Khando River restoration scheme design: application of 1-D and 2-D hydrodynamic and sediment transport modelling

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Abstract

One-dimensional (1-D) and two-dimensional (2-D) mathematical modelling are useful tool for designing flood risk and river behavior management schemes (Enggrob and Tjerry, 1999; Hassan et al. 2002). A 1-D and a 2-D models have been developed for designing schemes to improve drainage of Khando/Tilyuga and Jeeta River, and restoring efficient flow regime through the Khando/Tilyuga river. The study also aims for formulating schemes to minimising/eliminating flood risk in the adjacent floodplain, agricultural lands and settlements. Khando is a floodplain channel in the west bank of Kosi in Supaul district. The increased sediment load of Khando River has deposited silt in the upper reaches causing the river bed rise; in some cases, river bed has matched the level of the surrounding agricultural farmland. The bulk fraction of the discharges is now passing through Kunauli village. The bank and bed (deepest point) profile of the Khando and JAXA satellite imagery indicate shallow areas in the north of Kunauli, while river level is quite low in the south of Kunauli. While the lower terrain in the south will attract flood water due to gravity, the shallower terrain in the north also creates flood vulnerability; flood water can spill out of bank too fast (even at mid stage flow). Average water depth in the northern upstream reach (north of Kunauli) is below 2m, and thus, high stage discharges are likely to pass over the adjacent floodplains. A 1-D hydrodynamic model in MIKE11 and a 2-D sediment transport model in MIKE21C have been used in designing the scheme. The model provides dimensions and alignment of desilted scheme, location and dimension of flow guiding structure and embankment height. The model also identifies improved flow drainage route from the embanked sub-catchment, with Kosi main west bank embankment on the east, and Khando embankment on the right bank of Khando. The study demonstrates through short-term model prediction of the sustainability of the proposed desilting scheme.

Keywords: hydrological and hydrodynamic modelling, erosion prediction, MIKE11, MIKE21C, 1-D and 2-D modelling

1. Introduction

The Khando river, more commonly known as Tilyuga river in India, originates from the Churiya (Siwalik) range of hills, which is supposed to be the first line of mountain range and of lower elevation in Nepal. The Khando river enters into the Terai area (means low flat land) from about 4 km north of the East-West highway of Nepal territory and then enters into India near Kunauli Bazar in Supaul district of Bihar. The catchment area is approximately 146.00 sq km above the point of Nepal-India border. In recent years, floods with large discharge and shorter duration have become common. In Terai region due to mild bed slope, the river deposits substantial volume of sediment causing channel shifting, meandering, widening, bank erosion and inundation, and consequently siltation to farmland. The increased sediment load of Khando River has deposited silt in the reaches at immediate north of Kunauli Bazar causing the river bed rise. In some cases, river bed has matched the level of the surrounding agricultural farmland.

2. Objectives

The aim of this study is to improve drainage of Khando/Tilyuga and Jeeta River, and restoring flow through the Khando/Tilyuga river, and thus, minimising/eliminating flood risk in the adjacent floodplain and agricultural lands and settlements. The mathematical modelling study is expected to deliver alignment of flood embankments for containing flow within active flood plain and associated flow control structures.

3. Modelling Methodology

This study comprises following modelling works:

- Hydrological modelling for run-off estimation of the catchments of Khando/Tilyuga river and Jeeta Dhar in NAM software (DHI, 2019)
- One-dimensional (1-D) hydraulic modelling of Khando Tilyuga River and Jeeta Dhar in MIKE11 software (DHI, 2019)
- Two-dimensional (2-D) hydraulic modelling of Khando/Tilyuga river in MIKE21C software (DHI, 2019)
- Catchment sediment yield estimation of Khando/Tilyuga and Jeeta Dhar in SWAT modelling software (Neitsch et al. 2009)

NAM is DHI's hydrological modelling software to simulate rainfall-run-off processes at catchment scale. NAM is a coupled module to the river model (MIKE11) to add catchment run-off directly to the hydraulic model. NAM is a deterministic, lumped, conceptual model. NAM comprises of a set of linked mathematical statement describing in a simplified quantitative form the land phase of the hydrological cycle and simulates surface, sub-surface and baseflow.

MIKE11 is a professional engineering software for simulation of flows, sediment transport and water quality in rivers, estuaries, channels, lakes, reservoirs and other water bodies. MIKE11 is a fully dynamic, one-dimensional modelling software and solves vertically integrated Saint-Venant flow equations for conservation of mass and momentum. The tool is used for detailed analysis, design, management and operation of simple and complex river/channel systems.

$$\frac{\partial Q}{\partial x} + b_s \frac{\partial h}{\partial t} = 0 \qquad (1)$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left(\beta \frac{Q^2}{A}\right) + gA \frac{\partial}{\partial x} (h + H) + gA \frac{|Q|Q}{K^2} = 0 \qquad (2)$$

where Q is discharge, h is water depth, b_s is flow width, A is cross-sectional area, K is conveyance (where $K = CAR^{1/2}$), C is Chezy resistance coefficient, R is hydraulic radius, β is Boussinesq coefficient, H is bottom elevation, g is acceleration due to gravity.

MIKE21C is used to develop 2-D hydraulic model of Khando and Jeeta and their floodplains. MIKE 21C simulates hydrodynamics of vertically homogeneous flows, sediment transport and morphological changes. MIKE21C solves 2-D Saint-Venant's flow equations in curvilinear grid. The hydraulic model compute erosion/deposition by sediment continuity equation and allows bank erosion.

SWAT is used for sediment yield estimation from catchments. SWAT model uses the Modified Universal Soil Loss Equations (MUSLE) to compute the sediment transport from sheet erosion for each hydrologic response unit (HRU). The tool is developed by the United States Department of Agriculture (USDA) to predict the hydrological response of un-gauged catchments to natural inputs as well as the manmade interventions.

4. Model Set-Up

Hydrological model: delineation of the catchments of the Khando and Jeeta River was done using Arc-SWAT tool in ArcMap (version 10.3.1). Based on areas calculated, hydrological model was set-up for the two catchments (Fig. 1a) for Khando 175 km^2 and for Jeeta Dhar 119 km^2. Asian Precipitation - Highly-Resolved Observational Data Integration Towards Evaluation (APHRODITE-APH) collects and analyses rain gauge observations from thousands of Asian stations. APH has about 57 years of daily gauge interpolated precipitation datasets a between 1951 and 2007 at spatial resolution of 0.25° latitude-longitude (approximately 9 km cell). As there is no rainfall observation station within the catchment of Khando and Jeeta River, hence APH rainfall data (Fig. 1b-c) has been used for run-off estimation in NAM from January 1985 to December 2007. The calibration of the hydrological model's parameter was done using donor catchments from Bagmati and Kosi rivers, which have similar characteristic parameters, and located on either side of Khnado. Both Kosi and Bagmati hydrological models are calibrated and validated against long records of observed discharges for the period 2001-2007 and 2009-2015 (KOSIFEWS, 2018). The hydrological model parameters for the Khando and Jeeta catchment are presented in Table 1.

Parameter	Description	Typical Value Range	Values used	
			Khando	Jeeta Dhar
Umax	Maximum depth of surface storage (mm)	10-20	16	16
Lmax	Maximum depth of root zone storage (mm)	50-300	75	75
CQOF	Overland flow runoff coefficient	0-1	0.65	0.65
TOF	Threshold value for overland flow	0.0-0.7 (max 1.0)	0.75	0.75
CK1,2	Routing time constant for overland flow (hour)	3-48	12	12
TIF	Threshold value for inter flow. Represents the root zone moisture content above which interflow is generated.	0-1	0.65	0.65
CKIF	Routing time constant for interflow	500-1,000	700	700
TG	Threshold value for groundwater recharge	0.0-0.7 (max.1.0)	0.4	0.4
CKBF	Routing time constant for baseflow	500 to 5,000	1500	1500

Table 1: NAM parameters for Khando and Jeeta catchments

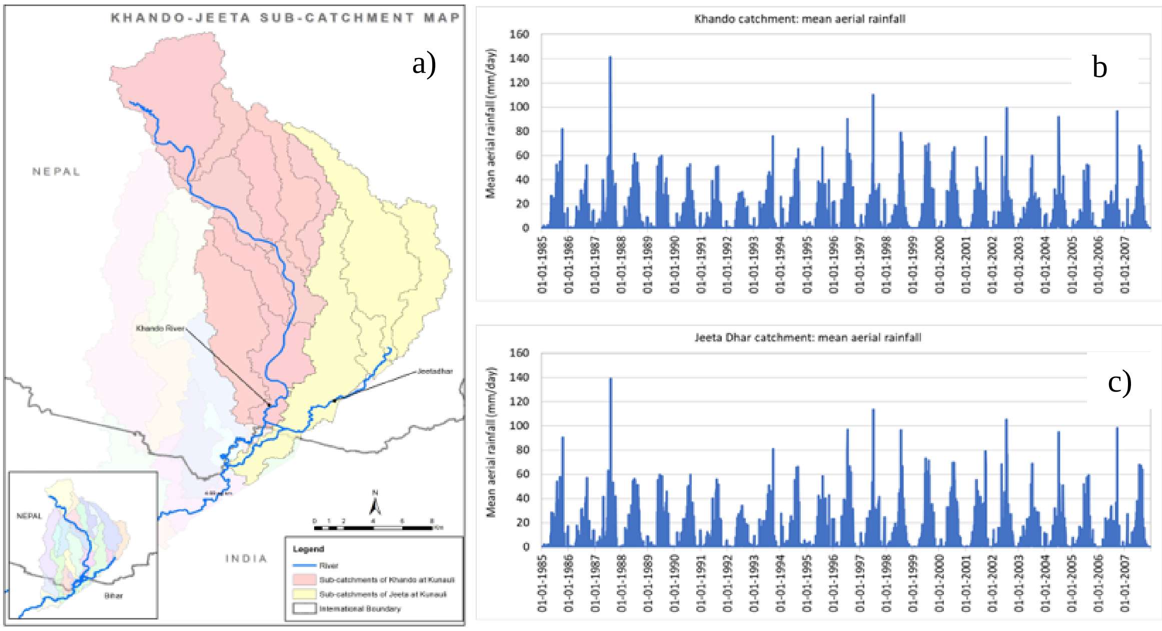

Fig.1 Catchments of Khando and Jeeta Dhar at confluence point of the two rivers (a), mean aerial daily rainfall Khando catchments (b), and Jeeta Dhar catchments (c)

1-D hydraulic model: the 1-D hydrodynamic model of the Khando and Jeeta Dhar and the branch (un-named) connecting them have been developed (Fig. 2a). River lengths considered in the model are 11.68 km of Khando, 8.94 km of Jeeta Dhar and 1.40 km of the connecting branch. The channel layout in model set-up is shown in Figure 2a. The cross-sections used in modelling were surveyed in pre-monsoon 2017 in KOSIFEWS project by FMISC. An example cross-section from Khando is shown in Fig. 2b, longitudinal bed profile in Fig. 2c and river bank levels in Fig. 2c.

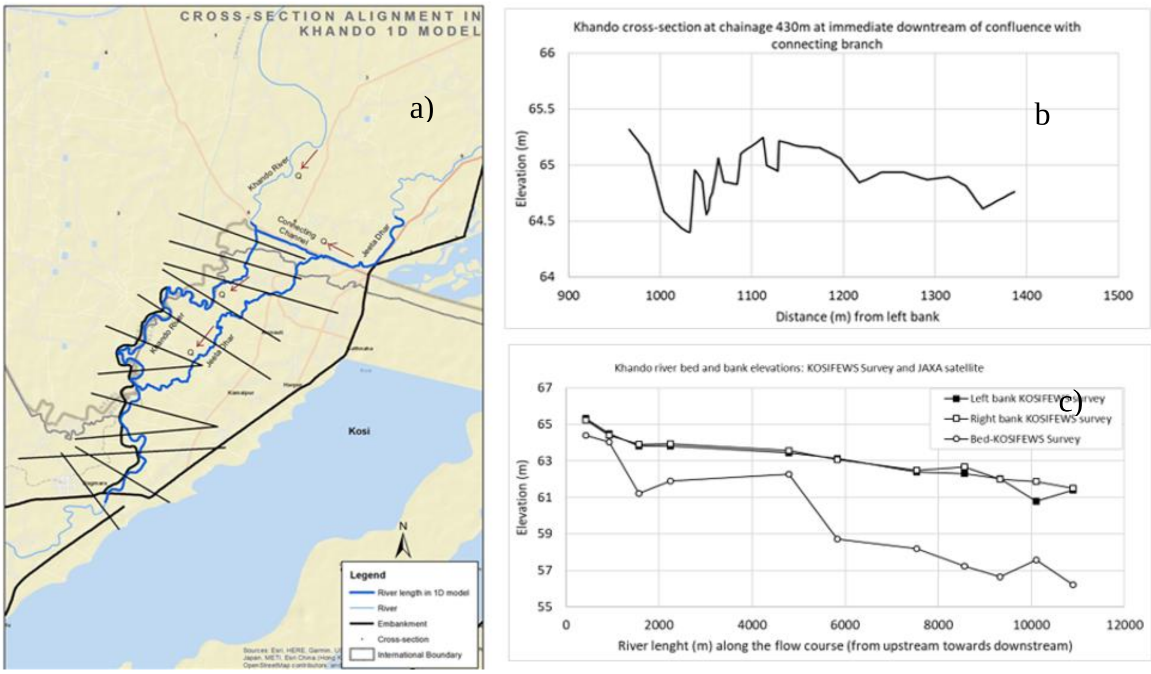

Fig.2 Khando and Jeeta Dhar channel and cross-section alignment (a), an example river cross-section of Khando (b), Longitudinal elevation profile of bed and banks of Khando (c)

2-D hydraulic model: flood inundation maps have been derived from the 2-D model. The 2-D model is built in MIKE21C; topography used in the model is from JAXA satellite imageries. Inflow boundary to the model are taken from the run-off hydrograph and the highest peaked hydrograph has been used where Khando peak is 184 m3/s and Jeeta Dhar peak is 120 m3/s. Flood maps then have been derived for different stage/flow condition: for 20, 40, 80, 120, 140 and 304 m3/s. No datum correction has been provided to the ground elevations of the JAXA imagery. As the flow is mainly friction and gravity dominated over this floodplain, satisfactory and representative water depth and flow speed could be estimated without any datum correction. However, water level could not be calculated without proper datum correction or without using surveyed bathymetry data from the field. Thus, the 2-D model delivers depth, speed contours, velocities in existing and in proposed embankment condition scenario.

SWAT model: inputs required to setup SWAT model include the Digital Elevation Model (DEM), land use, soil and weather data. Spatial data used to set up the SWAT model comprised of the 30 m pixel resolution JAXA satellite imagery; a climatic Gridded dataset for 1971–2005 published by IMD with a spatial resolution of 0.5° X 0.5°, the 1 km resolution Harmonized World Soil Database, and a land use/land cover map. The Khando river catchment has been subdivided in 13 subbasins. In total 166 HRUs have been identified in the basin. The simulation period has been 1971–2005, including five years of model warm-up (1971–1975). Surface runoff was simulated via the Curve Number CN method to account for the impact of slope on the curve number. Evapotranspiration has been modelled with Penman-Monteith method. Water routing was modelled with the variable storage coefficient method. This routing of streamflow, sediments and other pollutants occurs in the cascading sequence of single reaches along the stream network. The daily sediment balance of a given reach has been calculated by considering the reach flow capacity to transport sediments and the sediment inputs to the reach from upstream reaches as well as the HRUs of the sub-basin. Sediment compositions were sand fraction as 40%, silt as 38% and clay as 22%.

5. Results and discussions

Catchment run-off, based on 23-years of rainfall from 1985 to 2007, was estimated. Maximum run-off from Khando is 184 m^3/s and the same from Jeeta Dhar is 120 m^3/s. The peak run-off occurred in 1987.

There is high sediment yield from the catchments of Khando and Jeeta Dhar, 0.43 Million tons/year and 0.28 Million tons/year resulting in 2,453 t/km^2/year from Khando and 2372 t/km^2/year from Jeeta Dhar. These rates are based on annual load of 23 years (Fig. 3). These rates are similar to the high load from the catchments of Kosi and Bagmati (Sinha et al. ,2005). Estimated sediment load from Bagmati at Dheng bridge point (Indo-Nepal border) is 10 Million tons annually. The catchment area of the Bagmati at Dheng bridge is 3790 km^2 and sediment yield for unit area of catchment is 2,744 t/km^2/year. Catchment area of Kosi at Barakshetra is 59,550 km^2 and sediment yield is 1,594 t/km2/year (Sinha et al. 2005).
Water depths of Khando river from 1-D model demonstrate the river maintains good flow during monsoon period. Average and maximum depth are very similar. Average depth is about 1.0 m at upstream end near Rajbiraj-Kunauli Road Bridge and Kunauli Bazar area. Jeeta Dhar depths also demonstrate good flow through the channel during monsoon. Again, average and maximum depth are very similar. Average depth is about 4.0 Kunauli Bazar area.

Water depth in un-named connecting branch is very shallow and indicates easy out of bank flow and flooding.

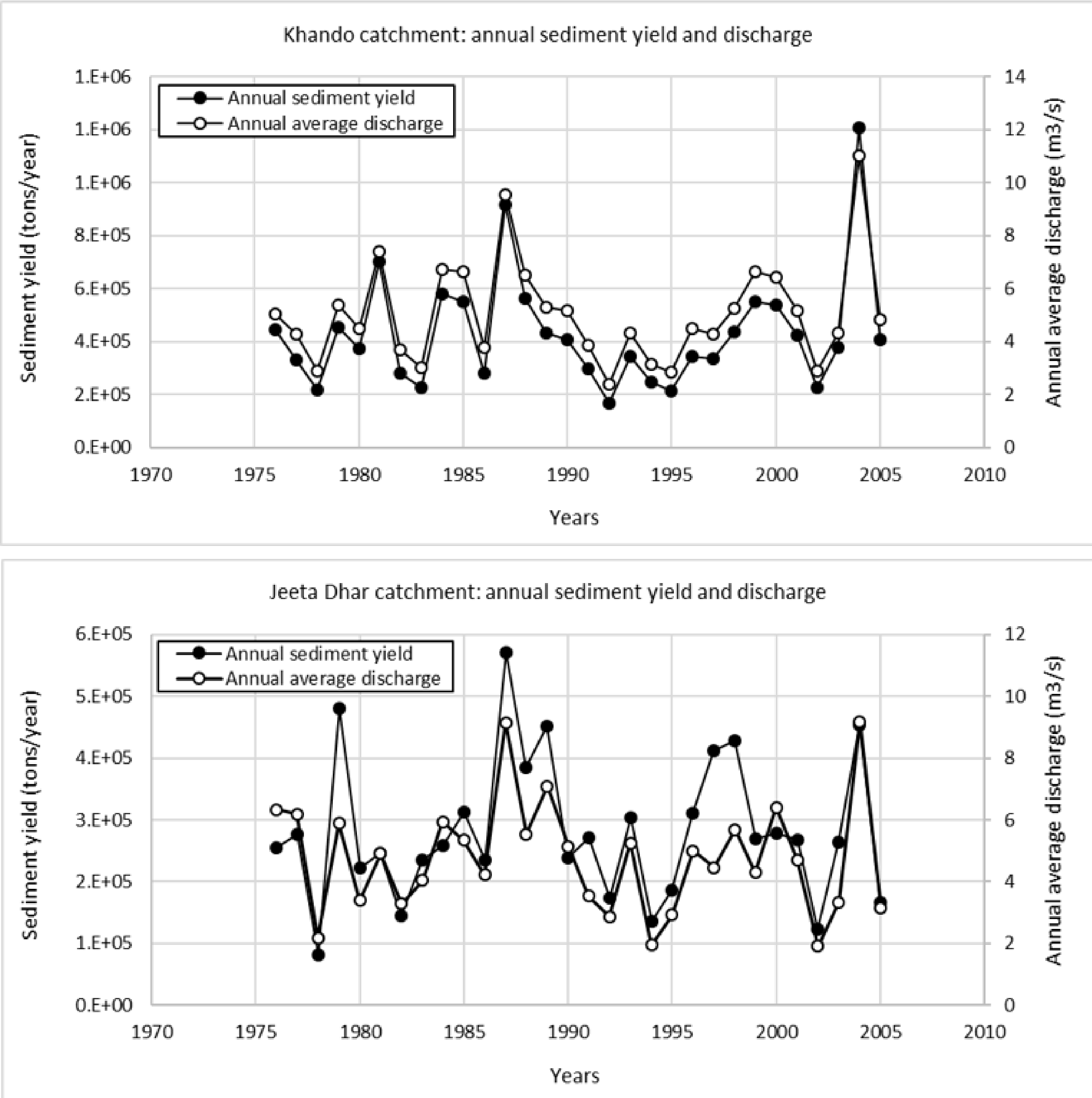

Fig.3 Annual catchment sediment yield from Khando catchment (a) and Jeeta Dhar catchment (b)

Inundation mechanism in floodplains of Khando and Jeeta Dhar are demonstrated in Fig. 4 and 5. Both floodplains are vulnerable to flooding even at very low flow. Floodplain of Jeeta Dhar is particularly prone to early flooding. In low flow ranges, from 20 m^3/s to 140 m^3/s, inundation area increases rapidly (Fig. 5) indicating channels of lower flow conveyance capacity. For high flow of 140 m^3/s to 304 m^3/s, the inundation area does not increase so rapidly. By the peak flow condition (304 m^3/s), almost entire Kunauli Bazar is flooded except few houses/installations.

The flood maps show inundation of Kunauli bazar, even in low flow, as low flow as $10m^3/s$. Therefore, silt deposition over the floodplain and agriculture land is very likely as there is high sediment yield from the catchments.

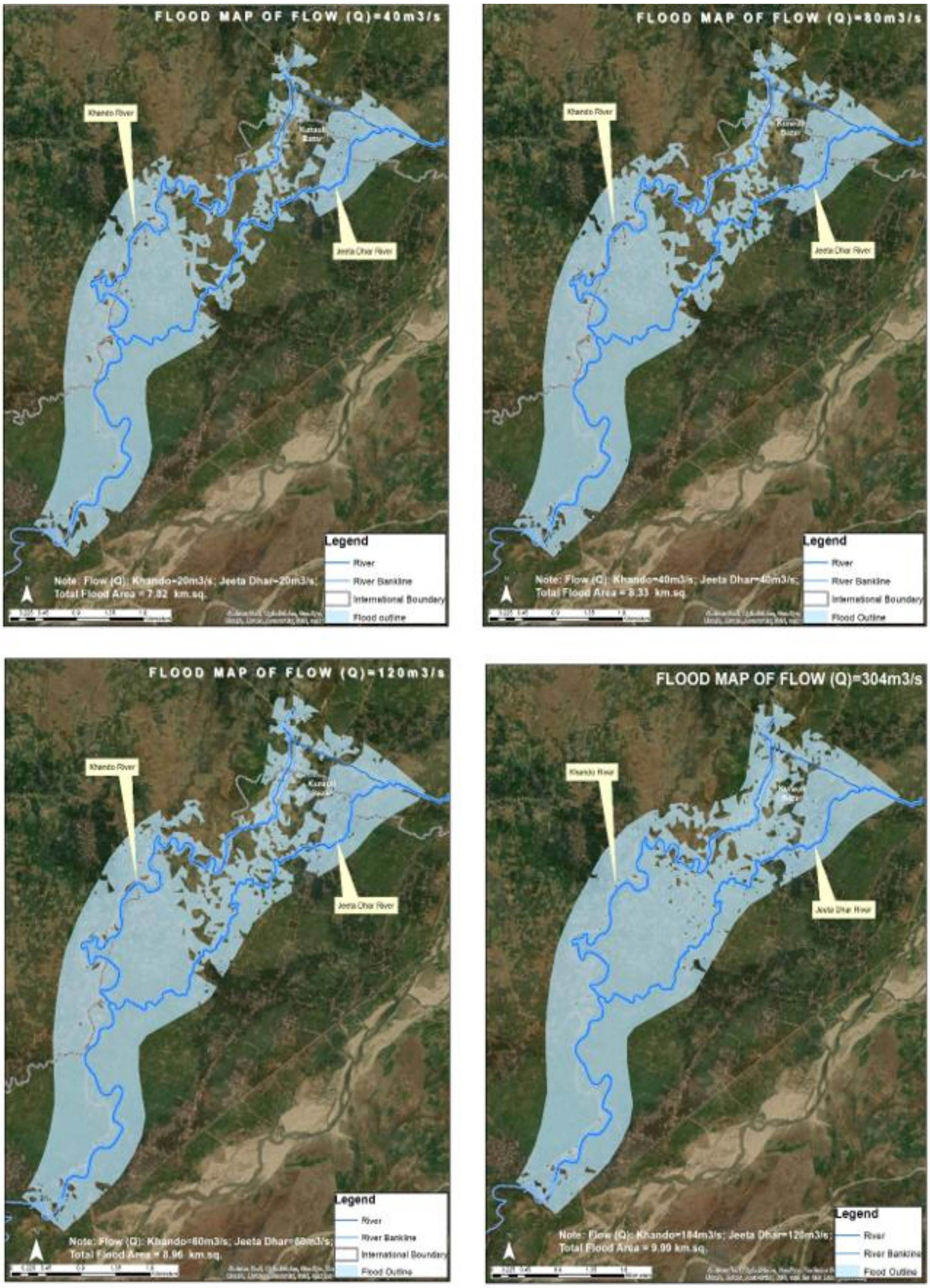

Fig.4 Local flood inundation map of the Khando and Jeeta Dhar floodplains at different flow conditions

Flood embankment has been proposed along both banks of Khando and Jeeta Dhar. Three options (Fig. 6) have been evaluated in the hydraulic 2D models. Option 3 will have the longest embankment length and is expected to eliminate flooding from Kunauli Bazar.

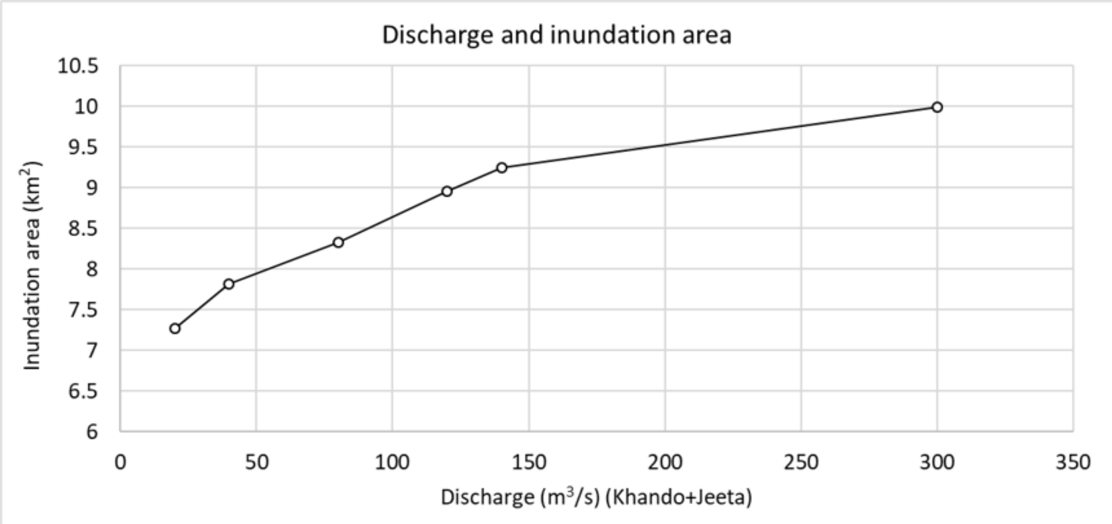

Fig.5 Flood inundation area as a function of discharge

- Option 1 has the lowest embankment length; however, it has negative impact due to backwater flow behind the embankment towards Kunauli Bazar, and can flood and deposit silts to settlements and to agricultural lands
- Option 2: embankment has been extended further to the south to minimize backwater flow; as the flow is highly sediment laden, the backwater flow may stop from accumulation of silt deposits
- Option 3: embankment has been extended further to the south and a ring bundh has been formed to eliminate backwater flow; however, in this extension should only be implemented if backwater flow does not eliminate over time by deposits of silts on floodplain. However, because of forming the ring, it is recommended that the design engineer should consider two minor sluices, valved only for positive flow direction, to drain out local run-off from within Kunauli Bazar.

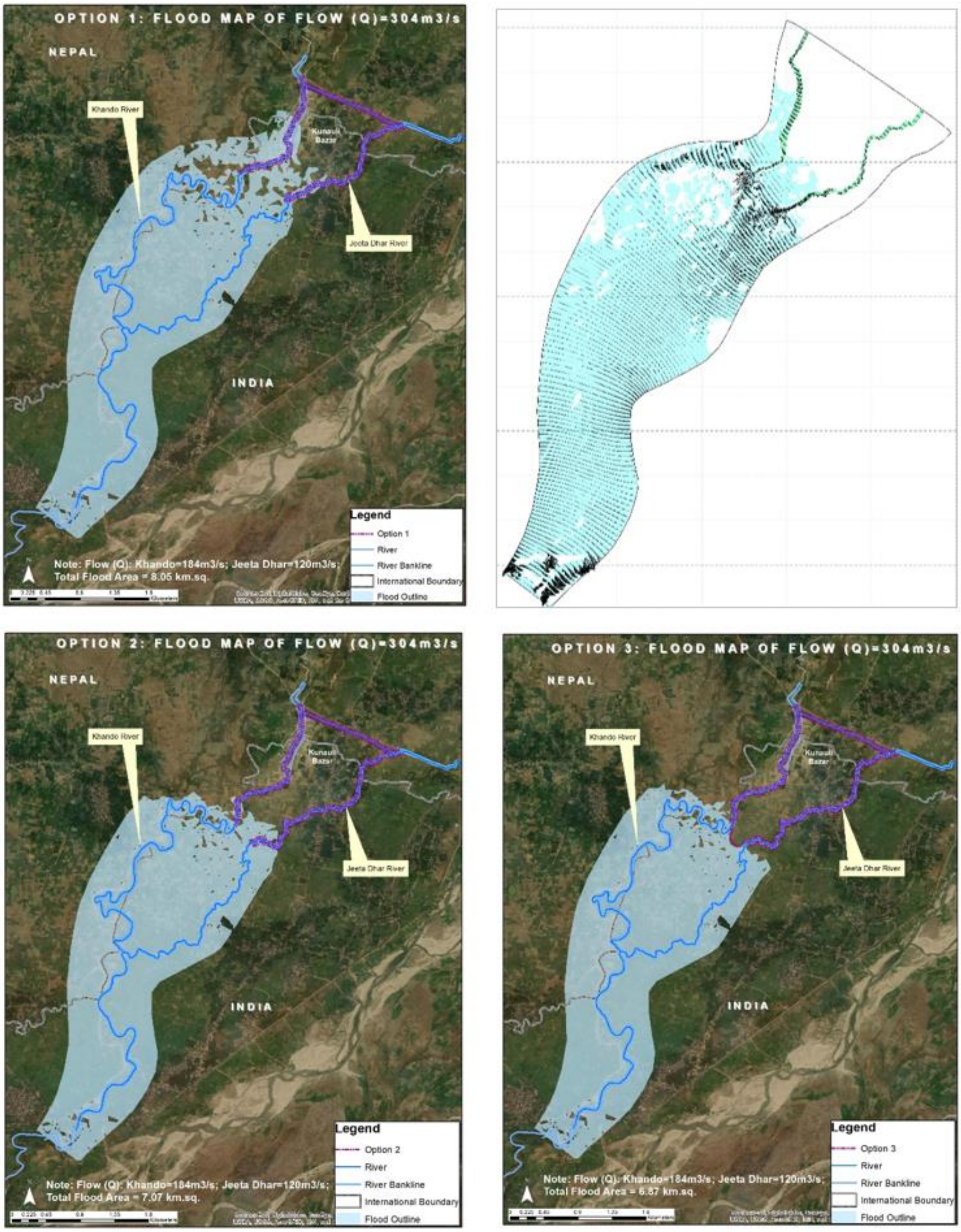

Fig.6 Flood inundation area as a function of discharge

6. CONCLUSION AND RECOMMENDATIONS

One-dimensional (1-D) and two-dimensional (2-D) mathematical modelling are useful tool for designing flood risk and river behavior management schemes. Rivers in north Bihar carry high sediment load, and have low stream power and thus, are prone to river bed aggradation. This compounds the flooding problem more. Thus, a combination of 1-D and 2-D model together with SWAT model can effectively design flood alleviation scheme which address both hydrodynamics, flooding and sediment transport. A hydrological and a sediment yield model of the Khando and Jeeta catchments have been developed using 23 years of hydro meteorological data; using the run-off as inputs, 1-D and 2-D model of Khando and Jeeta Dhar have been developed. the 1-D and 2-D models have been applied to design flood embankments, which eliminate flood risk from the Kunauli Bazar against the historic highest flood of 23 years. Such deterministic and analytical models are recommended for planning and design of any flood risk management projects.

ACKNOWLEDGMENTS
River topographic data, hydrological data and other data and information used in this model were provided by Flood Management Improvement Support Centre (FMISC), Water Resources Department (WRD), Bihar, India. The authors gratefully acknowledge the support from the Joint Director of FMISC.

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