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CHAPTER 7. SEDIMENT

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Soil erosion and sediment transport are natural processes that have been substantially modified by humans. Anthropic activities have simultaneously increased sediment transport by global rivers through soil erosion, and yet reduced the flux of sediment reaching the world's coasts because of retention within reservoirs (Syvitski *et al.*, 2005).

Sediment is made up of solid particles of soil that consist of minerals and organic matter that move from their site of origin by soil erosion. Soil erosion processes are the detachment, transport and deposition of sediments. Solid particles of soil detach from the soil layer when the soil is uncovered and exposed to raindrops, shearing of water and wind, or surface runoff. Deposition of sediments occurs when the erosive force (e.g. wind or water) is no longer able to move the sediments. Sediments may be moved over land into rivers systems and ultimately end up in the oceans, but frequently they are intercepted and deposited at a wide range of sites such as in a riparian zone, at the bottom of a hill slope, a lake, a reservoir or a floodplain. The deposition process of sediments is called 'sedimentation' (National Research Council, 1993).

Under normal conditions, sediment loss from land is balanced by new soil production through weathering of rocks. Human activities, however, have altered the magnitude of land erosion, which increases when soils are exposed to rain or wind and when their structure is degraded. The key drivers responsible for altered sedimentation rates include deforestation, land clearance for agriculture, inappropriate agriculture practices, earth moving in construction works and mining activities. These human activities lead to higher sediment loads in river systems (Syvitski and Kettner, 2011; Walling, 2009). Effects of climate change, such as intensified and changed patterns of precipitation, also influence sediment loads to the world's rivers (Walling and Fang, 2003; Walling, 2006, 2008).

This section focuses on the agricultural contribution to soil erosion and sediment transport to water, and its consequences for human health and agroecosystems.

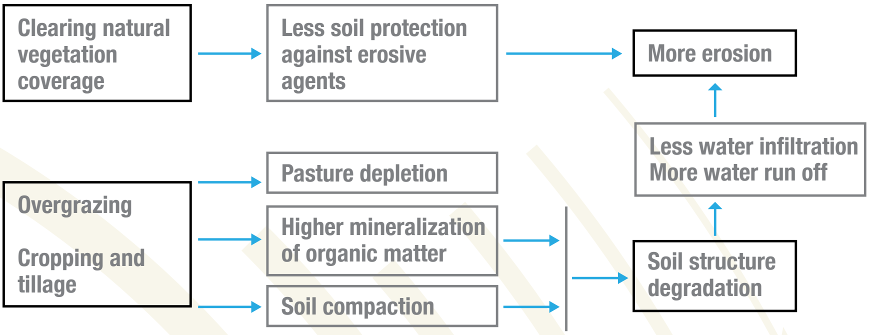
7.1 Agricultural erosion and sediment loads to water

Agricultural activities contribute to increased soil erosion and sediment loads in river systems. The key mechanisms behind agricultural soil erosion are depicted in Figure 7.1. Land clearance, whereby natural vegetation is converted into agricultural cropland or pastures, reduces soil protection against erosive agents and lowers the input of organic matter to soils, which weakens the soil structure. In croplands, excessive tillage can lead to soil compaction and higher organic matter mineralization, which further degrades the soil structure. In addition, inappropriate tillage up and down slopes (as opposed to along the contours) favours soil erosion. In pasturelands, overgrazing reduces vegetation, leaves the soil uncovered and increases soil degradation (e.g. through compaction). Degradation of structure makes soil more vulnerable to erosive agents and can reduce water infiltration and increase run-off, all conductive to more erosion. Uncovered soil also results in faster runoff that exacerbates overland transportation of sediments (Montgomery, 2007; Syvitski and Kettner, 2011). Higher erosion rates decreases soil fertility and reduces biomass productivity, which may lead to additional land clearing or tillage in a negative feedback loop. However, the magnitude of increased sediment loads by land clearance depends on the topography, the extent to which the catchment is affected and the local climate (Benavides and Veenstra, 2005; Walling and Fang, 2003; Walling, 2006, 2008, 2009).

Soil typology also affects erodibility. Most clay-rich soils (e.g. vertisols) have a high resilience because they are resistant to detachment. Sandy soils (e.g. arenosols) are also resilient because of low runoff even though these soils are easily detached. Medium textured soils, such as silt loam soils, are only moderately resistant to erosion because they are moderately susceptible to detachment and they produce moderate runoff. Soils having a high silt content are the most erodible of all soils. They are easily detached, tend to crust and produce high rates of runoff. Organic matter reduces erodibility because it reduces the susceptibility of the soil to detachment (FAO-ITPS, 2015).

Sediments can be physical pollutants but can also be carriers of chemical pollutants and pathogens. Sediments have high ionic exchange rates, which allows them to adsorb contaminants (Ongley, 1996). While being transported over land, sediments can adsorb

FIGURE 7.1 | **Key mechanisms of agriculture soil erosion**



and carry pollutants such as nutrients, pesticides and heavy metals. However, the binding capacity depends on the sediment characteristics (such as the organic matter content). For instance, hydrophobic contaminants (such as some pesticides) bind more easily with organic matter (Dunlop, McGregor and Horrigan, 2005). Pollutants can be released from sediments when the environment (e.g. redox potential or pH) changes. Therefore, in addition to the dissolved pollutants that reach water bodies, sediments can carry more pollutants to aquatic ecosystems, and are effectively the most important pathway for some types of pollutants with low solubility such as phosphates (Coelho *et al.*, 2012), some metals (Peng *et al.*, 2009) and pesticides (Weston *et al.*, 2004). Global estimates suggest that soil erosion by water is responsible for annual fluxes of 23–42 Mt of nitrogen and 14.6–26.4 Mt of phosphorus from agricultural land (FAO–ITPS, 2015), much of which contaminates freshwater ecosystems.

The quantification of agricultural soil erosion at a global scale is difficult because the variability of soil erosion in space and time is extremely high. Nevertheless, there have been a number of attempts to make global estimates, a summary of which is provided in Table 7.1.

Table 7.1 | Global estimates of soil erosion

Soil erosion	Gt/y	Sources
Total soil erosion	50–201	Oldeman *et al.*, 1991; Lal, 2003
Soil erosion by water	20–172	FAO–ITPS 2015; Ito 2007
Soil erosion by wind (on arable land)	<2	FAO–ITPS 2015; Ravi *et al.*, 2011
Soil erosion from agriculture (crops and pasturelands)	20–75	Doetterl, Van Oost and Six, 2012; Wilkinson and McElroy, 2007; Berhe *et al.*, 2007

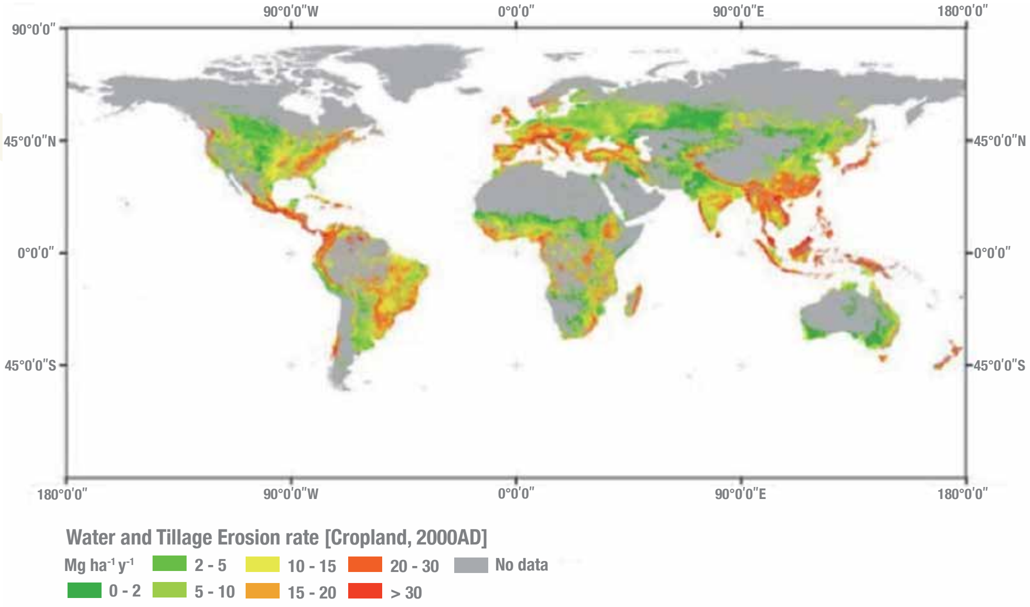
Estimated rates of soil erosion in arable and intensively grazed lands are 100–1 000 times higher than natural erosion rates and far higher than rates of soil formation (Montgomery, 2007). With loss of soils, nutrients are also lost and need to be replaced with fertilizers to maintain fertility, at significant economic cost. For example, using US farm-gate prices for fertilizers, global soil erosion is estimated to cost annually USD 33–60 billion to compensate for nitrogen loss and USD 77–140 billion for phosphorus (FAO-ITPS 2015).

Estimates of global erosion are often based on the extrapolation of results derived from soil erosion experiments at the plot scale. Using these methods, existing estimates of agricultural soil erosion range between 28 and 75 Gt/y (Wilkinson and McElroy, 2007 and Berhe *et al.*, 2007, respectively). Experimental data used in these estimates are derived from a few observations which may be biased towards steep slopes, bare soil and extreme rainfall, and hence may overestimate global rates of erosion. To reduce this uncertainty, a more recent study by Doetterl, Van Oost and Six (2012) parameterized a simplified erosion model driven by coarse global databases, using an empirical database that covers the conterminous United States of America and that represents a wide range of climatic, soil, topographic, cropping and management conditions. The model results showed good agreement with empirical estimates at continental scale and the application of the model globally allowed an estimate of global erosion rates for agriculture (cropland and pastures).

Estimates from Doetterl, Van Oost and Six (2012) show an average annual global erosion rate for cropland and pastures of 10.5 and 1.7 tonnes/ha, respectively, which results in a global annual average of 4.2 tonnes/ha for total agricultural area. Despite these estimated averages, annual erosion rates on hilly croplands and grasslands in tropical and sub-tropical areas may reach 50–100 tonnes/ha (FAO-ITPS, 2015). In terms of total flux, estimates from Doetterl, Van Oost and Six are equivalent to 20.5 Gt of soil per year. This global erosion rate corresponds to an annual rate of 193 and 40.4 kg/ha of soil organic carbon from cropland and pasture respectively. Soil erosion rates are shown in Figure 7.2 for cropland and Figure 7.3 for pastureland. High erosion rates occur particularly in tropical regions where steep slopes and high rainfall coincide. About 43% of the agricultural sediment flux appears to be in Asia (Doetterl, Van Oost, and Six, 2012).

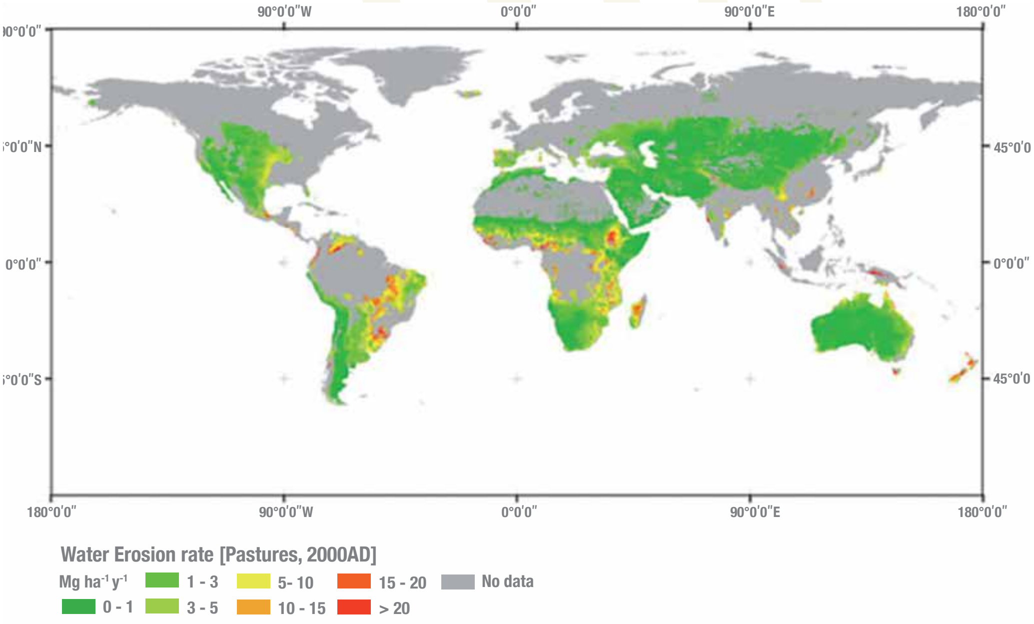
The estimates of soil erosion from agriculture discussed above do not include the soil lost due to erosion from deforestation (unless this deforested land was transformed into agricultural land and captured in global statistics as such). Nevertheless, satellite observations suggest that between 2000 and 2012, 2.3 million km^2 of forest were lost

FIGURE 7.2 Global soil erosion estimates for croplands for the year 2000



Source: Doetterl, Van Oost and Six, 2012.

FIGURE 7.3 Global soil erosion estimates for pastureland for the year 2000



Source: Doetterl, Van Oost and Six, 2012.

globally, while only 0.8 million km^2 were reforested (UNCCD, 2017), with potential effects on soil erosion that are not captured in the preceding estimates.

Within the agricultural sector, the contribution from aquaculture to global erosion is probably small compared to erosion from overgrazing or cropping, but it can be locally important, particularly in coastal areas. One of the largest threats to coastal integrity is the rapid conversion of mangroves into fish and shrimp ponds. Such conversion across the entire intertidal zone sets off cascading effects that contribute to subsidence and erosion of the coastline. Removal of mangrove forests increases the exposure and vulnerability of the coast to waves and jeopardizes sediment trapping and accumulation, all conducive to more coastal erosion (van Wesenbeeck *et al.*, 2015).

The emerging consensus suggests that erosion rates will increase in response to climate change. A model-based study predicts a reduction in average erosion rates for North America and Europe, but a global increase of about 14 percent by 2090, 65 percent of the increase attributed to climate change and 35 percent to population pressure and changes in land use (Yang *et al.*, 2003).

7.2 Sediment concentration, turbidity and sediment yields in surface waters

Globally, while deforestation and agricultural expansion and intensification have increased soil erosion and the sediment loads to rivers, the flux of sediment reaching the world's coasts has been reduced (Syvitski *et al.*, 2005). Sediment eroded from land may be far higher than sediment actually transported by rivers since the sediment might be trapped and stored, for example at the bottom of a slope, before it enters the river system. In addition, yields of sediment at the river basin outlet do not directly reflect sediment loads into rivers because sediments might be deposited within the river system in reservoirs, river banks and the like. By contrast, sediment yields at the river mouth could be higher than on land when river banks function as a source of sediment.

Despite these complex sediment dynamics, rivers are the most important carriers of sediment from land to ocean. Approximately 95 percent of sediments enter the ocean through river systems (Syvitski *et al.*, 2003). Estimates of the global sediment flux to oceans vary but a relatively recent study by Syvitski *et al.* (2005) indicate it to be 12.6 Gt/y (16.2 Gt/y in a hypothetical scenario with no reservoirs).

Different rivers show different patterns of sediment transport. A survey of 145 rivers, mainly in the northern hemisphere, conducted by Walling and Fang (2003) revealed that

BOX 7.1 Research needs on sediment

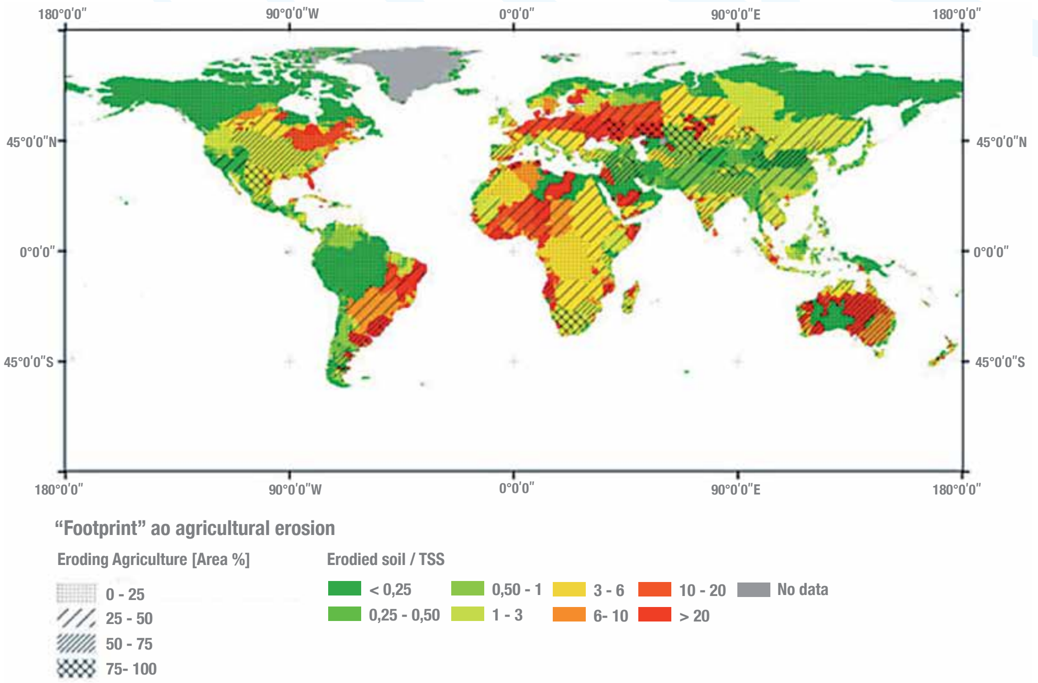
Although rough global estimates exist of agricultural contribution to total sediment fluxes, there is still a need for improved sediment monitoring programmes:

- Monitoring sediments fluxes in smaller rivers instead of only major rivers (Walling, 2009);
- More monitoring of sediment yields for rivers in developing countries. At present, data are mostly available for developed regions such as North America and Europe (Vanmaercke *et al.*, 2011).
- Longer monitoring periods to identify the causes and the extents of sediment fluxes in river systems (Walling, 2009);
- More accurate and reliable research addressing the agricultural contribution of sediments to water bodies – particularly rivers;
- Research on the economic consequences of sediment pollution of water bodies by agriculture.

48 percent of the samples had experienced no change in sediment delivery, 47 percent had decreased and only 5 percent showed an increase. An example of declining sediment fluxes is the Chao Phraya in Thailand where sediment delivery has fallen from 28 Mt/y in 1960 to 6 Mt/y in 1990, without a significant reduction in river outflow. A contrary example is the Rio Magdalena basin in Colombia, where sediment loads at the outlet increased by 40–45 percent between 1975 and 1995 (Walling, 2006).

The relative contribution of agricultural soil erosion to river sediment flux in global major basins is depicted in Figure 7.4. In general, the contribution of agriculture is relatively small compared to natural erosion processes (Doetterl, Van Oost and Six, 2012; Syvitski and Kettner, 2011; Walling, 2009). This is because most of the time sediments from agricultural land are deposited in terrestrial zones such as reservoirs, floodplains and wetlands (Smith *et al.*, 2005). In river basins where the topology consists mainly of mountain uplands, natural erosion processes have a dominant role on river sediment fluxes, for example, the zones in South America, North America and Southern and Eastern Asia shown in green in Figure 7.4. In low lands with intensive agriculture, the relative contribution of human activity on both soil erosion and river sediment fluxes is high, as shown for Central Europe and West Africa in red (Doetterl, Van Oost and Six, 2012).

FIGURE 7.4 Estimated contribution of agriculture to river sediment fluxes for the year 2000



Source: Doetterl, Van Oost and Six, 2012.

7.3 Impact on the aquatic environment and reservoirs

Sediments can affect water bodies physically and chemically with consequences on human health, ecosystems and economic activities.

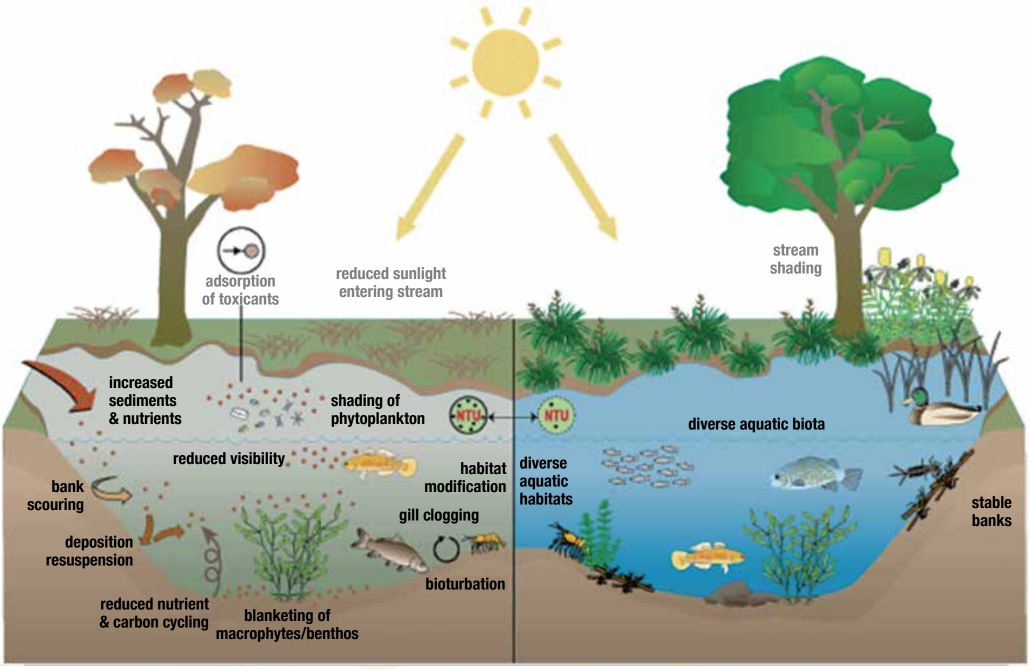
7.3.1 Physical effects

Increased suspended sediments enhance the turbidity of water bodies. Higher turbidity leads to multiple undesirable effects on aquatic plants, algae, invertebrates, and fish (see Figure 7.5), which ultimately results in disturbed functioning of aquatic and terrestrial ecosystems (Dunlop, McGregor and Horrigan, 2005). Less sunlight, the result of increased turbidity, inhibits the photosynthesis and growth of algae and rooted aquatic plants (Li, 2013). Less food is thus available to species higher on the food chain such as fish. Moreover, reduced penetration of sunlight can lower the water temperature, which can alter breeding cues of temperature-sensitive species (Dunlop, McGregor and Horrigan, 2005). In addition, turbidity reduces the visibility of both prey and predators that rely on their sight. Prey are no longer able to avoid predators or find safe places to live, while for predators reduced visibility hampers their ability to find food (Abrahams and Kattenfeld, 1997). For species that do not rely on sight, high turbidity may be beneficial. Prey and predators with highly developed alternative senses, for example smell, are more successful in turbid conditions (Dunlop, McGregor and Horrigan, 2005).

High sediment concentrations also affect fish species in other ways. Fine sediment particles clog and damage fish gills, leading to respiration problems. Some fish species are able to flush their gills, but this requires a lot of energy. If flushing continues for too long, energy reserves are depleted and death may occur. Sedimentation also destroys fish spawning habitats. Deposited sediment forms a blanket over the spawning beds, which inhibits spawning and results in the loss of biodiversity (Dunlop, McGregor and Horrigan, 2005).

High rates of sedimentation disrupts the hydraulics and transportation capacities of the river channel. Accumulated sediments reduce the depth in rivers and increase risks of floods and inundation. Sedimentation also reduces the storage capacity of reservoirs,

FIGURE 7.5 Visualization of in-stream processes and impacts of turbidity on aquatic biota



Source: Dunlop, McGregor and Horrigan, 2005.

which can affect irrigation schemes, reduce water supplies and make hydroelectric power stations less effective (Walling, 2009). More than 100 Gt of sediment are now sequestered in reservoirs built largely in the past 50 years (Syvitski *et al.*, 2005). Wisser *et al.* (2013) suggested that the world may have gone beyond peak reservoir storage capacity because new dams are not compensating for the declining water storage capacity of large reservoirs. A recent study (Basson, 2008) estimates that by 2050, approximately 64 percent of the world's current reservoir storage capacity will have been filled with sediment. Moreover, increased sediment in water bodies can affect industries such as tourism, which in turn may result in devastating economic losses (Benavides and Veenstra, 2005).

7.3.2 Chemical effects

As previously mentioned, contaminants such as nutrients, pesticides and metals easily attach to the surface of sediment particles and exacerbate the pollution of water bodies that receive the sediments. Sediment transport can thus increase the concentration of other pollutants in water (Dunlop, McGregor and Horrigan, 2005; Ongley, 1996). This reduces the water quality for drinking and irrigation and increases the cost of water treatment. The binding capacity of sediments can also alter global geochemical cycles of key elements, especially the carbon cycle (Walling, 2009).

Contaminated sediments also affect aquatic species. Some toxic substances can kill species that live in the benthic environment at the bottom of water bodies. Benthic species – such as worms, crustaceans, and insect larvae – are important food sources for larger animals. When benthic species die, less food is available to larger species such as fish. In addition, the consumption of toxic substances by benthic organisms leads to bioaccumulation of toxins in the organism. These toxins can also move up the food chain as larger animals eat smaller animals that contain toxic compounds, resulting in biomagnification. A high concentration of toxic compounds can kill species that are not resistant, while species that can tolerate the toxins often experience health problems such as tumours, fin rot and disrupted reproduction. Biomagnification may ultimately pose a threat to the health of humans who eat contaminated fish and other aquatic species (Li, 2013).

This chapter has reviewed how human activities and agriculture have increased and accelerated natural erosion rates, resulting in increased sediment loads entering bodies of water. Crops and pasturelands alone are responsible for the mobilization of huge amounts of sediment every year, much of which ends in water. The global cost to society, including the environment, is not well quantified but a simple extrapolation of the local evidence available (ICOLD, 2009) suggests that it exceeds billions of dollars.

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