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FLOOD FORECASTING AND INUNDATION MAPPING OF A RIVER BASIN IN SOUTH-EAST INDIA

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ABSTRACT

Flood forecasting and flood inundation mapping are very useful for reducing the losses resulting due to frequent occurrence of floods. This study is carried out to estimate the design floods, formulate real time flood forecasts and assess the extent of flooding in the downstream of Govindpur site up to the confluence of Bay of Bengal falling in Budhabalang river basin in south-east India. For this purpose, hydrological analysis is carried out using HEC-HMS and HEC-GeoHMS and Arc-GIS employing three transform models, viz Clark, Snyder and SCS models. Employment of rainfall-runoff data of five flood events yields Clark model to have performed the best, and SCS model the poorest. Real time flood forecasts are derived using Clark Model. 100-year flood hydrograph is computed using (a) 100-year 1-day rainfall, (b) its hourly distribution and critical sequencing (single bell as and double bell) of rainfall and (c) convolution of the excess hyetograph with representative unit hydrograph. The resulting peak is compared with that derived from frequency analysis of annual maximum peak flood series. Finally, a flood inundation map is prepared using HEC-RAS and design flood hydrograph.

Keywords: *Calibration, critical sequencing, design flood, flood inundation map, simulation, validation, flood forecasting.*

INTRODUCTION

Temporal and spatial variability of rainfall make floods and draughts inexorable. Odisha being a coastal state faces cyclonic storms causing floods. Flood forecasting and warning system is a non-structural measure frequently employed to reduce flood impact. Keeping these in view, a study has been carried out for Budhabalang river basin for forecasting streamflow and generating flood inundation map.

The amount of runoff and its nature can be suitably evaluated by hydrological modelling (Neha et al., 2016), which can be used to assess the hydrologic response of the watershed under climatic variations. An event-based model simulates single storm event, reflecting the hydrological response of the basin to single event of storm. For flood damage mitigation, there exists a need for an effective and accurate method of assessment of incoming flood and the timing of its occurrence for taking suitable measures in the flood plain. Use of satellite technology has become a necessity in flood forecasting and subsequent preparedness for flood mitigation because of its reliability, cost effectiveness, time saving and approachability to remote locations (Sindhu et al., 2017). With further advance of remote sensing and computer software techniques, new methods can be an edge to traditional methods of assessment of flood and flood risk management (Rao et al. 2011).

The popular HEC-HMS is being widely used considering its general acceptability, better technical support and free availability. It is a rainfall-runoff simulation model suitable for large to small catchments encompassing different losses, runoff transform models, open channel routing, error estimation, and parameter optimisation. Verma et al. (2010) evaluated its usefulness over WEPP in simulating rainfall-runoff in Upper Baitarani River basin of south-eastern India and recommended for future use. Razi et al. (2010) used it for Johor river in Tinggi basin, Malaysia. They found it reliable and useful for deriving missing data, estimating flood and predicting flood levels for design of different hydraulic structures. Thakur et al. (2017) coupled it with ArcGIS and HEC-GeoHMS for spatial analysis in Copper Slough watershed in Champaign, Illinois. Similarly, the works of Nandalal et al. (2010) and Choudhari et al. (2014) among others are worth citing.

Yuan (2011) carried out flood plain modelling of the Kansas River Basin, United States, using HEC-HMS and HEC-RAS to study the impacts of urbanization and wetland mitigation. Similarly, Khadka and Bhaukajee (2018) used these models for Kankai basin in Nepal and Kavalinge basin in Sweden. They found the land use and land cover pattern to have been more sensitive than the climatic factors. The deterministic approach was better for Kavalinge basin, and probabilistic approach for Kankai basin to obtain peak discharge. A flood plain mapping of Kabul river model was carried out by Shahzad et al. (2016) using the flood hydrographs of different return periods. Using HEC-RAS, Ezz (2017) assessed water velocity and depth of flow at different locations for constructing a road connecting the airport to the city in Egypt.

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Coupling remote sensing and GIS with HEC-HMS and HEC-RAS, Durga Rao et al. (2014) modelled the flash flood of Mandakini river due to unprecedented rainfall of 16^{th} to 18^{th} June 2013, which caused breaching of Chorabari lake upstream of Kedarnath. A few examples among many others include Romali (2018) for Segamat city in Malaysia, Rao et al. (2011) for Godavari basin and Mandal et al. (2016) for Teesta river basin, a tributary of Brahmaputra, in Sikkim show usefulness of flow simulation model for flood predictions.

The present study deals with the hydrological and hydrodynamic studies of Budhabalang river basin in south-east India for design flood estimation, streamflow forecasting, and flood inundation, for no scientific study appears to have been carried out for this river basin.

STUDY AREA AND DATA AVAILABILITY

Burhabalang river is an independent river situated in the north-east corner of Peninsular India. It originates from south of Similipal hills and falls into the Bay of Bengal. The river drains a total catchment area of 4,379 km^2 up to Govindpur gauging site covering Mayurbhanj and Balasore districts of Odisha. The catchment area lies between $21^0$19’44” to $22^0$21’14” N and $86^0$17’27” to $86^0$56’20” E. Major floods occurred due to cyclonic storms occurred during October 1999, August and September 2007, June 2008, October 2009, September 2011, Phailin in October 2013 and Hudhud during October 13^{th} to 14^{th} 2014. Figure 1 shows the study area and drainage network and land use-land cover of the basin.

Paddy cultivation is the main source of livelihood for the inhabitants living in the study area. The basin has a good drainage network. Out of the total catchment area, 51.09% and 17.30% areas fall under 5m-100m and 100m-200m elevation ranges, respectively, whereas an area of 31.60% is covered under more than 200m elevation.

Freely available SRTM DEM data of 30m resolution was used generating various topographical and hydraulic parameters of the basin, Bhuvan thematic image Land Use Land Cover (50K): 2011-12 of 63.5m resolution was used in determining the percentage of impervious area. The Digital Soil Map of the world available freely from Geo network web portal of FAO (Food and Agriculture Organization) with pixel size 1000m x 1000m was used for soil mapping of the basin. Daily discharge data for the period 1992-2017 and hourly gauge data for the period 1978-2017 at Govindpur gauge station were collected from CWC, Bhubaneswar region. Daily rainfall data from seven rain-gauge stations and three-hourly rainfall data from two rain gauge stations covering the whole catchment area for the event periods was used.

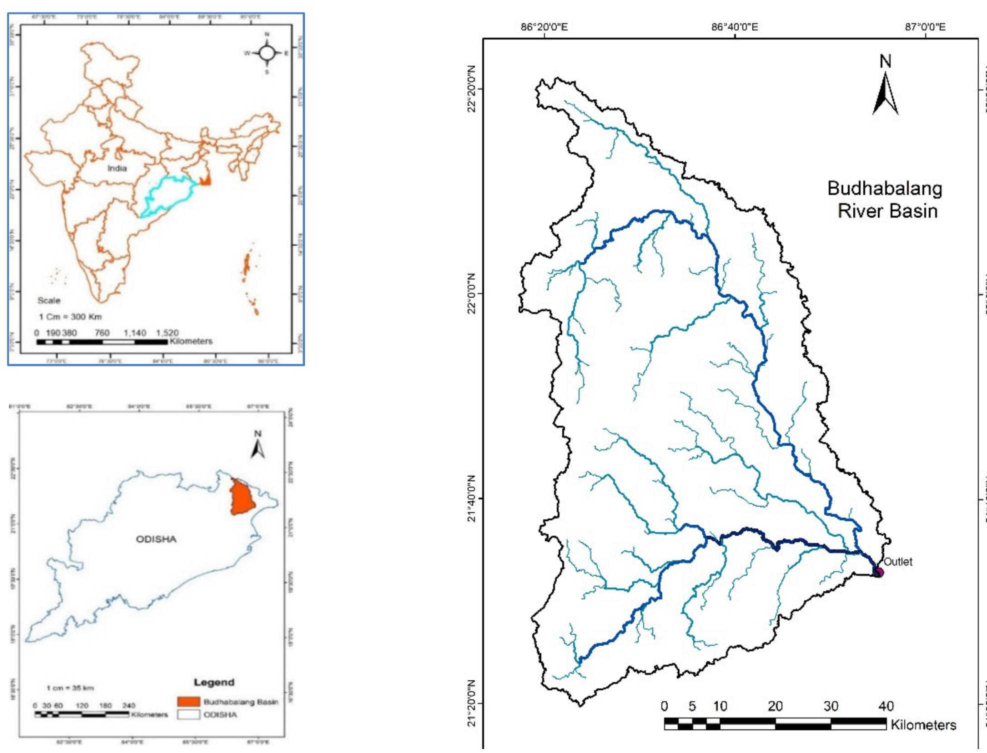

Fig.1: Study Area of Budhabalang Basin

METHODOLOGY

The study couples hydrologic and hydrodynamic models for generation of runoff using HEC-HMS and HEC-RAS. Figure 2 shows the modelling structure of the study for hydrologic and hydrodynamic modelling of the basin and its flood inundation mapping.

software by downloading the SRTM 30m resolution DEM data freely available from USGS website. Thiessen polygon map was prepared by adding shape file identifying all nine rain gauge stations with their latitude and longitude in ArcGIS. The respective weightages of rain gauge stations

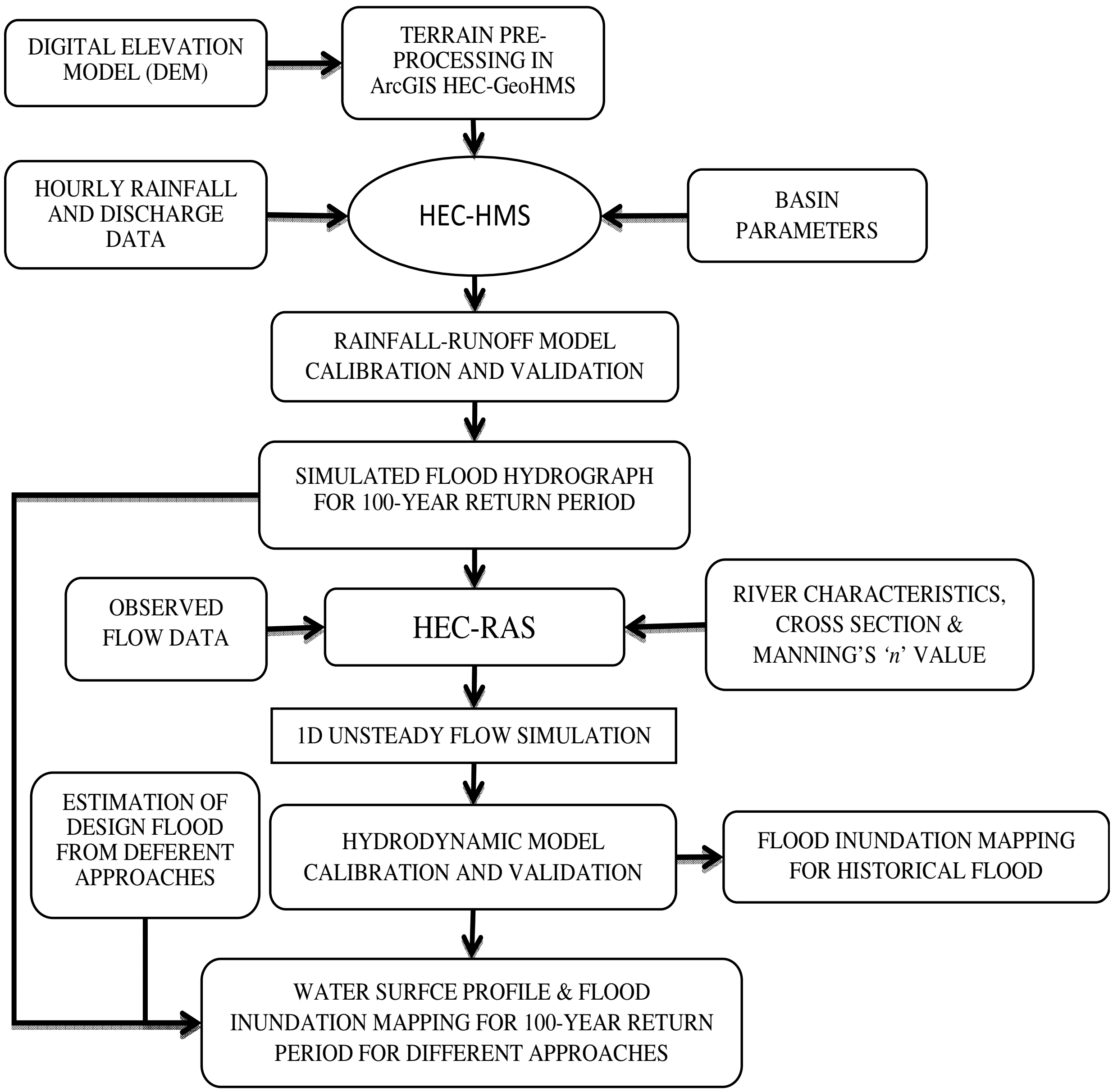

Fig. 2: Modelling structure for generating Flood Inundation Map incorporating HEC-HMS, HEC-RAS and ArcGIS

Spatial Data Processing

The watershed map of the Budhabalang river up to the gauged site at NH-5 bridge at Govindpur (Lat 21^0 32' 41" Long 86^0 55' 07") in India was prepared using ArcGIS

are exported as input to HEC-HMS platform. The land use land cover map gives the percentage of urban settlement for determination of imperviousness of the basin. Digital Soil Map data from FAO for the study area was used for determination of infiltration.

With isochronal map and time-area diagram, the longest flow path of the basin was identified using HEC-GeoHMS software. Different river segments were identified and the physical characteristics such as length, elevation, and slope, etc. were determined for each segment of the river by HEC-GeoHMS. The total time of travel from different locations in the basin along the river reaches is computed as a sum of time of travels for each river segment. The time of travel of rainwater from the furthest point to reach the outlet is the time of concentration, *Tc* for the catchment.r The initial value of time of concentration *Tc* is equated to the Max value of $C\sum(L/\sqrt{S})$ and accordingly, the value of the proportionality constant *C* was determined. Kriging interpolation method was used for preparation of isochronal map.

Temporal Data Processing

Seven major flood events were identified and corresponding rainfall data from rain gauge stations were observed from the year 1992 to 2017. Rating curves were developed and used to convert hourly gauge values to the corresponding discharge values. Flood events of Sep. 2007, June 2008, Sep 2009, Sep 2011 and Oct 2013(B) were considered for calibration of HEC-HMS model whereas flood events for Aug. 2007 and Oct. 2013(A) are considered for validation. Hourly rainfall data for the periods of occurrence of events from all the rain gauge stations are derived from available rainfall records and Thiessen polygon is used for converting point rainfall to average value of basin area.

Application of HEC-GeoHMS and HEC-HMS

The SRTM raw DEM data was processed for terrain pre-processing in HEC-GeoHMS for generation of drainage paths, stream, basin and sub-basin delineation, basin slope, length of stream segments, upstream and downstream elevations, longest flow path, centroids and centroidal flow path etc. The developed HEC-GeoHMS files are exported to HEC-HMS as input and used as background map. Initial and Constant Rate for losses and Exponential recession model for baseflow have been considered for the basin. In this study, the Clark Unit Hydrograph, Snyder Unit Hydrograph and SCS Unit Hydrograph transformation models were used for transformation of rainfall to runoff.

Calibration and Validation of Hydrologic Model

HEC-HMS was calibrated using optimization routine of the software by maximising Nash-Sutcliffe Efficiency (NSE) value for each event. The average value of such optimised parameters for each event is considered as representative parameters of the basin and these are used for validation. The NSE, Percentage error in Peak and Percentage error in Time to Peak for different transform models are compared for validation.

Computation of Unit Hydrograph using Clark Model

The Time-Area diagram represents the inflow that contributes the flow to the outlet over the successive periods of time. The inflow from the incremental areas between two successive isochrones is converted into discharge units. The inflow into the hypothetical reservoir is proportional to the area between two successive isochrones and this inflow is routed through hypothetical linear reservoir using the storage coefficient *R* to obtain the outflow hydrograph which is called instantaneous unit hydrograph (IUH) of the basin. IUH is then converted to unit hydrograph for desired duration to convolute the rainfall excess of design storm. Addition of suitable base flow yields the Design Flood Hydrograph.

Frequency Analysis

Frequency analysis for precipitation and flood series are carried out to determine their values corresponding to a desired return period. The 1-day maximum annual rainfall or annual maximum historical flood series for the catchment has been derived. Popular statistical distributions are attempted and using the best fit distribution, the T-year return flood has been computed. The 100-year flood is estimated for single-bell and double-bell storms using unit hydrograph technique together with frequency analysis of rainfall. In probabilistic approach using flood frequency analysis of annual maximum peak flood series, the 100-year flood has been estimated and the results are compared.

Real-Time Flood Forecasting

Accurate and sufficiently advance flood forecasting and warning can help in suggesting non-structural measures for reducing the loss of life and property (Subramanya 2008). The representative unit hydrograph for the catchment is used for formulating the real-time forecasting of direct surface runoff hydrograph for Budhabalang basin based on the occurrence of real-time average hourly rainfall. For each rainfall block of 4-hour, the forecasted flood ordinates are derived. The maximum of such flood ordinates is the forecasted peak flood and the corresponding time of occurrence is the time to peak. The lead time is computed as the difference between the time of occurrence of peak and the period of the rainfall.

Hydrodynamic Modelling

HEC-RAS is used for hydraulic modelling of the channel. It includes topographical parameters, i.e. extraction of channel and flood plain area from DEM, computation of water surface profile, discharge and flow depth at different cross-sections in the channel. The river centre line is marked from upstream to downstream from the Govindpur gauging site having a reach length of about 37 km up to the confluence point with the sea. The cross-sections are provided at an interval of 100m to 500m. For gradual transition, the coefficient of contraction and that of expansion are typically of 0.1 and 0.3 respectively (U.S. Army Corps of Engineering 2016).

In this study, the flow hydrograph is the upstream boundary condition and normal depth is the downstream boundary condition. It is run for unsteady flow for 5 minutes computational interval and one-hour mapping output interval. The water surface profile, discharge and depth of flow at different channel cross-sections were computed and checked with observed data for calibration of channel roughness value.

RESULTS AND DISCUSSION

Thematic map preparation

Budhabalang river basin covers a catchment area of 4379 km^2 up to Govindpur gauging site and is having well distributed rainfall gauge stations. The major portion of the terrain is flat, and the elevation varies from 5m to 1189m above the MSL. Budhabalang river basin is covered by 38.13%, 48.19%, 1.50%, 3.73%, 4.34%, 2.27% and 1.90% of the basin area with forest area, agriculture land, urban settlement, rural settlement, barren land, pastureland and water body respectively. The percentage area of the urban settlement, i.e. 1.50% has been considered as the imperviousness of the basin for HEC-HMS model.

On the GIS platform, utilising the time of travel, the isochronal maps were drawn. The cumulative times of travel, *t* (hour) and corresponding cumulative areas, *At* (in km^2) of contributions were computed. The percentage values of *t/Tc* i.e. the ratio of cumulative time of travel to

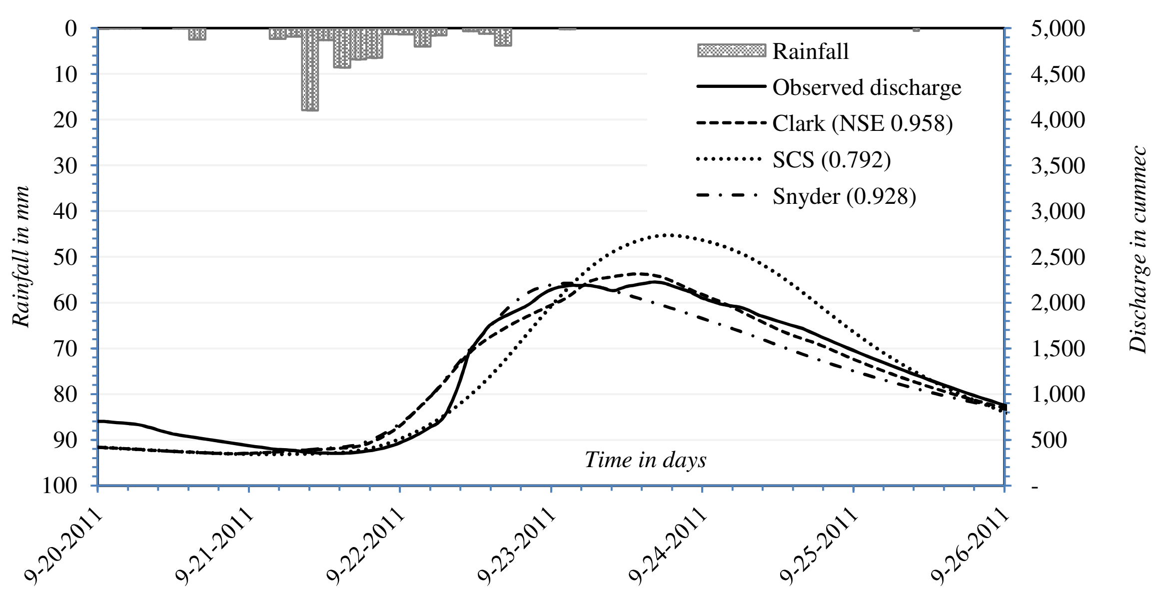

Fig. 3: Observed and simulated flood hydrographs of three models for the calibration event Sep-2011

the time of concentration, were computed. The corresponding values of *At/A* i.e. the ratio of cumulative area to the total area in percentage were also computed. The cumulative percentage values of *t/Tc* & *At/A* were utilised to prepare the cumulative Time-Area diagram. Kriging method of interpolation was adopted for interpolating the ordinates of the cumulative time-area diagram during the computations of the Clark transform Model in HEC-HMS for the simulation of flood events.

There are nine rain gauge stations, located in the basin, out of which seven rain gauge stations are ordinary rain gauges, and two are recording rain gauges. The 3-hourly rainfall was uniformly distributed to obtain the hourly rainfall values within each block of 3-hourly rainfall. The daily rainfall values observed at different ORG stations were distributed into hourly rainfall values based on the hourly rainfall values of the representative recording rain gauges for the respective days.

The hourly discharge values at Govindpur site were calculated using the rating curves, developed by analysing the daily gauge & discharge data for respective periods for use in HEC-HMS. The developed rating curves were also used to determine the annual maximum flow series corresponding to the annual maximum stage values observed for 40 years (1978-2017).

Calibration and Validation of HEC-HMS Model

The HEC-HMS tool was calibrated, by optimisation, using five events using Clark, SCS and Snyder models. The calibration results obtained for flood event Sep. 2011 for three transform models are best and shown in Figure 3. The calibration was poorest on Oct-2013(B) flood event (Figure 4).

It is observed that the Clark model performed the best of all in all such applications. The resulting error criteria such as NSE, Root Mean Square Error, Mean Absolute Error and Percentage Error in peak also indicated it.

The above transform models were also validated using the other two extreme events using calibrated parameters. Figures 5 and 6 compare simulated hydrographs using three transform models with the observed flood hydrographs for Oct. 2013(A) and Aug. 2007 events, respectively. Based on the percent error in time to peak, the Clark and SCS models overestimated by 2.50% and 17.50 %, respectively, whereas Snyder Model by 5.00% for Oct. 2013 (A) event. It can also

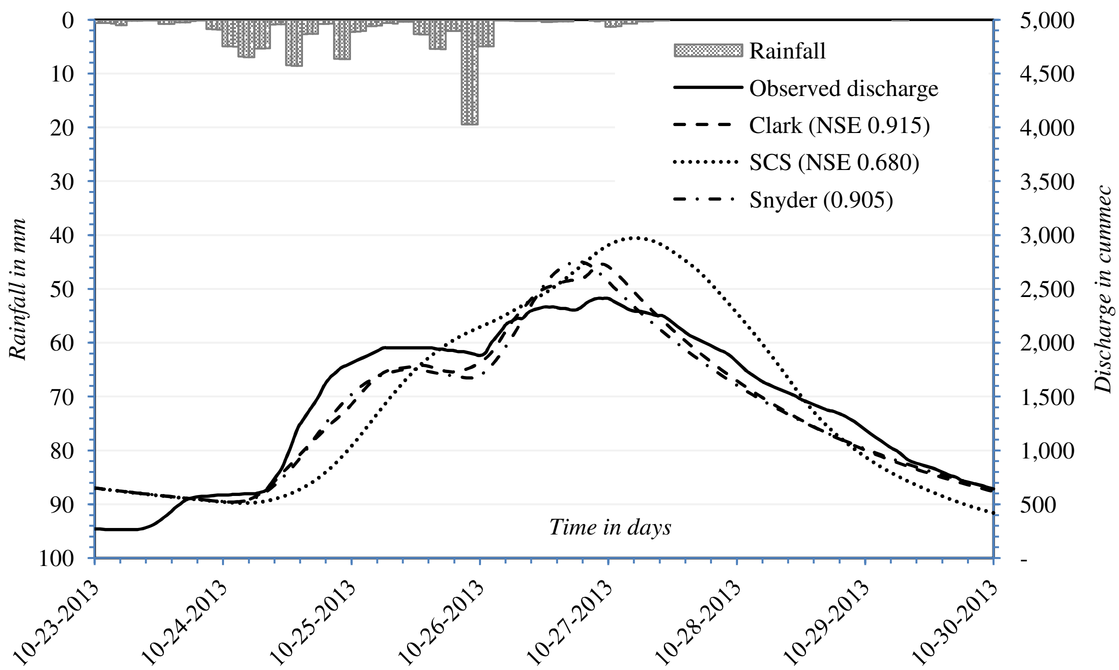

Fig.4: Observed and simulated flood hydrographs of three models for the calibration event Oct-2013(B)

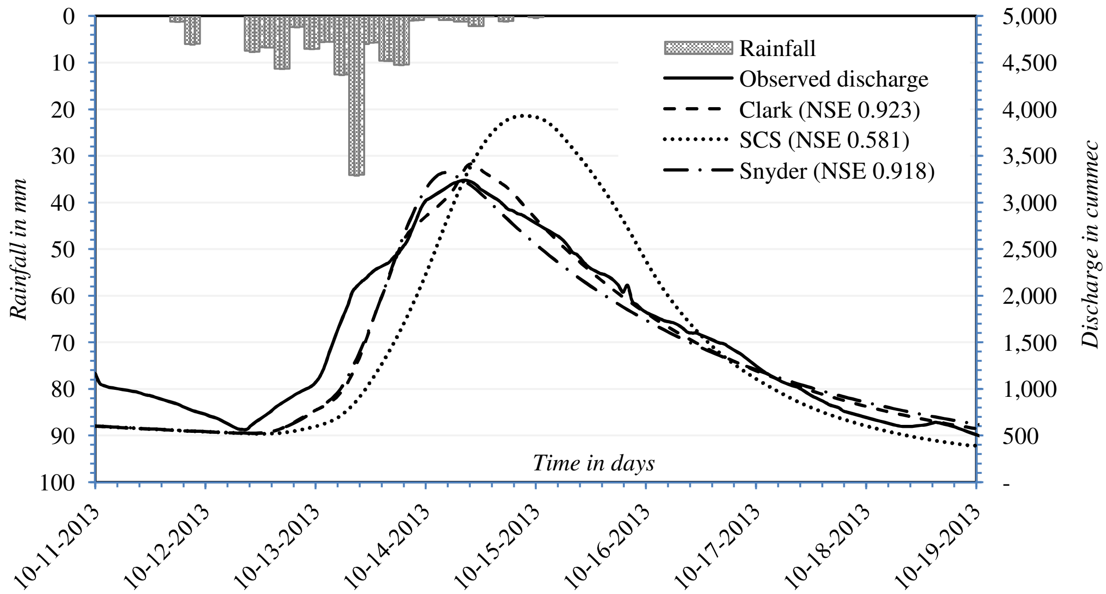

Fig.5: Comparison of observed and simulated flood hydrographs of three models for the validation event Oct-2013 (A)

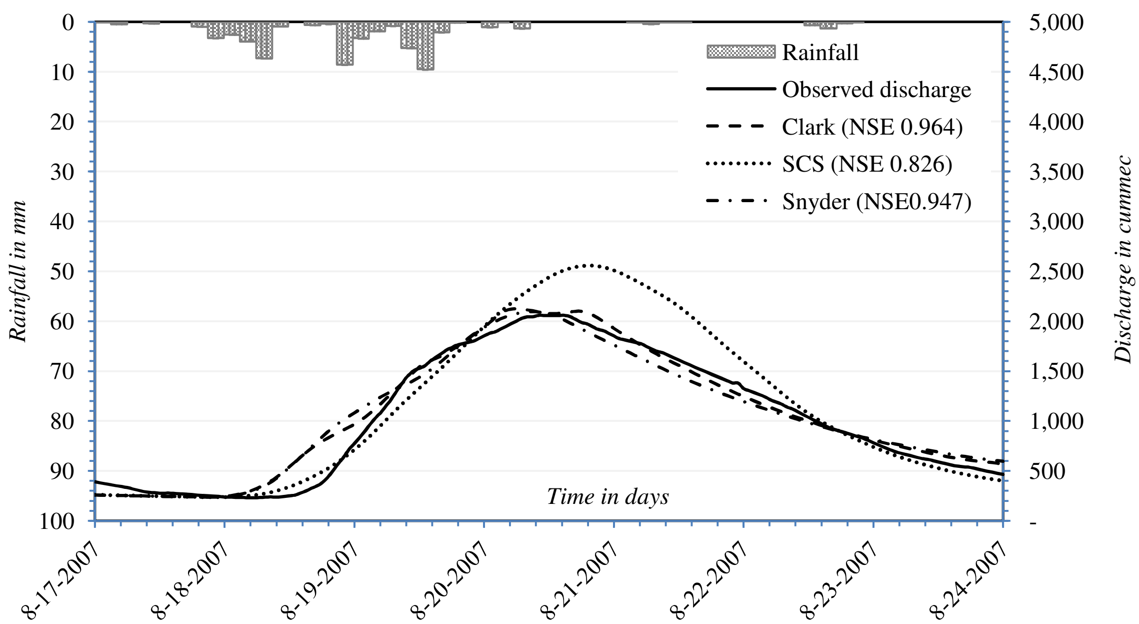

Fig. 6: Comparison of observed and simulated flood hydrographs of three models for the validation event Aug-2007

be inferred if other error criteria are employed. Similarly, the percent error in time to peak, the Clark and Snyder models underestimated by 4.88% and 1.22%, respectively, whereas SCS model overestimated by 10.98% for Aug. 2007 event.

For the event of Oct. 2013(A) (having high peak discharge), NSE is estimated as 0.923, 0.581 and 0.918 for Clark, SCS and Snyder models, respectively. For Aug. 2007 event (having low peak discharge), NSE has been estimated as 0.964, 0.826 and 0.947 for Clark, SCS and Snyder models, respectively. In validation, Clark and Snyder models have, in general, performed very well whereas the performance of the SCS model was not good. Hence, the Clark model was used for flood estimation. The representative parameters of Clark Model, T_c, and R, i.e. 29 hrs and 47 hrs, respectively, for the catchment were considered for computation of 1-hr unit hydrograph.

Frequency Analysis of Annual Maximum Daily Rainfall

Normal distribution, Log-Normal distribution, EVI or Gumbel distribution, Pearson Type III and Log Pearson Type III are fitted with the annual maximum one-day rainfall series for determination of 25 years, 50 years, 100-year and 200 years return period floods, as shown in Table 1.

Table:1Projected rainfall (mm) for different return periods for different distributions

Return Period T in years	25	50	100	200
Normal Distribution	92	206	220	231
Log Normal Distribution	204	230	258	258
Gumbel Method	206	232	258	284
Pearson Type III	208	235	262	287
Log Pearson Type III	214	250	289	330

The Gumbel distribution has the lowest D-index value of 0.2907, and therefore, it was taken as the best fit distribution for frequency analysis of 1-day maximum rainfall series and its employment yielded 1-day rainfall of 100-year return period as 258 mm.

Estimation of 100-Year Return Period Rainfall

The maximum hourly rainfall values were obtained from the available data of severe most storm of Oct. 2013(A). The resulting 258 mm, 24-hour rainfall was distributed as shown in Figure 7.

Estimation of Design Flood Hydrograph

Considering uniform loss rate (i.e. ø index) of 2 mm/hr, the rainfall excess was convoluted with the 1-hour design unit hydrograph for derivation of direct surface runoff hydrograph for the 100-year return period. Incorporating appropriate base flow, the peak was computed to be 4,236 cumec and 4,195 cumec at 44 hours and 39 hours for the single bell and double bell, respectively.

Comparison of Hydrographs from Two Storm Patterns

Table 2 shows the variation of Flood Peak (*Qp*) and Time to peak (*Tp*) for 100-year return period with single bell and double bell types of storm patterns. The analysis for double bell pattern underestimated the peak discharge by 0.97%, and the peak water level by 0.38% and time to peak by11.36%. Thus, the double bell rainfall pattern yields peak

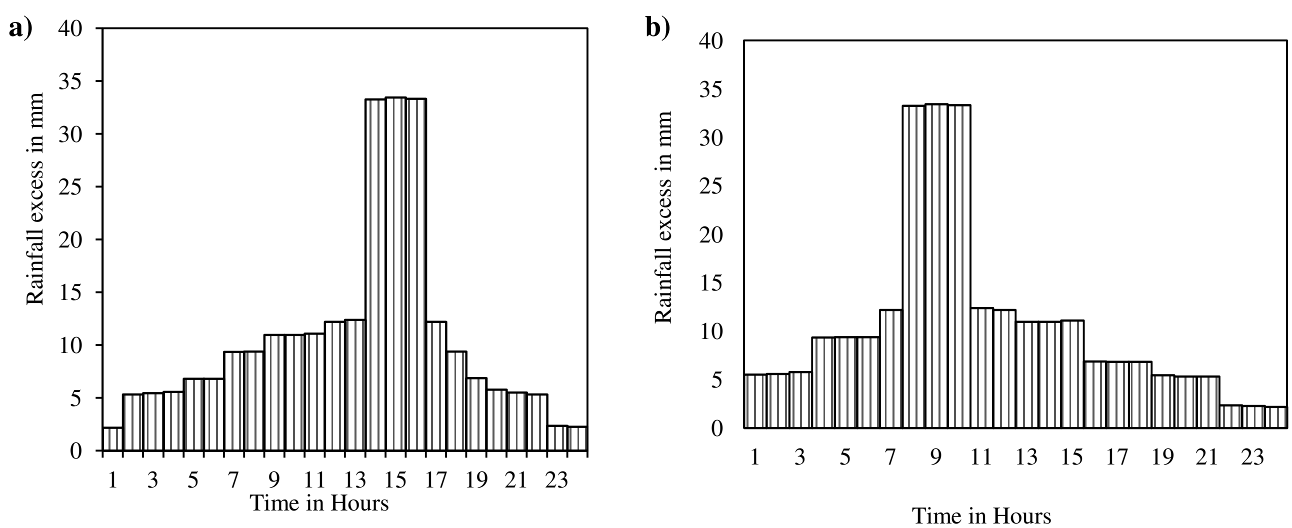

Fig. 7: Design Hourly Rainfall Hyetograph as a) Single Bell b) Double Bell

discharge very close to the observed, but the time to peak occurs little early, which is also quite crucial for flood management.

Estimation of Design Flood using Probabilistic Approach

The frequency analysis of annual maximum peak flood series was carried out fitting the above same statistical distributions to the series. The flood discharges for various return periods are shown in Table 3. The EVI distribution yields the lowest D-index value of 0.287 and therefore it was used for computing 100-year return flood as 3,522 cumec.

In brief, the 100-year return floods of 4,236 cumec and 4,195 cumec with corresponding water levels at Govindpur as 10.40m and 10.36m have been computed using Unit Hydrographs technique for single bell and double bell storm patterns, respectively. On the other hand, the probabilistic approach yielded 3522 cumec with water level 9.59m.

Real-Time Flood Forecasting

The Clark unit hydrograph is used for real-time flood forecasting for the event of Oct. 2013(A). The loss rate is taken as 5.5 mm/hour. Subsequently, the direct surface runoff hydrographs were obtained in real time convoluting the different sets of the excess rainfall hyetographs in rainfall blocks of 4-hours, 8-hours, 16-hours, 20 hours, etc., as shown in Fig. 8.

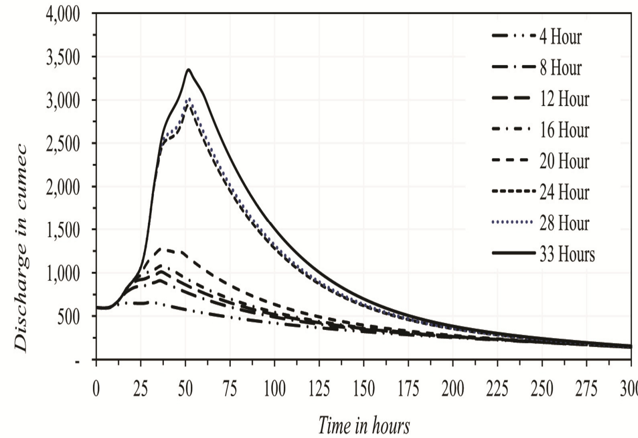

Fig. 8: Forecasted Flood Hydrograph for different rainfall blocks for event Oct. 2013(A)

The water levels of the river at Govindpur site were categorized as warning level and danger level as 7.21M and 8.13M, respectively. For the highest flood event of Oct. 2013(A), the forecast was made up to 33 hours duration hourly rainfall-excess and it is found closely matching the flood hydrograph simulated using the Clark Model (Figure 9).

Table 2: Table showing the variation of flood peak with various types of storms

Design Storm Patterns	Peak Discharge (*Qp*) in cumec	% variation in *Qp*	Time to Peak (*Tp*) in Hours	% variation in *Tp*	Peak water level	% variation in Peak level
Single Bell	4,236	Ref. run	44	Ref. run	10.40	Ref. run
Double Bell	4,195	0.97%	39	11.36%	10.36	0.38%

Table 3: Floods for different return periods in cumec using fitted frequency distributions

Return Period (T) in years	25	50	100	200
Normal Distribution	2,863	3,007	3,137	3,255
Log Normal Distribution	3,118	3,377	3,628	3,873
Gumbel Distribution	3,002	3,263	3,522	3,781
PT3 Distribution	2,860	3,003	3,131	3,248
LP3 Distribution	2,739	2,806	2,854	2,889

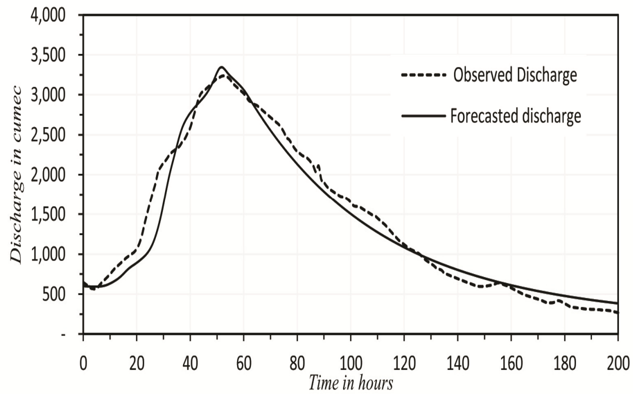

Fig.9: Comparison of observed and forecasted hydrographs for the event Oct-2013 (A)

Flood Inundation Mapping

For flood inundation mapping, HEC-RAS was used for hydraulic modelling, employing river geometry derived from ArcGIS. 70 cross-sections were created for the reach with upstream start section at 36.975 km and downstream end section at 0.290 km from the tail end. The area being a coastal plain is plain without rifts or deep pools but with a few windings. The flood plain is covered with high grass and cultivable lands with row field crops during monsoon periods when a flood occurs, suggesting Manning's *'n'* as 0.025 for main channel and 0.035 for banks. The simulated maximum water level at railway bridge site i.e. at cross-section 29.040 km matched the maximum flood level of 9.05m observed on 14th Oct 2013 at 14:00 hrs with the calibrated value of Manning's '*n*' as 0.029 for main channel and 0.033 for the left and right of the riverbanks (Figure 10).

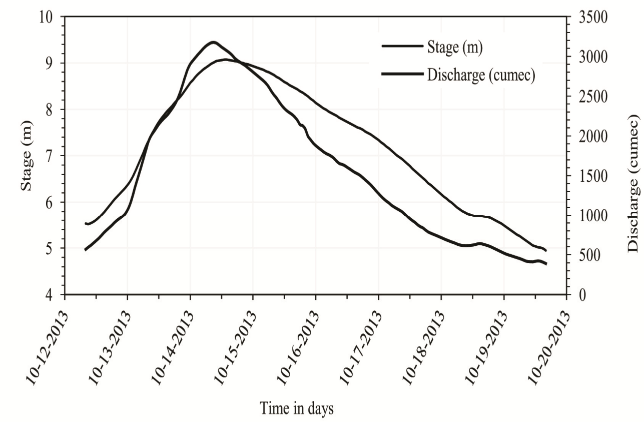

Fig.10: Calibrated stage and flow hydrographs at CS 29.04 km for the event Oct-2013 (A)

Finally, inundation map for the flood plain area was prepared using contour maps of 2m interval, as shown in Fig. 11.

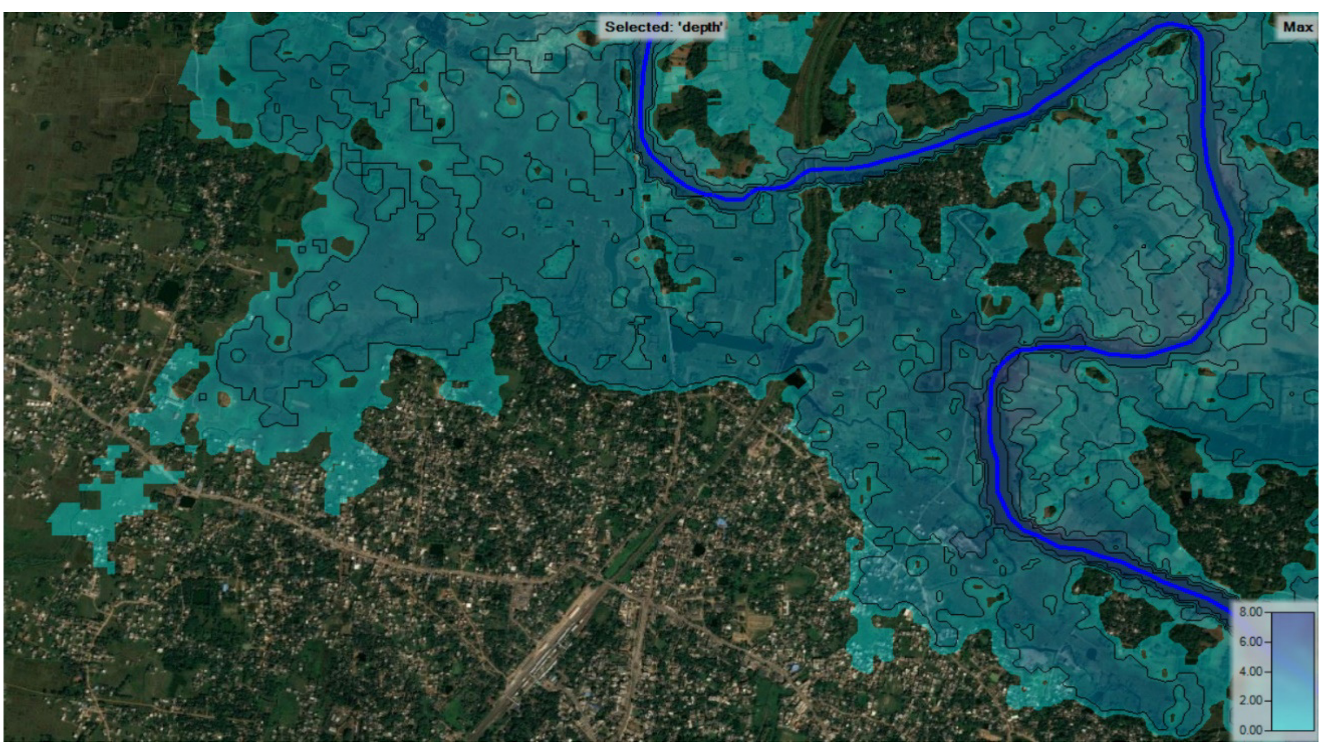

Fig. 11: Inundation map for flood with 100-years return period

CONCLUSION

The following conclusions can be drawn from the study:

a) Based on the NSE (Nash-Sutcliffe Efficiency) and other error criteria, the Clark model performed the best and SCS-CN model the poorest for flood events of Budhabalang river basin up to Govindpur gauging site.

b) The 100-year return period flood obtained from double bell method was 4195 cumec and it was 3522 cumec from flood frequency analysis of annual maximum peak flood series.

c) Real-time flood forecasts and corresponding water levels at Govindpur site can be useful for preparing the advanced warning schedule.

d) The water surface profile for the 100-year routed flood hydrograph was higher by 0.70M than the highest flood water level observed on 14^{th} Oct 2013 at the railway bridge site.

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