

Riverbank Erosion, Sediment Transport and Reservoir Sedimentation: An Overview

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Abstract:

Sedimentation is a key factor in determining the life of a reservoir. Because sedimentation is determined by sediment yield, and sediment yield is determined by soil erosion, most sediment delivered by rivers is continuously trapped in dam reservoirs. This reduces reservoir storage capacity and usable life while also significantly modifying the material downstream, causing riverbank and channel erosion, and damaging aquatic habitats. The aim of this article is to present an in-depth overview of riverbank erosion and its measurement techniques, as well as sediment transport and its conveyance modes. Additionally, the article outlines sedimentation and its effects, as well as riverbank contributions to sediment load. Therefore, the article presents a general outline regarding riverbank erosion and its contribution to sediment yield as well as sedimentation and its conveyance. Highlighting, sediment measurement techniques, the merits and demerits of riverbank erosion and previous studies regarding sediment contribution due to riverbank erosion. This overview will aid researchers in the choice of appropriate technique and applicability of the technique chosen.

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1. Introduction

Reservoir sedimentation has long been a key issue for dams around the world. Excessive sediment accumulation in reservoirs may not only be responsible for dam storage capacity loss, but it may also result in a variety of negative effects both within and downstream of reservoirs, such as high turbidity, loss of flood-carrying capacity, and reduction in water quality [1]. This implies that the reservoirs created along the river's natural course are subject to some level of sediment intake and deposition. Sediment is naturally transported through streams in a certain amount, but human activities are to blame for increasing general erosion rates, hence increasing the amount of sediment supplied to rivers and other bodies of water [2]. Riverbank erosion is considered a significant source of sediment contribution to rivers and stream. Previous research reveals that one of the primary sources of riverbed material is from sediment eroded from riverbanks and in some instances accounting for more than 80% of the total sediment load. Also, degraded banks constitute a substantial contributor in river nutrient loading, the contribution of eroded sediment to total phosphorus loading in small catchments is estimated between 40% and 47% [4, 5].

Riverbank erosion affects different countries to varying degrees, resulting in varying degrees of landscape deterioration and environmental and economic repercussions. People in Papua New Guinea, for example, have been permanently evacuated due to the erosion of the Busu River. The erosion of the Kolubara River's banks has

had an influence on the agricultural population and villages in Serbia [6]. The loss agricultural land to erosion along the Nile in Africa leading to reduce farm output, with riverbank erosion along the corridors of River Danube in Europe, Avon and Heathcote rivers in New Zealand, the Murray, Darling and Gordon rivers in Australia and the Mississippi, Missouri and Haw rivers in the United States. In several of the examples mentioned above, erosion has resulted in the loss of farmland as well as the threat to roads, buildings, and a variety of riverbank services. The magnitude of the effects on human settlements in each riverbank erosion situation is determined by the population density and economic conditions of the inhabitants in that location [6].

2. Riverbank Erosion

Human activities can alter sediment load and watershed hydrology, resulting in rapid channel changes, increased bank erosion rates, and lateral channel migration in river dynamics [3, 7]. Fitzpatrick and Knox [8], for example, discover that changes in flow after forest clearance enhance riverbank and channel erosion, which serves as the principal source of sediment downstream. Additionally, urbanization of a catchment can hasten riverbank and channel erosion. Trimble [9] discovered that riverbank erosion is exacerbated by the increase of impermeable surfaces in the study region as a result of downstream urbanisation, which contributes approximately two-thirds of the delivered total sediment yield.

Besides, Clark and Wynn [10] suggest that riverbank alone can contribute about 85 % of sediment yield in a catchment. Therefore, in the fluvial system, a substantial portion of sediments in rivers is contributed as a result of riverbank erosion. Excess riverbank erosion can initiate channel instability and sedimentation issues downstream [11]. Also, high sediment concentrations in rivers do not only reduce water clarity but also, damaging to the aquatic ecosystem due to its ability to reduce fish food finding, light needed for aquatic plants photosynthesis is reduced, alteration in dissolved oxygen and temperature in water [12].

Entrainment and erosion of riverbank materials are caused by two main mechanisms: hydraulic action and mass collapse [13]. The shear stress exerted on the boundary by the flowing water entrains riverbank and bed materials. Mass failure, on the other hand, happens because of rotational slip or slab failures. Because of weathering and gravitational forces, the bank toe was removed due to hydraulic action, leaving a protruded sediment mass hanging [14].

2.1 Riverbank Contribution to Sediment

The amount of eroded riverbank materials and sediment load can be used to evaluate the link between riverbank erosion and sediment load in a fluvial system [15], [16]. According to Russell *et al.* [16], riverbank erosion is a major contributor to suspended sediment concentration in specific catchments. The percentage variance in suspended sediment input owing to riverbank erosion varies greatly from one river to the next (Table 1). The rate of riverbank erosion varies from one section of a river reach to the next and is characterized by spatial heterogeneity dependent on watershed factors. The spatial diversity of riverbank erosion rate is influenced by stream power, which is a function of discharge and slope. It is debatable whether the rate of riverbank erosion will accelerate if stream power is high and the substrate is erodible [17, 18].

Table 1: Contribution of riverbank to sediment load in some rivers

| River | Catchment area (Km ²) | Type of land use | Riverbank sediment contribution (%) | Reference |
|-----------------------------------|-----------------------------------|------------------|-------------------------------------|-----------|
| St. Lawrence River, North America | 1000 | Urban | 65 | [19] |
| Blue Earth River, Minnesota | 9028 | Agricultural | 31-44 | [20] |
| River Aire, England | 1,004 | Urban | 43-84 | [21] |
| River Torridge, England | - | Agricultural | 23 | [22] |
| River Frome, England | 437 | Agricultural | 7-19 | [23] |
| River Piddle, England | 183 | Agricultural | 7-21 | [23] |
| Forth Corb, Oklahoma | 800 | Urban | 46 | [24] |
| Valley Creek, Pennsylvania | 60.6 | Urban | 43 | [25] |
| River Kennet, England | 214 | Agricultural | 31 | [26] |

2.2 Riverbank Erosion Measurement Techniques

Estimating the amount of erosion that is likely to occur over time is arduous and tasking. Researchers and scientist generally employ the use of aerial photographs which are aided with satellites and planes [27, 28]. Riverbank erosion measurement can be achieved using conventional and field

measurement techniques such as erosion pins, erosion painting, cross-section resurvey or photogrammetry. These techniques are time tested, widely used and accepted for riverbank erosion estimates and can be used for small scale measurements [29]. Table 2 presents a summary of riverbank measurements techniques, its mode of operation, merits and demerits.

Table 0: Summary of riverbank erosion measuring techniques

| Technique | Operating principle | Merits | Demerits |
|-------------------------------------|--|--|---|
| Erosion pins | Installed pins exposure or deposition are measured | Low cost, sensitivity and simple set up | Spatial sampling difficulties, error due to pin movement and pin loss |
| Survey | Repetitive cross-sectional measurements | Easily set up and inexpensive. | Established benchmark stability issues, requires on-site personnel |
| Erosion painting | Monitoring painted surface after erosive events are analysed | Erosive events are easily noticed, easy setup. | Unreliable and requires on site personnel. |
| Photogrammetry | Captured pictures are converted to DEMs and analysed | Multiple angles capturing possible, availability of image processing software. | Capturing clear images is very challenging and expensive. |
| Photo electronic erosion pin (PEEP) | Sensor cells exposure to light are measured | Continues quasi-time series change measurement, automatic measurement system | Relatively expensive as more than one unit is required for measurements |
| Lidar Technology | Short light pulses released by laser scanners reproduced by earth surface are analysed | Wide range of coverage from multiple angles | Areas with dense vegetation are prone to have voids. |

3. Sediment Transport

Rivers can be thought of as a combination of flowing water and sediment. Rains (in the form of heavy precipitation or runoff) carry a significant volume of water into rivers. Rainfall transports much eroded soil and other materials (debris) from the surrounding environment, some of which are microscopic particles and others which are larger particles or boulders known as sediments [30, 31]. Most sediment is transported by water and is referred to as the fluvial process, such as river channel deposits and sandbars. Another method of transporting sediment is by wind or glaciers, which is known as the aeolian process; sand dunes and desert deserts are examples of this mode of transportation and deposition [32]. Sedimentation is the process by which sediments or particles are transferred from their place of origin by natural or human-assisted means and deposited in a location different from their source in water bodies or on land surfaces [33, 34].

3.1 Sediment Transport Modes

Sediment transfer happens only when an erodible border contacts a flowing fluid. The behaviour at this interface is extremely complex. Because two components are involved once the sediment is delivered, the flow is no longer a simple fluid flow. There are two (suspended and bedload) ways sediment move in water bodies throughout the conveyance process within the system.

3.1.1 Suspended load

The suspended load is suspended in the water column in this mode (typically relevant to smaller particles). Because of the turbulent fluctuations, particles may become suspended when water movement increases. Furthermore, stream movement eventually transports them downstream. The sediment particles are referred to as suspended load. Most natural rivers transmit sediment in the form of suspended load [35].

3.1.2 Bedload

The sediment transported by rolling or sliding down or near the river's floor (bed) creates the bed load. At low shear stress, particles roll or slide along the riverbed. The particles are constantly in touch with the bed, and the movement is periodic. The contact load refers to the sediment material transferred in this manner. As shear stress increases, some particles break contact with the bed and hop or bounce from one place to another along the direction of flow. The sediment particles moving in this manner are classified as siltation load. Bedload, often known as the bigger particles, is the sum of contact and siltation loads [36, 37]. The summation of suspended load and bedload is the total sediment load.

3.2 Sediment Transport Measurement Techniques

Fluvial processes are those that include the transport or transfer of sediment in rivers and streams from one place to another within a system, as well as erosion and deposition [38]. Sediment movement in rivers and streams is not easily separable into suspended sediment and bedload because there is rarely a clear distinction between the two types of sediment transport. Given the regional and temporal variations in river discharge, sediment measurement is difficult and time-consuming [39]. The collection of sediment concentration data enables indirect sediment estimations to be made by using general equations to anticipate the total sediment load [40, 41]. Investigations have revealed that the estimations from various indirect ways of measuring sediment loads varied significantly. Because of the wide variability in sediment content estimations, extensive sampling is required. There are numerous sampling methods available for measuring silt concentrations in real time.

As a result, it will be impossible to propose a single general approach that is appropriate for determining sediment estimates in natural rivers and streams, either theoretically or practically.

Table 0: Sediment Measurement Techniques for Suspended and Bedload Sediment

| Suspended Technique | Measurement required | Concentration range (mg/l) | Particle size range (mm) | Bedload Technique | Measurement required | particle size range (mm) |
|----------------------|--|----------------------------|--------------------------|--------------------------|---|-----------------------------------|
| Bottle | mass of sediment particles in sample | n/a | n/a | Helley - Smith | mass of sediment particles in the sample | fine sand to gravel |
| Acoustic | backscattered sound | 0.1-10 | 0.1-10 | PIHM | mass of sediment particles in the sample | fine sand to gravel |
| Pump | mass of sediment particles in the sample | n/a | n/a | CSU/FU bedload trap | mass of sediment particles in the sample | fine sand, gravel and small coble |
| Laser diffraction | laser angle diffraction | 0.05-5000 | 0.001-0.5 | River bedload trap (RBT) | mass of sediment particles in the sample | fine sand, gravel and small coble |
| Nuclear | radiation transmission | 0.1-1000 | n/a | Pit and Trough | mass of sediment particles in the sample | > 3 |
| Optical backscatter | backscattered light | < 3 | < 0.063 | Vortex tube | mass of sediment particles in the sample | finer < 0.5 |
| Optical transmission | light transmission | < 10 | < 0.063 | Radioactive tracer | sediment flow rate, moving layer thickness, average motion velocity | finer to pebbles |

Table 3, on the other hand, provides an overview of selected field measuring methodologies for suspended and bedload sediment.

4. Sedimentation in Reservoirs

Reservoirs are created when a river is dammed, the sediments that used to flow along with the flowing water naturally are in effect trapped in the reservoir. This is because the presence of the dam now regulates the flow regime and causes most of the sediments to settle to the bottom of the reservoir. The reservoirs slowly get filled up with sediments and eventually make them unusable for their intended purposes [42].

Sedimentation in reservoirs is a phenomenon due to which the sediment particles get deposited in the form of bed load and suspended load after separating from their origin. In fluvial hydraulics, sedimentation is an important parameter as it provides a probability of being used as a capacity predicting device in all storage zones due to which life of a reservoir can be predicted as there is a unique relationship between capacity and life of a reservoir. To be more explicit, for a given reservoir, sedimentation is dependent on sediment yield, which is defined as the sediment discharge through a river outlet per unit catchment area per unit time [43].

4.1 Upstream Sedimentation Effects

Building a dam over a river result in near-still water hydraulic conditions and reduced flow velocity in the system. This effect causes the silt delivered from upstream the dam to settle out over time, depending on sediment size, settling velocity, and incoming flow velocity. The

coarser materials drop out in suspension further upstream in the system, while the fines are carried and deposited lower down. The amount of silt retained behind a dam is determined by the sediment transport parameters of the catchment. Influencing factors include land use, runoff, rainfall intensity and depth, geology, topography, cleared area for agricultural reasons, and urban growth [44].

When managing the flow regime of a river system with a dam, two substantial geomorphological changes are expected to occur: reduction in storage capacity and flow capacities upstream the dam. These alterations are the result of silt infilling behind the structure. Another issue that may occur upstream of the reservoir is the creation of in-stream delta deposits, which can significantly reduce stream capacity [45].

Figure 1 depicts the basic concept of conventional upstream impacts, demonstrating that the reservoir's total storage capacity is the sum of active and dead storage. In the case of flood control dams, dead storage is located below the low water level specified by the elevation of the lowest outlet, whereas active storage comprises water that can be released for power generation or water supply or can be reserved for flood mitigation purposes. Sedimentation has a negative impact on hydropower output in two ways: the amount of power generated and the rise in turbine maintenance needs. This is because sedimentation reduces reservoir active storage, resulting in lower power generation. Furthermore, the presence of silt passing through turbines built primarily of hard minerals can cause abrasion, necessitating maintenance. Similarly, water supply demands will experience limitations as reservoir storage is reduced due to sedimentation [46].

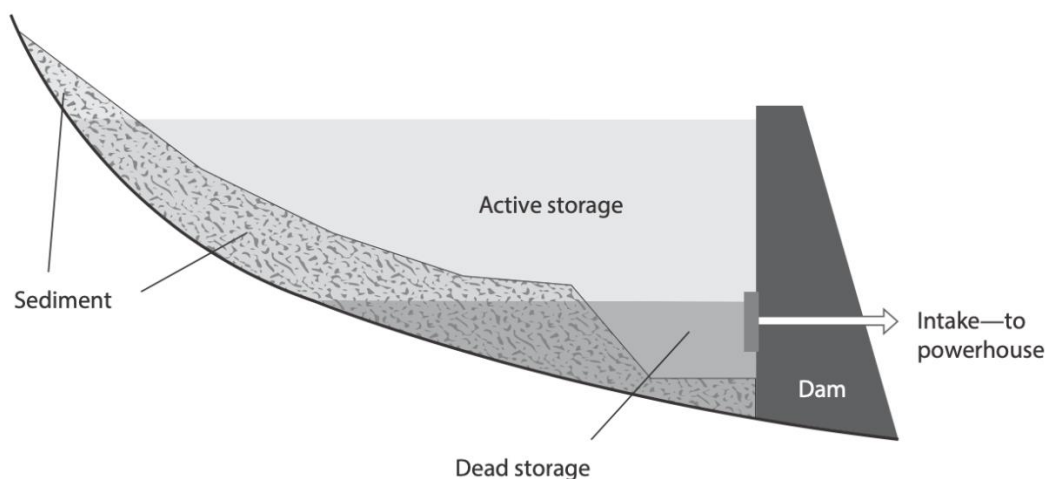


Figure 1. Reservoir storage loss due to sedimentation [47]

4.2 Downstream Sedimentation Effects

The regulated flow associated with dams and other similar structures in rivers is the main reason why the amount of sediment transported downstream by water flow has decreased [48]. Substantial, large materials carried by water are trapped upstream of the structure, with most of the smaller particles falling out to the crest, allowing just suspended sediment to be transported downstream [49]. The changes caused by flow regulation and sediment flux

are responsible for both spatial and temporal variations in river morphology downstream.

The river responds to changes according to the transport capacity and sediment available for transport to attain a balance in the system [50]. The river tends to erode its banks and beds in a bid to achieve equilibrium when the conveyance capacity exceeds the sediment supply. Adjustment in the morphology of a system downstream of a dam structure varies in response to some conditions, and a

lot of likely outcomes will result. The river channel downstream of the dam is characterized by erosion and degradation when the river transport capacity exceeds the sediment load [51]. Also, there will be channel incision and erosion at the banks due to rapid hydraulic head change caused by increased flow velocity and reduced sediment. This incision and degradation downstream have the effect of reducing the channel slope and eventually the transport capacity of the system as a new equilibrium condition is reached [49].

Downstream erosion and degradation are sometimes seen to differently erode channel banks; coarse materials associated with the regime before construction of the dam may be more resistant to erosion than finer channel bank deposits. Furthermore, erosion may occur downstream of a dam, while aggradation of sediment can happen further down in response to different channel conditions and an increased sediment load from upstream erosion. Consequently, the two primary effects of dams concerning changes in sediment supply and transport capacity are sediment shortage or sediment surplus, with the most common downstream river segments experiencing sediment shortage [52].

5. Conclusion

This overview is preliminary and, to some extent, limited in scope because it attempts to cover the vast peripherals of riverbank erosion, sediment transport, and sedimentation in a reservoir. It will assist readers in taking precedence into account when assessing riverbank erosion and sedimentation in the reservoir. Many studies have been conducted on soil erosion, sediment yield, and sedimentation in various reservoirs, and all of these studies help us grasp the practical significance of the sedimentation problem. However, it remains unexplored in various ways. Studies on riverbank erosion processes, sedimentation, and measurement techniques are still underway. Techniques and models capable of correlating riverbank erosion and sedimentation at the basin scale have not been adequately investigated for reservoirs. The complex processes of soil erosion, sediment yield, and sedimentation in a reservoir can be used to construct relationships between upstream and downstream of the reservoir. Further research on sediment influence on water quality and availability is also expected.

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