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Determination of Threshold Runoff for Flood Warning in Nepalese Rivers

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Abstract The Southern Terai plain area of Nepal is exposed to recurring floods. The floods, landslides and avalanches in Nepal cause the loss of lives of about 300 people and damage to properties worth about 626 million NPR annually. Consequently, the overall development of the country has been adversely affected. The flood risk could be significantly reduced by developing effective operational flood early warning systems. Hence, a study has been conducted to assess flood danger levels and determine the threshold runoff at forecasting stations of six major rivers of Nepal for the purpose of developing threshold-stage based operational flood early warning system. Digital elevation model data from SRTM and ASTER supplemented with measured cross-section data and HEC-RAS model was used for multiple profile analysis and inundation mapping. Different inundation scenarios were generated for a range of flood discharge at upstream boundary and flood threshold levels or runoffs have been identified for each river, thus providing the basis for developing threshold-stage based flood early warning system in these rivers.

Key Words Flood, danger level, threshold runoff, hydrodynamic model, geographic information system

1. INTRODUCTION

Nepal's Terai region is the part of the Ganges River basin, which is one of the most disaster-prone regions in the world. The Terai region amounting to 17% of the total area of the country and regarded as the granary of Nepal is recurrently suffering from flooding. The floods, landslides and avalanches in Nepal cause the loss of lives of about 300 people and damage to properties worth about 626 million NPR annually (DWIDP 2007). The rivers in the Terai area become wide and braided with wide spread damages to agricultural lands. The damages are further exacerbated by erosion of banks and deposition of infertile coarse material on the cultivated land. The channel capacity of the rivers in this regime is said to be decreasing due to increased sediment load coming from an increased erosion rate upland, thus making these rivers unable to accommodate large floods. As a result the adjoining areas suffer from inundation.

While many studies have been conducted for reducing the disaster risk in many river basins of Nepal,

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most of these studies have emphasized structural measures and have failed to address the root cause of disasters. The root cause of the disaster lies in the lack of comprehensive flood management which includes both structural as well as non-structural measures. Although various flood management measures are introduced in many places to prevent the negative consequences of flood disaster, the challenges are still at the forefront. It is generally found that the national and local governments have been mostly reliant on reactive approaches to disaster management focusing mostly on the relief and rescue operations. Although relief operations are essential for proper flood disaster management, they are not sufficient. Thus there is a need for measures to prevent hazards from turning into disaster. Moreover, for an effective and efficient framework of flood disaster management, it is necessary to reduce the vulnerability of the people through improved preparedness with early warning systems.

A flood early warning system could be developed using a variety of techniques such as upstream and downstream river level correlation, rainfall to river level correlation, rainfall-runoff modelling, hydrodynamic modelling etc. A simple approach could be the real-time monitoring of flood level at an index (forecast) station and issuing of a warning if the predetermined threshold level is exceeded (Dotson and Peters 1990). Although the more sophisticated warning systems could provide longer lead times, their reliability may not necessarily be greater than that of simpler systems (Corcoran et al. 2004). To set up a threshold-stage based early warning system, a comprehensive assessment of the threshold warning level is required.

Recently, the Flood Forecasting Project of the Department of Hydrology and Meteorology (DHM) of Nepal conducted a study to assess the threshold warning and danger levels at the forecasting stations of the major river basins for the purpose of developing a flood early warning system (DHM 2009, DHM 2010, DHM 2011). The study utilized Digital Elevation Model (DEM) data from the Shuttle Radar Topography Mission (SRTM) and data from the Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER) supplemented with measured cross-section data, and the United States Army Corps of Engineers Hydrologic Engineering Center's River Analysis System (HEC-RAS) hydraulic model. The SRTM DEM was released in 2003 whereas the ASTER DEM was released in June, 2009. Hence, DEM for Narayani and West Rapti River basins have been obtained from SRTM DEM downloaded from the website of the CGIAR Consortium for Spatial Information (http://srtm.csi.cgiar.org/Index.asp) which provides a 3 arc-second resolution (about 90 m). DEM for Koshi, Kankai, Karnali and East Rapti basins have been obtained from the ASTER DEM downloaded from the website of Japan Space Systems (http://gdem.ersdac.jspacesystems.or.jp) which provides a 1 arc-second resolution (about 30 m). This paper presents the methodology and results of the study.

2. STUDY AREA

The study areas are the southern plain areas of Narayani, East Rapti, Koshi, Kankai, Karnali and West Rapti River basins of Nepal. The areas downstream of flood forecasting stations up to the Nepal-India border of each river basin are taken as study area for the purpose of inundation modelling. Figure 1 shows the major river basins and flood forecasting stations covering the study areas. The descriptions of the study area are summarized in Table 1. All rivers except East Rapti are trans-boundary Rivers. Koshi (also called Sapta Koshi), Narayani and Karnali rivers are snow-fed rivers originated from the Himalayan range. These are the major tributaries of Ganges River. Kankai, East Rapti and West Rapti rivers are rain-fed rivers originated from the middle mountain range.

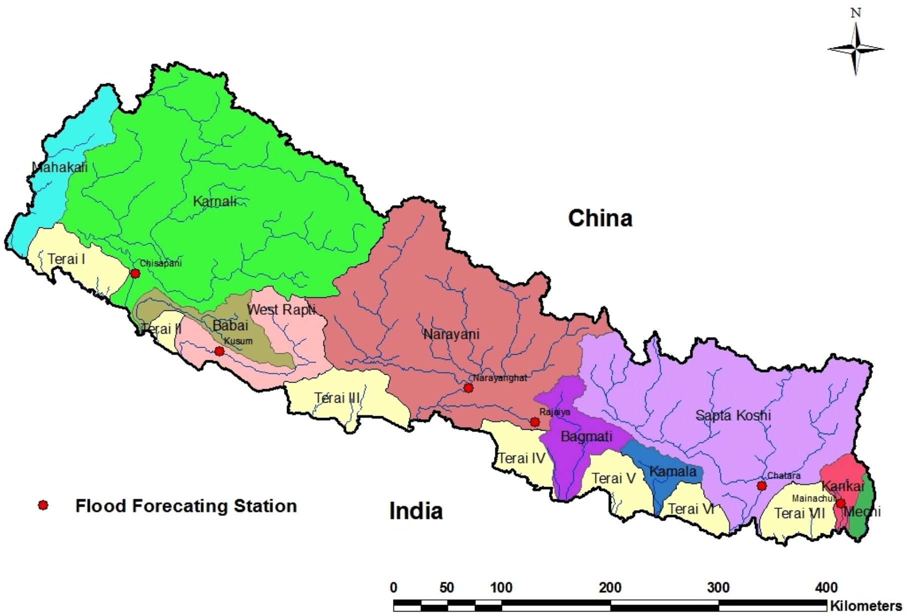

Figure 1. Major river basins and flood forecasting stations

Table 1. Description of study area (Source: DHM (2008) for catchment data and ICIMOD (2010) for glaciers and glacial lakes data).

S. No.	**River Name**	**Catchment Area at forecasting station (km^2)**	**River Length (km)**	**Major Tributaries**	**Special Features**
1	Narayani	31100	332	Kali Gandaki, Modi Khola, Seti, Madi, Marsyangdi, Trishuli, Budhi Gandaki and East Rapti	Snowfed, trans-boundary, passes through deepest gorge in the world around 5000 m deep, possesses 1025 glaciers and 338 glacial lakes
2	East Rapti	579	122	Manahari, Lothar, Rewa, Dhongre, Khageri and Kayar	Rainfed, Passes through Chitwan National Park
3	Koshi	54100	534	Sunkoshi, Tamakoshi, Dudhkoshi, Indravati, Likhu, Arun and Tamur	Snowfed, trans-boundary, possesses eight peaks over 8,000 meters high, including Mount Everest, 779 glaciers, and 1062 glacial lakes
4	Kankai	1148	108	Ratua, Mai Khola	Rainfed, trans-boundary
5	Karnali	42890	507	West Seti, Bheri, Humla Karnali, Mugu Karnali, Sinja, Tila, Lohare and Thuli Gad	Snowfed, trans-boundary, possesses 1,361 glaciers and 907 lakes, with glaciers covering an area of 1,740 km^2 and an estimated ice reserve of 128 km^3
6	West Rapti	5200	257	Jhimruk Khola, Mari Khola, Arun Khola, Lungri Khola, Sit Khola, Dunduwa Khola, Sotiya and Gandheli Nala	Rainfed, trans-boundary

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3. FLOODING PROBLEMS

Table 2 presents the hydrologic characteristics of the rivers of the study area. There is a very large variation of maximum and minimum discharge in each river. The peak discharge generally occurs from July to September during the monsoon period and the lowest flow is observed during the pre-monsoon period. The ratio of peak discharge to mean discharge varies from 10 to more than 100.

Table 2. Hydrologic characteristics (Source: DHM 2008)

S. No.	River Name	Station Name	Mean Annual Discharge (m^3/s)	Standard Deviation (m^3/s)	Instantaneous Maximum		Instantaneous Minimum	
					Discharge (m^3/s)	Date	Discharge (m^3/s)	Date
1	Narayani	Narayanghat	1550	171	15400	5/8/1974	146	30/3/2006
2	East Rapti	Rajaiya	26	6	3260	31/7/2004	2.18	7/6/1994
3	Koshi	Chatara	1620	239	25849	5/10/1968	185	28/3/ 2001
4	Kankai	Mainachuli	59	17	7500	12/8/1990	4.46	19/4/1994
5	Karnali	Chisapani	1380	215	21700	11/9/1983	171	21/3/2001
6	West Rapti	Bagasoti (U/S of Kusum)	109	45	6030	11/9/1981	3.76	26/5/1980

Almost 80 % of rainfall occurs in the monsoon period, which spans from June to September. For the rest of the period, there is very little rainfall. The spatial variation of annual rainfall is also very high as the total annual precipitation record ranges from 144 mm in Lomanthang to 5403 mm in Lumle, both places belonging to the Narayani River basin (Practical Action 2009).

Table 3 presents the summary of losses from floods, landslides and avalanches during 1983-2006 for Nepal. The flood of unprecedented magnitude in Bagmati, Narayani and East Rapti River during 19-21 July, 1993 had disastrous consequences with heavy loss of life and property as well as damages to infrastructures. 1336 people lost their lives and the estimated loss of properties was 4904 million NPR.

The Narayani River passes through 18 Village Development Committees and one Municipality downstream from the Narayanghat forecasting station. It receives a lot of sediment through small tributaries originating from the Siwalik Hills. Chitwan and Nawalparasi districts are among the most severely flood affected areas with damage and loss of life increasing annually along the East Rapti and Narayani Rivers as climatic conditions change. The deposition of sands on farmland by the torrents originating from the Chure/Siwalik range, inundation due to flooding, and bank cutting at various locations along the river are affecting lives and livelihoods.The Koshi River also receives a lot of sediment such as gravel, sand and clay through the small tributaries from the Siwalik Hills. The annual volume of sediment in the Koshi River has been estimated at 118 million cubic meters (Kattelmann 1991, Nayak 1996). It may also be one of the very few rivers in the world which has changed its course horizontally as much as 120 km in the last 250 years. Floods from the Koshi River in the past have created havoc in the downstream area of Nepal and India leading to loss of lives and property and causing widespread human suffering. In July 1991, the embankment of the Koshi River immediately downstream of the Koshi Barrage was breached due to flood discharge of 6700 m^3/s causing inundation over a vast area on the right bank. About 6000 people of 12 villages had to be evacuated to safer places and 40 ha of agricultural land were washed away.

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Table 3. Losses from floods, landslides and avalanches, 1983-2006 (Source: DWIDP 2007).

Year	People Death	People Injured	Livestock loss (No.)	House destroyed (No.)	Family affected (No.)	Land Affected (Ha.)	Infrastructure damaged (No.)	Estimated loss (million NPR)
1983	293	NA	248	NA	NA	NA	NA	240
1984	363	NA	3114	7566	NA	1242	869	37
1985	420	NA	3058	4620	NA	1355	173	58
1986	315	NA	1886	3035	NA	1315	436	16
1987	391	162	1434	33721	96151	18858	421	2000
1988	342	197	873	2481	4197	NA	NA	1087
1989	700	4	297	6203	NA	NA	NA	29
1990	307	26	314	3060	5165	1132	NA	44
1991	93	12	36	817	1621	283	25	21
1992	71	17	179	88	545	135	44	11
1993	1336	163	25425	17113	85254	5584	NA	4904
1994	49	34	284	569	3697	392	NA	59
1995	246	58	1535	5162	128540	41867.28	NA	1419
1996	262	73	1548	14037	36824	6093.4	NA	1186
1997	87	69	317	1017	5833	6093.4	NA	104
1998	273	80	982	13990	33549	326.89	NA	969
1999	209	92	309	2538	9768	182.4	NA	365
2000	173	100	822	5417	15617	888.9	NA	932
2001	196	88	377	3934	7901	NA	NA	251.1
2002	441	265	2024	18181	39309	10077.5	NA	418.91
2003	232	76	865	3017	7167	NA	NA	234.78
2004	131	24	495	3684	14238	321.82	NA	219.28
2005	141	31	360	1102	2088	NA	NA	130.56
2006	114	39	9980	3334	18385	3396.84	NA	288.63
Average*	299.4	80.5	2365.1	6725.5	27149.9	5530.2	328.0	626.0

* Average for years for which data are available, NA = Data Not Available

On 18th August 2008, the embankment 12.6 km upstream of barrage of the Koshi River breached. It caused the displacement of more than 107,200 people with a death toll of eight in Nepal. Approximately 493 lives were lost and 3,500 were reported missing after the disaster on the Indian side (GFDRR 2010). The death toll would have been very high if the flood had occurred at night. Progression of embankment breaching took place at the rate of about 500 m in every 5 hours. It was the country's worst flooding in five decades. Low intensity rains for several days during monsoon season and scouring of the embankment caused the embankment to collapse.

When the Koshi River changed its course towards the east breaching 1.70 km of its left embankment, it deposited silt on the flood affected area and adjoining villages covering 5475 ha of agricultural land. About 80 % of flow passed through the breached section. About 15 km of the East-West highway was obstructed and 3 km was completely destroyed. The floods had drastic impacts on habitats of wildlife, aquatic flora and fauna of the Koshi Tappu Wildlife Reserve. About two thirds of houses were severely damaged as most of them were huts made of mud, bamboo and thatch. It caused extensive damage to the optical fiber cable network laid along the highway. In addition, telephone exchange, power plant, the main distribution frame transmission system were submerged in the floods and caused disturbances to the communication network in the eastern region of Nepal (Baral 2009).

During the 2009 monsoon, seven villages were flooded by the swollen Kankai and Biring Rivers in southern Jhapa. More than 500 houses were submerged and thousands of hectares of paddy field were inundated. The Karnali River bifurcates into two branches downstream of Karnali Bridge, creating an island in the Rajapur area of Bardiya district. Floods from the Karnali River in the past have created havoc in the Rajapur area leading to loss of lives and property and causing widespread human suffering. Heavy rainfall in the lower West Rapti basin on 25-27 August, 2006 created havoc due to flooding. Similarly, Banke became the second most flood affected district in the country in 2007 due to flooding in the West Rapti River. At that time, the flood inundated the area for 3-4 days (ICHARM 2008).

4. METHODOLOGY

The methodology for this study included the following steps:

i. Preparation of the digital elevation model
ii. Field work for cross-section and longitudinal section survey, collection of historical flood records, discharge measurements, etc.
iii. Assessment of downstream boundary conditions
iv. Data pre-processing using HEC-GeoRAS
v. Hydrodynamic modelling using HEC-RAS for a range of upstream boundary conditions
vi. Analysis of multiple profiles and inundation maps using HEC-GeoRAS and assessment of threshold runoffs and danger levels

DEM for the Terai region of the study areas were prepared from SRTM and ASTER tiles in GeoTiff format by mosaicking to a new raster in ArcGIS 9.3. The raster DEM was then projected into UTM zone 44N coordinate system with a cubic resampling technique. HEC-GeoRAS needs DEM in the form of a triangulated irregular network (TIN) which was created using 3D Analyst Tools Raster to TIN.

Cross-section surveys were carried out at the forecasting station, near the downstream boundary and two more sections in between for all rivers. Additional cross-sections were extracted from DEM at an interval of 1500-2000 m of river reach. Longitudinal surveys were also carried out along river stretches of 100 to 500 m either upstream or downstream of the downstream boundary to find out river bed (water surface) slope.

During the field study detailed information regarding old flood marks were collected. Local people were interviewed to get information on the history of river flooding and observed flood levels. Discharge measurements were also carried out at flood forecasting stations by an area-velocity method. Land use data together with measured discharge data were used to infer Manning’s roughness coefficient, n. Since the discharges were measured for the low flows, the values of Manning's n were adjusted for high flows. The adopted values of Manning’s n for main channel and river banks are presented in the Table 4.

Different values of Manning's n are assigned for different main channel sections of each river and the river banks. Table 4 also presents the range of discharge values used as the upstream boundary conditions for HEC-RAS model to generate the scenario for multiple profile analysis and inundation mapping.

Table 4. Upstream boundary condition and Manning's n for different river sections

S. No.	River Name	Upstream boundary discharge (m^3/s)	No. of scenario	No. of cross-sections	Manning's n	
					Main Channel	River Banks
1	Narayani	500-20000	30	35	0.07, 0.06, 0.05, 0.04	0.08
2	East Rapti	500-1900	15	66	0.05, 0.04, 0.035	0.06, 0.05, 0.04
3	Koshi	1000-15000	43	37	0.05, 0.04, 0.035	0.06, 0.04
4	Kankai	1000-5000	42	20	0.035, 0.03, 0.025	0.04
5	Karnali	5000-12500	16	38	0.035, 0.03	0.05
6	West Rapti	100-15000	24	28	0.03	0.06

As there were no hydrological stations at the downstream boundaries, we generated rating curves based on the channel cross section and water surface slope data measured during the field trip using WinXSPro software (Hardy et al. 2005). The rating curves are shown in Figures 2-1 to 2-6. These rating curves provide the relationship between water level and discharge at various locations near the Nepal-India border which are required as the downstream boundary condition for HEC-RAS model.

A one dimensional steady flow analysis was performed using a HEC-RAS hydraulic model by providing a range of discharge as upstream boundary at the forecasting station and a rating curve as the downstream boundary and the flood inundation scenario was generated for each discharge value to assess the danger level and threshold runoff. HEC-GeoRAS was used for geometric data preparation and GIS analysis (USACE 2008).

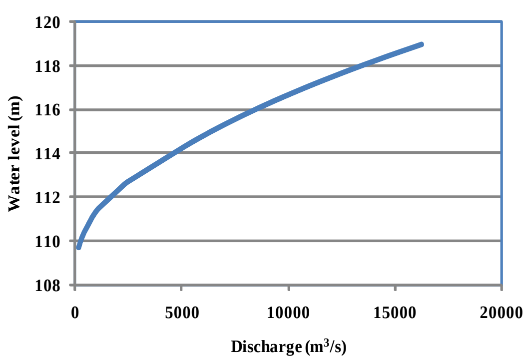

Figure 2-1 Rating curve at Tribeni**, Narayani**

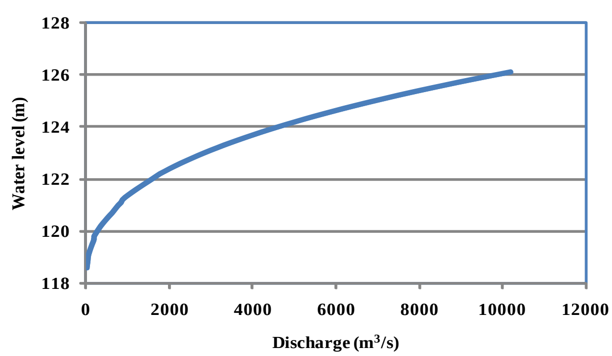

Figure 2-2 Rating Curve at Ramnagar, West **Rapti**

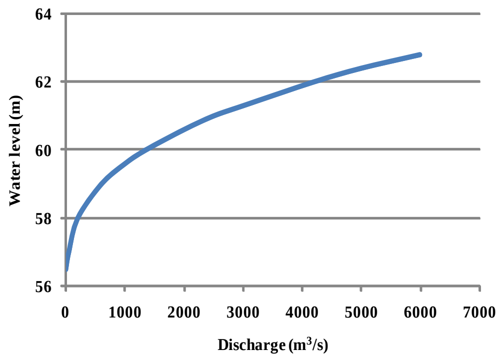

Figure 2-3 Rating curve at Sadakbari, Kankai

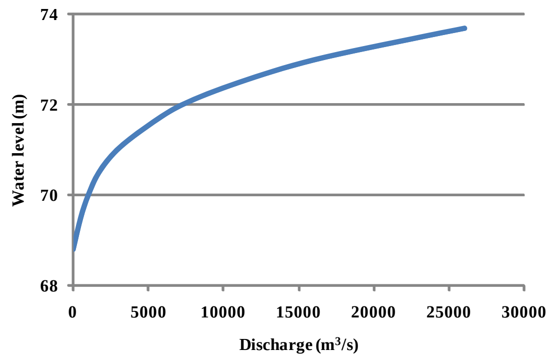

Figure 2-4 Rating curve at Saptakoshi barrage, Koshi

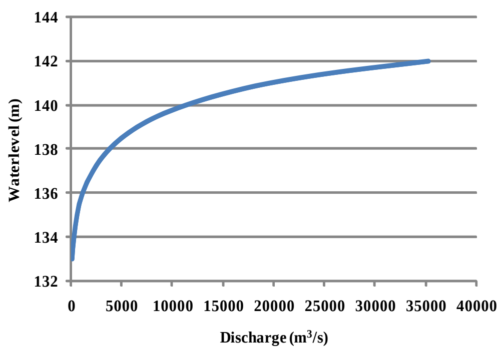

Figure 2-5 Rating Curve at Kothiyaghat, Karnali

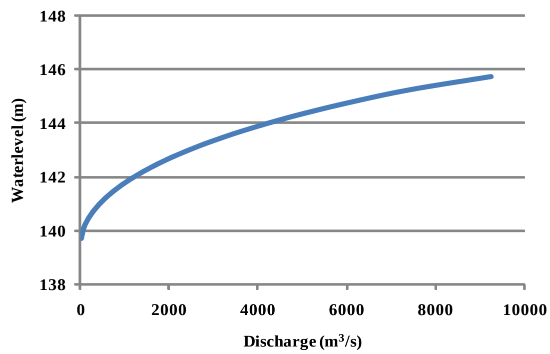

Figure 2-6 Rating Curve at Meghauli, East Rapti

5. RESULTS AND ANALYSIS

The Flood Forecasting Section of the Department of Hydrology and Meteorology has defined the warning level as the flood flow that just passes over the river bank, but does not affect the nearby settlements. It is the level of flow at bankfull stage of a river. The Danger level is that level of flow at which the flood water rises above the main stream channel and enters the settlements affecting people and their properties but the depth of inundation remains within one meter.

As a result of this work, the warning levels and danger levels have been identified by analysing the flood inundation scenario for a range of flow boundary conditions at forecasting stations for each river. Table 5 presents the threshold water levels with reference to mean sea level (MSL) and DHM gauge height and runoffs corresponding to warning level and danger level. Inundation maps have also been prepared for different flood levels above warning level and the villages likely to get inundated are identified so that warning could be given to the specific areas with advisory for emergency response (see supplementary material).

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Table 5. Threshold Runoff, Warning level and Danger level

S. No.	River Name	Station Name	Threshold Runoff (m^3/s)	Threshold Water Level (m)		Remarks
				DHM Gauge Height	With reference to MSL	
1	Narayani	Narayanghat	7500	6.80	187.78	Warning level
			10000	8.00	188.98	Danger level
2	East Rapti	Rajaiya	1000	3.30	345.14	Warning level
			1300	3.70	345.54	Danger level
3	Koshi	Chatara	5600	5.60	112.25	Warning level
			8150	6.80	113.45	Danger level
4	Kankai	Mainachuli	1900	3.70	120.09	Warning level
			3250	4.20	120.59	Danger level
5	Karnali	Chisapani	8200	10.00	201.64	Warning level
			10000	10.80	202.44	Danger level
6	West Rapti	Kusum	1500	5.00	204.19	Warning level
			2000	5.40	204.59	Danger level

Finally, the threshold levels were verified by comparing with the historical flood levels and inundation information collected during the field work and the values were found very closely matching. The flood warning and danger levels have been marked at the forecasting stations to help the gauge reader to easily read these threshold levels during the time of flooding.

6. CONCLUSIONS

Flooding is a serious problem in Nepal during the monsoon period, especially in the southern plain Terai area. However, due to the limitation of data, budget, infrastructure and manpower, flood forecasting and a warning system in Nepal are not yet fully operational. Hence, this study on the assessment of threshold runoff and flood danger level at flood forecasting stations of six river basins is a preliminary step for the development of flood forecasting and a warning system.

This study utilized SRTM and ASTER DEM data and a HEC-RAS hydrodynamic model to perform multiple profile and inundation analysis for a range of discharges at upstream boundary to assess the danger levels and threshold runoffs at the forecasting stations. SRTM and ASTER DEM data were utilized due to the constraint of adequate financial resources to conduct topographic survey of the study area. NASA's shuttle radar topography mission (SRTM) obtained elevation data on a near-global scale during an 11-day mission in February 2000. The ASTER instrument was launched onboard NASA's Terra spacecraft in December 1999 and global DEM were generated from data obtained during March, 2000 to August, 2010. Although SRTM and ASTER DEM provide old and coarse resolution data, these are freely available to download.

The limitations of the study are the use of coarse resolution DEM, limited number of measured cross-sections, lack of measured stage-discharge relation at downstream boundary and disregard of the flow from smaller tributaries downstream of forecasting stations. Due to lack of gauging stations and measured data downstream of forecasting stations, the Manning's n values could not be calibrated. These limitations introduce the uncertainties in the threshold levels in the range of about 20-50 cm. More precise assessment of threshold levels could be done by using high resolution digital elevation model derived from measured cross-section data with field survey which requires an intensive data collection campaign. Hence, it is recommended to reassess the threshold levels at the interval of a few years including the contribution from all tributary channels downstream from forecasting stations. Installation of gauging stations near flood prone villages and at the downstream boundary site near the Nepal-India border is also highly recommended.

Nevertheless, the threshold levels along with the real time water level and rainfall information have now been applied to issue flood warning in these six river basins in advance of about six to twelve hours lead time. There is a web based telemetry system for real time monitoring of water levels and rainfalls and community based warning dissemination and an immediate response mechanism has also been set up in East Rapti, Narayani, West Rapti and Karnali basins. An automated alert system has been set up at the office of the District Disaster Relief Committee of West Rapti basin which triggers the siren attached to the electronic display board automatically when the river level reaches the warning level. The inundation maps prepared for different flood levels are used to issue warning to the specific location. These maps have also been used to identify the safe areas for shelter and the escape route. The flood danger level information could also be used for land use planning at the town/village level. This approach of flood warning has been found simple, fast, reliable and cost effective. This approach is particularly suitable for flood warning in steep mountainous rivers, where the flood is generally of flashy nature. The research is now focused on developing a long-lead flood forecasting model for each river basin using rainfall forecast with a weather forecast model.

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