# Research Note

# DEVELOPING A UDA FRAMEWORK FOR SEDIMENT MANAGEMENT

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## INTRODUCTION

Sediment is a naturally occurring organic and inorganic material such as minerals, rocks; from sand to boulders and also remains of animals and plants which is transported by water, wind or ice and deposited in new locations. Erosion and weathering forms mineral sediments while detritus and decomposing plant & animal matter form organic sediment. Sediment is washed down from creek and accumulated into deltas and river banks. India has 5,202 large dams and many more small dams and barrages, 111 inland waterways classified as 'National Waterways' (NWs) having 20,275 kms spread across 24 States [1] and a coastline of total length 7516.6 km including mainland, Lakshadweep islands and Andaman. Specifically in tropical regions, there is high flow of water bodies due to concentration of annual monsoon in one quarter of the year causing excessive siltation. Thus, sediment deposition threatens the sustainability from both on site and off site damages causing enormous costs to the national economy. Hence it becomes extremely important to employ an effective and integrated system of sediment management in every water based project in the country.

1. **Siltation Procedure**

   Siltation occurs when supply of sediment locally exceeds sediment transport capacity of the water flow. Although sedimentation and soil erosion is a natural process, their rate significantly increases due to anthropogenic activities like poor agricultural practices, construction & expansion of harbour, deforestation etc. During transport of sediment it gets separated into 3 components: suspended load, Bedload & saltation load. Constituent particles & sampling methods differ for each of them. The composition of suspended load varies with depth. Measurement of bedload is comparatively difficult due to their movement only during high discharge, turbulent flows such as in floods making it hard for field measurement & sediment monitoring

   a) Harbour Basins

   They are a dip or depression in the water body sheltered by barriers to provide safe anchorage and permit the transfer of cargo and passengers between ships and the shore. In harbour basins major concern is fine sediments because siltation rates are higher for that and often contain contaminants and are carried by flow in suspension.

   Sediment flux = water flux x SPM x $\eta$ ( SPM = Suspended Particulate Matter, $\eta$ = Trapping . efficiency: fraction of sediment entering harbour)

   3 mechanisms of exchange of sediment between harbour basin and ambient water are:

   - Horizontal Exchange – large scale circulations caused by eddy currents, flow separation, stagnation effects and entrainment at the mouth of harbour.
   - Tidal filling- Sediment laden water fills the harbour during high tide while an equal amount of water but with low sediment content flows out of the basin during low tide.
   - Density currents- Salinity gradients induce density currents. The denser water containing more salts and sediments sink and flow along the bottom due to gravity.[9]

Net exchange is 0 in first and third mechanism

Mass balance and siltation rate differential equation is formed in Zero order sediment assessment the solution of which gives SPM values in harbour basin in terms of ambient SPM value and Exchange flow rate.

Exchange flow can be expressed as:

$\frac{1}{T}\int_0^T Qdt = < Q > = < Qt > + < Qe > + < Qd >$ where

$< Qt >$ = gross water exchange by tidal filling

$< Qe >$ = gross water exchange by horizontal circulation

$< Qd > =$ gross water exchange by density currents.

Eysink who was first to quantify siltation rate in harbour basin provided numerical coefficients to gross values as follows:

$< Qt > = \frac{Vt}{T}$ , $< Qe > = fe.AU - fe,t < Qt >$ , ≪

$< Qd > = fd.A\sqrt{\Delta\rho s.g.\frac{ho}{\rho}} - fd,t. < Qt >$

$\Delta\rho s =$ salinity-induced density difference

$ho = Local\ water\ depth$

coefficients $fe,t\ fd,t = reduction\ in\ exchange\ efficiency\ during\ high\ tide$

$T = Tidal\ period$ , $U = Characteristic\ flow\ velocity,\ Vt = Tidal\ volume\ of\ harbour\ basin,\ A = cross\ sectional\ area\ of\ harbour\ entrance$

Apart from this shipping itself induces some sedimentation in harbour basins but no general quantification occurs. [2]

b) Water Reservoirs

Factors determining sediment accumulation [4]:

Hydrologic Size: Total reservoir capacity/ Mean annual flow (C/I)

Hydrologically small reservoirs have short residence time and in downstream flows during floods, spill a significant part of stream. Can be emptied or drawn down periodically for sediment management. Reservoirs with C/I ratio greater than 50% are hydrologically large and couldn't be emptied periodically for sediment management due to unacceptable amount of water losses.

Reservoir pool geometry: Shallow reservoirs attract less sediment deposits than deep reservoirs

Many *empirical methods* for calculation of volume of suspended sediments in reservoir exists some of which are [21]:

- Goncarov's method: $Z_t = V_p.[1 - \left(1 - \frac{R1}{V_p}\right)^t]$

  $Z_t =$ Vol. of Sediments after t years (in $m^3$)
  $V_p =$ Initial Vol. of reservoir (in $m^3$)
  $t =$ Years of functioning
  $R1 =$ Vol. of sediments after first year of functioning (in $m^3$)

  R1 is calculated as follows:
  $R1 = \frac{\beta R_u}{\rho_0}$ where $\beta = \frac{R_z}{\sum R}$
  $\beta =$ retention factor, $R_u =$ average annual weight of sediments delivered (in $m^3$),
  $\rho_0 =$ bulk density of sediments, $R_z =$ Amount of suspended sediments retained in the reservoir (t), $R =$ Amount of suspended sediments delivered to the reservoir

- Stonawski Formula: $Z_R = 0.01V_p \times \exp\left(0.12 - \frac{0.17V_p}{SSQ}\right)$

  $Z_R =$ Volume of sediments (in million $m^3\ year^{-1}$)
  $V_p =$ Initial Vol. of reservoir (in million $m^3$)
  SSQ = Avg discharge flowing in the reservoir ($m^3 sec^{-1}$)

- Exner (sediment Continuity) equation: It is a statement of conservation of mass applied to fluvial system such as river. The equation states that change in bed elevation $\eta$ over time $t$ is equal to
  $\frac{\partial\eta}{\partial t} = -\frac{1}{\epsilon_0}\nabla.q_s$ , $\epsilon_0 = grain\ packaging\ density, q_s = sediment\ flux$ [12]

## 2. Applications of Sediment Management

Sediment related Problems : *storage loss, delta deposition, environmental pollution, earthquake hazards*

a) Water resource management (Reservoirs)

According to the annual survey during the year 2020 based on the sedimentation rate across 264 reservoirs in India, 0.95% of gross reservoir storage is being lost to sediment deposit annually. Sediment tends to accumulate at all levels(Dead and live storage) within the reservoir but the pattern varies from site to site. The average annual percentage loss in dead storage is 2.39% while in live storage it is 0.67%. [3]

| Region | No. of Reservoirs | Median value of Siltation (Th.cu.m/sq. km/yr) |
|---|---|---|
| Himalayan Regions (Indus, Ganga & Brahmaputra basins) | 2 | 0.504 |
| Indo Gangetic Plains | 11 | 0.4 |
| East flowing Rivers (up to Godavari, excluding ganga) | 11 | 0.730 |
| Narmada & Tapi basins | 10 | 1.079 |
| Deccan Peninsular east flowing rivers including Godavari and south Indian rivers | 43 | 0.719 |
| West flowing rivers (up to Narmada) | 2 | 0.66 |
| West flowing rivers (beyond Tapi) and south Indian rivers | 5 | 3.94 |

Table 1. Region wise sedimentation in Reservoirs. Src: [3]

Loss of reservoir storage results in reducing flexibility in generation and make hydropower plant dependent on seasonal flows. Apart from storage sediment accumulation also block low level outlets and clog spill way tunnels leading to reduction in spill way capacity. Sediment can also damage turbines and other equipment through erosion. Generally sediments coarser than 0.20 mm size is harmful for turbine blades.

**Figure 1 — Typical Reservoir Sediment Profile***

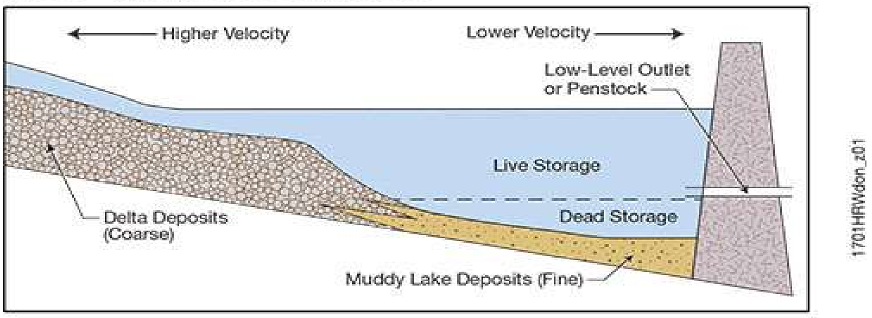



Fig 1. Typical Reservoir sediment profile

Typically, sedimentation in the reservoir behind a dam takes the form of progressively finer materials being deposited as the flows approach the dam.

*Adapted from Morris, G.L. and J. Fan, *Reservoir Sedimentation Manual*, McGraw-Hill, New York, 1998.

Src:https://www.hydroreview.com/world-regions/dealing-with-sediment-effects-on-dams-and-hydropower-generation/#gref

b) Port Management
India faces huge longshore sediment movement along the eastern coast by wave action. The littoral shift direction is from south to north during March to October and is from north to south during November to February when monsoon reverses its direction. Major shoreline harbours are Chennai, Visakhapatnam and Paradip with gross littoral drift of 2.56 million cubic meters, 1.13 million cubic meters and 2.16 million cubic meters per year respectively. During past few years due to deepening of harbour channels for expansion, siltation and coastal erosion has become more severe.[8]

c) Inland Water Transport
Shifting of river courses, channel logging in agricultural land & infrastructural areas along the flood plain poses difficulty in navigation.

d) Ecosystem management
Marine dredging, destruction of seagrass beds and mangroves, agricultural practices and deforestation particularly increase siltation of coastal waters. Seagrass beds act as natural sediment traps while mangroves act as buffer, filtering runoff from land and trapping sediments. Their destruction result in abnormal increase in ground water and soil salinity & rising of riverbeds. Accumulation of sediment

in reservoirs adversely changes ecology and effects fish and other species by covering spawn sites, reducing water clarity to visual feeding animals and destroying benthic food resources. [10]

## 3. Tools for Sediment Classification

a) Collecting Primary Data

a. Field surveys & aerial photography: topographic conditions and land cover often hinder accessibility to conduct complete field surveys such as geomorphological mapping [11]

b. Digital Elevation Model (DEM) Analysis: It is 3D computer representation of earth's terrain excluding trees, buildings or any other surface objects. India has a dedicated DEM platform 'BHUVAN, the Indian Geo-platform for ISRO.

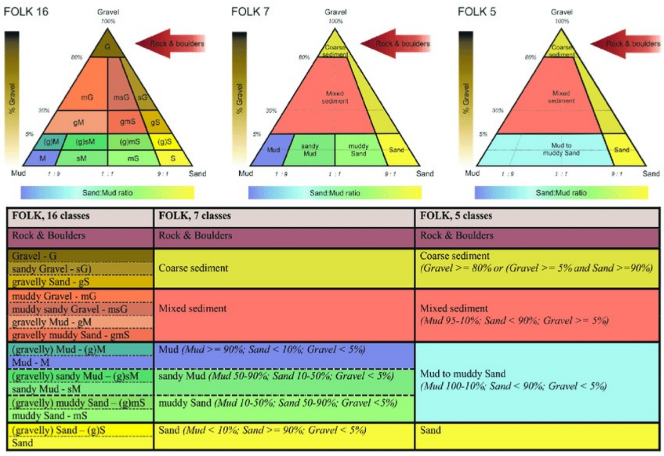
c. Satellite Remote Sensing: It is a quick method for monitoring sedimentation in lakes/reservoirs however it fails to provide very precise information which could be deployed for effective desiltation processes.

d. Acoustic Methods: Echo signal analysis, Seabed acoustic Imaging, Sonar

b) Standardization & Processing

The data collected from various sources needs to be converted into a uniform standard through the process of Harmonization. Further processing with GIS provides new openings for more quantative use of geomorphological mapping.

a. Harmonization – Folk's Classification: It is used on gravelly sediment and sedimentary rocks. First the sediment sample is analyzed and the content of sand (2-1/16mm), silt (1/16-1/256 mm) & clay <1/256 mm) is determined. Ratio of sand and silt is marked on the bottom line. When sand & silt are equally mixed, it is known as mud. Then line is drawn from the point marked on the bottom line towards clay corner till the sampled clay percentage. The location of the point gives the correct name for the sample. [16]




| FOLK, 16 classes | FOLK, 7 classes | FOLK, 5 classes |
|---|---|---|
| Rock & Boulders | Rock & Boulders | Rock & Boulders |
| Gravel - G<br>sandy Gravel - sG)<br>gravelly Sand - gS | Coarse sediment | Coarse sediment<br>*(Gravel >= 80% or (Gravel >= 5% and Sand >=90%)* |
| muddy Gravel - mG<br>muddy sandy Gravel - msG<br>gravelly Mud - gM<br>gravelly muddy Sand - gmS | Mixed sediment | Mixed sediment<br>*(Mud 95-10%; Sand < 90%; Gravel >= 5%)* |
| (gravelly) Mud - (g)M<br>Mud - M | Mud *(Mud >= 90%; Sand < 10%; Gravel < 5%)* | Mud to muddy Sand<br>*(Mud 100-10%; Sand < 90%; Gravel < 5%)* |
| (gravelly) sandy Mud – (g)sM<br>sandy Mud - sM | sandy Mud *(Mud 50-90%; Sand 10-50%; Gravel < 5%)* | |
| (gravelly) muddy Sand – (g)mS<br>muddy Sand - mS | muddy Sand *(Mud 10-50%; Sand 50-90%; Gravel <5%)* | |
| (gravelly) Sand – (g)S<br>Sand | Sand *(Mud < 10%; Sand >= 90%; Gravel < 5%)* | Sand |

Figure 2. Folk's classification chart

b. GIS Mapping: GIS systems consist of 5 layers. The fundamental layer creates spatial reference frameworks, the second layer transforms the framework into a spatial data model. The next layer is spatial data acquisition systems which collects data from various sources from surveying to satellite photography and plugs it into framework created by first two layers. The fourth layer spatial data analysis extracts relevant information from the collected data. The final layer is Geo-visualization and Information delivery which packages the information from all the previous layers and converts it into human consumable and digitally deliverable form.[19]

c) Results & Modelling:

- Particle size classification based on Wentworth Grade Scale:

| Particle type | Particle size (mm) | Cohesive properties |
|---|---|---|
| Cobble | 256 – 64 | Non – cohesive |
| Gravel | 64 – 2 | |
| Very Coarse Sand | 2 – 1 | Non – cohesive |
| Coarse Sand | 1 – 0.5 | |
| Medium Sand | 0.5 – 0.25 | |
| Fine Sand | 0.125 – 0.063 | |
| Silt | 0.062 – 0.004 | Cohesive |
| Clay | 0.04 – 0.00024 | |

Table 2 src:[7]

- EROSION 3D Model: Used for forecasting surface soil erosion and sediment input for each water section. Consists of 2 module: a) GIS Module b)Simulation model. The model has a GUI enabling users to command through keys and pull down options. [6]
- GSTAR model: GSTARS is a series of Generalized Stream Tube computer models for Alluvial River Simulation. It makes use of energy and momentum equation for determination of water elevation considering sediment grain size, variations in river width, armor layer formation & riverbank slope. This model can be used for simulating sedimentation and flushing procedure and was developed by the U.S. Bureau of Reclamation for steady and quasi-steady flows. [5]
- Many other simulation & computational models exist such as ArcMap, Delft3D along with use of ML & convolution Neural network for increased detailing and precision.

**4. Sediment Extraction**

The obvious solution for the siltation problem is removal of silt. Various methods are employed for the same:

a. Dredging: Debris & Unwanted sediments are pumped out by Dredge which creates a vacuum for suction. Cutter bar is used to loosen the settled material and pumps are used for extraction. However, there are some unintended consequences of dredging such as increase in flood risk for downstream communities since flow has increased, destruction of wildlife & habitat across floodplains and destabilization of riverbanks. Thus, dredging comes with significant risks and can't be the standalone solution for siltation problem [14,15]

b. Controlled sediment Flushing: In flushing the flow is used to remove any previously deposited reservoir sediments or a heavy sediment concentrated flow is passed through reservoir during high flow. Sometimes these flushing operations can be detrimental for downstream river reaches in terms of ecology and hence research are now shifting from maximizing flushing efficiency towards controlled flushing in order to minimize ecological impacts. [17,18]

c. Sediment extraction from canals through settling basins: Principle is to significantly reduce the velocity by increasing width & depth forcing the sediment to deposit. Donge (2002) derived the efficiency for settling basin.[13]

d. Vortex chamber extractors: Sediment is removed through vortex flow where high tangential velocity enters through central orifice of cylindrical chamber, removes highly concentrated sediment and exits through periphery. A sediment concentration gradient is created across the vortex. [13]

**5. Challenges**

- The maintenance of harbour entrances through dredging is an *expensive investment* in maritime administration and one of the major problems encountered by ports in India. Also, various dredging techniques occur and *selecting a particular method* will largely depend upon sediment study of the region. In major eastern coastline harbour, a part of dredging material is utilized to nourish (refill the eroded coastline) down drift shoreline while rest is dumped offshore.
- *Lack of proper dumping sites* poses a big problem in sediment disposal. On an average 0.2 to 0.3 million cubic meters of sand is used for direct nourishment in Visakhapatnam port and 0.5 to 0.6 million cubic meters along eroded coastline of Patidar. [8]
- Other aspects which need to be addressed range from Policy issues to technology gap and capacity & capability building requirement. Automation of data coverage methods, development of infrastructure, stakeholder involvement & adequate investment are essential.
- Tropical littoral waters show sub-optimal sonar performance for any acoustic survey which have been deployed in the region in past. There has been a lack of understanding of underwater medium due to random behaviour and underwater channel fluctuations, especially tropical regions face diurnal & seasonal fluctuations in surface parameters along with site specificity of bottom

6. **Stakeholder Fragmentation and Involvement at each level**.

Sediment management is large scale multilevel problem and requires cooperation from different stakeholders to avoid fragmented approach and formulation of policies in water & sediments that are not supported by the stakeholders. The stakeholders are involved from private, public, social and independent sectors. They include:

1) Policy making actors 2) experts 3) Citizens {ex people living near dumping sites) and NGOs

Ex.

Government – Has power to enforce laws regarding dumping of contaminated sediments, but lacks knowledge to formulate those rules.

Dredging Company – Has required knowledge so can enforce a change in sediment laws to its own benefit, but cannot develop that knowledge if customers don't buy their service (ex. port authorities) [ local dredging company, people living in vicinity, pressure groups working towards nature and habitat can provide better insight for development of dumping facility for dredged material]

Customers can't buy the service due to lack of resources for research and development. (Can be provided by government only)

Farmers, NGOs, environmental organization – have means to obstruct the development

It is important to note that no single actor can operate without input from others. The various inputs – Money, Support, Knowledge, authority etc. are contributed by different stakeholders and need each other's collaboration for success of the project. Each stakeholder is required in enrichment of the process by providing his share of ideas and solutions which increases the support for the proposed policy.

Challenges in Stakeholder Involvement:

- Lack of representation
- Different levels of Knowledge
- Confusing communication
- Clashing expectations

Involving all stakeholders wholly is impossible because the group would be too large to deal with. Hence different levels of involvement is required like some just want to stay informed while others want to give advice. A working-group of representatives from various stakeholder organizations needs to be formed and consulted to help prioritize sediment placement sites for each dredging centre in the region by collaboratively building a multi-criteria decision model. [20]

7. **Opportunities**

a. Precise sediment classification can facilitate effective desiltation and can also help in preventing further siltation by providing deeper understanding of siltation process.
b. Understanding sediment storage system for each area before planning any project.
c. Analysing the sedimentary depositional environment before any anthropogenic activities in an area.
d. Development of a comprehensive database management system and application & site specific measurements

8. **Research Directions**

a. Use of Analysis results for *prioritizing areas* for soil conservation measures for effective use of limited resources. [13]
b. Analyzing different *Sediment storage systems* for Indian Subcontinent. Ex. moraine dynamics for Indian mountainous region prone to Glacial landslides. Rock glacier permafrosts are potential storage system of debris and are not studied enough because of incapability of field observation in evidencing them. [11]
c. *Slope distribution* Analysis for identifying transfer and deposition zones
d. Pre-estimation of volumes of sediment and debris that might get collapsed into main channel during floods

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