GEOMORPHOLOGY, HYDROLOGY AND HUMAN-ENVIRONMENT INTERACTIONS IN THE KOSI MEGAFAN, INDIA

by

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DISSERTATION ABSTRACT

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The continuing channel modification and change in the course of the River Kosi have got a greater implication on the geomorphic evolution processes within its megafan surface. A considerable portion of the land in Kosi megafan remains flooded and later waterlogged every year, a phenomenon that has been exacerbated by the rapid development of roads and railroads. Crop yields are also lowest in parts of the megafan where waterlogging is a bigger problem. This research applies GIS and remote sensing techniques to examine the Kosi channel change from 1975-2015 and map waterlogging and transport network driven 'disconnectivity' of the Kosi megafan located in the Indo-Gangetic Plains, India from 2005-2015. This study also used semi-structured interviews of 960 farm-households from four case studies to analyze farm-related changes, especially due to waterlogging and identify factors responsible for a farmer's adaptation to waterlogging stress from 2014-2015. The findings reveal that there have been substantial changes in the main Kosi channel. The massive development in the road-rail transport network along with the increase in the minor channels within the megafan have led to staggering increase in transport-river intersections and foster both seasonal and permanent waterlogging. The case studies suggest that 90% of the farmers have made changes to their farms due to

waterlogging and other factors associated with that. The study also shows that there are limits to adaptation, which are caused by barriers of available technology, knowledge and institutional frameworks. These barriers undermine the effectiveness of the initiatives promoted both at the national as well as local level.

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For Babuji, Ma, Joy and Mijo

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CHAPTER I

INTRODUCTION

The Kosi River originates from the combined flow of three tributaries, each sourced from the Greater Himalayan range of Nepal. The combined discharge, after emerging from the confines of mountain valleys, flows transverse to the axis of the foreland basin and finally meets the axial River Ganges. However, immediately after entering the Gangetic alluvial plain, the flow of the Kosi River breaks up into a distributary network of channels, which contributes to the construction of the modern Kosi Megafan (Geddes 1960; Chakrabarty et al 2010). The Kosi River is well known for its recurrent avulsive changes in course and the pattern of these changes is much debated in the alluvial fan literature. Avulsion events have led to several devastating floods on the megafan surface. A considerable portion of the land in North Bihar where the Kosi megafan is located remains waterlogged every year, a phenomenon that has been exacerbated by development of roads and railway tracks. Official records suggest that nearly one million hectares of land in North Bihar, 85% of it in the Kosi megafan, stays waterlogged. Crop yields are increasingly getting poorer in parts of the megafan where waterlogging is a bigger problem. Decrease in agricultural yield affects the large population base who depends on agriculture for their livelihood. My research objectives for this dissertation were three-fold and relate to the three main chapters in this volume.

The first objective was to document the Kosi channel migration in the fan area from 1975 to 2015 and analyze significant aspects of fan morphometry. This study contains an overview of historic channel migration patterns and provides a temporal framework for the remaining chapters. Various fluvial land forms are mapped and changes in course of the river have been evaluated. This comprehensive study of channel migration of river Kosi with most recent data will help in better understanding of the underlying factors that control river course changes which are essential for better flood prediction and for adopting more effective strategies for disaster management.

The second objective uses remote sensing and GIS techniques to identify and quantify relationship between pre and post-monsoon surface waterlogging and rail-road transport network. Historical to recent spatial variability in pre and post-monsoon surface waterlogging and rail-road transport network in the Kosi megafan area was mapped and analyzed using satellite images from 2005 to 2015 and relevant topographical maps. This research can help government, land managers and land users to better understand how past human activity have impacted the megafan environment and offer the ability to project future trends in transport network development and its impact on waterlogging.

The third objective is to explore the significance of surface wetness (waterlogging) and socioeconomic factors that affect farmers' decision to change their farming practices for the period of 2014-2015. This study uses data from household surveys of 960 farm-families across four districts which suffer from severe waterlogging in the Kosi megafan. This study can help to analyze factors responsible for changes in land use pattern, especially increase in current fallows and shrinking net sown area. Additionally, this research will help government and local municipalities to better understand institutional, technological and informational barriers in designing and implementing adaptation to farms in the face of water-stress and in turn will allow more informed decisions to be made about how to utilize land and improve the livelihoods of the megafan inhabitants.

CHAPTER II

CHANNEL MIGRATIONS OF THE KOSI RIVER, INDIA, FROM 1975 THROUGH 2015

1. Introduction

Many of the rivers of the Ganga Plain are prone to abrupt switching of channel courses that cause devastating floods over some of the most densely populated regions on the globe. Among them, the Kosi River in the Eastern Gangetic Plain is one of the most avulsive and flood prone. The river drains the high core of the Himalayan Mountains (Figure 2.1), which include many of the world's 8,000m peaks, are extensively glaciated, and experience high intensity rainfall over large areas. The runoff from these glaciated high relief mountains carries a tremendous amount of sediment that forms a giant depositional fan, the Kosi 'megafan,' where the river enters the Gangetic Plain.

The broad, depositional Kosi megafan is remarkably flat. Lateral cross-sections across the Kosi megafan display little vertical relief, varying in elevation by only a few meters. Coupled with the large sediment loads, these low slopes lead to aggrading channels, hyperavulsive behavior, and frequent and extensive flooding (Jain et al. 2003). During bankfull runoff, which is common during the snowmelt/monsoon season, overbank spilling is common (Jain et al. 2004).

The floods and avulsions have caused extensive dislocation of residential areas, severe and persistent surface wetness in some areas, and loss of life and cultivable lands. During 2008, a single channel avulsion event resulted in a temporary eastward shift of the Kosi river by tens of kilometers resulting in extensive flooding that affected over 20 million people (Sinha et al., 2013; Chakraborty et al., 2010).

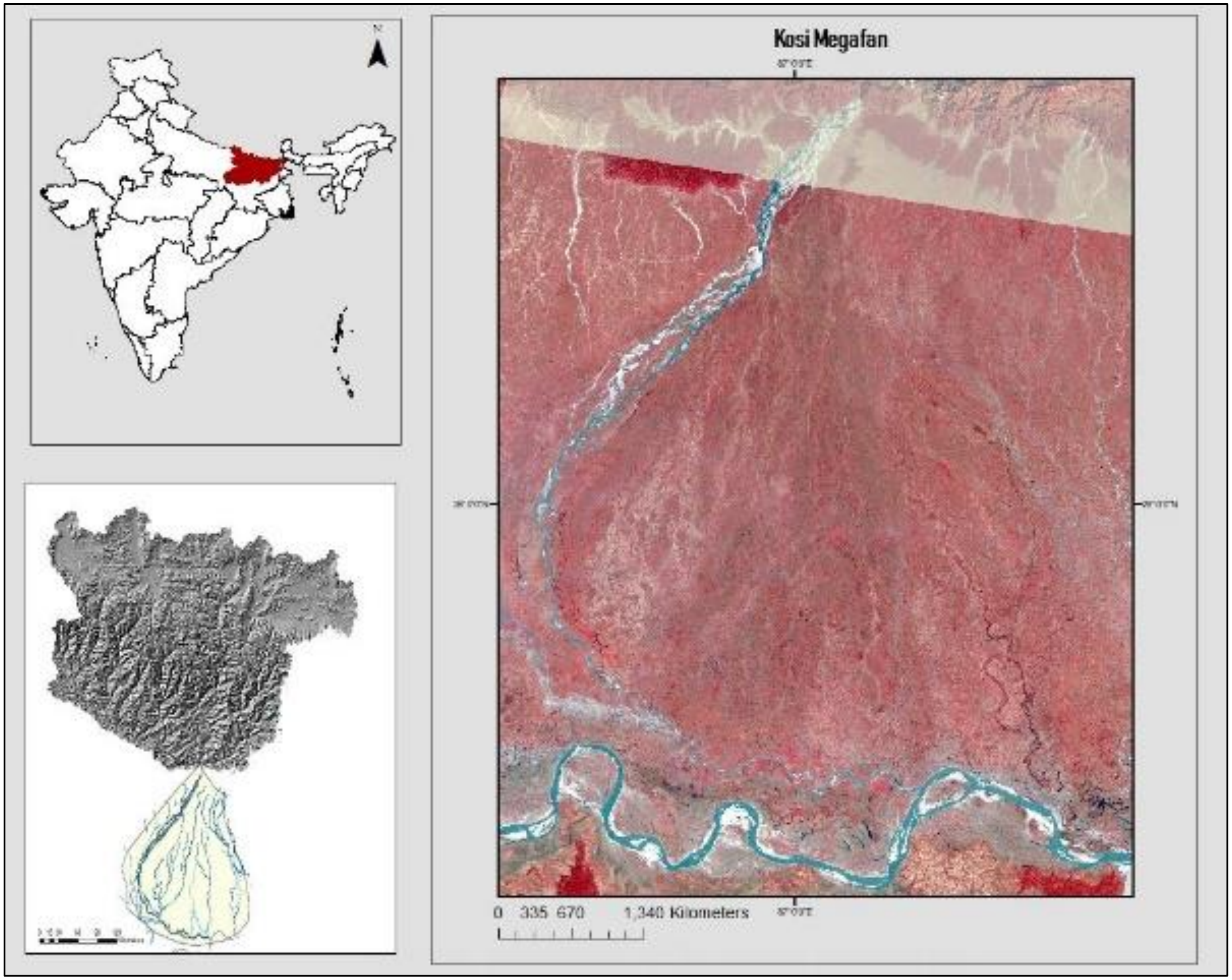

Figure 2.1. Location map, showing the state of Bihar in India in which the Kosi megafan is located(a), the upper catchment area and drainage network of the Kosi megafan (b), and a Landsat false color composite of the Kosi River in the mega fan (c).

Damage to life and property is likely to increase in the coming years, because climate-related, extreme events such as floods are likely to be more frequent (Kale, 1998) and because increases in population will result in more people settling in areas vulnerable to flooding. The pattern of channel changes also affects the availability of water and sediment in different reaches of the river, leading to significant variations in scouring or aggradation that pose serious river management problems in an area that is already flood-prone.

Given the significance of flooding, channel movement, and groundwater pathways in the densely populated, monsoon-dependent Kosi megafan, documenting and understanding variations in the morphology and migration of the Kosi River channels is a priority. Studies have largely focused on one or several flood events rather than documenting the sequence of pre- and post-flood changes in channels in the Kosi megafan over recent decades, a period when much better remote sensing data are available. To better understand rates and locales of river migration of the Kosi river over four decades, this paper documents and investigates:

- The locations and patterns of lateral channel migrations in the Kosi River from 1975 to 2015, and
- The degree to which channel changes in the Kosi River are linked to local fan characteristics.

2. Studies of Megafans and Associated Channel Movement

Megafans are major features in aggradational basins and constitute a significant proportion of the sediment in continental basin fills. This is particularly true of foreland basins such as the Ganga plain (Weissmann et al., 2005; Leier et al., 2005). The morphologic evolution of megafans is affected by sediment discharge, base level changes, riparian vegetation, and internally generated bed and planform irregularities such as barforms (Jain et al. 2003). From a geologic perspective, the nature and frequency of channel changes (migrations and avulsions) in megafans are major contributors to alluvial stratigraphy, defining large portions of the channel and floodplain deposits (Decelles et al., 1999).

Alluvial river channels in non-incisional megafan settings are highly mobile systems that interact dynamically with their beds and banks. Channel shifting or avulsions over megafans are thus common, but the higher frequency of such processes in the Kosi megafan and the resulting damage caused to tens of millions of residents make it notable even among megafan rivers. The average frequency of movement of the main channel of the Kosi River is 24 years, a rate that places it amongst the mostly frequently avulsing major rivers in the world (Chakraborty et al., 2010). By way of comparison, the Mississippi River in its delta (a good analog to a megafan) shifts it location every 1,400 years on average (Smith, 2008).

Given its mobility and the megafan's importance to agriculture and a large population, it is not surprising that the Kosi River has attracted research attention for more than 50 years. Investigations have implicated multiple processes in the large scale migrations of the main Kosi channel A variety of mechanisms have been suggested by researchers for its avulsions, including tectonic tilting and nodal avulsions (Gole and Chitale, 1966; Agarwal and Bhoj, 1992) and tectonically-driven subsidence (Sinha, 2013). Flooding, for example, can occur in a channel reach without an increase in discharge if the channel capacity is lowered. Such condition occurs upstream of any uplifting zone (Slingerland et al., 2004). For example, in the Baghmati River basin to the west of the Kosi, reaches upstream of the East Patna Fault are characterized by flood hazard, even though average discharge is less downstream than in upstream reaches (Jain and Sinha, 2004). Hence, flooding is not simply a result of increases in runoff, but is also subject to external, long-term tectonic controls.

At the basin scale, topography controls the spatial distribution of runoff and flow path geometry (Sinha 2013), with the drainage pattern playing an important role in controlling the runoff response and downstream flood hazard. As one example, in the ungauged Bagmati River to the west of the Kosi, (Jain and Sinha, 2003c) have shown that a unit hydrograph can be developed on the basis of drainage network pattern using classic morphometry ratios such as bifurcation ratio, area ratio, and length ratio (Horton, 1947). A regression analysis on these equations suggested that length ratio is the most significant parameter in hydrological analysis (Jain and Sinha, 2003c). The tributaries of the Baghmati River with higher length ratio are responsible for flooding at their downstream confluences, whereas other tributaries do not cause major flooding at these locations.

At a megafan or local scale, factors implicated in channel movement in the Kosi include the general braided nature of the river (Jain and Sinha, 2003c), conical delta building in the megafan (Sinha and Friend, 1994), sediment deposition in river channels that leads to severe flooding (Jain et al., 2004), and autocyclic and stochastic processes (Jain et al. 2003). In a recent work, Sinha et al. (2013) analyzed the channel connectivity structure of the Kosi megafan surface and presented a topography-driven model to simulate the avulsion pathway of the August 2008 major flood event. However, little has been done to translate these analyses to evaluate controls on recent fan-scale river channel behavior in the Kosi megafan (Sinha et al., 2005).

3. Study Area

The Kosi River is a major transboundary river system between China, Nepal and India, originating from the Tibetan Plateau in China and ending at the Ganga (Figure 2.1, Table 2.1). The basin covers five tectonically active morphological regions of the Himalayan region: the Tibetan Plateau, the high mountains, the middle mountains, the low mountains and hills, and the plains-Terai. The elevation range within the basins is extreme, extending from the highest point in the world, the 8,848m summit of Mount Everest, to 21m in the plains at the confluence with the Ganges.

The Kosi river basin include five climatic zones determined mainly by elevation (Agarwal et al., 2014), with nine distinct ecoregions. The climate in the basin varies from humid tropical in the south, through subtropical and temperate, to cold and arid in the north. The climate in the southern part of the basin and the central Himalaya is strongly influenced by the South Asian monsoon, while the Tibetan plateau to the north lies in a rain shadow area. The average annual precipitation ranges from 207 mm in the trans-Himalaya to more than 3,000 mm in the eastern mountains and mid-mountains of Nepal (Neupane et al., 2015). Owing to the great variation in topography, the spatial and temporal complexity of rainfall is large over short distances. The dominance of the summer monsoons means that about 80% of the annual precipitation falls between June and September (IPCC, 2007).

Table 2.1. Basic morphometric characteristics of the upper catchment and the megafan surface of the Kosi river basin. (Source: Combined results from Chakraborty et al., 2010 and this study).

	Factors	
Upper Catchment	Area (km2)	58,152
	Overall shape	Rectangular-longitudinal
	Highest stream order	6a
	Watershed length (km)	582
	Average precipitation (mm)	1456
	Peak precipitation (mm)	1600
	Mean main channel gradient (m/km)	16.33
	Drainage density	0.36
	Perimeter (km)	2747.05
	Circularity ratio (Rc)	0.295
	Elongation ratio (Re)	2.532
	Form factor (Rf)	0.438
	Upland-plain ratio	3.89
Megafan	Area (km2)	11,410
	Maximum elevation	~70 m above Ganga alluvial plain (Proximal part)
	Minimum elevation	~5–8 m above Ganga alluvial plain
	Width (km)	115
	Length (km)	155
	Slope gradient (degrees)	0.05-0.01 (Average slope 0.03° (slope at proximal part: 0.05° and distal part: 0.01°))
	River length (km)	277

East–west cross-profiles of the Kosi megafan show the channels having significantly more variation in relief than the interfluve regions, which vary in elevation by only a few meters. The active channels of the Kosi often flow at bankfull, so overbank spilling is common (Kumar et al., 2014). There is about a fivefold difference between average monsoon and non-monsoon discharge (Sinha et al. 2013). Monthly average discharge of the Kosi River fluctuates form 500 to 6000 m3/s, while the mean annual flood discharge lies around 8000 m3/s near Birpur (Sinha and Friend, 1994). In general, discharge in downstream reaches during the monsoon period are higher than the bankfull capacity (Sinha et al. 2005). Even the most probable flood and the mean annual flood with return periods of 1.58 and 2.33 years, respectively, have higher values than the bankfull discharge of river. This indicates insufficient carrying capacity of the channels and leads to frequent flooding during the monsoon period (Kumar et al. 2014). Peak discharge values at upstream stations are generally higher than downstream (Sinha and Jain, 1994).

The population density ranges from less than four people per km^2 in the northern, mountainous portions of the Kosi basin to more than 2000 people per km^2 in the plains (GOB, 2009).

4. Data Sources and Methodology

I integrated remote sensing data and topographic surveys to map the location and extent of channel change from 1975 to 2015 and used GIS to identify key fan characteristics. The next three sections describe: a) data sources and pre-processing of the data; b) methods for mapping channel migrations in the Kosi megafan from 1975 to 2015; and c) methods for documenting general morphologic characteristics of the Kosi fan area.

4.1 Data sources and pre-processing

Map and satellite data were collected for the period of 1975 to 2015, which is the range for which satellite data were available. Landsat images prior to 1975 and Survey of India (SOI) topographical maps for the entire study area after 2002 were not available. Data sets consisted of free remote sensing products, including: a) multi-temporal Landsat series satellite data with 30m spatial resolution (www.dgi.inpe.br) from 1975 to 2015; b) DEM-SRTM data (ftp://e0srp01u. ecs.nasa.gov/srtm/) for Feb, 2010; c) optical images derived from 1m Google EarthTM, which were used to cross check mapping down with

Landsat data; and d) geologic and geomorphologic data available in the literature. Thirty-five topographic maps at a scale of 1:60,000 acquired from Survey of India (SOI) were purchased. Table 2.2 summarizes the data sets and their sources.

Table 2.2 Data sources with respective dates and resolutions.

Nature and types of Data	**Acquired date**	**Resolution/Scale**
Radar: SRTM DEM	2002	90m
Multispectral: Landsat (OLI)	2015	30m
Multispectral: Landsat TM	1980, 1982, 1985, 1987, 1990, 1992, 1998 2012,2014,2015	30m
Multispectral: Landsat ETM+	2000, 2002, 2004, 2008, 2010, 2012	30m
Multispectral: Landsat MSS	1976	60m
Topographical Maps: Survey of India	1975-78, 1985-95, 1997-2000	1:63,360

Landsat images were selected based on the lowest cloud cover in the period immediately following the monsoon usually (October-November), which is the period which would display the post-monsoon flooding changes. These satellite images were registered and georeferenced using standard automated techniques in GIS (ArcGIS, 2011). Several band compositions were performed, with the 5(red), 4(green) and 3(blue) providing the best view of the features for manual mapping of channel change. All data were projected with geographic coordinates as reference units and WGS84 as the reference ellipsoid and datum.

The DEM-SRTM data used for elevation and flow path mapping were derived from the original 90-m resolution (3 arc seconds) C-Band synthetic aperture radar data from February 2002 (Earth Explorer, 2011). Negative flow path elevations (sinks) were corrected using the Topography tool in the ERDAS software for replacing bad values. The DEM-SRTM data were processed using customized shading schemes and palettes (Mantelli et al. 2009, Hayakawa et al. 2010) using Arc Map 10.2. This procedure was particularly useful for highlighting the morphological features of interest and computing morphometry for this research according to on-screen observations.

Integration of the DEM data with available geological and geomorphological data helped me to characterize, manually vectorize, and document the drainage network and fan surface morphology of the study area. The SOI topographic maps and Google EarthTM images were used to verify channel features identified on coarser resolution Landsat imagery.

4.2. Documenting channel changes

I mapped changes in position of major channels and confluences as well as channel widths, sinuosity index, and length for the post monsoon period from 1975 to 2015 annually. The years selected for the study were based on the lowest cloud cover (listed in Table 2.2). In this analysis, the term ‘channel’ refers to the active channel, which includes low-flow channels and unvegetated or sparsely vegetated bars. Table 2.3 shows the characteristics I used to distinguish the different channel types.

I mapped all the channels on Landsat imagery from 1975-2015 and used the SOI topographic maps and Google TM imagery to validate my mapping on a few dates (1985, 1992, 2004, 2008 and 2012). For each set of satellite images, I visually identified channel margins, which enabled me to map the channels and polygons and calculate their total area.

Table 2.3. Geomorphological features used for satellite image interpretation

Features	Typical characteristics
Main active channel	Contiguous perennial channel of the river that carries the majority of flow at any flood-plain cross-section. Vegetation virtually always associated with channel margins or bars.
Active Side channel/Tributary	Perennial channels joining main channel at the upstream and downstream ends during base flow. Vegetation typically associated with channel margins or bars.
Inactive abandoned channels	Flooded segments with no connection to the active channel except during floods; tributary occupied; infilled
Bar	Elevated sediment deposits without vegetation.

The centerlines of the main channels were defined through the automated procedure developed by Alber and Piégay (2011), from which channel lengths were calculated. I divided the channel polygons by the length of each segment between tributaries, from which I derived the changes in average channel widths over time.

I used the SOI maps to crosscheck the accuracy of the extracted data layers from the satellite images. Three sets of topographical maps were collated for proper scaling and rectification purposes for the years 1975-1980, 1981-1990, and 1991-2010. The individual maps did not cover then entire megafan, which is why I collated the maps across multiple years. The maps represent relief at 50 or 100-meter contour intervals in 1975-1980 contour intervals or at 20-meter intervals from 1980–2010. These maps were used for manual vectorization of the channel network for comparison by direct overlay analysis with the drainage networks extracted from the DEM and satellite images.

I mapped channel-bed longitudinal profiles for the year 2000, the only year since SRTM DEM data were available. In addition, previous studies (Sinha, 2009; Jain et al., 2004) investigated the main Kosi River's past channel changes from 2004 to 2008 and provided some data on bed-level changes in the channel, which allowed me to further document bed-level adjustments, channel movements, migration or avulsion events. Overall, however, the absence of bed level data meant that I focused the documentary portions of my study on planimetric data that could be extracted from imagery.

4.3 Documenting fan morphology

A series of morphological and hydraulic variables were documented for the Kosi mega fan (Table 2.1) to better characterize the fan area. Surface slopes were calculated by following longitudinal distances along the main stream identified on the SRTM DEM.

5. Results

5.1. Temporal and spatial variability in Kosi river migration

Figures 2.2 and 2.3 shows examples of the change analysis of the main Kosi channel. Table 2.4 shows the average shift of the main Kosi channel over ten-year period from 1975 to 2015. Figure 2.4 shows that the number of abandoned channels continually increased over the forty-year study period. There was a particularly sharp increase in the number of abandoned channels after the year 2000 as the frequency of major floods increased. Overall abandoned channel area also increased over the study period, with significant increases typically coinciding with large floods.

The overall area of active channels did not change notably, except for the big jump that is associated with the 2008 flood.

Both major and minor flood events produced changes in channel length and widening in the main channel from1975 to 2015 (Figure 2.5). The Kosi channel belt varies in width from 5 to 13.9 km from 1975 to 2015. The main channel got narrower and more sinuous (3-3.5) The mountain-fed main Kosi channel at the western extremity of the

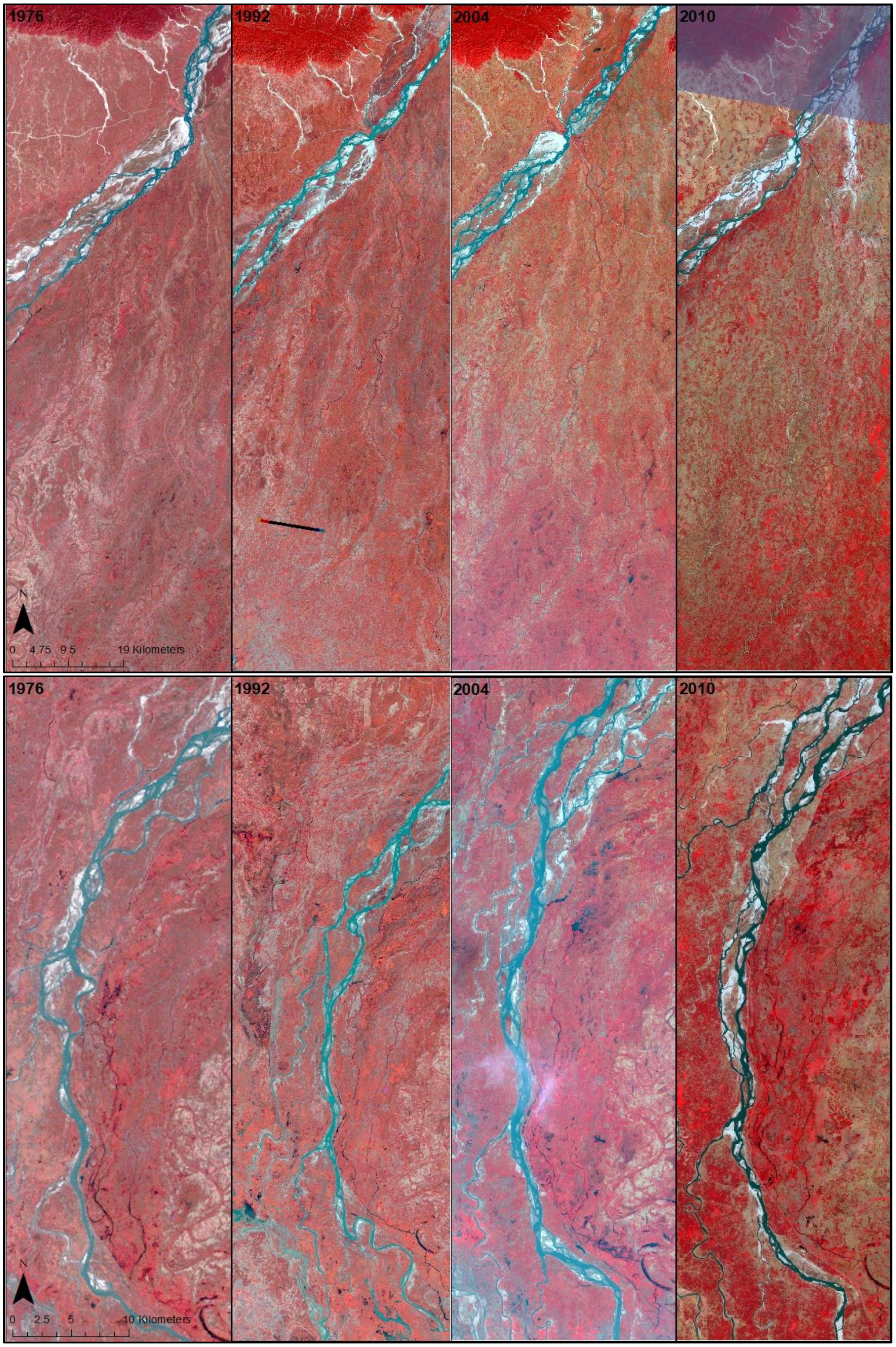

Figure 2.2. Example satellite images of parts of the research area. The upper image shows the same reach of the main Kosi river in the upper megafan surface in the dry season in

May of 1976,1992,2004 and 2010 and the scene below shows a different reach of the river in the lower Megafan area for the same period.

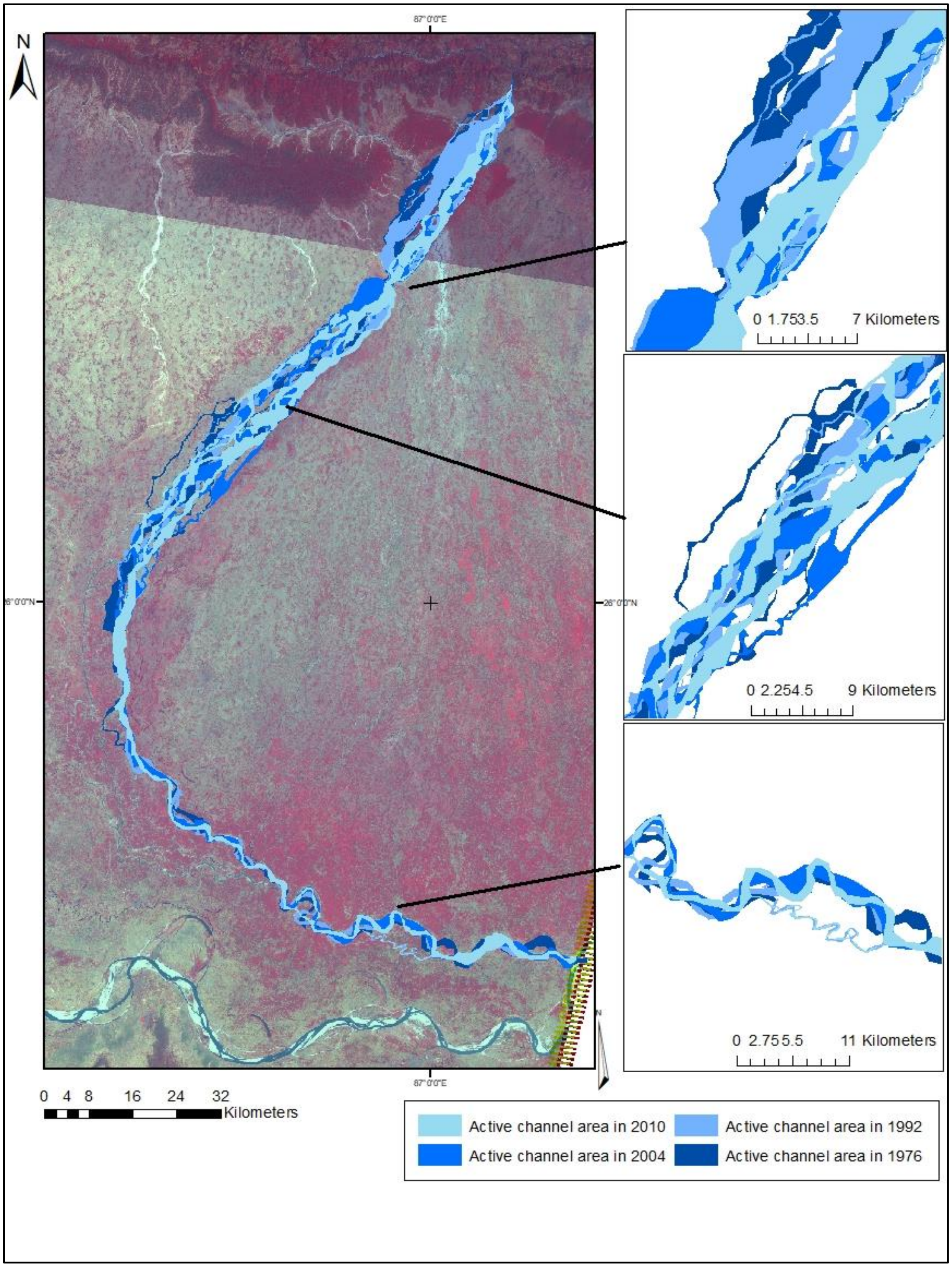

Figure 2.3. Overlay of active channel areas from different LANDSAT images (see Table 1 for the maps used; for methodology see text).

megafan is braided up to the central part of the megafan and increases its sinuosity downstream.

Table 2.4. Spatio-temporal sequence of average shifting of the main Kosi channel over 10-year periods.

Period	**Direction of Movement**	**Average Shift (km)**
1975-1985	Westward	0.5
1986-1996	Random	2.5
1997-2007	Random	33.5
2007-2015	Eastward	16.5

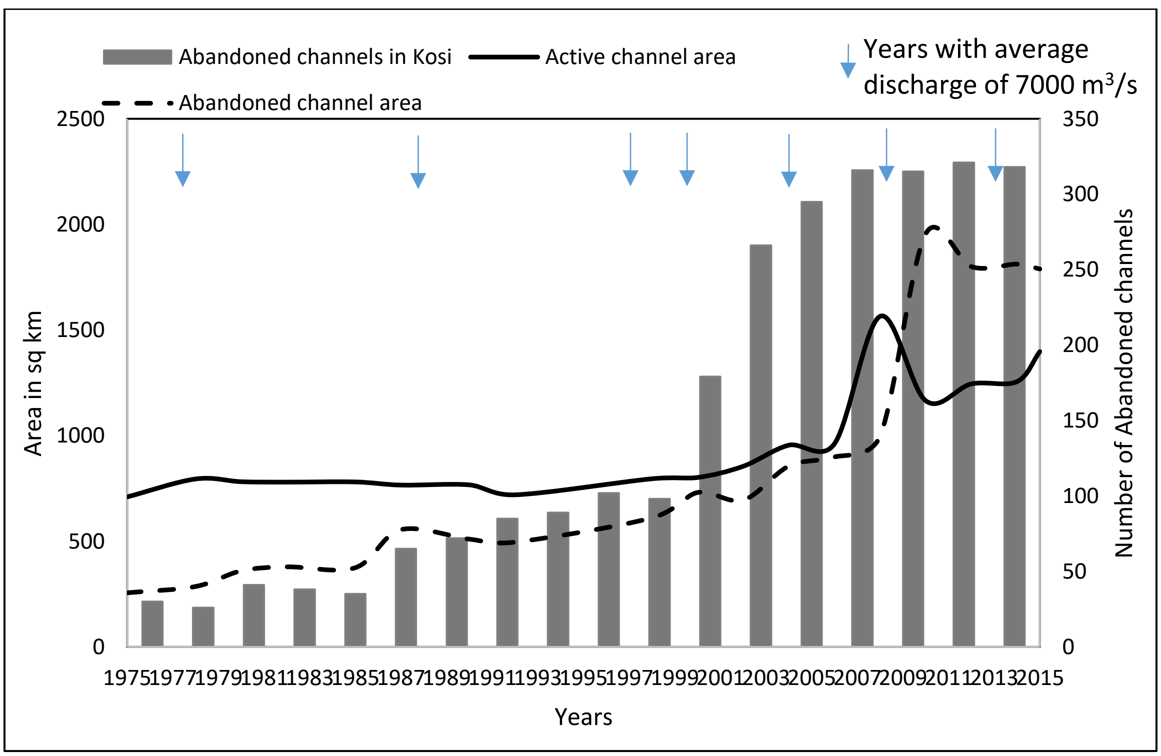

Figure 2.4. Variations in number of channels and area of abandoned and active channels from 1975-2015

Changes in the number and area of bars within the Kosi megafan, are reported in Figure 2.6. The increase in the number of bar growths corresponds with the increase in the number of abundant channels within the study period.

Increase in channel abandonment area shows a positive relationship between an overall increase in channel migration (Figure 2.7).

6. Discussion

Mapping of channel changes and the presence of numerous meander scars, minor channels, dry channels and water-logged areas on satellite images indicates a tremendously mobile river with a great deal of recent channel activity on the Kosi River megafan. The extensively interconnected channel network on the megafan probably indicates a net aggradational sediment system (Kumar et al., 2014). The transverse profiles of the megafan are irregular due to presence of raised and incised regions.

The planform pattern of a river is largely controlled by the available energy and caliber of the sediment load, and both these factors are largely a function of the slope of the channel (Brierley and Fryirs, 2006). Thus the long term spatial changes in the river migration and planform pattern studied here are attributed to the decreasing slope of the megafan surface and the high sediment loads, a concept which is common to many of the studied megafans (Decelles and Cavazza, 1999).

Increased sinuosity further downsteam with decreased width indicate decreased water and sediment load in these channels as compared to some of the wider, less sinuous braided upstream reach of the Kosi River.

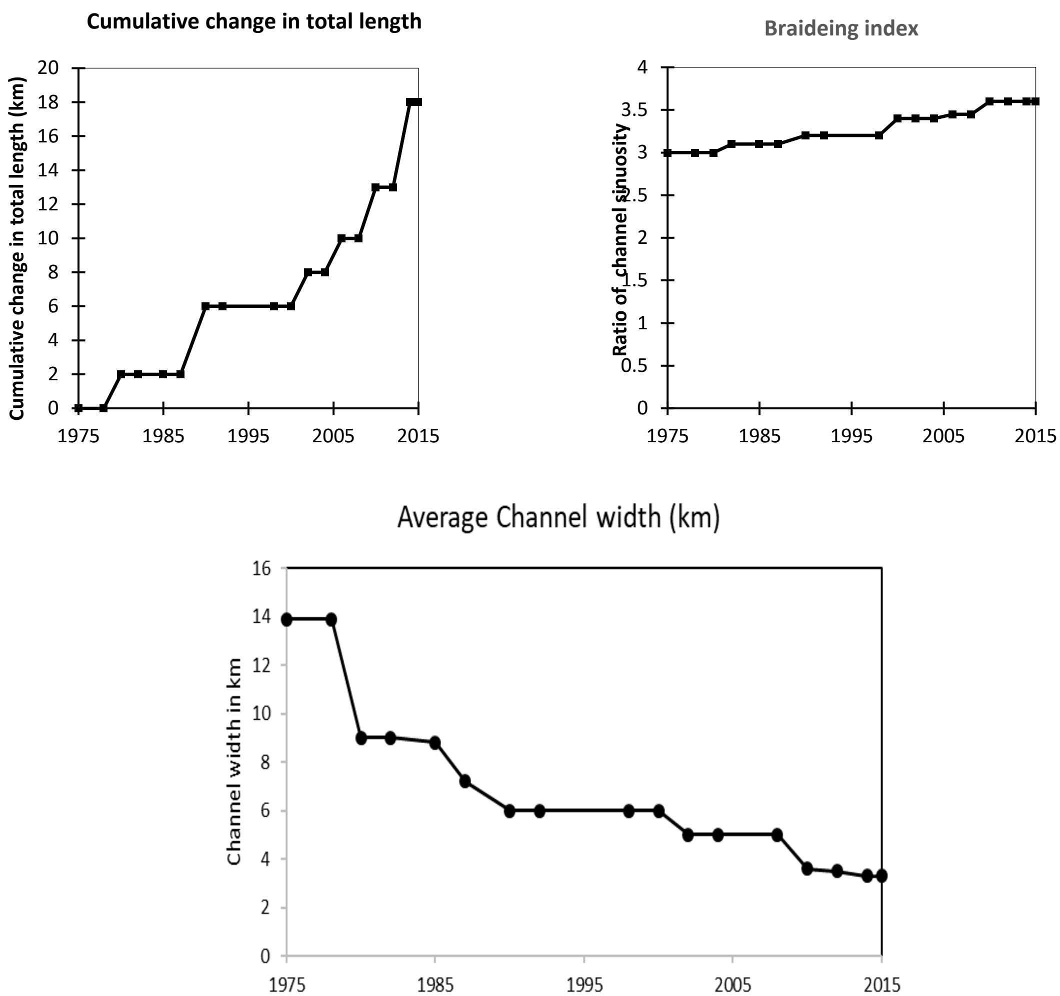

Figure 2.5. Changes in the length, width and sinuosity of the main Kosi channel from 1975-2015

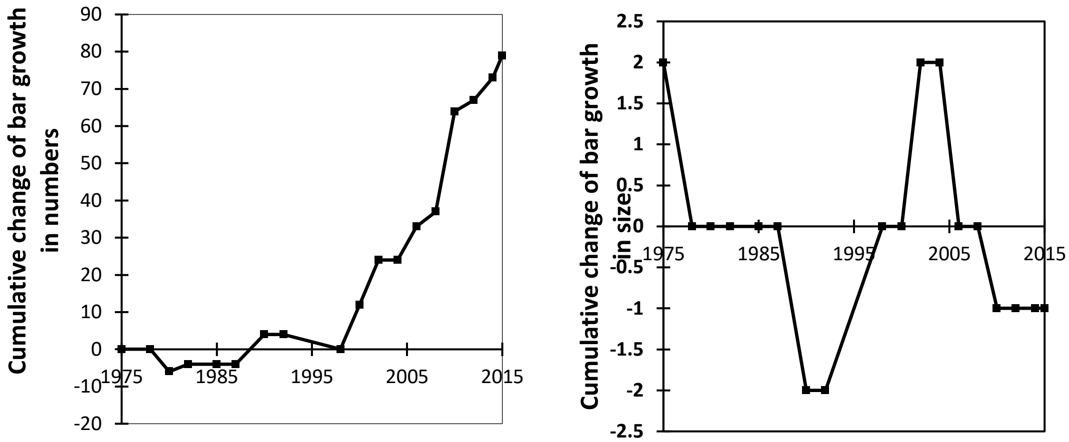

Figure 2.6. Changes in the bar growth within the megafan from 1975-2015

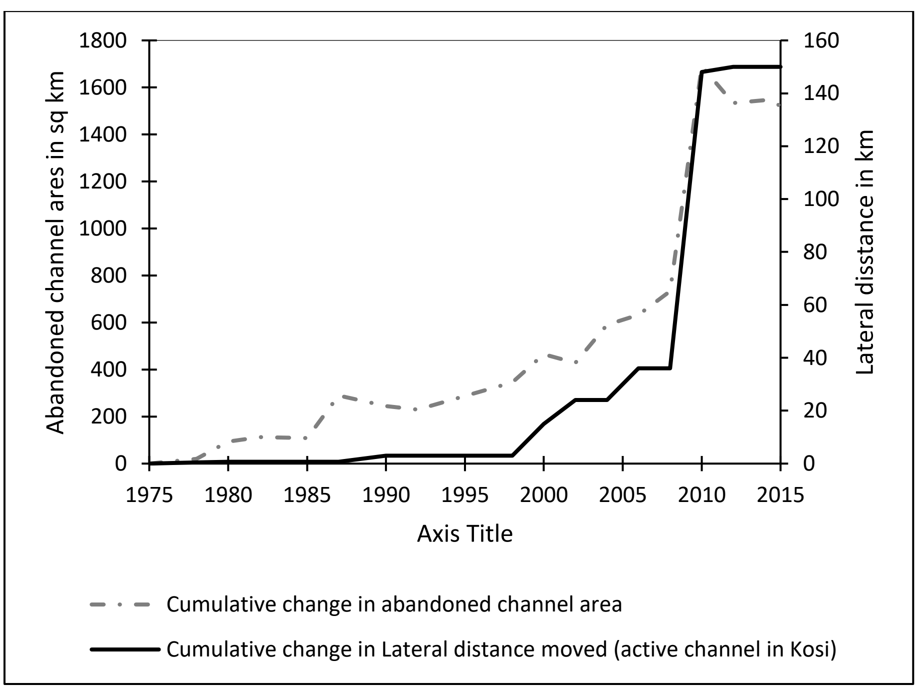

Figure 2.7. Relationship between lateral distance moved and abandoned channel area from 1975-2015

7. Summary and Conclusions

This paper presented an overview of channel migration of the main Kosi river within its megafan surface for the period of 1975-2015. These results establish an initial dataset to assess future channel migration changes and locations and evaluate natural and anthropogenic controls that influence channel-migration rates in the Kosi megafan. This study will also support establishing a more reach-scale framework of channel-migration rates to help evaluate locations more vulnerable to flooding.

CHAPTER III

THE ROLE OF ROAD AND RAILROAD NETWORKS IN CONTROLLING SURFACE WETNESS IN THE KOSI MEGAFAN, INDIA

1. Introduction

Waterlogging, which is the unwanted seasonal or longer-term saturation of agricultural soils, occurs due to flooding, over-irrigation, blockage of natural drainage, or high water at drainage outfalls (Lohani et al., 1999). In India, waterlogging is estimated to affect 3.3 million (Bhattacharya, 1992) to 6.0 million ha (National Commission on Agriculture 1976). Waterlogging thus has a major impact on agricultural productivity, livelihood strategies, and the quality of life for many millions of people in India.

This is particularly true in the state of Bihar which has a population of nearly 100 million (Pandey et al., 2010). Waterlogging covers an estimated area of nearly 0.9 million ha in Bihar (Pandey et al., 2011) and thus is of major concern to the large population that relies on agriculture for a living. The northern Bihar plain, which mostly sits with the Kosi megafan, is generally regarded as 'a water-surplus area' (Ghosh et al., 2004) that is characterized by extremely flat terrain, paleo-levees, swamps, relict palaeo-channels, meander belts, ox-bow lakes and cut-off loops (Ahmad, 1971). Hence, the area is very susceptible to flooding from the many channels of the Kosi River, as well as from the many irrigation canals.

However, the problem of waterlogging in the Kosi megafan area is largely a modern one. One major factor driving this is the introduction and growth of canal systems. Canal irrigation was first introduced at the end of the Nineteenth Century to provide water supply and expand the area under cultivation (Abrol 1971). Seepage from canals associated with the onset of intensive agricultural practices has resulted in almost 0.2 million ha of cultivated land being affected by soil salinity and waterlogging (Joshi and Tyagi, 1994).

Yet with almost a million hectares of waterlogged soils in the Kosi megafan, canal seepage alone does not explain the full, modern extent of waterlogging. Over-irrigation, defects in canal planning, canals obstructing drainage, and lack of proper land development have aggravated the situation (Dwivedi et al., 1999). Beyond that, another possible explanation is the tremendous growth of road and railroad networks, which have extended dramatically over the 1955–2015. The extensive network of roads and railroads across the Kosi megafan parallel or cross many flood channels, drainage ditches, canals, streams, and rivers. Road and railroad networks are built on elevated grades that can act as levees to block the flow of water and sediment, while bridges associated with the travel corridors can constrict flow and force water to back up on the upstream side (Blanton and Marcus, 2009; Kumar et al., 2014).

This study seeks to better understand the relative role of roads and railroads on waterlogging in the Kosi megafan. Specific research questions are:

- How have road-rail transport network patterns and densities and the intensity of waterlogging varied within the Kosi megafan from 2005 to 2015?
- To what extent do railroads and roads cross or impinge on natural and human-built channels across the Kosi megafan from 2005-2015?
- To what degree are the channel crossing and channel fringing structures associated with location and changes in the extent waterlogging in the megafan?

2. Background

2.1 Waterlogging in the Kosi megafan

Waterlogging can occur due to a high subsurface water table and/or due to accumulation of surface waters that are trapped and cannot runoff. Waterlogging occurs over vast regions of the world (Kozlowski, 1984), adversely affecting approximately 10% of global land area and posing a serious threat to the world's productive agricultural land (FAO, 2002). Seasonal and permanent waterlogging can convert fertile tracts into unusable agricultural land by creating anoxic soil conditions and promoting high salinity levels, thus affecting the livelihood of populations dependent on those lands (Pandey et al., 2012). Irrigated lands are prone to waterlogging; about one-third of the world's irrigated area faces the threat of waterlogging (Heuperman et al., 2002).

Unfortunately, surface waterlogging and flooding in areas suitable for kharif crops (crops grown during the monsoon season) and rabi crops (crops grown during the winter season) is a common problem in most of the downstream stretches of Kosi river basin in India (Agarwal et al., 1991; Bhattacharya 1992). Prior to 1998, the major causes of surface waterlogging in the Kosi megafan were the accumulation of rain and flood waters in bottom lands created by seismic activity, constant shifting of river courses due deposition of high sediment loads, and poor drainage (Dhar & Nandargi, 2003).

Dhar and Nandargi, however, did not evaluate the degree to which transportation networks affected the drainage and sediment loading, nor did they examine the primary drivers over the last 20 years, a period that has seen significant expansion of waterlogged extent in the megafan. From 2001 to 2010, the number of districts affected by waterlogging increased from nine to 25, the number of affected villages within these districts increased from 679 to 18,832, the number of affected people increased from 718,000 to 24,420,000. The total area affected from waterlogging increased from 181,000 to 1,969,000 ha, with impacted agricultural lands increasing from 160,000 to 1,440,000 ha (IPCC,2013).

The duration and severity of waterlogging events are influenced by the amount of water entering the system, the topography of the site, soil structure, the water absorbing capacity of the soil and anthropogenic disturbances (Gupta et al., 1994; Jain and Sinha, 2003c). The Kosi megafan located in the center of the summer monsoon belt, receives more than 75% of its annual rainfall during the four monsoon months of June to September (Kale, 1998). Likewise, the majority of floods in the Kosi River and subsequently seasonal waterlogging occur during this season too. The ground conditions also help in generating high percentage of run-off because of the antecedent wet conditions caused by rainy spells occurring within the monsoon period.

Studies have shown that extensive waterlogging at different crop growth stages reduces the harvest (CGWB, 2007). The reductions in yield become more severe the longer the waterlogging extends into non-monsoon months. The two major crops grown in the Kosi megafan a rice, which is a water-intensive crop grown in the monsoon seasons, and wheat, a dry season winter crop. Yields of both these crops are dramatically affected by waterlogging (Sharma et al., 2003).

2.2 Effects of roads and railroads

Roads and railroads affect drainage by 'disconnecting' the flowing water from the surrounding landscape (Blanton and Marcus, 2013). In floodplains, road construction (and by extension, railroad construction) generally follows two approaches: 'resistance' and ‘resilience’ alignments (Vis et al., 2003). The first approach increases the elevation of the road to create a dyke that prevents flood water from over-flowing the structure. In the second approach, the resilience strategy, roads are developed by somewhat increasing road elevations and adding flow-through structures (e.g. culverts) to allow floodwaters to move beneath the road (Vis et al., 2003). In both cases, the flood pathways, extent of flooding, and flood duration will be changed by the development (Tarolli., 2012), which in turn affects floodplain connectivity, surface wetness and erosion.

The nature of transportation infrastructure impacts varies with whether the features cross the channels (e.g. bridges and culverts) or are aligned with the direction of the channel (e.g. roads in the floodplain along a river). Culverts and bridges can increase stream flow velocity, shear stress, turbulence of flow, and induce channel degradation or aggradation, channel braiding and downstream bank erosion, all of which can significantly alter regional hydrology and ecology (Vermont Department of Fish and Wildlife, 2009; Blanton and Marcus, 2013). Wheeler et al. (2005), Bouska et al. (2010) and Merril and Gregory (2007) highlighted the impact of road crossings on in-stream aquatic fauna by modifying their habitat, biodiversity, movement, sources of food and other functions.

Even more pervasive than bridges are the many roads and railroads that run within floodplains. The elevated transportation grades can act as barriers to impede flow of water and sediment across the surface. This sometimes prevents water from reaching the floodplain, but at other times traps floodwaters so they cannot flow back to the river. Because this disconnection of the river from the surrounding landscape prevents the natural flow of sediment and water, it can have major impacts on channel and floodplain environments (Blanton and Marcus, 2014).

The proximity of a road to a stream can affect the level and type of impact. Forman and Deblinger (2000) estimated an average width of 600 m for the zone of ecological impacts for a busy 4-lane highway in Massachusetts. Forman (2000) extrapolated the ecological impacts of the highway to determine that 1/5 of the land area in the United States was ecologically affected by public roads. Barber et al. (2014) showed that 94.9% of all deforestation in the Brazilian Amazon has occurred in a well-defined accessible zone within 5.5 km of some type of roadway or 1.0 km of a navigable river, although the majority of these impacts was attributable to access rather than road effects on hydrology. In addition, the shape of the network can either lengthen or short overland flow paths, which can affect erosion and deposition (Pechenick et al., 2014).

Early studies on the impacts of road or railroad crossings tended to focus on the effects of one or several structures. For example, in India, Bhattacharya (1958) documented that bridge piers over the Rupnarayan River along the Kolkata–Mumbai National Highway, West Bengal, induced heavy sedimentation, frequent flooding, and reduction of river navigability with significant loss of water passing capacity. Sing (1983) noted that the construction of a bridge across the Gomti River modified the direction of channel flow and increased flow velocity, which in turn encouraged downstream erosion. Recently Roy (2013) in a micro-level study with a single road–stream crossing (bridge) on the Kunur River, West Bengal, observed that there is significant variation of channel geometry between upstream and downstream reaches of that crossing.

Researchers turned their attention to the more widespread impacts of entire transportation networks since approximately 1990. A report by the U.S. Federal Highway Administration (FHWE, 1990) was one of the first to note widespread effects of highway and bridge construction on fluvial geomorphology and hydraulics of river systems. Blanton and Marcus (2013) quantified the potential impacts of transportation infrastructure across the entire United States, noting that the extent and nature of impacts varied with physiographic regions. In recent work across the entire Kosi megafan, Sinha et al. (2013) analyzed the connectivity structure of the surface to predict the avulsion pathway of the August 2008 event and demonstrated that the connectivity structure can serve as a predictive tool for postulating future avulsion pathways. Although Sinha et al.'s study focused on documenting waterlogging and resultant effects on flooding, the results served to support the idea that drainage is affected by transportation networks in this region.

3. Study Area

The Kosi megafan covers approximately 94,000 km^2 and ranges in elevation from 50 to 100 m. This broad, flat alluvial fan was formed over time by immense sediment deposits left by the Kosi River as it exited the Himalayas (Chakrabarti, 2001) (Figure 3.1). The Kosi megafan is predominantly characterized by various south flowing channels that represent the former courses of the Kosi River (Fig. 1). Most of these paleochannels get activated during the monsoon season and influence the distribution of water and sediment flux over the megafan. Given this setting, it is not surprising that the Kosi megafan is one of the most dynamic river systems the world (Gole and Chitale

1966, Wells and Dorr 1987, Jain and Sinha 2003, 2004). Flooding, channel abandonment, and widespread sediment deposition are common.

The geological formations in the megafan are unconsolidated sediments of Quaternary and upper Tertiary–Recent age. Lithologically, the fan is made up of alternating beds of clay and fine to medium sands that form thick regionally extensive confined/unconfined aquifers down to a depth of 300 m (Jha et al., 2007). These alluvial formations constitute prolific aquifers with yield between 120 and 247 m3/h (Chakrabarti, 2001).

The climate in the area is tropical to sub-humid tropical with an overall average annual rainfall of 1,200 mm (Chakraborty et al., 2010), although precipitation increases as one gets closer to the Himalayan front, approaching 1.800 mm/yr. in the northern parts of the plain. About 75% of the annual rainfall in the region occurs during the four monsoon months from June to September, and temperatures range from a mean minimum in December and January of 10 to 11°C to annual mean maximum in May around 41°C.

There are four cropping seasons prevalent in the study area and major cropping pattern is cereal based with rice, maize, and wheat as the dominant crops. But the gross cropped area has remained stagnant for the last 26 years and agricultural activity declined rapidly over time in the Kosi megafan mainly because of the increase in the extent and duration of waterlogging following monsoonal floods (Dev, 2008). Several canal systems of the East Kosi Command Area facilitate irrigation throughout the megafan which are further known to contribute to the waterlogging severity.

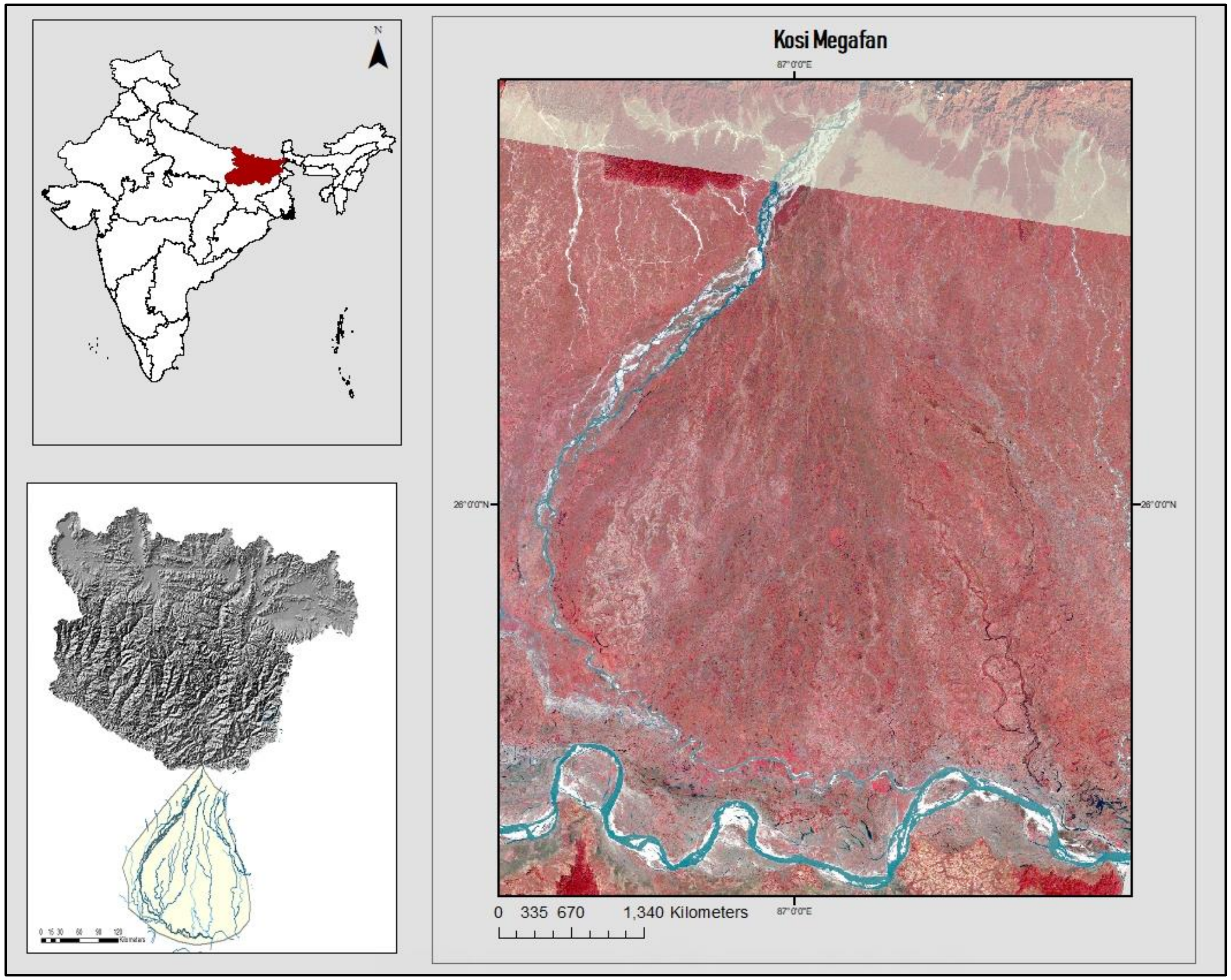

Figure 3.1. Location map of the Kosi megafan in the northern Bihar plains in India.

The megafan surface is traversed by an extensive road and railroad system now. These which run mostly in an E-W direction, transverse to the flow direction of the rivers. Nevertheless, in 1975s only a small percent of road lines followed or traversed drainage pattern, while the total length of road was also lower than 2010s (Kumar et al., 2014). No significant development of road network along the main Kosi river was witnessed in 1970s, whereas in 2010s rapid development of road network have been observed either side of the main Kosi river as well as other minor channels (Kumar et al., 2014). In the present time, 57 single-lane national Highways and 41 State Highways and district roads with a length of 11145 km connect 61 villages in the Kosi megafan (Ministry of Road transport and Highways).

4. Data Sources and Methodology

I integrated remote sensing data, topographic surveys, and classification techniques to map the location and extent of roads and railroads and pre- and post-monsoon waterlogged areas in the Kosi megafan for each year from 2005 through 2015. I then used GIS to identify the number and locations of road and railroad crossings over channels. Lastly, a buffer analysis mapped area of spatial association between the transportation networks and pre and post-monsoon waterlogging conditions to evaluate road and railroad effects on waterlogging.

4.1 Data sources

Table 3.1 describes the various datasets that are used in this study. Multitemporal satellite data from the Landsat 7 Thematic Mapper (ETM+) for the years 2005-2013 and Landsat 8 (OLI) sensor for the years 2013-2015 were used to monitor the spatial extent and distribution of pre- and post-monsoon waterlogged areas in the years 2005–2015. The Landsat 7 Enhanced Thematic Mapper Plus (ETM+) images consist of seven spectral bands and acquire reflectance in the 0.45-2.35 wavelengths. Similarly, Landsat 8 (OLI) images consist of nine spectral bands and acquire reflectance in the 0.43-1.38 wavelengths. To obtain the historical perspective on transport infrastructure, the topographical maps in Table 3.1 were used in addition to the satellite images.

When utilizing spatial data from diverse sources, it is required that all datasets should be accurately co-registered spatially. This requires georeferencing of all the maps to a common projection system. The Landsat imageries was digitally registered to Survey of India (SOI) topographical maps of 1:100 000 scale (Table 3.1) using ArcMap 10.x. Ground control points were uniformly selected across the images; locations could all be easily and clearly identified and precisely located. Image-to-map transformation was performed using a first-order polynomial transformation. The root mean square error (RMSE) in all the image-to-image registration processes was less than 0.03m. The resampling process was performed using the nearest neighborhood technique (Roy et al., 2016).

4.2. Mapping of surface waterlogged areas

The area of surface waterlogging was estimated using the Normalized Difference Water Index (NDWI) (McFeeters, 1996). The index is calculated using the digital number (DN) values from the green, red and near infrared bands (NIR) for each pixel:

$$NDWI = (Green - NIR)/(Green + NIR) \qquad (1)$$

Table 3.1. Data sources

a. Dates of Landsat 7 Thematic Mapper (ETM+) and Landsat 8 (OLI) imagery used in the study. The spatial resolution on all images was 30m.

Years	**Date of acquisition**	
	Pre-monsoon	**Post-monsoon**
2005	5 May	20 November
2006	13 May	12 October
2007	25 April	6 November
2008	13 May	22 November
2009	11 May	4 November
2010	11 May	4 November
2011	11 May	4 November
2012	11 May	4 November
2013	11 May	4 November
2014	11 May	4 November
2015	11 May	15 November

b. Topographical map from Survey of India (SOI) used in the study.

Source of publication / year	**Topographic sheet numbers**	**Scale**
SOI (2002)	72 G1, G2, G5, G6	1: 10,00 000

Using the NWDI, a pixel is classified as water or saturated soil if the digital number (DN) value of its NIR band is less than the DN value of the red band and the green band, and the Normalized Difference Water Index (NDWI) is greater than or equal to 0.32. Dry soil and terrestrial and vegetation features have zero or negative values which can be easily eliminated (McFeeters, 1996). I calculated the NDWI for all the imageries (Table 3.3.1) using ERDAS Imagine software. About 60% of the delineated surface waterlogged areas are verified using the ground truth information obtained from State Hydrology Cell and Water and Land Management Institute (WALMI), Patna, India.

4.3 Mapping of roads, railroads and channels

The georeferenced LANDSAT images were used to delineate and digitize active river channels, roads and railways for pre and post-monsoon from 2005 to 2015. I classified roads into 'major roads,' which are national and state highways, and "minor roads," which are district roads. The major roads include roads prepared by bituminous and/or pure concrete, whereas minor roads are covered by laterites, or other earth materials (Rural Works Department, Govt. of Bihar). Some seasonal roads (over the bare surface) have been also developed across the agricultural land during crop harvesting, which are not traceable for mapping. Present study has considered paved and unpaved road only with especially focusing on roads that connect the villages and urban centers. Numerous intra-village and intra-urban roads, seasonal roads have been excluded because they were not traceable for mapping. Results were calibrated with 2002 SOI map and recently available Google Earth View and Bing Roads (2013-2015) using open-layer plug-in in Q-GIS.

4.4. Analysis of transportation infrastructure impacts

To analyze the impact of transportation networks on waterlogging, I documented road and railroad intersections with channels, the density and type (by each transport network) of these intersections as they vary across the fan surface, the degree to which these intersections led to disconnections in the flow, and the length of roads or railroads within 500 m of a channel. These analyses for were run on the TM imagery for pre- and post-monsoon waterlogging conditions for every year (Table 3.1).

The intersection tool in ArcGIS has been used to acquire the point vectors of road-railroad-stream crossing for pre and post-monsoon period from 2005-2015 by superimposing layers of streamlines and transport lines. All the intersection points were visually classified on a false color composite image as connected, partially connected or disconnected points. If a channel was active in both pre- and post-monsoon periods it was designated as a 'connected' point. On the other hand, if a channel was found to be active in the post-monsoon period and inactive in the pre-monsoon period, then it was designated as 'partially connected' and if a channel was inactive in both periods, it was classified as 'disconnected' (Figure 3.2). Connected points are characterized by continuous flux (of both water and sediment) across the intersection points, while only seasonal or no movement will occur across the partially connected and disconnected points respectively. I also identified intersection points of channels with roads and railroads based on transport types.

Because roads and railroads that don't cross channels but are in the floodplain can still alter drainage and contribute to waterlogging, I also evaluated the degree to which proximity of roads or railroads are associated with waterlogging. To do this, I used the bilateral buffer polygon technique in GIS to create a 500m buffer on either side of railways, major roads and minor roads.

5. Results

5.1. Surface waterlogging

Figure 3.3 provides examples of grey and white pre- and post-monsoon NDWI images of

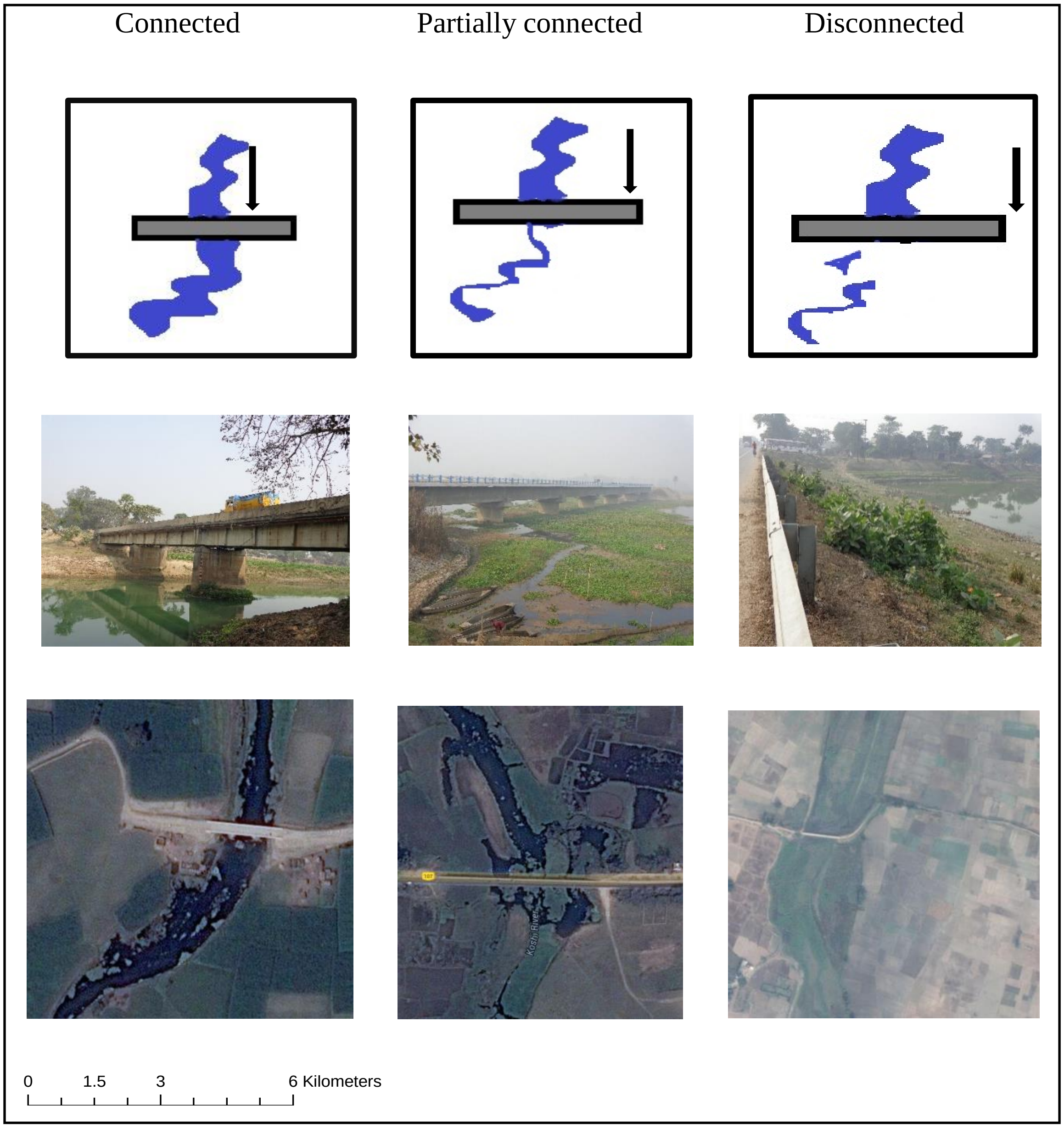

Figure 3.2. Classification of the railroad and river intersection points. The figure shows images acquired from field visit on November 2015 and corresponding Landsat 8 images in natural color.

the Kosi megafan for the years 2005,2008 and 2015). Waterlogging during both the pre and post-monsoon period is a major environmental hazard in Kosi megafan, with many thousands of km^2 being waterlogged on an annual basis (Table 3.2).

Table 3.2 and Figure 3.4 shows the overall temporal variability of waterlogging and the NDWI maps shows the spatial variability of waterlogging over the megafan surface (Figure 3.3).

Table 3.2 indicate an overall increase in the pre-monsoon surface waterlogged area from 3,230 km^2 in 2005 to 5,220 km^2 in 2015. The increase has generally been gradual from 2005 to 2015, except for a significant jump for one year in 2009 due to a massive avulsion and flooding incident in August 2008 (Figure 3.4). On average, 42.5% of the entire megafan area remained waterlogged every year during the pre-monsoon period from 2005 to 2015 (Figure 3.4). The problem of pre-monsoon surface waterlogging became more severe over the ten-year period of the study, with the total area covered in the peak year (2009) covering 61% of the megafan.

As with the increases in pre-monsoon waterlogging, Table 3.3.2 indicates that there has also been an overall increase in the post-monsoon surface waterlogged area from 6128 km^2 in 2005 to 8976 km^2 in 2015. The trajectory of this increase has not been consistent, however, with upsurges and drops in waterlogged area for a number of years in between 2005 and 2015 (Figure 3.4). On average, 74% of the entire megafan area remained waterlogged over the 10-year period. Overall, the problems of post-monsoon surface waterlogging have become more severe by the year 2015. The year 2008 saw the highest upsurge (16%) of waterlogging from previous year and had the highest area (86.6% of the megafan) under post- monsoon waterlogging. This was associated with the major flooding in August 2008.

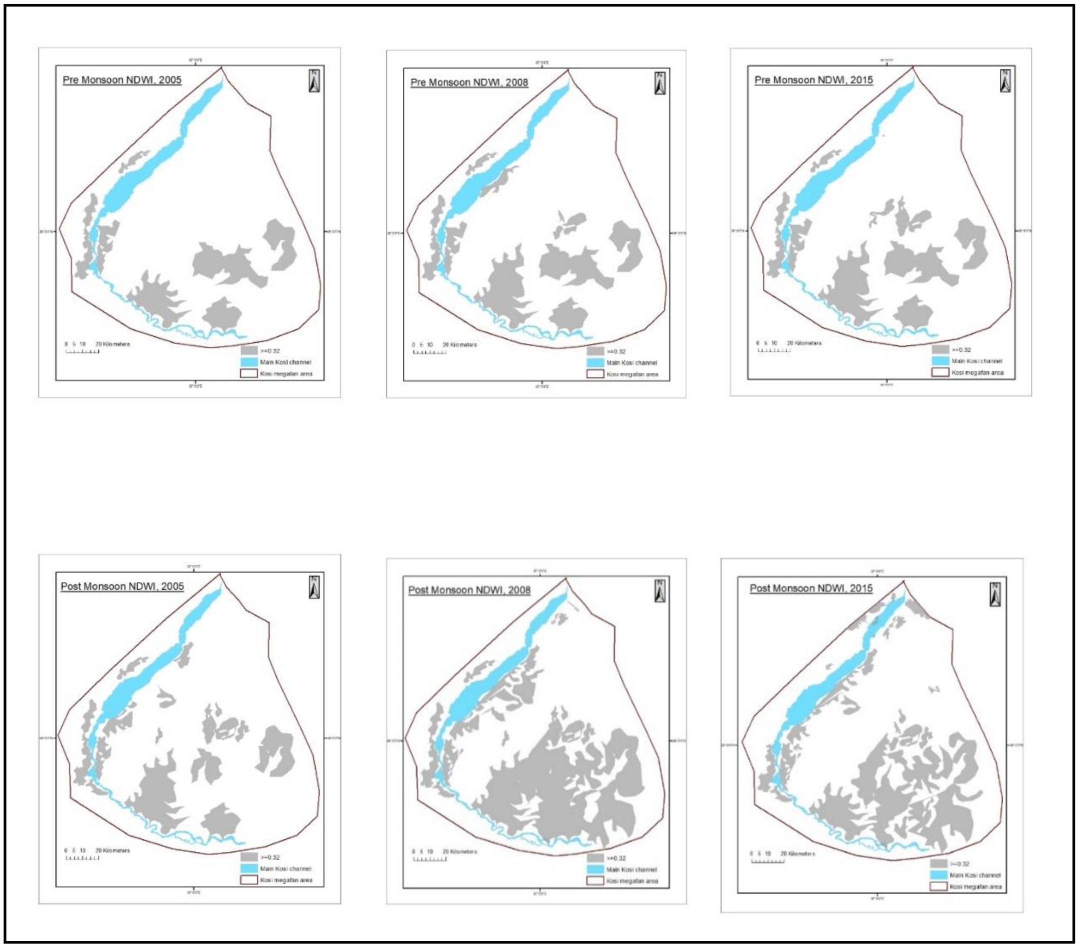

Figure 3.3. NDWI images. Area in gray represent areas where the NDWI is >0.32, which is presumed to be areas that are waterlogged.

In both the pre- and post-monsoon periods, the western and eastern parts of the megafan are generally more affected by waterlogging problems, with the most extensive waterlogging in the southeast portion of the megafan. In particular, the results indicate that there has been a sharp increase in the concentration of waterlogging in the Araria, Madhepura, Purnea, Munger, Jehanabad, Supaul, Saharsa and Kishanganj districts in the Kosi megafan. This pattern is in agreement with the earlier published waterlogging maps for the same region acquired on different dates (Kumar et al., 2014).

Table 3.2. Changes in the waterlogged area from 2005 to 2015 within the entire megafan surface area of 11410 km^2. Areas in km^2.

Years	Pre-monsoon waterlogged area	Post-monsoon waterlogged area
2005	3,230	6,128
2006	3,654	6,445
2007	5,101	7,973
2008	4,144	9,879
2009	7,041	9,432
2010	5,659	6,989
2011	5,989	9,698
2012	4,687	9,656
2013	4,321	9,342
2014	4,333	8,141
2015	5,220	8,976

5.2 Interactions of channels and transportation networks

This section describes the data results related to locations and changes in the transport network and channels; explanation of these trends is provided later in the Discussion section. The number of channels increased from 426 in 2005 to 701 in 2015 (Figure 3.5). Similarly, the length of roads increased from 9,869 km in 2005 to 10,385 km in 2015, while railroads increased in length from 1,623 km to 1,840 km over the same period (Table 3.3).

Paralleling the increase in the lengths of both channels and transportation infrastructure, the number of road or railroad intersections with channels increased significantly from 2005 to 2015 (Figure 3.6).

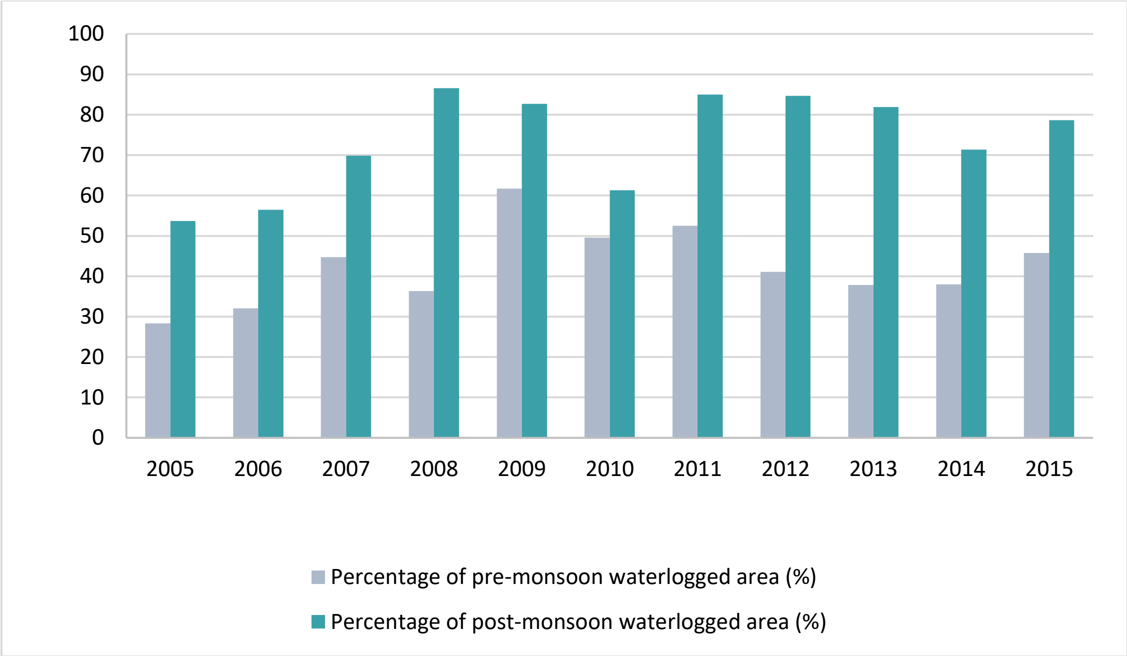

Figure 3.4. Changes in the waterlogging area between successive years. Area in %

Table 3.3. Changes in road and railroad length. Lengths in km.

Year	Road length	Railroad length
2005	9,869	1,623
2006	9,890	1,623
2007	9,961	1,659
2008	9,969	1,659
2009	10,200	1,659
2010	10,229	1,700
2011	10,298	1,800
2012	10,298	1,829
2013	10,300	1,829
2014	10,383	1,840
2015	10,385	1,840

The number of all intersections is highest in the post-monsoon period when high waters from flooding and rains open up crossings that are not crossings during seasons.

Visual analysis of the channel-transportation network maps (e.g. Figure 3.7) indicates that the western, central and south-eastern part of megafan area have more crossings than rest of the areas. It is also noticeable that the road-stream crossings are becoming more clustered in those areas over the 10-year period.

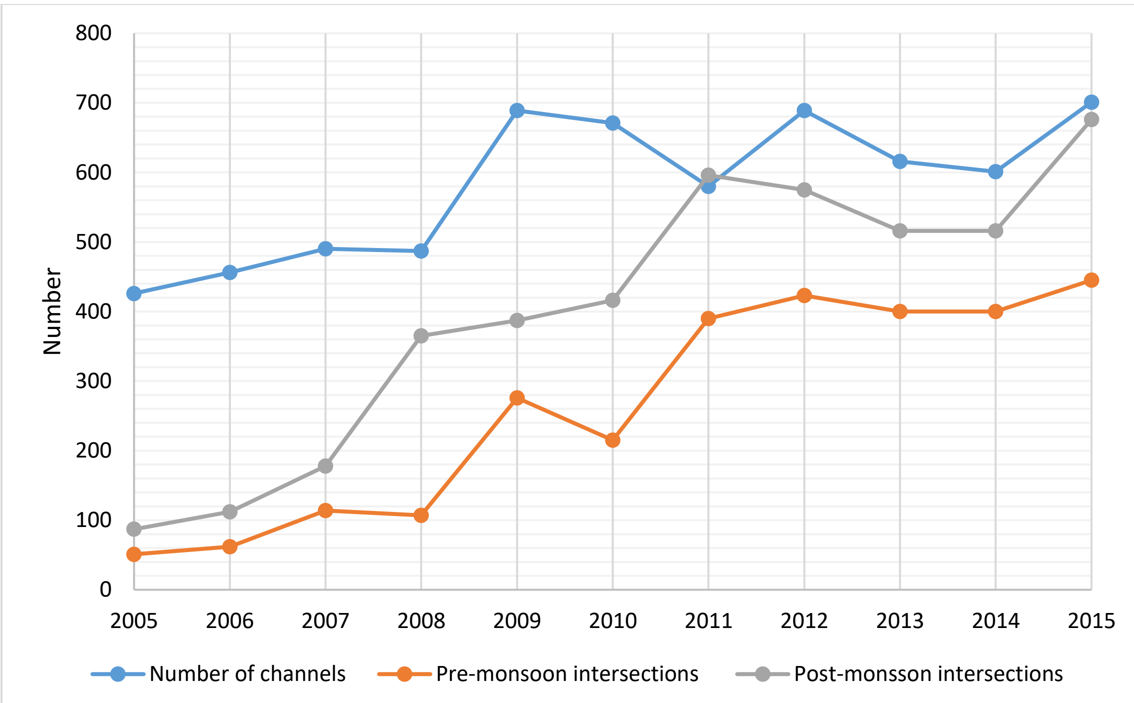

Figure 3.5. Changes in the number of channels and road-railroad-river intersections.

There are significant seasonal and longer trends in channel connectivity at the crossings. In terms of seasonal variations, there are more connected intersections in the post-monsoon than in the pre-monsoon, which reflects the way in which higher water can flow over or around barriers that might cause it to pond up in dry periods. In 2005, for example, 20% of all (railroad plus minor road plus major road) pre-monsoon channel crossings and 72% of the post-moon channels are connected. Similarly, by 2015, 6% of the pre-monsoon channel crossings and 23% of the post-moon channels are connected. There are also trends over the 10-year period. The number and proportion of disconnected intersections is much higher in 2015 than in 2005, which highlights the temporal variability and dynamic nature of the connectivity structure (Figure 3.7). The number of fully disconnected pre-monsoon crossings increased from 49% in 2005 to 75% in 2015, while 31 % of partially connected points in 2005 decreased to only 4% in 2015. Similarly, in 2005, 9% of the post-monsoon channel crossings fall in the disconnected category, compared to 47% in 2015. The proportion of fully connected crossing is the inverse of the disconnected trend. The total number of post-monsoon connected crossings has decreased from 72% in 2005 to only 23% in 2015; pre-monsoon connected crossings have decreased from 20% in 2005 to only 6% over the 10-year period. The percentage of all intersections that are disconnected decreased, but the total number of disconnected intersections increased quite a bit.

Figure 3.8 shows how the connectivity structure changes for intersections with railroads, major roads, and minor roads for the pre- and post-monsoon period from 2005 to 2015. Although railroads make up the smallest total length within the transportation network (Table 3.3), they are associated with more fully disconnected intersection in both the pre- and post-monsoon period, followed by minor roads, then major roads. Railroad induced disconnections increase sharply in 2008-2009, then jump again in 2011.

Likewise, the number of fully disconnected crossings created by minor and major roads increases significantly from 2005 to 2015 in both the pre- and post-monsoon seasons.

The proportion of disconnections driven by railroads remains relatively constant over the 2005 to 2015, ranging from 31 % to 48% of the pre-monsoon disconnections and 35% to 59% in the post-monsoon period. However, the proportion of disconnections driven by minor roads increases significantly over the 10-year period, increasing from 32% to 46% for pre-monsoon crossings and 28% to 45% in the post-monsoon period.

5.3 The spatial association of transportation routes and waterlogging

Table 3.4 clearly indicates that large areas of waterlogging are located within the 1 km buffer surrounding major and minor roads and railroads. Over the 10-year study period, there has been a total increase in waterlogged area, with the greatest increase in the years 2006 through 2008 (Figure 3.9). Waterlogging increased around all the types of transportation lines, with railways exhibiting the greatest increase.

Proportionally relative to their total length, railroads have a larger percent of waterlogged area in both the pre- and post-monsoon period, with 20.5 to 51.5% of the total buffer being waterlogged, depending on year and time of year (Table 3.4). In comparison major and minor roads had 4.6% to 27.1% and 8.5% to 35%, respectively, of the total buffer area being waterlogged. Both roads and railroads had less waterlogged area within buffers in the pre-monsoon than in the post-monsoon.

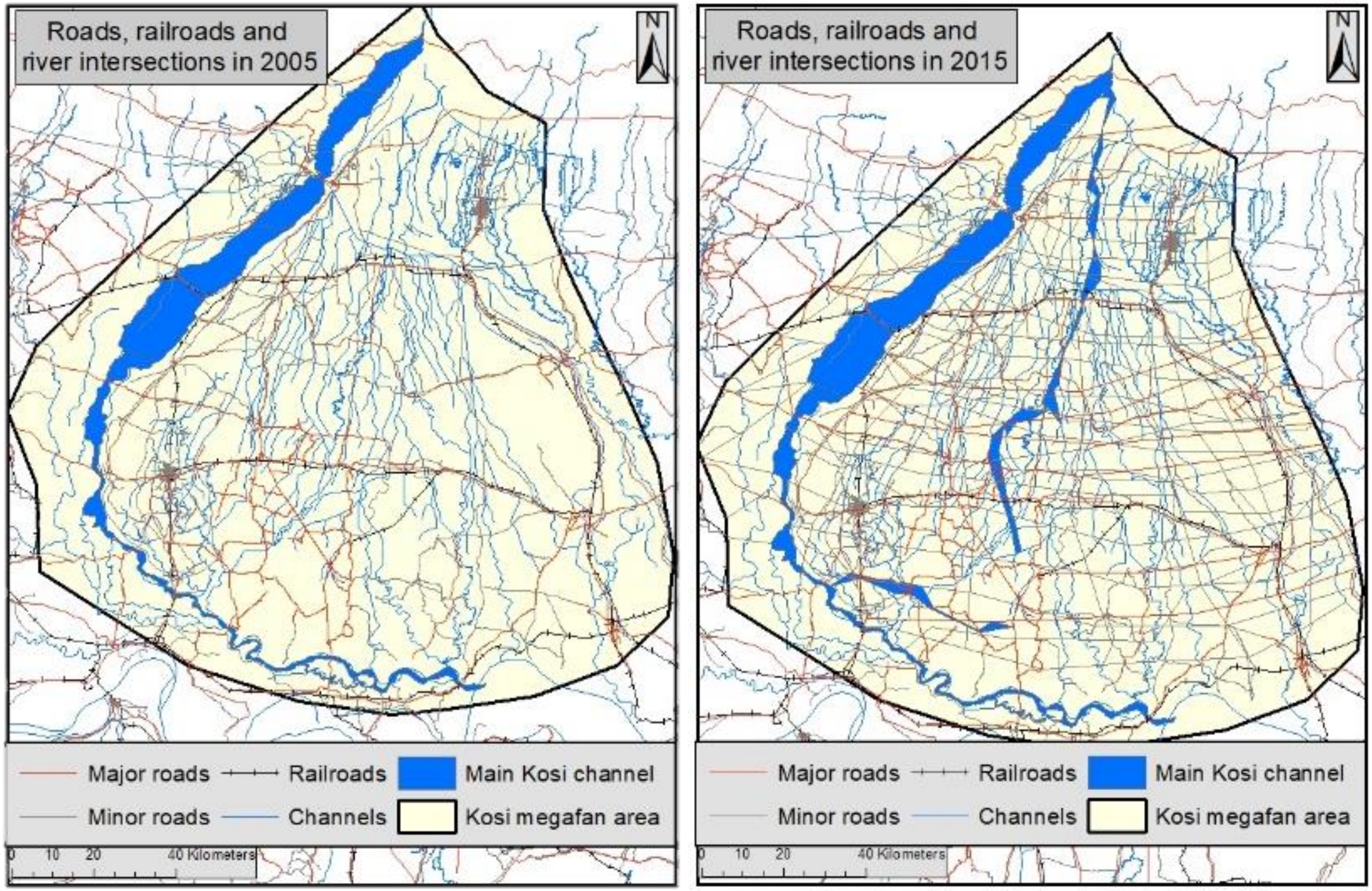

Figure 3.6. Roads and railroads in 2005 and 2015.

6. Discussion

6.1 Spatial and temporal variability of waterlogging in the Kosi megafan

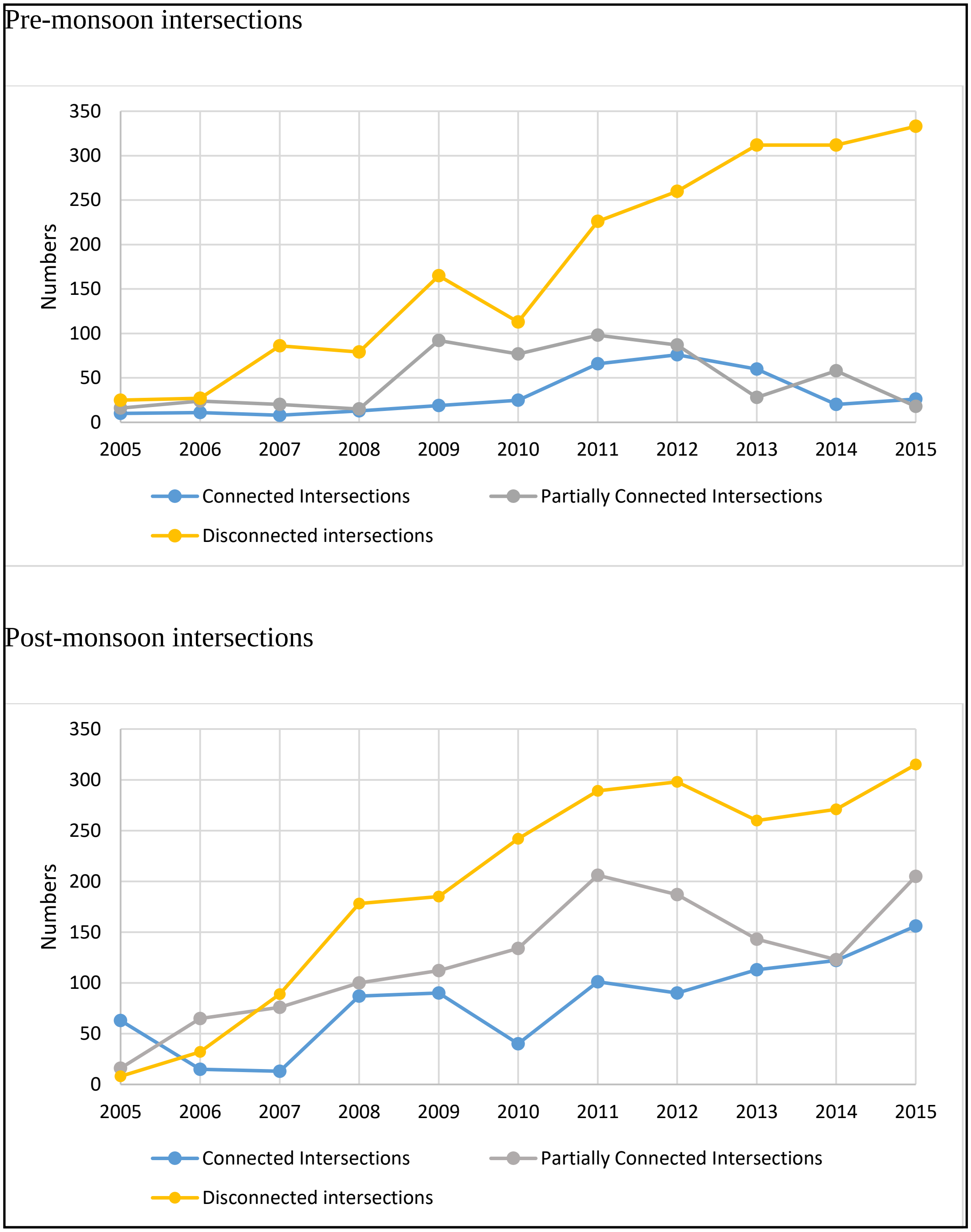

Figure 3.7. Changes in number of pre-monsoon road and railroad intersections with channels.

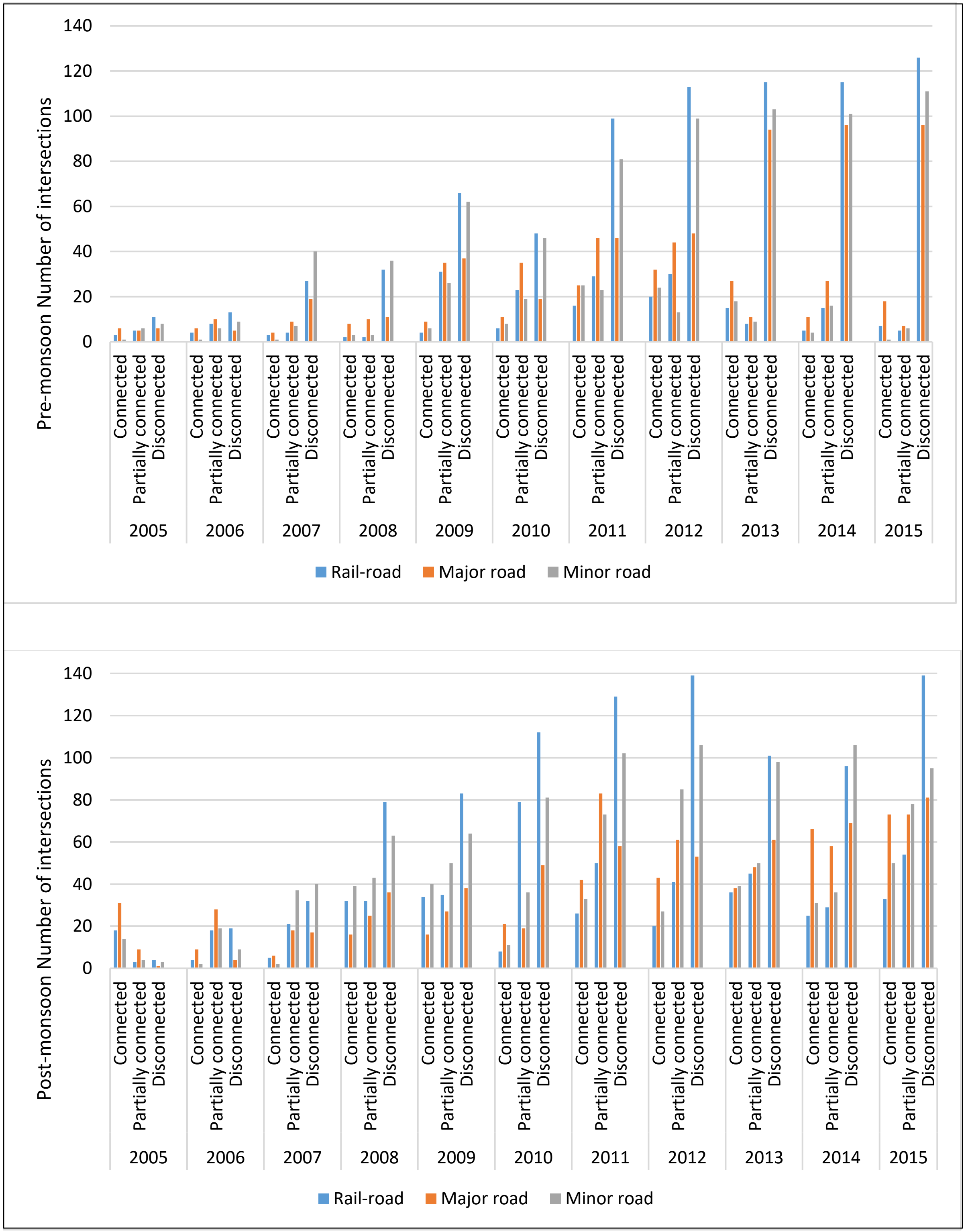

Figure 3.8. Pre and post-monsoon channel intersections by different transport networks from 2005-2015.

Large portion of the Kosi megafan were seasonally or permanently waterlogged from 2005 to 2015 (Table 3.2 and Figure 3.3). In general, lower elevation and lower slope gradient areas experienced more waterlogging. There is more waterlogging along the western side of the fan around the main active channel of the Kosi and the southeastern portion of the megafan (Figure 3.3). The southeastern area is characterized by a dense network of minor streams with low discharge and low sediment load traveling across a very low relief surface ranging from 10–40 m in elevation.

At one level, it is not surprising that waterlogging is a potential issue throughout the megafan. The location of waterlogging is known to depend on contributing drainage area, the drainage network, local gradient and topography, geology, and water supplied to the site (Merot et al. 1995; Holden et al., 2009). Terrain throughout the Kosi megafan is gently sloping to flat, with many oxbow lakes, meander scars and abandoned channels that reflect the avulsive nature of the Kosi River (Chakraborty et al., 2010). These local depressions are large, extensively used for agriculture, and provide large area where water tends to accumulate.

Likewise, the significant differences between extends of post- and pre-monsoon waterlogging in the Kosi megafan (Table 3.2, Figure 3.4) is not surprising. These differences largely reflect the seasonality of rainfall and runoff coupled with the high permeability of the substrate within the fan, which enables seepage of surface water to deeper levels. Following the monsoon and the cessation of regular precipitation and associated high runoff, the extent of waterlogging presumably decreases until it reached an annual minimum right before the onset of the next monsoon cycle.

The location of waterlogging within the megafan is also responsive to monsoon dynamics. The western and southeastern parts of the Kosi megafan receive very high rainfall (1,300 mm on average) (reference), compared to some lower annual average precipitation values ranging from 800mm to 1000mm in other parts of the fan.

In the northern (and upper) parts of the fan, monsoon rainfall constitutes the main source of saturation, with groundwater reaching within 1-2 m of the surface and waterlogging occurring during and immediately after the monsoon (CGWB, 2007).

What is surprising, however, is the significant increase in waterlogging extent over the years of the study (Table 3.2). The increase in waterlogging might be partially attributable to irrigation projects launched under various 5-year plans (Rao et al.1998). Unfortunately, I couldn’t get enough data on change in irrigation canal to incorporate to the findings from this study. Although it is known that many irrigation canals were destroyed in the massive avulsion and flooding event in 2008 and subsequently, efforts are in place to restore and rebuild new canals. However, the increases in waterlogging are almost certainly not due to changes in irrigation practices. In fact, data from this study indicate that most farmers are taking measures to reduce waterlogging.

One temporary increase that is clearly attributable to natural forces in the dramatic increase in post-monsoon waterlogged areas in 2008 (Table 3.2, Figure 3.4). This increase was due to a massive flood in August 2008 that covered large areas of the megafan and affected nearly 30 million people and is considered one of the worst ever to affect the state of Bihar (Kumar et al., 2014).

Table 3.4. Waterlogging with the transportation buffer zones that are 0.5 km to either side of the roads or railroads. Lengths in km and areas in km^2.

Years	Class	Pre-monsoon waterlogged area	Post-monsoon waterlogged area	Total buffer area	Percent pre-monsoon waterlogged area per km^2 of buffer zone	Percent post-monsoon waterlogged area per km^2 of buffer zone
2005	Railways	333	560	1,623	20.5	34.5
	Major roads	344	498	2433	4.6	6.7
	Minor roads	545	943	7435	22.4	38.8
2006	Railways	359	580	1,623	22.1	35.7
	Major roads	356	498	2,439	14.6	20.4
	Minor roads	637	985	7,450	8.5	13.2
2007	Railways	676	689	1,659	40.7	41.5
	Major roads	498	560	2,487	20.0	22.5
	Minor roads	1232	1654	7,473	16.5	22.1
2008	Railways	632	854	1,659	38.1	51.5
	Major roads	356	675	2,495	14.3	27.1
	Minor roads	999	2654	7,473	13.4	35.5
2009	Railways	612	716	1,659	36.9	43.2
	Major roads	287	545	2,551	11.2	21.4
	Minor roads	1120	1699	7,649	14.6	22.2
2010	Railways	665	676	1,700	39.1	39.8
	Major roads	312	334	2,563	12.2	13.0
	Minor roads	798	999	7,666	10.4	13.0
2011	Railways	569	689	1,800	31.6	38.3
	Major roads	348	487	2,598	13.4	18.7
	Minor roads	815	1160	7,700	10.6	15.1
2012	Railways	629	697	1,829	34.4	38.1
	Major roads	356	467	2,598	13.7	18.0
	Minor roads	689	871	7,700	8.9	11.3
2013	Railways	598	657	1829	32.7	35.9
	Major roads	312	423	2600	12.0	16.3
	Minor roads	611	989	7700	7.9	12.8
2014	Railways	596	670	1,840	32.4	36.4
	Major roads	320	468	2,676	12.0	17.5
	Minor roads	759	1,134	7,707	9.8	14.7
2015	Railways	634	689	1,840	34.5	37.4
	Major roads	327	476	2,676	12.2	17.8
	Minor roads	851	1,289	7,709	11.0	16.7

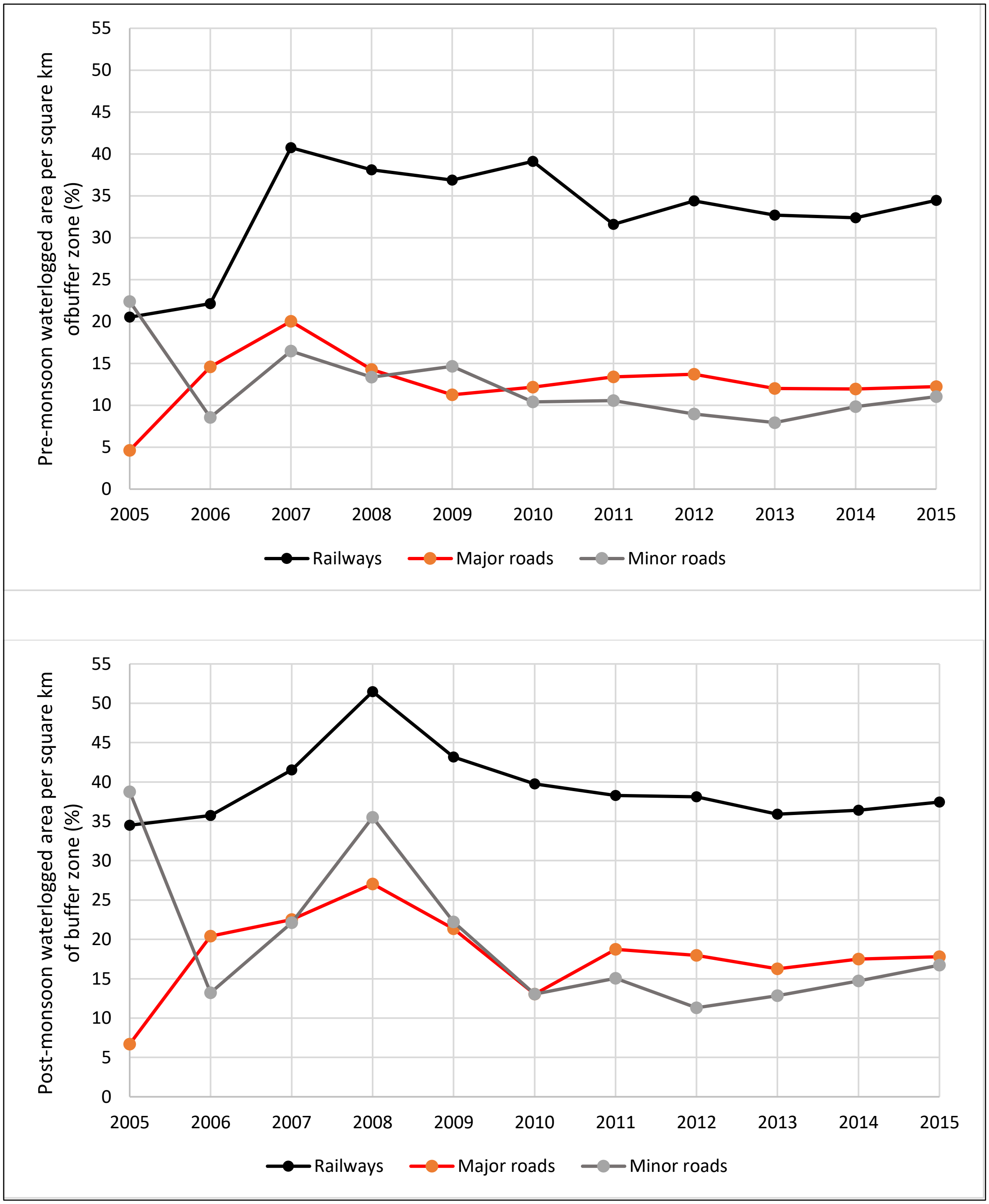

Figure 3.9. Pre and post-monsoon waterlogged area per square kilometer of buffer zone along selected features during the observation period.

Outside this one event, none of the standard explanations (over irrigation, poor management practices, increases in rainfall, etc.) seem to explain the consistent increase in waterlogged area. It is for this reason that the association between transportation networks and waterlogging deserves further attention.

6.2 Railroad and road channel crossings and connectivity

A large network of rail and road network exists throughout the Kosi megafan, crisscrossing the drainage network at many locations (Figure 3.6). Corresponding with the growth in both the number of channels and the lengths of roads and railroads (Figure 3.5, Tables 3), the number of intersections of railroads and roads with drainage channels increased by ~35 % in the Kosi megafan during the period 2005-2015 (Figure 3.5).

Likewise, the channel connectivity across the megafan has changed notably over this period (Figure 3.7), with the one dominant trend being an increase in disconnected crossings in both the pre- and post-monsoon seasons. This increase in disconnected areas may be attributed to the extension of railroads and road networks as well as rebuilding existing transportation damaged by floods or waterlogging. Channel aggradation at crossings and failed diversions may also have created more disconnection.

The interactions between the transport networks and channels are complex and subject to change after every flood. Approximately 72% of the connected intersections in 2005 became disconnected or partially disconnected by 2015, placing the total number of disconnected crossing near 50%. There thus has been a major increase in the barriers to movement of water and sediment.

Seasonal variations in the number of disconnected crossings display similar trends in the pre and post-monsoon period from 2005 to 2015 (Figure 3.7), with significant increases in the number of disconnected crossings in both seasons. However, the number of partially connected or fully connected crossings has remained about the same from 2005 through 2015 in the pre-monsoon period but increased in the post-monsoon. The increased connectivity in the post-monsoon compared to the pre-monsoon may be because of higher water levels than enable flow across barriers that are too high for water to cross in the dry season.

The growth in the partially connected and fully disconnected crossings in the post-monsoon of 2008 and the pre-monsoon of 2009 resulted from the giant flood of August 2008. In this event, the Kosi River avulsed from its channel, flooded vast areas, and wreaked havoc with many transportation routes.

It is of concern that the number of disconnections has continued to grow since that event. This may be due to the expansion of the minor road network, an expansion that has taken place in large part because of floods and waterlogging. Many villages were left stranded and permanently surrounded by water following the 2008 floods, so that access was only by boat. Local villages and districts therefore took it upon themselves to build minor roads that would link them to other villages and transportation routes. In many cases, these mud and gravel roads are built without the guidance of engineers and therefore lack adequate culverts or bridges to drain water from surrounding terrain. Ironically, the very attempt to escape a water locked existence thus may be leading to even more waterlogging, as is discussed in more detail in the following section.

6.3 Waterlogging within the transport buffer zones

It is clear that the extent of waterlogged area within a 500 m buffer to either side of transportation corridors has increased significantly from 2005 to 2015 (Table 3.4

and Figure 3.9). The significant increase in both pre- and post-monsoon disconnections at drainage crossings discussed in the previous section provides one reason for the expansion of waterlogged area. Disconnected crossings prevent the flow of water and sediment and cause water to back up and saturate areas upstream of the blockage.

But channel crossings are not the only way that roads and railroads affect drainage connectivity. The elevated structures that support roads and railroads can act as barriers to prevent drainage (Kumar et al., 2014), which appears to be happening across the Kosi megafan. Areas with higher concentrations of roads and railroads have greater extents of waterlogging (Figure 3.3 and 3.6).

Minor roads make up 74% of the total road length in Kosi megafan in both 2005 and 2015 (Table 3.4). These roads are typically funded by the Government of India as part of their integrated rural development program (e.g. Pradhan Mantri Gram Sadak Yojana, 2000) and their Rural Infrastructure Development Fund (RIDF, 1995, 19967). Since the 1970s, these programs have supported converting local cart-tracks, pack-tracks and foot-paths into paved and unpaved roads. Unfortunately, the growth of minor roads creates barriers to the flow of water and induces erosions and channel sedimentation, with unpaved roads that are common throughout the region creating more problems than paved roads (Fu et al., 2010; Thomaz et al. ,2014, Thomaz and Peretto, 2016). Moreover, the quarried laterite often used for constructing minor roads in the study area become a major source of granular to coarse sediments that erode and fill adjoining channels, thus promoting further disconnections and potential waterlogging (Fu et al., 2010). Roads in the floodplain thus contribute to waterlogging both by acting as barriers to flow and by contributing sediment that further chokes drainage channels.

In terms of relative impacts of different kinds of transportation infrastructure, railroads have a larger proportion of their surrounding buffer area associated with waterlogging than do roads. 34.5% to 51.5% of the buffer zone around railroads is waterlogged, in contrast 6.7% to 27% for major roads and 11.3% to 39% for minor roads for the post-monsoon period (Table 3.4). This parallels the high proportion of disconnected points associated with railroads in the pre and post-monsoon periods from 2005 to 2015 (Figure 3.8). The higher waterlogging along the railway lines may in part reflect their age, with many of the rail beds being built many decades or even over a century ago without much consideration given to installation of culverts and drainage passages. Modern roads are built with more consideration given to drainage. Even when railroad culverts are in place, I observed that many are associated with erosion and scour due to high velocity flows exiting the culvert leading to more sediment accumulation at other areas disturbing the local slope characteristics. Alternatively, culvert intakes can accumulate sediment when culverts are over-wide or accumulate debris when multiple small openings are used, creating barriers to drainage.

7. Summary and conclusions

Waterlogging in the Kosi megafan increased significantly from 2005 to 2015. Both the growth in number of channel crossings (i.e. intersections) and the increasing presence of road and railroad beds in the megafan appear to play a significant role in this expansion of waterlogging. Results from the study suggest that railroads have the greatest impact in terms of the proportion of area surrounding them that become waterlogged, but because of the much greater length of roads relative to railroads, the overall impact of roads is greater. Unfortunately, waterlogging appears to be continuing to expand, with the growth of minor roads being a major contributor to that.

Addressing the problem of waterlogging will require that the policies and practices with regard to roads and railroads will have to be put in place. Any remedial measures will require mapping drainage pathways surrounding transportation routes and modification of the road or railroad beds to allow drainage—or complete removal of the structure in some cases. The old undersized rail-road crossings should be upgraded to ensure that they can accommodate the expected discharge volumes. With over 10,000 km of existing roads and railroads (Table 3.2), remedial efforts could be very costly. Therefore, a comprehensive mapping and analysis will be necessary in order to prioritize efforts that maximize the benefits of mitigation measures.

Any new roads or railroads should be built with much more attention given to the potential for exacerbating waterlogging. Many measures might be taken to reduce or eliminate impacts on drainage, ranging from siting roads and railroads farther away from drainage channels, using designs that allow drainage beneath structures, or routing roads and railroads to avoid or minimize stream crossings. Regular monitoring and maintenance of crossing sites can reduce the problems related to road stream interactions.

In a scientific context, this study contributes to the understanding of the scope of road and railroad impacts on hydrologic connectivity and the relation of waterlogging to transportation structures at a regional scale. It also provides a baseline for tracking future waterlogging in the Kosi megafan. Further regional research is needed develop mitigation strategies and allocate resources to the critical problem of increasing severity of waterlogging that so dramatically impacts the agriculture sector and livelihoods of the millions of megafan inhabitants.

CHAPTER IV

SURFACE WETNESS AND ITS EFFECT ON CHANGING AGRICULTURAL PRACTICES IN THE KOSI MEGAFAN: CASE STUDIES IN BIHAR, INDIA

1. Introduction

In the Kosi megafan in the state of Bihar (Figure 4.1), 80% of the people depend directly on irrigated agriculture for their living, with the majority of production in rice and wheat (GoB, 2009). Over the last decade cereal productivity growth has stagnated in this region and, despite technological advancement in agriculture, there are large year-to-year variations in production due to fluctuations in monsoon rainfall, frequent and catastrophic flooding of the Kosi river, and waterlogging, which refers to seasonal or year-round saturation of soils (Bharati et al., 2016). More specifically, nearly 70% of the megafan is frequently affected by floods (Mishra, 2008a) of which 85% is seasonally or permanently waterlogged (GoB, 2009). Flooding and waterlogging can make areas inaccessible, impact soil fertility and productivity, cause loss of standing crops and livestock, reduce cropping intensity and, in some cases, make lands unusable for agriculture and living. This, in turn, has increased landlessness and distress amongst the local communities (Mishra, 2002).

The stress on locals is compounded by Bihar's rapid population growth, which had a decadal population growth rate of 25.1% from 2001 to 2011, a period when India as a whole grew by 17.6% (GoB, 2012). Likewise, the number of people per km^2 (1102) is nearly three times that of the national average (382). Moreover, Bihar is the poorest state in India. The average annual per capita income of Bihar is Rupees 38,546 ($529 U.S.)

relative to Rupees 121,768 ($1,670 U.S.) for India as a nation (GoB, 2012), which makes it difficult for people to respond to environmental and economic stresses.

The northeast portion of the Kosi megafan (Figure 4.1) experiences the most adverse effects of waterlogging. Eighty percent of the land falls within six major canal irrigation projects; in recent years' improper irrigation practices, unplanned development of roads and rail roads, and unrestricted construction of embankments have disturbed the floodplain connectivity and the extent of waterlogging has increased from 1975 to 2016 (Goswami, 2019). Eighty-five percent of the Kosi megafan now suffers from seasonal and permanent waterlogging with almost seven million hectares of land at risk annually. From 2001 to 2010, the number of districts affected by waterlogging increased from nine to 25, the number of affected villages within these districts increased from 679 to 18,832, the number of affected people increased from 718,000 to 24,420,000, and impacted livestock increased from 10,000 to 8,686,000 (IPCC, 2013). The total area affected from waterlogging increased from 181,000 to 1,969,000 ha, with impacted agricultural lands increasing from 160,000 to 1,440,000 ha. Associated loss of sown crops over this period ranged from 10,000 ha in 2001 to 1,060,000 ha in 2010 (Tiwari et al., 2012).

Restoring these damaged ecosystems is expensive, time-consuming and frequently requires coordinated action over large areas. The lack of regionally coordinated disaster management in the transboundary Kosi river and the marginalization of the state of Bihar within India has hindered infrastructure development that would mitigate impacts of flooding and waterlogging and provide alternative agricultural strategies. Moreover, most of the farmers in the Kosi megafan region are marginal or smallholders with less than two hectares of land; involving them in the process of agricultural transition and linking them to new opportunities to share the benefits of such a transition is a major challenge. As a result, communities in northeast Bihar generally have little capacity to respond effectively to flooding and waterlogging and are among the poorest in the region despite the highly fertile floodplain and potential for agriculture.

The poorest of these households are particularly vulnerable, being most likely to be in flood zones and to have their mud and brick houses severely damaged or destroyed by flooding. In the absence of alternatives, most of these individuals and families have opted to stay in the floodplains and try to develop strategies to cope with flooding and waterlogging.

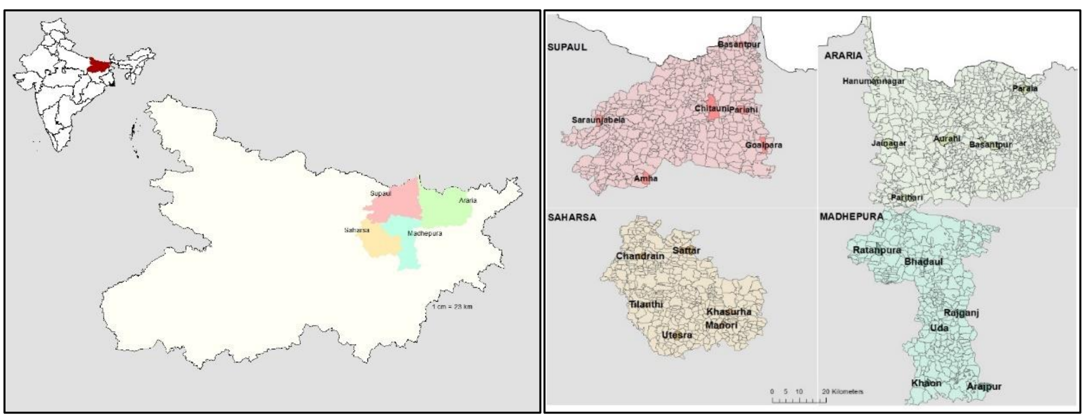

Figure 4.1. Location of the studied villages within the Kosi megafan.

It is the goal of this study to document and understand how these local landholders or farm laborers are adapting to degradation of their land by flooding and waterlogging. To address this, I explore and identify broad patterns of changes in agricultural practices among different groups of farmers ranging from landowners to seasonal agricultural workers who are on farms of different land size across four districts in the Kosi megafan that were affected by severe surface wetness for the period of 2011-2015. In particular, I focus on two major research questions:

- How have agricultural practices changed (if at all) in response to changes in the extent and duration of waterlogging (the condition where soils are saturated to the point that anaerobic conditions prevail)?
- What factors affect the vulnerability of farm laborers and farm households to waterlogging?

This study draws its findings from existing literature and from data collected in a survey of 960 farm-households. The paper thus documents how people are affected by hydrologic hazards, the short- and long-term adaptation strategies at local or community levels to hazards related to waterlogging, and the extent to which these strategies reduce vulnerability to water stress and hazards. This exploration of the adaptation strategies, the reasons for their use, and the degree to which they are successful across a diverse range of sites will contribute to a better understanding of individuals' rationales for adapting certain measures and will help inform the government so that any future interventions have a greater chance of adoption and success.

2. Background and Study Area

2.1 The phenomenon of waterlogging

Waterlogging can occur due to a high subsurface water table and/or due to accumulation of surface waters that are trapped and cannot runoff. Waterlogging occurs over vast regions of the world (GoB, 1994), adversely affecting approximately 10% of global land area and posing a serious threat to the world's productive agricultural land (FAO, 2002). About 10 to 15 million ha of the world's wheat growing areas are affected by waterlogging each year (Surminski, 2010), representing 15–20% of the 70 million hectares annually cultivated for wheat production (Prowse et al., 2008).

Irrigated lands in particular are prone to waterlogging; about one-third of the world's irrigated area faces the threat of waterlogging, with 60 million hectares experiencing waterlogging and 20 million hectares harmed by salt accumulation (Abid et al., 2015; Heuperman et al., 2002). On a global scale, irrigation-induced salinity and waterlogging severely affects about 30 million hectares, with an additional almost 80 million hectares affected to a lesser extent (Bartlett et al., 2010).

Lands degraded by water logging are distributed around the globe. In Western Australia, land degradation in the form of saline, waterlogged soil is the largest and least-manageable natural resource issue threatening profitable pastures and broad-acre crops (Australian Bureau of Statistics, 2002). Elsewhere, dryland salinity associated with waterlogging poses a threat to 800,000 hectares of arable land in the Great Plains region of the USA and the prairie provinces of Canada (Doering et al., 1999), with further large areas affected in South Africa, Iran, Afghanistan, Thailand and India (Abrol et al., 1988).

The effects of waterlogging are most widespread in rice–wheat rotation agricultural practices that are commonly followed in South and Southeast Asia (Samad et al., 2001). In India, an estimated 6 million ha of land is subject to waterlogging, of which 3.4 million hectares is waterlogged due to surface flooding and 2.6 million hectares due an elevated ground water table (National Commission on Agriculture, 2002). Land degradation mapping carried out for the entire country on 1:500,000 scale using multitemporal resources revealed that 32.07 % of the total geographic area of the country is subjected to waterlogging and salinity induced land degradation National Commission on Agriculture, 2002).

2.2 Flooding and waterlogging in Bihar, India and the Kosi megafan

In India, the inhabited area vulnerable to flooding has increased from 2.5 million hectares in 1954 to 6.8 million hectares in 1994 due to river channel changes and the encroachment of people onto floodplains (Bharati et al., 2011, 2012). The Kosi megafan accounts for 16.5% of this flood-prone area and 22.1% of the flood affected population in India. By way of example, a disastrous flood in the Kosi River in August 2008 affected five districts in North Bihar and rendered 2.5 million people homeless. It also resulted in heavy loss of agricultural lands, which made up 81.45% of the inundated areas, reflecting the high vulnerability of farmers to flood hazard (Singh et al., 2011).

As a result of the intensive farming in flood prone areas, it is therefore not surprising that degraded lands now cover 4,150 km^2 of Bihar, of which 1,881 km^2 (45.31 %) is waterlogged. Much of the waterlogging in Bihar is within the Kosi megafan (Bihar State Irrigation Commission, 2004). A study by Pandey et al. (2010a) indicates that in the northern Bihar plain alone, waterlogged area increased from 31 km^2 in 1925 to 102.6 km^2 in 2006.

The major cause of waterlogging in the Kosi megafan is the accumulation of rain and floodwaters in low-lying areas and depressions where slow natural drainage coupled with human obstacles to flood waters returning to the river promote retention of water (Pandey et al. 2010). In particular, construction of road and railroads and numerous bridges, embankments and local dams have aggravated the waterlogging scenario (Goswami, 2019). Over-irrigation and seepage losses from canals into farmers’ fields also contribute to the problem (Dutta et al., 2004).

Table 4.1. Location of villages within districts in reference to the river Kosi

Districts	Selected villages	Location of the selected villages regarding the embankment/river	Accessibility pre- and post-monsoon	Stress from waterlogging
Aararia	Hanumannagar, Jainagar, Aurahi, Parihar, Basantpur, Paraia	Not protected by any embankment. The Kosi flows freely until it reaches the villages where it is forced to flow under a railway bridge, which promotes erosion. Several of its 'tolla' (temporary islands) have been constantly shifting to new places. Another unique feature of the villages is that they are trapped between the Kosi and the Bagmati river, a tributary and suffers from extreme floods every year.	Accessible by roads	Severe for more than five months of the year
Madhepura	Ratanpura, Bhadaul, Rajganj, Uda, Khaon, Arajpur	All six villages are located between the embankment and river; an island between two channels of the Kosi.	Accessible by roads	Severe waterlogging for more than five months of the year; constant fear of embankment breaches
Saharsa	Sattar, Chandrain, Khasurha, Utesra, Manori, Tilanthi	0-2 kms from the embankment	Accessible only by boats from June-November	Severe waterlogging for more than eight months of the year; undulations in agricultural fields; fields inside the embankment suffer from sand deposition; constant fear of embankment breaches
Supaul	Chitauni, Basantpur, Amha, Pariahi, Goalpara, Saraunjabela	8-10 kms from the embankment	Accessible only by boats from June-November	Severe waterlogging for more than eight months of the year

Table 4.2. District-wide total cropped area and total waterlogged area (Goswami, 2019 and Neupane et al., 2015). All areas in km^2.

District	Average annual rainfall (mm)	Total geographical area	Average Total cropped area 2011-2015	Total waterlogged area in 2011	Total waterlogged in 2012	Total waterlogged in 2013	Total waterlogged in 2014	Total waterlogged in 2015
Araria	1582	2830	2457	960	966	1156	1276	1326
Madhepura	1231	1788	1455	955	980	980	1137	1166
Saharsa	1360	1645	1071	780	845	834	938	940
Supaul	1404	2420	1328	876	932	923	1102	1312

Table 4.3. District-wide irrigated area from different water sources (CGWB, GWD, 2007). All units in km^2.

	Araria	Supaul	Saharsa	Madhepura
Canals	812	413.7	453	433
Tank	0.5	0	40.4	0
Tube well	496.8	267.7	316	306
Dug well	0	0	3.3	0
Other sources	79.6	56.4	1312	22

2.3 Agriculture and rural livelihoods in the Kosi megafan

India grows approximately 118 million tons of rice across roughly 44 million hectares. Bihar contributes 40% of the total national production of which 55% of area is sown within the Kosi megafan (FAO, 2002). Such a high percentage of cultivated land is possible because so much of Bihar lies within floodplains, because rice is cultivated in all districts of the state, and because most forest had been converted into farmland. Autumn rice, Aghani rice, and summer rice are the varieties of rice grown at three different times of the year (FAO, 2002). The average annual rice production in Bihar is around 47 million tons, while wheat production is approximately 4-4.5 million tons and maize production is approximately 1.5 million tons (FAO, 2002; ISET, 2008).

In relative terms, the overall economy of Bihar performed poorly over the last ten years with an overall growth rate of only 0.38% compared to India's 7.8% (ICIMOD, 2008). Bihar has the lowest GDP per capita in India. As of 2012, agriculture accounts for 70% of the economy of the Kosi megafan and land holdings are fragmented, with more than 80 percent of farmers having less than one hectare of land (Hussain et al., 2015, 2016). Given the small land holdings which restrict the ability to move locations and the already low GDP, there is little capacity to adjust to floods and waterlogging.

Table 4.4. Predominant work done by household members in the four selected districts, 2014-2015. (Source: Government of Bihar, 2015, Economic survey 2013-2015).

Districts	Agricultural (%)	Household industry workers (%)	Other workers (%)
Araria	87	11	2
Madhepura	84	4	12
Saharsa	95	5	0
Supaul	72	24	4

While there is a fair bit of information on agricultural productivity of the Indo-Gangetic Plain (Erenstein et al., 2010a), there is relatively little information about the strategies adopted by individual farmers to maintain crop production in the face of changing hydrologic conditions. In the mid-1990s there were a series of surveys of rice-wheat farmers regarding production practices and problems in selected districts in the Indo-Gangetic Plain and neighboring Nepal, Bangladesh and Pakistan (Fujisaka et al., 1994 and Kataki et al., 2001) for summaries of existing studies at the time of their publications). These studies focused in the northwest Indo-Gangetic Plain–with no sites in Bihar on the eastern side of the plain–a situation that continues with more a more recent study. All the studies focusing on local livelihood strategies are based on relatively few villages (Samaddar and Das, 2008).

These previous studies indicate that that there has been significant experimentation and exploration of adaptive practices in agriculture in the northwestern Gangetic plain, but there has been a tremendous gap in resource allocation and adoption of adaptive strategies in the east. In the eastern sector, which is the focus of this study, the responses to climate variability, waterlogging and associated land degradation tend to be reactive and implementation is scattered and slow. The studies indicate that the main adaptive strategies used by Bihari farmers in the eastern region have been out migration, on-farm diversification, and restoration of embankments (Sharma et al., 2000; Gurung at al., 2009). To date, research has not documented the location specific actions that farmers and laborers are taking and how these actions differ (if at all) between districts and among different classes of population, which is a major goal of this study.

2.4 The Araria, Madhepura, Saharsa and Supaul districts

The focus of this study is on the previously understudied northeastern portion of the Kosi megafan, including the districts of Araria, Madhepura, Saharsa and Supaul (Figure 4.4.1). All four districts have experienced increasing temperatures over recent decades with an increasing depth to groundwater and more erratic rainfall events (Ellis, 2000; Dixit et al., 2009). Specific characteristics of all the three districts and their location within the Kosi megafan are presented in Table 4.1 and Figure 4.1 respectively.

The Kosi embankments have breached more than eight times in these regions since 1980, so all the districts have suffered from seasonal and permanent waterlogging

(Table 4.2). The average annual precipitation in this area ranges from 1200-1600 mm, of which 10% occurs during early summer season (March to June), 85% occurs during monsoon season (July to October), and the rest during winter season (November to February).

The four districts selected for this study all are characterized by decreasing soil fertility, relatively lower productivity, food insecurity, and smallholder subsistence farming (Deshingkar et al., 2006; Devkota et al., 2015). All available arable lands are under cultivation; these lands all have access to irrigation through tube-wells (a type of water well) or canals (Table 3). The workforce is predominantly agricultural in all four districts (Table 4.4). The cultivated area in Supaul comes to 98%, in Saharsa it is 95%, in Madhepura it is 84%, and in Araria it is 75% (GoB, 2012). The area under more than one crop yield is variable in the different districts. Paddy rice is the main crop in the area, with maize and wheat playing important roles. Oilseeds, pulses (the various lentils used to make daal), and cash crops such as sugarcane and tobacco take a more minor role.

3. Methods

3.1 Site selection and characteristics

To document livelihood strategies in these districts, I randomly selected six villages in each district. To select villages, I stratified the districts to map all villages where 95% or more of the population were involved in some sort of agricultural activity. Agricultural activity was defined as including the census categories of: marginal landholder (<1 hectares), smallholder (1-2 hectares), medium holder (>2 hectares), and other agricultural workers. In the sampled area large landholders (>5 hectares) were almost non-existent and so were not considered for this study.

Within each village, I selected 40 households from voter lists, resulting in 240 total households surveyed within each of the four districts, or 960 households for the entire study. An equal number of households was selected randomly from each landholding category. The number of households surveyed per village was not proportional to the total population of that village because the intent was to capture the range of socio-economic and biophysical conditions across the megafan rather than have a representative census.

I used a random route selection process (Kelley et al., 2003; Bauer, 2016; GWP-JVS, 2014;) to select individual households. Beginning at the center of each settlement, I walked in a direction chosen at random and sequentially selected households until I had 10 in each category, for a total of 40 for the village. If a selected house was empty or the household did not wish to participate, the next adjacent house was selected.

3*.2 Survey instruments and the variables*

I developed a baseline semi-structured questionnaire (Appendix 1) that could be implemented across a wide range of sites affected by waterlogging. The survey questionnaire was provided to participants in Hindi, which is the local language.

One section of the survey focused on cropping or livestock rearing practices. Households were asked to document their observations about: a) physical factors affecting their region (e.g., floods, waterlogging, salinity), b) perceived changes in weather patterns (timing or amounts of rainfall, temperature increases or decreases, etc.), c) farm-related changes made to deal with waterlogging problems, and d) farm-related changes in response to non-waterlogging factors. Non-waterlogging factors examined by the survey included market-related forces (higher market prices of the products, new marketing opportunities, reduced marketing costs), crop productivity (access to higher yielding crop types/varieties or more productive animal/breeds and better quality products), changes in available resources and the quality of those resources (land, water, labor, other inputs), and changes in government or non-government policies, projects or other support (including research and extension). Households were also asked about the changes they made over the last two years with respect to a wide range of practices relating to crop types, crop varieties, and land and livestock management. A rough proxy for adaptability, or innovativeness, was derived by adding up the total number of changes that each household had made over the past five years with respect to their farming practices.

The other section of the survey documented socioeconomic characteristic of each household, focusing on income and food security. These questions addressed household demographics, occupations, food security, and information regarding social networks, which potentially influences adaptive actions to waterlogging. Food security questions focused on food availability during each month in a year with no extreme events and whether the primarily source of food in each of those months was from their farm or elsewhere.

3.3 Data analysis

I first examined relationships between the number of changes in farm practices and waterlogging across farms of different sizes using linear regressions, although the narrow range of surface wetness across sites (i.e. most sites were waterlogged at least seasonally) meant that the analysis could not capture the full extent of changes related to “dry” versus waterlogged sites.

I also analyzed the relationship between socioeconomic factors and dependent dichotomous variables for farmers' adaptive agricultural actions using a multiple regression model, evaluated with a Wald test (RWALD). The advantage of RWALD is that the model does not have to be refitted (excluding each variable) to calculate F statistics and probability (Rao et al., 1984). Variables with a Wald statistic below 10% were excluded.

The key socioeconomic factors that might be driving agricultural response and adaptation in the Kosi megafan were identified from a review of literature. Education of household head was taken as a variable based on the assumption that more education might give farmers more ability to adjust to changing conditions (Ndambiri et al. 2013). Diversity of income sources was taken as a proxy for non-farm income, because greater financial capacity may result in longer-term adaptation planning (Deressa et al. 2008; Mulatu 2013). Agricultural land holding was a proxy for farm income and farm surplus (Hussain and Thapa 2015; Garrett and Ruel 1999; Ram et al. 1999). Insurance facilities by government agencies that provide a guarantee of compensation for specified loss, damage, illness, or death in return for payment of a premium was a proxy for institutional services which may influence farmers' behavior on adaptation (Tiwari et al. 2014). Household size was important because having more household members can increase the likelihood of taking adaptation actions (Abid et al. 2015). The variable of having at least one migrant from a household was used to assess if: (a) outmigration results in labor shortages for agriculture (Hussain et al. 2016), which in turn could reduce the ability to take adaptive actions, and (b) that outmigration may result in increased income in the form of remittances, which could enhance the capacity to take adaptive actions (Banerjee et al. 2011).

4. Results

4.1 Socioeconomic characteristics of the surveyed households

The findings on the socioeconomic characteristics of the households are summarized in Table 4.5. The average household size was six and ranged from four to 26. All the households had at least one and often more individuals working in agriculture. Ninety percent of the households owned, rented or collectively used agricultural land, with males with small landholdings (<1 hectares) making up the large majority of the sample. Overall, the average land holding size is 0.5 hectares. Out of all 960 households surveyed, only two in Araria owned large farm lands (>5 hectares) and were therefore not included in the analysis given the exceptionally small sample size. For all farmers, average cultivated land size was 0.5 ha (range 0.38- 3.5 ha).

On average, more than four members of a household worked on local agricultural lands. The dependency ratio, which is the ratio of non-wage-earning members to wage-earning members, was high at an average of 57%. Many of these dependents were unable to work in the fields (e.g., they were too old or too young), so close to 50% of households faced regular labor shortages during prime periods for agricultural activities during a year. Another cause of labor shortage is out-migration, driven in significant part by the risk to livelihood from flooding in the monsoon period and permanent waterlogging. Seventy-three percent of households had at least one out-migrant member.

Table 4.5. District-wide household socio-economic characteristics.

	Araria	Madhepura	Supaul	Saharsa
Total number of households surveyed	240	240	240	240
Total number of participants	401 340 (M) 61(F)	413 310 (M) 103 (F)	388 360(M) 28 (F)	400 367(M) 33(F)
Household size mean	5.7	6.1	7	6.5
Dependency ratio (%)	48	57.8	66.7	57.2
Average landholding size (in hectares)	0.98	0.48	0.23	0.37
Number of household members working on farm, mean	6	5	3	5
% of households with member who migrate for labor	46	50	80	60
% households ‘always’ facing labor shortages	15	26	77	50
% households facing labor shortages seasonally	30	59	84	69
% households having income from crops, vegetables and fruits	70	86	95	95
% households with income from livestock	40	33	10	20
Average number of income sources per household	5	5	3	3

More than 91% of the farming households reported that agriculture and livestock contributed to their household income, but only 18% state that these were their main source of domestic food (Table 4.6). Most households therefore are not self-sufficient in terms of food supply and require other sources of income. This may be attributed in part to the decline in production of some of the major staple food crops and replacement with cash crops for income rather than consumption, as well as increasing demand for food from the growing population which cannot be met by increased production from the small landholdings. Growing demand for processed food items, especially among young people, is another important factor adding to the dependence on external food items (Adhikari et al. 2017). The increased dependence on food obtained from elsewhere is reflected in the reported distribution of household expenditure, with 60% required for food and only 40% for other items (Figure 4.4). The move to expending more income on food items may impoverish households in other ways as they cut down on non-food expenditure such as education, health, clothing, and housing.

Results show that there are diverse cropping systems (Table 4.6), with more household crops marketed, followed by mixed and cash crops. Cover crop was only present on three farm types and its main use was fuel.

4.2 Agricultural practices

Farmers mainly raised field crops (rice, wheat, maize, millets) with only a small number having trees or orchards. Rice, wheat, and maize are the major cereal crops (Figure 4.2). Paddy (i.e. rice) is the main staple monsoon crop, being cultivated by three quarters of farming households, followed by wheat and summer maize. Since the Green Revolution, wheat is

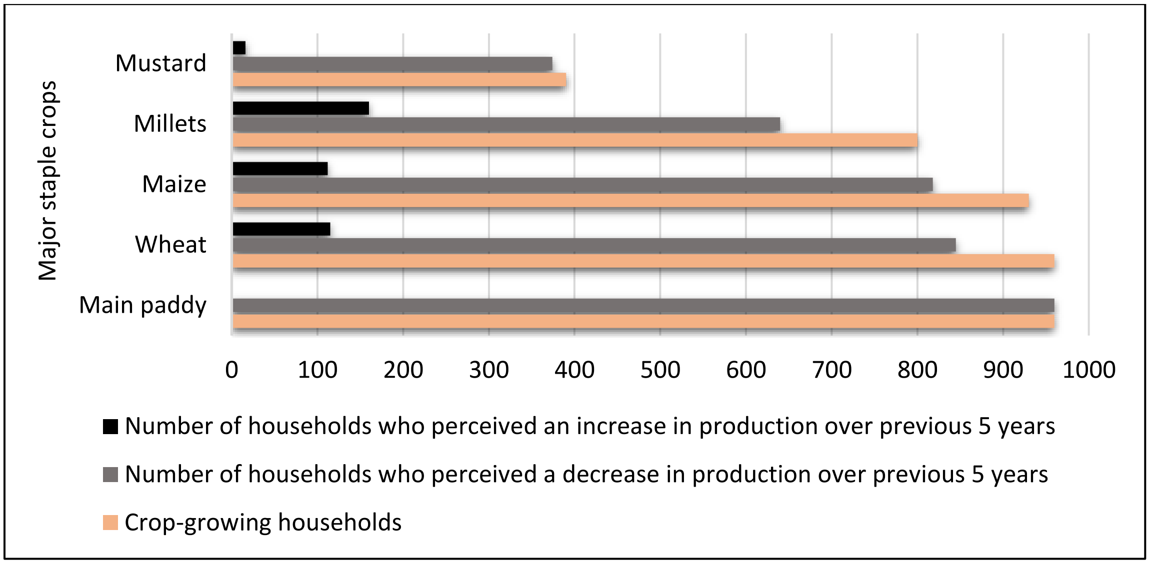

Figure 4.2. Household perception of crop production of major staple crops from 2011-2015

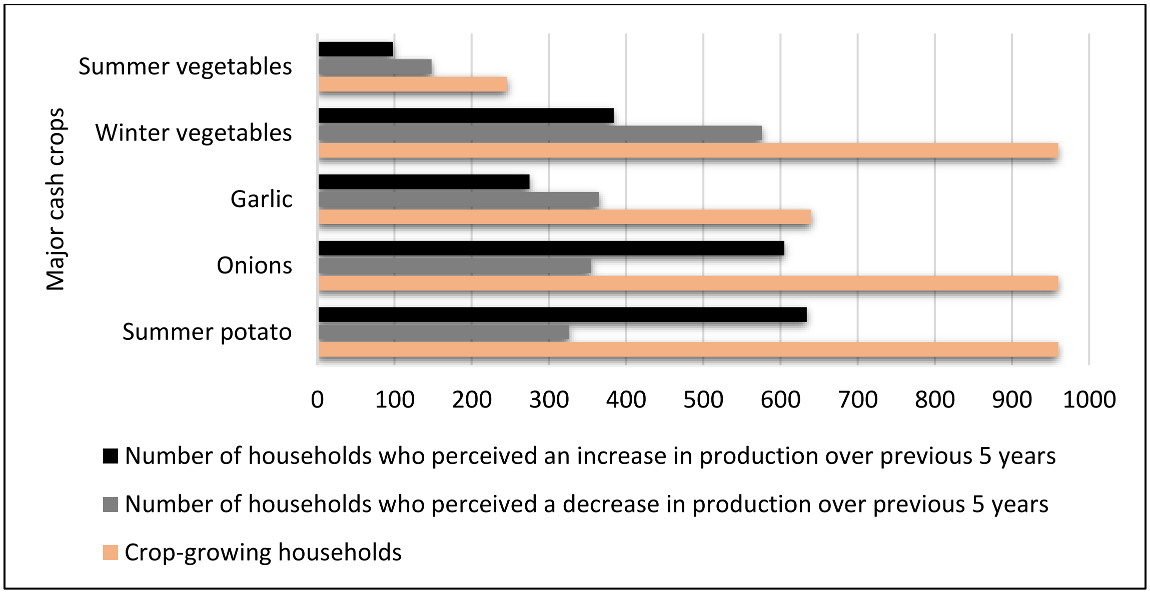

Figure 4.3. Household perception of crop production of major cash crops from 2011-2015

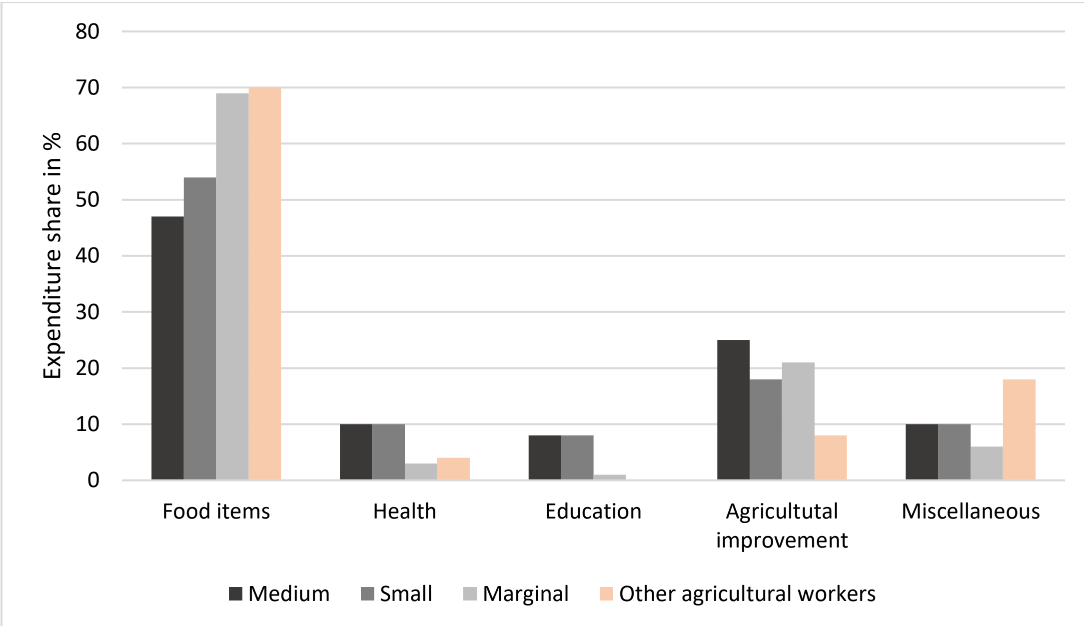

Figure 4.4. Share (%) of expenditures made on food and non-food items for a year

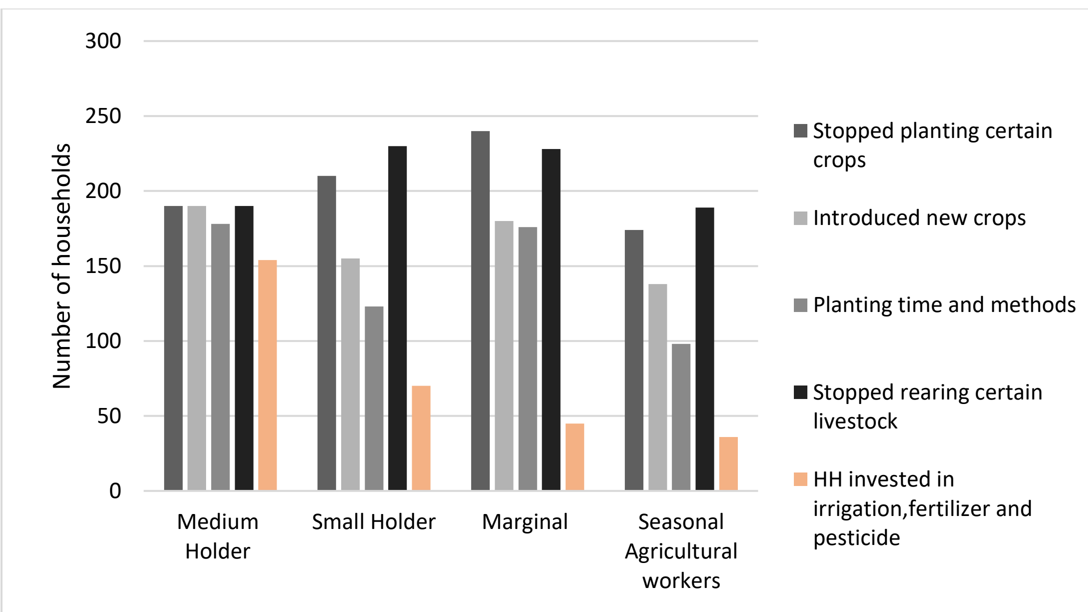

Figure 4.5. Common Farm related changes made by 90 percent of households within each landholding category from 2014-2015

Table 4.6. Farm typology and income distribution

Farmer type	Number of crops grown	Number of Livestock owned/raised	Mechanization level	Typical crops and livestock income
Medium (>2 hectares)	4-9 (range) 5.6 (average)	5-10 (range) 6 (average)	Relatively high land pressure with low mechanization level	Full-time and market-oriented farmers, with medians of proportion of income from crop (60%) and livestock activities (30%). Diversified (3 cereals, vegetables and oilseed). 50% crop goes to the market.
Small (1-2 hectares)	4-7 (range) 4.2 (average)	3-8 (range) 5 (average)	This groups have the highest proportion of land dedicated to rice followed by wheat. Relatively high land pressure with low mechanization level	Diversified crop: 3 cereals, for household consumption. 40% crop is income. Intensive use of crop residues for animal feeding (75 % as fodder), and a good proportion of income coming from livestock activities (median of 27.5 %).
Marginal farmers (<1 hectare)	2-5 (range) 3 (average)	1-3 (range) 1.5(average)	Lowest level of mechanization.	Livestock for home consumption, not source of income. With income dependent on crop produce sold (a median of 70%).
Other agricultural workers	2-3 (range) 2.2 (average)	0	Highest pressure on land (a median of 28.2 adult equivalents per Ha)	Cropping systems of this group are exclusively dedicated to rice and wheat food staples for home consumption. Most of the income of this group comes from off farm work. Livestock is not present or not important in this group and most crop residues are either sold or used for fuel

increasingly planted by the farmers (Fujisaka et al., 1994) it currently is the major crop grown in the post-monsoon winter season. Maize, millet and mustard are also important. Summer potato was the most important cash crop, cultivated by 41% farming households, followed by onion, garlic, and winter and summer vegetables (Figure 4.3).

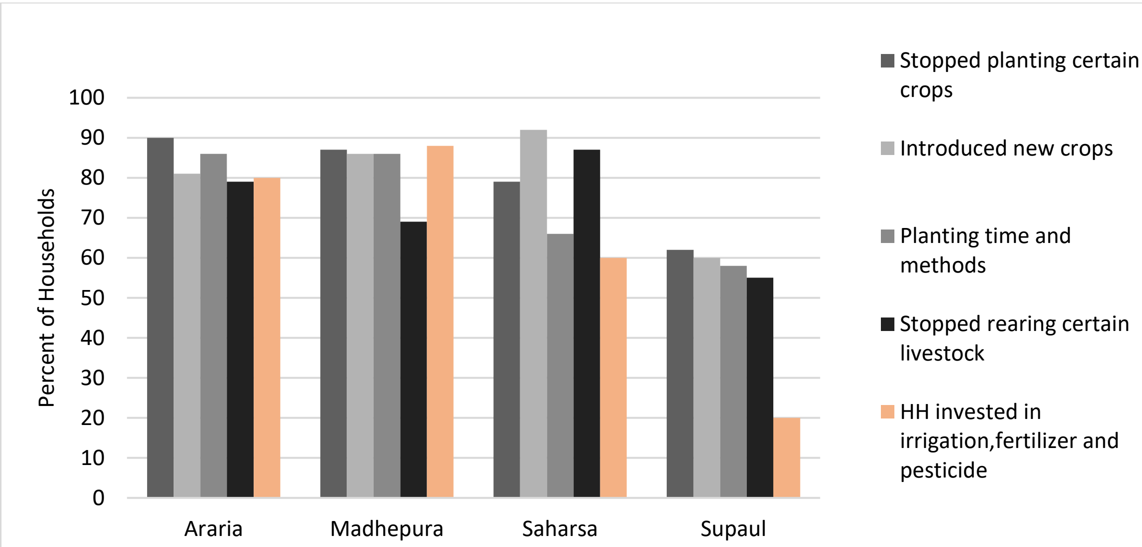

Figure 4.6. Per cent of households from each district who made at least one farm related changes from 2014-2015

More than 60% of households raised livestock, with both goats and cattle kept by more than 40% of households (Table 4.6). Water buffalo were also raised by a substantial proportion of households, as were poultry and other birds. Pigs and sheep were only being kept by a few. Livestock accounts for about 35 percent of the total value of output from agriculture and allied activities in Bihar (for T.E. 2008/09), almost 10 percent higher than the national average of 25 percent. Milk is the most important livestock product in Bihar, with a share of 71 percent of the livestock output (for T.E. 2008/09).

Bihar produces about 5.4 million tons of milk annually, almost 5.4 percent of the total milk produced in the country; and since 2004/05, milk production in Bihar has grown at 6.8 percent as compared with 4.3 percent at the national level.

On a regular annual basis, nearly 70% of land is either underwater or left fallow following monsoon floods; some of the villages are only accessible by boat from June through November during the monsoon season (Table 4.1). The survey also recorded households' perception of production trends for the five main staple and cash crops over the 2011-2015 period (Figures 4.2 and 4.3). A majority of the households reported a decrease in production of all five main staple and cash crops. A significant percentage also reported a decline in vegetable production. A few households (10%) from the Araria district reported an increase in the production of paddy and wheat, but these households reported an overall decrease in the production of other crops like summer maize, millet, and mustard.

4.3 Drivers of changes in farming practices

Figure 4.7 summarizes the reasons for changes in farming practices, including those related to waterlogging. The dominant forces driving change varied depending on the landholding size and labor status of the farmers.

Overall, waterlogging (both seasonal and permanent) was the most common agro-climatic hazard, reported by ~95% of households. Waterlogging in all the four districts has been increasing over the years (Table 4.2) due to the combined action of a number of factors (as reported by the households) such as (i) non-lining of the canal and embankments that leads to seepage, (ii) lack of drainage, (iii) inadequate withdrawal of groundwater by pumping, and (iv) heavy irrigation in areas identified only for light irrigation. Interestingly, out of all household's questions, only two from the Araria district reported blockage of drainage by roads and railroads to be one of the main drivers of increased waterlogging, despite clear evidence of this being a significant driver of saturation in the Kosi megafan (Goswami, 2019). This may reflect, however, the fact that most roads and railroads have been in place for decades and therefore are not perceived as playing a role in exacerbating recent changes, even if they do. Although improper and superfluous irrigation have been found to have worsen waterlogging in the study area (Neupane et al., 2015), households have put little stress on it as compared to other factors.

In general, all the four categories of farmers irrespective of the land holding size from all four districts reported an increase in erratic rainfall events and consequent flooding and waterlogging and considered them to be the main drivers for farm-related changes (Figure 4.7). The other main factors for farm-related changes are the by-products of the waterlogging stress and the most important among them are livestock disease, insect attacks and crop pests.

The difference between the farmer categories is noticeable regarding the other reported drivers of changes. Medium land-holders who are comparatively more resourceful than the other farmers report lesser stress on resource and productivity. Only the small land-holders and marginal farmers report non-climatic factors such as policy, resource and productivity as important as the reported climatic factors.

4.4 Adaptive agricultural responses

Households were queried about what changes they had made over the period 2014-2015 with respect to a wide range of practices in agriculture.

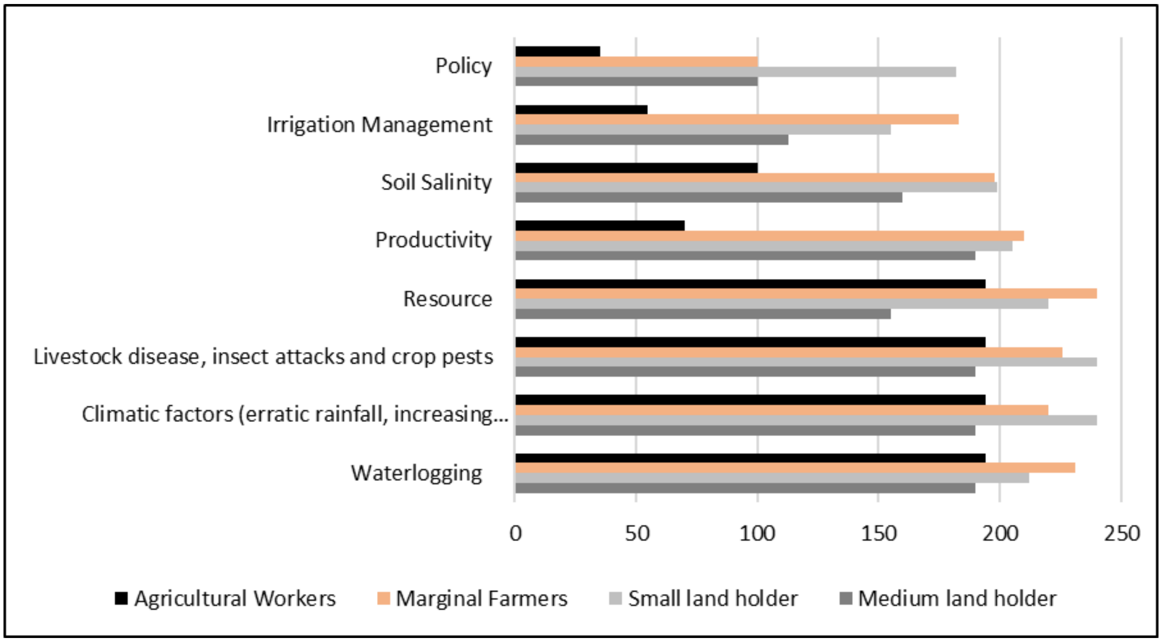

Figure 4.7. Reasons for farm related changes from 2014-2015 based on land size holding. Ninety percent of households (864 households out of 960) reported making changes in response to the issues outlined below.

The majority of the surveyed households (90%) made some changes to farming practices and farm level changes have taken place in all the locations (Figures 4.5 and 4.6) but only 28 % made adaptive changes/significant amount of changes (more than 10 changes per household made in an agricultural field in a single crop year) (Figure 4.8).

Among the changes made in farming practices across the four districts due to waterlogging, the most common one was changing at least one crop variety as reported by over 90% of households from all four districts followed by stopping rearing of certain livestock. Other most common actions were to stop planting some crops (44%) and/or introduce new crops (38%).

These were followed by changes in farming practices, stopping rearing certain livestock, and investing in irrigation Late or early planting, adopting new crops and/or varieties, introducing legumes in rotations, and planting improved, disease- and pest-tolerant varieties are the most frequently cited changes being made to farming practices in these surveyed areas.

The frequency in changes made in the timing and methods of planting (e.g. later planting, earlier planting/land preparation and a shift to mechanized planting) vary according to the crop selected. It does appear that these shifts are related to rainfall and waterlogging constraints. Strategies such as adjusting planting dates and new varieties have been found to contribute to climate change adaptation. A wide range of improved practices that have been shown to increase agricultural adaptation to climatic risk are resource-conserving technologies (zero tillage practice which is the same as residue management introduced in all the three study sites), various approaches for enhancing water use efficiency, expansion of areas under cultivation to compensate for reduced yields during droughts and switching to more drought tolerant crops. Other farming practices that help deal with climatic risks are improved pasture and livestock management strategies, introduction of crop cover or mulching, planting trees on-farm (agroforestry) and the adoption of new crop varieties that are flood tolerant, disease and pest resistant, or shorter cycle, among others.

Table 4.7. Generalizations regarding farmers' perceptions about environmental change and land use over the last five years preceding the 2016 survey. The generalizations represent response from 200 farming households out of 960 total surveyed households who perceived a change in climate.

Factors	Monsoon (July-October), Kharif	Post Monsoon/winter (October- March), Rabi	Winter/summer (March-June), Zaid
Rain	less predictable rainfall	No consistent observations	Not enough moisture for certain crops
Temperature	Increase in daily minimum temperatures	Increasing faster in March. Difference between day and night temperatures are increasing.	Increasing in general. Changes in frost patterns.
Floods	Area affected is increasing	Area affected is increasing	No consistent observations
Waterlogging	No consistent observations	A huge loss of net sown area due to waterlogging in this season. Increase of fallow lands and/or cropping intensity.	Increased wasteland which are waterlogged land that are not or cannot be reclaimed
Use of land	There was flooding in lowlands, upland had rice. Now both uplands and lowlands are fallow/maize.	Wheat area has decreased because temperatures are higher. Yield loses. Tobacco planting is substituted	Certain crops like mung bean has stopped growing. Not enough moisture
Cultivation timing	Delayed 30 days	Delayed	Delayed
Pest and diseases	More disease in livestock, low milk supply. Food and mouth disease in cattle	More disease in livestock, low milk supply. Food and mouth disease in cattle	More disease in livestock, low milk supply. Food and mouth disease in cattle
Non-seasonal changes			
Other changes	More farmers in the region are switching to orchards.		

On average, approximately eleven, eight and three changes in farm related practices are made by medium, small holder and marginal farmers, respectively. Many smallholders lack the capability to invest in soil fertility management or changing other inputs. Efforts and adaptations being pursued by the lowest income groups (e.g. living on marginal and small farms) largely appear to be 'survival strategies,'.

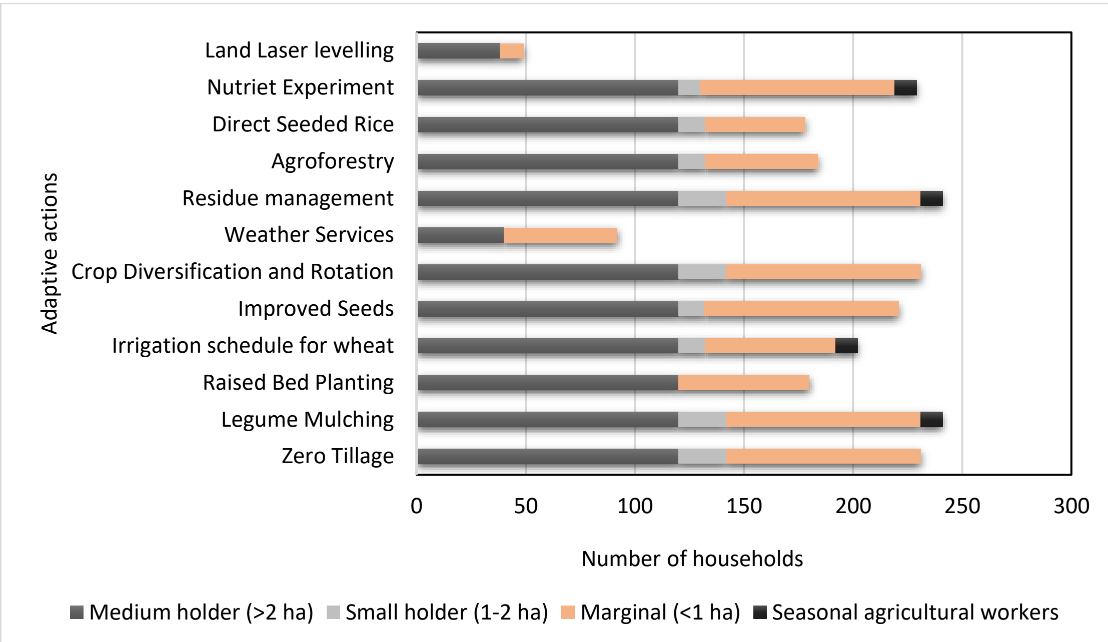

Figure 4.8. Adaptive actions by farmers based on Landholding size type from 2014-2015 (28% of 864= 242 households)

In other words, small/marginal farmers in severe waterlogged areas have been undertaking remarkable farm-related changes. This is counter-intuitive given the resource constraints that households with small landholdings face.

More households in Araria (80%) and Madhepura (87%) made changes in crop management practices (irrigation use and methods, agrochemical use, disease and pest management) than in Supaul and Saharsa (64%) (Figure 4.9). The majority of households reported making changes in their livestock management practices (including fisheries) in all four districts. Only 28% of households from all four districts reported taking any adaptive actions against waterlogging, with two to three adaptive actions taken by each of these households on average. Marginal farmers and owners of small land holdings were the least to make adaptive changes in all the four districts.

Although 90% of households made some changes, only 28 % of household made adaptive changes to farms (Figure 4.8 and Figure 4.9). Households were also asked about their perceptions on irrigation management in their farms; less than two-quarter of respondents mentioned irrigation-related reasons as being one of the most important drivers of change in farming practices. For those households that did, the specific reason mentioned were perceptions of an increase in groundwater table. Only 25 % of households reported irrigation to be augmenting waterlogging problem and having influenced the changes in farm-related practices they had made over the 2014-1015 years.

Overall the results show that farmers are flexible, and many (90%) made some changes in their farming practices over the study period. There were a wide range of adaptive changes to climate change and waterlogging, and about 28% of the households made adaptive changes (the remainder probably being due to economic and social forces).

4.5 Factors influencing local adaptation

This section attempts to capture the factors affecting the likelihood of a household undertaking adaptive actions (innovation). Adaptation refers to a process of adjustments in behavior and/or activities in response to experienced or expected changes or stress. Adaptation includes new strategies and taking advantage of new opportunities. Autonomous adaptation refers to automatic responses to changes. Planned adaptation refers to the response of a deliberate policy decision, based on an awareness that conditions have changed or are about to change and that action is required (IPCC 2007).

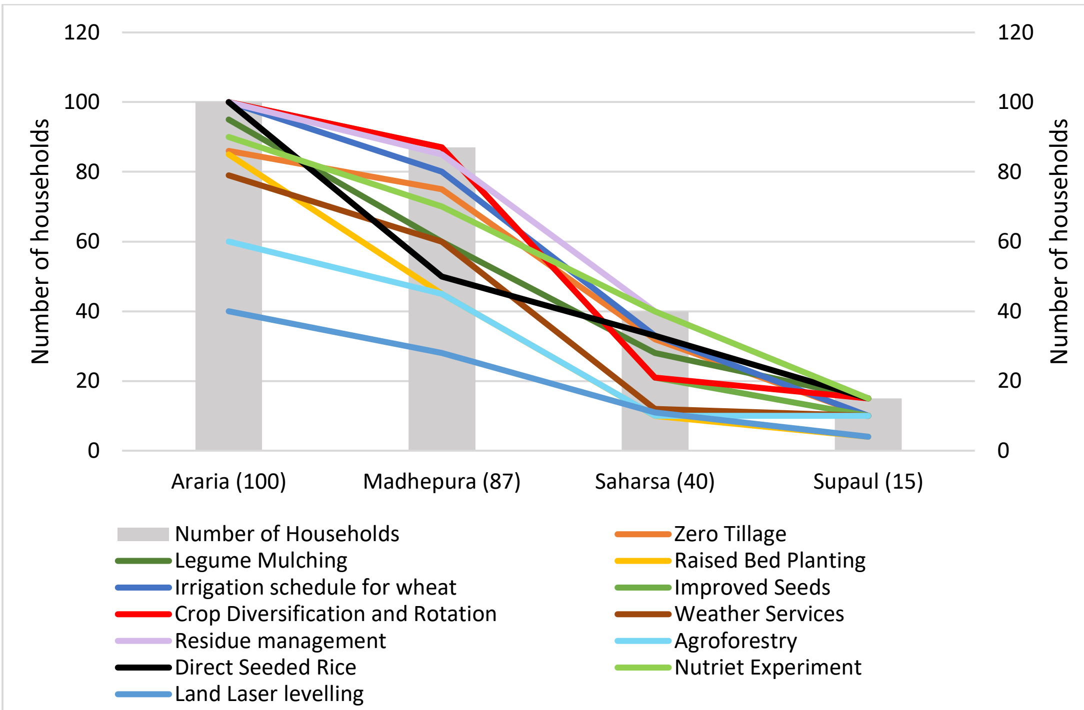

Figure 4.9. Adaptive actions taken by Districts from 2014-2015 (242 households)

I explored the relationship between multiple factors using regression analysis to estimate the influence of the explanatory variables (Table 4.9) on "innovativeness" of the farmers, with innovativeness being defined as the number of adaptations implemented by farmers. There was no co-linearity among the variables, however the analysis helped identify the important factors affecting the vulnerability of farm laborers and households to waterlogging.

5. Discussion

This section discusses how the results of this study inform answers to the two main research questions: a) how have agricultural practices changed in response to waterlogging and related environmental changes, and b) which factors affect the vulnerability of farm laborers and farm households to waterlogging?

5.1 Changes in agricultural practices due to waterlogging

Unfortunately, 83% of the households in this study note a decline in net sown area and the production of staple food crops and cash crops due to waterlogging related problems (Figure 4.2 and Figure 4.3). Rice, the major crop in the region, requires standing water for its early growth, but even here, prolonged surface wetness acts negatively on the crop. The situation is worse for other crops that cannot tolerate saturated conditions for longer periods of time. For example, the majority of households growing vegetables reported a decrease in production over the five years preceding the survey.

Beyond direct impacts of waterlogging on the ability to plant and grow crops, a significant proportion of households reported changed patterns in the incidence of livestock disease, insect attacks, and other crop pests due to changing climate conditions and recurrent, prolonged waterlogging (Figure 4.7) all of which negatively affect crop productivity. These household perceptions are consistent with reports in the literature on impacts associated with changing environmental conditions (Bharati et al. 2012). The reported increase in livestock disease is consistent with the findings that changes in temperature, rainfall patterns, and humidity are directly related to increased incidences of livestock disease (Singh et al. 2000; Basu and Bandhyopadhyay 2004; Sirohi and Michaelowa 2007). Similarly, changes in temperature and rainfall patterns may lead to an increase in weeds and pest attacks and diseases affecting grasses and crops (Sirohi and Michaelowa 2007).

The declines in agricultural productivity have in turn led to declines in local food availability and household income (Figure 4.4 and Table 4.8). Given these circumstances, it is not surprising that 90% of the surveyed household have made changes to their agricultural practices to try to enhance productivity (Figure 4.5).

Table 4.8. Major sources of food consumption (%) for households of different types for a year

	Farm production	Bought from store/market	No single major source
Medium	46	40	14
Small	33	37	30
Marginal	21	66	45
Other agricultural workers	10	28	62

Rice is the most important crop and farmers are changing both the types of rice they plant and where and when they grow them. Cultivation of flood-resistant rice varieties is being undertaken by medium land-holders in some villages in the Araria and Madhepura districts. This is a response to the acute problem of waterlogging in villages and lands close to the embankment and outside it. For example, in all the villages, sowing ‘aghani’ (monsoon) paddy is a risk as the fields become flooded. Yet people broadcast paddy seeds on these lands every year in the hope that they might survive if the floods are low. This risk is worthwhile if once every three years they get a bumper crop. This applies for all the lands that lie between the embankment and the river or which are unprotected. Paddy varieties which can survive standing water for a long time are generally sown on these lands. The same categories of land also support a good crop in the ‘rabi’ season depending upon where the river is flowing. If the river has deposited a thick layer of sand, then either there will be no crops or the crop yields will be very low. If it has deposited a good layer of silt (as happened in Paraia village in the Araria district after 1990), however, then these lands will produce a very good crop of wheat or maize and some pulses (daals).

New varieties of rice also make it possible to plant at different times of ear to avoid bad conditions. The ‘garama’ cropping season (crops sown in February-March and harvested in May-June) is new in this area. Acreage under this new variety of paddy, generically called ‘garama dhan’, has increased over the past few years. Most of the waterlogged and seepage areas in the studies villages are beginning to increase their cultivation of garamadhan. But garamadhan is a coarse paddy (less palatable), grown mostly for household consumption unlike other rice varieties which are grown for market. Its cultivation has partially addressed the food security problem of poor households. It should be mentioned, however, that this particular variety of paddy was not consumed by the people earlier, especially the better-off people, as it is a coarse variety.

Beside rice, high-yielding varieties of other crops have been also introduced. New varieties of wheat and maize give much better yields than previous varieties. High-yielding varieties of vegetable crops have been introduced also mostly by the medium and small land-holders in the Araria and Madhepura districts. Adjustments in the cropping cycle are evident in all the villages. Post-monsoon cultivation in waterlogged areas of the villages has been pushed from early October to late November. Selection of crop type and variety and improved irrigation techniques have been central to coping with and adapting to the changing environment. Cultivation of a new variety

of paddy, known as 'garama dhan' before the monsoon (sown in February-March and harvested in May-June) is an example of introduction of new varieties to cope with the variability in waterlogging. Sunflower and an early variety of maize have been introduced also into the cropping cycle. Uncultivable sand-cast lands within villages are used primarily by small farmers to cultivate fruit. Vegetable farming is also widespread in all the districts.

Replacement of crops with those that can withstand higher amounts of water, such as sugarcane, is also being considered. However, to bring sugarcane back to the fields, the sugar industry in the state needs to be revived. Historically, Bihar led India in cane and sugar production (Rasul, 2011), but once the state-driven mills started crumbling, sugarcane lost the interest of the farmers. However, some efforts have been made recently to put the sugar industry on a revival track.

Local municipalities have also helped in some cases with land reclamation, which includes efforts to restore waste lands or land under water so that it can be cultivated. For example, the households reporting an increase in paddy and wheat (two households from the District Araria) stated it was only possible because of a recent land reclamation effort by the local municipality in the district. Land reclamation projects are usually government funded and are critical political issues in the state of Bihar. Past land reclamation projects have been random meaning the restoration areas have not been selected based on recovery/risk priorities rather based on the political affiliations and official influences.

Another option for replacing lost food production is improved, community-based management of the depressions, ponds, and reservoirs for fisheries and aquatic crop production. 15% of the households mostly from medium and small land-holders have taken this initiative in this study. As farm boundaries coalesce during the floods, the individual interventions are infeasible, but state and nongovernmental organization–assisted community ventures with agreed cost and profit-sharing mechanisms have the potential to succeed.

The water shortages in growing season also have led a small percentage (30%) of households to develop irrigation to address water shortages and ensure a stable water supply for agriculture. One of the major problems in these districts is the cultivating of crops needing heavy irrigation in areas only meant for light irrigation. This has created waterlogging in areas not having proper natural drainage. It is also difficult for the revenue officials to strictly implement the planned cropping patterns. Monitoring the irrigation, cropping and water use practices of a large number of farmers and making them adhere to the planned cropping pattern is a difficult logistical problem, costly, and hard to enforce.

Finally, some households have also stopped rearing certain livestock. There is possibility that households are shifting from bigger animals to small ruminants (e.g., breeds of local goats) which are more resilient to water and fodder/forage stress, as reported by a study in drought affected areas in Pakistan (Shafiq and Kakar 2007).

5.2 Vulnerability of farming households to waterlogging

This section discusses the different factors influencing adaptations to waterlogging. 90 percent of the surveyed household are implementing changes to maintain or increase productivity, largely at the farm and community levels (Figure

4.5) but only 28% of them made adaptive changes (more than 10 changes per household in an agricultural field in a year) (Figure 4.8 and Figure 4.9). The drivers of change were dependent on the famers' perception of their "vulnerability." Policy makers often do not understand the concept of vulnerability and frequently use the term as a substitute for poverty or the state of being poor, but it is also a function of farmers'' perceptions of their defenselessness (insecurity, and exposure to risks, shocks, and stress) (Eriksson et al., 2009; Deressa et al., 2009; Turner et al., 2003).

This is borne out in the study area, where perceptions of vulnerability and the need to implement changes differ with many factors. The literacy of the head of household, household size, size of agricultural land, number of income sources, insurance provisions, and out migration of a household member all had a positive statistically significant relationship with the probability of a household taking adaptive actions (Figure 4.8, Table 4.9).

Table 4.9 Factors affecting the vulnerability of farm laborers and households to waterlogging.

Education

- Literate household head

Household with at least one out-migrant member

Resources

- Size of owned/ rented agricultural land
- Households having more than one income source (income source diversification)
- Farm households having access to financial services to undertake new improvements in agriculture
- Households having year-round food security

Community networks

- Membership in any farmers group, community-based organizations, cooperatives etc.
- Number of agricultural meetings attended over the previous five years

These results are consistent with the findings of others. Literate farmers are known to be more likely to have better information on an understanding of climate change, its impacts, and possible adoption options and thus more likely to take adaptive action (Tesso et al 2012; Deressa et al. 2009). More household members generally mean greater availability of labor and thus increased ability to undertake adaptive actions which, at the farm level, are labor intensive. Similarly, larger land holdings are more likely to provide greater surplus food and income (Hussain and Thapa 2015), providing farmers with the resources and financial capacity needed to invest in adaptive measures such as soil conservation, irrigation, changing crop patterns, and livestock production (Mulatu 2013). Diversification of income sources also helps household by providing the financial resources to take adaptive actions. Insurance (e.g., for property damage, livestock death, human health and life) increases the adaptive capacity and resilience of households (Surminski 2010), and the sense of security it provides increases the likelihood that households continue to practice agriculture as well as the propensity to take risks in terms of costlier adaptive measures

In general, no one of these factors alone is going to determine whether or not a group implements changes or the nature of these changes. Marginalized, low income farmers and communities, for example, especially feel that their vulnerability is caused by their poor asset base (Table 4.5), which is a function of land holding, income, insurance and labor availability. This group also experiences a sense of defenseless due to the constant threat of being evicted from their lands or homes (if they do not own land) and the unpredictable nature of the Kosi and weather.

Likewise, these factors do not uniformly influence the adaptive strategies of people from different sections of society living or in different areas of the basin. For example, the sense of vulnerability among the poor and lower castes was more pronounced the more inaccessible the village, particularly in Supaul and Saharsa, which become waterlogged for nine months every year (Table 4.1). At a social caste level, people from lower castes (e.g., the Rashin) often find it difficult to open a bank account and have to depend on the traditional system of sending their remittances through their social networks.

The impact of labor shortages was notable in the study area; during the months of monsoon (prime growing season) and during the incidence of seasonal waterlogging; 73% of households had a migrant member (Table 4.5), most commonly one of the young and active members who would normally be involved in agriculture. Households with at least one migrant member were less likely to take adaptive actions (Table 4.5); for example, labor shortages may also be one of the reasons that significant portion of agricultural land was left fallow or under grass, as reported by others (Ghimire and Thakur 2014).

Out-migration from Bihar is a well-established phenomenon that started back in the nineteenth century and has gradually increased in the recent decade (Giribabu,2013; Erenstein et al., 2010). Most of the migration is taking place towards the north-western and western parts of India; the states of Delhi, Maharashtra, Punjab, Haryana and Gujarat account for half of the Bihar migrants. The prime reason of such heavy out-flow is related to employment and earning, a portion of which are sent as remittances to family members at their native places. My data indicates that out-migration for employment is taking place across all types of farmers (Table 4.5) and is not confined to poor or to relatively affluent households.

Around one fifth household in this study received remittances sent by the migrants of the household. The remittances comprise almost half to one third of the household expenditure, irrespective of economic status of the households. It is mostly spent on food and other items of consumer expenditure, health care and education of the family members. Remittances received through migration have provided an important cushion against food insecurity for many households in Bihar. At the same time, the resultant labor shortages during the main periods of agricultural activity seem to reduce the capacity of households to adopt adaptive measures. The relative importance of these factors must be evaluated in addressed by policy makers while formulating programs for mitigating poverty in Bihar.

The complexity of this equation is captured in the interplay between the decrease in food production, which as increased households' dependence on other sources of income and food items purchased from elsewhere. On average, households had more than two sources of income (Table 4.5), which also indicates an increased dependence on non-agricultural income to buy food and other items. In total, only 18 % of the total surveyed households had year round food security. This indicates serious food insecurity for the region. The move to expending more income on food items may impoverish households in other ways as they cut down on non-food expenditure such as education, health, clothing, and housing (Figure 4.4).

I hypothesize that poor infrastructure, poor incentives, and nonexistent technological support to farmers in Bihar negate private initiative and undercut the ability to take on adaptive measures. In other words, assets created by private initiative and investment are not being leveraged well due to lack of infrastructure and incentives. Ownership of land is a key variable and determines the possibility to capitalize on incentives provided by the government. Areas with small and fragmented holdings are hot spots of rural poverty and need immediate policy changes toward consolidation, but it is too complex an issue in Bihar to be sorted out in the near future. The politics attached with land reforms would take many years to work through, which the residents of Bihar cannot avoid to wait on. In such a scenario short-term schemes such as diesel subsidies and crop insurance need to be coupled with better implementation mechanisms to incentivize adaptations that promote better food security.

6. Conclusions

With more than 600 individual farmers/km^2, most of whom are extremely poor, Bihar harbors one of the highest concentration of rural poverty in the world (Moser, 2007). The slow growth in the state's economy has failed to reduce the rural poverty, because agricultural production in the study area has declined), in large part due to the waterlogging that is the focus of this research. Waterlogging and associated hazards reduce crop productivity, are detrimental to livestock, and lead to reductions in net sown area.

The net results of this are of great concern. Traditionally, agriculture contributed significantly to the food security and livelihoods of households in the Kosi megafan by providing a diversity of food and contributing to household income (Hussain et al. 2016; Adhikari et al. 2017). However, the contribution of agriculture to household food consumption and household income has declined significantly over time due to recurrent inundation and permanent waterlogging (ISET 2008). Such is the case in all the surveyed villages and especially in Supaul and Saharsa, where the agricultural lands are waterlogged for sevento nine months every year (Table 4.1). This study clearly indicates that the extent of waterlogging in the Kosi megafan is a complex problem affecting the livelihood and well-being of the farming households and requires much more attention.

This study also shows that almost all farmers, even those who are resource-poor or purely agricultural workers, are trying to adapt to seasonal and permanent waterlogging and related hazards. The number of adaptations that farmers adopt is tied to literacy, income diversification, access to farm insurance, government policies and support, and other socio-economic factors. Medium and small land-holders from all studied villages take on more adaptive strategies compared to resource-poor marginal and seasonal agricultural workers. Districts Araria and Madhepura are more adaptive compared to Saharsa and Supaul.

The fragility of the local economy and the severe impacts of waterlogging indicate that adaptation to flooding, flood proofing and improved flood management need to be a high priority to bring stability to Bihar's agriculture. Adaptation to flooding includes measures such as cultivating makhana (fox nut), which can be integrated with fish cultivation. But approaches like this are limited to the small, local areas. Even with new types of crops and varieties, it not clear how productivity of the monsoon (kharif) crops, especially paddy rice, can be improved in the vast agricultural lands so long as waterlogging is expanding. Clearly, both floods and waterlogging must be reduced, which will require a multipronged strategy of short-, medium-, and long-term measures. Major remedial measures to reduce waterlogging could include:

(i) Providing drainage: A detailed assessment of drainage (vertical and horizontal drains) should be taken up and implemented immediately. This may need large investments, and provisions for this have to be made.

(ii) Lining canals: The canal and major distributaries should be lined to reduce seepage.

(iii) Use of ground water for irrigation. Water withdrawal presently is low because irrigation water from rivers is released from canals for 10 months during the year. For reducing waterlogging, water may have to be drawn out from the ground every year.

(iv) Creating public awareness: One of the main reasons for increased waterlogging is poor public awareness regarding risks of waterlogging and opportunities for preventing or fixing it. Educating farmers regarding the impact of waterlogging on agricultural productivity and efficient use of water for irrigation is the most critical corrective action. The marginal cost of these measures, including the pumping of groundwater, will be less than the marginal benefits that a farmer will obtain through increased yields.

(v) Reducing the duration of water release: The option of reducing the duration of water release vis-a-vis the possibility of extending the irrigation to downstream areas should be evaluated. The water saved by reducing the irrigation in upper areas can be used for extending the downstream areas under irrigation. Moreover, stoppage of irrigation water during the rabi season (September- December) should be considered in waterlogged areas, especially in the light of higher ground water levels during the monsoon season.

Measures should also be taken to address the social frameworks that hinder adaptive measures to waterlogging. For example, further research should be carried out to understand the efficacy of informal social institutions such as cooperatives, kin enclaves, and credit networks to enhance security in the face of stressors to agricultural production and ways to strengthen

the reach and accessibility of these organizations, especially for poor and marginalized groups, and to women in particular. Likewise, the interplay of outmigration of labor and the use remittances to address variations in agricultural productivity needs to be further investigated.

Ironically, even as the problem of waterlogging is growing, water availability is becoming more unpredictable and, in recent years and in some areas, scarcer. Farmers surveyed in this study perceive changes in rainfall conditions, temperature, evapotranspiration and growing period. These changes have impacted rain fed and irrigated cropping systems through changes in crop evaporation, runoff, soil water storage, crop water requirement, crop growth period, photosynthesis ability, crop respiration and yield.

South Bihar, for example, is a water-scarce area, contrary to North Bihar (location of the Kosi megafan) This has prompted the state government to consider interlinking 28 rivers within the state. Six out of the 30 canal links envisaged in the ambitious National Interlinking of Rivers Project (Mustafa et al., 2008) lie in Bihar. In addition to bringing water to 1.2 million ha of relative dry area, the canals might play a role in reducing the intensity and frequency of floods and waterlogging in North Bihar. The state government has also proposed diversion of water from the flood-prone rivers of North Bihar to different rivers in South Bihar.

If this project is carried out, detailed analyses have to be carried out for estimating the possible occurrence of waterlogging potentially resulting from canals and irrigation, as well as the potential to reduce waterlogging in presently saturated areas. This will require development of computer simulation models that should be part of the environmental impact assessment exercise. One of the prerequisites for doing this will likely be developing a cadre of multidisciplinary technologists with modelling and simulation expertise.

At a more general level, Bihar needs to improve its infrastructure so that farmers can enhance agricultural production. Fortunately, Punjab, Haryana, and very recently Gujarat, provide examples of how improved infrastructure and innovative policy interventions can achieve this goal. Unfortunately, the limited reach of the Bihar's state government, corruption, and inefficient bureaucracy have led to poor delivery of programs and schemes that otherwise might increase the adaptive capacities of the communities in Bihar.

One locally based activity that could be promoted by state government would be the formation of local self-help groups. The role of social institutions and networks is an important element that allows the local community to cope with floods. Unfortunately, the role of self-help groups was never mentioned in any of the different interviews and interactions. Absence of this is perhaps because of the lack of a suitable facilitating organization in the region.

Given population growth, climate change, and the economic forces in the region, the impacts of waterlogging and climate variability are only going to increase in future years unless mitigation measures are taken. Locally adopted and regionally uncoordinated strategies documented in this study have, at best, helped the communities to cope with existing water stresses and hazards, but have not laid the foundations for long-term sustainable agriculture throughout the region. Moreover, fear that embankments along the Kosi will be breached and that catastrophic floods and further waterlogging will occur haunts the local population and hinders peoples' willingness to invest in local infrastructure. It is clear that the onus lies on the state and central governments to develop and implement an integrated, regional plan that provides greater security from floods, waterlogging, and water scarcity in order to enhance agricultural productivity, reduce the human uncertainty and distress that plague the area, and create a more sustainable economy.

CHAPTER V

SUMMARY

My research objectives for this dissertation were three-fold. I examined the migration patterns of the Kosi river from 1975 to 2015 in the second chapter. Next, I mapped pre and post-monsoon surface wetness in the entire Kosi megafan from 2005 to 2015 and analyzed the spatial distribution and impact of roads and railroads on connectivity within the megafan. The third objective was to explore the significance of surface wetness (waterlogging) and socioeconomic factors that affect farmers' decision to change their farming practices for the period of 2014-2015. This body of work contributes information on the processes that influence and control the Kosi megafan's main stem geomorphology and its interaction with humans. Documenting channel migration patterns show the spatial and temporal patterns of sediment flux in these systems and reveal that the main channel migrates an average distance of 5km every year. Mapping waterlogging coupled with transport network induced disconnectivity study reveals the sensitivity of the megafan to transport networks. And, the third objective helped to analyze factors responsible for changes in land use pattern, especially increase in current fallows, shrinking net sown area.

Though only small pieces to the many existing gaps in our knowledge regarding the geomorphology and human-environment interactions in the megafans, this research also provides a foundation from which to build further work on the Kosi megafan and other humid tropical megafans. The overarching objective of this study was to provide information that would help inform decision-making in regard to management and policy in the context of waterlogging hazard. Specifically, this research provides a conceptual model that identifies select geomorphic and human components and illustrates their complex interactions and relative influence on surface wetness throughout the study area. At multiple spatial scales I demonstrate the utility of methods that use GIS, free or inexpensive geospatial data, and relatively simple metrics to map and analyze channel migration, surface wetness and floodplain disconnection caused by roads and railroads. The simplicity of these methods allows for their application across other geographic regions and landscapes. In addition, my results show the importance of simple landscape-based analysis as a complement to other methods and techniques (particularly more complex and data intensive remote sensing and modeling techniques, as well as time and labor-intensive field data collection) in multi-scale assessments of human impacts on river systems. This dissertation documents the institutional, technological and informational barriers to designing and implementing adaptation to farms in the face of severe water-stress and in turn will allow more informed decisions to be made about how to utilize land and improve the livelihoods of the megafan inhabitants.

APPENDIX

QUESTIONNAIRE FOR HOUSEHOLDERS

Survey Code No.

District

Block

Name of village

Name(s) of the nearest rivers:

Name of river	Distance from village
1	km
2	km
3	km

Name of respondent(s) to this questionnaire

Name

Position in household

Date

Interviewer's Name (Print clearly)

Interviewer's Signature

Notes

A1. Background data on householder

1	How long have you lived in the village?	years	

2 What is your age? years **3** Male

Female

4 What is your main language?

5 What is your religion?

6 Are you married?	Yes	No

How many children? Male

Female

4 What is your main occupation/activity:

Status	Days employed per year

Farmer/Landowner		
Tenant farmer		
Agricultural laborer		
Skilled laborer		
Unskilled laborer		
Other (specify)		

A2. Background data on ownership

1 What is your business?

2 In which year did you establish your business?

3 How long have you lived in the village? years

B. Flood location and flood risk

1 What is the name of the nearest river?

2 What is the location of your house/business relative to the river?

More than 1 km from the river Specify approx. Distance

Are you in a flood risk area?

Yes	No	Don't know

4. How would you assess the flood risk in your locality?

- High
- Medium
- Low
- Other (specify) ____________

5. How often does the locality flood?

- Every year ☐
- Most years ☐
- Some years ☐
- Never ☐
- Don't know ☐

6. In the last 10 years how often has your locality been flooded? ☐ times

7. What is the nature of flooding in your locality?

Direct from rainfall

Embankment breached due to erosion

Embankment breached due high water level in river (overtopped)

Flood flow from upstream location

Other cause (please give details) Details:

Don't know

How, any suggestions?

8.

Can be prevented?	If so, what can you do?
Is an act of God?	
Is something to be lived with?	
Something you can do something about?	
Don't think anything can be done	Other details:
Not bothered, doesn't affect me or my family?	
Other (please give details)	

9. Do you think that you could be better protected from flooding?

Yes	No	Don't know

If Yes, how?

C. Flood forecasting and flood warning

1 Does any government agency provide you with information on flooding and flood risk?

Yes	No	Don't know

a). If Yes, which agency or agencies?

b.) What information do they provide?

c.) When do they provide this information?

d.) Is the information useful?

2 Do you get any information on flooding from the radio/TV/newspapers? How useful and timely is the information?

Source	Usefulness	Timeliness

Radio	*1=excellent,*					*2=good,*
Television	*3 =*					*moderate, 4 = poor,*
						5 =

very poor, 9 = don't know

Newspapers

Other (specify)

3 Do you think that the current flood warning system is adequate or not? | | *1=excellent, 2=good,*

What is wrong with the system? *3 = moderate, 4 = poor,*

5 = very poor, 9 = don't

a. *know*

b.

c.

Do you have any suggestions for improvements?

a.

b.

c.

d.

e.

4 Once a warning is provided are you given any help with evacuation?

No warning provided	
No help with evacuation	
Some help with evacuation Detail:	
A lot of help with evacuation	Detail:
Don't know	

5 How would you assess the flood evacuation systems? [ ] *1=excellent, 2=good, 3 = moderate, 4 = poor, 5 = very poor, 9 = don't know*

6 Do you have a mobile telephone?

Yes	No

a.

b. Would you like to have future flood warnings on your mobile?

Yes	No

c. Would you be prepared to pay for this service?

c) How much? Rupees/year

7 Do you have any other comments or suggestions for flood warning and flood evacuation?

D. Flood preparedness and mitigation

1 Which government department is responsible for flood prevention?

9 = Don't

know

2 a) Do you know any WRD staff personally?

Yes	No

9 = Don't know b) If Yes, who do you know and in what capacity?

____

____

3 a) Have you ever interacted with the WRD?

Yes	No

9 = Don't know b) If Yes, when and in what way?

____

____

4 a) What is your understanding of the work that WRD do? Please describe it:

b) How well do you think they do these tasks?

1=very well, 2=well

3 = adequately, 4 = poor,

5 *= very poor, 9 = don't know*

c) What do they need to do better?

5 a) Are there any flood defence works in your locality?

Yes	No

8 = *Don't know*

b) What are these works?

Embankments

River groynes

Other (specify) *1= very well maintained, 2=well maintained*

c) What is your opinion about the condition of these works?

3 = adequately maintained, 4 = poorly maintained,

5 = very poor maintained, 9 = don't know

d) Do you ever inspect the flood protection works?

9 = Don't know

Yes	No

- If Yes, how frequently?

e) Have you ever commented or complained about the condition of the flood protection works?

9 = Don't know

Yes	No

- If Yes, when and to whom?

6 Do you have any suggestions on how floods can be prevented or reduced in your locality?

E. Flood events

1 Have you ever been affected by a flood?

Yes	No

9 = Don't know

2 How many times in the last 10 years?

Once	
Twice	
More than twice	
Every year	

3 Please summarise the flood event (up to 4 events):

Duration Type of

	Year	How severe?	(days)	flood
1.				
2.				
3.				
4.				

1=very bad,

2=bad,

3 = moderate impact, 4 = little impact

5 = no impact, 9 = don't know

1=Heavy rainfall

2 = embankment breach

3 = overland flow

9 = don't know

4 Please describe one flood event: a) Year of flood

b) How severe was the flood?

c) What duration?

d) Type of flood?

e) Were you given any warning (Yes/No)?

By whom? ______

f) What happened?

______

______

______

______

g) Did you have to leave your home/business (Yes/No)?

- For how long?

days

h) **Householder only** - Did you lose any assets? | Estimated value of lost items (Rs) | Notes

			Estimated value of lost items (Rs)
House			
Household goods			
Crops			
Livestock			
Motorbike			
Vehicle			
Other (specify)			

i)

Householder only -Was your income affected by the flooding (Yes/No)?

9 = Don't know

Yes	No

- Please describe how:

____

____

____

j) **Businesses only** - Did you lose any assets? items (Rs) Notes

Business property			
Business goods			
Business vehicle(s)			
Motorbike			
Vehicle			
Other (specify)			

Yes	No

i) Was your income affected by the flooding (Yes/No)?

9 = Don't know

- Please describe how:

____

____

____

F. Waterlogging events

5 Have you ever been affected by a waterlogging?

Yes	No

9 = Don't know

6 How many times in the last 10 years?

Once	
Twice	
More than twice	
Every year	

7 Please summarise the flood event (up to 4 events):

Year	How severe?	Duration (days)	Type of flood

1.

2.

3.

4.

1=very bad,

2=bad,

3 = moderate impact, 4 = little impact

5 = no impact, 9 = don't know

1=Heavy rainfall

2 = embankment breach

3 = overland flow

9 = don't know

8 Please describe one waterlogging event:

By whom?

h) Did you have to leave your home/business (Yes/No)?

- For how long?

days

h) **Householder only** - Did you lose any assets? items (Rs)

Estimated value of lost

Notes

House			
Household goods			
Crops			
Livestock			
Motorbike			
Vehicle			
Other (specify)			

i)

Householder only -Was your income affected by the waterlogging (Yes/No)?

9 = Don't know

Yes	No

- Please describe how:

____

____

____

j) **Businesses only -** Did you lose any assets? items (Rs) Notes

Business property			
Business goods			
Business vehicle(s)			
Motorbike			
Vehicle			
Other (specify)			

Yes	No

i) Was your income affected by the waterlogging (Yes/No)?

9 = Don't know

- Please describe how:

____

____

____

1.

a) What are the names of the rivers in your area?

b) What are the approximate distances to these rivers from the agricultural field and home?

c) What are the flood risks from these rivers?

d) How often do they cause flooding (perception)?

e) How often have they caused flooding in the last five years?

2 a) Name of river	b) Distance (km)	c) Flood risk	d) Flood frequency (perception)	e) Flooding on last 5 years

	c) Flood risk	d) Flood frequency
	1 = High	*1 = Every year*
	2 = Medium	*2 = Most years*
	3 = Low	*3 = Some years*
	4 = None	*4 =Never*

3 What is the nature of flooding in this locality (tick those applicable)?

Direct from rainfall

Embankment breached due to erosion

Embankment breached due high water level in river (overtopped)

Flood flow from upstream location

Other cause (please give details)

Don't know

5 Do you have any suggestions on how to reduce the risk of flooding in this locality?

6 In your experience, have you encountered any cases of deliberate breaching of embankments?

a) What is the reason for this?

b) By whom was this done?

c) What can/should be done to reduce the incidence of deliberate breaching ?

Education

Training

Community Engagement

Other	

1 What is your estimate of the general condition of the key items of infrastructure?

Percentage in each condition grading

	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5	Overall
Embankments						
Groynes						
Etc, etc.						

Grade 1 - Excellent, Grade 2 - Good, Grade 3 - Moderate, Grade 4 - Poor, Grade 5 - Very poor

3 What measures do you take to prepare for floods each year?

a) Who is involved within the Division or Sub-Division

b) What are each the EE, the AE and JE doing during this time? What is each of their roles?

4 a) How well prepared were you for the flooding in 2011? [ ] *1=very well prepared, 2= well prepared*

(or the last flood event - state the year) *3 = moderately well prepared, 4 = not well prepared,*

5 *= poorly prepared, 9 = don't know*

b) If you were not well prepared, why not?

c) What would help you be better prepared?

5 What measures did you adopt last year (or in previous years) to mitigate the flood risk or the impact of flooding?

6 Do you have any suggestions for being better prepared for floods or for mitigation measures?

7 What is the process for maintaining flood embankments? How often is this done?

a) What equipment and facilities are available for maintenance?

8 What is the process of inspecting embankments? How often is this done?

9 Do you think that this system is adequate ? If not, what suggestions do you have for improvement?

10 Does the community participate in maintenance of the embankments?

11 Are there sufficient funds and/or resources to conduct maintenance of the flood embankments in your Division or Sub-Division?

Survey Code No.

E. Flood events

1 How many times have you had to manage floods in the last 10 years?

Once

Twice

More than twice

More than twice (give number)

Every year

2 Please summarise the flood event (up to 4 events):

Year How severe? Duration (days) Type of flood Name of river

1. 2. 3. 4.

1=very bad, 2=bad,

1=Heavy rainfall

3 = *moderate impact, 4 = little impact* *2 = embankment breach*

5 = no impact, 9 = don't know 3 =

overland flow

9 = don't know

4 Please describe one typical flood event and the work you had to do:

a) Year of flood

b) How severe was the flood?

c) What duration?

d) Type of flood?

e) Were you given any warning (Yes/No)? By whom?

f) Did you warn the villagers (Yes/No)?

g) What happened?

h) What role did you play during the flood event?

i) What would you like to have done, or have been able to do, better? What resources would you have needed?

5 Does the community assist you during flood events?

Yes	No

9 = Don't know

a) If Yes, please describe how/in what way:

6 Do you have specific people in the community that you liaise/work with on flood management? Please describe who and the role they play.

7 Does any other government organisation help during the flood? Please detail the organisation(s) and the help provided.

8 Do you expect to get flooded again in the future?

9 = Don't know

- If Yes, what can you do about it?

Yes	No

10 Is there a Flood Control Cell or Centre at the Division level?

a) How is this set up?

b) What kind of equipment does it have?

c) What kind of staffing does it have?

d) What resources do they have?

e) In your opinion, do you think the flood fighting task force or cell is effective during past flood events? If not, what can be done to improve its effectiveness?

How does the WRD work with the Disaster Management Department (DMD) during floods?

11 Are there training days by the DMD for the WRD staff?

Survey Code No.

F. Flood relief and recovery

1 a) Does the WRD give help with flood relief?

Yes	No
	No

9 = Don't know

2 a) Does the community work together to rebuild the damage following a flood event?

Yes	No

9 = Don't know b) If Yes, describe work done/help provided:

c) If No, why does the community not work together?

j) Have you been able to recover from the flood?

Completely	
Moderately well (>70%)	
Partially (>50%)	
Not well (<50%)	
Not at all (0%)	

k) Did you get any assistance during the flood?

Yes	No

9 = Don't know

- From who and in what form?

l) Did you get any assistance after the flood?

Yes	No

9 = Don't know

- From who and in what form?

____

9 Does the community work together during flood events?

Yes	No

9 = Don't know

a) If Yes, please describe how:

b) If No, please describe why not:

10 Do you expect to get flooded again in the future?

Yes	No

9 = Don't know

- If Yes, what are you doing about it?

11 Other comments or suggestions: ____

____

____

F. Flood relief and recovery

1 a) Have you ever been given help with flood relief?

Yes	No

9 = Don't know

b) If Yes, please describe when, by whom and nature of help given:

____

____

____

c) Was this help adequate?

9 = Don't know

Yes	No

d) If not, why not?

a) Following a flood event have you had to borrow additional money in order to recover from the

2 flood?

Yes	No

9 = Don't know

b) From whom did you borrow the money, and at what interest rate?

c) Have you been able to pay the money back?

Yes	No

9 = Don't know

3 a) Did the government provide any assistance to the community following flooding?

Yes	No

9 = Don't know b) What was the nature of this assistance (new buildings, shelters, etc.)?

________________________________ ________________________________

4 a) Does the community work together to rebuild the damage following a flood event?

Yes	No

9 = Don't know b) If Yes, describe work done/help provided:

____

____

c) If No, why does the community not work together?

5 Can you provide any suggestions for improving waterlogging and flood relief and recovery?

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