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Original Article

Impact of Fine Sediment on Benthic Macroinvertebrates Communities of Freshwater Ecosystem: A Review

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ABSTRACT

The freshwater environment in Ethiopia is exposed to severe human influence because of fast population growth and other factors. Anthropogenic activities in developing countries such as river regulation and pollution have a potentially negative cumulative impact on water quantity and quality of the rivers and wetlands, hence negatively impacting benthic invertebrates and fishes. This review aims to identify the impacts of fine sediment on the community of benthic macroinvertebrates, and freshwater food webs, and to assess the response of benthic invertebrates to fine sediment pollution. Literature review was used as a methodology. Fine segment load on the freshwater ecosystem from both point and nonpoint sources may directly/indirectly alter the macroinvertebrate communities. Organic and inorganic contaminants as well as other sediment variables (sediment grain size, total organic carbon, nutrients, etc.) were affecting the community composition of benthic invertebrates. However, habitat features like the number of supplements or the silt grain measure clarify the variation in macroinvertebrate indices and metrics. The impact of metals and, to a lesser extent, organic contaminants may also be significant. Benthic macroinvertebrates are commonly used indicators of river ecological conditions that can be adversely affected by fine sediment loads. Sedimentation can change the suitability of the substrate for some taxa, increase macroinvertebrate drift, and affect respiration and feeding. To conclude, excessive fine sediment severely alters the structure and function of macroinvertebrates. At the regional and national levels, different governmental and non-governmental organizations, research institutions, and policy makers are recommended to take responsibility for reducing sediment discharge to the freshwater ecosystem by applying different conservation measures of benthic macroinvertebrates.

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INTRODUCTION

Water bodies are energetic and subjected to different natural and human-induced variables. For example, human population growth and the increasing strong demand for food have extended agriculture and urbanization which has also resulted in habitat destruction, fragmentation, and pollution of freshwater ecosystems and inevitably in loss of biodiversity (MEA, 2005). Freshwater biodiversity is threatened due to manifold impacts, frequently related to human-induced changes on the catchment scale (Allan, 2004) which affect the freshwater environment on different spatial and temporal scales. Berry et al. (2003) considered the effects of increased deposition of sediments on benthic invertebrates as one of the most important concerns within the sediment pollution issue, especially regarding the dependence of freshwater fisheries on benthic productivity.

Sediment is a naturally occurring element in many bodies of water, though it can be influenced by anthropogenic factors. Sediment discharges in freshwater systems due to changes in agricultural activities; for example, increased areas of arable cultivation, leading to greater areas of bare exposed soil susceptible to erosion by rainfall, climatic (precipitation, temperature), geologic (soil type) and topographic conditions (slope and gradient) as well as by the catchment vegetation cover (Yamada & Nakamura, 2009), and mechanized farm practices which compact the soil and increase runoff and soil erosion (McMillan, 2023; Bilotta et al., 2013). Due to the human activities in catchments the amount and rate at which fine sediment discharges to the freshwater environments has been enormously increased by anthropogenic activities such as horticulture, forestry, mining, road construction, and expansion of urbanization (Vasconcelos & Melo, 2008).

Increased sediment rates have overloaded many rivers and streams, exceeding their ability to flush sediment (Relyea et al., 2000), and resulting in sedimentation and impairment of benthic habitat. Sediment particles are transported by flowing water and deposited in streams and receiving waters, such as lakes, wetlands estuaries, and coastal bays, as the result of flowing water (Growns et al., 2017). Sediment is naturally moved along a river system, so the landscape, climate, geology, and current velocity all affect the state of the sediment at any particular time. By increasing the movement of silt into the freshwater ecosystem and increasing the quantity of smaller molecule sizes, human activities can have an impact on this common silt cycle. The flow and shape of the channel affect the migration of silt. For example, higher water velocities can transport larger particles. Sediment size categories have been used to describe the deleterious effects of high amounts of fine particles in the substrate on benthic macroinvertebrates (Kaller & Hartman, 2004).

Clastic sedimentation is an expression used to describe inorganic clumps of sand, gravel, and other worn rock fragments. Chemically derived sediments consist of naturally existing triggers like gypsum and rock salt. Organic sediments are composed of organic remains, such as plant material, coal, or shells, and finally, water is also an important component of sediment, and is described as interstitial pore water (Soman et al., 2015). Sediments can be eroded, transported, or deposited depending on their particle size and the flow rate of the water. Sediment particles come in

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different sizes (*Table 1*) and can be inorganic or organic in origin.

Table 1: Conventional grain size ranges for different sediment types

Sn	Diameter of grain size range (mm)	Type of sediment
1	> 256 mm	Boulder
2	64-256 mm	Cobble
3	32-64 mm	very coarse gravel
4	16-32 mm	coarse gravel
5	8-16 mm	medium gravel
6	4-8 mm	fine gravel
7	2-4 mm	very fine gravel
8	1-2 mm	very coarse sand
9	0.5-1 mm	coarse sand
10	0.25-0.5 mm	medium sand
11	125-250 µm	fine sand
12	62.5-125 µm	very fine sand
13	3.9-62.5 µm	Silt
14	1-3.9 µm	Clay
15	< 1 µm	Colloid

Source: Piman & Shrestha, 2017)

Fine sediment is described as sediments less than 2 mm in size, thus encompassing sand, silt, and clay (Angradi, 1999). Very small clay particles (up to 0.004 mm) exhibit a strong influence from electrical charges on their surface, resulting in cohesive forces. Particle sizes between 0.004 mm and approximately 0.0625 mm are known as silt and are in a transition range. The silt particles are too large to feel much influence from the electromotive forces and too small to mobilize inertia against flowing water. When particle size exceeds 0.0625 mm, electromotive forces are insignificant. These particles are non-cohesive and are classified as sand, gravel, cobble, etc. (Merritt et al., 2003). The fine fraction consists of particles with a relatively large surface area to volume ratio. Typically, surface electric charges cause the fine particles to be more chemically and biologically active (Collins et al., 1997) and have a high affinity for soluble metals and organic contaminants and nutrients (Warren et al., 2003) that may be deposited (Collins et al., 2011) and consequently become bioavailable, resulting in influences on ecosystem processes. The electro-chemically interacting clay particles in fine sediment can affect the fluid properties and settling velocity of larger particles. For phosphorus and metals, clay particle size is of primary importance due to the large surface area of very small particles.

In an aquatic environment, sediment can either be suspended (floating in the water column) or bedded (settled on the bottom of a body of water) (Schäffer et al., 2020). Suspended sediment represents that component of sediment that stays in suspension for an appreciable length of time and represents a dynamic equilibrium between the upward forces of turbulence holding particles in suspension against the downward force of gravity (Holtschlag, 2001). Turbulent forces are directly related to stream flow rate, and the effectiveness of gravitational forces is related to particle sizes and densities. In most natural rivers, sediments are transported mainly as suspended sediment (Peters, 1996). Suspended sediment is ultimately deposited at some point in the system, and this can also result in negative impacts on the aquatic macroinvertebrates. Additionally, strong negative responses in EPT-related metrics to increased deposited inorganic fine sediment resulting from reduced habitat availability have been reported (Burdon et al., 2013; Larsen et al., 2011; Mathers et al., 2017; Pollard & Yuan, 2010; Zweig & Rabeni, 2001). Burdon et al. (2013) suggested a critical threshold of 13–20% for surficial sediments, whereas, Shearer & Young, (2011)

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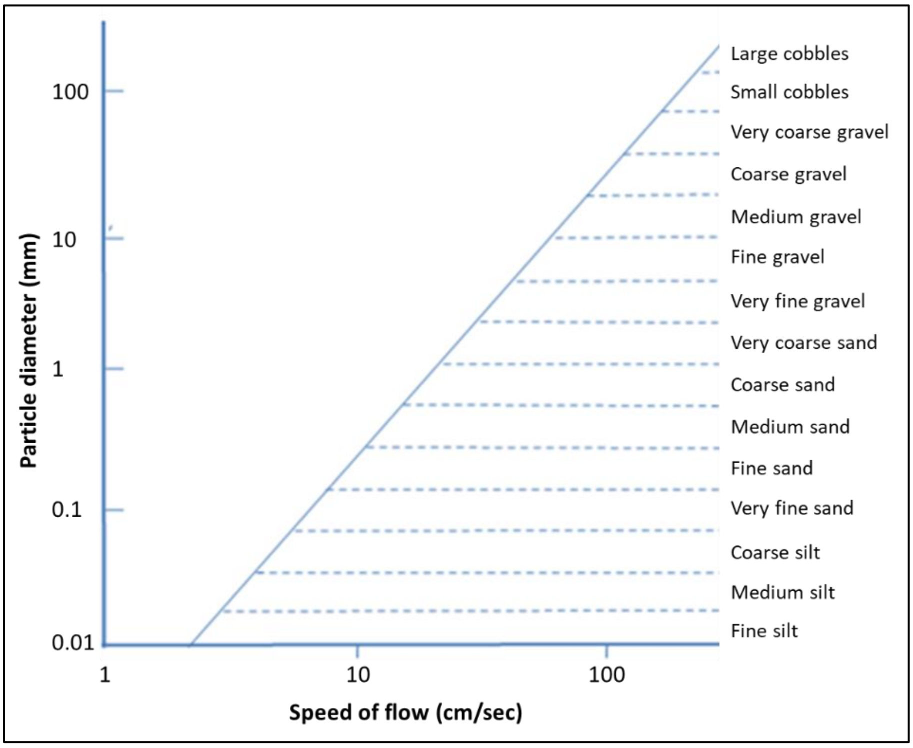
observed that pastured areas had a lower macroinvertebrate community index due to saprobic pollution, compared to sites in native forest areas.

Deposited sediment refers to the particles covering the streambed (Waters, 1997). Generally, accumulated sediments include larger particles, which lie in the sand to silt size range, while suspended sediments comprise smaller particles mostly of clay and silt (Mou & Sun, 2011). There are two common upper-size limits, which are different for suspended versus deposited sediment. The silt/sand boundary of 63 µm is typically taken as the upper cut-off for fine suspended sediment, that is, particles in the clay or silt range (Table 1).

The rationale for this upper size bound is that mineral particles of greater size generally deposited quickly and so contribute to the suspended load only for a small proportion of the time during floods when flows are highly turbulent. Indeed, organic particles of much greater size, but low density relative to water, will remain suspended for extended times. For deposited sediment, in sharp contrast, sand-sized material is still considered ’fine‘, apparently because its effects when deposited are not easily separable from that of deposited silt and clay, whereas there is a clearer separation from coarser material into the fine gravel range. So the upper bound for fine deposited sediment is typically taken as 2 mm (=2000 µm) diameter (Piman & Shrestha, 2017), although the literature is not consistent on this upper size limit.

In natural ecosystems, the concentration of suspended sediments and rates of deposition are temporally and spatially variable depending on the seasonal changes in flow rates (e.g. drought, rainfall, snow-melt events) and the characteristics of the river network and surrounding catchment (Walling & Fang, 2003). In addition, there can also be catastrophic events (e.g. volcanic eruptions, landslides) that can increase sediment levels significantly above normal variability. Each sediment type moves at a different speed according to its size (FAO, 2001). FAO, (2001) gives a relationship between the current speed and size of the sediment particles moved by the flow (Figure 1).

Figure 1: Relationship between flow speed and size of particles moved.



Source: as cited in Baran & Guerin, 2012).

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Fine sediments are vastly affected when manageable limits have been exceeded due to excessive inputs (Henley et al., 2000). The deposited fine particles can provide the aquatic biota with an essential food source (Wipfli et al., 2007) as it is necessary for the development of the freshwater environment through nutrient replenishment and the creation of benthic nest and spawning areas. This importance occurs due to sediment deposition when the water flow slows down or stops. However, when sediment concentrations and rates of deposition exceed natural background levels, aquatic biota can be negatively affected resulting in reduced abundance and diversity, and shifts in community composition (Collins et al., 2011), because high fine sediment loads lead to alterations to the physical, chemical and biological properties of the water body. Physical alterations caused by suspended sediment include reduced penetration of light, temperature changes, and infilling of channels and reservoirs when solids are deposited. Chemical alterations include the release of contaminants, such as heavy metals, and nutrients such as phosphorus. The accumulation of excess fine sediment decreases substrate particle size, resulting in a change from a heterogeneous substrate with complex habitats to a more homogenous sand/silt substrate as deposited fine sediment can clog interstitial spaces (Bryce & Lomnicky, 2010), reduce substrate stability (Richards et al., 1993), and increase substrate embeddedness for benthic macroinvertebrates.

Thus, the aim of this review is to make the community and policy makers to have good awareness about the impact of fine sediment on benthic invertebrate communities as well as to introduce ways for reducing sediment discharge to the freshwater ecosystem.

Review Questions

The study is guided by the following research questions.

- What is the impact of fine sediment on the community of macroinvertebrates in the freshwater ecosystem?
- What is the impact of fine sediment on the freshwater food web?
- What is the response of macroinvertebrates to the fine sediment in the freshwater ecosystem?

Objectives of Review

- To identify the impacts of fine sediment on the community of benthic macroinvertebrates
- To identify the impact of fine sediment in the freshwater food web
- To identify the response of benthic invertebrates to fine sediment pollution

METHODOLOGY

The review involved mainly the collection of secondary data from various sources such as peer-reviewed journal articles, books, and technical reports from Google and Google Scholar. More specifically desk reviews of relevant literatures on the area of the impact of fine sediment on communities of macroinvertebrates in freshwater ecosystem were involved.

RESULTS AND DISCUSSIONS

In the heterogeneous physical environment of streams, benthic invertebrates have evolved a diverse array of morphological and behavioral mechanisms for exploiting foods (Wallace & Webster, 1996). Dead organic matter is one of the main sources of energy for benthic species in shallow-water environments foods (Wallace & Webster, 1996). Benthic spineless creatures discharge bound nutrients into an arrangement by their nourishing activities, excretion, and burrowing into the silt. Microscopic organisms, parasites, green growth, and sea-going angiosperms can rapidly take up these broken-up nutrients, quickening microbial and plant growth (Pelegri & Blackburn, 1996). The increased growth of benthic microbes, algae, and rooted macrophytes are in turn consumed by herbivorous and omnivorous benthic invertebrates (Lodge et al., 1994). Many benthic spineless creatures are predators that control the numbers, areas, and sizes of their prey (Crowl & Covich, 1990). Food

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supply for both freshwater and earthly vertebrate buyers (e.g., angels, turtles, and fowls), and benthic organisms accelerate the nutrient transfer to overlying open water of lakes (Raffaelli et al., 2003). As benthic invertebrates inhabit the stream bottom; any modification to streambed will most likely have a profound effect upon the benthic invertebrate community. Fine sediment disturbance in aquatic invertebrates as a result of the loss of interstitial space and shelter (habitat), affects photosynthesis and therefore reduces food availability (Graham, 1990), oxygen depletion (Edwards, 2014), misfortune use of quick capability (Nuttall & Bielby, 1973), and physical expulsion of living beings by scouring (Culp et al., 1986).

The intermediate disturbance hypothesis suggests that in the absence of disturbance, the superior competitors could eliminate the inferior competitors, reducing the species richness of the system (Zweig & Rabeni, 2001). However, anthropogenic activities such as channelization of waterways, and high sediment load can increase the frequency and magnitude of disturbance or can upset the natural occurrence of disturbance and keep stream communities in perpetual disequilibrium (Growns et al., 2017). It is useful to consider the disturbance of fine sediments into two components, effects from suspended sediments (Figure 3) and deposited sediments (Figure 4). Each component can have differential effects on macroinvertebrates.

Impact of Fine Sediment Loading on Macroinvertebrates

Impact of Fine Sediment Loading on Macroinvertebrates Community Composition

Considerable evidences indicate that changes in the abundance and composition of invertebrate communities are associated with increases in suspended solids and turbidity. Porterfield (1972) found that suspended loads between 40-120 mg/l resulted in a 25% reduction in macroinvertebrates density; macroinvertebrates density decreased by 60% for a sediment load of more than 120 mg/l. Gray & Vard, (1982) found that densities of Chironomids also decreased in abundance by 90% after a release of suspended solids downstream from Guernsey Reservoir, Wyoming. Benthic invertebrate community composition characteristically changes from a community dominated by Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies) (EPT) taxa to one dominated by animals adapted to burrowing such as Oligochaetes worms, Chironomidae larvae, and bivalves when sediment loading is high (Armitage & Cannan, 2000). Such tolerant invertebrates can also increase (Soluk, 1986) particularly if the deposited sediments are organically enriched even though the overall density and diversity of benthic invertebrate communities commonly decrease with increases in suspended and deposited fine sediments (Figure 2) (Fossati et al., 2001). Macroinvertebrate community composition is strongly correlated with river-bed surface particle size composition (Jones et al., 2011) and such correlations have been used to identify taxa associated with a low proportion of fine sediment in the bed (Carlisle et al., 2007; Cormier et al., 2008; Bryce & Lomnicky, 2010). By necessity, taxa that dominate in fine sediment habitats are tolerant of mobile fine-grained sediments, and many are also tolerant of low dissolved oxygen levels and the pollutants that can be adsorbed onto fine sediment particles. However, changes in community composition are not restricted to habitats receiving heavy deposition of fine sediments that blanket the river bed, but also the efficiency of feeding may also be reduced by restricted visibility, due to decreases in water clarity (Ciesielka & Bailey, 2001).

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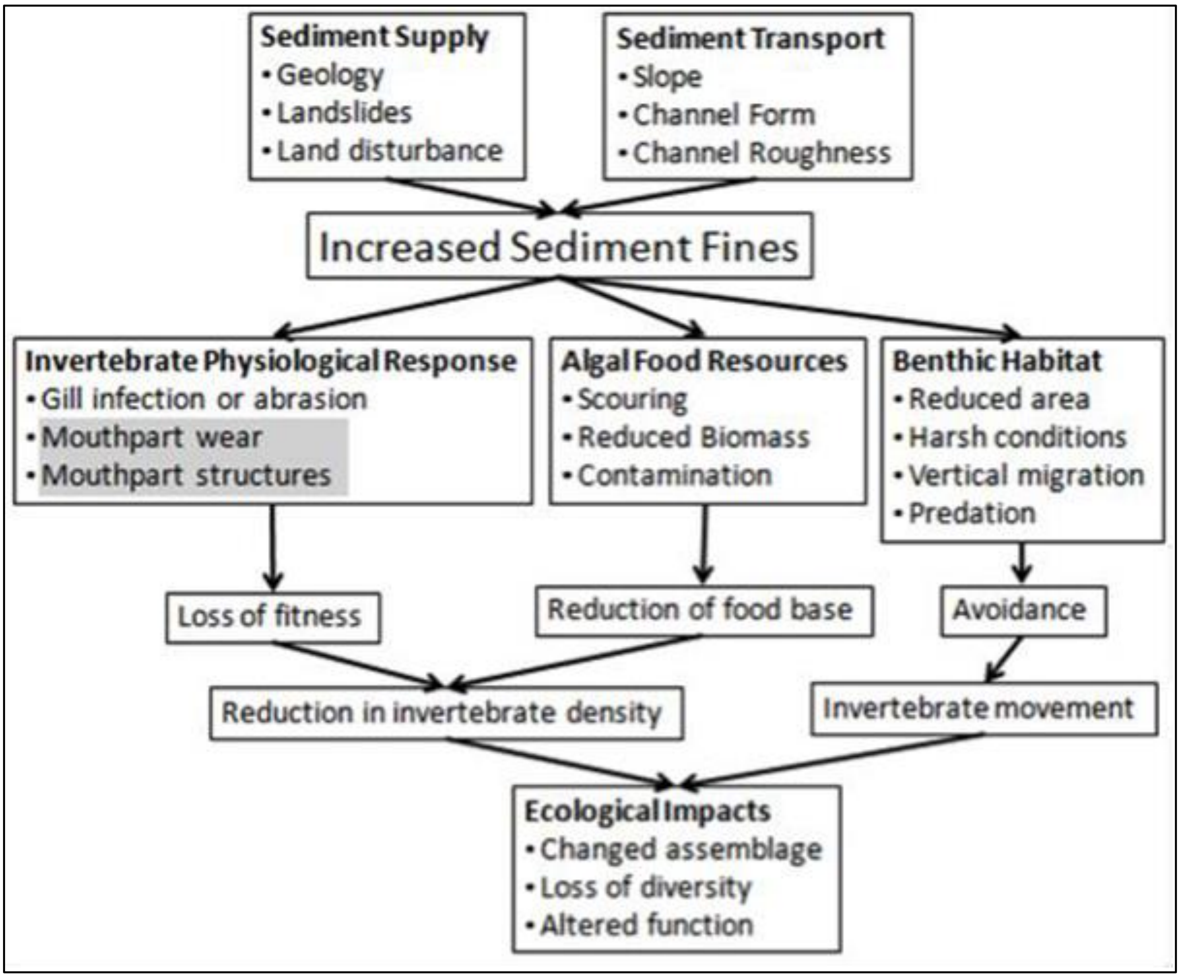
Figure 2: Conceptual diagram showing fine sediments in streams and their mechanistic effects on invertebrates and benthic habitats.



Source: (Edwards, 2014).

Impact of Fine Sediment Loading on Freshwater Food Web

Benthic macroinvertebrates are the middle link of the food chain and the integral components of food webs in stream ecosystems (Li et al., 2018). In nature, suspended fine sediments severely attenuate light penetration and affect key components of the food chain, first influencing primary production, and then zooplankton (Hart, 1992), benthic invertebrates (Suren & Jowett, 2001) and ultimately fish communities (Kent & Stelzer, 2008). Increased turbidity associated with suspended solids reduces the penetration of sunlight. This in turn reduces photosynthetic activity and limits primary production (Anderson et al., 1996). Reductions in primary productivity and the associated decreases in benthic algal biomass, phototrophic content and can have flow-on effects on biota further up the food chain, such as grazing invertebrates. Macroinvertebrates and periphyton provide important food for many species of freshwater fish (Jones et al., 2011). Accumulation of fine sediments can also reduce the biomass of periphyton and aquatic macrophytes through direct smothering of existing plants via a reduction in stable attachment surfaces for attached algae, such as periphytic diatoms and filamentous taxa (Wood & Armitage, 1997). The documented effects of fine sediment on macrophytes include physical damage to leaves, a reduction in photosynthetic activity, a slower growth rate, and a reduction in the maximum depth of colonization (Kerr, 1995). Shifts in the quantity and composition of these resources can also directly influence fish growth and community structure. The spatial variation of resources has direct effects on aquatic assemblages, especially the grain size of the

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bottom sediments, which is one of the most important parameters determining the composition of benthic communities (Sarriquet et al., 2007).

High and sustained levels of sediment may cause permanent changes in community structure, diversity, density, biomass, growth, and rates of reproduction and mortality. Impacts on aquatic individuals, populations, and communities are expressed through alterations in local food webs and habitats. The effects of reduced primary production on herbivorous insects and fishes at higher trophic levels are compounded when sediment settles on remaining macrophytes. Thus, not only is primary production reduced by sedimentation and turbidity, but macrophytes quality also is reduced as a food source (Ryan, 1991). These impacts can occur with small increases in inorganic-based turbidity. Lloyd et al. (1987) found that an increase in turbidity of only 5 Nitro turbidity units decreased primary production by 3 to 13%, and increases of 25 NTU decreased primary production by up to 50%. Not only does turbidity decrease available food sources for herbivores, but a reduction in phytoplankton also translates to a reduction in zooplankton (Lloyd et al., 1987). Consequently, a reduction in phytoplankton, and therefore zooplankton, may create cascading effects at higher trophic levels via a reduction in available food energy.

Macroinvertebrates link the lower and higher trophic levels in wetland trophic structures (Butkas et al., 2010; Pace et al., 2012). They are also known as an important food source for amphibians, fish, and other invertebrates, and they are therefore an integral component of aquatic food webs (Gezie et al., 2019). Fine sediment can directly smother invertebrates (Kefford et al., 2010), limit oxygen supply, reduce the quantity and quality of periphyton, zooplankton, and macrophytes food sources, and alter the food chain (Kemp et al., 2011). As invertebrates comprise the main food resource of many species of fish, invertebrates are released from predation where fish populations decline as a consequence of increased fine sediment loading (Berkman & Rabeni, 1987). Even where fish populations are not impacted, increased turbidity can reduce the visibility of invertebrate prey to fish, thus reducing predation risk (Zamor & Grossman, 2007). The implications for the invertebrate community will depend on the extent to which predation controls population growth. Sedimentation inhibits periphyton as food, density of prey items, available oxygen for respiration, and interstitial space for refuge, which are necessary for the existence of many of these taxa, are inhibited by increased sedimentation (Harrison et al., 2007). The feeding guilds most negatively correlated with siltation were those most specialized to feed from the substratum. Benthic insectivores were adversely affected. It has been well-documented that increased sedimentation reduces insect diversity, density, and species richness (Ciesielka & Bailey, 2001; Porterfield, 1972).

Direct Impact of Fine Sediment Loading on Macroinvertebrates

Scraped (Gill Infection)

Freshwater macroinvertebrates and fishes are exposed and easily affected by abrasive sediment particles. Fish species have been found with increasing levels of deformities, eroded fins, lesions, tumors, gill flaring, and coughing, all related to increasing suspended solids in the water column (Berg et al., 1997; Schleiger, 2000). Increases in soil erosion rates are likely to be reflected in increased river sediment loads, increased concentrations of suspended particles, and increased rates of deposition (Walling & Fang, 2003). Invertebrates that inhabit exposed streambed substrates are subject to scouring, which can damage exposed respiratory organs or make the organism more susceptible to predation through dislodgment (Newcombe & Macdonald, 1991). Bigger particles, especially sand, moving by saltation or as bed load in freshwater ecosystems, bring the most harm. Macroinvertebrates showing the delayed response initially avoid saltation of sediments because of their deeper distribution, but an apparent vertical distribution exposed these taxa to saltating

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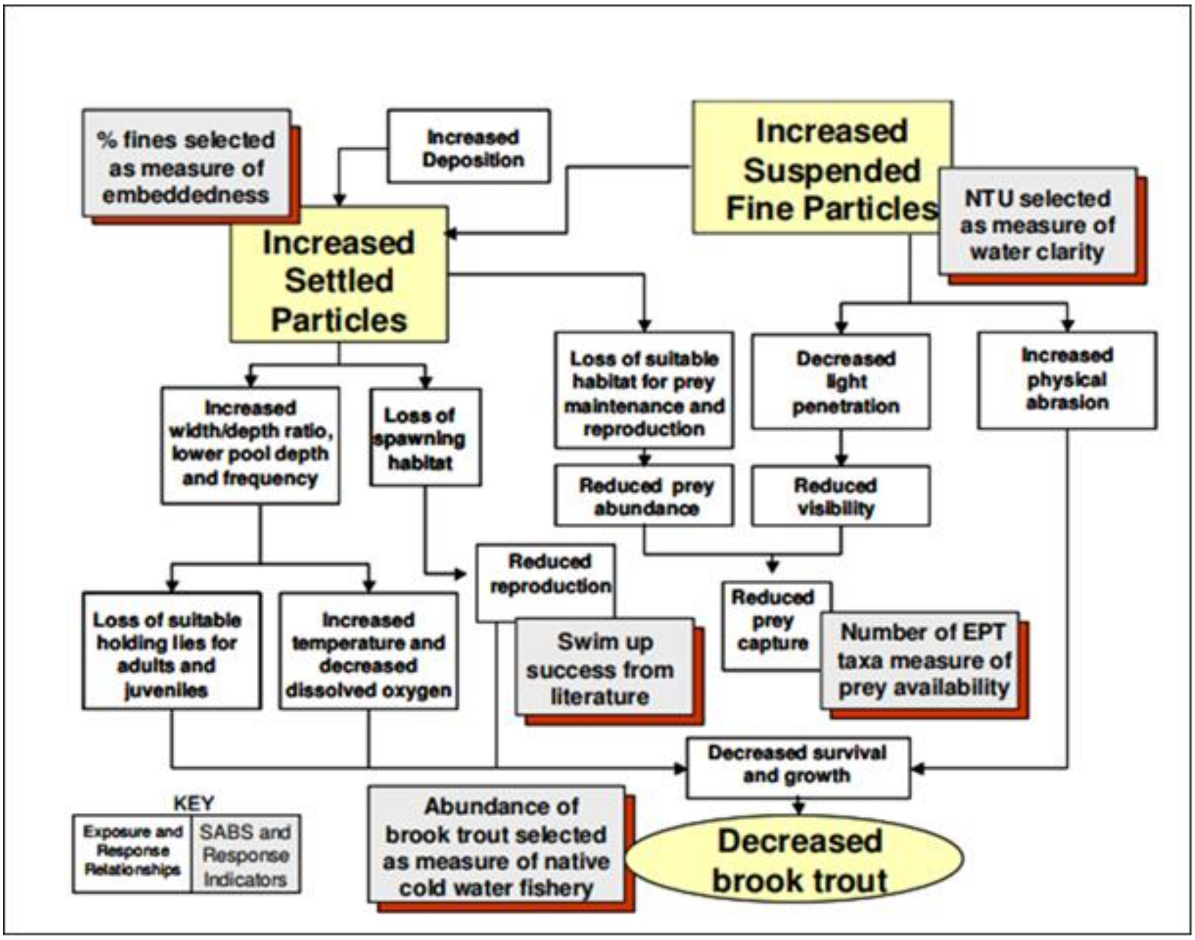
sediments 6-9 h after sediment additions (Culp et al., 1986). Nevertheless, smaller particles may be equally damaging if moving at high velocity. Unprotected, beefy body parts, such as gills and filter-feeding devices, are especially inclined to harm, with self-evident results for the people influenced. The ecological effects of the increased sediment on the streams are extensive, including physiological responses and behavioral changes in individuals and changes at the community level (Yin et al., 2017). For example, Brachycentrus (Trichoptera) switch from filtering with limbs extended into the water to trap particles to grazing when suspended sediment loads are high (Voelz & Ward, 1992), presumably because of abrasion from particles. Where withdrawal is not conceivable, people may withdraw to areas of moo speed or spend time cleaning and repairing harmed structures.

Figure 3: Conceptual model of SABS (suspended and bedded sediment) sources and effects: suspended fine sediment model.



(**Source**: Paul et al., 2008)

Altered Movement

The transport of fine particles, especially clays, and residues can result in a buildup of organs, disturbing the ordinary working of gills and filter-feeding devices, making breath and nourishing troublesome fish (Jones et al., 2011). Many species of invertebrates collect particles from water by filter-feeding and have a variety of special structures for doing so. Due to their position in the substrate, cockles collect particles from the near-bottom water mass, where sediment suspension may lead to pulses of particle concentration of a considerable magnitude (Iglesias et al., 1996); thus, considerably reducing the efficiency of feeding (Figure 2). Inter-specific differences in response to suspended sediments may involve structural/morphological, behavioral, or physiological differences (Hart,

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1992). Inhabitants of sediment-rich waters, such as D.barbata and D.gibba, might be expected to have evolved much coarser filters than D.pulex or D.laev as a means of avoiding or reducing the interference impact of fine inorganic suspensions on their food particle-collecting capabilities (Hart, 1992). Subsequently, the ingestion rate of blackfly hatchlings decreases with expanding inorganic suspended dregs as their guts fill with inactive particles. So also, numerous species of caddis fly hatchlings deliver nets of silk to trap passing particles. These nets can become clogged with fine sediments, leading to an increase in cleaning activity and eventual abandonment (Strand & Merritt, 1997).

Burial (Bed composition)

Benthic macroinvertebrate communities in streams are potentially structured by various disturbances (Mcelravy et al., 1989), which Gordon et al. (2013) define as discrete events in time. Burial presents difficulties for sedentary animals and, where rates of deposition are high, even motile animals can be affected fish (Jones et al., 2011). Expanded mortality in certain species of bivalve mollusks was noted as a result of rapid fine sediment burial. Burial with particles 1–2 mm and 2–4 mm resulted in an interlocking substrate with smaller interstitial spaces which nymphs had to burrow through to escape (Extence et al., 2013). Filter-feeding benthic invertebrates, such as caddis fly larvae from the family Hydropsychidae, are likely to be more susceptible to increased suspended sediment concentrations and deposition, particularly when feeding (Strand & Merritt, 1997). We identified many ways in which high concentrations of fine sediment adversely affect freshwater benthic macroinvertebrates and fishes. For example, it limits fish swimming in the water and either reducing their rate of growth, reducing their resistance to disease or direct mortality, lethal concentrations primarily kill by clogging gill rakers and gill filaments (Hogstrand & Wood, 1998; Ryan, 1991). It also reduces the suitability of spawning (Leonard et al., 1999; Moring, 1982), alters species composition and abundance (Hogstrand & Wood, 1998), reduces the feeding activity of fish due to a reduction in light penetration. As result, it affects photosynthesis, primary production, and a reduction of habitat available for insectivore prey items (Ryan, 1991; Doeg & Koehn, 1994; Gray & Vard, 1982) and the efficiency of hunting, particularly in the case of visual feeders (Hogstrand & Wood, 1998; Ryan, 1991). Depth of burial significantly affect the time taken to emerge, individuals buried to 2 cm require longer to emerge, particularly if buried in fine (10 mm) sediment. Two-thirds of those buried 2 cm deep in fine sediment abandoned their cases before emerging, whereas very few of those buried in coarser sediments and none buried to 1 cm depth emerged without a case (Dobson et al., 2000).

Indirect Impact of Fine Sediment Loading on Macroinvertebrates

Impact on Habitat and Behavior

Benthic macroinvertebrates are highly adapted to a wide range of natural conditions in freshwater environments. In benthic invertebrates, substrate is the primary refuge of benthic residents and plays the role of the principal habitat (Duan et al., 2009). Habitat modifications such as vegetation clearance and improper management of solid and liquid wastes contribute to the deterioration of water quality by raising water electric conductivity and nutrient enrichment levels leading to a decline in aquatic biodiversity (Gezie et al., 2019). Sediment accumulation can also alter the micro-topographical structure of a riverbed, thereby altering the substrate habitat characteristics for benthic invertebrate taxa, as well as reducing connectivity between the benthos and the hyporheic zone, beneath the riverbed. Invertebrates are strongly related to benthic substrate size, composition, and texture (Dobson et al., 2000). There is a strong relationship between substrate composition and invertebrate distribution at the patch scale (Culp et al., 1986), and invertebrate community is strongly correlated with mesoscale habitat patches (Armitage & Cannan, 2000). The degree of sediment accumulation on the body surface and respiratory structures of invertebrates (and invertebrate assemblage) is altered (Quinn et al., 1992;

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Richards et al., 1993), richness is reduced (Larsen & Ormerod, 2010), and abundance is decreased. Moog & Janecek, (1991) found that substrate layers with high proportions of fine sediment particles seemed to limit the downward colonization of macroinvertebrates and reduce the penetration of trophic resources into the substrate.

The decrease in refugia caused by fine sediment deposition makes invertebrates more exposed to predation and the effects of floods, and is likely to result in greater exposure to high current velocities, thus increasing the energy expenditure required in swift river habitats (Harding et al., 2000). Holomuzki & Biggs, (2003) observed that fine sediments result in significantly higher mortality of invertebrates (through smothering). The presence of fine sediments can also reduce oxygenation of the riverbed and hyporheos (Bylak & Kukuła, 2022) and this can be exacerbated if the fine sediments have a high organic content (Ryan, 1991). Because, the organic component of sediments has a direct negative impact on dissolved oxygen through its oxygen demand as organic compounds consume oxygen for oxidation processes, which reduces the amount of dissolved oxygen available in the water column (Bartley et al., 2015). Fine sediments infiltrate into the interstitial spaces between coarser substrates, filling crevices used as invertebrate habitat and refugia, and blocking connections between surface and hyporheic sediments (Jackson et al., 2007). Due to the filling of interstitial spaces between gravels and decreasing oxygen in the substrate, macroinvertebrates are inclined to leave their original niche to find safety. But, some taxa, such as Chironomidae, Oligochaetes, and Sphaeriidae, are adapted to take advantage of fine sediment and flourish during sedimentation as they can burrow into the sediment for shelter events in which EPT (Ephemeroptera, Plecoptera, and Trichoptera; or mayfly, stonefly, and caddis fly) taxa decline. Even though Trichoptera makes use of the fine sediment to construct cases and tubes to live inside, their sand cases cause them to settle out of drift more rapidly than non-case-bearing organisms. Filter-feeding macroinvertebrates such as Trichoptera larvae from the Hydropsychidae family are also likely to be more susceptible to increased sediment accumulation when feeding escape. Most probably EPT taxa are the most productive food sources for aquatic fishes, and their presence or absence plays a vital role in the suitability of space for fish habitation (e.g. reduced supply of oxygen). As a result, greater effort is required to excavate the body and during this time individuals may be susceptible to predation escape (Extence et al., 2013).

Impact on Feeding

Changed foraging behavior and reduced territoriality turbidity can reduce feeding rates, and affect prey selection and prey abundance. This is particularly significant for visual feeders, such as salmonids, where suspended solids can reduce the effectiveness of obtaining food (Berg et al., 1997). However, research also suggests the turbid-clear water interface may sometimes assist feeding, by offering concealment and protection within the turbid water (Scullion & Edwards, 1980). Feeding can be affected directly, by clogging of filtering and food-trapping apparatus (and thus, impeding filter-feeding) and by a reduction in suitable attachment surfaces for feeding (Calambokidis et al., 2007). Small increase in turbidity provides visual isolation from predators. As sediment levels were increased to over 180 mg/L this foraging activity declined along with a rapid reduction in territorial behavior (Calambokidis et al., 2007). Such responses to increased water turbidity have been shown to instigate increased emigration from preferred habitats as excess sediment makes habitats unsuitable. Although salmon were less responsive to increases in suspended sediment levels in colder water temperatures (winter months) this work highlighted the importance of non-selective salmon are more sediment tolerant at these times. Pulses of turbid water have also been shown to break down normal social organization and territoriality, which can decrease feeding rates and may affect overall growth rates (Berg et al., 1997).

Indirect effects may also occur via impacts on algal productivity, nutritional content (Graham,

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1990), desirability of the food source (Walting, 1991), and, in some cases, incorporation of toxicants associated with fine sediments into algal food sources. Fine sediment contamination of algae reduces feeding (Suren & Jowett, 2001), growth (Peeters et al., 2006), and assimilation rates (Broekhuizen et al., 2001). Suspended sediment reduces light penetration in the water column, resulting in less algal growth and therefore poorer nutritional quality of periphyton (Quinn et al., 1992). Reduced light penetration also affects sight-feeding invertebrates by reducing the efficiency of prey location. Due to the decline in periphyton (the film of attached algae, fungi, bacteria, organic matter, and sediment material found on the surface of stones) food quality may have extreme inclinations for invertebrate creatures that depend upon assets such as snails. Fine sediment affects macrophytes (both in suspension and deposition form). It can be used as food directly for invertebrates and as a substrate for periphyton in the water column. Correspondingly, if the impacts of fine sediment lead to the loss of prey species or basal resources from the community, those invertebrates that are reliant on these resources will have to alter their diet or in turn be lost from the community.

Direct and indirect impacts of fine sediment can manifest in the rates (Broekhuizen et al., 2001; Kent & Stelzer, 2008) and mortality of individuals, which can be detected through reduced population growth rate (Broekhuizen et al., 2001). Growth rates of invertebrates may also decrease as a result of reduced feeding activity as well as diminished food value (Klotz et al., 2023). Moog & Janecek, (1991) observed that several invertebrates (e.g. Deleatidium & Pycnocentrodes) preferentially grazed on unsalted periphyton when silted and unsalted periphyton were available, and that early instar Pycnocentrodes fed on silted periphyton had significantly lower growth rates than those grazing on unsalted periphyton. Dilution of the organic content of the periphyton matrix, through sediment contamination, would therefore, be expected to reduce the growth rates of invertebrate grazers or initiate behavioral avoidance responses. Generally, a negative relationship between growth rates and sediment contamination of food resources exists for aquatic insects. However, the case may not be necessary for all invertebrates. In further investigation of growth rates of P. antipodarum, Broekhuizen et al. (2001) found that despite the decrease in short-term assimilation rates as the proportion of fine sediment in the periphyton matrix increased, growth rates were highest at intermediate levels of sediment contaminant on invertebrate density, biomass and taxonomic richness in the Tongariro River, New Zealand (Collection (5:1 and 10:1 by dry weight), and were significantly lower in treatments with no sediment added. They suggested that P. antipodarum may derive trace nutrients from the sediment they ingested aiding increased growth rates. This seems a reasonable explanation, especially given that growth was measured in terms of shell height gain (with snail shells being mainly inorganic in substance). Moreover, ex-situ experiments have indicated that fine sediment particles may reduce invertebrate growth rates, as suggested by Hoess et al. (1999), who found that body lengths of the nematode Caenorhabditis elegans (Maupas) were associated positively with sediment particle size.

Chemical effects of Increased Fine Sediment Loading

Depressed Oxygen Levels in the Water

Suspended solids can contribute towards raising the Biological Oxygen demand (Milner et al., 2001), and hence lowered oxygen levels potentially to stressful or lethal levels for vulnerable species and life stages. Greater oxygen availability may enhance nitrification in the oxic sediment zone, while higher $N0_3^-$ supply to the suboxic sediment zone will enhance denitrification and $N0_3^-$ ammonification (Pelegri & Blackburn, 1996). The deposition of fine sediments on the freshwater ecosystem is more often than not related to significant changes to the chemical environment. The extent and direction of surface–subsurface exchange may regulate the supply of oxygen and organic material to the hyporheic zone, thus influencing hyporheic

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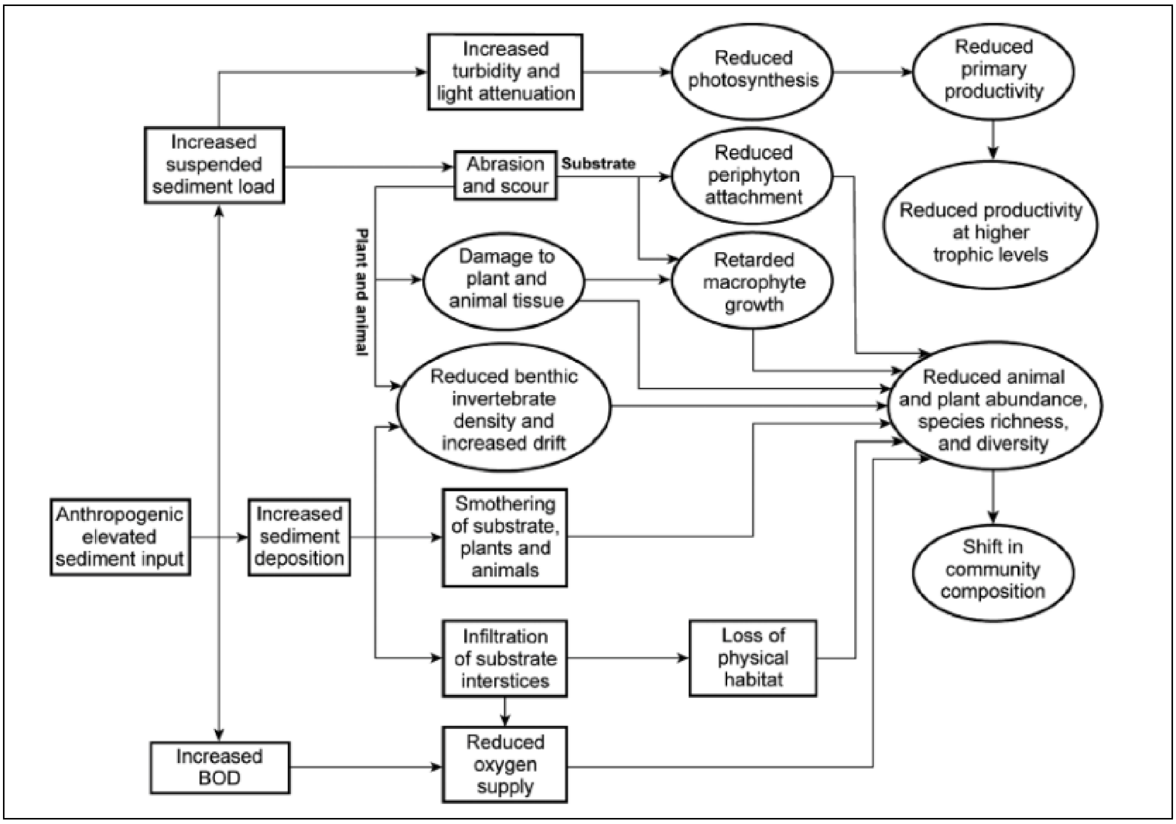
metabolism (Haxton & Findlay, 2008; Jones et al., 2012) and the processing of key nutrients (Pretty et al., 2006).

The deposited material has a high organic content. Microbial activity can lead to oxygen depletion and a buildup of potentially toxic substances such as ammonium, ferrous, and manganous ions (Jones et al., 2012). The process of collimation, where fine organic and inorganic material clogs the interstices between coarser substrates, can create very compacted river bed sediments and produce layers with low hydraulic conductivity (Pretty et al., 2006). Many species are sensitive to oxygen depletion, and associated chemical changes (Haxton & Findlay, 2008). Small particle size and/or a highly compacted streambed may impose physiological constraints on the meiofauna by limiting oxygen replenishment at low flow, generating patches of anoxia and thus reducing meiofauna abundance or changing species composition (Swan & Palmer, 2000). The excretion rates of benthic Chironomids and tubificid are not affected by the presence or absence of a sand substrate or type of water medium. However, by maintaining a high hydraulic conductivity in sediments, tubificid worms promoted water-sediment exchanges, which are essential for the metabolism of the aquatic ecosystem (Grimm, 1988). In addition to their effect on hydraulic conductivity, invertebrates can also modify biogeochemical and microbial processes occurring in sediments (Nogaro et al., 2006; Zimmerman & Szalay, 2007).

Figure 4: Effects of high sediment loads on aquatic ecosystems. Rectangles = Physicochemical effects. Ovals = Direct/long-term biological and ecological responses



Source: (Kemp et al., 2011)

Organic Matter and Nutrients

Organic matter in sediment consists of carbon and nutrients in the form of carbohydrates, proteins, fats, and nucleic acids. Bacteria quickly eat the less resistant molecules, such as the nucleic acids and many of the proteins. Sediment organic matter is derived from plant and animal detritus, bacteria, or plankton formed in situ, or derived from natural and anthropogenic sources in catchments. Sewage and effluent from food-

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processing plants, pulp and paper mills, and fish farms are examples of organic-rich wastes of human origin. Sediment nutrients are assessed as Total Nitrogen (TN) and Total Phosphorus (TP) concentrations, and have inorganic as well as organic sources. The amount of organic matter found in sediment is a function of the amount of various sources reaching the sediment surface and the rates at which different types of organic matter are degraded by microbial processes during burial.

Organic matter breakdown (mineralization) reduces sediment carbon and nutrient concentrations (Froelich et al., 1978). Dissolved nutrients are released from the sediment to the water column. Carbon is released as CO_2 gas and as dissolved organic carbon (DOC) (Froelich et al., 1978). Organic carbon burial efficiency is strongly correlated with the length of time accumulating particles are exposed to molecular oxygen in sediment pore waters (Hartnett et al., 1998). Variations in the mineral sedimentation rate will affect the rate at which material moves through the oxic horizon at the sediment surface, and thus alter O_2 exposure time (Hartnett et al., 1998). TP is exchanged between sediment and water to maintain water column P concentrations at near-constant levels.

Sediment carbon and nutrient concentrations increase with decreasing grain size. The presence of a high silt load or the nature of the benthic sediment does not appear to have had a detrimental influence on mysid and copepod abundance (Adams et al., 2002). Benthic microalgal biomass is reduced due to high sediment load and light reduction. The relative importance of these contrasting processes ultimately determines the biogeochemical pathways that dominate in the system and the fate of nutrients and phytoplankton organic matter in the ecosystem (Pennock et al., 1998). Organic matter with very high TOC: TN ratios consumes more dissolved oxygen (Pennock et al., 1998) supports less de-nitrification, and releases fewer nutrients to the water column (Rivera-Monroy & Twilley, 1996) when it breaks down than organic matter with low TOC: TN ratios. The decomposition of organic matter with very high TOC: TN ratios can even be nutrient-controlled meaning that it can cause the uptake of dissolved inorganic nitrogen (DIN) from the water column (M. Gray et al., 2013). Sediments with high TOC: TN ratios (and lower N contents) tend to support lower biomass of benthic invertebrates (M. Gray et al., 2013). Elevated nutrient concentrations have been reported to have profound effects on aquatic invertebrate communities. For example, macroinvertebrates have been shown to respond to agricultural runoff through increased drift (Olsen & Watzin, 2009). Drift enables organisms to escape unfavorable conditions and allows them to colonize new habitats (Brittain & Eikeland, 1988) and has been observed in response to various pressures including acidification, oxygen depletion, predation, change in light regime, and flow among others. Increases in suspended sediments (often associated with increases in discharge or environmental disturbance) generally cause an increase in the number of drifting macroinvertebrates (Doeg & Milledge, 1991; Suren & Jowett, 2001).

Heavy Metal Pollution

Many studies have revealed that heavy metals in sediments have strong adverse impacts on benthic communities (Seddon et al., 2019; Ryu et al., 2011; Blanco & Bécares, 2010). However, the response of benthic communities to heavy metal stressors can be, in terms of taxon richness and abundance, in streams and rivers, reflect the land use and physicochemical conditions modified by external factors, such as light that favor co-tolerance, and internal variables, which are influenced by multiple environmental factors (Blanco & Bécares, 2010; Shen et al., 2020; Fu et al., 2016). The expansion of agricultural activities around the freshwater environment, effluent discharges from wastewater treatment plants (WWTPs), catchment urbanization, water irrigation and supply, hydropower generation, and industrial discharges (McKenzie et al., 2023; Soman et al., 2015), increases sediment metal concentrations. The distribution of various contaminants in sediments depends largely on the physicochemical properties of the ecosystem, the

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partition coefficients of individual contaminants, the organic contents, and microflora activities (Doong et al., 2002).

Sediments can act as sinks of chemical substances that enter aquatic ecosystems in which contaminants accumulate over time and could represent a potentially significant hazard to the ecosystem (Alvarez-Guerra et al., 2007). They are not only a sink but also a known source of pollutants in river catchments (Ryan, 1991). Re-suspension of sediments also leads to the release of entrapped soluble metals and the oxidation of solid metal compounds in sediments (Brils, 2008). Heavy metal fluxes at the water/sediment interface represent a dissolved heavy metal source for the fluvial system which probably influences dissolved-particulate heavy metal partition (Audry et al., 2004). Moreover, sediment depth remobilization that causes historically accumulated metals to be exposed to overlying waters contributes to elevated metal levels in rivers (McKenzie et al., 2023; Soman et al., 2015). The effects of suspended sediment on stream ecosystems are many and varied. Sediment particle size and the level of acid volatile supplied in sediments determine the degree of metals leaching from the sediment and it could be argued that any increase in sediment carried by a stream could have a detrimental effect on stream ecosystems as well as aesthetic values (Ryan, 1991).

Heavy metals are common pollutants that are distributed in aquatic environments. They may occur due to industrial, anthropogenic, and agricultural wastes and heavy metal contamination has been shown to increase the susceptibility of mayflies to predation by stoneflies (Olsen & Watzin, 2009). Metal-contaminated sediments serve as sources of metals that can cause lethal and/or sub-lethal effects to stream macroinvertebrates as well as fish and other higher organisms through food chain transfer (Jagoe et al., 2002). Metals principally originate from natural mineral deposits, drainage from mining activities, industrial pollution, and municipal wastes. In the freshwater ecosystem if the concentration of metal is high it may reduce the quality of water and sediment (Taylor et al., 1990) which may lead to mortality of fish (Wicks et al., 2002), reduced survival and growth of macroinvertebrates (Ogendi et al., 2007c), and decreased taxa richness of other benthic macroinvertebrates (Ogendi et al., 2007c).

Metals have the potential to be toxic to living organisms if present at availability above a threshold level. This threshold varies between taxa and metal speciation. The distribution of trace metals through complex processes of material exchange within these aquatic environments can also be affected by anthropogenic inputs. Heavy metals are distributed globally with a wide range of concentrations. They are also naturally present in biota, aquatic environments, and sediment. The problems of metal pollution are currently increasing in many Ethiopian Lakes. It is mainly associated with the expansion of industrial activities and intensification of agricultural activities. Human factors, in combination with the natural conditions of climate and geology, strongly influence water quality and in turn affect aquatic biota (Zinabu & Pearce, 2003). For example, the total concentration of metals in Lake Hawassa was higher in sediment than in macrophytes and water, and this also mostly affects benthic macroinvertebrates (Amare et al., 2014).

Pesticides

Pesticides are used to control organisms occurring on agricultural products and crops and serve to protect plants, animals, and humans. Worldwide, an estimated 2.3 billion kg of 1600 different pesticides are applied yearly (Kleinman et al., 1995). Agricultural expansion around the freshwater ecosystem may cause to increase in the nutrients and pesticides in benthic sediments. The increased deposition of fine sediments from agriculture increases sediment contamination because silt and clay fractions sorb pesticides and trace metals (Shuman et al., 1999). Many pesticides are organic and have hydrophobic properties. These hydrophobic contaminants,

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once enter the water ecosystems, tend to bind to suspended particulate matter and accumulate in the bottom sediments of freshwater such as rivers and streams. In this condition, contaminants tend to be less degradable.

Conversely, sorbed molecules are unavailable for uptake by bacteria; they are located deep in the natural organic-matter matrix where pore sizes are too small for bacteria to penetrate or degradation is limited by diffusion to sites where microorganisms are located (Warren et al., 2003). The hydrophobic properties of the compounds also make them accumulate in aquatic biota, which is more hydrophobic than the surrounding water. Benthic macroinvertebrates may take up environmental pollutants via several different routes, e.g. overlying water, interstitial water, and sediment particles (Bender & Conrad, 1994). Sedimentation problems in river ecosystems are nutrient enrichment and toxic pollutants from agricultural waste and settlements that affect benthic macroinvertebrates (Sudarso et al., 2021). Sharpe & Mackay, (2000) estimated that benthic organisms attain about 95% of their accumulated contaminant from the sediment. The extensive use of pesticides as well as their relatively high persistence in aquatic sediments may result in high concentrations of pesticides, especially in intensive agricultural areas (Shaw & Richardson, 2001).

Glyphosate on non-target freshwater organisms, including invertebrates, has toxicological effects. Glyphosate in water has a half-life of 7 to 14 days and does not degrade rapidly in sterile water, but in the presence of microflora in water, glyphosate is broken down into microbes and carbon dioxide (Hillaby & Randall, 1979; Solomon & Thompson, 2003). In field studies of the toxicological effects of glyphosate on stream organisms, investigators were unable to distinguish invertebrate drift rates caused by glyphosate contamination from those occurring naturally in response to changes in stream discharge (Kreutzweiser et al., 2008). Nonetheless, in a laboratory experiment, a concentration of 10,000 µg/L glyphosate was required to induce avoidance movements of nymphs of the mayfly Ephemerella spp. (Folmar et al., 1979). Pesticide-driven drift responses may also be related to invertebrate body size (Solomon & Thompson, 2003) because the higher surface-area-to-volume ratio of smaller individuals may make them more susceptible to contaminants, such as pesticides, and thus, more likely to enter the water column and drift.

Response of Benthic Invertebrates to Fine Sediment Pollution

Turbidity, suspended load, and bed load were found to have significant influences on the species richness and diversity of the macroinvertebrate community. Macroinvertebrates may be strongly affected by immoderate fine sediments (Lemly, 1982). Responses to fine sediment stress incurred by benthos through the direct effects of elevated suspended-sediment levels may impose chronic, low-level stress, and thus invoke indirect effects upon benthic invertebrate populations and communities (Strand & Merritt, 1997), burial (Extence et al., 2013), egg-hatching (Kefford et al., 2010), growth (Kent & Stelzer, 2008), feeding (Hornig & Brusven, 1986), and relative abundance and richness (Kaller & Hartman, 2004). Analyzing taxon-specific responses or tolerances to fine sediments allows for the creation of a diagnostic index to identify a specific cause of impairment.

Organisms respond to increased suspensions in a variety of ways. If the level is high, such as in a flood, the immediate response of some organisms is to move (if they can). The actual displacement depends upon a variety of factors including the species involved and the velocity of the current. Organismal drift is usually maximal at night and minimal during the day. However, there is a wide range of responses of benthic invertebrates to increased sediment including changes in invertebrate feeding and growth, behavior, community composition, diversity, and abundance (Ryan, 1991; Waters, 1997; Bylak & Kukuła, 2022). Increased invertebrate drift in response to suspended sediment in the long term contributes to decreased abundance and diversity of benthic invertebrates.

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Accumulation of fine particles on body and respiratory surfaces (Lemly, 1982) and scouring and abrasion of respiratory surfaces (Newcombe & Macdonald, 1991) can occur with elevated suspended sediment concentrations, and may contribute to elevated levels of drift (accompanied by an increased susceptibility to predation), increased levels of infection, decreased respiratory ability and mortality. The most immediate response to an increase in the concentration of suspended fine sediment is an increase in the number of animals entering the drift (Suren & Jowett, 2001; Matthaei et al., 2006). The sudden increase in densities of drifting invertebrates can also result in a depletion of the standing stock in the benthos, particularly of motile taxa, resulting in a change in abundance and composition of the remaining community (Doeg & Milledge, 1991; Suren & Jowett, 2001; Matthaei et al., 2006; Larsen & Ormerod, 2010). Accumulation of fine sediment has had negative effects on hyporheic, and benthic fauna, inducing a reduction in benthic densities (Fossati et al., 2001). Similarly, changes in community composition can occur as changes in the available habitat favor different species (Armitage & Cannan, 2000). Most of these studies have reported relatively strong negative effects on stream biota. However, increases in sedimentation commonly affect long stretches of streams, calling into question the applicability to real streams of results of small-scale experiments. Responses to fine sediments are often taxon-specific as each taxon responds to different loads of fine sediment.

CONCLUSIONS AND RECOMMENDATIONS

High fine sediment loads in freshwater ecosystems may lead to alterations to the physical, chemical, and biological properties of the water body. Physical alterations caused by suspended sediment include reduced penetration of light, temperature changes, increased turbidity, and infilling of channels when solids are deposited. Chemical alterations include the release of contaminants, such as heavy metals, pesticides, and nutrients such as phosphorus, and depletion of oxygen levels. Such physical and chemical changes in the freshwater ecosystem affect the biota environment. Macroinvertebrates are ecologically important organisms that mostly inhabit in the stream and river beds. Any modification to natural habitats directly affects macroinvertebrates. Fine sediment (sediment that is less than 2 mm in diameter) suspension and deposition has a critical impact on macroinvertebrates.

Suspended sediments contribute to turbidity which may adversely affect algal growth via a reduction in light penetration and lower oxygen concentrations and in turn affect the primary food source for many macroinvertebrates. Suspended sediments can clog filter feeding nets or structures which can reduce feeding efficiency leading to reduced growth rates, stress, or killing these organisms and scouring exposed respiratory organs or make the macroinvertebrates more vulnerable to predation through dislodgement. Similarly, deposited sediments disturb stream biota by smothering the stream bed. The accumulation of excess fine sediment decreases substrate particle size, resulting in a change from a heterogeneous substrate with complex habitats to a more homogenous sand/silt substrate as deposited fine sediment can clog interstitial spaces.

Generally, the effects of fine sediments on benthic invertebrates are wide-ranging and can include a reduction in feeding ability, alteration of habitat, reductions in food availability and environmental quality, drift, and increased scouring and abrasion. Ultimately, these changes result in a change in community composition, with taxa that are intolerant to the impacts of fine sediment being replaced by those more adapted to these conditions. As invertebrates comprise the main food resource of many species of fish, reductions in these specy's density, biomass, and diversity throughout a trophic level are translated into reductions in energy input to the next trophic level.

The two main hypotheses regarding the responses of macro-invertebrate communities are (a) changes in biomass or abundance (which are

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distinguished from each other because they are not always consistently correlated) of individual taxa, groups within the community, or the community as a whole and (b) a change in the taxonomic composition of the community, which includes changes in dominant taxa, richness, and dominant feeding or habitat preferences.

Research on the responses of individual taxa to fine sediment accumulation, the impact of various flow habitats, separating its impact from other related land uses, and the relationship between fine accumulation of sediment and macroinvertebrates at a regional scale are all necessary to improve our understanding of the impact of fine sediment on macroinvertebrate communities. Appropriate guidelines for managing the ecological impact of fine sediment accumulation also need to be implemented to manage its deleterious impacts. This may then aid the managers in implementing appropriate mitigation measures to protect areas from fine sediment accumulation.

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Conflict Of Interest

The authors declare that they have no conflict of interest.

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