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Analysing the spatio-temporal changes in the flood risk zone to mitigate flood hazards using GIS techniques: A case study of Sitamarhi District

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Abstract : *Flooding constitutes one of the most frequent and devastating hydro-meteorological hazards in the northern alluvial plains of Bihar, with the Sitamarhi district experiencing recurrent flood events due to its physiographic and hydrological characteristics. The present study examines the spatio-temporal dynamics of flood risk zones and identifies areas of heightened vulnerability through the application of Geographic Information System (GIS)–based analytical techniques. Secondary datasets encompassing rainfall patterns, river networks, elevation parameters, land use/land cover characteristics, and historical flood records were systematically integrated and analysed using spatial modelling tools within a GIS environment. The findings indicate pronounced temporal variations in flood susceptibility, with low-lying terrains, floodplains, and areas in close proximity to river channels exhibiting consistently high flood risk. The study demonstrates the robustness and efficiency of GIS as a scientific tool for flood risk assessment and spatial decision-making, and offers critical insights to support flood mitigation strategies, land-use planning, and disaster management initiatives at the district level.*

Keywords: *Flood Risk Assessment; Spatio-temporal Analysis; Geographic Information System (GIS); Flood Vulnerability; Land Use/Land Cover; Sitamarhi District; Disaster Management.*

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Introduction:

Floods are one of the most common and recurring natural disasters in India, causing significant effects on human life, agricultural productivity, infrastructure, and regional economies. Due to its monsoon-driven climate, extensive river systems, and large alluvial plains, the nation frequently faces flooding, especially in the northern states. North Bihar is widely acknowledged as one of the most flood-affected areas in India, where districts like Sitamarhi experience yearly flood occurrences. The combination of heavy monsoonal rainfall, high sediment levels, flat and low-lying landscapes, and poor natural drainage greatly heightens the vulnerability of this region to flooding.

In the Sitamarhi district, multiple rivers and their tributaries, along with the failure of embankments and

water-logging, exacerbate both the intensity and duration of floods. Repeated flooding not only disrupts livelihoods and economic activities but also leads to land degradation, population displacement, and long-term developmental challenges. Losses in agriculture, damage to transport infrastructures, and risks to public health emphasise the critical necessity for structured flood risk evaluation and management in the area.

Over recent decades, improvements in geospatial technologies—especially Geographic Information Systems (GIS) and remote sensing—have revolutionised the examination and monitoring of natural disasters. GIS offers a powerful platform for integrating, visualising, and analysing spatial data from various sources, including rainfall, elevation, river systems, land use/land cover, and historical flood records. These capabilities facilitate a detailed understanding of flood behaviour and allow for more accurate delineation of flood risk zones. The application of spatio-temporal analysis further improves the assessment of changing flood risk patterns over time.

Grasping the spatial distribution and temporal changes of flood-prone areas is essential for crafting effective flood mitigation strategies, enhancing disaster preparedness, and promoting sustainable land-use planning. In this context, the current study aims to explore the spatio-temporal variation of flood risk zones in Sitamarhi district through GIS-based approaches. By pinpointing areas of high vulnerability and analyzing the physical and human-induced factors that contribute to flood events, this research intends to provide a scientific foundation for informed decision-making in flood risk reduction, disaster management, and sustainable regional growth.

Literature Review:

Flooding is one of the most frequent and damaging natural hazards, particularly across low-lying alluvial tracts such as the Indo-Gangetic Plain. Research shows that both the frequency and severity of floods arise from a combination of intense monsoonal rainfall, river morphology, sediment transport processes, land-use alteration, and human interventions, especially embankment construction and modified drainage networks. In northern Bihar, these interacting factors have created persistent and widespread flood susceptibility, highlighting the need for detailed spatial and temporal assessment. Studies of Indian monsoon rivers also demonstrate that high-magnitude seasonal floods substantially reshape channel form and redistribute sediments across adjoining floodplains (Kale, 2003).

Sitamarhi district lies within the Bagmati–Adhwara floodplain of North Bihar and is widely regarded as one of the most flood-prone districts of the state. The Bagmati River system carries heavy sediment loads, frequently shifts its course, and flows across an extremely gentle gradient, which together promote extensive overbank flooding during the monsoon season. District disaster records and local assessments consistently document repeated inundation in Sitamarhi, resulting in crop damage, infrastructure loss, displacement of settlements, and long-term socio-economic and health impacts. Hydrological investigations further suggest that variability in rainfall and catchment discharge strongly influences flood occurrence in Himalayan-fed rivers of North India (Negi, 2004).

Historical evidence reinforces this vulnerability pattern. The severe Bihar floods of 1987, documented by SANDRP (2016), identified Sitamarhi among the worst-affected districts, where intense monsoon rainfall combined with multiple embankment breaches along the Bagmati system produced sudden and widespread flooding. Such events indicate that structural flood-control measures, when exposed to extreme hydrological stress and inadequate maintenance, may intensify rather than reduce flood impacts, demonstrating the role of human factors in disaster outcomes. Comparable concerns regarding structural flood management and governance complexity have also been discussed in broader flood-risk studies (Dieperink, 2016).

Although district-specific research remains limited, studies from neighbouring districts such as Darbhanga, Madhubani, and Muzaffarpur show that drainage congestion, sediment accumulation, and aggrading riverbeds significantly amplify flood severity across North Bihar (Thakur et al., 2017). Local-scale observations from Sitamarhi villages located between embankments reveal how trapped sediment and restricted channel flow lead to prolonged waterlogging,

land degradation, and heightened vulnerability of communities. The socio-economic consequences of channel migration in Bihar are considerable (Ranjan, 2025). Recurrent erosion and deposition reduce agricultural productivity, force relocation of households, and create chronic livelihood insecurity within floodplain settlements. Damage to infrastructure can isolate villages, raise service costs, and weaken market connectivity, while repeated flood losses deepen poverty and social vulnerability. Because river courses shift over time, risk boundaries also change, making planning based on fixed alignments quickly outdated. District-level analyses likewise classify northern Bihar, including Sitamarhi, as highly vulnerable to recurrent flooding due to its physiographic setting and socio-economic exposure (Senapati, 2022).

Remote-sensing-based flood assessments provide important spatial evidence of Sitamarhi's continuing risk. Flood Hazard Maps prepared by the National Remote Sensing Centre (NRSC), ISRO, using multi-temporal satellite data from 1998–2019, place large parts of the district within moderate to very high flood-hazard categories, particularly along the Bagmati and Adhwara corridors. Reports of embankment breaches as recently as 2024 further emphasise the persistent fragility of flood-control infrastructure and the ongoing threat of inundation. Geospatial techniques employing satellite imagery and GIS-based delineation have therefore been widely recommended for efficient identification of flood-prone zones and monitoring of hazard dynamics over time (Bonacci et al., 2006).

In summary, existing literature indicates that flooding in Sitamarhi arises not only from intense rainfall but from a complex interaction of river dynamics, structural interventions, and socio-economic vulnerability. Previous studies consistently support the application of GIS and remote-sensing approaches for spatio-temporal flood mapping and hazard zonation, providing a strong foundation for the present investigation.

Aims and Objectives:

- To identify and map flood hazard zones in Sitamarhi district using GIS and remote sensing techniques.
- To analyse spatial patterns of flood inundation and frequency using multi- temporal satellite data.
- To assess the vulnerability of communities based on socio-economic and infrastructural factors.
- To generate flood risk maps for supporting disaster preparedness and sustainable land-use.

Hypothesis:

1. The Bagmati River has undergone significant changes in its course over time.
2. Flood hazards had affected the settlement area directly or indirectly in the Sitamarhi district.

Data Collection and Methodology:

This study utilises Sentinel-2A multispectral satellite imagery obtained from the Copernicus platform to investigate flood dynamics in the Sitamarhi district. Data pertaining to flood events during peak monsoon months in July from 2017 to 2021 were gathered, along with post-flood imagery for each year, to analyse inundation trends and alterations in river morphology. Additional spatial datasets, such as district boundaries and topographic maps, were obtained from government and open-access platforms to support spatial analysis.

Land Use/Land Cover (LULC) data for the years 2017 and 2021 were extracted from Sentinel-2A imagery available via the ESRI Sentinel data repository. The main land cover categories recognised in this study consist of agricultural land, urban areas, vegetation, barren land, and water bodies. Areas impacted by flooding were identified through visual interpretation and colour-based classification of satellite images, facilitating the creation of annual flood-inundation maps that reflect the spatial extent of flooding and the spread of river water. After the LULC supervised classification has been done with the help of ArcGIS software.

Post-flood satellite images were digitised to examine shifts in the course of the North and South Bagmati rivers. Channel migration, course deviations, and regions of significant change were assessed using spatial measurement techniques. LULC classification and change detection analysis were conducted using ArcGIS 10.8.2 by comparing the datasets from 2017 and 2021. All spatial processing activities, including mapping, digitisation, geoprocessing, and visual representation of flood-prone areas, were carried out within the ArcGIS framework.

Study Area:

The Sitamarhi district (Fig.1) is situated in the northern region of Bihar, India, adjacent to the Indo-Nepal international border. It is located roughly between 26°30 N to 27°N latitude and 85° to 86°E longitude. This district is part of the fertile alluvial plains of North Bihar and is traversed by multiple rivers, including the Bagmati, Lakhandei, and Adhwara river systems, which contribute to frequent flooding in the area.

The landscape of Sitamarhi district is mainly flat and low-lying, featuring gentle slopes that impede natural drainage. The region experiences a sub-tropical monsoon climate, marked by intense rainfall during the monsoon season, which plays a significant role in flood occurrences. The primary livelihood of the local population is agriculture, making flood risks a serious threat to food security and socio-economic stability.

Given its geographical position, river dynamics, and climatic characteristics, Sitamarhi district is regarded as one of the most flood-prone areas in Bihar. These features render the region ideal for examining the spatio-temporal changes in flood risk and for applying GIS-based methods for flood hazard assessment.



Fig.1. Study Area

Flood Map Delineation: The flood map of 2017 (Fig. 2) shows that the northeastern part of Sitamarhi was the worst affected by floods.In the FCC (Fig.3), it is represented by the dark blue colour, which shows that the area is waterlogged, probably due to flooding. The dark red colour shows dense vegetation and is also healthy, but not in the areas of floodwater. The settlements are of a greyish colour, not visible due to the spectral similarity. The flood delineation map is shown in which dark blue colour is cloud and bluish green is waterlogged area, and green is for land area. According to the census of India, there was almost 34,23,574 population in Sitamarhi, out of which 22 lakh residents were affected by flood, out of which 47 deaths occurred there according to the national disaster report.

False colour composition image of 2017 and flood delineation map of Sitamarhi 2017.



Fig.2. The FCC of Sitamarhi (2017)

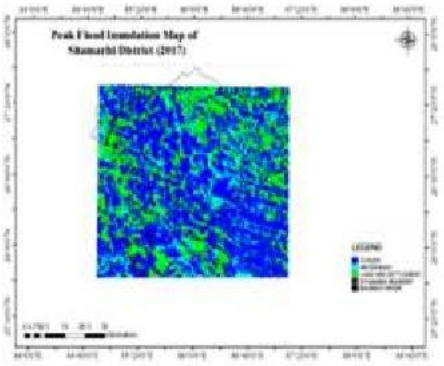


Fig.3. The flood delineation map of Sitamarhi

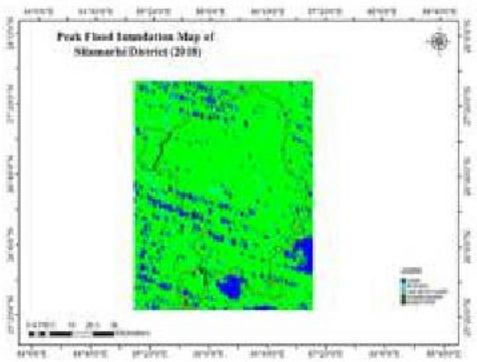


Fig.4. FCC of Sitamarhi (2018)

The False Colour Composite (FCC) of Sitamarhi for the 2017 (Fig.3) monsoon period reveals a clear hydrological disturbance consistent with widespread flooding and prolonged waterlogging. Heavy damage to kharif crops, according to the state disaster management department, the flood affected approximately 8.85 million people across 13 districts, with Sitamarhi reporting the highest number of fatalities among affected districts (around 37 deaths reported). Relief operations in Sitamarhi housed over100,000 displaced people in temporary camps. The flood delineation map shows the majority of the area covered by a bluish green colour, and green for vegetation is flooded, and the rest is dark blue, representing clouds

The 2018 map (Fig.4) shows dominant green areas, representing stable land and settlements. Flooded areas (light blue) were smaller and scattered, mostly confined to river-adjacent lowlands. This indicates localised and moderate flooding, with limited impact on agriculture and settlements. Clouds (dark blue) may obscure some areas, but overall flood intensity was lower than in 2017.

In the FCC image, there is barely any waterlogged area, and with a lower percentage of clouds and settlements, the soil is of grey, brown or muted pink colour. Also, there are some dark blue colour lines which are surface water body or, river channels or oxbow lakes, etc. We can say that mostly kharif crops are grown here, like rice, wheat, pulses, and rabi crops are also grown like oilseeds, pulses, etc., so this is a good time for cultivation.

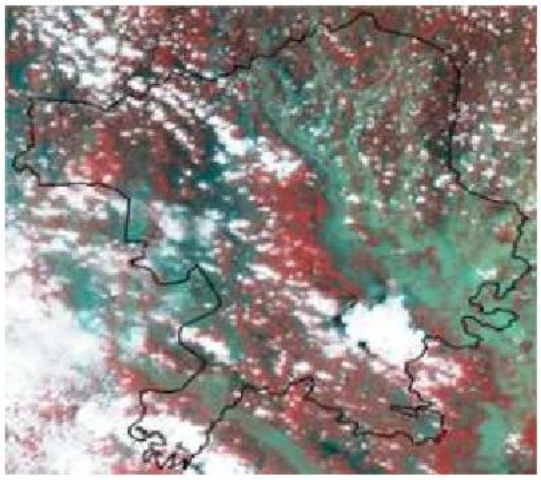


Fig.5 False Colour composition image of 2019

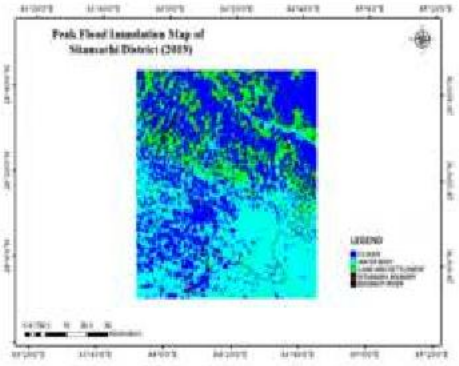


Fig. 6. Flood delineation map of Sitamarhi, 2019

In the flood map 2019 (Fig.6), we can see that the low-lying area of the southern district is mostly affected. The vegetation and settlement areas are not majorly affected, and clouds are only seen in the southern areas of Sitamarhi. So, we can say that not major but localised inundated areas are affected. The images of August-September 2021 show there was a short-term disruption to some of the villages in localised areas. The FCC shows (Fig.5) Sitamarhi dominated by agricultural vegetation (red), with significant moisture-saturated and waterlogged areas (cyan/blue), interspersed with rural settlements with grey-white textured patches. Darker tones indicate deeper water channels.

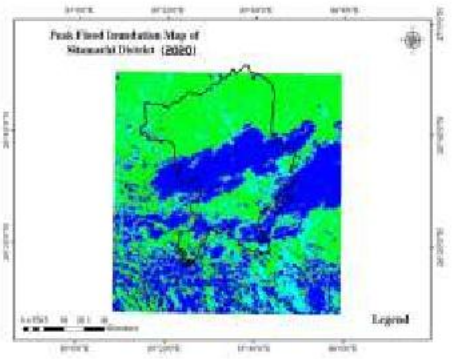


Fig.7. Flood Inundation map of Sitamarhi District (2020)



Fig. 8 FCC map of Sitamarhi (2020)

In the flood map 2020 (Fig. 7) reports and hydrological continuity suggest moderate flooding, with light blue areas in low-lying regions. Settlements (green) in recurrent flood-prone blocks like Sonbarsa, Parihar, Bairgania, and Sursand were partially affected. Flood severity was less than in 2019 but still caused seasonal crop damage and waterlogging.

The false color composition image (Fig.8) shows the area with healthy vegetation, and it can be seen that a few patches of dark blue color showing no major damage to people or the crops. Their settlements could be found there in greyish color or brown color with soil patches. There was minor impact according to the disaster management authority only the agricultural tracts of low-lying areas affected rest all of the kharif rice and maize and rabi crops like wheat and pulses were stable. No large-scale displacement of people was seen there.

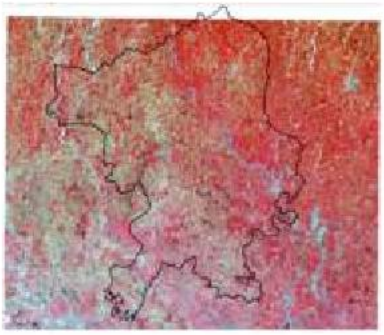


Fig.9. FCC image of Sitamarhi (2021)

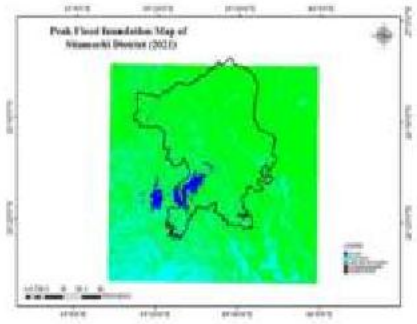


Fig.10. Flood delineation map of Sitamarhi (2021)

The FCC shows Sitamarhi (Fig.9) dominated by agricultural vegetation (red), with significant moisture-saturated and waterlogged areas (cyan/blue), interspersed with rural settlements (grey-white textured patches). Darker tones indicate deeper water channels, while light green suggests transitional cropland states.

The 2021 flood map (Fig.10) shows predominantly green areas, indicating that most land and settlements were stable. Light blue areas indicate localised flooding, mostly along river channels and lowlands. No large-scale displacement occurred, and the flood intensity was moderate. Clouds (dark blue) may obscure some sections, but overall, the flood impact was lower than in 2019 and 2017.

In the map, we can see that the low-lying area of the southern district is mostly affected like RunniSaidpur, Belsand, Parsauni, Riga and some areas of Nanpur, Charaut, Sursand and Suppi are also affected. The vegetation and settlement areas are not majorly affected, and clouds are only seen in the southern areas of Sitamarhi. So, we can say that not major but localised inundated areas are affected. The Images of August-September 2021 show there was a short-term disruption to some of the villages of localized areas.

Land Use and Land Cover Analysis: In the present analysis, LULC maps were generated for the years 2017 (Fig.11) and 2021 (Fig.12) to represent land-cover conditions of the study area. The classes in the map include major categories such as agriculture, built-up areas, vegetation/ forest, river/water bodies, bare ground, such as cloud and mist, which account for atmospheric and seasonal image conditions. These classes were selected based on relevance to regional land-use changes.

In 2017 (Fig..11), the spatial distribution indicates a landscape predominantly dominated by agricultural areas, the main occupation of the region. Built-up areas appear as compact and concentrated patches, mainly associated with urban centres and rural settlements. Vegetation and forest cover occur in fragments largely along the river and less-disturbed zones, while river and bare ground classes show active fluvial and seasonal processes, showing the presence of an alluvial floodplain environment.

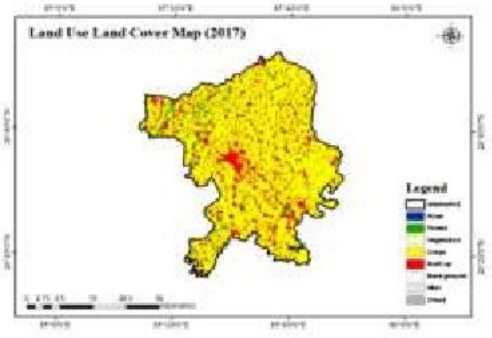


Fig. 11. LULC of Sitamarhi (2017)

Source: Esri. (2017). Sentinel-2 Land Cover Explorer. https://livingatlas.arcgis.com/landcover/

The 2021 LULC map (Fig.12) shows that built-up areas have expanded both radially from existing urban areas to transport areas, indicating a rapid increase in urbanisation and urban growth. Although agriculture is the dominant land-cover type, its percentage has reduced because of fragmentation due to land conversion. Vegetation and forest cover show a decline in extent and connectivity due to human activities. Changes in the river and adjacent bare ground areas highlight ongoing channel migration, erosion, and deposition processes

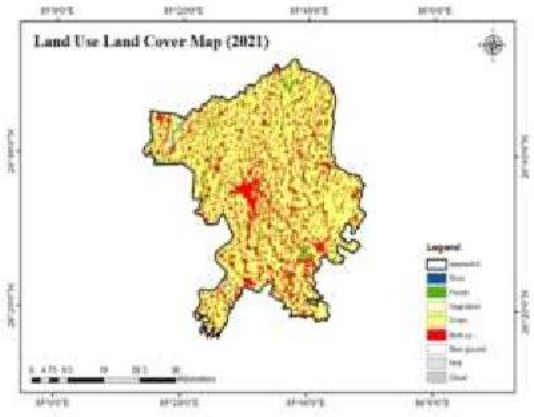


Fig. 12. LULC of Sitamarhi (2021)

Source: Esri. (2021). Sentinel-2 Land Cover Explorer. https://livingatlas.arcgis.com/landcover/

Change Detection: The most important transition can be seen from agricultural areas to built-up areas that are found mostly around urban centres and major transport corridors. This transition represents the most significant change due to human activities during the study period. Rapid urbanisation is the main reason for sustainable urban development. LULC maps of the study area, based on satellite images from 2017 to 2021, clearly indicate that land use patterns have changed over time (Fig.13).

Conversions from vegetation or forest to cropland and built-up areas suggest a gradual reduction in tree cover due to an increase in agricultural expansion because of an increase in population. Transitions involving river, bare ground, and cropland reflect seasonal changes in flooding, sediment deposition, and river channel dynamics. These are features of floodplain environments.

Thus, the observed LULC changes between 2017 and 2021 (Fig.15) reflect a landscape undergoing progressive anthropogenic modification. While agriculture continues to dominate land use, the expansion of built-up areas and the reduction of vegetative cover signify increasing human pressure on land resources. The spatial concentration of changes near riverbanks and low-lying areas.

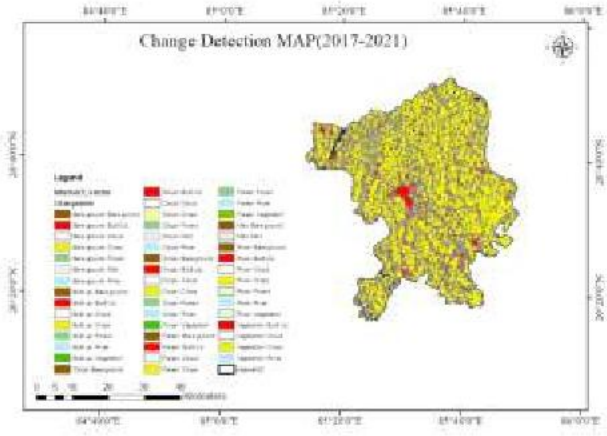


Fig. 13. Change Detection map of Sitamarhi (2017-2021)

Source: Post classification change detection analysis derived from Sentinel 2 based on land use and land cover data of 2017 and 2021obtained through Esri Sentinel 2 land cover explorer.

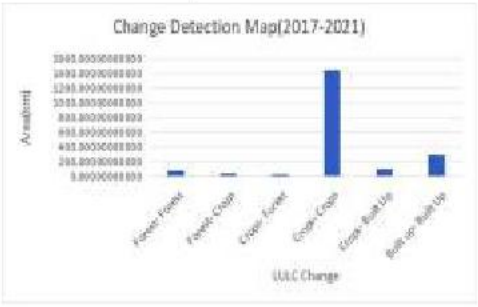


Fig.14. Area of change detection (2017-2021)



Fig. 15. Percentage of distribution of LULC change (2017-2021)

Interpretation of Bagmati River Channel Migration (2017–2021)

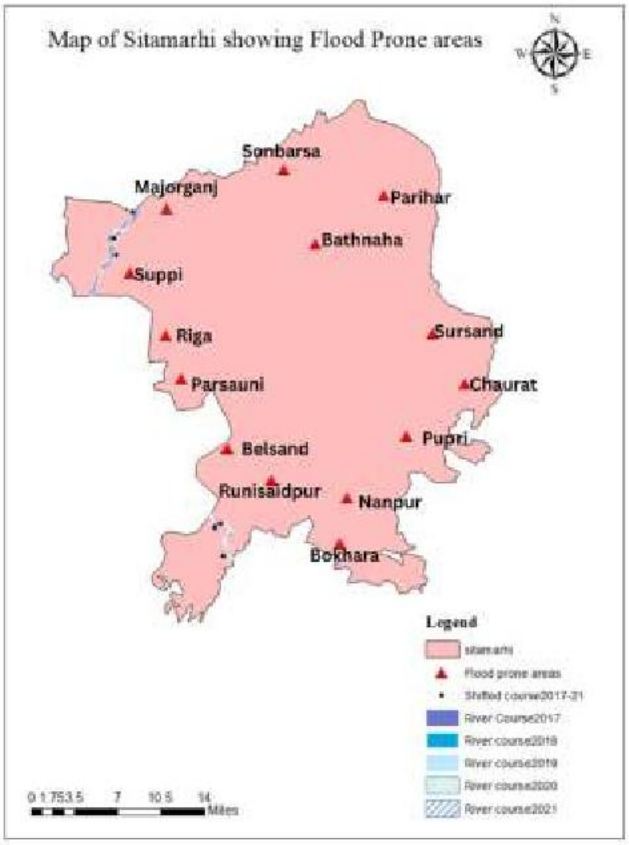


Fig.17. Interpretation of the Bagmati river channel migration

Multi-temporal analysis of Sentinel-2A post-flood imagery (November 2017–2021) combined with GIS-based manual digitisation reveals pronounced lateral instability in the Bagmati River within Sitamarhi district. Distinct blue-shaded overlays representing annual channel positions clearly illustrate spatial and temporal variations in river course behaviour.

In the northern Bagmati reach (Parihar–Sonbarsa region), the river exhibits severe channel instability. Measured displacements range from 228.72 m eastward to 577.13 m westward, indicating non-uniform and oscillatory migration. The maximum westward shift (>570 m) reflects major channel realignment caused by repeated flood events, intense Himalayan sediment influx, and weak alluvial banks. Such extreme lateral movement confirms that the northern section is highly erosion-prone and dynamically reshaped during peak monsoon years, resulting in elevated flood vulnerability.

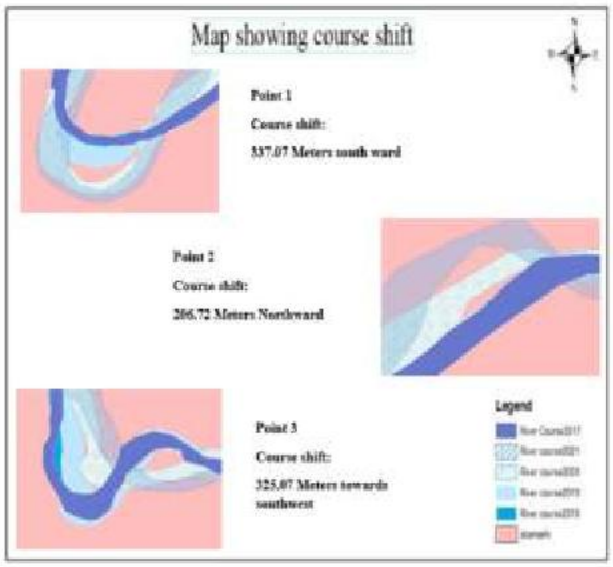


Fig. 18. Change in the course shift of the Bagmati River

The southern Bagmati stretch (Runni Saidpur–Belsand) (Fig.18) shows comparatively moderate but directional migration. Channel shifts vary between 206.72 m northward and 337.07 m southward, with an additional 325.07 m south-west ward displacement, (Fig.18) suggesting combined lateral and downstream migration. This behaviour reflects floodplain widening and gradual expansion of the meander belt into downstream blocks. Although relatively more stable than the northern reach, the southern segment remains strongly influenced by monsoon-driven flow energy.Channel migration analysis indicates that the northern bank of the Bagmati River experienced dominant westward erosion (~130 m/year), while the southern bank shifted towards the south-southwest (~85 m/year) Fig. 18.

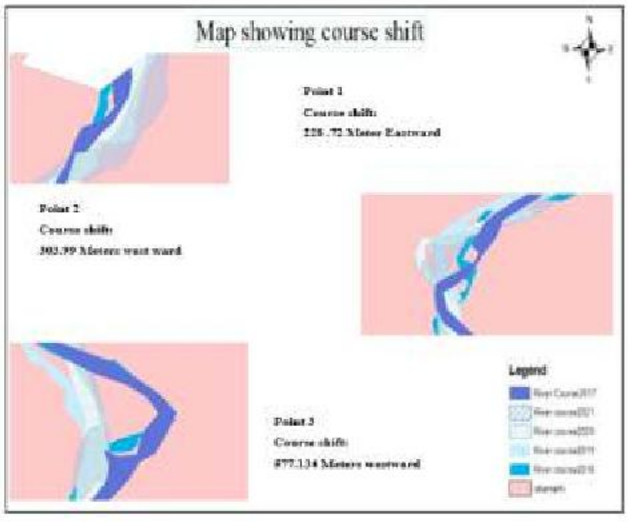


Fig. 19. Change in the course shift of the Bagmati River

Overall, the Bagmati River demonstrates braided to semi-meandering characteristics, with lateral migration ranging from 200 m to nearly 600 m within four years (Fig.19). Continuous sediment deposition, high monsoonal discharge, and floodplain congestion have raised the riverbed, enhancing lateral channel shifts during flood events. These permanent geomorphic changes have expanded the flood hazard zone, particularly in areas experiencing shifts exceeding 300 m, which represent high-risk erosion and inundation zones.

Summary of Key Findings (Sitamarhi District): During the study period (2017–2021), the Bagmati River in Sitamarhi district was examined for flood dynamics and channel migration using Sentinel-2 satellite imagery, Normalized Difference Water Index (NDWI), and GIS-based Land Use/Land Cover (LULC) analysis. The research team has. Below are the key findings.NDWI analysis has effectively identified flood-affected regions, revealing significant year-to-year variations in the extent of flooding. 2017.

According to analysis of the Bagmati River channel migration, erosion on the northern bank was mainly westward facing (130 m/year); while erosion along the southern bank had moved south-southwest (>85 mm/yr). LULC findings indicate that there is a decline in agricultural land and settlements, while water bodies, vegetation being flooded up to 40 megatons, and land degradation along the active channel belt. Sonbarsa, Parihar; Bairgania, Sursand and the Bajpatti along the Karmapatch plain are among the flood-prone blocks such as Charaut which have been affected by repeated inundation of rivers and channel instability.

It shows that this study confirms the very unstable and meandering nature of the Bagmati River in the Sitamarhi district. The expected patterns of flood and channel migration in Sitamarhi based on the flood map extents, LULC transitions and measured channel migration rates these are the following future trends: If the geomorphic and hydrological conditions remain unchanged, there is a high likelihood of increased flooding in Sitamarhi district, particularly in the northern and western areas. Further loss of agricultural land and homesteads may occur if the northern bank continues to migrate west, especially in low-lying floodplain villages. Potential downstream expansion of the floodplain is indicated by the south-southwestward shift towards the eastward bank, which could lead to an increase in waterlogging conditions. Permanent alterations in river alignment could pose an immediate danger to settlements, roads and embankments situated near the active channel zone. Food security and livelihoods will be negatively affected by the projected reduction in agricultural productivity caused by land loss of almost 20–22 hectares per kilometre of river length.

Concluding Recommendation:

Need for continuous monitoring, due to the rapid movement of the Bagmati River, ongoing monitoring through remote sensing and GIS is necessary. It is necessary to conduct regular analysis with satellite data before and after the monsoon season to ensure: Every year, floodhit areas expand and contract. Patterns of channel migration and bank erosion. Changes occur in water circulation and duration of floods. Flooded or barren land is commonly converted into cropland due to LULC changes.

Early warning systems and district-level flood preparedness can be enhanced through monitoring. flood occurrence. It concludes, "Not only is flooding occurring during extreme monsoonal events but also due to channel migration and change in land use"; this paper reports that the study finds that "In order to reduce flood vulnerability and promote sustainable development of the Bagmati floodplain", an integrated approach combining remote sensing with advanced techniques such as NDWI-based flood mapping, LULC analysis, and GIS-supported policy planning has to be adopted.

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