	118.786	117.131	123.148	4.362	6.017
44,491	77.444	76.663	81.742	4.298	5.079
23,433	52.131	53.1	56.753	4.622	3.653
19,760	49.475	48.006	54.376	4.901	6.37
17,895	48.35	48.006	52.128	3.778	4.122
13,921	44.236	43.349	48.476	4.24	5.127
12,169	43.038	41.441	47.803	4.765	6.362

From the calibrated and validated 1D hydrodynamic model, the critical (most overflowing) cross-sections have been identified. Table 2 shows the reduced level (R.L.) of left and right bank with chainage and water level for critical cross-sections. The most critical cross-sections identified from the water surface elevation profile of model are located at (i) chainage 82,619 which is Deesa Taluka located at downstream of the confluence of Banas and Sipu River, (ii) chainage 44,491 which is near Umbari village, and (iii) chainage 19,760 which is near Khariya and Mota Jampur village. The width of the river near confluence is around 3 km while it becomes around 1 km near the Deesa Bridge located at chainage 82,619, which makes this area more vulnerable to flood. The Deesa Taluka was fully submerged due to 2017 flood in Banas River which has been reported by local media as well as government offices. The width of the river near Umbari village located at chainage 44,491 also decreases, and the surrounding regions are almost at a same elevation which causes a flood in this region. The highest overflowing cross-section which is located at chainage 19,760, near Mota Jampur and Khariya village where the depth of the river is around 2–3 m. The Khariya and Mota Jampur village located at just upstream of the Narmada main canal. The canal is partly above the ground level which causes the obstruction to floodwater. Due to this, the upstream area of Narmada main canal is inundated.

4.3 Flood Damages

Due to the floods, the livelihoods and lives have been affected in the region. The damages to roads, national- and state-level highways, railways, and airports because of flood have impacted education and public transportation as well. 550 panchayats roads, 156 state highways, and 5 national highways were affected due to Banas flood in 2017. For the rescue of villagers, National Disaster Response Force (NDRF), Army, and Air Force were also deployed with the State Disaster Response Force and fire brigade personnel. As per the officials of state administration, 54,517 people were shifted to safe areas due to flooding of low-lying areas. According to government official reports, about 4333 villages having an agricultural area of 10.98 lakh hectares and 2431 villages having horticulture area of 16,808 hectares were affected due to 2017 floods in northern Gujarat. Devastating floods in parts of Gujarat damaged agricultural crops worth Rs. 867 crore, while horticulture damage stands at Rs. 9.71 crores. As many as 6.44 lakh farmers have faced agricultural crop losses and about 4989 farmers have faced loss in horticulture crop. Almost 25 percent of kharif crops like groundnut, cotton, pulses, castor, cereals, and guar have been lost because of torrential rain and flooding in the semi-arid region of Gujarat. The electricity supply of 492 villages has been affected, out of which 418 villages are in Banaskantha district. As per the results of extensive survey for damage assessment by the state government, total payable relief for land damage, agriculture, and horticulture lost stands at Rs. 1653 crore. Cattle loss stood at 14,300 while more than 200 human lives were lost during the 2017 monsoon season. 18 members of the same family found dead in Khariya village in Banaskantha because of Banas flood in 2017.

5 Conclusions

Following outcomes can be summarized from the present study:

Due to activation of low-pressure system in Bay of Bengal and Arabian Sea simultaneously, the Mount Abu, Deesa, Banaskantha, and Dantiwada regions of the catchment received a maximum of the past 112 years rainfall of 1473 mm, 269 mm, 150 mm, and 490 mm respectively within 48 h, i.e., on 24/7/2017 and 25/7/2017, while the annual rainfall of the Basin is 921 mm. The Dantiwada dam received an inflow of 267,216 cusecs, and at the time, dam was already filled up to rule level, i.e., 182.5 m due to local rainfall on 24/7/2017. Due to this, the authorities were forced to release inflowing water as a direct outflow in the river for the safety of the dam. The Sipu dam received an inflow of 373,329 cusecs on 24/7/2017 which cause the dam water level 186 m (i.e., 4 m above rule level). So for the safety of the dam, all the gates were kept open releasing nearly 2 lakh cusecs of water. The one-dimensional hydrodynamic model has been developed for Banas River reach from downstream of Dantiwada and Sipu dams up to Kamalpur gauging station. The maximum releases from Dantiwada dam were 6465.9 m^3s^{-1}, and from Sipu dam, it was 7025.04 m^3s^{-1}. These releases were at same time which makes highest flow of 13,490.9 m^3s^{-1}. The developed model has been calibrated for 2017 flood event and identified best performance for Manning's n value of 0.02. The performance of the 1D hydrodynamic model has been assessed by different performance indices like RMSE, NSE, and R^2. The obtained value of RMSE, NSE, and R^2 for July 2017 flood is 1.618, 0.695, and 0.891, respectively. The critical cross-sections have been identified from 1D hydrodynamic model which shows that the cross-sections of the river at chainage 82,619 (i.e., near Deesa Taluka), 44,491 (i.e., near Umbari village), and 19,760 (i.e., near Narmada main canal) are most critical sections.

Following measures are proposed to mitigate the flood conditions:

The operational policies of both the dam should be revised to have a flood-control reservation for the accommodation of floodwater. The planning policy should be formed to stop the habitat settlement and construction of roads in flood plains. The capacities of available cross-drainages in Narmada main canal should be increased to safely pass the floodwater to the downstream of the river.

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