

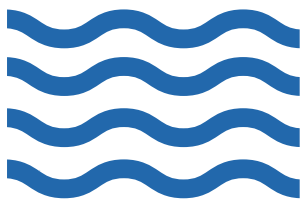
# IMPROVING UNDERSTANDING OF FLOODING AND RESILIENCE IN THE TERAI, NEPAL



THE UNIVERSITY *of* EDINBURGH







**Rivers sourced from the Himalaya irrigate the Indo-Gangetic Plain via major river networks that support approximately 10% of the global population and their livelihoods.** However, many of these rivers are also the source of devastating floods. This brief captures the collaboration between an interdisciplinary team of geoscientists, engineers, social scientists and architects from the University of Edinburgh alongside practitioners from the NGO Practical Action and the Nepal Department of Hydrology and Meteorology. The teams applied new science and appropriate technology, and conducted research with communities to better understand flood risk in the Karnali river basin, Western Nepal from an interdisciplinary perspective.

## CONTRIBUTORS:

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## RESEARCH FOCUS

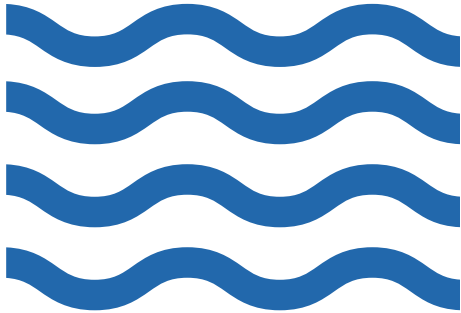
- A novel approach was used to assess flood risk in the Karnali River by integrating field techniques used to measure the amount of water flowing down the river (water discharge), channel geometry, and sediment load, with new satellite data coupled with a 2D hydrodynamic flood model (Delft3D).
- The new higher-resolution satellite data and the new field observations were combined to generate a 2D hydrodynamic flood model that was compared to existing flood inundation predictions used by the Department of Hydrology and Meteorology.
- The research aimed to improve understanding of the controls on channel stability versus their susceptibility to migration and switching across the Karnali River system.
- The research explored community views on their flood experiences, their strategies for building flood resilient dwellings, and how they respond to flooding.
- Interdisciplinary research integrated the knowledge of scientific and social science researchers, practitioners, and communities to identify and address the multiple and interlinked factors influencing flood risk.
- River-related hazards occur via a combination of over-bank flooding and channel migration/switching on the Karnali River. However, channel migration/switching cannot be modelled easily and is seldom incorporated into flood risk assessments.
- Understanding both hydrological processes and sediment dynamics are key to mitigating flood risk in the Karnali floodplain. Flood modelling outputs suggest that even small changes in channel bed elevation (driven by 1 or 2 m of sediment deposition on the channel bed) can markedly increase the extent of flood inundation; this should be incorporated into existing early warning systems and flood risk models of the region.
- To enhance the reliability of these models, regular field observations (e.g. water discharge down each branch, bed elevation) need to be fed into the model and used to verify model outputs to capture the constantly evolving nature of the system. Flood inundation extents and depths also need to be ground-validated with communities.

## CHALLENGES

- Flood risk may currently be incorrectly estimated in Nepal. Episodic changes in river course and sediment dynamics that alter the morphology (e.g. geometry, form) of the river channel and adjacent floodplain can modify the likelihood of flooding, but these processes are rarely considered in flood risk assessment.
- Flood hazard maps used to inform communities and build resilience are based upon static and outdated digital elevation models, which do not reflect the dynamic river configuration or hydrology.
- Implications of flood hazard maps need acceptance by local communities and government organisations if they are to have impact, therefore an understanding and appreciation of people's perceptions, attitudes, and relationship with the river is needed.
- Observations in the field, corroborated by satellite imagery, show that river channels are highly mobile and constantly evolve through each monsoon season. Construction of irrigation canals, embankments, and other engineering structures will alter the rate of channel migration, natural sediment dispersal across the wider floodplain, and sediment dynamics within the river channel; these effects should be integrated into environmental impact assessments prior to construction.
- Implications of these new scientific approaches need acceptance by local communities and government organisations, if they are to have an impact.
- Effective flood risk management must integrate both scientific and local knowledge, rather than only focusing on engineering measures, such as embankments, to mitigate flooding and river-related hazards.

## IMPACTS

- A new field-calibrated, flood inundation model was generated which incorporates geomorphological evidence and uses a higher resolution model of the landscape which more closely reflects the current Karnali River configuration.
- Flood inundation models were tested for several flood scenarios, incorporating varying channel geometries, to improve the understanding of the impact of changes in bed elevation due to sediment deposition and erosion on flood inundation.
- Communities living within the river basin have indigenous vernacular strategies for coping with floods. It is important to be sensitive to the multiple ways that local communities cope with flooding, drawing on oral knowledge and local practices.
- Local strategies for building are evolving, as the availability of new construction materials increases. It is apparent there are some skill shortages in both vernacular and contemporary building in rural housing.



## SECTION 1:

### UNDERSTANDING THE ROLE OF RIVER SEDIMENT ON FLOODING IN THE KARNALI AREA

#### PROBLEM AND WHY IT MATTERS

Rivers originating from mountains in Nepal carry millions of tons of sediment during the monsoon. Two major implications for flood risk are highlighted here:

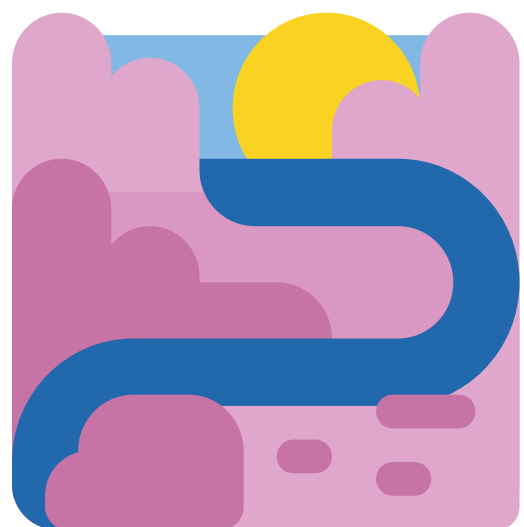
- Current early warning systems monitor upstream river levels to predict downstream flooding. However, where sediment accumulates on river beds, or is removed by erosion, water levels may not accurately correspond to the amount of water in the river.
- Flood prediction maps are based on a static digital landscape. However, during monsoon floods, erosion and deposition of gravel and sand changes the route of river channels across the Terai - these processes are not predicted by current flood models.

#### RESEARCH FOCUS

The amount of water discharged in the river at different times of the year, and the grain size of sediment in the river were measured. Grain size analysis determines how easily sediment is mobilised in the river.

#### HOW

For the first time, an Acoustic Doppler Current Profiler (ADCP)<sup>1</sup> was used to accurately measure river channel cross sections and their flow velocities at several locations along the Karnali River (Figure 1). Sediment grain size was measured using sieves on gravel bars, and filtered water samples from within the flow.



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<sup>1</sup> An ADCP is used to measure water current velocities over a depth range using the Doppler effect of sound waves scattered back from particles within the water column.



## RESULTS

The Karnali river splits into two branches and the ADCP measurements revealed that the west branch was responsible for 80% of the flow when river water levels were low, but only 50% during the monsoon. Historical information shows that these ratios vary significantly from year to year due to changes in sediment redistribution (see Section 3); this is critical input to flood models. The point of bifurcation of the two channels determines the amounts of water that flow down each channel, and this is defined by a gravel bar made of very coarse cobbles which are only mobilised during peak floods. Gravel gives way to sand on the bed of the river at about 30 km downstream of the mountain front, which is very near to the border with India.

## APPLICATION

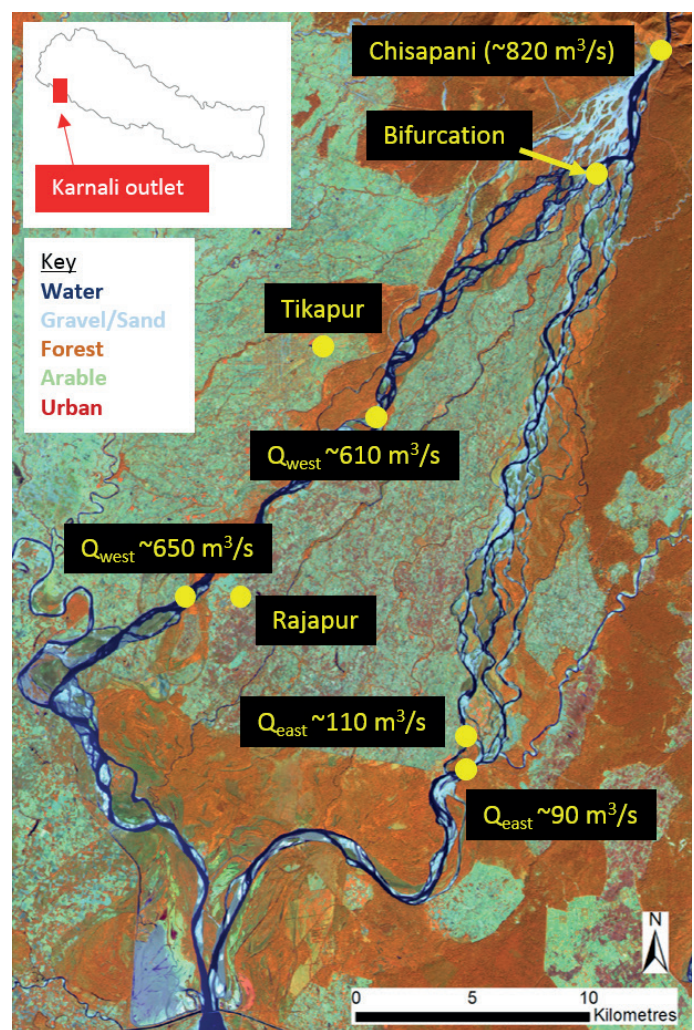
A team from the Nepal Department of Hydrology and Meteorology (DHM) accompanied researchers in the field and compared conventional methods for recording water discharge to the newly acquired ADCP data. The results were reassuringly comparable and so gave confidence to the new data. This is important as the ADCP enables measurement from bridges and boats throughout the river network. Repeated ADCPs at chosen sites can provide data on changes of channel shape as sediment is moved during floods. The water discharge data are critical input to the flood inundation modelling (such as HEC-RAS currently being used by DHM and Delft3D that is currently being trialled by Edinburgh University; see Section 2). This can then be used for land management, informing irrigation practices, and suggestions for crop usage by government bodies, as well as improving early warning systems for floods (see Section 3). Regularly measuring changes in sedimentation can also be used to update flood models.

## SUSTAINABILITY

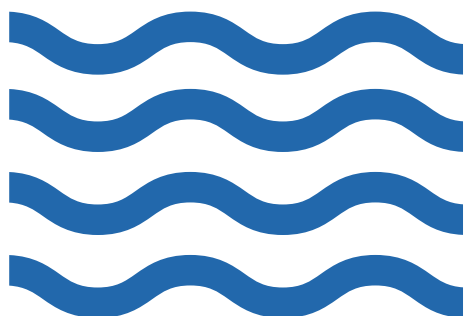
The route to sustainably embedding this technique into Flood Risk Management is through the DHM. DHM plan to procure two to three ADCPs in the next few years as a complement to their current measurement strategy. The data which has already been gathered will form the initial basis of a long-term programme to monitor channel sedimentation and water discharge.

## BROADER IMPACT

The role of sedimentation and erosion in modifying channel courses and flooding underpins much of the flood devastation across the Ganga Plains. The Karnali River represents the first series of experiments to use measurements of water and sediment in a flood model. This has implications for rural planning, particularly investment in embankments and irrigation systems. Improved confidence in predictions of water inundation during floods will also help engagement with local communities and support local resilience building.



**Figure 1:** 2014 Sentinel-2 false colour satellite image of the Karnali River downstream of Chisapani. The approximate discharges ( $Q$ ) measured from select ADCP surveys in October 2016 are also shown.



## SECTION 2: IMPROVING FLOOD INUNDATION MAPS

### PROBLEM AND WHY IT MATTERS

Current flood prediction maps are produced using satellite data (digital topography) and hydraulic models. In Nepal, current topography maps used for flood modelling are based on data acquired in 2001 (Figure 2). The Karnali is a dynamic river and its course changes frequently (see Section 3). The 2001 data do not account for recent changes to the river or changes in bed elevation caused by the movement of sediment during the monsoon season. Current maps constrain the effectiveness of flood risk management planning and undermine confidence in the reliability of flood inundation maps.

### RESEARCH FOCUS

Research explored the impact of using higher resolution satellite data (Figure 2), obtained in 2013, on numerical model results. The sensitivity of flood inundation maps to changes in bed elevation was also tested.

### HOW

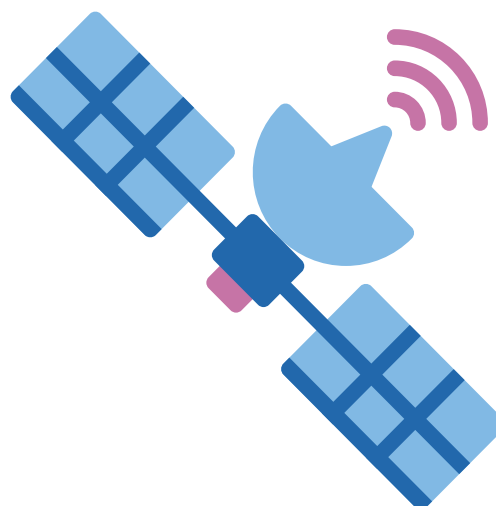
Higher resolution satellite data was input into hydraulic numerical models. A variety of flooding scenarios of different magnitudes were analysed, and the results were compared to existing flood inundation maps. In addition, the model was run several times with different channel geometries and river conditions to investigate how changes to the river may affect flood extent.

### RESULTS

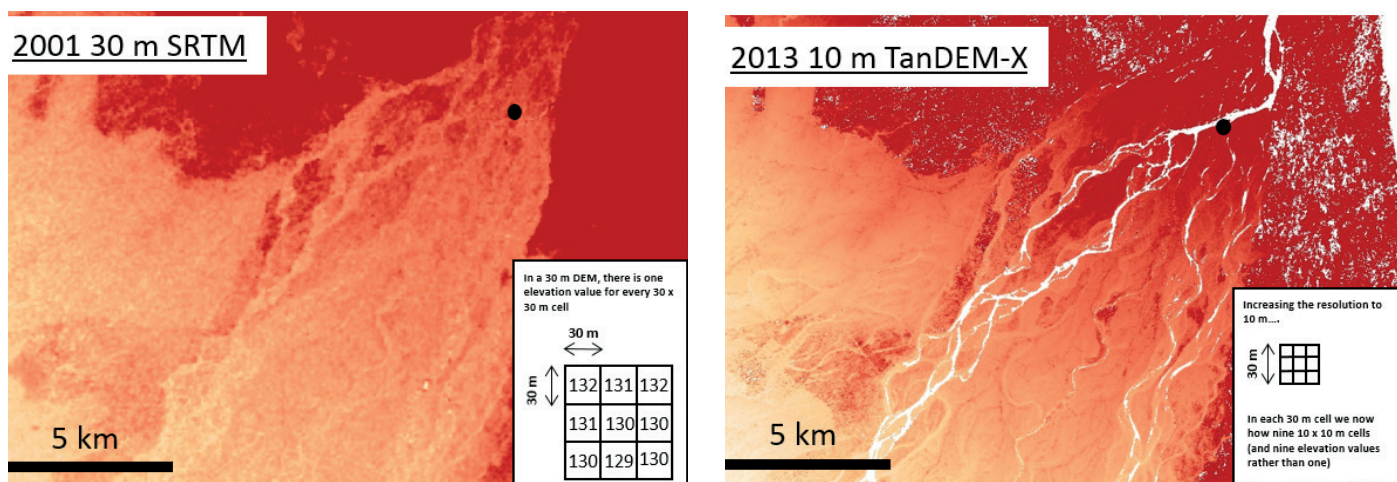
This technique enabled the production of more detailed flood inundation maps. Flood risk in certain areas of the floodplain was shown to be sensitive to changes in river geometry caused by the movement of sediment. In some regions, flood extent was different from the current flood inundation maps used in Nepal. This work highlights the need to validate the flood inundation maps with local community knowledge of past flood events.

### APPLICATION

The detailed flood maps produced using this method can be used to identify hazard-prone areas, and to estimate the likely extent and depth of flooding. Use of satellite data updated to represent the present river bed geometry could enhance the accuracy and effectiveness of the flood early warning system. Improving the confidence in the reliability of flood maps may also be useful to influence flood resilient housing, investment, and sustainable river management.







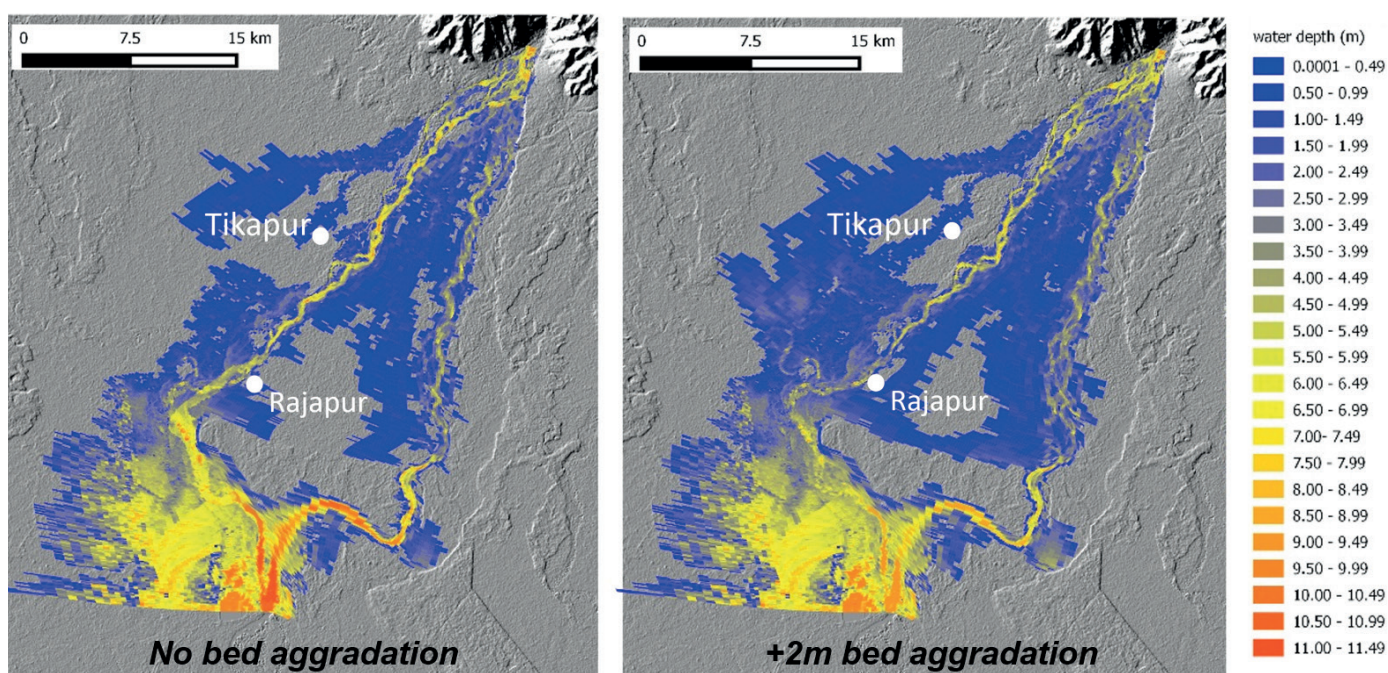
**Figure 2:** Comparison of Digital Elevation Models (DEM) for the Karnali River at 30m (left) and 10m (right) resolutions. The right image is of the unprocessed TanDEM-X data which has no data values shown in white. The black dot represents the bifurcation point in both images.

## SUSTAINABILITY

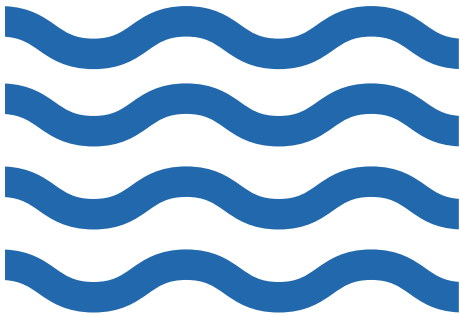
Sustainability can be achieved through adoption of the new technique by DHM and other government institutions involved in flood and river management. Validation and calibration of results from the flood inundation maps with communities would be critical to have confidence in using the new maps and adopting the technique. This would also engage the local communities more actively in the development and implementation of the early warning systems.

## BROADER IMPACT

This technique can be generally applied in other river basins to generate flood inundation maps.



**Figure 3:** One in 20 year flood inundation maps (using a Delft3D model) to examine the effects of sediment deposition on flooding extent. The two model runs are identical except for a uniform 2m increase in channel bed elevation (figure on right), which results in a notable increase in inundation extent for the same flood discharge.



## SECTION 3:

### IMPROVED UNDERSTANDING OF RIVER CHANNEL MIGRATION AND SWITCHING

#### PROBLEM AND WHY IT MATTERS

The Karnali River has one of the greatest sediment loads of any river in Nepal, which is a key control in determining the rate of channel migration and switching across the river floodplain. Satellite imagery from the last ~50 years illustrates the high rates of channel migration and switching. Channel migration occurs by lateral erosion of one of the river banks, whilst channel switching typically occurs as a result of sediment deposition on the river bed. In this instance, the river bed rises above the adjacent floodplain and eventually changes course (or switches) to an alternative route at a lower elevation. If the river channel switches during floods, the new channel may direct flow into areas where previously there had been no channel.

Embankments may also accelerate the rate of river switching and migration. Channel migration is a natural process allowing sediment to be dispersed across the wider floodplain over decadal to thousand year timescales (Chakraborty et al., 2010). Constraining movement of the channel prevents sediment dispersal, focusing sediment deposition onto the channel bed between the embankments. This may increase the rate of channel bed sedimentation, and thus the rate of channel switching. Erosion of the embankment also compromises its strength, especially during high flows. The 2008 Koshi flood was initiated in a similar manner (i.e. an embankment breach through a weakened portion) (Sinha, 2008). Disconnecting the river from the wider floodplain will also have negative effects on the replenishment of soil nutrients and on land drainage.

#### RESEARCH FOCUS

This research seeks to map out historical channel pathways of the Karnali River and to determine the rates of past channel switching and migration.

#### HOW

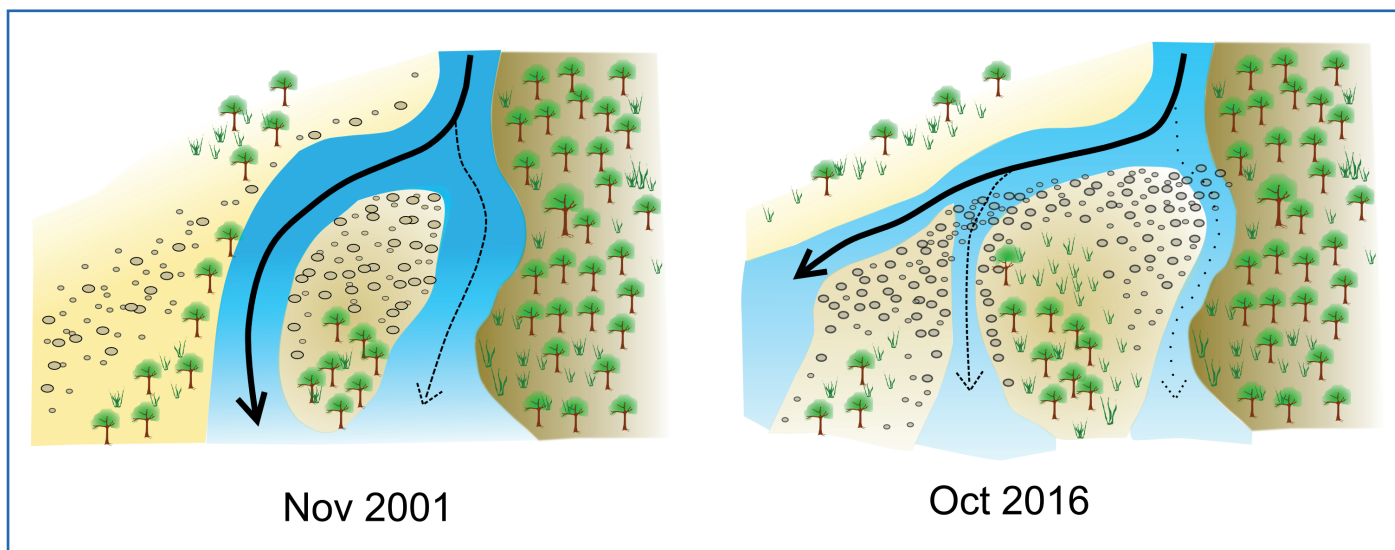
Past channel shifting was mapped using optical satellite imagery. Optically Stimulated Luminescence (OSL)<sup>2</sup> samples were also collected from abandoned river terraces and channels to date these features and to understand the timeline of river channel switching.



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<sup>2</sup> OSL dating is a technique used to date the last time quartz sediment (sand in this instance) was exposed to light. Using this technique, we can sample buried river sand deposits in old channels and terraces to determine when they were deposited by the river. channels has occurred on a >100 year timescale.





**Figure 4:** Schematic of Karnali bifurcation migration (same spatial frame in both images). Plan view of the bifurcation point in 2001 and 2016 showing the change in the bifurcation morphology.

## RESULTS

Noticeable channel reorganisation was noted over the past 50 years, particularly at the bifurcation (where the river splits into two branches - see Figure 4) and lower portions of the west branch. The OSL ages from abandoned channels range from about 500 to 2000 years old suggesting that large scale re-routing of channels has occurred on a >100 year timescale.

## APPLICATION

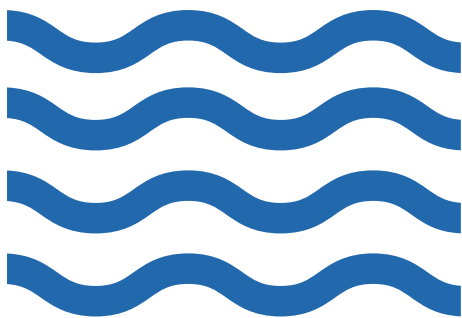
Channel migration and switching are not taken into account during flood risk assessments. It is well known that the main river switches channel, but the frequency and patterns of switching vary as a function of the river discharge and the sediment supplied to the channel and floodplain. Identifying parts of the river system which are most mobile or at risk of channel switching is integral in defining regions at risk to this type of flooding. This information could also help guide embankment design and placement.

## SUSTAINABILITY

Whilst the results of this research would be useful to the DHM, there is not sufficient capacity at present to continue the research and take specific actions based on the findings. Collaboration with other departments such as the Department for Water Induced Disasters Management (DWIDM) under the Ministry of Irrigation would be crucial.

## BROADER IMPACT

Historically, communities living along the most active parts of the river have adapted, such as being mobile in their location. However, it is uncertain whether their past adaptation methods will be viable in the future as styles of house construction change and become more permanent (see Section 5). The long-term effects of embankment construction along these types of sediment-laden (and mobile) rivers on channel switching are poorly understood, but are applicable to many other river systems.



## SECTION 4:

### SOCIO-CULTURAL AND POLITICAL ECONOMY LANDSCAPE OF FLOODING

#### PROBLEM AND WHY IT MATTERS

Floods affect people, who are shaped by uneven geographies of caste, class, ethnicity, gender and age, making some people more vulnerable to flooding than others, resulting in uneven flood impacts. We need to better understand the differences in the social landscape, so that the most vulnerable are protected and supported.

Scientific and engineering practices dominate flood interventions in the Karnali region, including early warning systems, the construction of embankments to 'train' water flows, and construction of refuges as protection during inundation. These interventions assume that the region is static, despite evidence of significant socio-economic transformations and changes to the physical landscape. These changes need to be better understood to manage flood risk more effectively.

#### RESEARCH FOCUS

To develop a better understanding of how physical and socio-economic processes produce new opportunities, change expectations, and affect vulnerabilities to flooding in the Karnali basin.

#### HOW

The study team interviewed people in communities between Chisapani, Rajapur, and Tikapur in the Rajapur and Bardiya districts, in the lower Karnali basin and observed their everyday life and livelihoods, settlements, construction of buildings and physical infrastructure.





## RESULTS

Research suggested households with fewer social and political networks and economic capital are more vulnerable to impacts of floods than others. Floods often have lasting impact on their inability to improve well-being and livelihoods.

The entire region is going through a major social transformation, most visible in the form of commodification of land and labour, as well as new physical infrastructure and buildings (see Section 5). While viable social transformations in the entire region (such as out-migration of young men) may have provided people with cash and opportunities to integrate with the market and thus diversify their livelihoods, they have also exposed people to new vulnerabilities, such as unstable income and less social support during the flooding season.

For the people, the river is more than solely flood risks; it has been a site of development interventions, such as irrigation canals and bridges, as well as extraction of stone and gravel for construction of embankments and increasing concrete housing construction. These development interventions create new opportunities for adaptation and progress, and create a sense of security to communities. However, these developments also expose people to new vulnerabilities, such as less mobile and higher valued housing which may be at risk of increased flooding if the river changes course (see Section 5), decreased drainage leading to increased inundation, and increased populations who perceive themselves as 'safer' despite being located in areas at risk from the breaching of embankments.

## APPLICATION

Physical interventions need to account for community livelihoods, perceptions, and practices holistically rather than just focussing on flood risks. Socio-economic profiling of people is necessary to identify those most vulnerable to flooding. Flood inundation maps will need to be developed in sync with socio-economic maps. and sustainable river management.



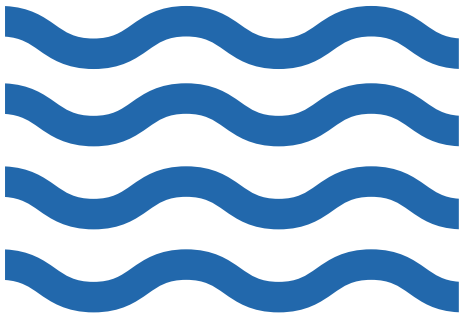
**Figure 5:** Woman in Rajapur arranging a mud dung paste for flooring in her house. Dung makes mud more resistant to disintegration and improves its capacity to absorb water. It also acts as a natural disinfectant and mosquito repellent, protecting residents from the spread of disease.

## SUSTAINABILITY

Research and technical inventions on flood control will need to account for the dynamic political economy and local people's perceptions of the river systems. This requires involvement of social science researchers as well as social scientists working with stakeholders such as local government, NGOs, and communities to consider social dimensions alongside the physical side. Inequities in social systems and uneven geographies specific to the Karnali region will also need to be considered.

## BROADER IMPACT

The research highlights the need for Disaster Risk Reduction programmes to understand both people's perceptions and aspirations of the river systems, as well as the socio-cultural and political economic profile of the flood plains that are going through significant transformations and developments.



## SECTION 5:

### INDIGENOUS AND EVOLVING FLOOD RESILIENCE CONSTRUCTION STRATEGIES IN THE KARNALI

#### PROBLEM AND WHY IT MATTERS

Indigenous local knowledge and traditional practices are necessary in developing resilience to both recurring and extreme flood events exacerbated by climate change (MoSTE, 2015). Vernacular construction techniques are inherently specific to location, available material, and skill, having evolved through generations by custom and practice. Nepal has many examples of flood resilient construction (Gautam et al., 2016). Nevertheless, they are often displaced by more modern techniques and materials, predominantly reinforced concrete. The resilience of these buildings can be verified in engineering terms more easily than comparable vernacular designs. However, these systems require different skills, technical expertise, and much higher levels of finance.

#### RESEARCH FOCUS

The research involved a short but intensive field-study of construction practice in the Karnali river plain, between Chisapani, Rajapur and Tikapur.

#### HOW

A range of settlements in the area were visited to observe and discuss construction methods and attitudes to developing practice, including flood refuge buildings, with local communities.







**Figure 6:** Traditionally constructed flood resilient house in Karnali. The main living space sits on a platform raised above the height of the highest flood level on moisture-resistant timber posts. The electrical supply to the house is connected just below roof level.



**Figure 7:** House with limited resilience, located less than 50 metres from the river. Constructed of timber, bamboo and earth, it sits on a slightly raised platform below the levels reached by water during flooding.

## RESULTS

Flood-resilient vernacular houses are constructed using large timber posts to support the main living floor above the extreme flood level. One house had been completely rebuilt by the owners after the 2014 flood and re-located to a higher level on the site (Figure 6). This demonstrates a key aspect of resilience – the family unit was able to respond quickly and largely autonomously to the disaster.

In other settlements, the same skills in building were not apparent (Figure 7 and Figure 8). The ground floor was elevated less than a metre above ground on a raised plinth, despite being approximately only 50 metres from river. The overall quality of building was much lower and the use of good quality timber considerably less.

Three reinforced concrete flood refuge platforms were inspected and these were to a high standard of construction (Figure 9). They represent major investments in the communities that they serve. Subject to community consultation, more guidance in detailed design would provide additional benefits.

There is a clear desire to build robust, resilient buildings using concrete. An indigenous form of concrete construction is evolving with many examples under construction, often adjacent to traditional vernacular housing; concrete columns project from raised plinths, built using recovered river stone (Figure 10). The quality of workmanship was generally much lower than the flood refuge, particularly in terms of formwork and reinforcement (Figure 11). The cost of materials is high, particularly in comparison to daily wage rates.

In all sites there was a lack of basic safety, including in handling materials, lifting, and lack of protective equipment.

## APPLICATION

Appropriate vernacular construction can provide culturally appropriate resilience but does require knowledge to be shared and transferred between communities; the poorest communities may not have access to either the vernacular knowledge or the materials. Further research is necessary to fully understand the economic and skills barriers to self-development among certain communities.

It is apparent that local practice in reinforced concrete construction is evolving. The difference between the contemporary buried foundation (Figure 9) and the localised raised foundation using recovered river stones (Figure 10) is clear. Practical training and development in both vernacular and modern techniques is essential. Ideally through locally led workshops and practical demonstration projects. Simple rules of thumb and guidance on small scale domestic construction could be developed to suit local needs and available resources. Hybrid construction systems should be developed, which may bring together both vernacular materials and modern construction in a more economic and resilient way.

## SUSTAINABILITY

Vernacular systems are inherently sustainable. Evolving systems should use concrete and steel only where most essential to guarantee resilience and, in turn, reduce costs for households and ensure sustainability.

## BROADER IMPACT

An effective system of development that embraces local knowledge and practice could be broadened and adapted to many similar situations.





**Figure 8:** Ad-hoc timber construction. This image demonstrates a number of important points, the lack of availability or access to appropriate timber in long enough lengths, the use of random pieces of timber to provide additional height and little or no skill in carpentry to make an effective joint.



**Figure 9:** Engineered reinforcement for flood refuge shelters. Eight deformed steel bars, which have a rippled surface to attach more effectively to the concrete, are tied at frequent intervals with horizontal steel links for a robust structure. This type of reinforcement did not seem to be available at the local suppliers we visited.'



**Figure 10:** A new concrete house being built adjacent to a traditionally flood resilient house. Note the raised plinth platform and concrete pillars. Concrete represents a considerable financial investment compared to vernacular construction and may be perceived by local communities to be more resilient.



**Figure 11:** Building under construction. Note the ad-hoc, poorly constructed formwork and inadequate reinforcement. The local supply of materials was limited to smaller diameter, plain (non-deformed) bars with little attention to the use of steel links. Scrap timber boards are used to contain wet concrete, with little or no effective carpentry in evidence.



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