RESEARCH NOTE

SEDIMENT TRANSPORT STUDY OF INDIAN TROPICAL RIVERS

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Abstract

This research highlights the importance of creating an Underwater Domain Awareness (UDA) Framework specifically for managing sedimentation. Sediment management is a complex challenge that requires collaboration among various stakeholders to avoid fragmented approaches and ensure effective policy development. Sediment management has applications in water resource management, port management, inland water management, and ecosystem management.[1]

The concentration of annual monsoon rainfall leads to high water flow, causing excessive siltation. Sediment deposition poses risks to both on-site and off-site areas, resulting in significant costs to the national economy.[2] Understanding sediment stability and transport is crucial for assessing environmental impact, habitat stability, public health risks, and marine hazards such as ship grounding, port access, seabed erosion, harbour siltation, reservoir infill, and coastal protection. These global issues have commercial, aesthetic, social, and scientific implications, contributing to sustainable development and coastal zone management.

Key words: Underwater Domain Awareness, Sediment management, Sediment deposition, Suspended sediment, Soil erosion, bed-load transport, suspended-load transport.

Introduction

In the study of sediment transport, we delve into the intricate processes that govern the movement of sedimentary materials across riverine landscapes. This research report aims to shed light on the dynamics of sediment transport, examining the factors that influence sediment mobilization, transport mechanisms, and deposition patterns. Through comprehensive analysis and field observations, this report aims to contribute to the understanding of sedimentary processes, which play a pivotal role in shaping river morphology and influencing aquatic ecosystems.

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[1] Sediment management for UDA framework. Retrieved from: https://mrc.foundationforuda.in/sediment-management-for-uda-framework/

[2] The Underwater Domain Awareness Framework: Infinite Possibilities in the new Global Era, The Underwater Domain Awareness Framework: Infinite Possibilities in the New Global Era – India Foundation

Stakeholders of Sediment Transport

The involvement of stakeholders in sediment management is crucial. Managing sediment at the river basin level involves various policy levels and diverse stakeholders with different interests. Few stakeholders are as mentioned below:

Government Agencies: These can include local, regional, and national agencies responsible for environmental protection, water resources management, and infrastructure. They set regulations, monitor river health, and manage sediment-related projects.

Environmental Organizations: Non-governmental organizations (NGOs) and advocacy groups focus on preserving natural habitats, water quality, and ecological balance. They often engage in conservation efforts, policy advocacy, and public education.

Local Communities: Residents living near rivers are directly affected by sediment transport as it impacts water quality, flood risks, and recreational opportunities. They may also rely on rivers for fishing, agriculture, and transportation.

Farmers and Agricultural Interests: Sediment transport can affect soil fertility and irrigation systems. Farmers depend on stable river systems for reliable water supply and often participate in watershed management practices.

Industries and Businesses: Companies involved in mining, construction, and manufacturing may impact and be impacted by sediment transport. They need to manage sediment to avoid pollution and ensure sustainable operations.

Scientists and Researchers: Academics and researchers study sediment dynamics to understand ecological impacts, geomorphological changes, and to develop sustainable management practices. They provide essential data and analysis for informed decision-making.

Infrastructure Managers: Entities responsible for dams, levees, and other infrastructure must manage sediment to ensure structural integrity, prevent blockages, and maintain navigability.

Tribal and Indigenous Groups: Indigenous communities often have cultural and historical ties to river systems. They advocate for sustainable practices that honor traditional knowledge and preserve their heritage.

International Organizations: In cases where rivers cross national borders, international bodies may be involved in coordinating efforts to manage sediment transport collaboratively and sustainably.[3]

Future sediment management must consider the perspectives of these stakeholders. However, communication can be challenging due to differing viewpoints and lack of a common language. Prioritizing the stakeholder process is essential for effective management.[4]

Indian Tropical Characteristics

Indian tropical rivers are distinct in their dynamism, frequently altering their courses and vigorously eroding their beds and banks. They transport vast quantities of sediment, often as large as sand particles. The rarity of such features in Himalayan rivers can be attributed to the exceptional hydro-climatic and morpho-tectonic conditions they experience.

Balanced ecosystems, which include soil, water, and plant environments, are critical for human survival and well-being. Unfortunately, many ecosystems worldwide, including parts of India, have been disrupted due to overexploitation. This imbalance manifests in various undesirable effects, such as soil degradation and frequent intense floods**.** Across the country, large areas of land have been irreversibly transformed into infertile surfaces due to accelerated soil erosion caused by various factors. These degraded lands also contribute to water pollution**,** as eroded soil deposits downstream. In India, approximately 1,750,000 km^2 out of the total land area of 3,280,000 km^2 is susceptible to soil erosion and thus causing excessive siltation and sedimentation.[5]

Soil erosion poses a significant challenge across approximately 53% of India's total land area. The Himalayan and lower Himalayan regions have been particularly impacted by soil erosion due to factors such as deforestation, road construction, mining, and cultivation on steep slopes. Large and medium-sized reservoirs in India have already lost more than 25% of their capacities due to sediment accumulation. In this context, let's explore some key points:

1. Ecosystem Imbalance: Balanced ecosystems, comprising soil, water, and plant environments, are crucial for human survival and well-being. Unfortunately, overexploitation has disrupted ecosystems worldwide, including certain regions in India. Undesirable effects, such as soil surface degradation and intense floods, result from this imbalance.[6][7]

2. Shiwalik Ranges: During the 1960s, extensive deforestation in the Shiwalik ranges of the Indian Himalayas exposed soil directly to rainfall. The fragile Shiwaliks experienced rapid soil removal due to rain and subsequent flow. Consequently, vast areas of land have irreversibly transformed into infertile surfaces, contributing to water pollution.[6][7]

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[3] Sediment Transport | U.S. Geological Survey (usgs.gov)
[4] Sediment Management and Stakeholder Involvement: https://sednet.org/download/1%20-%20abstract%20Slob%20and%20Mery.pdf
[5] Sediment transport in Cauvery basin: https://www.semanticscholar.org/paper/Sediment-transport-in-the-Cauvery-River-basin%3A-and-Vaithiyanathan-Ramanathan/4549fa40601a33841a7f7487add0505e2772f7c7
[6] Recent trends of sediment load in tropical rivers of India: https://www.semanticscholar.org/paper/Recent-trends-in-sediment-load-of-the-tropical-of-Panda-Kumar/6e31a100372016feff53f8c63f330c2dadb8c4ff
[7] How important and different are tropical rivers: https://sdml.ua.edu/wp-content/uploads/2014/10/Syvitski_etal2014_TropicalRivers.pdf

3. Himalayan Vulnerability: The northern and eastern Indian states, especially the Shiwaliks, consist of sandstone, grits, and conglomerates with fluvial deposits and deep soils. Geologically weak and unstable, these formations are highly susceptible to erosion. Intensive deforestation, road building, mining, and cultivation on steep slopes have accelerated erosion in this region.[6][7]

4. Desertification and Sediment Load: Deforestation-induced soil erosion has led to desertification in the Shivalik hills of Punjab. Additionally, an intense thunderstorm in the Alaknanda valley of the Himalayas during 1970 triggered severe erosion and landslides. The resulting sediment load significantly increased, affecting the Ganga River at Haridwar. The Upper Ganga canal, which diverts water from the Ganga, had to handle this heavy sediment burden.[6][7]

Addressing these challenges requires comprehensive strategies that balance development with environmental conservation, ensuring sustainable land use and minimizing soil erosion.

Challenges Due to Soil Deposition and Reservoir Sedimentation

Soil eroded from headwater catchments can accumulate downstream in rivers, leading to several problems. For instance, the Upper Ganga Canal, diverting water from the River Ganga at Haridwar, experienced a substantial sediment load—approximately 0.17 Mm^3—deposited over a 10 km stretch within a single day. Reservoir sedimentation remains a critical issue, affecting dams across India. Over 126 dams, each 30 m or taller, were constructed for purposes like irrigation, hydropower generation, and flood control before 1971. Many of these dams now contain significant accumulations of sediment eroded from their catchments. Srirama Sagar reservoir in Andhra Pradesh was found to have lost 25 % of its capacity during the first 14 years of impounding.[8]

<u>Different Aspects of Sediment Transport in Sediment Management</u>

Sediment management in sediment transport involves various strategies and considerations, including:
Dredging Operations: Dredging is the process of removing sediments and debris from the bottom of lakes, rivers, harbours, and other water bodies. It is essential for maintaining navigable waterways, constructing maritime infrastructure, and even for mining purposes. Dredging helps prevent sediment accumulation that can lead to reduced water depth and potential flooding.[10]
Coastal Erosion Prevention: Coastal erosion is a natural process exacerbated by human activities and climate change. Strategies to prevent erosion include hard engineering solutions like sea walls and groynes, as well as soft solutions like beach nourishment and dune restoration. These measures aim to protect shorelines and infrastructure from the loss of land due to wave action and sea-level rise.[9][10]

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[9] Coastal Erosion Protection: http://surl.li/uoqwx
[10] ST Research Paper: https://www.academia.edu/Documents/in/Sediment_transport

Impact Evaluation: This involves assessing the effects of human activities such as construction, dredging, and deforestation on coastal and riverine ecosystems.

Evaluations are conducted to understand how these activities alter sediment transport patterns, which can affect habitat quality for wildlife and lead to increased erosion or deposition.[10]

Habitat Restoration: Habitat restoration aims to return disturbed or degraded coastal areas to their natural state. This can involve re-establishing native vegetation, removing invasive species, and recreating natural hydrological conditions to support biodiversity and ecosystem services.[10]

Climate Change Planning: As climate change affects sea levels, storm frequency, and rainfall patterns, it also impacts sediment dynamics. Planning involves creating adaptive management strategies to mitigate these effects, such as reinforcing coastlines or restoring wetlands to act as natural buffers against storms.[10]

Flood and Erosion Control: Managing River basins through the construction of levees, dams, and reservoirs can help control flooding and prevent erosion. These structures regulate water flow and sediment transport to protect land from damage and maintain water quality.[10]

Resource Exploitation: Sediment transport is closely related to the extraction of resources like petroleum, minerals, and aggregates. Understanding sediment dynamics is crucial for designing extraction methods that minimize environmental impact and prevent issues like land subsidence or habitat destruction.[10]

Complexity of suspended sediment transport

The process of sediment transfer from fields to catchments and rivers is continuous, involving erosion, transport, and deposition. Suspended sediment (SS) plays a crucial role in this system. It constitutes both organic and inorganic material carried within the water column.[11] Approximately 70% of the annual sediment delivered by rivers to the oceans consists of SS. Soil erosion is a primary source of SS in rivers. It occurs in two phases: first, individual soil particles or small aggregates detach from the 'in-situ' soil due to processes like rainfall impact, running water, biological activity, and weathering. Then, these detached particles are entrained by wind or water flow, transporting them away from their original location.

Sediment transport in rivers is influenced by the availability of sediment in the catchment, the erodibility of soil, land cover, and field operations. Sediment availability depends on natural sources (such as weathering and landslides) and human activities (like mining and construction). Erodibility varies with soil texture and land cover, while vegetation plays a protective role. Arable and horticultural lands are particularly prone to erosion due to soil disturbance during field operations. Effective sediment management involves strategies like soil conservation and sustainable land use practices.[11]

In the context of sediment transport, shallow water experiences a combined influence of surface gravity waves and currents, while deep-sea environments are predominantly shaped by dense water circulations and internal waves. Sediment transport in natural water bodies can be categorized into two primary modes: bedload and suspended-load transport.[12]

1. Bed-load transport involves the movement of sediment grains within a thin layer just above the seabed. This mode encompasses rolling, sliding, and saltation of grains. Although some literature considers saltation as a form of suspended-load transport, it is more appropriate to treat it as bed-load transport in numerical models.
2. Suspended-load transport refers to the entrainment and movement of sediment by fluid flow. In this mode, sediment particles sink slowly and are carried over long distances before settling. The boundary between bedload and suspended-load transport is not sharply defined, as the relocation range of a sediment particle depends significantly on ambient water motions.

However, precise modelling of sediment transport faces several challenges in marine environments:

1. Genetic Diversity of Sediment Particles: Sediment particles exhibit varying physical and biochemical properties due to their genetic diversity. Fine particles with a diameter less than 0.063 mm behave differently, often forming cohesive aggregates rather than existing as individual entities.[13]
2. Stochastic Nature of Particle Movement: Sediment particle motion in fluids is inherently stochastic. Turbulence remains a complex and unsolved problem in fluid dynamics, contributing to the randomness of particle movements.[14]
3. Uncertainty in Pickup Process: The process of particles being lifted from the seabed is fundamentally ambiguous. Sediment particles initiate movement when the driving forces (exerted by ambient water motion) surpass the stabilizing forces.[13]

These obstacles underscore the need for robust modelling approaches that account for the intricate interplay of sediment dynamics and environmental factors.

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[11] Suspended sediment transport dynamics in rivers: Multi-scale drivers of temporal variation: https://www.sciencedirect.com/science/article/pii/S001282521630229X

[12] Linking temporal scaled of suspended sediment transport in rivers: https://link.springer.com/article/10.1007/s11368-020-02673-5

[13] Sediment Transport Model: https://www.researchgate.net/publication/272826732_Sediment_Transport_Models?enrichId=rgreq-ac768cf0ddf1e5a00dae0e60bfd24493-XXX&enrichSource=Y292ZXJQYWdlOzI3MjgyNjczMjtBUzoyMDE0ODQ4Mzk5ODUxNTZAMTQyNTA0OTEzODE0Mw%3D%3D&el=1_x_3&_esc=publicationCoverPdf

[14] A stochastic multivariate framework for modelling movement of discrete particles: https://link.springer.com/article/10.1007/s00477-017-1410-3

<u>How to do transport study?</u>

Dealing with sediment management is important, and one good way to do it is by using simulation models. Sediment transport models are steadily improving. Numerical models have become increasingly accessible, with older models evolving and merging. For instance, SCHISM, derived from SELFE. These simulations rely on refined preprocessing and postprocessing techniques. Additionally, emerging tools leverage high-resolution shoreline digitization using platforms like Google Earth[15]. As traditional measurement techniques improve, more precise formulations are emerging to account for various sediment transport mechanisms. For instance, recent advancements include:

Bedload Grain Size Distribution: Considering the range of grain sizes associated with bedload transport.

Entrainment Flux Method: An alternative approach for quantifying erosion properties of surface sediments. These developments enhance our understanding of sediment dynamics and improve accuracy in modelling sediment transport.

New models are developed, tested, and evaluated on straightforward configurations to enhance understanding of fundamental mechanisms at a detailed scale. Examples include direct numerical simulations of bedform evolution and sediment transport, as well as innovative methods such as smoothed particle hydrodynamics for fluid-flow interactions. Let's explore some of these simulation models.

HEC-RAS (Hydrologic Engineering Center's River Analysis System):

- **Purpose**: HEC-RAS is a powerful hydraulic model used for channel flow analysis and floodplain determination.
- **Capabilities**:
    1. One-dimensional steady flow calculations.
    2. One and two-dimensional unsteady flow simulations.
    3. Sediment transport and mobile bed computations.
    4. Water temperature and water quality modelling.
- **Applications**:
    1. Floodplain management.
    2. Flood insurance studies.[16]

Drawback: HEC-RAS is not specifically designed for coastal environments, and it lacks built-in modules for simulating tidal dynamics, wave action, and longshore sediment transport, which are crucial for port and coastal studies.

Delft3D:

- **Purpose**: Delft3D is an integrated modelling suite that simulates various processes:
    1. Hydrodynamics (Delft3D-FLOW module).
    2. Morpho-dynamics (Delft3D-MOR module).
    3. Waves (Delft3D-WAVE module).
    4. Water quality (Delft3D-WAQ module, including the DELWAQ kernel).
    5. Particle transport (Delft3D-PART module).

- **Open Source**: Delft3D is open-source software, allowing users to explore and contribute to its development.
- **Applications**:
    1. Coastal and riverine systems.
    2. Sediment dynamics.
    3. Water quality assessments.[17]

SSFATE (Suspended Sediment FATE):

- **Purpose**: SSFATE is a computer model developed jointly by the U.S. Army Corps of Engineers Engineer Research and Development Center and Applied Science Associates.
- **Function**: It estimates water column suspended sediment concentrations and bottom deposition patterns resulting from dredging operations.
- **Applications**:
    1. Assessing the fate of suspended sediments during dredging activities.
    2. Understanding sediment transport dynamics in rivers and coastal areas.

TUFLOW (Flood, Urban Stormwater, Coastal, and Water Quality Modelling):

- **Overview**: TUFLOW is an industry-leading hydraulic modelling software suite with over 30 years of continuous development.
- **Capabilities**:
    1. Simulates flooding, urban drainage, estuarine and coastal hydraulics, sediment transport, particle tracking, and water quality.
    2. Offers 1D, 2D, and 3D modelling options.
- **Key Features**:
    1. **1D Solver**: Supports detailed 1D modelling of rivers, floodplains, and complex pipe networks.
    2. **2D Grid/Quadtree Mesh**: Preferred for simulating flooding, urban drainage, catchment hydrology, and dam break scenarios.
    3. **2D/3D Flexible Mesh (TUFLOW FV)**: Simulates estuarine, lake, and coastal hydraulics, sediment transport, water quality, and more.[18]

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[15] Sediment Transport Models: https://www.researchgate.net/publication/272826732_Sediment_Transport_Models
[16] https://www.youtube.com/watch?v=d416442IC4c&list=PL26VoPqZfrgC-9qYKOHVr7ITbHh1akkU7
[17] https://www.youtube.com/watch?v=RcGytRMDDIE,
[18] https://fvwiki.tuflow.com/Tutorial_M07

For the Brahmaputra River, **HEC-RAS** is also a strong choice, particularly for integrated flood risk and sediment management studies.

For JNPT Port, **Delft3D** are highly recommended due to their robust capabilities in simulating coastal and riverine interactions, detailed sediment transport processes, and their extensive use in port and coastal management projects globally. These models provide the flexibility and detail needed to address the unique sediment dynamics and operational challenges of port environments. The Delft3D model is widely utilized at Cochin Port due to its versatility and robust capabilities. It integrates hydrodynamics, sediment transport, and water quality modules, allowing for the simulation of complex interactions between water flow, sediment movement, and pollutant dispersion. This is crucial for sustainable management of Cochin Port, particularly in predicting sediment movement patterns and assessing water quality changes, including pollutant dispersion and algal blooms.

Conclusion

Several methods for sediment routing leverage changes in sediment discharge over time to regulate flows during peak sediment yield periods, minimizing sediment accumulation in reservoirs. The fundamental approach involves holding back clear water while allowing sediment-laden flood flows to pass through. Implementing sediment routing techniques involves allocating a portion of river inflow and storage capacity to transport sediment around or through the reservoir.

Way Ahead

The problems of soil erosion and deposition mentioned earlier aren't just in India, they're all over the world. To deal with this, we need to first figure out where erosion and sediment build-up are really bad by studying streams and reservoirs more closely. Then, we can pick certain places to try out different ways to stop soil erosion and manage reservoirs better. Once we find ways that work, we can use them in other areas too. But stopping erosion with just soil conservation might not be enough for big areas. However, we can fix the problem of sediment building up in reservoirs by building traps to catch it before it gets there and by coming up with better ways to move and get rid of sediment in existing reservoirs. Addressing sediment management is crucial, and one effective approach involves utilizing simulation models.

Appendix

Methods for Estimating Soil Erosion in India

Regional soil erosion estimation is crucial for effective planning and designing soil conservation measures. Governmental agencies in India conduct surveys to determine soil erosion rates from catchments and deposition rates in reservoirs. Sediment load measurements are also carried out in many rivers across the country. The **Universal Soil Loss Equation (USLE)** is commonly used to estimate on-site erosion rates. Additionally, methods have been developed to determine off-site deposition of eroded soil and sediment yield from large catchments. The equation goes like:

$$S_{am} = C\, P^{0.6}\, F_e^{\;1.7}\, S^{0.25}\, D_d^{\;0.10}\, (P_{max}/P)0.19$$

The key components of the USLE include:

- **Sam**: Mean annual sediment yield in centi-meters.
- **C**: Coefficient based on the geographical location of the catchment.
- **P**: Average annual rainfall in centi-meters.
- **S**: Land slope.
- **Dd**: Drainage density in square kilometers per kilometer squared.
- **Pmax**: Average maximum monthly rainfall in centi-meters.
- **A**: Catchment area in square kilometers.
- **Fe**: Erosion factor.
- **Fa**: Area of arable land in the catchment.
- **FG**: Area occupied by grass and scrub.
- **Fw**: Area of waste land.
- **Ff**: Forested area.

High erosion rates, observed in the northeastern region, parts of Punjab, Uttar Pradesh (UP), Bihar, and certain areas of Andhra Pradesh, can be attributed to both higher rainfall in these regions and specific geologic conditions and land use practices.