ICIMOD

POLICY BRIEF

Sediment management in the Koshi basin

Lessons learnt and challenges ahead

KEY MESSAGES

The Koshi is a highly dynamic and sediment-charged river; therefore, sediment management is a major challenge

The high sediment flux of the Koshi basin is linked to several river-related hazards such as floods and channel shifting in the downstream reaches

Human interventions such as embankments and barrages have significantly impacted sediment dynamics

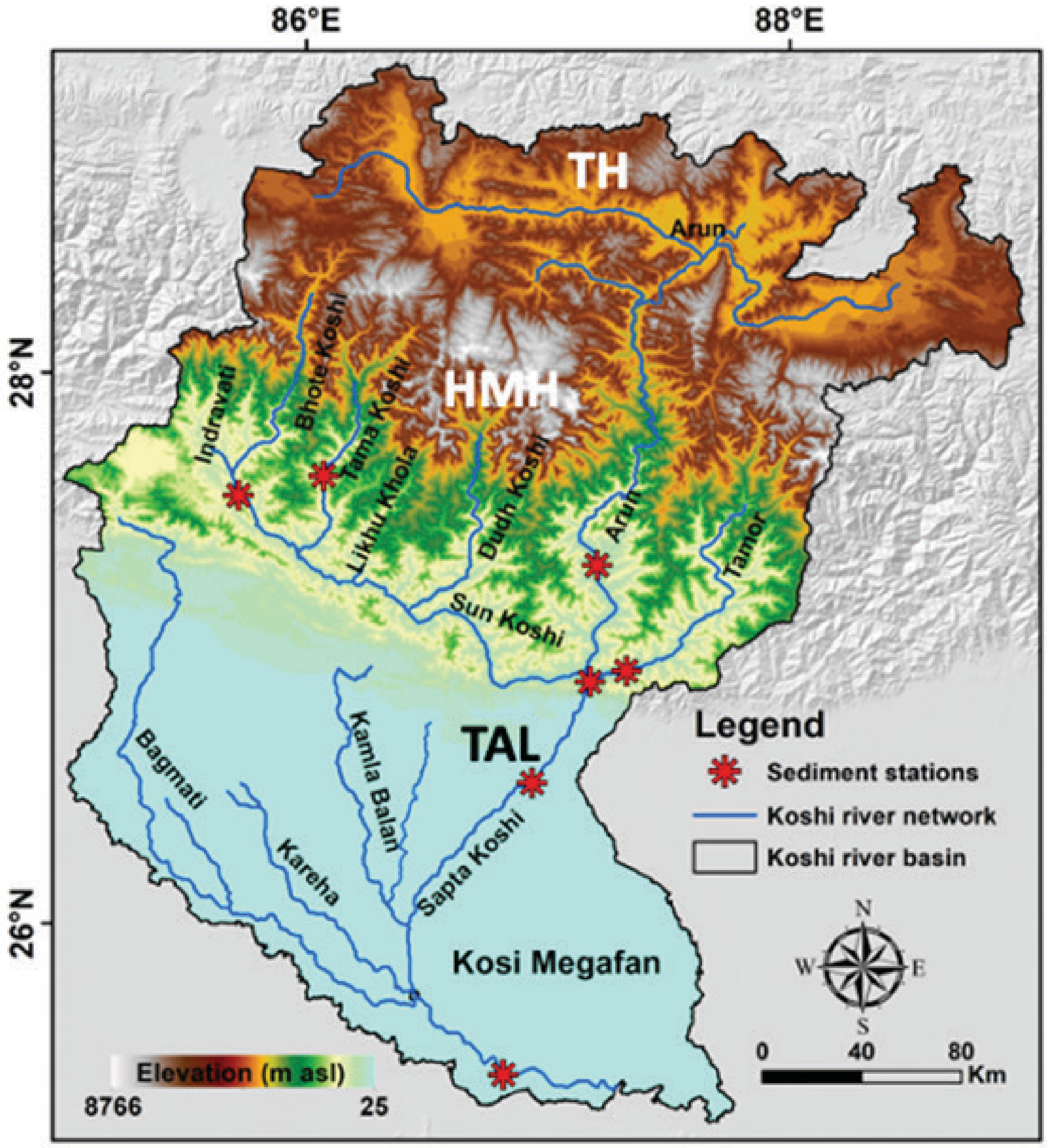
An efficient sediment management strategy, therefore, needs a comprehensive understanding of processes of sediment production, sediment dynamics, and pathways of sediment movement (sediment connectivity)

The Koshi: A large sediment dispersal system

The transboundary Koshi River (also known as the Kosi) is characterized by exceptionally high sediment flux produced by frequent landslides and mass wasting in the upper catchments. High sediment production in this region is facilitated by geological factors while high rainfall mobilizes sediment downstream.[1] This, in turn, leads to several associated hazards such as frequent channel migration and extensive floods in the alluvial plains. While these issues in the Koshi basin are well known, a comprehensive scientific understanding which could provide long-term solutions to these recurring problems is lacking. This policy brief highlights the causal factors of high sediment flux in the Koshi basin and its linkage to associated hazards, emphasizes the need for a process-based understanding of sediment production and transfer, and recommends policy-level interventions through transboundary cooperation.

The Koshi drains a large part of the east-central Himalaya including Mount Everest and Kanchenjunga, the highest peaks in the world, before debouching into the alluvial parts of Nepal and India. The Koshi basin can be broadly divided into three major physiographic zones: (a) the Trans-Himalaya covering the high mountainous areas of Tibet, (b) the High and Middle Himalaya mostly in Nepal, and (c) the alluvial part consisting of the Terai region of Nepal and the flat plains of India characterized by a large megafan and interfan area (Figure 1). In the Himalayan part, seven major tributaries, namely, Bhote Koshi, Dudh Koshi, Tama Koshi, Indrawati, Sun Koshi, Arun, and Tamor join to form the Sapta Koshi. In the alluvial

FIGURE 1 **THE KOSHI BASIN, COVERING PARTS OF TIBET AUTONOMOUS REGION OF CHINA, NEPAL, AND NORTHERN INDIA, IS DIVISIBLE INTO THREE PHYSIOGRAPHIC ZONES**



(a) Trans-Himalayan (TH) part, (b) High and Middle Himalayan (HMH) part, and (c) Terai and alluvial (TAL) plains. The background colour shows the elevation and the red dots show the hydrological stations.

Source: Sinha et al. (2019).

part, the Bagmati and Kamla Balan are the two major tributaries that join the Koshi. With a total area of 87,481 km^2, the Koshi sustains the livelihoods of almost 40 million people who are mostly dependent on subsistence agriculture. Yet, a clear understanding of sediment dynamics and their associated problems in the Koshi basin continues to elude researchers and policy managers. This is because they lack adequate understanding of the processes of sediment production and transport, and do not have sufficient estimates of sediment accumulation (Figure 2). The absence of comprehensive plans for beneficial and economic use of sediments adds to the problem, particularly in terms of policy interventions.

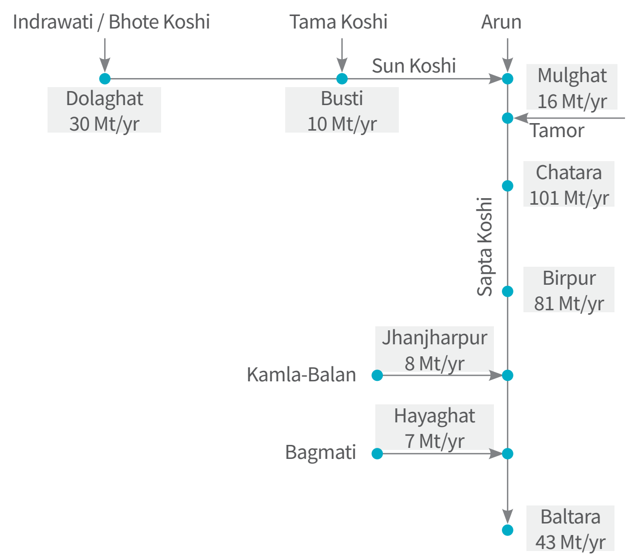
A recent study[2] in the Koshi basin based on the Revised Soil Loss Equation (RUSLE) estimated total soil erosion as 724 x 10^6 t/yr, a large part of which comes from the mountainous region. Sediment yield at the mountain exit of the Koshi basin (Barahachhetra) was computed as 86.4 x 10^6 t/y which corresponds to ~15% of the total soil erosion from the contributing area of the basin. Further, a first-order sediment budgeting from measured hydrological data[1] revealed that the

FIGURE 2 **REASONS WHY THE SEDIMENT PROBLEMS IN THE KOSHI BASIN HAVE REMAINED UNRESOLVED**

1. Lack of process-understanding, basin-scale data on hydrology and sediment flux
2. No basin-scale maps of erosion and hotspots of sediment production and deposition
3. No quantitative estimates of catchment erosion rates, sediment flux and silt accumulated in the channel
4. No comprehensive plans to utilize the removed sediment

average annual sediment load at Chatara is 101 x 10^6 tonnes, which decreases to 81 x 10^6 tonnes at Birpur and 43 x 10^6 tonnes at Baltara (Figure 3). A conservative estimate based on this data suggests that 408 and 1080 million m^3 of sediment may have accumulated within the embankments in the Chatara-Birpur and Birpur-Baltara stretch, respectively, in the last 4–5 decades[1]. The problems induced by high sediment flux have been aggravated in recent years primarily due to several interventions for water resource development, including a barrage at Chatara (Nepal) and Birpur (India) and embankments on both sides of the river that were completed around 1965. Future multi-purpose river projects such as reservoirs and bridges in the Koshi basin, too, are likely to face serious problems of high sediment transport and aggradation. Additionally, these projects may also trigger population displacement and have adverse socio-economic impacts on the livelihoods of the communities. Yet, none of the countries sharing the Koshi basin have incorporated sediment management strategies into their standard protocols for river management to date. This policy brief aims to sensitize the different stakeholders on the issues related to sediment management in a transboundary river basin such as the Koshi and to initiate meaningful consultations among the policy makers.

FIGURE 3 **A FIRST-ORDER SEDIMENT BUDGET OF THE KOSHI BASIN BASED ON AVERAGE ANNUAL SEDIMENT LOAD DATA AT DIFFERENT STATIONS**

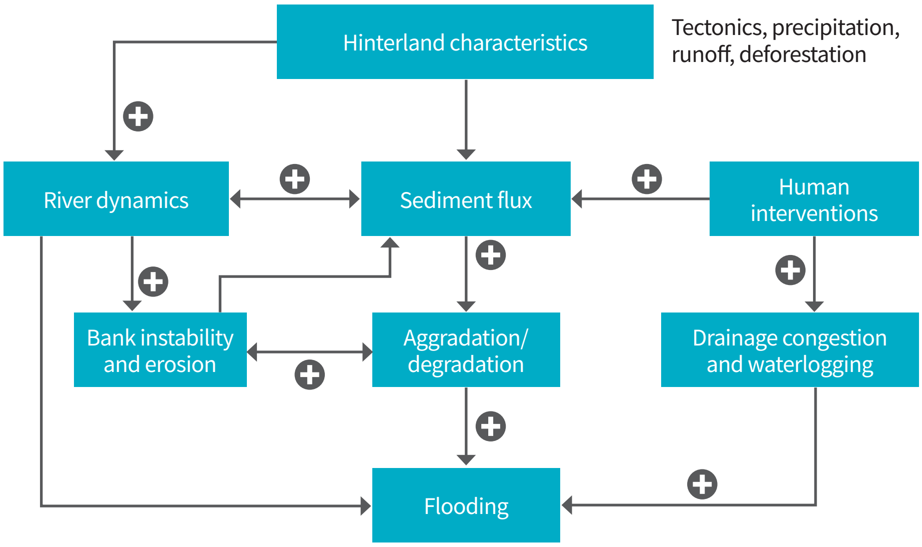


Modified from: Sinha et al. (2019).

The process–response system in the Koshi basin – linking sediment flux to hazards

In river basins, both natural and anthropogenic factors are responsible for erosion and sedimentation, although natural forces operate on a larger scale compared to anthropogenic activities. The Koshi basin has attracted significant international attention over the last couple of decades with several studies focusing on basin-scale hydrology, erosion, and sediment production, and sediment transfer pathways in the mountainous catchment. High sediment flux in the Koshi basin is a central problem, which is linked to several hazards through a process-response system (Figure 4). In the Koshi basin, high sediment flux is primarily the result of a diverse hinterland consisting of the Tethyan sedimentary sequence, the Greater Himalayan crystalline series, the Lesser Himalaya and the Outer Himalaya/Siwalik Hills. These major geological units are separated by major thrust systems which are tectonically active and often cause major landslides and mass wasting. Furthermore, degraded

FIGURE 4 SEDIMENT FLUX, HUMAN INTERVENTIONS, BANK INSTABILITY AND EROSION, DRAINAGE CONGESTION AND WATERLOGGING



land use patterns and deforestation on mountain slopes accelerate erosion. Intense rainfall during the monsoon season amplifies the erosional processes and mobilizes the sediments down into the alluvial reaches of the rivers where lower slopes and wider channels encourage natural deposition. The confinement of the river within the embankments exacerbates the natural sedimentation processes in the alluvial reaches. This leads to excessive riverbed aggradation ('superelevation'), which triggers frequent breaching, flooding and bank erosion[3]. Amplified bank erosion can heighten the risk of water-induced disaster during the monsoon while increasing the likelihood of the river shifting its course.

Understanding the upstream–downstream linkage in the Koshi basin

The need for better understanding the upstream–downstream linkage in assessing the sediment dynamics in a mountainous basin[4] is simple: The sources of sediment production, sediment transfer pathways, and their impacts may lie in different parts of the basin. Some important questions that need to be asked while designing evidence-based sediment management strategies for the Koshi basin, therefore, are as follows: How does Land Use and Land Cover (LULC), particularly forest cover change in the upper catchments, impact the runoff and sediment flux in the alluvial reaches – in particular, the peak flows and in-channel siltation? How well connected are the hillslopes and channels to enable transport of eroded sediment to the main stem and how efficiently does the main channel transfer the sediment downstream? Can the temporal changes in natural (e.g., climate) and anthropogenic (e.g., hydraulic structures) factors modify this connectedness and amplify sediment delivery? If so, how? What roles have anthropogenic structures such as hydroelectric projects and the Koshi Barrage played in influencing sediment dynamics and downstream impacts?

Forest cover generally influences local hydrology through the combined effects of evapotranspiration and infiltration, which, in turn, impact erosion dynamics[5]. In general, forest reduction increases water yield and vice versa. However, there is ample evidence to show that forest cover reduction in the upstream catchment may not necessarily impact downstream flooding significantly, particularly, in the case of large events[6,7]. However, this is by no means to justify large-scale deforestation in any river basin. Studies in several small catchments in the Koshi basin have indicated that soil erosion is significantly higher in rain-fed agricultural areas compared to areas of forests and grazing land[8,9]. However, the relative impact of LULC changes on erosion may be low in regions with high precipitation, steep terrain, and high natural erosion rates due to fragile lithology, as is the case in the Koshi basin[10,11]. In addition, large-scale road construction activities in the mountainous region have also enhanced erosional activities, which adds a significant amount of sediment to the Koshi River through slope failures.

In mountainous catchments, the degree of linkage between the upstream sediment sources and downstream areas is generally analysed through the concept of 'sediment connectivity'[12,13], which primarily includes slope and LULC factors to define the likely pathways of sediment transfer. Studies have indicated that there is significant spatial variability in sediment connectivity in different parts of the Koshi basin, which eventually influences the sediment yield from individual sub-basins[14]. For example, the sub-basins, Dudh Koshi, Bhote Koshi, and Tama Koshi, were found to be well-connected but the large size and variable slope of the Arun basin result in an overall moderate sediment connectivity. Similarly, the high forest cover in the Tamor basin reduces the efficiency of sediment remobilization from the hillslopes to the channel, making it a moderately connected system. The Indrawati, Sun Koshi, and Likhu Khola are elongate sub-basins that are mostly dominated by forest cover which stabilizes the hillslopes and results in a minimal channel gradient that impedes sediment connectivity. Therefore, integration of the connectivity analysis with a hydrological analysis has proved to be extremely rewarding in understanding erosion dynamics and sediment transport potential[15].

Major lessons learnt and key messages

THE CENTRAL PROBLEM - HIGH SEDIMENT YIELD

The high sediment yield in the Koshi basin is attributed to high rainfall, steep topography, unstable channel longitudinal profiles, and high sediment connectivity[1,14,15]. In particular, approximately 40% of the Koshi basin in the Higher Himalaya and Siwalik Hills is characterized by steep slopes and high rainfall, which substantially increase the sediment generation potential and shorten the travel time of sediments to the outlet[16].

EXCESSIVE SEDIMENT FLUX ENHANCES CHANNEL DYNAMICS AND FLOOD RISK

Excessive sediment flux and in-channel siltation enhance the flood risk in two ways: (a) a reduction in channel capacity to convey flood waters and (b) deterioration in flood protection structures due to channel dynamics and scouring. In the Koshi basin, excessive siltation in several reaches has resulted in a 'superelevated' channel[17,18] leading to channel avulsion and extensive flooding, a recent example being the Kusaha breach in 2018[19-22]. It is, therefore, important to understand such linkages between sediment flux and associated hazards in order to plan science-based mitigation measures.

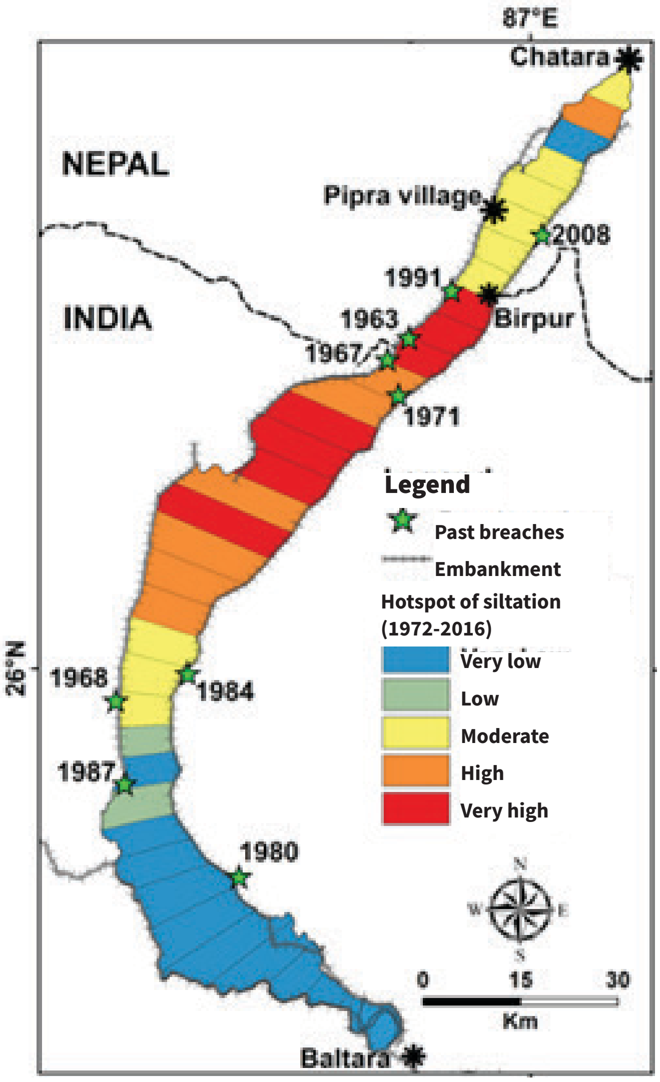
HUMAN INTERVENTIONS HAVE AGGRAVATED IN-CHANNEL SILTATION

Anthropogenic interventions such as embankments, barrages, and hydroelectric projects significantly influence downstream conveyance of water and sediment encouraging, thereby, in-channel siltation. The construction of the Koshi Barrage as well as embankments on both sides of the river has impacted the natural process of channel shifting[24] resulting in several breaches and extensive flooding during the last ~50 years[21,25]. Figure 5 shows that several of these breaching sites coincide with the hotspots of siltation[26].

SPATIAL VARIABILITY IN SEDIMENT CONNECTIVITY IS THE OVERARCHING ISSUE

Significant spatial variability in sediment connectivity in the Upper Koshi basin[14] is influenced by catchment attributes, channel characteristics, and the combined effects of vegetation. A key finding is that slope is not always the governing factor; rather, LULC, too,

FIGURE 5 HOTSPOTS OF SILTATION IN THE ALLUVIAL REACHES OF THE KOSHI COINCIDE WITH BREACHING SITES SUGGESTING A CLOSE RELATIONSHIP BETWEEN SEDIMENT AND RIVER DYNAMICS



Source: Sinha et al. (in press). This includes the August 2008 breach at Kusaha, which resulted in extensive flooding even though it occurred at a relatively low water discharge (4,320m^3/s) compared to the design discharge (28,500 m^3/s) of the embankment.

influences the connectivity values significantly in the upper Koshi basin. The interrelationship between sediment connectivity and sediment flux is clearly underscored by the fact that ~80% of the total annual sediment flux of ~101 million tonnes at Chatara in the Koshi basin is contributed by the western and central tributaries[1], which are amongst the most dynamic and well-connected systems[14]. Therefore, understanding this relationship is critical in assessing downstream sediment delivery and in designing region-specific sediment management strategies.

Policy recommendations and way forward

Sediment management should be an essential component of river management strategies. It must be based on a strong understanding of sediment dynamics. The sediment management framework in the Koshi basin must be based on scientific principles grounded in fluvial geomorphology. The following policy recommendations are proposed for sediment management in the Koshi basin:

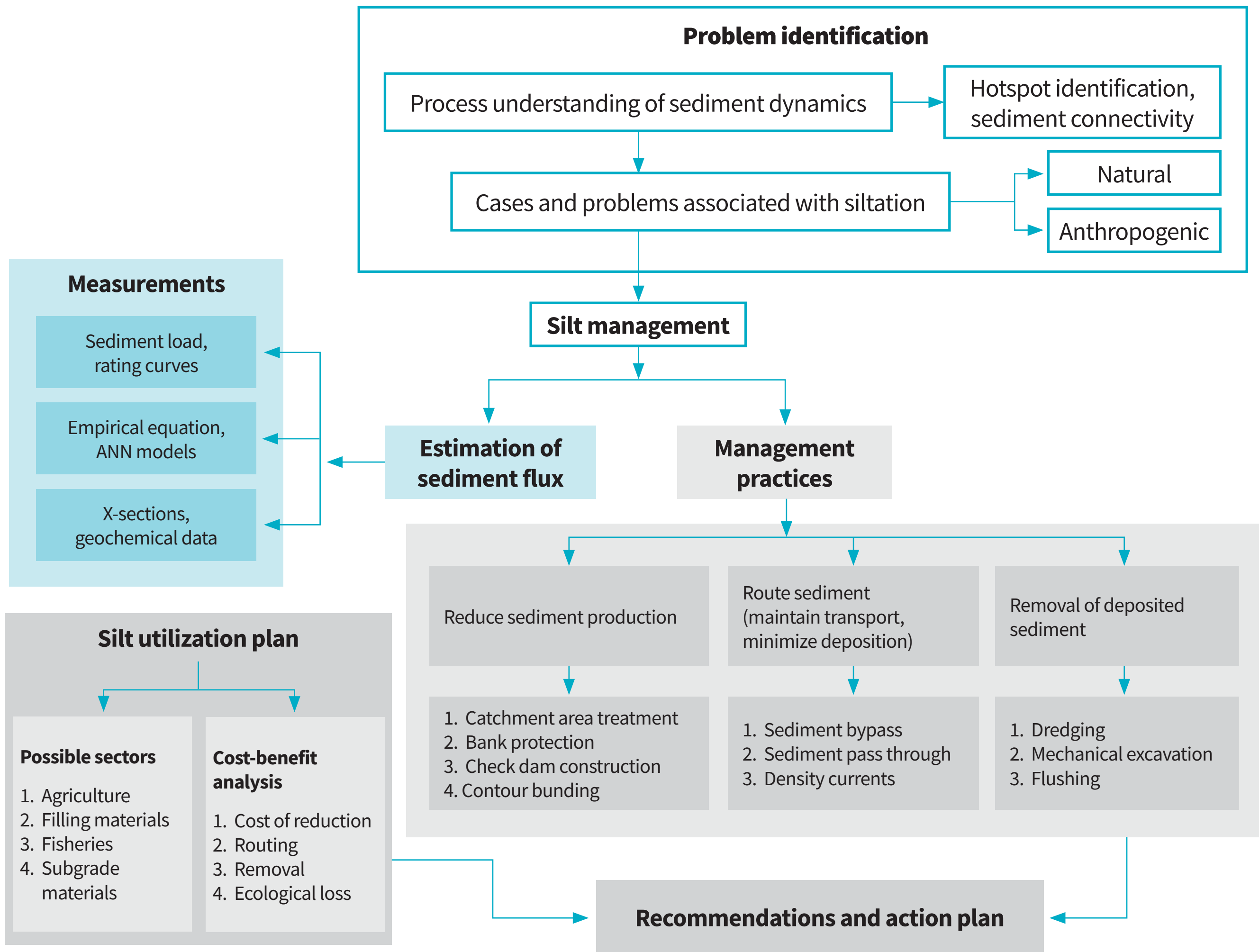
1. High sediment yield has emerged as the most important problem in the Koshi basin[1,2] which, in turn, has a role to play in river-related hazards such as avulsion[19-21] and floods[3]. Therefore, an integrated multi-hazard approach using the catchment context of sediment production and transport is required for a long-term solution. It should focus on treating the 'cause' rather than the 'symptoms' of the problem.
2. Recent studies in the Koshi basin[1,2] have identified the hotspots of excessive erosion in the basin. They should be of help in understanding sediment dynamics and in developing efficient sediment management strategies. Given the spatial inhomogeneities in erosion processes and sediment production demonstrated by previous studies, detailed management plans should be devised to arrest catchment-scale erosion. These solutions may include afforestation in highly eroding parts and slope stabilization at specific locations.
3. Identification of vulnerable stretches is critical in safeguarding against breaching and flood risk. An example would be 'superelevation' due to excessive siltation as in the case of Kusaha. Available data from the Koshi basin[21] has clearly identified the stretches prone to such risks based on morphometric characteristics, connectivity, and sediment dynamics. It is important to design site-specific mitigation strategies based on these studies.
4. Human interventions such as embankments and barrages have impacted sediment dynamics in the Koshi River as manifested in geomorphic forms and processes[4,19-21]. All sediment management actions in the Koshi basin must, therefore, be directed towards preserving or restoring geomorphic forms and processes. In particular, flow and flood control structures should be constructed in such a way that lateral sediment connectivity between channel and floodplain is maintained, which is critical for lowering the flood risk and improving the fertility of floodplains.
5. Barring Birpur and Baltara, there are no stations in the entire Koshi basin where long-term sediment load data is available. Keeping in view the importance of sediment management in the Koshi, a wider network of sediment load measurements should be established at strategic locations both in the Nepali and Indian parts of the basin. In addition, periodic surveys of critical sections must be a part of the standard operating protocol of river management.

6. The sediment management framework for the Koshi basin must incorporate (a) identification of hotspots of erosion and siltation, (b) estimates of silt accumulated, (c) techniques for desilting and, most importantly, (d) a business plan for utilizing the excavated silt (Figure 6). In particular, sediment dredging or desilting plans for the Koshi must be evidence-based, e.g., identification of hotpots of aggradation or superelevated reaches[21]. Strategic dredging of sediments from several reaches along the Koshi may be necessary to increase the water holding capacity and lower the flood risk. However, as per current international practice, dredging or de-siltation in the river channel should not only have a scientific rationale but be planned in such a way that there is minimal disturbance to the hydro-geomorphic regime and riverine biodiversity.

7. The involvement of the local community in sediment management and hazard mitigation is critical. The community-based flood warning system for the Koshi basin developed by ICIMOD is a good example of such involvement. Similar efforts are needed for knowledge dissemination on sediment dynamics and such success stories should be documented.

8. For transboundary rivers such as the Koshi, it is important to foster strong regional cooperation among the different stakeholders, including institutions and governmental organizations. Therefore, the Kosi Commissioner in Bihar and his institutional counterpart in Nepal must together develop a strong mechanism for data/information sharing, which is necessary for sediment management and mitigation of associated hazards such as landslides and floods.

FIGURE 6 PROPOSED FRAMEWORK FOR SEDIMENT MANAGEMENT IN THE KOSHI BASIN



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For further information please contact **Santosh Nepal** | **santosh.nepal@icimod.org**

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International Centre for Integrated Mountain Development
GPO Box 3226, Kathmandu, Nepal
T +977 1 5275222 | **E** info@icimod.org | **www.icimod.org**