MAUSAM, **70**, 4 (October 2019), 815-824

551.509.331 : 556.166

Assessment of parameters and preparation of hydrodynamic model for lower Damodar Basin using geomatic techniques

RAVINDRA KUMAR SINGH, VASANTA GOVIND KUMAR VILLURI and SRINIVAS PASUPULETI*

Indian Institute of Technology (ISM), Dhanbad – 826 004, India

(*Received 21 December 2018, Accepted 15May 2019*)

***e mail : srinivas@iitism.ac.in**

सार - बाढ़ के जोखिम वाले संवेदनशील स्थानों की पहचान के लिए उन प्राचलों का आकलन करना आवश्यक है जो बाढ़ को प्रभावित करते हैं। वर्तमान अध्ययन में पश्चिम बंगाल के दामोदर बेसिन में बाढ़ से होने वाले नुकसान को प्रभावित करने वाले पैरामीटर की पहचान की गई है। इसके अलावा, वर्तमान अध्ययन दुर्गापुर बैराज से जमालपुर तक के क्षेत्र की पहचान करता है जो दामोदर नदी के कारण बाढ़ के लिए अतिसंवेदनशील होते हैं। बाढ़ वाले वर्ष के लिए उच्च रिज़ॉल्यूशन वाले डिजिटल एलिवेशन मॉडल (डीईएम) से निकाले गए क्रॉस-सेक्शन का उपयोग MIKE HYDRO RIVER हाइड्रोडायनामिक मॉडल में किया गया था। मैनिंग के गुणांक (n) का उपयोग मॉडल अंशांकन पैरामीटर के रूप में किया गया था जिसमें मॉडल अंशांकन प्रक्रिया के दौरान 0.02 से 0.05 तक का अंतर था। मैनिंग के n मान के लिए जमालपुर वर्षा मापन साइट पर 0.035 का पूर्वानुमान किया गया था और जल स्तर का अच्छी तरह से मिलान किया गया था। यह देखा गया कि अत्यधिक उफान के दौरान दामोदर नदी अपने तट को पार कर गई। इसके अलावा, मॉडल परिणामों के आधार पर, नदी में आने वाली बाढ़ को नियंत्रित करने के लिए कुछ सुझाव दिए गए हैं।

ABSTRACT. The flooding risk hotspots identification needs the assessment of parameters which influence the flood. The present study identifies the parameters which influence the flood damage in lower Damodar basin in West Bengal. Also, the present study identifies the area from Durgapur barrage to Jamalpur which are susceptible to flooding due to the Damodar River. Extracted cross-sections from high resolution Digital Elevation Model (DEM) for flood year were used in MIKE HYDRO RIVER hydrodynamic model. Manning’s coefficient (n) was used as model calibration parameter which varied from 0.02 to 0.05 during the model calibration process. For Manning’s n value of 0.035 predicted and observed water level match well at Jamalpur gauging site. It was observed that during peak flow Damodar river overtopped its bank. Further, based on the model results, some suggestions are purposed for controlling the riverine flooding.

Key words – DVC, HEC-RAS, DEM, CWC, Hydrodynamic model.

1. Introduction

Many countries of the world are susceptible to floods, which is one of the most devastating natural calamities. Flood distresses more population relative to other natural calamity as world’s maximum settlements generally located along water bodies (Sanders, 2017). Major parts of India specifically eastern parts are under threat of flooding during the southwest monsoon whereas in Northern Himalayan region cloudburst event causes serious flash floods (Villuri *et al.*, 2018). Climate and physiography are two different but important sets of parameters that decide hydrological characteristics of a drainage basin or the flow of the stream (Ghosh and Guchhait, 2016). Basic causes of flood are poor drainage system in flat pains or low laying areas, siltation in the river with time and improper flood management approach (Pramanik *et al.*, 2010). In southern districts of West Bengal, Damodar river is the main contributor of floods during the southwest monsoon. Since the Damodar river basin is located in the major rainstorm zone and also with its unique physiographic, it has a good potential for extreme floods (Ghosh and Guchhait, 2016). During 1950 Damodar Valley Corporation (DVC) of India, constructed a number of large and medium-sized dams on the upstream catchment of Damodar river basin to regulate floods and at the same time for different purposes. With the passage of time dams lost its previous capacity due to siltation. Also carrying capacity of Damodar river diminished due to siltation and at the time of peak monsoon, excess water overflows its banks in the lower segment of the basin.

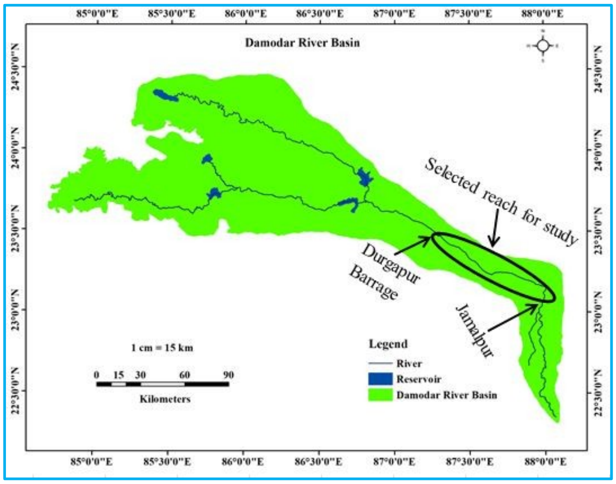


Fig. 1. Location map of the Damodar river basin

Literature (Quiroga *et al.*, 2016; Pappenberger *et al.*, 2006**;** Jung and Merwade, 2011) suggests that hydraulic models play an important role in structural and non-structural measures of flood management by identifying flooding risk hotspots. Thus, by understanding the magnitude of floods hazards, decision planners select about how to distribute resources to combat flood disasters (Timbadiya *et al.*, 2014). Developments in numerical modeling approach, accessibility of remote sensing data and advancement of computational systems makes the flood inundation and river hydraulics study easier to considerable extent (Pramanik *et al.*, 2010; Hsu *et al.*, 2003**;** Aronica *et al.*, 1998**;** Pappenberger *et al.*, 2005; Bates and Roo, 2000; Bates *et al.*, 2003). The commonly applied models like HEC-RAS (Hydrologic Engineering Center-River Analysis System), MIKE11 and LISFLOOD-FP uses the method of finite difference. In the finite difference method, the solution is obtained at a number of discrete points and for a number of discrete times (Di Baldassarre *et al.*, 2010). However, the choice of the modeling approach in river hydraulics study basically depends on the technical approach of the problem (Dyhouse *et al.*, 2003; Dung *et al.*, 2010). Resource availability is the major issue in this type of studies because such studies are highly influenced by topographic data, geometric configuration and modeling approaches. Field data availability is also a vital issue in the modeling study. The combination of GIS with the hydraulic model is the latest progress in the river hydraulics (Pramanik *et al.*, 2010; Cook and Merwade, 2009; Correia *et al.*, 1998; Dutta *et al.*, 2000; Renyi and Nan, 2002). Nowadays, Remote sensing technology has become exceptionally significant in case of consistent and decisive mechanisms for awareness and flood management. A wide range of preventive actions can be recognized and executed to diminish or curtail the effect of flooding in flood prone areas (Merwade *et al.*, 2008; Sindhu and Durga Rao, 2016).

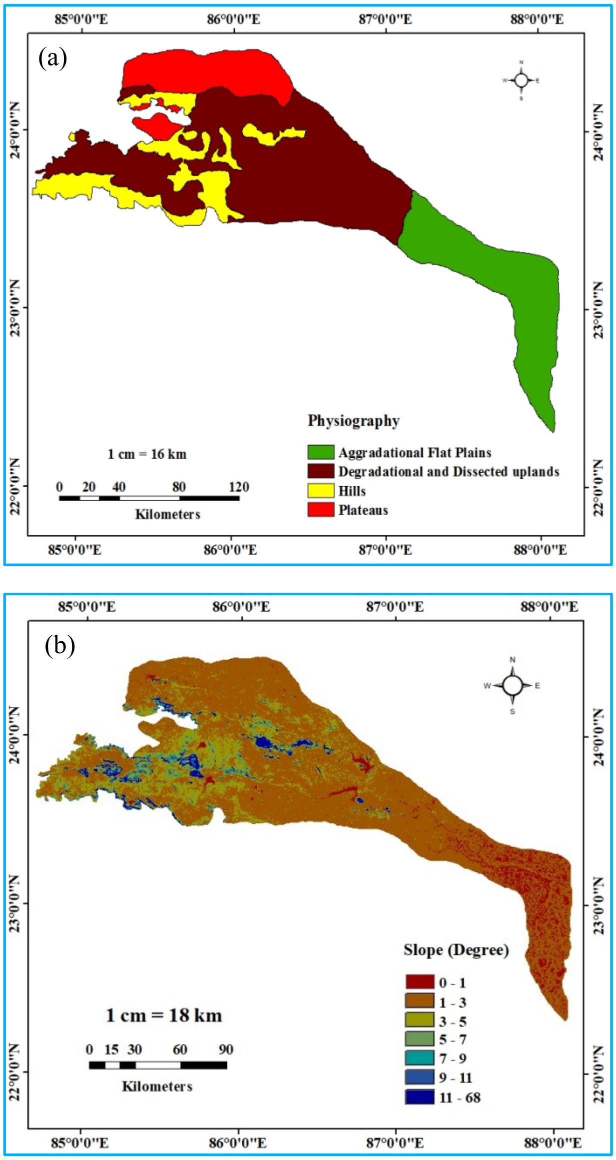
Keeping in view of the above obstruction and the resource availability the present study undertake the flood problem of lower Damodar river. The aim of this study is to highlight the parameters influencing the floods in lower Damodar basin and to check temporal changes in cross-sections between Durgapur barrage to Jamalpur in lower Damodar basin. Further, to identify the area between Durgapur barrage to Jamalpur in selected reach of Damodar river which is susceptible to flooding by hydrodynamic modeling. For this forty-seven river cross-section extracted from high resolution CARTOSAT-1 DEM was used in the 1-D MIKE HYDRO RIVER model which was developed by DHI Denmark. Model calibration and validation were done for the year 2007 and 2009 respectively.

2. Study area

The Damodar river basin geographical lies between 22°15' to 24°30' N latitude and 84°30' to 88°15' E longitude. The upper catchment of basin spreads in the state of Jharkhand whereas lower catchment in state of West Bengal with a total catchment area about 24,235 sq. km. Source of the Damodar river is in the Palamu hills of Chotanagpur in Jharkhand at about 609.57 m above mean sea level. Damodar river flows along south-easterly direction for 540 km before joining to Hooghly river. The lower part of the basin affected by the floods due to heavy rainfall and huge runoff volume generated in the upper catchment which consists of two drainage systems: (*i*) Damodar drainage system and (*ii*) Barakar drainage system. P. K. Sen (1991) termed the stretch below the joining of the Damodar River and the Barakar river as lower Damodar. The length of the Lower reach of Damodar river is approximately 250.15 km (Bhattacharyya, 2011)**.**The selected reach of the Damodar river for the present study is from Durgapur barrage to the Jamalpur site. The location map of the Damodar river basin is shown in Fig. 1. This particular reach is selected for the study purpose because Durgapur Barrage is the last hydraulic structure that controls the river flow in the downstream segment of the Damodar river and also due to availability of data like discharge and gauge.

2.1. *Data*

Daily gauge data and discharge data at Durgapur barrage and Jamalpur were collected from Central Water Commission (CWC) and reservoir storage data was collected from DVC. High resolution CARTOSAT-1 DEM was procured from National Remote Sensing Centre Hyderabad. Measured river cross-section collected from



Figs. 2(a&b). (a) Physiography map and (b) Slope map

DVC. Using high resolution CARTOSAT-l DEM with spatial resolution of 10 m cross-sections at different locations of the Damodar river were extracted which were forty seven in number. Extracted Cross-sections were modified with field measurement before applying them in the hydrodynamic model namely MIKE HYDRO RIVER.

2.2. *Methodology*

The present work is divided into two section. First part discuss the parameters influencing the damage due to flood and temporal changes in river cross-sections. Second part on hydrodynamic modeling in which MIKE HYDRO RIVER model was run to simulate the discharge and water level on Damodar river during flood year. First step consists of a collection of information, reports, previous literature and data from various government agency. The second step of study consists of preparation of various thematic layers using Arc GIS software and graphs of influencing parameters of floods. Next step consists of analysis and interpretations of generated thematic layers and map of influencing parameters. After that hydrodynamic model was run using DEM extracted cross-sections for flood year. On the basis of output interpretations, conclusions were drawn with some suitable recommendations.

3. Parameters influencing the damage due to flood

3.1. *Physiography and slope*

The Damodar river basin is composed of two different land systems. The upper segment of Damodar river basin is their regular topography of simple stony hills, plateaus and divided uplands with sloping land which are rich in mineral resources whereas the lower segment of the basin that lies in West Bengal is a flat, fertile stretch of land made of layers of alluvial soil. The physiography of the Damodar river basin is shown in Fig. 2(a). Degradational and dissected uplands cover 50% whereas hills cover 13% and plateaus cover 15% areas of the river basin. These features mainly lie in the upper segment of the basin which aids in high runoff in the upper part of the basin. On the other hand, 22% area of the basin is a flat plain which is basically part of a lower segment of the basin. The slope of the basin varies from flat to the very steep slope (0-68°). Upper reaches are steep to gently slope due to the presence of hills and plateaus whereas lower reaches are gently sloping to nearly flat due to the presence of flat plains (0-3°) which is shown in Fig. 2(b). Due to gentle to nearly flat longitudinal slope and presence of flat plains in the lower segment, the drainage efficiency is very low in the downstream portion of Damodar river basin. So physiography of the basin aids in a high runoff in the upper part of the basin whose flood caused huge damage in the lower catchment of the basin.

3.2. *Rainfall and climate*

The annual rainfall over the basin varies between 1000 mm and 1800 mm which depends on the variation of topographical features and atmospheric condition all over the basin. From the past record of 60 years rainfall in lower Damodar basin including district of Burdwan, Hooghly and Howrah it is observed that average rainfall in monsoon season (June-October) is 1400 mm whereas it increases to more than 1800 mm during flood year like in 1978, 1984, 1995, 2000, 2007, 2009 and 2013. The

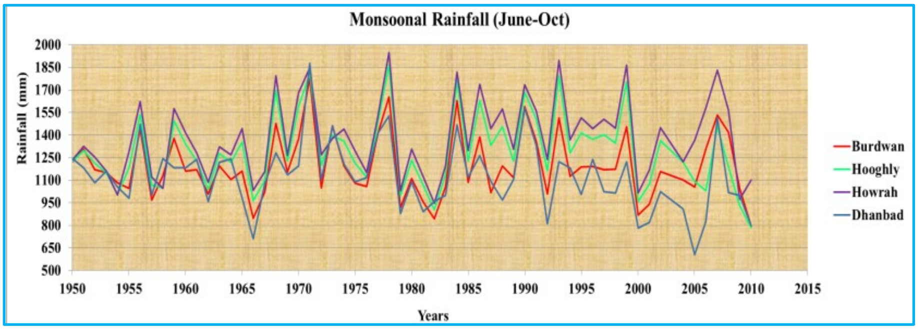


Fig. 3. Annual monsoonal rainfall (*Source*: IMD)

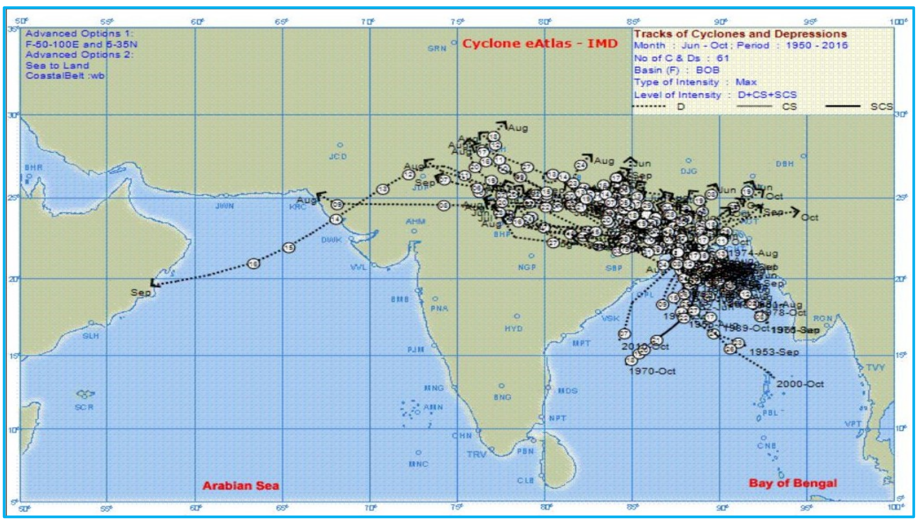


Fig. 4. Tracks of cyclone over Bay of Bengal (*Source*: IMD, RMC, Chennai)

rainfall in monsoon season is shown in Fig. 3. Damodar basin experiences high rainfall due to Southwest Monsoon in every year. The cyclonic disturbance formed over the Bay of Bengal and by observing the tracks of the cyclones it can be seen that magnitude of the cyclones is strong in downstream catchment of the Damodar river basin as shown in Fig. 4. The heavy rainfall occurs in the southern parts of West Bengal due to the strong convergence of cyclones depression (Ghosh and Guchhait, 2016; Rao, 2001). Heavy continuous rainfall due to the cyclone is the basic cause of floods because huge amount of water collected on the surface flowing as runoff due to its upper physiography. The month of September and early October considered as a critical one for lower Damodar river because the entire major floods appeared in this season if there is heavy rainfall.

3.3. *Land use land cover (LULC)*

Runoff generated after rainfall is significantly decided by the land use/land cover pattern of that region. Anthropogenic activities which carried out on the land denotes the land use and natural cover of the land like vegetation water bodies tells about the land cover. Here LULC of only study area is shown in Fig. 5 not for the whole basin. From the LULC map of the selected reach, it is observed that 73% of the area under agricultural land close to the river bank. Settlement of the population occurred close to river and in the scattered form which covers 14% of the area. Forest, river and industrial area cover respectively 5%, 6% and 2% of the area. Due to the presence of flat, fertile stretch of land made of layers of alluvial soil and agriculturally productive, people settled close to the river and also encroached the floodplains for agricultural purpose which cause huge losses during flood times.

3.4. *Siltation and river cross-sections modifications*

Natural and Anthropogenic activities in a river system affect the morphology of the river. Rate of sediment transport, compositions of the bed materials, vegetation and other environmental factors will decide its morphology. Dam construction on the river is the human intervention that will affect the flow of the river consequently changes the fluvial system and forced it to

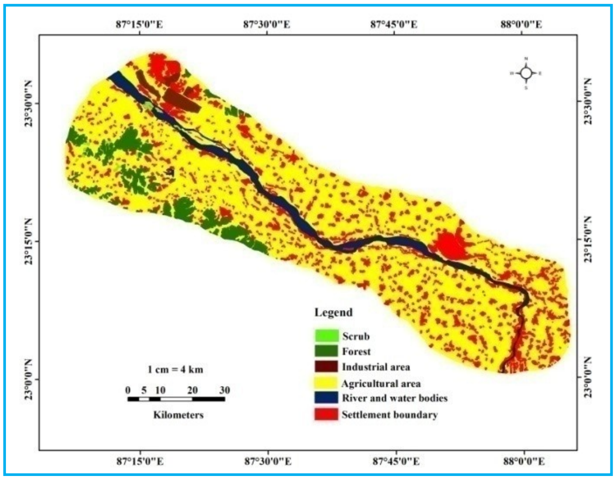


Fig. 5. LULC map of the study area

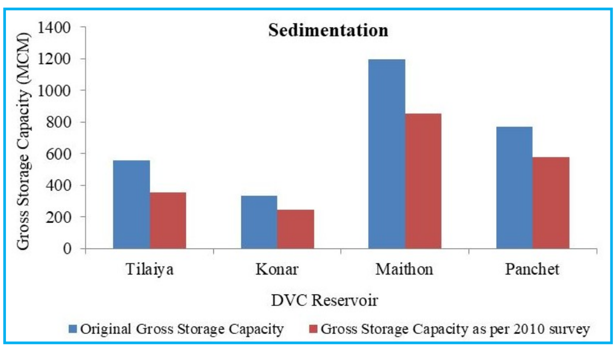
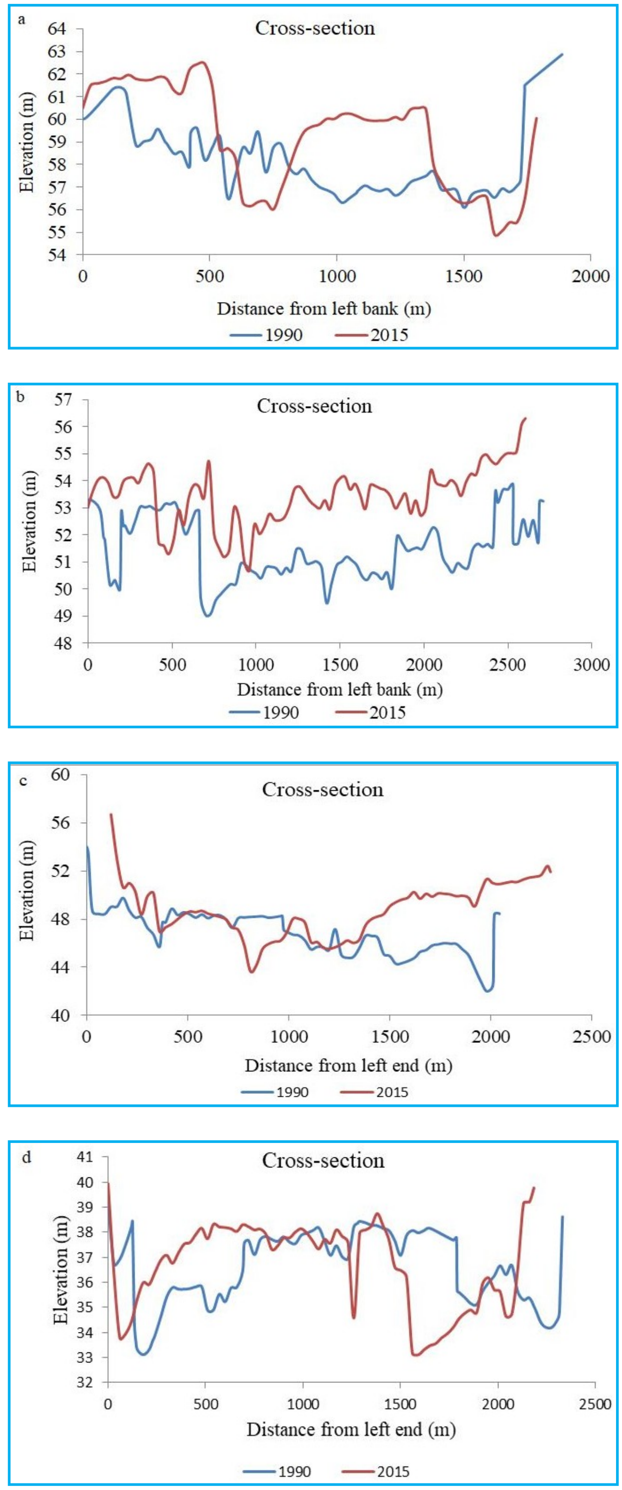


Fig. 6. Gross Storage loss in capacity of DVC reservoir (*Source*: DVC)

enter in a new equilibrium (Assani *et al.*, 2006). Flow of the Damodar river is controlled by upstream dams which change the morphology of river in lower reaches by affecting the rate of sediment transport. Due to the accumulation of sediments in the reservoir as river carries sediment along its flow storage capacity of reservoir get reduces with the passage of time. As per the 2010 survey, the gross storage capacity of DVC reservoir, namely Tilaiya, Konar, Maithon and Panchet reduces 36.5%, 26.30%, 28.50% and 25.20% respectively due to sedimentation which is shown in Fig. 6.

DVC conducted field survey on lower Damodar river in 2015 to check the temporal changes in river cross-sections due river regulation by anthropogenic activities and compared the field survey data of 2015 with that of 1990 of lower Damodar river. In selected reach comparison of 4 cross-sections are presented in Figs. 7(a-d) which shows reduction in cross-sectional area. The cross-sectional area reduces due to deposition of sediments in the river bed consequently the river bed rises. As the river bed rises due to sediment deposition consequently, it affects the carrying capacity of the river. Due to this river easily spills the bank during flood times and the adjacent area near to river get inundated. Location of DVC cross-sections of Damodar river on satellite image is shown by blue line in Fig. 8. Field photograph of aggradation



Figs. 7(a-d). Damodar river cross-sections (*Source*: DVC) process of Damodar river shown in Fig. 9. It is the reality that reducing carryings capacity of the river due to siltation, inadequate runoff storage systems are some of the factor which cause flooding in low laying areas.

4. Hydrodynamic modeling

4.1. *MIKE HYDRO RIVER model*

MIKE HYDRO RIVER a 1-D hydrodynamic model used in the present study was developed by Danish Hydraulic Institute. Model fully solves the St. Venant Equations, which is basically the conservation of mass and conservation of momentum equation.

St. Venant equations for 1-D flow are as follows (Chow *et al.*, 1998)

Continuity equation

$$\left[\frac{\partial q}{\partial x}+\frac{\partial A}{\partial t}=q_{in}\right]$$

Momentum equation

$$\frac{\partial q}{\partial t}+\frac{\partial}{\partial x}\left(\alpha\frac{q^2}{A}\right)+gA\frac{\partial h}{\partial x}+gAl_f=\frac{f}{\rho_w}$$

where, q = Discharge (m^3/s); A = cross-sectional area perpendicular to flow (m^2); q_{in} = lateral inflow (per length unit (m^2/s)); g = acceleration due to gravity; h = water level; α= momentum distribution coefficient; l_f = friction slope; f = momentum forcing (per length unit); ρ_w = density of water; x = distance in direction of flow (m); t = time step. St. Venant Equations are the partial differential equations. Approximate solution of the above equation in MIKE HYDRO RIVER was determined by using the implicit finite difference numerical schemes (six-point Abbott method).

In present work hydrodynamic modeling was run for the Damodar river reach from Durgapur barrage to Jamalpur reach. Using high resolution CARTOSAT-l DEM of spatial resolution 10 m, forty seven river cross-sections of Damodar river at different points were extracted. These cross-section were modified with field measurement. Figs. (10&11) shows pictures of field measurement. All the input files were prepared in ArcGIS using high resolution satellite imagery. Cross-sections were modified before using them in the model (MIKE HYDRO RIVER). Fig. 12 shows river network in MIKE HYDRO RIVER model.

Fig. 8. Location of DVC cross-sections on high resolution satellite image

Fig. 9. Aggradations of Damodar river

Fig. 10. Measurement of water depth at Jamalpur in Pre-monsoon

Fig. 11. Normal flood level mark at Jamalpur

5. Results and discussion

5.1. *Calibration and validation*

MIKE HYDRO RIVER 1-D hydrodynamic model was run from 1st July to 15th October, 2007 during

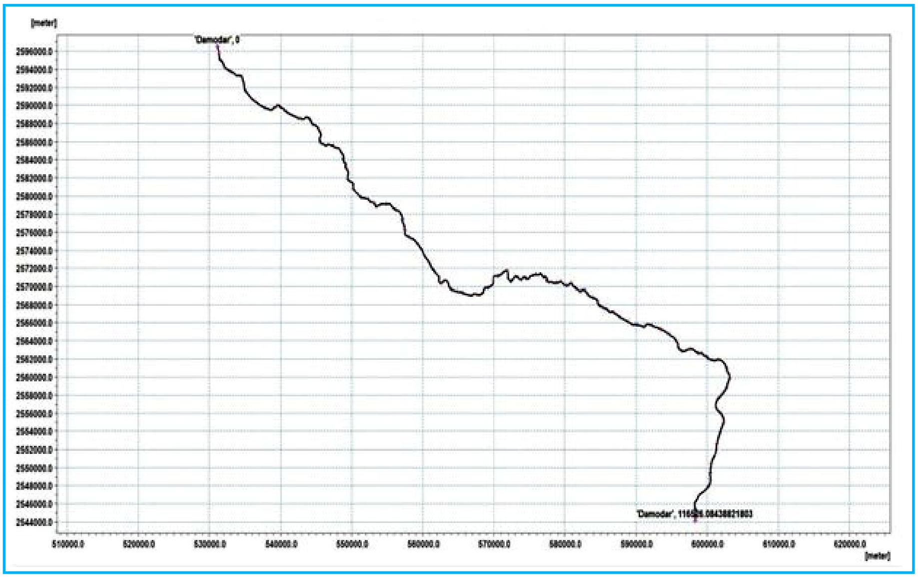


Fig. 12. River network in MIKE HYDRO RIVER

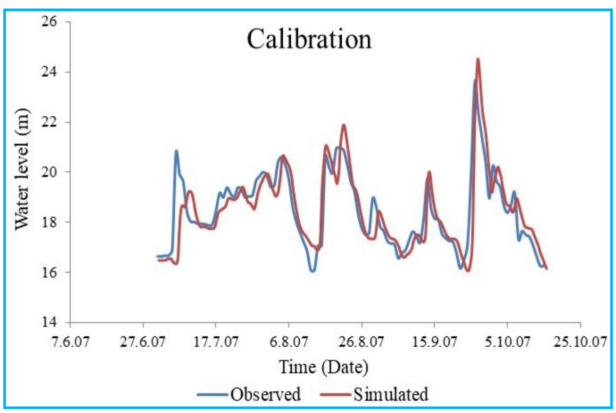


Fig. 13. Comparison between observed and simulated gauge level at Jamalpur gauging site in 2007

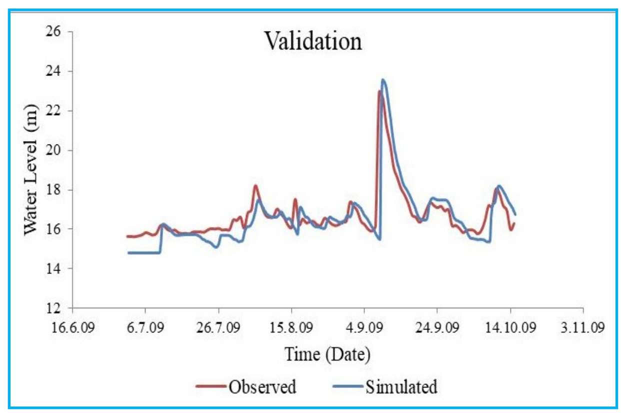


Fig. 14. Observed and Simulated water level at Jamalpur site in 2009

calibration to simulate gauge and discharge at different cross-sections of the selected reach of Damodar river. Flow data in form of daily discharge at Durgapur barrage site was used as an upstream boundary condition and Q/h curve used as a downstream boundary condition. Locations of upstream and downstream boundary conditions shown in Fig. 12. Manning's roughness coefficient was used as a model calibration parameter. 5 min was set up as the computational time step for model and computational grid (cross-sections) were varied from 1500 m to 4000 m. The Manning's n value was varied from 0.02 to 0.05 during the model calibration process. Fig. 13 shows a comparison between measured and simulated water levels at Jamalpur (chainage 108122 m) gauging site for the year 2007. For Manning's n value of 0.035 simulated gauge level at Jamalpur gauging site was very close to observed data. Maximum simulated water level is on higher side at Jamalpur site. From Fig. 13 it was observed that the simulated gauge level at Jamalpur gauging site matched well with the measured values.

The validation was performed by simulating the calibrated model for the flood event of 2009. MIKE HYDRO RIVER model was run by taking Manning's n value 0.035 and keeping entirely same other model parameters which were used in the year 2007. The model validation was performed by comparing the model predicted simulated water level at Jamalpur site with the corresponding measured values. The site is presented in Fig. 14 which shows the comparison between the measured and model predicted water level at Jamalpur during validation. Graph signify the good matching of model predicted water level to measured water level at Jamalpur. For peak, water level model value is on higher

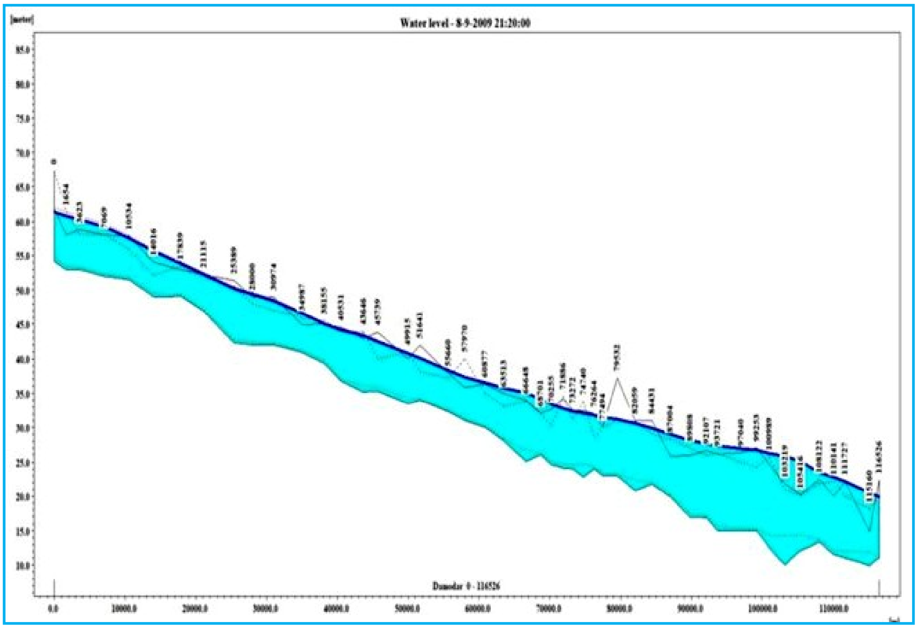


Fig. 15. Predicted Water Surface profile of Damodar river

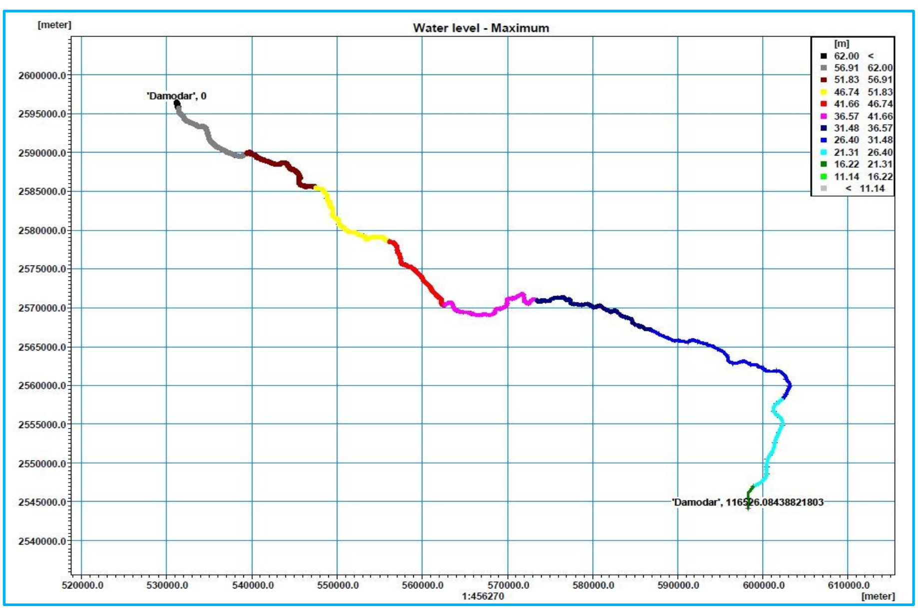


Fig. 16. Predicted Maximum Water level of Damodar river

side whereas for lower water level, model values are on lower side due to some uncertainity in extracted cross-sections.

Fig. 15 shows the simulated water level profiles of the Damodar river between Durgapur barrage to Jamalpur for 2009. Maximum water surface level is shown by blue line in fig.15. The water level and bank line and river bed slope were shown in the Fig. 15. Along the selected reach of Damodar river maximum water level range at different locations shown in Fig. 16. From the Fig. 15, it was found that during peak flow Damodar river overtopped its bank. At some locations, it was very high. Details of overtopping and types of bank overtopping with chainage is shown in Table 1. Thus, on the basis of predicted water surface profile by MIKE HYDRO RIVER model, left and right bank of Damodar river at the majority of locations need to be elevated by providing embankments to control flood. Further, short-term measures like deepening of the channel to increase the

TABLE 1

Cross-Section Chainage and Bank failure for year 2009

S. No.	Chainage	Maximum RL of water surface	Bank failure	S. No.	Chainage	Maximum RL of water surface	Bank failure
1.	0	62.001	Right	24	68700.8	34.233	Both
2.	1653.84	61.412	Right	25	70254.6	33.392	Both
3.	3622.82	60.8	Both	26	71885.7	32.789	Both
4.	7068.57	59.65	Both	27	73271.7	32.437	Left
5.	10534.2	57.928	Nil	28	74739.9	32.086	Nil
6.	14016.4	55.894	Both	29	76263.8	31.762	Left
7.	17839.1	54.146	Both	30	77493.6	31.485	Both
8.	21114.9	52.522	Left	31	79531.5	31.169	Nil
9.	25389.5	50.529	Nil	32	82059	30.555	Nil
10.	27999.8	49.71	Both	33	84431	29.918	Left
11.	30973.5	48.659	Left	34	87003.6	28.985	Both
12.	34986.9	46.854	Both	35	89807.8	28.113	Both
13.	38154.9	45.272	Nil	36	92106.8	27.632	Both
14.	40530.5	44.4	Left	37	93721.5	27.38	Both
15.	43645.8	43.536	Right	38	97039.7	26.957	Both
16.	45738.9	42.671	Left	39	99253.3	26.766	Left
17.	49915	40.93	Right	40	100989	26.33	Both
18.	51641.1	40.225	Left	41	103219	25.867	Both
19.	55659.6	38.41	Both	42	105416	25.116	Both
20.	57970.1	37.461	Right	43	108122	23.389	Both
21.	60877	36.583	Left	44	110141	22.82	Both
22.	63513	35.859	Left	45	111727	22.229	Left
23.	66648.3	35.149	Both	46	115160	20.582	Both

cross-sectional area and reducing the channel roughness by clearing vegetation from the channel perimeter are proposed for accommodating peak flood flow.

6. Conclusions

In this study various parameters were discussed which influenced the damage due to flood. It was observed that southwest monsoon causes heavy rainfall and physiography of the basin aids high surface runoff in the upper catchment of the basin. Sedimentation reduces the storage capacity of dams which moderate the flow in lower reaches. With the passage of time carrying capacity of river in lower reaches reduces due to siltation and also cross-sections changes due to sediments deposition and scouring. So when river doesn't accommodate the flow in active limit then water overtops the banks and create flooding condition. Encroachments of area closed to river in floodplain for agricultural purpose causes huge losses during flood times. So in the present study forty seven cross-section extracted from high resolution Cartosat-l DEM were used for flood year to detect the flood vulnerable area between Durgapur barrage to Jamalpur by performing hydrodynamic modeling. MIKE HYDRO RIVER hydrodynamic model was run for July to October 2007 to simulate water level and discharge at different locations of the Damodar river reaches. The Manning's n value was varied from 0.02 to 0.05 during the model calibration process. For Manning's n value of 0.035 model predicted water level at Jamalpur gauging site was very close to observed water level. Model validation was performed for 2009 using the same model parameters of 2007 and taking Manning's n value 0.035. It was observed that during peak flow Damodar river overtopped its bank. Thus, on the basis of predicted water surface profile by MIKE HYDRO RIVER model, left and right bank of Damodar river at majority of locations need to be elevated by providings embankments to control flood. Further, short-term measures like deepening of the channel to increase the cross-sectional area and reducing the channel roughness by clearing vegetation from from the channel perimeter is proposed for accommodating peak flood flow. A further detailed hydrodynamic modeling study for far lower reaches of Damodar river where river bifurcates in two parts Mundeswary and Amta will beneeded to find out the clear picture of flood hazards. This can assist the planners in flood hazard zonation and to take policy decisions for controlling the floods in the lower Damodar basin.

Acknowledgements

The authors are grateful to Damodar Valley Corporation (DVC) Maithon, Central Water Commission (CWC) for providing the essential data for the study. Authors acknowledge the technical support provided by DHI India regarding MIKE HYDRO RIVER hydrodynamic model.

The contents and views expressed in this research paper/ article are the views of the authors and do not necessarily reflect the views of the organizations they belong to.

References

Aronica, G., Hankin, B. and Beven, K., 1998, "Uncertainty and equifinality in calibrating distributed roughness coefficients in a flood propagation model with limited data", *Advances in Water Resources*, **22**, 4, 349-365.

Assani, A. A., Stichelbout, E., Roy, A. G. and Petit, F., 2006, "Comparison of impacts of dams on the annual maximum flow characteristics in three regulated hydrologic regimes in Québec (Canada)", *Hydrological Processes*, **20**, 16, 3485-3501.

Bates, P. D. and De Roo, A. P. J., 2000, "A simple raster-based model for flood inundation simulation", *Journal of hydrology*, **236**, 1-2, 54-77.

Bates, P. D., Marks, K. J. and Horritt, M. S., 2003, "Optimal use of high-resolution topographic data in flood inundation models", *Hydrological processes*, **17**, 3, 537-557.

Bhattacharyya, K., 2011, "The Lower Damodar River, India: understanding the human role in changing fluvial environment", Springer Science & Business Media.

Chow, V. T., Maidment, D. R. and Mays, L. W., 1988, "Applied hydrology", p572, Editions McGraw-Hill, New York.

Cook, A. and Merwade, V., 2009, "Effect of topographic data, geometric configuration and modeling approach on flood inundation mapping", *Journal of Hydrology*, **377**, 1-2, 131-142.

Correia, F. N., Rego, F. C., Saraiva, M. D. G. and Ramos, I., 1998, "Coupling GIS with hydrologic and hydraulic flood modelling", *Water Resources Management*, **12**, 3, 229-249.

Di Baldassarre, G., Schumann, G., Bates, P. D., Freer, J. E. and Beven, K. J., 2010, "'Flood-plain mapping: a critical discussion of deterministic and probabilistic approaches", *Hydrological Sciences Journal-Journal des Sciences Hydrologiques*, **55**, 3, 364-376.

Dung, N. V., Merz, B., Bárdossy, A., Thang, T. D. and Apel, H., 2010, "Multi-objective automatic calibration of hydrodynamic models utilizing inundation maps and gauge data", *Hydrology & Earth System Sciences Discussions*, **7**, 6, 1339-1354.

Dutta, D., Herath, S. and Musiake, K., 2000, "Flood inundation simulation in a river basin using a physically based distributed hydrologic model", *Hydrological Processes*, **14**, 3, 497-519.

Dyhouse, G., Hatchett, J. and Benn, J., 2003, "Floodplain modeling using HEC-RAS", Haestad Press.

Ghosh, S. and Guchhait, S. K., 2016, "Dam-induced changes in flood hydrology and flood frequency of tropical river: a study in Damodar River of West Bengal, India", *Arabian Journal of Geosciences*, **9**, 2, 1-26

Hsu, M. H., Fu, J. C. and Liu, W. C., 2003, "Flood routing with real-time stage correction method for flash flood forecasting in the Tanshui River, Taiwan", *Journal of hydrology*, **283**, 1-4, 267-280.

Jung, Y. and Merwade, V., 2011, "Uncertainty quantification in flood inundation mapping using generalized likelihood uncertainty estimate and sensitivity analysis", *Journal of Hydrologic Engineering*, **17**, 4, 507-520.

Merwade, V., Cook, A. and Coonrod, J., 2008, "GIS techniques for creating river terrain models for hydrodynamic modeling and flood inundation mapping", *Environmental Modelling & Software*, **23**, 10-11, 1300-1311.

Pappenberger, F., Beven, K., Horritt, M. and Blazkova, S., 2005, "Uncertainty in the calibration of effective roughness parameters in HEC-RAS using inundation and downstream level observations", *Journal of Hydrology*", **302**, 1-4, 46-69.

Pappenberger, F., Matgen, P., Beven, K. J., Henry, J. B. and Pfister, L., 2006, "Influence of uncertain boundary conditions and model structure on flood inundation predictions", *Advances in Water Resources*, **29**, 10, 1430-1449.

Pramanik, N., Panda, R. K. and Sen, D., 2010, "One dimensional hydrodynamic modeling of river flow using DEM extracted river cross-sections", *Water Resources Management*, **24**, 5, 835-852.

Quiroga, V. M., Kurea, S., Udoa, K. and Manoa, A., 2016, "Application of 2D numerical simulation for the analysis of the February 2014 Bolivian Amazonia flood: Application of the new HEC-RAS version 5", *Ribagua*, **3**, 1, 25-33.

Rao, G. N., 2001, "Occurrence of heavy rainfall around the confluence line in monsoon disturbances and its importance in causing floods", *Journal of Earth System Science*, **110**, 1, 87-94.

Renyi, L. and Nan, L., 2002, "Flood area and damage estimation in Zhejiang, China", *Journal of environmental management*, **66**, 1, 1-8.

Sanders, B. F., 2017, "Hydrodynamic modeling of urban flood flows and disaster risk reduction", Oxford Research Encyclopedia of Natural Hazard Science.

Sen, P. K., 1991, "Flood hazards and river bank erosion in the Lower Damodar Basin", *Indian geomorphology*, Concept Publishing Co., New Delhi, 95-108.

Sindhu, K. and Durga Rao, K. H. V., 2016, "Hydrological and Hydrodynamic Modeling for Flood Damage Mitigation in Brahmani-Baitarani River Basin, India", *Geocarto International*, **32**, 9, 1-28.

Timbadiya, P. V., Patel, P. L. and Porey, P. D., 2014, "One-dimensional hydrodynamic modelling of flooding and stage hydrographs in the lower Tapi River in India", **106**, 5, *Current science*, 708-716.

Villuri, V. G. K., Pasupuleti, S., Jain, K., Gairola, A. and Singh, R. K., 2018, "Hydrodynamic simulation of a cloudburst event in Asi Ganga Valley of Indian Himalayan region using MIKE11 and GIS techniques", *Mausam*, **69**, 4, 523-534.