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Rainfall Variability and Spatio Temporal Dynamics of Flood Inundation during the 2008 Kosi Flood in Bihar State, India

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ABSTRACT
The devastating flood in Kosi River initiated on 18 August 2008 resulted in heavy loss of human life and natural resources in the Bihar state of India. About 2.5 millions people become homeless and 2516 km^2 of agricultural land including fallow land is damaged by the flood inundation. The spatio-temporal dynamics of flood inundation during a period of two months from 20 August to 21 October 2008 has been carried out. The temporal satellite images of RADARSAT were used to map the spatial-inundation pattern of Kosi flood whereas, IRS P6 LISS III optical satellite data of October 2004 was used to map the land use characteristics of the region in a non flood situation to evaluate the loss of agricultural land inundated by Kosi flood. Rainfall variability in the entire Kosi river catchment was assessed by comparing the monthly rainfall during monsoon season for a period of 1998-2009. The variability in rainfall pattern during the pre and post Kosi flood event was examined to develop insight into genetic aspect of flooding. The study revealed a loss of 2135 km^2 of standing crops due to highest flood inundation of 3089 km^2 as on 5 September, 2008. Rainfall pattern indicates much higher rainfall in the lower Kosi catchment which probably induced the conditions causing breach of embankment and resulted in the initiation of Kosi flood on 18 August 2008.

Key words: Flood, Kosi river, RADARSAT image, optical satellite data, TRMM

INTRODUCTION
The Kosi, known as Kaushiki in Sanskrit, is one of the most ancient rivers of India. It rises in the Himalaya, drains the foothills to the east of Kathmandu in Nepal and plains of Bihar state in India before joining the river Ganga. Its three tributaries within the Himalaya, the Sun-Kosi, Arun and Tamur, confluence before entering to the plain region further downstream. The combined discharge of the three tributaries of Kosi has traveled through a deep gorge extending for 10 km length downstream of their confluence. The turbulent water with high sediment flux emerges out of the canyon and form the world's largest, 180 km long and 150 km wide alluvial fan. Due to the fanning of material, the single river acquires a distributary channel pattern in the plain areas (Agarwal and Bhoj, 1992).

Gole and Chitale (1966) described the Kosi system as an inland delta built by large sediment flux which was also attributed to be the primary factor causing westward shifting of Kosi and extensive flooding. The recurrent flooding in the plain areas of lower Kosi catchments in Bihar state induces condition of water logging which is resulting in development of vast tract of productive agricultural lands into wastelands. Pandey *et al.* (2010a) examined the impact of natural and anthropogenic features on flood induced waterlogging in parts of Bihar plains and revealed that canals and railway line induced highest waterlogging conditions. The flooding also raises the levels of water table which result in development of salt affected soils in this region. Low topography, low carrying capacity and avulsive behavior of the Kosi river are attributed to frequent and prolonged flooding in this region (Chowdary *et al.*, 2008). To avert conditions of disastrous flood events in this region and to reduce flood induced environmental hazards scientific understanding of the river hydrodynamics is essential.

The dynamic nature of the Kosi River has attracted attention for over a century and a variety of mechanisms have been suggested ranging from tectonic tilting and nodal avulsions (Gole and Chitale, 1966; Arogyaswamy, 1971; Agarwal and Bhoj, 1992) and discharge peakedness and autocyclic processes (Leier *et al.*, 2005, Bridge and Karssenberg, 2005).

To avert the frequent flooding events in the plain areas, Kosi river flow was controlled through embankments constructed in the year 1963 to protect about 2800 km^2 of land in North Bihar and Nepal (Sinha *et al.*, 2008). The 18 August 2008 avulsion of the Kosi River recorded an Eastward jump of about 120 km which is an order of magnitude higher than any single avulsive shift recorded in historical times. The avulsion was triggered by a breach in the eastern afflux bund of the Kosi at Kusaha, 12 km upstream of the Kosi barrage. The Sanjai, Sursara and Bhenga canal streams, on which the Kosi flowed earlier, were fed afresh, leading to the spread of water in areas located along the banks of these streams. The river then abandoned the prescribed western channel and occupy a straight course near the center of its alluvial fan. The water in this course spread out widely and inundated towns, villages and cultivated fields in the densely populated region of Bihar State in India. The five worst affected districts in Bihar are Supaul, Madhepura, Araria, Saharsa and Purnea. The rampaging Kosi has left at least 3.02 million people marooned in these five districts of Bihar (Unicef India, 2008). The new course has a much lower carrying capacity, the water flows like a sheet, 15-20 km wide and 150 km long as a result of which a very large area remains inundated/waterlogged for more than four months after the breach (Sinha, 2009). Pandey *et al.* (2010b) have described that areas with high waterlogging risk in Northern Bihar plains also corresponds to high flood hazards and vulnerability due to poor socio-economic conditions in these areas.

Since, the launch of the Earth observation satellites, remote sensing data have been used frequently for analysing and mapping of floods (Rango and Salomonson, 1974; Phillipson and Hafker, 1981). Although optical remote sensor data can be used effectively for flood mapping, they have major drawback due to the necessity of obtaining imagery in time and extensive cloud cover during flooding obscures the inundated area and makes it difficult to acquire good quality optical imagery. The availability of microwave data from ERS/Radarsat can penetrate clouds and is capable of detecting and delineating flooded areas (Kussul *et al.*, 2008). Multi-date radar data together with optical remote sensing data provide real time solution in mapping, monitoring and management of floods and related hazards during flood transgression and regression phase (Pandey, 2008). Satellite based precipitation measurement obtained through TRMM is being widely used for monitoring of floods in regions that regularly experiences extreme precipitation and flood events (Asante *et al.*, 2007).

The IRS P6 LISS III optical satellite image of non flooded period of 22 October-2004 was used to map the landuse/landcover characteristics in this region to evaluate the loss of agricultural land inundated by Kosi flood. The Tropical Rainfall Measuring Mission (TRMM) data was analyzed for the period of 1998-2009 to examine the spatio-temporal variability of rainfall in the Kosi catchment during monsoon period as well as to evaluate change in rainfall pattern during pre-post flood event.

MATERIALS AND METHODS

Study area: The area under investigation comprises the lower Kosi catchment a part of which was affected by 2008 Kosi flood. It is located between 86° 20' 00" to 87 °30 00" E longitude and 25 °20' 00" to 26° 45' 00" N latitude, covering a total area of 10536 km^2 mainly in the state of Bihar (Fig. 1). The total catchment area of Kosi river is 54419 km^2 majority is located in Nepal.

Data used and methodology: The availability of satellite data products provided by various organizations world-wide which can be accessed online has increased the understating about happening of major natural disasters in any part of the world. Such information can be utilized collectively to obtain genetic aspects of such disasters in near real time. In the present study we have utilized the RADARSAT data derived images showing flood affected regions due to Kosi flood in the year 2008 which was available in the NRSC image gallery (www.nrsc.gov.in). These images of different dates from 20 August to 21 October 2008 have been used in the analysis. The data was downloaded from NRSC image gallery and georeferenced with reference to state and district boundary maps of Bihar. Survey of India (SOI) political map on 1:4 million was used for delineation of boundary of Bihar state whereas district boundary maps were obtained from the census hand book of Bihar, 2001. IRS P6 LISS III satellite data of 22 October, 2004 was procured from NRSC, GoI to map the land use-land cover in the area during the end of Kharif season (June-October) in a non flood period. Satellite data was processed using ERDAS IMAGINE software whereas the spatial data was created under ArcGIS platform for spatial analysis. To assess the spatio-temporal variability of rainfall, TRMM Multi-satellite Precipitation Analysis (TMPA) product was downloaded. The monthly TRMM 3B43 data for the period of 1998-2009 covering the month of June to September was downloaded in ASCII format. The data was registered to real

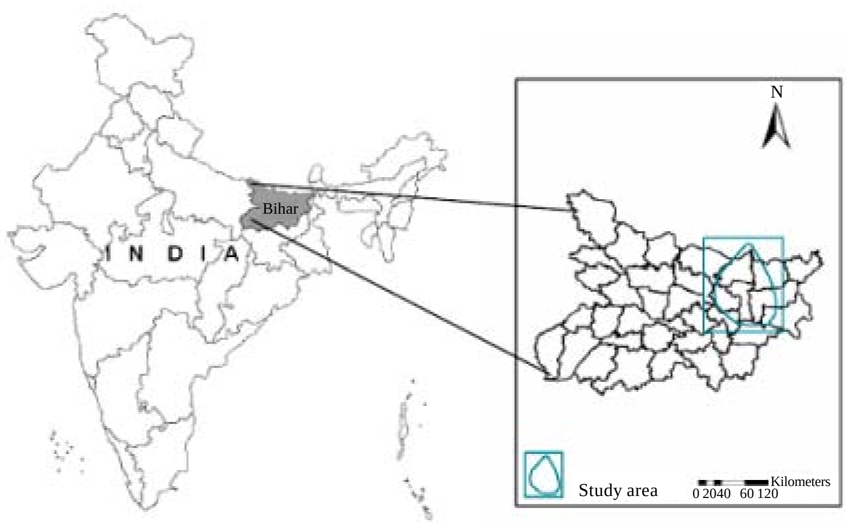

Fig. 1: Location map of the study area

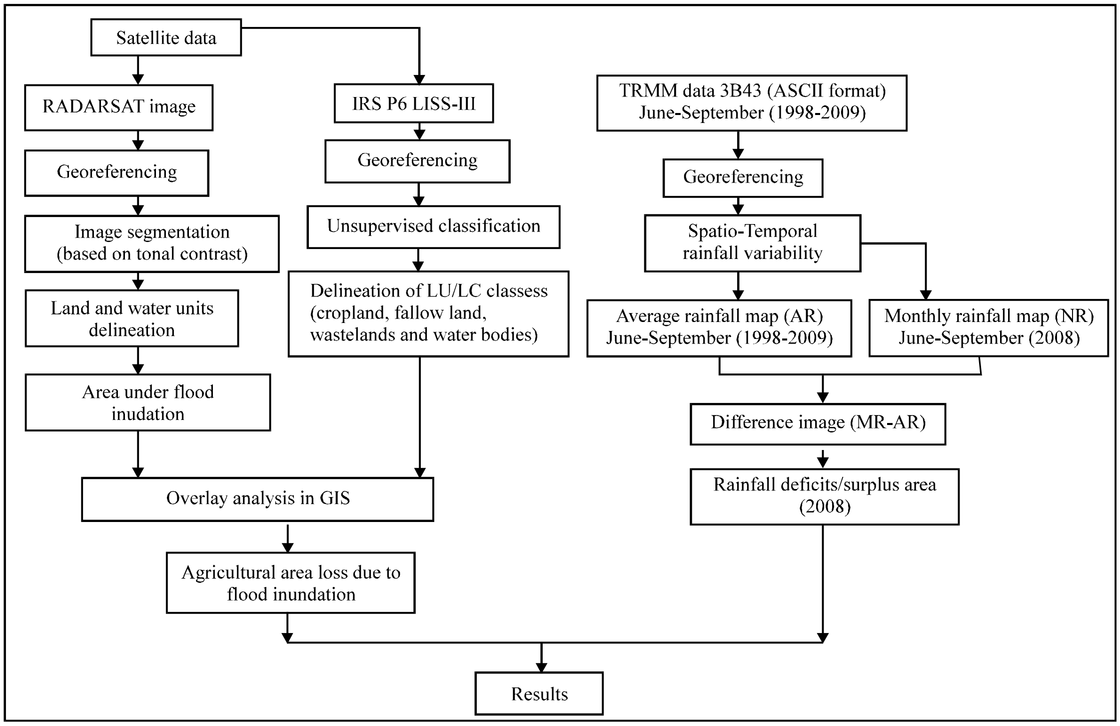

Fig. 2: Flow chart of the methodology for spatio-temporal dynamics of flood inundation

world coordinates in GIS to obtain variability of rainfall intensity with reference to geographic location (Fig. 2). The TRMM rainfall intensity values recorded at various points were interpolated in GIS environment using IDW method of spatial interpolation to examine spatial variability of rainfall over the entire Kosi catchment. The IDW method is selected in the present study as it is one of the standard spatial interpolation procedures in geographic information science (Burrough and McDonnell, 1998).

RESULTS

Flood dynamics: The geo-referenced RADARSAT data derived images were segmented primarily into water and land units based on their tonal contrast. Flood inundated areas appear black in RADARSAT images due to forward scattering of incoming microwave radiation whereas over the land units more backscatter cause bright signature on the satellite images (Jensen, 2005). This tonal contrast was used to segment the flood inundated area from non flooded areas. The RADARSAT satellite images (Fig. 3a-j) and their corresponding classified output (Fig. 3k-t) helped in understanding the flood dynamics during the period of observations. The classified output in raster format was converted to vector format for spatial analysis of flood dynamics and loss of agricultural land due to flooding in Arc GIS platform.

It is evident that on 2 day of flooding (i.e., on 20 August, 2008) flood water traveled a distance of only 55 km whereas, on 22 August, it reached a distance of 93 km from breach point and finally merges with river Ganga on 27 August. The width of flood water also changes from 12 km in the upper reaches to 45 km in the lower parts of Kosi fan areas. The flood water follows a straight course till 22 August, 2008 after which it spreads more, further engulfing large area down slope. It is important to note that a flood stream course originated from the main flood course and flowing

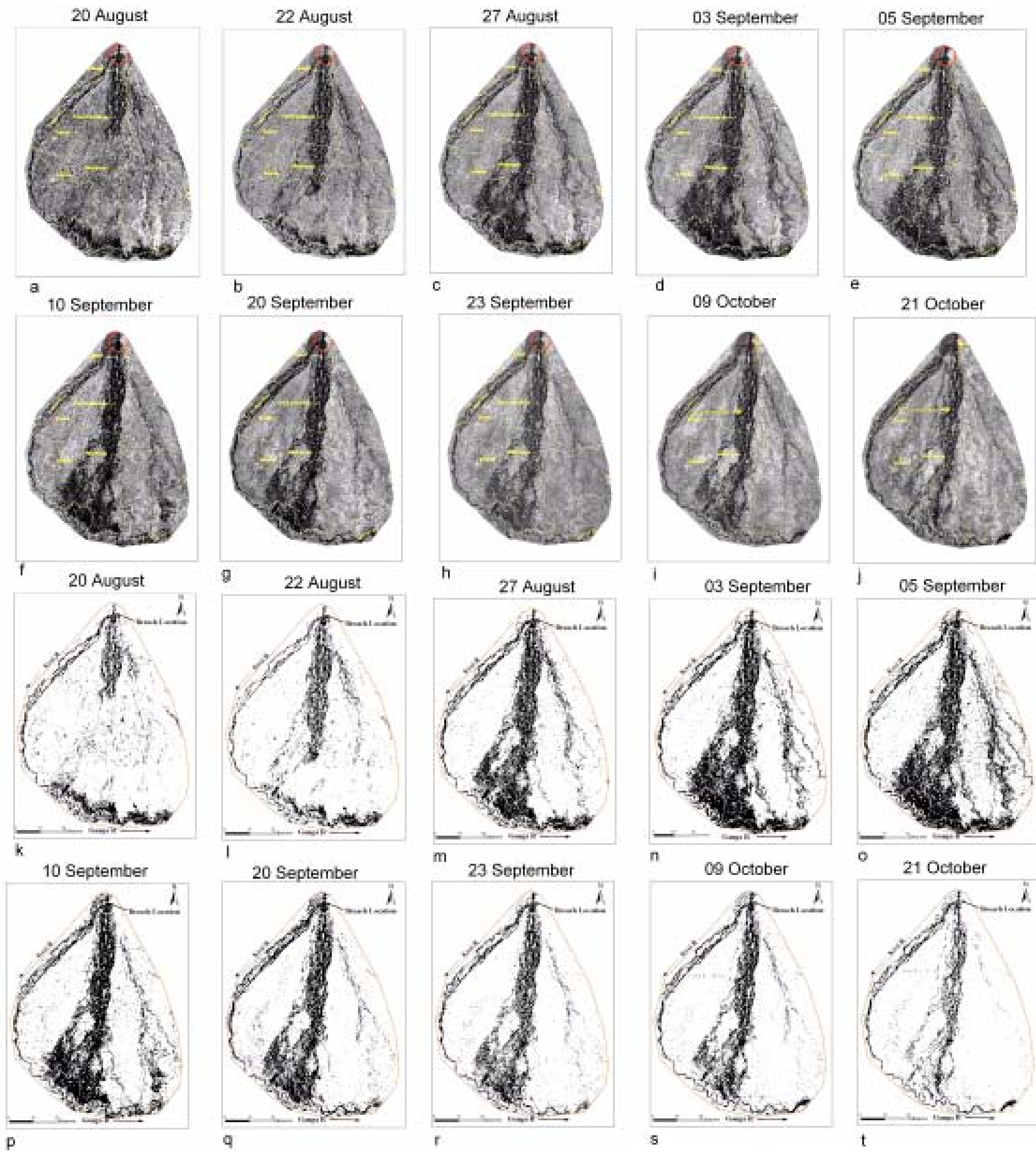

Fig. 3: Satellite image a-j representing sequence of flood inundation (transgression and regression) from 20 August to 21 October 2008 and the corresponding classified output k-t derived from satellite images showing land (white) and water (black) covered regions in the flood effected parts in the lower Kosi catchment

in SE direction entered into the adjacent watershed of Mahanada river flowing east of Kosi fan area causing flooding outside Kosi catchment. The area statistics of flood dynamics obtained through classified outputs clearly revealed that the area under flood inundation was maximum on 5 September 2008 (3089 km^2) thereafter decreasing to (950 km^2) on 21 October, 2008 (Fig. 4, Table 1).

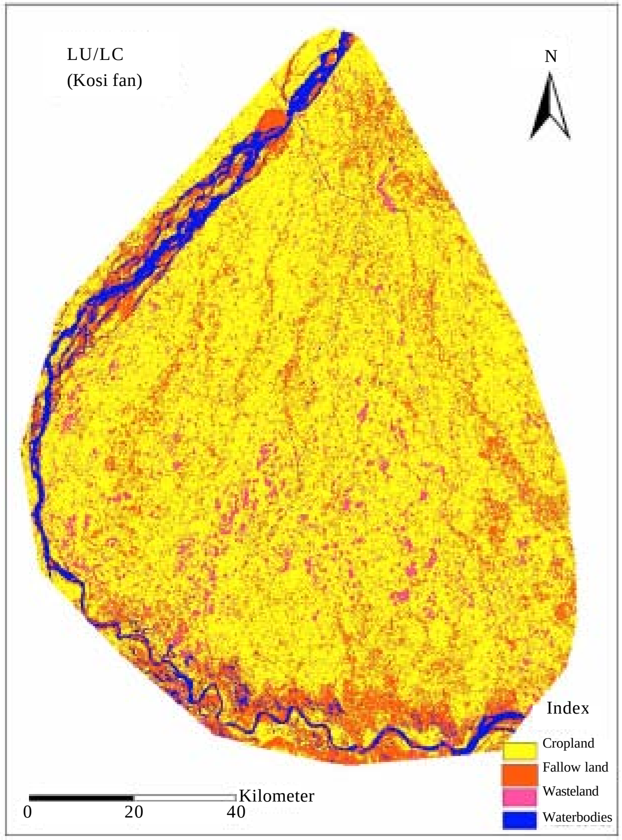

Fig. 4: Land use/land cover map of the study area

Table 1: Satellite image based statistics of area under flood inundation and non flooded land for selected periods from 20 August to 21 October 2008

Radarsat image acquisition date (year 2008)	Area under flood inundation (km^2)	Non flooded area (km^2)	Percentage of area under flood inundation	Percentage of non flooded area
20 August	1266.00	9270.19	12.02	87.98
22 August	1270.14	9266.05	12.05	87.95
27 August	2326.38	8209.81	22.08	77.92
03 September	2858.61	7677.58	27.13	72.87
05 September	3089.87	7446.32	29.33	70.67
10 September	2707.62	7828.57	25.70	74.30
20 September	2089.21	8446.97	19.83	80.17
23 September	1582.90	8953.29	15.02	84.98
09 October	1558.73	8977.46	14.79	85.21
21 October	950.15	9586.04	9.02	90.98

Agricultural area loss due to flood inundation: Digital satellite image based land use/land cover (LU/LC) mapping was performed using unsupervised classification technique to compute the area statistics of major land use/land cover types in the flood affected Kosi fan area. The classified

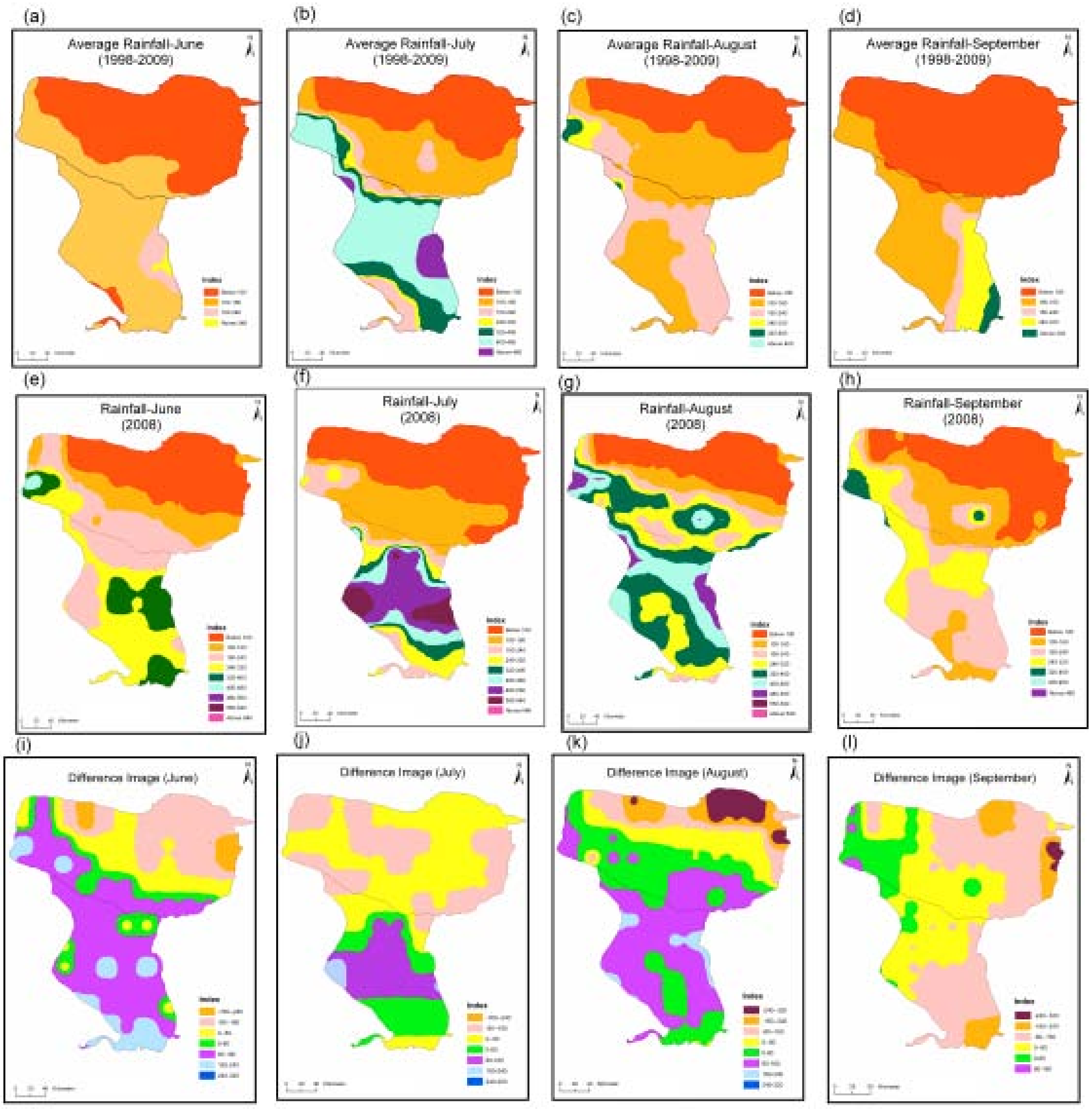

Fig. 5: TRMM based rainfall variability maps representing average rainfall from June to September during 1998-2009, a-d and e-h representing monthly rainfall from June to September in 2008. Difference image i-l represent rainfall deficit/surplus conditions in 2008 (positive values indicate increase in rainfall whereas negative values indicate decrease in rainfall)

map clearly depict that majority of area is under cropland (72.18%) and associated fallow lands (17.41%). The wasteland comprises (5.93%) of total area mainly consists of seasonal and permanent waterlogged areas, whereas water bodies (4.48%) mainly comprising the rivers of Kosi and Ganga (Fig. 5, Table 2).

Further, the land use/land cover map was overlaid with flood inundation area during peak flood period on 5 September 2008 to ascertain the loss to agricultural lands due to flooding. It was

Table 2. Area statistics of various landuse/landcover categories in the Kosi fan area

Land use/Land cover class	Area (km^2)	% of area
Cropland	7600.73	72.18
Fallow land	1832.87	17.41
Wasteland	624.56	5.93
River and water bodies	471.37	4.48

estimated that an area of 2516 km^2 of agricultural land (cropland: 2135 km^2 and fallow land: 481 km^2) comprising the 81.45% of total flood inundation area was destroyed due to flooding. It signifies the impact of agricultural loss due to the destruction of existing crops and unsuitability of fallow lands which could be cultivated in the Rabi season (October-April) due to prevailing water logging condition during the post flood periods.

Assessment of spatial variability of rainfall: In the present study for the assessment of spatio-temporal variability of rainfall in the entire catchment (upper and lower) of Kosi river, satellite based rainfall data using TRMM Multi-satellite Precipitation Analysis (TMPA) product was used. The TMPA provides a calibration-based sequential scheme for combining rainfall estimates from various satellites, at fine scales (0.25°×0.25° and 3-hourly) (Huffman *et al*., 2007). The monthly TRMM 3B43 accumulated rainfall (0.25°×0.25°) product which is the combination of TRMM Precipitation Radar (PR) and TRMM Microwave Imager (TMI) were acquired from TRMM Online Visualization and Analysis System (TOVAS), (http://disc2.nascom.nasa.gov/Giovanni/tovas/). Rainfall intensity spatial maps of individual months of June, July, August and September were prepared for the period of 1998-2009. The raster data pertaining to monthly rainfall was further categorized into 7 classes representing rainfall variation from less than 80 mm to more than 640 mm. In this way we obtained maps representing average monthly variability from June to September from the year 1998-2009. The monthly data was analyzed to obtain spatial rainfall variation across the monsoon months to asses the rainfall induced flood vulnerability at various stages during the monsoon season.

The spatial analysis of rainfall pattern clearly revealed that the onset of monsoon in June clearly exhibit low rainfall over the entire region among the four monsoon periods under observation. The July and August comprises wetter condition whereas in the month of September the rainfall again decreases. The monthly assessment of average rainfall condition and its comparison with rainfall event during 2008 is given below to emphasize on rainfall variability in inducing flood conditions in the area.

Comparing average rainfall of June with monthly rainfall of June 2008 revealed that in the month of June 2008 the upper catchment received much higher rainfall (100-480 mm) over many areas where average rainfall varies from less than 100-180 mm. Similarly the average rainfall in the month of June in the lower catchment also exhibited substantial increase from average value of 100-180 mm to 320-400 mm in June 2008, especially in the central parts (Fig. 5a, e). In the month of July 2008 also we observed significantly higher rainfall especially in the lower catchment which received 480-560 mm and at place up to 640 mm against the average rainfall of 400-480 mm (Fig. 5b, f). In the month of August 2008 the upper catchment also received higher amount of rainfall (240-560 mm) than the average rainfall. The lower catchment also received substantially high rainfall of 240-560 mm as compared to 100-240 mm of average rainfall (Fig. 5c, g). During

September although their was a decrease in rainfall but still it was much higher than the average rainfall especially in the lower catchment which received 180-320 mm of rainfall in September 2008 as compared to 100-180 mm during average rainfall (Fig. 5d, h).

A rainfall difference image was prepared by subtracting average rainfall value (1998-2009) from monthly rainfall value (2008) recorded at all the observation points in the entire catchment. The output image clearly exhibits the areas where rainfall deficit/surplus condition prevailed in the year 2008 (Fig. 5i-l). The positive values in the map indicate increase in rainfall whereas, negative values indicate decrease in rainfall. The upper and lower catchment areas received comparatively very high rainfall in all the three months i.e., June, July and August during the year 2008 than the average rainfall. This clearly implies that the high runoff generated by these rainfall events especially in the lower parts of the catchments resulted in high soil saturation which probably induced the factors which lead to the breaching of the embankment at places and resulted in a disastrous flood in Bihar.

DISCUSSION

The flood dynamics obtained through RADARSAT data derived images exhibit that the area under flood inundation was maximum on 5 September 2008, 3089 km^2 thereafter reduced to 950 km^2 on 21 October, 2008. The slope in the lower catchment areas is very gentle causing flood water to spread over large areas. Satellite based rainfall data from TRMM clearly exhibit much higher rainfall during the monsoon months of 2008 as compared to average rainfall which probably induced conditions for breaching of the embankment at places. In terms of agricultural area loss an area of 2516 km^2 of agricultural land was destroyed due to flooding. The main causes of floods in the Gangetic plains are inadequate capacity within river banks to contain high flows, river bank erosion and silting of river beds (Kumar *et al.*, 2005). The excess water with high sediment flux released during monsoon periods therefore causes extensive floods in Gangetic plains of Bihar region. The changing climatic conditions with more intense rainfall in future (Singh and Sontakke, 2002) may trigger more sediment flux in the upper catchment. This may get accentuate if the snow and glacier covered regions in the upper parts of the catchment shrink with increased temperature conditions (Bajracharya *et al.*, 2006). Under these conditions there would be an increase in the cases of Glacier Lakes Outburst Floods (GLOF) (Bajracharya and Kumar, 2005) and natural damming of the river in the upper catchment, outburst of which may leads to flash floods in the lower catchment areas and plain regions. The high seismic activity in the region (Sukhija *et al.*, 2002) also indicates possibilities of future damage of embankment which may result in similar or more devastating floods in the future.

It is evident that high discharge moving down slope would follow the straight course as observed in the Kosi 2008 flood event. The straight course cause hydraulic gradient of the flood water to be nearly double of that which existed in the earlier sinuous course (Reddy *et al.*, 2008) and therefore have more sediment carrying capacity. Therefore, to avert the future disaster of this sort it is proposed to develop the straight course of the Kosi river and adopted valley deepening activity at regular intervals. To regulate the hydrological regime towards sustainable agricultural setup, the old river course, as well minor distributary channels may be supplied with regular discharge of water. Any planning for regulating the flood water discharge should be done after proper evaluation of micro relief as well as sub surface hydrological regimes in the Kosi fan area. Remote sensing technique is very useful as it provide accurate, time and cost-effective method for spatio-temporal flood dynamics assessment and evaluation of loss due to flooding. The TRMM based rainfall study provided a continuous mapping of rainfall events throughout such a large catchment of Kosi where ground based meteorological monitoring is not possible at large number of places. The study provided significance of satellite based monitoring towards analyzing flood events.

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