RAINFALL RUNOFF MODELLING AND INUNDATION ANALYSIS OF BAGMATI RIVER AT TERAI REGION OF NEPAL

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ABSTRACT

Climatic variability, unplanned land use pattern and encroachment into the flood plain are affecting the hydrology of Bagmati river basin of Nepal. In this study, methodology to improve present flood management system with non-structural countermeasures has been elaborated. Study of hydrological condition, basin scale rainfall runoff modeling and inundation analysis is helpful to prepare community level flood risk management techniques. In order to develop the relationship between rainfall and runoff and hence to develop flood forecasting model, simple statistical tools for hydrological analysis and least square methods of best fit technique is applied within the available historical rainfall and stage data (1980-2004). Flood frequency analysis is performed and floods of different return periods are identified. To minimize the risk from flood, different level inundation of the predicted flood should be known at community level. Hence inundation analysis is performed based on available digital data, satellite imageries, and GIS based numerical models (Arc GIS, its extension HEC-GeoRAS and HEC-RAS software) together with some field observation data. Real time flood forecasting model and inundation depth identifying technique for lower Bagmati watershed are the main outcomes of this study. Results of this analysis are understandable even to the community level people and such approach can be applied to other river basins as well for non structural countermeasure of flood disaster mitigation.

Keywords: Rainfall-runoff modelling, Inundation analysis, Community, Disaster mitigation

INTRODUCTION

Global nature of changes in climate and land use pattern is affecting the hydrology of every river system. Consequences of such effect can be observed as a magnified risk of flood hazard in the downstream reach of Bagmati river basin. In order to minimize the risk from flood hazard, both structural and non-structural mitigation measures have been taken as countermeasures. Rather than relying completely on large structural measures, which may not be sustainable due to economic condition of the country, policies and guidelines need to be developed and implemented as non-structural countermeasures against flood hazard at the community level. Non-structural measures mainly include conservation of watershed, flood plain management, flood forecasting, warning and evacuation system. Hence it is essential to develop methodology to improve present flood management system with non-structural countermeasures. Such non structural countermeasure of flood risk reduction is possible with rainfall runoff modeling and inundation analysis. The main objective of study is to develop the simple rainfall runoff flood forecasting model and inundation depth analysis technique for community level people as a community approach of flood disaster management. As a case study, rainfall-runoff modeling and inundation analysis is elaborated for Bagmati river at Terai region (Plain area in the downstream reach) of Nepal.

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STUDY AREA AND PROBLEM DESCRIPTION

Bagmati river basin lies in central region of Nepal and it covers an area of about 3741 sq. km (Fig.1). It originates in the mountains at about 16 km north-east of Kathmandu and drains out of Nepal across the Indian State of Bihar to reach the Ganges. Its total length is 597 km of which 206.8 km lies in Nepal (DWIDP, 2005). The watershed area draining upto the Pandhare Dovan is 2772 sq.km is called upper watershed area which is the mountainous area whereas below it is called lower watershed area and it's the plain (Terai) area. Every year in monsoon season, high flood at Bagmati river is causing loss of lives and property in the downstream reach of the basin. Due to increasing trend of extreme events and present economic condition of the country, government will not be able to afford huge investment for structural interventions for the entire watershed. So, combination of structural as well as community approach of non-structural flood disaster management would be most economical and effective approach of flood disaster mitigation to save the life and property in the Terai region of Bagmati river basin.

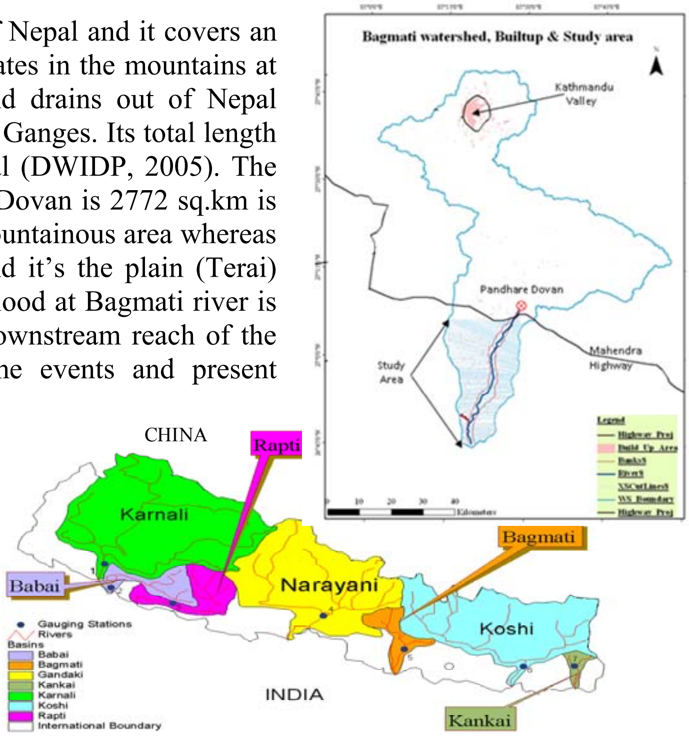


Fig.1 Map of Nepal and study area

DATA

In this study, hydrological analysis is performed using precipitation data (1980-2004) of eleven rain gauge stations within the periphery of the basin. Flood frequency analysis is carried out with instantaneous maximum discharge (1965-2006) measured at Pandhare Dovan. For rainfall runoff modeling, observed stage and flow data (1980-2004) at Pandhare Dovan are used. Inundation analysis is performed utilizing the Digital Elevation Model downloaded from HydroSHEDS. Topographic maps (1:25000), land use map and past historical inundation depths of the study area which were collected from DWIDP, Nepal. Image of the study area is produced from digital data of ALOS, JAXA.

THEORY AND METHODOLOGY

Hydrological modeling of Bagmati river basin

Hydrological modelling of river basin is essential for rainfall runoff modelling and inundation analysis. The rainfall pattern of the region was analyzed with the 25 years (1980- 2004) of available rainfall data. In order to calculate the mean rainfall over an area, Thiessen polygon method is used. This method is considered superior to the arithmetic mean. But this method does not consider the topographical effect (Jayawardena, 2007). In order to simplify the flood forecasting techniques to the community level people, rainfall over an area is correlated with one precise Kathmandu airport station. Using this correlation average rainfall over the region could be calculated if the rainfall of Kathmandu station is known. To establish the relation between flood magnitude and corresponding inundation depth, flood of different recurrent interval are calculated with normal and Gumbel distribution. The primary objective of the flood frequency analysis is to relate the magnitudes of the extreme events to their frequency of occurrence through the use of probability distribution (Chow et al., 1988).

Basin scale flood forecasting modelling

The real time flood forecasting is one of the most effective non- structural measures for flood management. Rainfall covering the river basin and stages at the forecasting station data form the basis for flood forecasting. Out of various techniques available, statistical approach of modeling is chosen for this study. Statistical approach and least square methods of error minimization technique were used to set up the appropriate model within the available data sets. Stages and average rainfall over an area were first of all fitted for the calibration of the model. For calibration, data of 1980 to 1998 are used. After calibration and finding the model coefficients, it's validated using the data from 1999 to 2004. Out of many models set up and tested, modelling using stage and rainfall gave the better result than other setup like rainfall-discharges, only rainfall etc.

Flood characteristics and Inundation analysis

Study of flood characteristics and inundation analysis are essential for non-structural measures of flood management. It is one of the techniques to identify the areas under the risk of flood damage. In this study, inundation analysis is performed using GIS-based numerical models (Arc GIS, its extension HEC-GeoRAS and one dimensional modelling software HEC-RAS). Result of such analysis gives the depth of inundation for flood of different recurrent interval. The most devastating flood in the Bagmati river was in year 1993. So inundation depth simulation was performed for 1993 flood condition and results are compared with the actual inundation depths. To develop a graph which shows the relationship between flood magnitude and inundation depth, simulation with different return period floods were performed. Using such graph, even the community level people can easily find the depth of inundation for different flood magnitude. As the government has planned to protect the whole area by constructing levee, inundation simulation was further elaborated for future full levee protected and levee breach conditions.

RESULTS AND DISCUSSION

Rainfall analysis

Rainfall analysis shows that more than 80% of the rain falls in the monsoon period (June-Sept.) and trend of rainfall is significantly (α=0.05) increasing at 95% level of confidence.

Rainfall correlation

Daily average rainfall of Kathmandu airport (st.no.1030) and eleven stations mean rainfall over an area are correlated (Fig. 2). This correlation establishes the relation of rainfall between them.

$$R_{t-1(\text{average over region})} = 1.3\, R_{t-1(\text{Kathmandu\_St})} + 0.327$$

Using this correlation, average rainfall over the region could be calculated if the rainfall of Kathmandu station is known. This correlation would be easier even for the people at community level to find the rainfall over the region for flood forecasting.

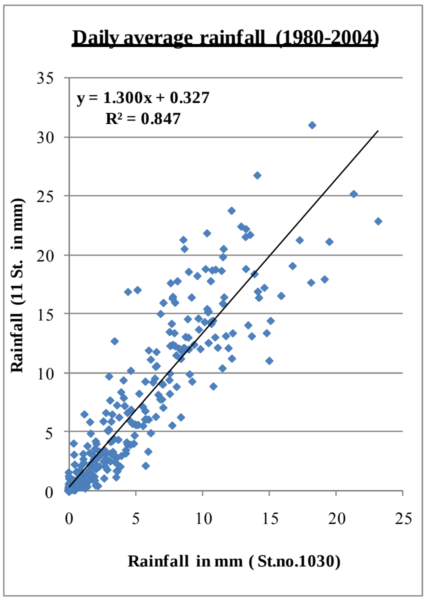


Fig.2 Rainfall correlation

Flood frequency analysis

Available 42 years (1965-2004) instantaneous maximum flood events probability distribution shows the Gumble distribution fits better (Chi-square goodness of fit test) than Normal distribution. So for this study purpose, flood magnitude, its frequency and return periods are taken from the Gumbel distribution (Table 1).

Table 1 Recurrence interval and flood magnitude of Gumbel distribution.

Return Period T_r (Year)	1.58	2	2.33	5	10	20	25	50	100	200	387	500	1000
Flood magnitude Q(m3/sec)	2688	3511	3985	6043	7719	9327	9837	11408	12968	14522	16000	16572	18122

Flood forecasting modeling

The best fitted model for the study area is

$$S_{8am(t)} = C_1\ S_{8am(t-1)} + C_2\ S_{av(t-2)} + C_3\ R_{t-1}$$

Where,

$S_{8am(t)}$ = Stage at 8 am at forecasting time t

$S_{8am(t-1)}$ = Stage at 8 am at time t-1, i.e. previous day

$S_{av(t-2)}$ = Average Stage (average of 8am, 12 midday and 4pm stages) of time t-2, i.e. two days before

R_{t-1} = Mean rainfall over an area of eleven rainfall stations of last 24 hours. (8 am of the day to 8 am of previous day)

Observed stage value of time t is modeled with observed values of time t-1, t-2 and rainfall of past 24 hours. This model considers the effect of both rainfall and stage for flood forecasting. Previous day stage at 8 am ($S_{8am(t-1)}$) and past 24 hours rainfall (R_{t-1}) considers the effect of both rainfall and stage of the past 24 hours in the model. Whereas, in order to simplify the model parameters to the community level people, average stage of two days before ($S_{av(t-2)}$) is used. When modeling was done, this combination of model parameters gave the better result so modelings with these parameters are adopted in this study. In order to set up the model and to find the coefficients with least square methods of error minimization, stepwise modeling was performed. First of all modeling was done for complete data sets. As the extreme flood events occur during May to October and floods are called extreme when the stages values are higher (Fig. 3 & Fig.4),

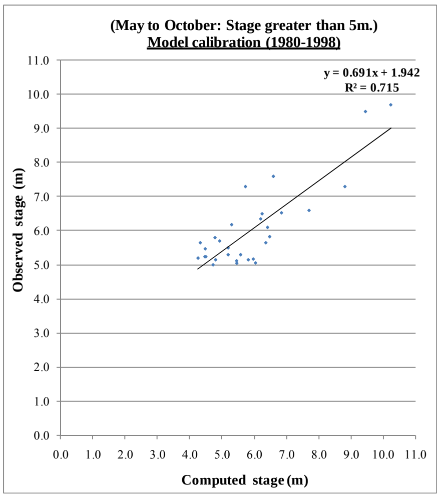


Fig.3 Model calibration

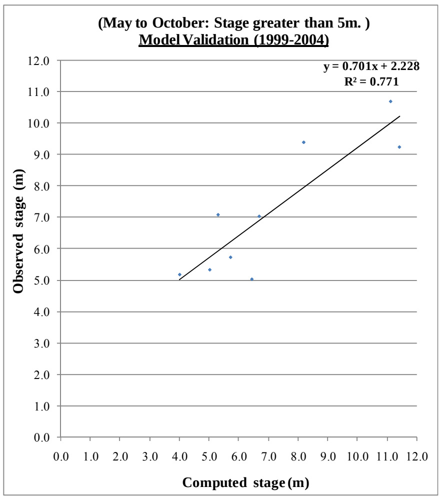


Fig.4 Model validation

Floods with stages value higher than 5m were seperated for modelling and coefficients ware determined. The model coefficients, R^2, MBE and RMSE of the analysis are presented in the Table 2

Table 2 R^2, model coefficients & errors of model calibration & validation

Calibration and validation with stage greater than 5m. (May to October)

Calibration (1980 to 1998)				Model coefficients			Validation (1999 to 2004)			
R^2	MBE (m)	RMSE (m)	(RMSE/Av.Stage) (%)	C_1	C_2	C_3	R^2	MBE (m)	RMSE (m)	(RMSE/Av.Stage) (%)
0.72	0.11	0.715	12.98	0.5958	0.6435	0.0229	0.77	0.10	1.15	15.93

Knowing these model coefficients, stages can be predicted. DHM has given stage and discharge values to define the rating curve for the period 1999 to 2006. Using these values and hqrating software (Goutam, 2007), rating curve is defined to calculated the discharge.

$$\mathbf{Q = 87.796\ (S_{8am(t)} - 0.668)^{1.856}}$$

So, using this stage discharge relationship, flood magnitude can be calculated,when the stage is known.

Flood characteristics and Inundation analysis

Inundation depth simulation of 1993 flood condition (T_r 387)

Inundation simulation result of 1993 flood condition is presented in Fig.5. Simulation results are compared with the available field inundation depth of year 1993 (at Bhranhapuri and Hathiaul VDC) and found to be closely approach the past inundation depths. In order to develop the relationship between flood discharges versus inundation depth, simulation was further elaborated with flood of different recurrent interval. Result of simulation is plotted for four village road junction point at Bhrahmapuri tola (ward no.8) & Belbichuwa(ward no.1,2&9) VDC (Fig.6). Using this relationship; even the community level people can identify the depth of inundation at that particular place for forecasted flood of different magnitude.

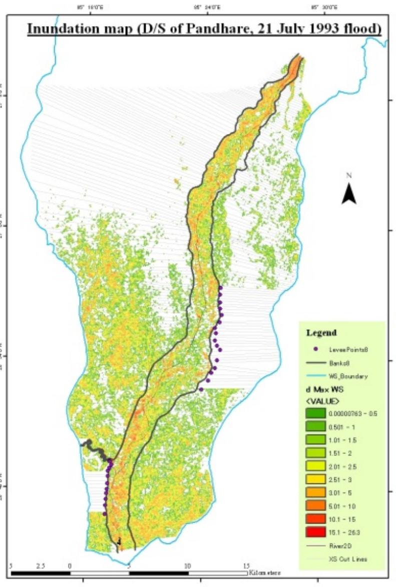
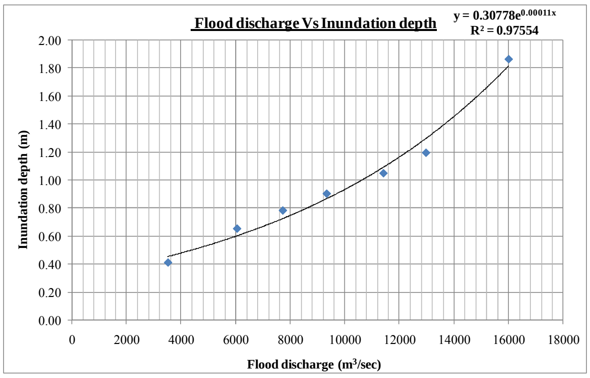


Fig.5 1993 flood condition

$$\textbf{Inundation Depth} = \mathbf{0.30778\ e^{0.00011*(Q)}}$$



Exponential plot is found better fitted. Without incorporating 1993 flood (i.e. T_r 387), linear plot was found best fitted.

$$\textbf{Inundation Depth} = \mathbf{8E\text{-}05*(Q) + 0.146}$$

Such relationship can be developed for even for other places within the downstream reach of watershed boundary. With these graphs, inundation depths can be indentified for particular magnitude of flood.

Fig.6 Inundation depth Vs Flood discharge

Inundation analysis of Levee breach condition

Result of complete levee protection and breaching at one point is shown in Fig.7. Inundation depth simulation result of levee breach at Deviparsa and Matsuri village (Near temple at Matsuri village ward no. 5) shows the greater depth of inundation than 1993 flood condition. Depth of inundation found higher, if the area is fully protected from levee and levee breaches at particular area.

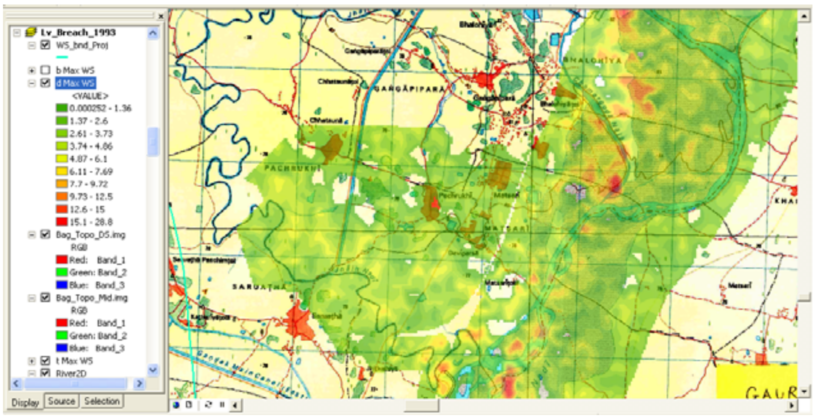


Fig.7 Levee breach condition

In order to develop the relationship between flood discharges versus inundation depth, simulation was further elaborated with flood of different recurrent interval for levee breaching condition (Fig.8). These graphs are useful to identify depth of inundation for particular magnitude of flood when the levee breaches.

Inundation Depth = $0.96189e^{0.00008*(Q)}$

In order to find the inundation depth for particular magnitude of flood, such relation can be developed for other places of inundation area.

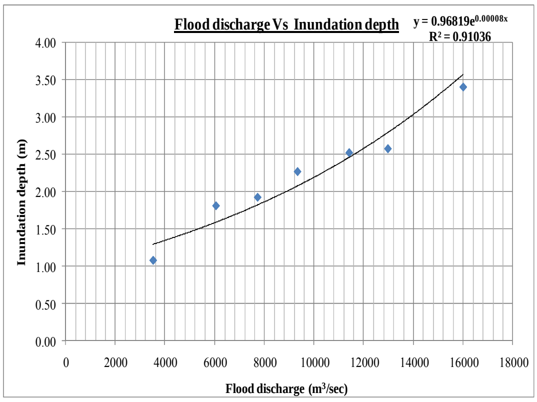


Fig.8 Inundation depth Vs Flood discharge

CONCLUSIONS

Performed analysis of hydrological condition, rainfall runoff modeling and inundation analysis are very much useful tools for flood risk assessment and community approach of flood risk management for the Terai region of Bagmati river basin. With an application of these technique, rainfall of one precise station is can be correlated with rainfall over an area. Knowing rainfall over an area and measured past stages, stage can be predicted using the developed flood forecasting model and identified model coefficients. Once the stage is predicted, probable flood can be calculated using rating curve. Ultimately, developed flood magnitude versus inundation depth graphs can be utilized to identify the depth of inundation for particular magnitude of flood. Such analysis could be done for other river basins as well.

RECOMMENDATION

Further study should be conducted using advance GIS based numerical models and digital data together with precise field observation data. It would be worthwhile to

i. Validate the result with more field observed data.
ii. Analyze with more precise data and advance simulation models.
iii. Develop inundation depth identifying technique for wider areas.

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