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The Role of Sediments in the Survival of Benthic Organisms

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Abstract

Sediments are soil-based mineral matter, decomposing organic and inorganic substances that can be carried away by water, wind, or ice. The benthic organisms reside on or in the bottom part of the sediment of a water body. This review assesses the positive and negative impacts of sediments on the aquatic environment, benthic flora and fauna survival, and factors affecting sediment load of water, some listed physicochemical parameters of sediments, and some studies on sediment qualities on benthic organisms. Positive impact of sediments on benthic organisms includes provision of nursery and breeding grounds for aquatic organisms, provision of habitat for aquatic organisms, nutrient recycling, source of food to aquatic biota, reservoir for contaminants, etc. Excessive deposition of sediments on a water body can significantly deteriorate water quality, make the water murky, loss of the fauna community, and subsequent colonization by pioneer species in the affected water body when it exceeds a natural threshold. Factors that affect the state of sediment load variations include relief, channel slope, basin size, rain seasonality, tectonic, and anthropogenic activities. The study recommends cautious mitigation of human activities that alter sedimentation, leading to reduced levels of sediments and enhancing the survival and diversity of benthic organisms.

Keywords: Benthic flora and fauna, negative impacts, positive impacts, and sediment load

INTRODUCTION

Sediments refer to a collection of organic and inorganic materials that can be transported by natural forces, such as water, wind, or ice [1]. While the term commonly describes soil-derived mineral particles, like sand, silt, and clay, it also includes decomposing organic matter and inorganic biogenic substances. Sediments consist of a blend of various mineral elements, biological species, and organic debris, serving as the final repository for materials discharged into aquatic systems. Their movement and accumulation in water bodies influence both the physical-chemical properties and biological dynamics of the environment (from producers to invertebrates to fish) (Figure 1) [2–4].

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Sediments play a crucial role in aquatic systems, acting both as a storage site and a potential source of pollutants in the water column. Over time, contaminants tend to build up in sediments, often reaching significantly high concentrations. Metals and other waterborne pollutants, whether in suspension or dissolved form, typically travel downstream, where they interact with various compounds to form complexes. These substances eventually settle at the bottom and become incorporated into the sediment. Aquatic sediments originate from natural physical, chemical, and biological elements that are closely linked to their surrounding watersheds. Sediments are essential drivers of the aquatic food cycles and play a crucial role in determining water quality [5]. Organisms that inhabit the sea floor, such as microbes, plants, and invertebrates, are referred to as benthic organisms (Figure 2). Benthic organisms are a community of living beings that inhabit the bottom of a water body, either on its surface or within the sediment. They are categorized by size into microbenthos (<0.63 mm), meiobenthos (0.063–1.0 mm), macrobenthos (>1.0 mm), and megabenthos (>10.0 mm). Additionally, they can be classified into phytobenthos, which includes bacteria and plants, and zoobenthos, which consists of animals, playing essential roles across different levels of the aquatic food web. The benthic organisms often deposit feeders, obtaining nutrition from ingesting biota, organic (biodegradable) and inorganic particles (mineral composition, origin, particle shape, size, and distribution) from the sediment surface or within the sediments [6]. By substratum, the benthic community can be divided into Infauna (Organisms that live in the sediment), Epifauna (organisms attached to the bottom or substrate and they live within sediments or on the sediment surface), and Demersal (those that feed on the benthic infauna and epifauna). By type, they can be divided into zoobenthos (of animal origin) and phytobenthos (the plant origin) [7]. By location, they can be divided into epibenthos (benthos living on top of sediments) and Hyperbenthos (those that live just above the sediment). Examples of benthos include sea stars, oysters, clams, sea cucumbers, brittle stars, sea anemones, etc. Bioturbation, which is the transportation of sediments and pore water, occurs as organisms interact (live, forage, and respires) with the sediments at the benthic zone of water [8].

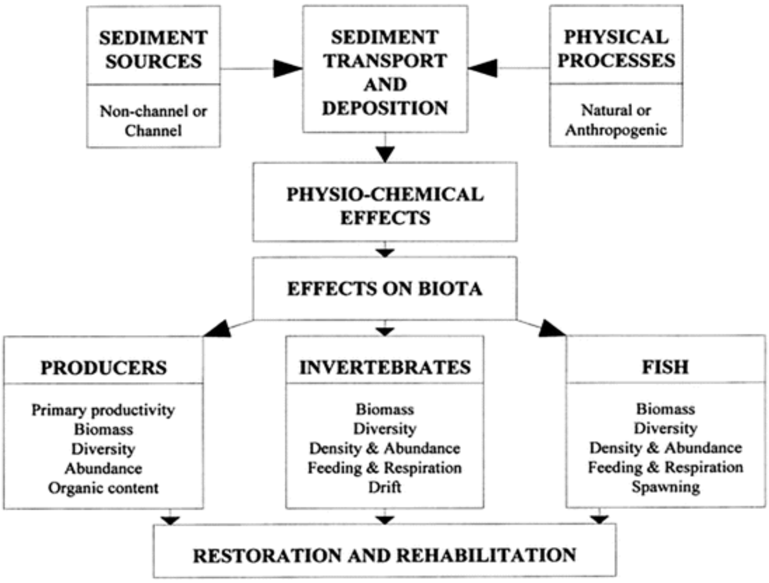

Figure 1. Parameters affected by the transportation and deposition of sediments in water.
Source: [2–4].

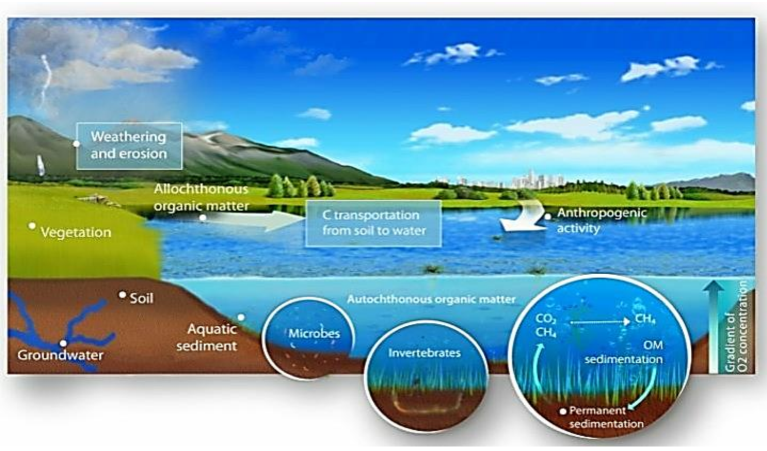

Figure 2. The sediment and benthic organisms that depend on it (its transportation into the aquatic environment) [9].

TYPES OF SEDIMENT

There are three types of sediment, which are:

- *Clastic Sediment:* Clastic sediments are fragments of preexisting rocks that have been weathered, eroded, and transported by natural forces like water, wind, and ice. Sediments are composed of fragments of rock. In fact, a "clast" is the word used to describe a rock fragment [10]. Clastic sediments are made up of small fragments or particles derived from the mechanical weathering of rocks. These fragments can range from fine silt to large boulders, depending on the degree of weathering and the energy of the transporting medium. The word "clast" refers to a fragment of rock or mineral that is broken from a larger mass. These particles are broken off or weathered from preexisting rocks due to natural forces, such as water, ice, and wind. Because of this continuous erosion and abrasion, they are sometimes referred to as detrital, meaning "worn away." Clastic sediments are classified based on grain size, ranging from extremely fine particles like clay to larger fragments, such as boulders. The primary categories include Clay (less than 0.004 mm), Silt (0.004 to 0.0625 mm), Sand (0.0625 to 2 mm), and Gravel (2 mm and larger) [11, 12].
- *Biogenic Sediment:* Biogenic sediments consist of organic materials originating from the remains of living organisms, including shells, skeletons, and plant fragments. In marine ecosystems, these sediments are commonly formed by planktonic organisms like foraminifera, diatoms, and radiolarians. On land, they may include plant debris that gathers in lakes and swamps [13]. Biogenic sediments originate from the life processes of organisms. Certain marine species develop shells, and when they die, their remains contribute to these sediments. Limestone is a sedimentary rock primarily composed of calcium carbonate, derived from the skeletal remains of marine organisms. Similarly, coal forms when plant and animal matter accumulate, undergoes compression, and transforms into solid carbon over time [14]. The major types of biogenic sediments include the Calcareous biogenic sediments (formed from calcium bicarbonate remains of organisms like corals, etc. in the marine environments), Siliceous biogenic sediments (made of silica from diatoms or radiolarians in areas with high biological productivity) and Organic-rich sediments (materials, such as peat: accumulated plant debris in swamps, sapropel: organic rich muds in oxygen-poor marine environments). These sediments are formed from three processes, which are biological production (Organisms produce hard parts (e.g., shells, tests) during their lifetime.
- *Sediment Transport and Deposition* (Once produced, these materials may be transported by water currents or gravity before settling in marine basins or terrestrial lowlands) and
- *Diagenesis***:** Over time, biological sediments may undergo chemical and physical changes, such as lithification into rock (e.g., chalk or chert) [15].
- *Chemical Sediment:* Chemical sediments result from the precipitation of minerals directly from water, without significant input from biological activity or detrital fragments. These sediments often form in evaporitic settings (e.g., salt flats, lagoons) or hydrothermal environments. Common precipitating processes include evaporation, cooling, and supersaturation of mineral-rich water. They differ from other sediment types because they are not made up of fragments that get weathered or broken down, but instead they are composed of mineral crystals that formed out of solution. The various types of chemical sediment include the evaporites (Formed through the evaporation of water, leaving behind minerals like halite (rock salt) and gypsum), Carbonates (Often precipitate in warm, shallow marine waters as limestone or dolomite. Examples include calcite and aragonite deposits), Siliceous deposits (chert, formed from the precipitation of silica, often in deep marine environments) and Iron-rich Deposits (banded iron formations, which result from the precipitation of iron oxides in ancient oxygen-deficient ocean) [16–20].

This review paper is aimed at assessing the impacts of sediments on the aquatic environment, the impacts of sediments on the survival of benthic flora and fauna, and factors affecting the sediment load of a water [21].

BENEFITS OF SEDIMENTS IN THE AQUATIC ENVIRONMENT

Provision of Nursery and Breeding Grounds for Aquatic Organisms

The aquatic ecosystem, along with its sediment habitats, is recognised as the natural breeding and nursery grounds for many aquatic juveniles, providing refuges for adult and larval stages of fishes, crustaceans, molluscs, etc., both resident and migrant. Habitats, such as mangrove, salt marshes, mudflats, sea grass, and seaward beds in these estuaries play a very productive to play role as breeding and nursery grounds for many important aquatic species. Sediment and Mangroves also play the role of nurturing juvenile species from other habitats like estuaries and lagoons. Various animals in both marine and freshwater environments rely on the replenishment of sediments for their reproductive habitat [22–25].

Provision of Habitat for Aquatic Organisms

Sediment acts as shelter to some species of benthic algae, especially in oligotrophic aquatic ecosystems. The dependence of benthic algae on sediments could be grouped into epilithic (growing on hard, relatively inert substrata like the gravel, pebble, cobble or stone surfaces), epipsammic (growing on hard inert sand which is smaller than the smallest diatoms), and epipelic (those that grow on inorganic or organic sediments, usually large motile diatoms). The sediments are major habitats for benthic organisms (i.e., several invertebrates, small crustaceans, and some fishes) [26, 27].

Coral, as a component of sediment, provides a foundation for primary production, serves as a habitat for invertebrates and fish, and helps protect coastlines from wave action. Overall, sediments play a crucial role in shaping biodiversity and habitat composition, significantly influencing the quality and long-term development of ecological features [28]. The role of sediments in a river varies based on its morphological type – they can either shape habitats hydraulically or function as structural elements that influence the river's flow patterns. Aquatic organisms, such as macroinvertebrates and fish, have specific sediment-related needs, including adaptations to sediment quantity and distribution at different life stages. While some species spend their entire lives within sediments or the water, others exist at the interface between the two or alternate between the water column and saturated sediments. Additionally, certain aquatic species, particularly insects, transition through life stages that occur on land or in the air [29].

Nutrient Recycling

Inorganic and organic nutrients are constantly carried to the bottoms of lakes through sedimentation. Various biological, physical, chemical, and mechanical processes can release certain nutrients back into the water. This cycling between sediments and water occurs in different patterns depending on the type of lake and bottom conditions. Factors, such as lake morphology, temperature, trophic level, and sediment type significantly impact the size of nutrient pools and their turnover rates [30]. The interactions of bacteria, benthic algae, macrophytes, benthic invertebrates, and fish, along with the effects of temperature, pH, redox potential, water content, organic matter, and the elemental composition of sediments, make nutrient cycling highly complex. Nutrients generally enter lakes and reservoirs from external sources like sewage, agricultural runoff, and wastewater from farming [31]. Over time, these nutrients can accumulate in the sediment, potentially creating an internal nutrient load that can be recycled back into the water under certain environmental conditions. Internal nutrient sources can also play a significant role, especially during summer when dissolved oxygen levels are low, as this can cause nutrients to be released from the sediment into the water column, stimulating algal growth. However, the exact nature of these internal sources is still unclear. The complex exchange of nutrients between sediment and water is crucial for understanding the chemical composition and trophic level of aquatic ecosystems. Sediments are a key source of nutrients for freshwater environments. Various processes, such as the desorption and dissolution of phosphorus (P) from precipitates, microbial mineralization of organic matter, and the diffusion of dissolved P from sediment pore waters, contribute to the release of phosphorus into the water column. Key environmental factors influencing the rate of phosphorus release from sediments include temperature, dissolved oxygen levels, pH, and redox potential [32].

Sediment as a Source of Food for Aquatic Biota

The soil or sediment food web of any ecosystem is the place where organic and inorganic particles are eventually trapped, mineralized, or stored, and this has important consequences for the global carbon balance [33]. The organisms in both soils and sediments interact in dynamic food webs, and the regulation of organisms by their consumers within the food web controls the fate of organic matter at local and global scales. Terrestrial, freshwater, and marine environments contrast in abiotic conditions, such as oxygen availability and temperature fluctuation. The sediment also contains some organic materials which serve as a food source to some holothurians, echinoids, and gastropods, which are bottom-dwelling [34].

Sediment as a Pollution Indicator

Sediment quality serves as a reliable indicator of water column pollution, as it tends to accumulate heavy metals and other organic contaminants. Sediments act as a final repository for heavy metals released into aquatic environments and are essential for assessing anthropogenic pollution in rivers. In river systems, sediments are commonly used as environmental markers, and their chemical analysis offers valuable insights into human activities [35]. As a key component of the aquatic environment, river sediment not only serves as a site for pollutant accumulation but also acts as a secondary source of pollution that can affect water quality. Thus, sediment quality is an effective indicator of water column pollution due to its tendency to concentrate on heavy metals and organic pollutants [36].

Other Positive Impacts of Sediments on the Aquatic Environment

Sediments primarily function as both a reservoir and a potential source of contaminants to the water column. They are also useful for indicating whether a water body is polluted. Sediments play a crucial role in the diversity and composition of habitats, significantly influencing their quality, particularly in the medium to long-term development of aquatic environmental features.

The load of the sediment of a water body is known to be one of the factors that form the morphological structures of various water bodies [37]. When sediments are transported by erosion to a water body, it affects the building of new substrates for the development of marshes. The sediment contains some unconsumed bacteria. These bacterial species play very important roles as mineralizers of organic detritus and recyclers of essential nutrients needed in water bodies, which other benthic organisms (both plants and animals) depend on for survival [38].

Negative Impacts of Sediments on Aquatic Environment Biota

If there is excessive deposition of sediments on a water body, it can significantly impact the condition of freshwater habitat, which will result in the deterioration of the quality of the water. Other impacts of excessive sedimentation on the aquatic environment include loss of important or sensitive aquatic habitat, decrease in fisheries resources, loss of recreation attributes, loss of coral reef communities, changes in the nutrient balance of the water body, increase in water turbidity, circulation changes, loss of submerged vegetation and coast line alteration (PI, 2021) [39]. Rapid flow of sediments into a water body can lead to a change in the size and shape of the water body, which could also result in new patterns causing erosion or sediment removal from some sensitive areas of the water body. Sediment deposits in rivers can alter the flow of water and reduce water depth. Bioturbation activities modify the partitioning of contaminants between dissolved and particulate forms, as they frequently release contaminants from sediments to the water column for both dissolved (from pore waters) and particulate forms (fine suspended solids). When Sediments are deposited in excess quantity in a water body, it leads to a murky nature of that water. Murky water prevents natural vegetation from growing in that water body. Sediments block sunlight, as well as having negative effects on the reduction of growth of beneficial aquatic species. A water body that is polluted with excess sediments becomes cloudy or more turbid, and this prevents bottom-dwelling animals from seeing their food. Sediments in stream beds disrupt the natural food chain by destroying the habitats for benthic organisms [40].

When sedimentation exceeds natural thresholds, it could lead to total loss of the fauna community and subsequent colonization by pioneer species in affected water bodies. Sediments that have low permeability could affect the level at which some benthic faunas migrate vertically through benthic and subsurface substrates. Benthic bivalves, like the *Macoma baltica,* which burrows into the sediments in marine water bodies, tend to accumulate various pollutants (heavy metals, etc.) from the sediments into their bodies. Acute toxicity is a major impact on marine and freshwater invertebrates that are bottom-dwelling from contaminated sediments (Increased sediment concentration in water can lead to egg abrasion, reduced bivalve pumping rates, and direct mortality. Filter-feeding benthic organisms, like oysters and clams, when exposed to increased sediment loads, are at particular risk due to their nature of being sessile nature [41]. Figure 3 indicates that sediments have the ability to suffocate fish eggs and bottom-dwelling organisms, reducing the habitats for their eggs to be laid, as well as abrading the gills of fish [42].

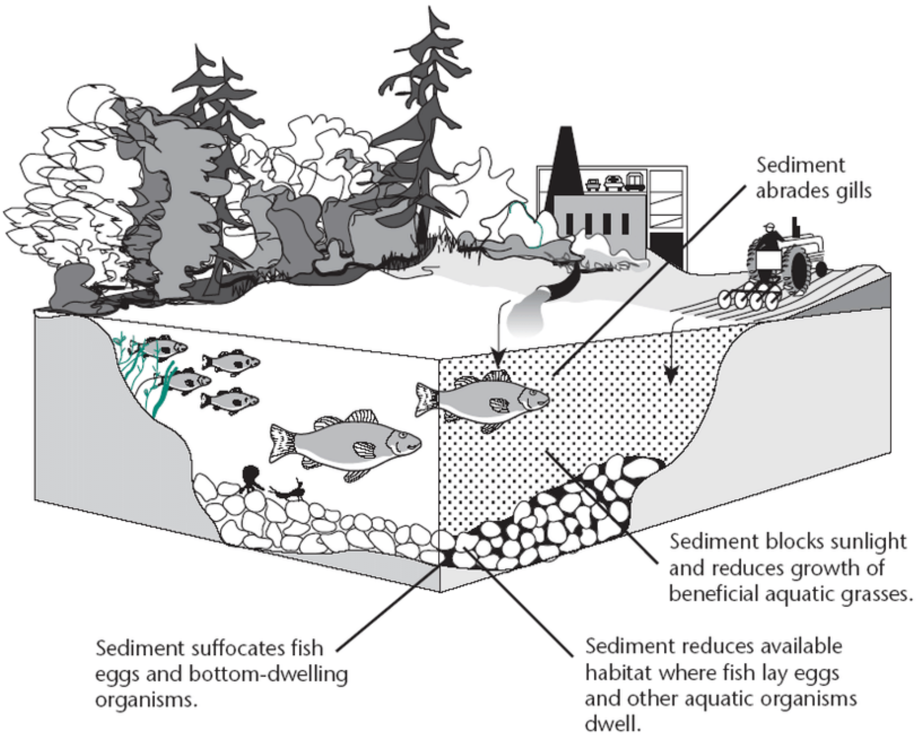

Figure 3. Some effects of sediments on aquatic organisms.
Source: [43].

FACTORS AFFECTING THE STATE OF SEDIMENT LOAD OF WATER BODIES

Prothero & Schwab (2004) [44] listed the factor that affects the variations in river sediment load as relief, channel slope, basin size, seasonality of rains, tectonic activities, and anthropogenic activities.

- *Relief:* Relief is one of the determining factors of the possible erosive component of the catchment area. It shows the difference between the highest and lowest elevations.
- *Channel Slope:* Channel slope affects sediment load by influencing transport, deposition, and erosion. A steeper slope increases water energy and sediment capacity. Gentler slopes reduce flow velocity and promote sediment deposition. Steeper channel slopes lead to greater shear stress on the riverbed, facilitating the transport of larger sediment particles downstream. This relationship is often quantified using sediment transport equations, such as those integrating parameters like slope, discharge, and grain size. High slopes increase the erosive power of water, often resulting in significant sediment removal from the channel bed and banks. In contrast, areas with lower slopes act as depositional zones where sediments settle due to reduced flow energy. Channel slope also influences the grain size of sediment loads. Steeper channels typically carry coarser materials due to higher transport energy, while finer sediments dominate in flatter sections where deposition is prevalent [45, 46].

- *Basin Size:* Basin size significantly influences the sediment load in water bodies, as it determines the volume and dynamics of sediment production, transportation, and deposition. Larger basins encompass more land area subject to erosion, contributing to greater sediment generation
- *Seasonality of Rains:* Seasonal rainfall patterns greatly influence sediment load in water bodies. During periods of intense rainfall, such as monsoon seasons, erosion increases significantly, leading to higher sediment discharge into rivers and lakes. Conversely, drier seasons often result in reduced sediment transport due to lower water flow. Heavy rainfall events, particularly during monsoons, can amplify soil erosion and transport sediments downstream, contributing to high sediment flux in water bodies. However, sediment deposition in reservoirs and slower-moving sections of rivers is common during these times. The seasonal variability of rainfall impacts the amount and type of sediment. Fine sediments, such as silt and clay are more likely to be transported during high-flow periods, while coarser sediments settle upstream. Changes in seasonal rainfall patterns due to climate change further affect sediment dynamics. Increased rainfall variability may result in extreme sedimentation events during wet seasons and reduced transport during prolonged dry periods. Seasonal rains also influence the movement of nutrients and pollutants bound to sediments, affecting water quality and aquatic ecosystems [47–49].
- *Tectonic Activities:* Tectonic uplift creates steep slopes and high-relief terrains, which enhance erosion and increase sediment supply to rivers. Conversely, subsidence can create basins that trap sediments, reducing sediment load downstream. These effects are evident in areas, like the Tibetan Plateau, where tectonic uplift impacts sediment grain size and channel morphology. Tectonic activities, such as earthquakes trigger landslides and debris flows, introducing large volumes of sediment into rivers. These sediments may include fine-grained materials and coarse debris, significantly altering sediment dynamics. Uplift can steepen river gradients, increasing the sediment transport capacity, while tectonic subsidence flattens profiles, leading to sediment deposition. For instance, in the Min River, tectonic activity has reshaped channel gradients, affecting sediment fluxes and bedrock erosion. Tectonic processes can expose different rock types, altering the composition and texture of sediments transported by rivers. This is crucial in regions with diverse lithology, where tectonic movements govern sediment characteristics [50].
- *Anthropogenic Activities:* Anthropogenic activities, like dredging lead to elevated suspension of sediments, which then settle and pose a high risk to benthic filter-feeding organisms. It also leads to the alteration of light in the water body, thereby making the water more turbid. It is of particular significance for habitat-forming benthic groups, such as corals and seagrasses, etc., as their loss would result in a loss of habitat-associated biodiversity. It also has negative effects on water quality. The impact of changes in rainfall is a means of transportation of sediments into rivers, as during the rainfall periods, there can be a higher ability of water run off [51, 52].

Physicochemical Features of Sediments That Enhance Survival and Interaction of Benthic Organisms

Some physicochemical parameters of the sediments that benthos depends on for survival include the dissolved oxygen, salinity, pH, nutrients, etc., and they are grouped into physical and chemical parameters. Table 1 indicates some works done on the physicochemical parameters of sediments that benthic organisms depend on for survival [53, 54].

Table 1. Some studies within and outside Nigeria have assessed the physicochemical parameters of waters and sediments that Benthic organisms depend on.

S.N.	Parameter (Group)	Location	Source
1	Cadmium, lead, and copper (chemical parameters)	Niger Delta, Nigeria	[55, 56, 57]
2	Total hydrocarbon content, total organic carbon, pH, and electric conductivity (physical and chemical parameters)	Trans-Okpoka Creek, Upper Bonny Estuary, Nigeria.	[58, 59, 60]
4	pH, water content and organic matter (physical and chemical parameters)	Krzynia Reservoir, Slupia River, and the European Low Dam Reservoir.	[61, 62, 63]
5	Total organic matter content, minerogenic residue, manganate oxide, chromium, zinc, nickel, cobalt, copper & lead (chemical parameters)	Danube Delta Biosphere Reserve, Romania.	[64, 65, 66]

CONCLUSIONS

Sediment plays an advantageous role in the survival of benthic organisms, but it can have negative effects on them as well. They have major importance as habitats to benthic organisms, just as they serve as reservoirs to various substances like heavy metals, PCBs, minerals, organic and inorganic matters, etc. The quantity of sediment in a water body can negatively alter the survival of benthic organisms if they are in excess quantities, as well as if anthropogenic activities, like dredging, are carried it destroys sediments which are known to be habitats for these organisms.

Recommendation

It is recommended that human activities that alter the levels of sedimentation should be cautiously mitigated in order not to lead to reduced levels of sediment for the survival of benthic organisms, as well as high levels of sedimentation around and in various water bodies, as sediments could alter the diversity of benthic organisms.

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