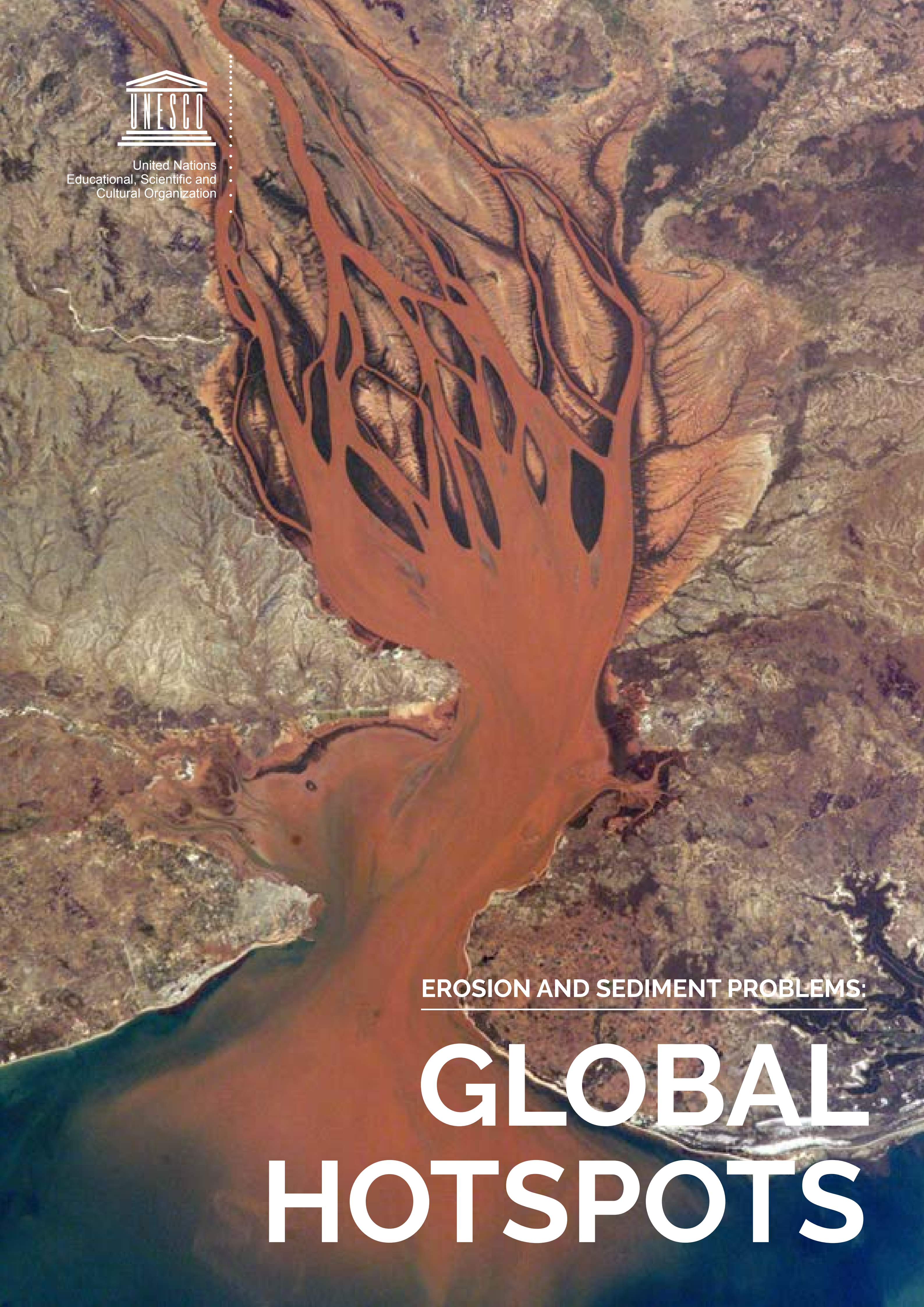

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EROSION AND SEDIMENT PROBLEMS:

GLOBAL HOTSPOTS

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EROSION AND SEDIMENT PROBLEMS:

GLOBAL HOTSPOTS

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EROSION AND SEDIMENT PROBLEMS: GLOBAL ISSUES AND HOTSPOTS

1 The Context

Water erosion of the land surface of the globe by rainfall and associated fluvial processes and transfer of the mobilized sediment to the oceans by rivers must be seen as an integral part of the natural functioning of the Earth system. For example, it underpins the geological cycle of erosion, sedimentation and orogenesis that has formed the current land surface of the earth (Pinter & Brandon, 2005) and it also represents a key component of the global biogeochemical cycling of important nutrients such as carbon, nitrogen and phosphorus as well as numerous other elements (Lerman & Meybeck, 1988; Ludwig, Probst & Kempe, 1996). In addition, it has played a key role in developing the contemporary landscape of the earth's surface (Tucker & Hancock, 2010) and it has a continuing role in maintaining that landscape and its associated habitats and ecosystems (Kirwan & Megonigal, 2013).

The natural processes of erosion and sediment transport also interact with human activity and society and this interaction is important from two perspectives. First, human activities, such as forest clearance, the development of agriculture, infrastructure construction and water resource development involving the construction of dams and irrigation systems, have had a major impact on erosion rates and sediment transfer from the land to the oceans. Montgomery (2007) suggests that erosion rates associated with conventional cultivation practices have increased by one to two orders of magnitude relative to natural or background rates and a global assessment of the impact of dams on sediment transport to the oceans reported by Vörösmarty et al. (2003) estimated that 25-30% of the global land-ocean sediment flux was trapped in reservoirs. Walling (2012) used different data to suggest that dams could be reducing contemporary sediment transport to the oceans by as much as 24 Gt year^{-1}, a value which is similar in magnitude to estimates of the current land-ocean sediment flux. Not all human impacts on erosion and sediment transport should be seen as detrimental. Soil and water conservation strategies developed in many agricultural areas can result in major reductions in erosion rates (Nearing et al. 2017), although they may not succeed in reducing erosion rates to the levels found prior to the development of agriculture. If contemporary climate change is recognized as being caused by human activity, this must also be seen as causing further changes in the natural system. In many areas, climate change has resulted in increases in both storm magnitude and intensity, causing increased soil loss. In other regions of the world, climate change can result in reduced erosion. Recent studies undertaken in agricultural areas of the Russian Plain (Golosov et al., 2017, 2018) have, for example, demonstrated that increased winter temperatures have reduced snow accumulation and soil freezing, resulting in reduced erosion during spring snowmelt.

From the second perspective, the processes of erosion and sediment transport, both essentially natural or accelerated/increased by human activity, have many important implications for society, particularly in terms of the sustainable development and management of natural resources. The soil is a key resource for agriculture and therefore food production, since it has been estimated that ca. 95% of world food production comes from the soil. Ongoing erosion and soil loss can result in both loss of agricultural land and reduced crop productivity and therefore has important implications for global food security.

The impact of dams in trapping sediment formerly transported by rivers to the oceans and thereby reducing the sediment loads of many of the world's rivers and disrupting load-ocean material transfer has been mentioned above. Sediment trapped behind dams will in most cases occupy valuable storage and progressively reduce the capacity of dams to store water for water supply, flood control and hydropower generation (Morris & Fan, 1998). Dam design can take account of this loss of storage, by providing 'dead' storage for sediment, to ensure that the dam functions effectively over an extended period, or by taking account of the effects of progressive sedimentation on long-term reservoir operation. However, sedimentation will inevitably result in a finite life for most reservoirs, or at best a progressive reduction in their efficiency, and therefore represents an important problem for sustainable water resource and hydropower development. Basson (2008) estimated that approximately 73% of the total storage capacity of existing large Asian dams was free of sediment at that time, but he indicated that this value would reduce to about 47% by 2050. The available storage is currently being increased and will continue to be increased to offset this and future losses and provide further storage to meet increased demand by constructing new dams. However, cost and locating suitable new dam sites are likely to prove important problems. The impact of dam construction in reducing the downstream sediment loads of many of the world's major rivers (Walling, 2006) could be seen as beneficial, where the sediment load transported by a river causes problems for its management. However, reduced sediment loads caused by dam construction can impact on channel morphology and aquatic habitats, sometimes causing problems (Petts & Gurnell, 2005). Reduction of the sediment loads of large rivers have also recently been recognized as posing major problems for the future stability and longer-term sustainability of many of the world's major deltas (Syvitski et al., 2009). These deltas frequently represent important centres of population and key areas of agricultural production. Reduction of the sediment supply to the delta can disrupt the delicate balance between sediment input and ongoing subsidence, causing the delta to shrink or to be increasingly susceptible to flooding by the sea and river floods. This disruption can be further exacerbated by subsidence caused by groundwater abstraction for local water supplies or by oil and gas abstraction and comes at a time when deltas are additionally threatened by a rising sea level caused by climate change and melting of the polar ice sheets.

The importance of erosion and sediment transport for the sustainable management of the environment and aquatic habitats and ecosystems is emphasized by a growing awareness of the important role of fine sediment in the transport of many persistent environmental pollutants and in degrading aquatic habitats as a result of both its physical and biogeochemical impacts. For these and other reasons, fine sediment is frequently referred to as the world's number one pollutant. However, when considering these issues, it is important to recognize that the seriousness of the problem is frequently not directly related to the magnitude of the fine sediment flux or concentrations. There are many situations where the greatest problems occur in those areas where fine sediment concentrations and fluxes are naturally low and small increases can give rise to serious degradation of the aquatic habitats and ecosystems. This is, for example, frequently the case with salmonid fish habitats, where small increases in sediment flux can result in siltation of spawning gravels, reduction in the availability of dissolved oxygen to the fish eggs during hatching and spawning success and consequent reduction in fish populations.

This contribution provides a global perspective on contemporary erosion rates and sediment fluxes and the impact of global change, with particular emphasis on the problems posed by erosion and sediment transport for the sustainable management of the Earth system and for society more generally. Since the greatest problems are commonly associated with high erosion rates and high sediment loads, emphasis will be placed on identifying those areas of the world that could be classified as hotspots in terms of erosion rates and sediment yields.

In one context, however, problem areas will represent locations where serious problems are generated by reduced sediment loads and lack of sediment, namely river deltas. Since erosion exerts a fundamental control over the mobilization of sediment for subsequent transport through river systems to the oceans, attention will initially be directed to erosion rates, before moving on to consider sediment loads and the problems associated with reservoir sedimentation and reduced sediment supply to deltas.

2 Erosion hotspots

2.1 The approach

Data availability and quality represent major constraints on any attempt to identify areas of the world where soil erosion rates are high and could therefore be seen as representing 'hotspots'. What could be seen as reliable, high quality, field-based data, founded on long-term monitoring or application of other indirect techniques capable of providing reliable estimates of the mean annual erosion rate based on a period of ca. 20 years, are available for only a limited number of countries. In this study, it was necessary to make use of data derived using a variety of approaches. These include runoff plot studies, mostly of short duration, catchment monitoring, again often of short duration, fallout radionuclide measurements that provide estimates of medium-term average erosion rates and observations of the development of gully systems. Such data were primarily available for areas of Europe, as well as North America, Australia and New Zealand. Empirical erosion models or erosion prediction procedures can be seen as providing an alternative to field-based data, but reliable input data are unavailable for many parts of Africa, Latin America and Asia. This problem is well illustrated by Figure 1, which presents a map of the location of measuring stations capable of providing the data required to derive accurate values of annual rainfall erosivity, a key parameter (R) in the Universal Soil Loss Equation and its many derivatives that are often used to estimate soil erosion rates. Only 9% of the available measuring stations are located in Africa and South America. Recent advances in the application of high resolution satellite images in combination with GIS has greatly facilitated the construction of land use maps and digital terrain models for use with such models and prediction procedures, but reliable soil erodibility data are again unavailable for many areas of the world, particularly in developing countries. For some parts of the world reliable information on erosion rates is limited to measurements of catchment sediment yield and reservoir sedimentations rates. However, such data provide information on net rates of sediment loss from the upstream catchment area, rather than on-site rates of soil loss and therefore require additional interpretation.

Another issue which adds further complexity to identifying erosion hotspots is the fact that to some degree the exercise involves a 'moving target'. Under natural conditions, erosion rates can be expected to demonstrate considerable inter-annual variability and, as indicated above, there is a need to base their quantification on a period of sufficient length (e.g. 20 years), in order to generate a representative value. However, erosion rates may show trends through time in response to changes in the driving factors. Particularly important here are changes in land use. These could include the effects of land clearance for agriculture or intensification of land use in increasing erosion rates. Conversely, progress in the implementation of soil and water conservation strategies could result in a reduction in erosion rates. This is the case in many European countries, the USA, Canada, Australia, Brazil and some Asian countries. In Brazil, for example, the introduction of no-till soil management over an area of 32 x 10^4 km^2 has had a major impact on soil erosion rates. The increasing evidence of recent climate change also has important implications for erosion rates, with potential for both ongoing increases and decreases in erosion rates. However, current uncertainty relating to the magnitude and direction of such changes in erosion rates and the global patterns involved has precluded detailed consideration of this factor.

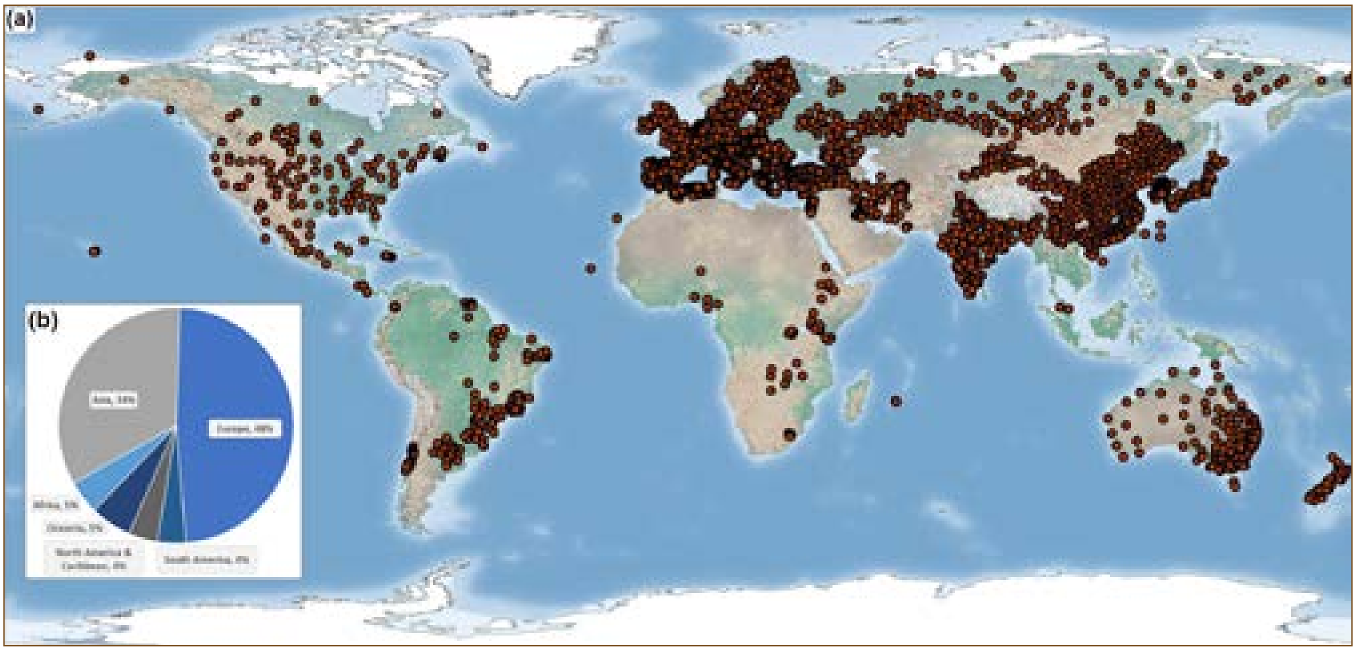

Figure 1. The global distribution of rainfall erosivity stations (red dots) included in the Global Rainfall Erosivity Database (GloRED)is shown in (a); (b) shows the distribution of rainfall erosivity stations by continent. Maps generated with ESRI ArcGIS ver. 10.4 (http://www.esri.com). (After Panagos et al., 2017)

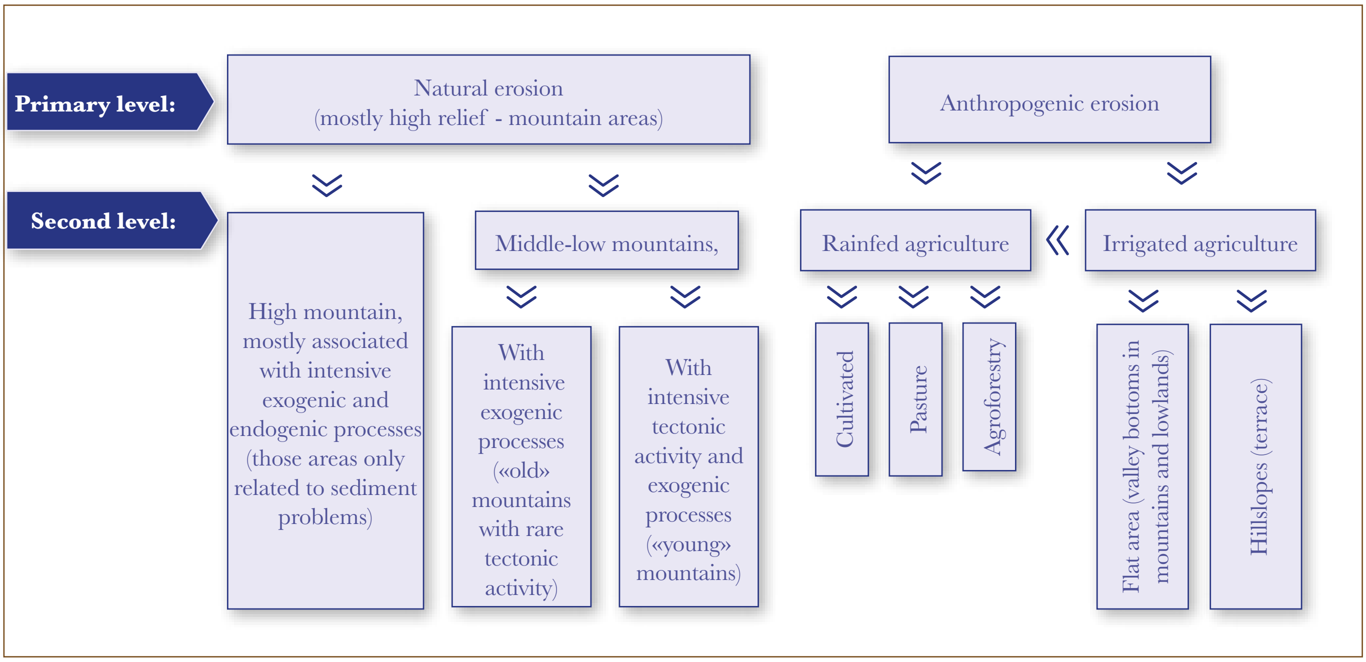

Figure 2. The approach used for identifying erosion hotspots

Figure 2 summarises the approach used for identifying and classifying erosion hotspots. A distinction is made between those reflecting essentially 'natural' drivers and those where anthropogenic factors are important in causing erosion rates to increase relative to those expected based on natural drivers. The latter essentially represent erosion rates associated with agricultural land. The two are, however, not mutually exclusive, in that many erosion hotspots linked to anthropogenic activity will be found in areas characterized by high natural erosion (e.g the Magdalena River basin in Columbia, Restrepo & Syvitski, 2006). Attention was directed to each continent in turn. Initially, hotspots associated with natural erosion were identified and mapped. Subsequently, hotspots associated with anthropogenic erosion were similarly considered. The mapping aimed to show the general location and approximate extent of hotspot areas, but did not involve detailed analysis of the factors responsible for the high erosion rates associated with a particular hotspot, their spatial distributions and thus the likely precise boundaries of a particular hotspot area. Although the aim was to provide global coverage, the erosion rate thresholds used to define hotspots varied between the continents, in order to take account of differences between the continents in the intensity of natural erosion/denudation processes and the extent to which soil and water conservation practices were being implemented.

Hotspots with high natural erosion rates are mainly located in mountains areas, where relief, climate conditions and tectonic activity promote the intensification of exogenic processes. The natural erosion rates are higher within continents most susceptible to tectonic activity and endogenic processes (Figure 3). In the case of anthropogenic erosion hotspots, more intensive erosion processes are observed in regions where cropland, pasture and orchards are located in areas with steeper slopes and high frequency of extreme rainfall. Such areas are mainly located in foothill areas and in low mountains. However, the scale of application of soil conservation measures is a key factor influencing erosion rates on agricultural land. It is difficult to identify a uniform threshold value of erosion rate for the hotspots located on different continents, because of the different intensity of exogenic processes and the different productivity of soils on agricultural land. However, a threshold value equal to 10 Mg ha^{-1} year^{-1} or 1 000 t km^{-2} year^{-1} has been used. This value is an order of magnitude higher than the tolerable erosion rates for soils in most parts of the world (Pierce et al., 1984; Verheijen et al., 2009). The annual erosion rate is calculated by dividing the total material losses (including the different denudation processes within the catchments: sheet, rill and gully erosion, landslides screes, rockfalls, avalanches etc.) by the area involved (field, catchment). Usually, soil losses from agricultural land are reported in units of Mg per ha^{-1} per year^{-1}. However, units of t km^{-2} year^{-1} are more often employed for the evaluation of denudation rates in mountain areas or when considering erosion rates based on the measurement of sedimentation in reservoirs. We use values expressed as t km^{-2} year^{-1} for evaluation of mean annual erosion rates for both natural and anthropogenic erosion.

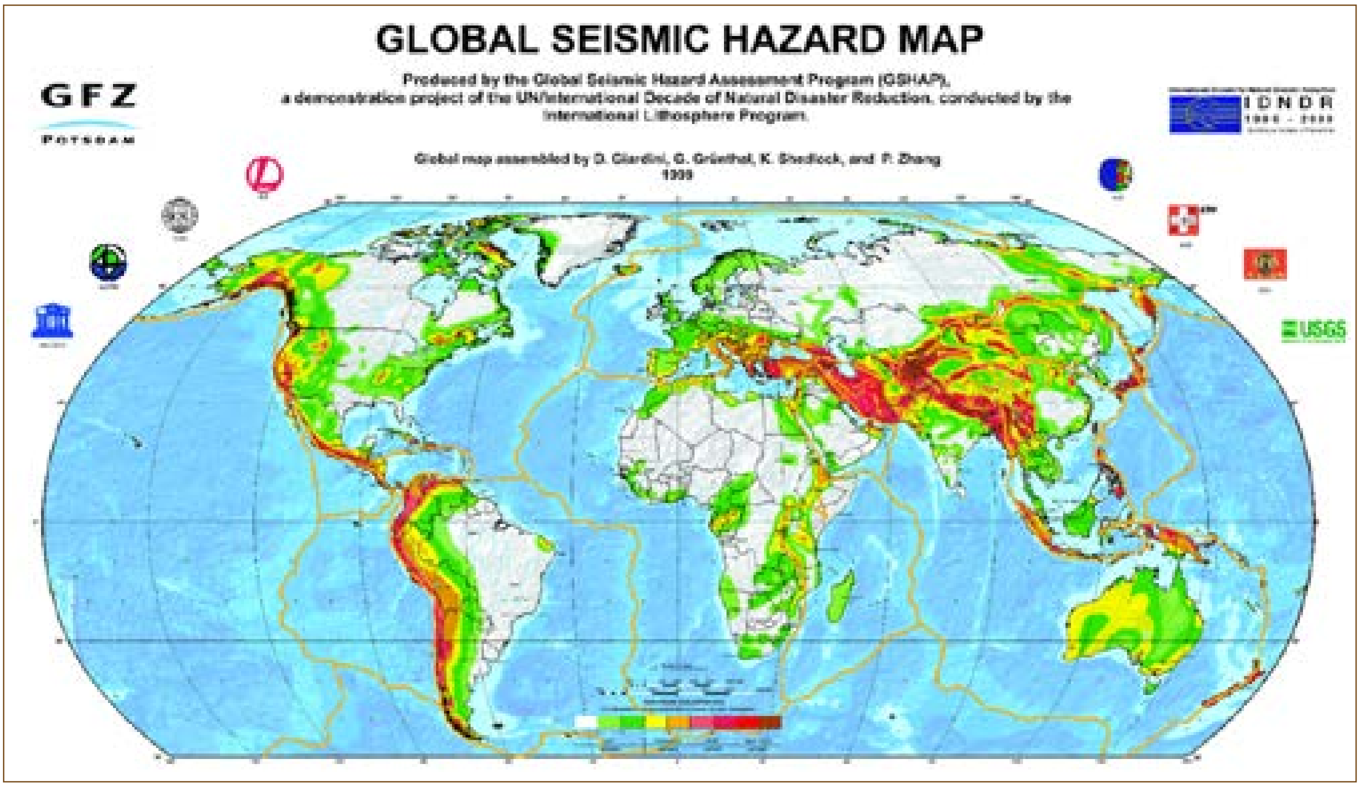

Figure 3. A world map produced by the Global Seismic Hazard Assessment Programme showing the distribution of seismic activity and therefore those areas most susceptible to tectonic activity and endogenic processes. (Original version available at http://static.seismo.ethz.ch/GSHAP/global/)

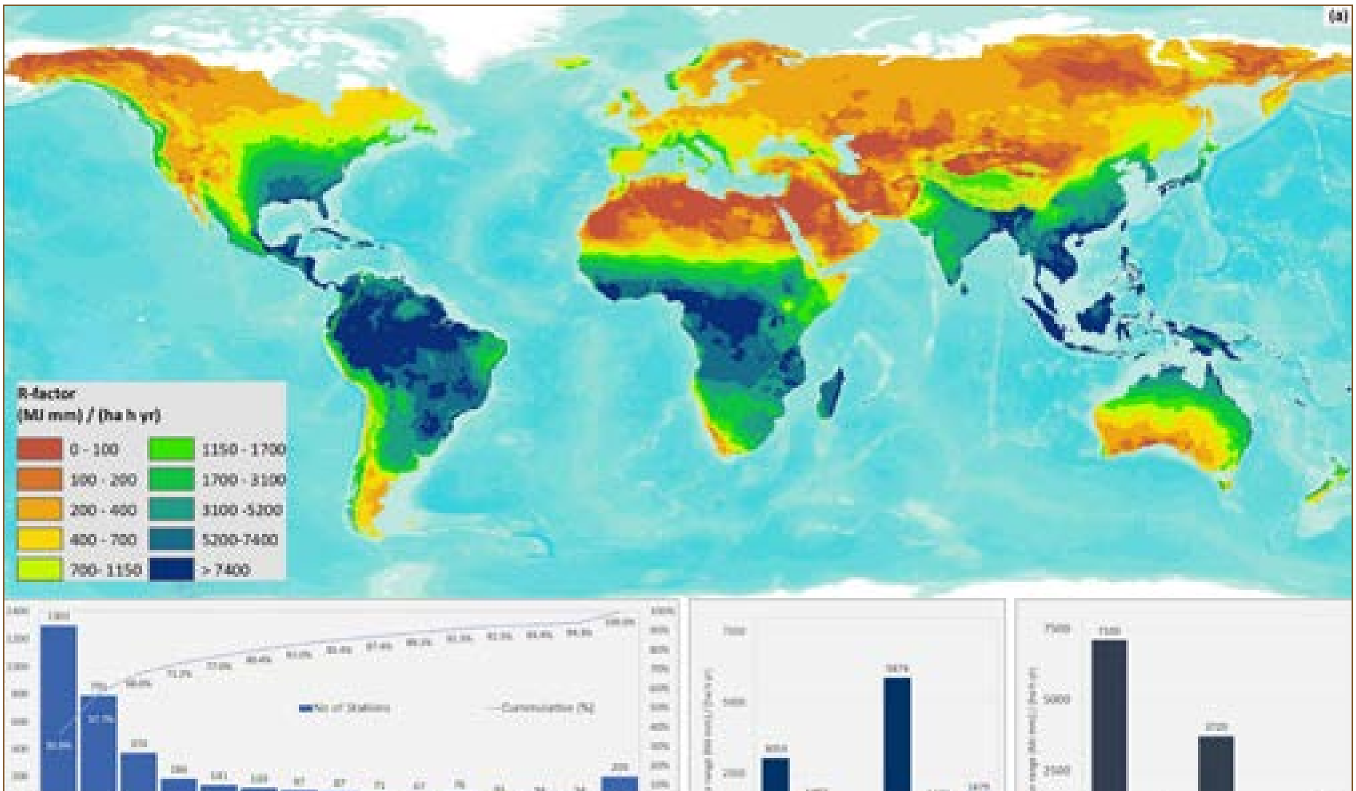

Figure 4. World map showing the global pattern of rainfall erosivity as represented by the R factor in the Revised Universal Soil Loss Equation. (Based on Panagos et al., 2017)

2.2. Natural erosion

At the global scale, the occurrence of high natural erosion rates is largely controlled by the interaction of five key factors or controls, which reflect both the nature of the terrain and the intensity of the processes causing erosion. The first is relief, which reflects the steepness of the terrain. High erosion rates are commonly associated with steep terrain. The second is tectonic or seismic activity (Montgomery & Brandon, 2002). This affects the stability of the terrain and the occurrence of uplift, which promotes down-cutting. In the context of erosion, tectonic activity is frequently referred to as an endogenic process, whereas rainfall and runoff are classified as exogenic processes. Figure 3 presents a world map showing the areas of the world where seismic activity is significant. Areas of the world such as New Zealand and Taiwan, China are frequently cited as experiencing high erosion rates and here tectonic or seismic activity is an important driver of the high erosion rates. The third is the vegetation cover, since this can protect the soil surface from the erosive effects of both rainfall and surface runoff. The fourth is the erodibility of the soil and rocks, which assesses their susceptibility to erosion. This will reflect the properties of the soil, regolith or bedrock found at the surface, including its grain size composition, organic matter content and depth. The high erosion rates that characterize the Loess Plateau of China are largely attributable to the influence of this factor and more particularly the deep loess deposits that characterize this region. The loess is readily eroded by rainfall and runoff and can be as much as 100 m thick. The fifth is the erosivity of the rainfall and runoff. This will primarily reflect the amount and duration of precipitation and its intensity which in turn exert an important influence on the incidence of surface runoff. Figure 4 presents a world map showing the global distribution of the rainfall erosivity or R term in the Revised Universal Soil Loss Equation (Renard et al., 1997) based on the work of Panagos et al. (2017). The R values shown on the map represent mean annual values and reflect the magnitude and timing of the annual rainfall, as well as its intensity and they provide a direct measure of the erosive energy of the annual precipitation as well as an indirect measure of the likely occurrence of surface runoff. Together, these provide a useful indicator of the erosivity associated with a given location. The magnitude of the natural erosion rates found at different locations across the globe will reflect the interaction of the five controls outlined above. In the Central Amazon basin in Brazil, for example, the rainfall erosivity is shown by Figure 4 to be very high, but this is countered by the lack of tectonic activity, the low relief and the natural vegetation cover of tropical forest to produce low erosion rates. In contrast, the mountain relief with steep slopes and the high level of seismic activity found in the Southern Alps of New Zealand combine to produce high erosion rates, despite the intermediate level of rainfall erosivity shown on Figure 4. Further consideration of the global distribution of hotspots evidencing high rates of natural erosion will consider the different continents in turn.

2.2.1 Hotspots of natural erosion in Africa

Figure 5. Natural erosion hotspots, Africa

It is difficult to identify the hotspots of natural erosion in Africa, because of the very limited data available regarding contemporary denudation rates, when compared with other regions of the world (Figure 5). It is important to emphasize that in some areas where quantitative evidence of high erosion rates is available (e.g. the highlands of Ethiopia and Madagascar and the mountains of Uganda, Kenya and Tanzania), the influence of natural factors is important but anthropogenic disturbance causing increased erosion rates is widespread and exerts a key influence on the occurrence of high erosion rates. As examples of high erosion rates reported for Africa, Christiansson (1981) reports an annual soil erosion rate for Tanzania of 1 800 t km^{-2} $year^{-1}$. Rates of gully erosion in Madagascar can reach 30 000 t km^{-2} $year^{-1}$ (Braun et al., 1997). For the Madagascar highlands some uncertainty exists regarding the contribution of anthropogenic factors to the high rates of sheet and rill erosion. However, even under 'natural conditions' they are unlikely to fall below 3 000 t km^{-2} $year^{-1}$(Braun et al., 1997). The Atlas Mountains of Morocco and mountain areas in the south of the continent (i.e. Lesotho and South Africa) have also been included as African hotspots, despite the relatively low natural erosion rates when compared with the hotspots identified in other continents. Erosion rates reaching 1 000 - 2 500 t km^{-2} $year^{-1}$ have been reported by Chakela (1981), Fox et al., (1997) and Boardman et al., (2015) for these mountain areas. The natural erosion rates in these areas are relatively high for Africa and the ongoing erosion is seen as resulting in serious problems of land degradation.

2.2.2 Hotspots of natural erosion in Asia

The hotspots of natural erosion in Asia shown in Figure 6 largely coincide with mountain areas where both the steep terrain and tectonic instability promote high erosion rates. The Himalayan mountain region is characterized by the highest natural erosion rates in Asia. There, erosion rates can reach values of ca. 20 000 t km^{-2} $year^{-1}$. This is an area with extremely high rainfall erosivity (Figure 4) and frequent tectonic activity (Figure 3) which together result in high natural erosion rates. These are increased further by human activity and associated land disturbance (Finlayson et al., 2002; Burbank et al., 2003; Avouac, 2003; Grujic et al., 2006). Although erosion rates within the Loess Plateau of China have decreased markedly following the implementation of large scale soil and water conservation programmes across the region, the natural erosion rates in this area associated with the high erodibility of the parent material and the relatively high frequency of recurrence of extreme rainfall events remain comparable with natural erosion hotspots in other continents (Zhuang et al., 2017). High natural denudation rates are also found in the southwestern part of China. Despite the important impact of increased agricultural activity in Northern Thailand, the background or natural erosion rates are also high (600 - 1 200 t km^{-2} $year^{-1}$) due to a combination of the monsoon rainfall, tectonic activity and the steep slopes (Ziegler et al., 2014, Golosov et al., 2015). High erosion rate in the southern part of Japan are primarily a reflection of natural controls (high precipitation and tectonic activity) (Sidle & Chigira, 2004). Even more intense natural erosion rates (>15 000 t km^{-2} $year^{-1}$) have been reported in Taiwan, China (Chen et al., 2017). The Kamchatka Peninsula, an area with high volcanic activity, is also an area with high natural erosion rates because the unconsolidated volcanic deposits are easily eroded and transported by surface runoff (Kuksina & Alekseevski, 2017). All other locations identified on Figure 6 as natural erosion hotspots, are characterized by high tectonic activity (Figure 3) and high magnitude low frequency extreme events, which are associated with a range of natural disasters, including rapid draining of glacial lakes, mudflows and debris flows, and large landslides. The local consequences of such events can be very dramatic (Huggel et al., 2005; Kääb et al., 2005; Korup & Clague, 2009).

Figure 6. Natural erosion hotspots, Asia

2.2.3 Hotspots of natural erosion in Australasia and Oceania

Figure 7. Natural erosion hotspots, Australasia and Oceania

High natural erosion rates are common in New Zealand (Figure 7) due to the high levels of tectonic activity (Figure 3), relatively high rainfall erosivity (Figure 4) and the steep relief. In most of these areas, mass movements, such as landslides, are an important contributor (Hovius, et al., 1997), but the contribution of other exogenic processes is also important (Dymond, 2010). According to the results of a national assessment (Dymond, 2010), natural erosion rates in many areas are in the range, 5 000 - 20 000 t km^{-2} $year^{-1}$. It is likely that deforestation in the mountains of North Island has intensified erosion processes (Hicks et al., 2000; Marutani et al., 1999), but the intensity of extreme events in combination with local relief and tectonic activity are key factors in promoting high denudation rates (Trustrum et al., 1999).

2.2.4 Hotspots of natural erosion in Europe

It is possible to identify three main hotspots of natural erosion in Europe (Figure 8). All of them are located in mountain regions and the mean erosion rates within the three hotspot areas range from ca. 1 000 - 1 500 t km^{-2} $year^{-1}$. The European Alps are an area where most exogenic processes operate at high intensity and there is evidence that erosion rates have increased in recent years due to global warming, particularly within the periglacial zone (Haeberli et al., 1997; Harris et al., 2009; Hilker et al., 2009). Two other regions (the Pyrenees, and the Balkans) represent areas where high natural erosion rates occur in response to the steep terrain and, more

Figure 8. Natural erosion hotspots, Europe

particularly, the frequent occurrence of high magnitude extreme rainfall events which increase the intensity of exogenic processes. Extreme erosion events with erosion rates up to 4 000 t km^{-2} year^{-1} have been reported (Llasat & Rodríguez, 1992; Garcia-Ruiz et al., 2002; Dragićević et al., 2013; Petrović et al., 2015). Tectonic activity is also important in increasing erosion rates within the Balkan region.

2.2.5 Hotspots of natural erosion in North and Central America

Figure 9. Natural erosion hotspots, North and Central America

The hotspots of high natural erosion rates in the North America (Figure 9) are all located along the western margin of the continent and coincide with areas of steep topography, high tectonic activity (Figure 3) and, in most instances, relatively high rainfall erosivity. Global warming is responsible for intensifying erosion processes and increasing erosion rates in the high mountains of the northern half of the continent, because of active glacier retreat (Iverson, 1997; Holm et al., 2004; Bovis & Jakob, 2000; Moore et al., 2009 etc.). Erosion rates can be as high as 18 000 - 20 000 t km^{-2} year^{-1}. In the southern part of the continent wildfires are an important cause of high natural erosion rate due to destruction of the vegetation cover. After wildfires in the mountains, erosion rates equivalent to up to 1 500 - 2 000 t km^{-2} can be associated with single events, with the frequency of debris flows being greatly increased. (Cannon et al., 2001, 2010; Santi et al., 2008).

2.2.6 Hotspots of natural erosion in South America

Figure 10. Natural erosion hotspots, South America

As with North America, hotspots of natural erosion in South America are located on the western margin of the continent (Figure 10). The Andean mountains are an area of very steep terrain coupled with intense tectonic activity and relatively high rainfall erosivity. Climate change has resulted in active recession of glaciers, which have almost disappeared from central parts of the Andes. Together, the above factors increase the intensity of exogenic processes in high mountain areas leading to erosion rates of up to 18 000 - 20 000 t km^{-2} year^{-1} in the Bolivian Andes, with some reduction outside this area (Pepin et al., 2013; Latrubesse & Restrepo, 2014).

2.3 Anthropogenic erosion

Erosion rates can be considerably increased by human activity, particularly that associated with agriculture, deforestation and other land uses which result in removing the natural vegetation cover and surface litter, disturbing the soil and leaving it bare and exposed to heavy rainfall and surface runoff for significant periods of time. Disturbance of the soil, particularly by cultivation, and production of crops can also degrade the soil structure and reduce its organic content, thereby increasing its erodibility. As indicated above, Montgomery (2007) suggests that erosion rates associated with conventional agricultural tillage are about one to two orders of magnitude greater than natural or background erosion rates. In a recent paper, Nearing et al. (2017) provided an overview of erosion rates on cultivated land in the USA and Northeast China. Erosion rates associated with non-cropped land are typically < 200 t km^{-2} $year^{-1}$, whereas, when averaged over large areas of cropped land, current erosion rates in the USA are typically 600 t km^{-2} $year^{-1}$or more. In Northeast China, land brought into production during the last century is now characterized by erosion rates of 1 500 t km^{-2} $year^{-1}$ or more. In more recent years, the introduction of soil conservation practices has resulted in reduced erosion rates on cultivated land in many areas of the world. The adoption of conservation tillage and no-till have reduced the average rate of soil loss from cropped land in the USA from 900 to 600 -700 t km^{-2} $year^{-1}$ and where cropped land was taken out of production under the Conservation Reserve Program, the rate of soil loss reduced to ca. 100 t km^{-2} $year^{-1}$ (Nearing et al., 2017). In this study, attention is focused on hotspots where erosion rates are high as a result of human impact. However, the factors influencing natural erosion rates outlined above will still be important in providing an environment already conducive to erosion.

2.3.1 Hotspots of anthropogenic erosion in Africa

Figure 11. Anthropogenic erosion hotspots in Africa

Three hotspots of erosion where human impact represents an important driver can be identified in Africa (Figure 11). The areas involved also figure on the map of natural hotspots in Africa, because of their natural propensity for high erosion rates. Human activity further increases these high rates. Two of these hotspots are located in the eastern part of the continent, where the existence of high relief and high rainfall erosivity are coupled with a growing population which has caused an expansion of the area of cultivated land. They are located in the upper part of the Blue Nile basin (Ethiopia) and in the area surrounding Lake Victoria. In the first case, it is likely that land use change is the key factor driving the high erosion rates, but natural erosion is also high (Vanmaercke et al., 2010; Haregeweyn et al., 2015). According to available runoff plot data, sheet and rill erosion rates found in this area closely reflect the total annual precipitation and fall within the range 200 - 11 000 t km^{-2} $year^{-1}$ and average about 3 000 t km^{-2} $year^{-1}$ (Haregeweyn et al., 2015). Sheet, rill and gully erosion all occur in the region (Nyssen et al., 2008, 2009; Gelagay & Minale, 2016), but there are insufficient field-based quantitative data to produce a reliable assessment of the relative importance of natural and anthropogenic drivers. The existence of a hotspot around Lake Victoria is based on sketchy field-based data and some assessments of erosion rates based on erosion model calculations. Available field data indicate that erosion rates here can be as high as 15 000 - 37 000 t km^{-2} $year^{-1}$ depending on the type of anthropogenic activity (De Meyer et al.,2011). The features of the local environment (i.e. relief, soil erodibility and rainfall erosivity) promote high erosion rates, but anthropogenic pressure on the area has caused further intensification of the erosion (Angima et al., 2000, 2003; De Meyer et al., 2011.

The eastern part of the island of Madagascar is the third African hotspot. Here, erosion rates on croplands can reach 6 000 t km^{-2} $year^{-1}$ (Braun et al., 1997). The very high rainfall erosivity is a key factor promoting the intense sediment redistribution occurring in this region, but major land use change has resulted in further increases in erosion rates (Randrianarijaona, 1983; Zavada et al., 2009). However, there is still some uncertainty regarding the key causes of the catastrophic erosion that it found in this region (Klein, 2002; Wells & Andriamihaja, 1993). Both erosion and deposition cause serious problems for agriculture. Soil degradation is coupled with sedimentation of paddy fields and natural lakes. There is a need to direct more attention to quantification of erosion/sedimentation rates and understanding the relative contribution of the natural and anthropogenic factors influencing soil loss (Bakoariniaina et al., 2006).

Although only three hotspots of anthropogenically accelerated erosion have been explicitly identified within Africa, it is likely that much of the continent is experiencing increased erosion rates, due to high rates of population growth and the lack of funds for the design and implementation of soil and water conservation programmes. The lack of quantitative information regarding contemporary erosion rates remains a problem for most of the continent (Lal, 2001).

2.3.2 Hotspots of anthropogenic erosion in Asia

Asia is the largest continent, but large parts of the continent can be excluded from any attempt to identify areas with high erosion rates driven by anthropogenic activity. The northern part of the continent is located in a region with permafrost, which is unsuitable for agriculture and most other human activities. Extraction of natural gas and oil within this region causes major disturbance of the land surface around the extraction sites and erosion rates can be extremely high. Nevertheless, such areas are small when viewed at the continental scale. Furthermore, most of Central, Western and South-Western Asia is a very dry area where wind erosion dominates and water erosion is of limited importance. However, in parts of Iran, Turkey and several other countries extreme rainfall can still occur, producing flash-floods and intense erosion.

Most of the hotspots of anthropogenic erosion in Asia are located to the south and south-east of the Himalayas and on islands affected by both high magnitude typhoons and earthquakes (Figure 12). In the foothills of the Himalayas, erosion rates are typically within the range 7 500 - 15 000 t km^{-2} $year^{-1}$. The only region located to the north-west of the Himalayas where high erosion rates have been documented is in the foothills of the Tien Shan Mountains. Natural erosion rates are high in this region and overgrazing of rangelands associated with high local population densities has resulted in severe erosion. High erosion rates (3 000 - 5 000 t km^{-2} $year^{-1}$) are also associated with irrigated areas in this region where furrow irrigation is widely practiced (Reddy et al.,2013) and as a result reservoir sedimentation is a serious problem. (Rakhmatullaev et al., 2009, 2010, 2011, 2013). Quantitative information concerning erosion rates on rangelands, and cultivated fields within this region in recent years is, however, very limited (Golosov et al., 2012).

Figure 12. Anthropogenic erosion hotspots in Asia

In Southwest China, recent intensive economic development has involved deforestation, road construction and mining, as well as expansion of agriculture. When combined with the high natural erosion rates associated with the high relief and frequent tectonic activity, very high erosion rates (up to 6 000 t km^{-2} $year^{-1}$) have resulted (Barton et al., 2004; Dai & Tan,1996; He et al., 2003; Chen et al., 2005). As a result, this region can be seen as an erosion hotspot.

The Shivalik foothills represent another hotspot of anthropogenic erosion (Saha et al., 2012, Mandal et al., 2006). Here erosion rates are relatively low under natural conditions, because the dense vegetation cover protects the slopes. However, ongoing deforestation and land use change associated with rapid population growth, have resulted in increased erosion rates up to 4 000 t km^{-2} $year^{-1}$ in many areas within the region. Measurements of contemporary erosion rates within the region are limited, but it is clear that erosion rates are likely to increase further in the future due to population growth which in turn leads to deforestation (Yousuf & Singh, 2016; Yousuf et al., 2015; Hewawasam, 2010; Singh et al., 2011). The Murree Hills (Pakistan) is another area adjacent to the Himalayas with extremely high erosion rates up to 15 000 t km^{-2} $year^{-1}$ (Ellis et al, 1994). Erosion rates reaching 5 000 - 7 000 t km^{-2} $year^{-1}$ have also been reported for the croplands and tea plantations in the highlands of Sri Lanka (Hewawasam, 2010; Diyabalanage et al., 2017). These erosion rates are considerably higher than the natural denudation rates, which according to cosmogenic nuclide dating range from 5 - 20 t km^{-2} $year^{-1}$ (Hewawasam et al., 2003).

Two other erosion hotspots in Asia are located in areas characterized by frequent typhoons, steep relief and high levels of tectonic activity, which together cause high natural erosion rates. Erosion rates are increased further by intense anthropogenic pressure due to the high population density (Sidle et al., 2006; Valentin et al., 2008; Kao et al., 2005, 2008). These two hotspots, namely, Taiwan, China and the Philippines, are characterized by intensive deforestation and active land use changes resulting in an increase in the area of cultivated land (Lin et al., 2002; Sidle et al., 2006). Erosion rates vary according to the crops grown, reaching a maximum of 39 000 - 46 000 t km^{-2} $year^{-1}$ for bare soil and coffee plantations (Sidle et al., 2006).

2.3.3 Hotspots of anthropogenic erosion in Australasia and Oceania

Figure 13. Anthropogenic erosion hotspots in Australasia and Oceania

By virtue of its relatively low relief, lack of tectonic activity and limited rainfall erosivity, erosion rates in Australia are relatively low and no hotspots are identified in this general review (Figure 13). However, as indicated above, New Zealand represents a hotspot for natural erosion because of the relatively high rainfall erosivity, steep unstable slopes in many areas, erodible soils and tectonic activity. Human activity has doubtless increased erosion rates, but in the case of the mountains of South Island, it is not seen as resulting in a substantial increase in erosion rates and they are therefore not included here. However, the high erosion rates (> 20 000 t km^{-2} $year^{-1}$) found along the eastern coastal area of North Island, and particularly in the Eastern Cape area, can be seen as a classic example of the impact of human activity in accelerating erosion rates within an area already susceptible to high natural erosion rates (Hicks et al., 2000). Typhoons can give rise to very heavy rainfall, with totals of 100 - 300 mm in 24 hours. The arrival of settlers in the late 1800s was associated with clearance of the natural forest to provide pasture for sheep grazing. As a result, mass movements and severe gully erosion occurred on the steep slopes which are underlain by soft sedimentary rocks. In more recent years, targeted reforestation programmes have greatly reduced erosion rates but this region is seen by some as providing examples of the most severe pastoral erosion in the world. High erosion rates within the range 4 000 - 8 000 t km^{-2} $year^{-1}$,reflecting both the local natural conditions and the impact of agricultural land use can also be found on some Pacific Islands within Oceania (Glatthaar, 1988; Terry et al., 2002). The Highlands of Papua New Guinea is another area with high anthropogenic erosion rates associated with agricultural activity and mining (Gillieson et al, 1987; Sillitoe, 1993).

2.3.4 Hotspots of anthropogenic erosion in Europe

Figure 14. Anthropogenic erosion hotspots in Europe

Based on the available information (e.g. Cerdan et al., 2010; Panagos et al., 2014), two main zones characterized by erosion hotspots representative of different sets of drivers were identified in Europe (Figure 14). The first includes areas in central and southern Italy and Sicily where human activity and particularly agriculture are superimposed on high natural erosion rates promoted by the steep terrain, tectonic activity and high rainfall erosivity (Ciccacci et al., 2003; Della Seta et al., 2007, 2009; Di Stefano & Ferro, 2011; Vergari et al., 2013; Vergari, 2015). Here erosion rates can reach 10 000 t km^{-2} $year^{-1}$. The second is Moldova, which is located in the eastern part of Romania and the central part of the Republic of Moldova (Ionita et al., 2006; Kuharuk & Crivova, 2014). This represents an area with high rates of soil loss (up to 4 000 - 6 000 t km^{-2} $year^{-1}$) from cultivated land under row crops, which reflect extreme rainfall, poor agricultural practices and the highly dissected relief (Krupenikov et al., 2011; Leah & Kuharuk, 2017).

2.3.5 Hotspots of anthropogenic erosion in North and Central America and Carribean

Figure 15. Anthropogenic erosion hotspots in North and Central America and the Caribbean

Because of the national soil conservation programmes in both the USA and Canada and the widespread adoption of minimum till management, soil losses from agricultural areas have reduced substantially. There is therefore now limited scope to identify hotspots of anthropogenic erosion in these two countries (Figure 15). According to the National Agro-Ecological Report for Canada, only an area adjacent to the Great Lakes (Ontario Province) is characterized by relatively high values of erosion rates due to the high proportion of row crops (e.g. potatoes). However, this area falls short of being identified as an erosion hotspot. Only the area of the Rocky Mountains identified as a hotspot for natural erosion has been identified as an erosion hotspot for anthropogenic erosion. Here, human activities such as forest harvesting and clearcutting are likely to further increase the high natural erosion rates associated with this area. However, the precise contribution of anthropogenic factors remains to be determined. Available information on erosion rates on agricultural land in Central America and the Caribbean indicate that they don't exceed 1 000 t km^{-2} $year^{-1}$ (Krishnaswamy et al., 2001; Gellis et al., 2006).

2.3.6 Hotspots of anthropogenic erosion in South America

Figure 16. Anthropogenic erosion hotspots in South America

Limited quantitative field data regarding erosion rates are available for much of South America (Figure 16). The most detailed information available is for Brazil, where information derived using a range of methods and techniques, including monitoring of erosion plots, application of fallout radionuclides and estimation of mean annual erosion rates based on the siltation of small reservoirs, is available (Minella et al., 2009, 2014; Guerra et al., 2014; Didoné et al., 2015, 2017; Tiecher et al., 2017). Some quantitative field data are also available for Chile, Colombia, Venezuela, Peru, Argentina and other countries, but in most cases empirical erosion models (USLE, RUSLE, SWAT etc.) are used to assess erosion rates at the field, small catchment and river basin scales. The erosion model calculations can be verified very approximately through comparison with measured catchment sediment yields. Three types of anthropogenic erosion hotspots can be identified within South America viz.

1. Erosion prone areas where agricultural activities that generate high rates of soil loss (>2 000 t km^{-2} $year^{-1}$) are found. These include the cultivation of tobacco (up to 10 000 - 15 000 t km^{-2} $year^{-1}$) and soybeans, as well as degraded pasture. The southeastern part of Brazil has been identified as a hotspot of anthropogenic erosion for this reason, although the implementation of soil conservation measures in this region in recent decades has significantly reduced erosion rates. However, it has also been suggested that there has been some deterioration in soil conservation programmes in recent years and that erosion rates are increasing again.

2. Areas with high natural rates of erosion further intensified by human impacts, including deforestation, land clearance for agriculture and mining. This is the situation with the eastern tributaries of the middle reach of the Magdalena River basin (Colombia), and the Bermejo River (Argentina and Bolivia), among several others. Despite the lack of measurements of erosion rates within the Magdalena River basin, satellite imagery has documented a major reduction in the forested area within the catchments of the eastern tributaries of the basin and an associated increase in the area of agricultural land of up to >50% of the basin area since 1970. This has been linked to an increase in sediment yield (Restrepo & Syvitski, 2006; Restrepo et al., 2006; Kettner et al., 2010).

3. A similar situation exists in the Andean headwaters of the Rio Madeira in Bolivia. Here the naturally high erosion rates (Latraubesse & Restrepo, 2014) have been further intensified by human activity leading to reduced slope stability and erosion rates as high as 20 000 t km^{-2} $year^{-1}$.

3 Sediment transport hotspots

3.1 Background

When assessing variations in the magnitude of sediment transport by rivers or fluvial sediment fluxes across the globe, reference is generally made to either the magnitude of the mean annual load of different rivers or the specific sediment yield of their basins. The annual load represents the total mass of sediment in tonnes transported during a given year. Information on the load transported by individual rivers is important for quantifying the land-ocean sediment flux and the relative contribution made by individual rivers, continents or regions. However, such data are of limited value when assessing global patterns of sediment transport, since they will be strongly influenced by the size of the river basin. For this purpose, information on specific sediment yields is used. The specific sediment yield of a river basin is calculated by dividing the load by the basin area to provide a value of load per unit area (i.e. t km^{-2} $year^{-1}$). Usually a mean annual value is calculated to provide a representative value for a given river basin. The specific sediment yield provides a measure of the intensity of sediment mobilization within a catchment which is analogous to an erosion rate. However, it differs from an erosion rate (as discussed in section 2) in three important respects. Firstly, it is a measure of the amount of sediment leaving a river basin and thus reflects both sediment mobilization by erosion and subsequent deposition of sediment as it is transported through the upstream river basin. In this respect it can be seen as a measure of net sediment mobilization. Secondly, the sediment yield from a drainage basin will include sediment from all sources within the basin and not only the slopes to which estimates of erosion rates or rates of soil loss commonly refer. The banks and bed of a river channel can be an important sediment source. Thirdly, and closely related to the first feature above, the magnitude of the values of specific sediment yield associated with individual river basins will commonly show an inverse relationship with basin area. Values of specific sediment yield will therefore reflect the size of the basin to which they relate. Larger basins commonly have a greater proportion of lowland characterized by lower erosion rates. Equally, as the size of a river basin increases, the opportunity for deposition of sediment moving through the channel system, for example as a result of overbank sedimentation on floodplains, will increase due to both the increased transport distance involved and the more extensive floodplains and reduced channel gradients commonly found in the lowland areas of larger basins. When using values of specific sediment yield to compare different areas, it is therefore important to take into account the important effect of basin size on the magnitude of the values involved and to use values representative of basins of a similar size.

The global pattern of sediment yield will closely reflect that of erosion considered above, since a large proportion of the sediment transported by rivers is mobilized by erosion of the basin slopes It will therefore reflect similar controls. However, it will be influenced by two additional factors. The first is the efficiency of sediment delivery from the land surface to and through the river network. This is often referred to as the connectivity of the landscape. The second is the contribution of the channel system as a sediment source. This will often increase in large river basins.

It is also important to recognize that, like erosion rates, the sediment loads of rivers are highly sensitive to human impact and global change and that annual sediment fluxes and specific sediment yields must therefore be viewed as a dynamic measure or parameter. Walling (2006) provides an overview of the impact of human activity on the sediment loads of the world's larger rivers and has shown how land clearance and disturbance for agriculture and mining can result in major increases in sediment loads and therefore specific sediment yields, whereas the

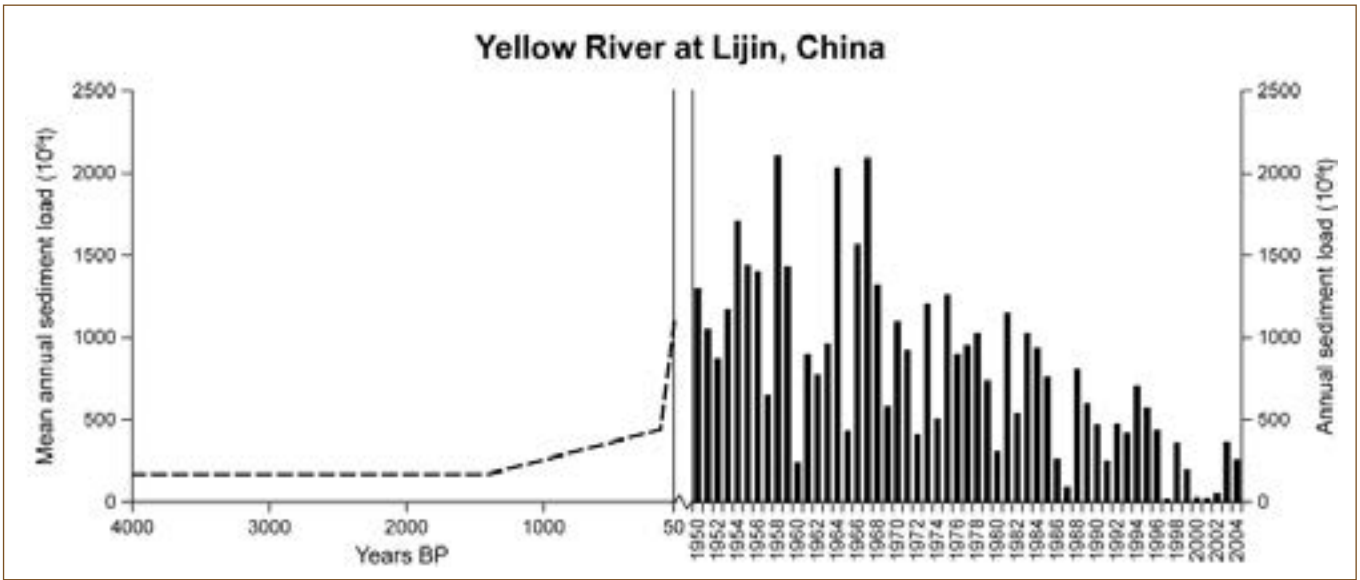

Figure 17. A tentative reconstruction of the long-term trend in the suspended sediment load of the Lower Yellow River over the past 6 000 years. (Based on Walling, 2011)

construction of dams and other hydraulic structures on rivers can result in major reductions. In some areas of the world, implementation of soil conservation and sediment control strategies have proved successful in reducing sediment fluxes and specific sediment yields which had increased previously as a result of land use activities. Two examples can be usefully introduced to demonstrate this feature of sediment loads and sediment yields. The first is the River Nile. Prior to the construction of the Aswan Dam the mean annual sediment load of this river in its lower reaches was about 120 Mt year^{-1}. After the dam was commissioned, most of this sediment was trapped by the dam and the mean annual sediment load was reduced to about 2 Mt year^{-1}, a reduction of ca. 98%. This change resulted in a reduction of the specific sediment yield of the Nile basin from ca. 41 t km^{-2} year^{-1} to ca. 0.7 t km^{-2} year^{-1}. The second is the Yellow River in China. The central part of the Yellow River basin is occupied by the Loess Plateau, which is well known for its very high erosion rates prior to the introduction of extensive soil and water conservation programmes. Walling (2011) presents an attempt to reconstruct the long-term variation of the sediment load of this river at its lowest measuring station, close to its delta at Lijin (Figure 17). It is estimated that prior to about 1400 BP the sediment load of the Lower Yellow River was approximately 100 - 200 Mt year^{-1}, representing a specific sediment yield of ca. 130-265 t km^{-2} year^{-1}. Subsequently, population growth and associated forest clearance and expansion of agriculture resulted in increased erosion rates and sediment mobilization. These changes began to have a marked effect about 150 years ago and by the middle of the 20th century the mean annual sediment load was about 1 100 Mt (1 466 t km^{-2} year^{-1}). Subsequently and beginning around the 1970s, the sediment load of the river declined markedly as a result of the construction of dams, increased water abstraction, implementation of extensive soil and water conservation programmes and reduced rainfall over its basin. As a result, its mean annual sediment load reduced to about 150 Mt year^{-1} (200 t km^{-2} year^{-1}). In this river basin the mean annual specific sediment yield was therefore initially ca. 130 - 265 t km^{-2} year^{-1}, it then increased to ca. 1 466 t km^{-2} year^{-1} and it subsequently declined to ca. 200 t km^{-2} year^{-1}. This represents variation across approximately an order of magnitude.

In addition to taking account of the dynamic nature of annual sediment loads or sediment yields, any attempt to evaluate global patterns of sediment yield also needs to recognize that sediment load measurements are available for only a limited number of rivers, that the available data cover different periods and are of variable quality, and that most sediment load data relates only to the suspended load and does not include the bedload component, which is more difficult to measure. It is frequently assumed that the bedload component of the total sediment load of a river is small relative to the suspended load and can be ignored without incurring major errors. A value of 10% is often assumed and in estimating the total land-ocean sediment flux for the land surface of the globe Milliman and Meade (1983) assumed that inclusion of bedload would increase the flux by 7 - 15%.

3.2 The global pattern of sediment yield

To provide an overview of the global pattern of specific sediment yield and its key controls, as a precursor to identifying hotspots, use will be made of data representing measurements of the sediment yields of world rivers undertaken over the past ca. 60 years, without considering the time period to which the data relate or possible trends in the data which could indicate that sediment yields are declining or increasing. Because of the problems of standardizing the reference period, the lack of data for many areas of the world and the variable quality of the existing data, as well as problems of taking account of the inverse relationship between sediment yield and basin area there have been few attempts to generate global maps of sediment yield. The scale problem noted above means that a global map of specific sediment yield based on catchments of the order of 10^3 km^2 in size could be expected to be very different from one based on data representative of river basins ca 10^6 km^2 in size. Equally, lack of data for the headwaters of a river basin could obscure the variation of sediment yield across its basin. A useful example of this problem is provided by the Amazon. At the lowest measuring station on this river, which measures the sediment output from a basin of 6 300 000 km^2, the mean annual sediment load is estimated to be ca. 1 200 Mt year^{-1}. This is equivalent to a specific sediment yield of ca. 190 t km^{-2} year^{-1}. However, for its headwaters in Bolivia, specific sediment yields of >5 000 t km^{-2} year^{-1} have been documented for sub-basins with areas of ca. 10^3 - 10^4 km^2. One attempt to generate a map showing the global pattern of sediment yield is that produced by Walling & Webb (1983), which is presented in Figure 18. This was based on information from about 2 000 measuring stations on the world's rivers collated in the 1970s. It aims to represent the sediment yields associated with river basins of intermediate size (ca. 1 000 – 10 000 km^2). Lack of data from many areas of the world and the need to extrapolate the available data to include those areas, at a time prior to the general availability of GIS techniques, global DEMs and other global data sets, means that the map has many limitations. However, it is seen as providing a meaningful basis for demonstrating the key features of the global pattern of sediment yield and thus where hotspots might be expected. The pattern show by Figure 18 reflects the five key controls on erosion rates reviewed in section 2.2, namely, relief, tectonic activity, vegetation cover, the erodibility of the soil and rocks and erosivity, which reflects the amount and intensity of rainfall and runoff. To these can be added the impact of human activity in increasing the susceptibility of the landscape to erosion through disturbance. The influence of relief is clearly evident, in that many of the areas with high sediment yields are mountain areas, for example, the Andes, the western Cordillera of North America, the Atlas Mountains of North America, the Himalayas and

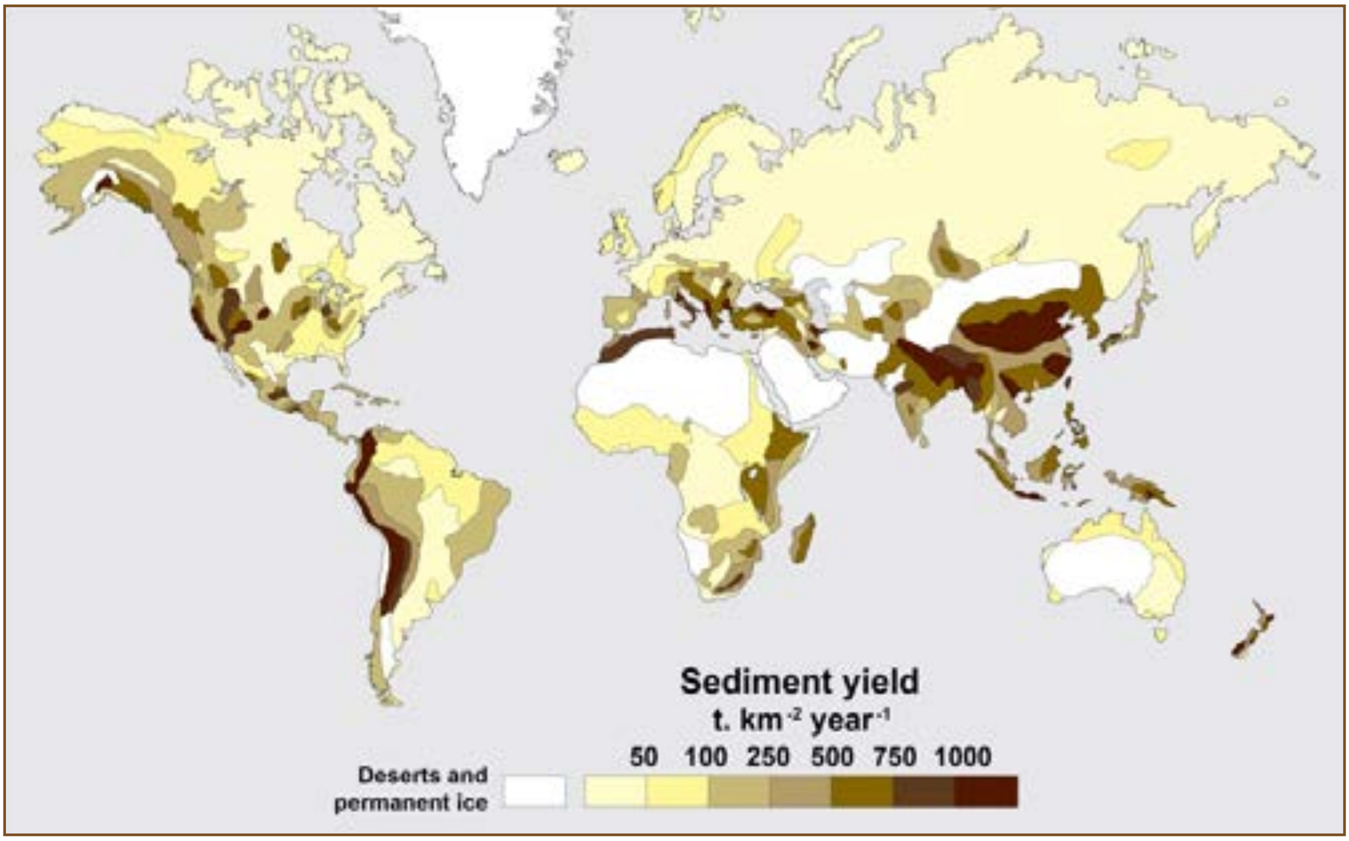

Figure 18. The map of global mean annual specific sediment yields produced by Walling & Webb (1983)

the Southern Alps of New Zealand. Often the mountain areas coincide with areas of tectonic activity and many, if not most, of the areas with high sediment yields coincide with areas of increased seismic activity shown in Figure 3. Vegetation cover and erosivity are in many respects a function of climate, which is frequently cited as exerting an important influence on erosion rates and sediment yields. Here it is important to consider the interaction of the two controls. Maximum erosivity will be associated with areas of high rainfall, particularly areas subject to typhoons and hurricanes, but high erosivity can be partially countered by the denser vegetation canopy found in areas with high rainfall, such as tropical rainforests. As a result, high erosion rates and sediment yields can frequently be found in semi-arid areas where the vegetation cover is limited and this increases the effectiveness of the limited, but often intense, rainfall. The erodibility of the soil and rock is closely linked to relief and tectonic activity, since mountain areas are often characterized by more recent sedimentary rocks. The importance of erodibility is well demonstrated by the high sediment yields associated with the Loess Plateau of China. Here the deep loess deposits are easily eroded and dissected by dense networks of gullies, resulting in some of the highest sediment yields found anywhere in the world.

3.3 Sediment yield hotspots

Figure 18 provides a useful starting point for identifying sediment yield hotspots. The highest sediment yields shown on this map are in excess of 1 000 t km^{-2} $year^{-1}$. Sediment yields an order of magnitude or more greater than 1 000 t km^{-2} $year^{-1}$ are, however, found in some areas of the world, such as the Loess Plateau and Taiwan, China, the Andean headwaters of the Amazon in Bolivia and the Southern Alps of New Zealand. Perusal of the available data on rivers with high mean annual specific sediment yields indicates that values of the order of 50 000 t km^{-2} $year^{-1}$ should be seen as representing the maximum values likely for rivers basins of an intermediate size (i.e. ca. 1 000 km^2) and that a value of 4 000 t km^{-2} $year^{-1}$ could be seen as providing a meaningful threshold for designating hotspots.

Table 1 River basins with documented specific sediment yields (SSY) in excess of 4 000 t km^{-2} year^{-1}

Country of Measurement	River	Area(km^2)	SSY (t km^{-2} year^{-1})	Record+
Argentina	Bermejo	25 000	4 800	G
	Iruya	2 120	8 349	G
	Pescado	1 700	14 117	G
Albania	Semani	5 288	4 150	G
	Vijose	6 700	4 328	G
Algeria	Allalah	295	6 654	G
	Ain Dalia	196	5 281	R
	Agrioun	660	7 273	G
	Bouroumi	150	6 933	R
	Ighil Emda	652	4 040	R
Bolivia	Unduavi	270	7 850	G
	Tamampaya	1 900	4 120	G
	Luribay	810	7 900	G
	La Paz	6 500	18 250	G
	Espiritu Santo	160	66 600	G
	Caine	9 200	11 560	G
	Grande	23 700	5 730	G
	Grande	31 200	6 520	G
	Cotacajes	5 600	7 240	G
	Paracti	320	10 940	G
	Juntas Co-rani	2 300	4 960	G
Colombia	Lengupa	774	6 498	G
	Lengupa	1 640	5 739	G
China	Ching	56 930	7 190	G
	Dali	96	25 600	G
	Dali	187	21 700	G
	Dali	3 893	16 300	G
	Gushan	1 263	22 130	G
	Huangfu	3 199	18 060	G
	Jialu	1 121	24 980	G
	Jin	3 145	6 010	G
	Jin	13 246	5 920	G
	Jin	14 214	6 690	G
	Kuje	8 645	15 270	G
	Pu	3 522	8 104	R
	Pu	7 190	6 580	G
	Tuwei	3 253	9 880	G
	Unknown	3 893	16 300	G
	Wei	16 827	4 060	G
	Wei	23 385	6 460	G
	Wuding	30 217	5 270	G
Ethiopia	Unta	113	6 265	G
	Borkenna Dam	465	8 387	R
Indonesia	Cikeruh	250	11 200	G
	Cilutung	600	12 000	G
	Cimanuk	3 200	7 800	G
Iran	Sorkhab	3 340	4 736	G
Kenya	Tana	353	6 330	R
	Perkerra	1 310	19 520	G
Morocco	Nekor Reser-voir	780	4 620	R
Nepal	Baghmati	585	4 552	R
	Kali Gangaki	7 130	4 173	G
	Kankai Mai	1 148	4 840	G
	Kamali	42 890	5 130	R
	Narayani	31 100	5 684	G
	Rapti	3 512	4 730	G
	Seti	582	5 286	G
	Tamur	5 900	8 210	R
	Tamur	5 640	10 205	G
New Zealand	Cleddau	150	13 000	G
	Haast	1 000	13 000	G
	Hikuwai	307	13 890	G
	Hokitika	350	17 000	G
	Waiapu	1 400	20 000	G
	Wangaromia	175	17 340	G
	Waipoa	1 600	5 800	G
Papua New Guinea	Unknown	420	7 857	G
	Aure	4 360	11 126	G
	Jaba	460	56 521	G
Philippines	Agno	229	7 420	G
	Agno	1 225	4 350	G
	Agno	686	5 008	R
	Agno	686	8 740	G
	Angat	568	8 010	G
	O'Donnel	112	22 740	G
Taiwan, China	Chishui	3 700	5 300	G
	Choshui	3 150	20 000	G
	Erhian	350	36 000	G
	Erhjen	140	71 000	G
	Hoping	550	29 000	G
	Houtung	540	8 000	G
	Hsiukoulinan	1 800	11 000	G
	Huallien	1 500	13 500	G
	Kaoping	3 250	11 000	G
	Lanyang	980	8 200	G
	Linpian	340	5 400	G
	Pachang	470	6 750	G
	Peinan	1 600	14 800	G
	Taan	770	6 300	G
	Tanshui	2 700	4 100	G
	Tungkang	470	11 000	G
	Tsengwen	1 200	26 000	G
	Yangchui	220	10 000	G
Tunisia	Oued Kasseb	101	5 070	GR
	Siliana	1 040	4 036	R

Data From:
Milliman & Farnsworth (2011)
FAO, World River Sediment Yields Database (2016)
Aalto et al. (2006)
Vanmaercke et al. (2014)
Guyot et al. (1996)
Latrubesse and Restrepo (2014)
+ G= River Gauging Station, R= Reservoir Survey

Figure 19. The location of the river basins for which mean annual specific sediment yields > 4 000 t km^{-2} year^{-1} are reported in Table 1. (Locations are approximate)

A search of existing databases for rivers basins greater than ~100 km^2 in area and with mean annual specific sediment yields in excess of 4 000 t km^{-2} year^{-1} yielded a list of more than 90 river basins which could reasonably be viewed as sediment yield hotspots during the period to which the data for the individual river basins relate. These are listed in Table 1 and their approximate locations have been indicated on a world map as Figure 19. Most plot as groups which could in turn be seen as representing hotspot zones. As such, they are only able to designate hotspots in those areas of the world for which data are available. Other hotspot zones may not be represented by virtue of lack of information, but it is though that most of the world's sediment yield hotspots are probably represented. Furthermore, it should again be emphasized that the areas identified as hotspots represent areas where high mean annual specific sediment yields (i.e. >4 000 t km^{-2} year^{-1}) have been recorded at some time in the past ca. 60 years in catchments larger than 100 km^2. Current sediment yields could be significantly lower or possibly higher and further points would be shown if the threshold catchment area of 100 km^2 was reduced.

In general terms, the locations of the hotspot zones shown on Figure 19 coincide with areas designated as being characterized by high sediment yields (i.e. > 1 000 t km^{-2} year^{-1}) on Figure 18 and their existence can be linked to the factors responsible for producing high sediment yields outlined above. In particular, the location of the hotspots indicated on Figure 19 is closely linked to the global distribution of seismic or tectonic activity shown on Figure 3. The hotspots located in the Maghreb region of Morocco, Algeria and Tunisia can, be linked to the steep terrain, the highly erodible rocks, the semi-arid climate which results in a sparse vegetation cover, but is also associated with intense rainstorms, and human impact resulting in forest clearance in the historical past and generally reduced vegetation cover. The hotspots associated with mountain areas of Nepal, the Andean headwaters of the Amazon in Bolivia, Andean rivers in Colombia and Argentina and the Southern Alps of South Island, New Zealand can be linked to steep slopes, high annual rainfall, erodible rocks and tectonic activity. It has been estimated that the annual rate of uplift along the Alpine fault in South Island, New Zealand, which crosses the basins of the rivers involved is of the same order of magnitude as the annual rate of surface lowering within these basins, meaning that the two achieve an approximate balance. In these areas, physical controls are far more important than human activity in giving rise to high sediment yields. Tectonic instability, steep slopes, heavy rainfall associated with tropical cyclones and erodible rocks are similarly important factors accounting for the sediment yield hotspots identified in Taiwan, China, the Philippines, Indonesia and Papua New Guinea. However, here, human impact resulting in reduced vegetation cover and increased surface runoff and slope instability are also important in promoting high sediment yields. The sediment yield of ca. 56 000 t km^{-2} year^{-1} reported for the Jaba river on Bougainville Island in Papua New Guinea can be linked to another form of human activity, namely open cast mining activity and the discharge of mine tailings to the river (Wright et al., 1980).

The Loess Plateau of China has been widely cited as an area of high specific sediment yields in the literature and the region appears as an important hotspot on Figure 19. The high sediment yields can be linked to the limited vegetation cover, intensive agricultural activity, the semi-arid climate with high intensity seasonal rainfall and the highly erodible loess deposits which are deeply dissected by gully systems. In many parts of the region suspended sediment concentrations will sometimes reach levels referred to as hyperconcentrations. These high concentrations and the dense gully networks result in very high sediment delivery ratios which further promote high sediment yields. Sediment delivery ratios of 100% have been reported. In Table 1, values of specific sediment yield in excess of 20 000 t km^{-2} $year^{-1}$ are reported for four river basins in this region, of which two exceed 1 000 km^2 in area. The values of sediment yield reported for the Loess Plateau of China in Table 1 relate to periods of record in the middle and latter part of 20th century and erosion rates have been substantially reduced across this region in recent years as a result of extensive soil and water conservation programmes involving the construction of terraces and check dams, as well as tree planting, increase of grassland cover and improved agricultural practices aimed at reducing surface runoff and local erosion rates. Equally, annual rainfall has also declined, causing reduced sediment yields. The value of 18 060 t km^{-2} $year^{-1}$ listed for the Huangfu River in China in Table 1 relates to the period spanning the 1950s to 1970s when sediment yields could be expected to have been high. The equivalent value for 2000 - 2009 is much lower at around 3 000 t km^{-2} $year^{-1}$. Because of these changes, the Loess Plateau does not figure as a clear hotspot on the map of contemporary hotspots of anthropogenic erosion in Asia presented as Figure 12.

Other hotspot zones identified on Figure 19 and Table 1, can be linked to a range of factors promoting high erosion rates and efficient sediment delivery. They include the Perkerra basin in Kenya, where the high sediment yield was ascribed primarily to the very high erosion rates associated with its heavy overgrazing, and two relatively small river basins in Ethiopia where the high sediment yields reflect steep terrain, human influence through intensification of land use and the semi-arid climate which is associated with intense seasonal rainfall and a sparse vegetation cover. The high specific sediment yields cited for the Sorkhab River in Iran and the Semani and Vijosi Rivers in Albania can likewise be related to the steep mountain topography, highly erodible terrain, unstable slopes, tectonic activity, limited vegetation cover and relatively high runoff.

4 Reservoir Sedimentation

4.1 The context

Reservoir sedimentation represents a key problem associated with the transport of sediment by rivers. Trapping of sediment behind a dam will progressively reduce the storage capacity of the impounded reservoir and, depending on the amount of sediment involved in relation to the total original storage capacity, this is likely to impact on the future functioning of the reservoir and its useful life. A storage loss of 0.5 - 1% per year is frequently cited as an average value for the world's larger reservoirs. The loss can be much lower where sediment loads are relatively low and dams impound large reservoirs, but, equally, much higher storage losses can occur. The Sanmenxia Dam, a multipurpose dam constructed on the Yellow River in China in the late 1950s provides a useful, although extreme, example of this potential problem (Wang et al., 2005). The dam was constructed prior to the more recent reduction in the river's load shown on Figure 17. At that time, the mean annual sediment load of the river at the dam site was ca. 1.6 Gt $year^{-1}$. The dam was closed in 1958 and the reservoir with an initial design capacity of 9.7 billion m^3 and a surface area of 2 350 km^2 reached its operating level in 1960. However, within 18 months of the closing of the dam, 1.8 Gt of sediment had been deposited behind the dam causing the reservoir to lose 17% of its capacity. The dam incorporated bottom sluices to permit sediment to pass through the dam, but only 7% of the sediment load entering the reservoir was discharged downstream during this 18 month period. The high rate of sedimentation caused many problems upstream, including sedimentation and increased backwater flood levels in the River Wei, a tributary of the Yellow River, that posed a threat to the city of Xian. The operation of the dam was changed in an attempt to pass a greater proportion of the floodwater containing high sediment concentrations through the sluices beneath the dam, but by 1964 nearly 63% of the storage capacity had been lost and the useful life of the dam and its reservoir was being quickly reduced. This situation prompted a decision to reconstruct the dam to provide more bottom sluices, two bypass tunnels and several flushing pipes. The reconstruction took place between 1966 and 1971 and this succeeded in increasing the proportion of sediment laden floodwater that could be passed through the dam to limit further deposition. Between 1970 and 1973 attention was directed to operating the bottom sluices to scour some of the sediment stored in the reservoir. This was successful and new operating rules were introduced in 1974. These involved storing water during the part of the year when sediment concentrations were relatively low and passing water through the dam during the flood season when concentrations were high, as well as controlled releases aimed at scouring deposited sediment. Wang et al (2005) indicate that the reconstruction of the dam and the new operating rules succeeded in effectively stopping further deposition in the reservoir. In 2001 the amount of sediment stored in the reservoir was estimated to be 3.15 billion m^3 and this is significantly less than the value of 3.72 billion m^3 accumulated in the reservoir by 1964, only six years after the dam was closed.

Considering large dams more generally, control of sedimentation is now generally included in their design and in many river basins integrated basin management strategies aim to reduce the sediment load entering the reservoir. However, progressive loss of storage due to sedimentation continues to pose major problems for dam sustainability and therefore the sustainability of the hydropower, water supply, irrigation, flood control and other programmes and activities reliant on such dams. Palmieri et al (2003) suggested that the annual loss of storage due to sedimentation was around 45 km^3 per year. This can be equated to a global need to replace about 300 large dams each year, at an estimated annual cost of ca. $13 billion. Finding suitable new dam sites can prove difficult and the environmental and social costs of dam construction are attracting increasing attention.

4.2 The global scene

Comprehensive information on sedimentation rates and associated loss of storage capacity for the numerous large dams existing around the world is difficult to obtain. This reflects both the lack of reliable surveys for dams in some countries and the sensitive nature of such information. The International Commission on Large Dams (ICOLD) (http://www.icold-cigb.net), an international non-governmental organisation founded in 1928 as a forum for the exchange of knowledge and experience in dam engineering, comprises nearly 100 National Committees and maintains a database of the world's current ca. 55 000 large dams, defined as dams with a height of > 15 m and/or a storage capacity of > 3 million m^3. The Reservoir Sedimentation Committee of ICOLD coordinated a global synthesis of reservoir sedimentation data in the early years of the 21st century (Basson, 2008) and this provides a useful basis for exploring the issue further.

The Committee assembled reliable data on reservoir sedimentation from 28 countries and these data are summarized in Figure 20 which presents the mean sedimentation rate, expressed as the annual loss of storage (%) for each country. These data emphasize the appreciable spatial variability in the annual loss of storage, with national mean values ranging from 0.05% in Egypt to 3.27% in Tanzania. This variability reflects the magnitude of the sediment load entering the reservoirs, their storage capacities and their trap efficiency (i.e. their efficiency in trapping sediment). Averaged across all 28 countries, the annual loss of storage was 0.96%. To provide a global perspective, the study estimated the annual loss of storage in a total of about 33 000 dams from the ICOLD World Register for 2006, using both available records and estimates where no data were available. This permitted the average annual loss of storage capacity to be estimated for eight major regions of the world, as indicated in Table 2. The average values provided for each region represent the weighted average (weighted by total storage capacity) of the values for each country included in the region. The values are all of a similar magnitude and range from 0.59% for Africa to 1.01% for the Middle East.

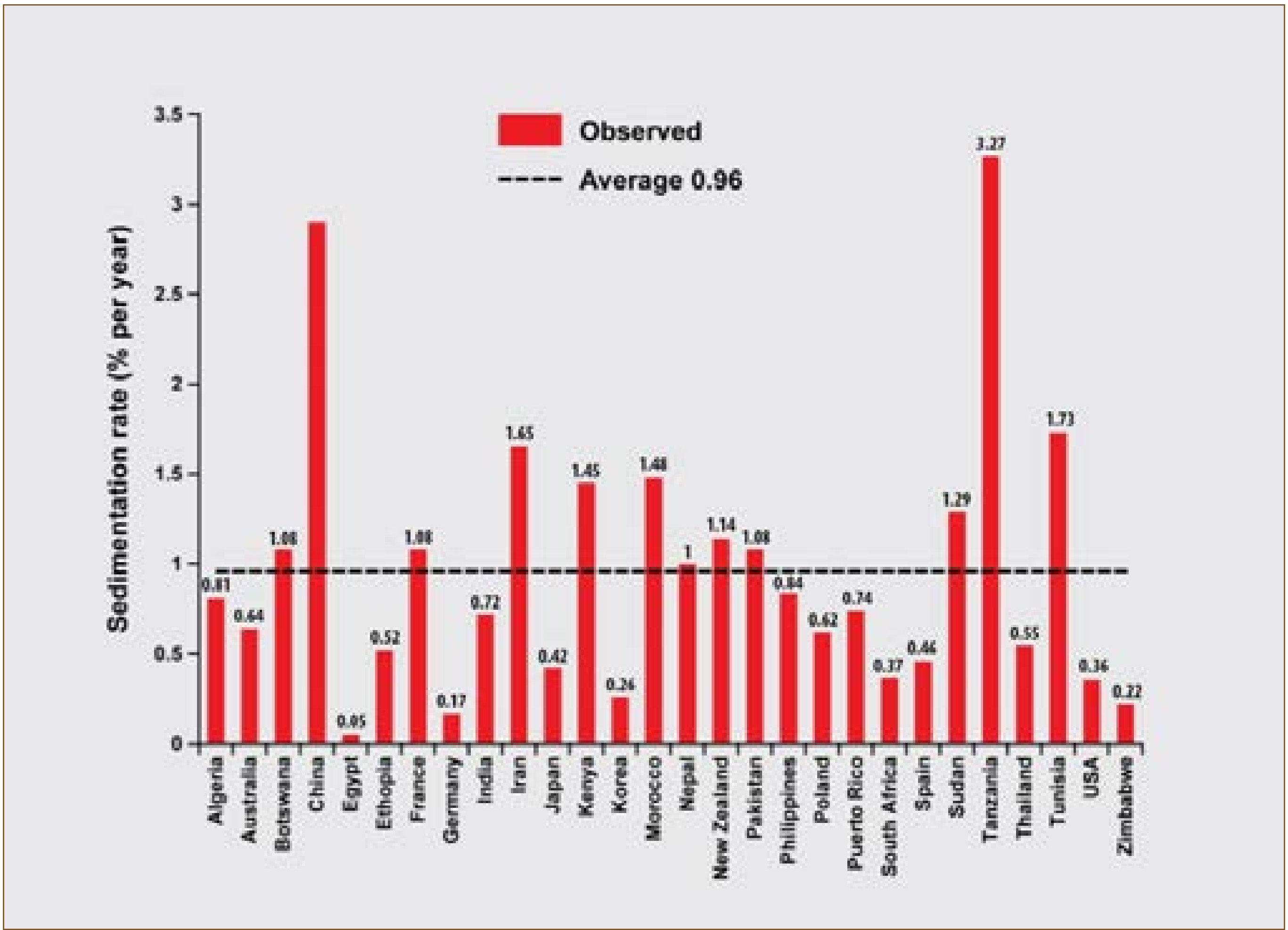

Figure 20. Average observed rates of storage loss for large reservoirs in different countries. (Based on Basson, 2008)

Table 2 Average annual rates of annual storage loss due to sedimentation for dams/reservoirs in different regions of the world, as estimated by Basson (2008)

Region	Average annual storage loss due to sedimentation (%)
Africa	0.85
Asia*	0.85
Australasia and Oceania	0.94
Central America	0.74
Europe (including Russia)	0.73
Middle East	1.02
North America	0.68
South America	0.75

*Asia here excludes Russia and the Middle East

The findings reported above provide little indication of the amounts of sediment trapped behind dams in different areas of the world and the associated global variation. To assess this aspect of the problem, there is a need for information on the total amount of sediment deposited or total storage lost in different regions of the world. Figures 21 and 22, provide information on the growth of the gross storage capacity of reservoirs in the individual regions since the 1940s and through to 2010 and equivalent information on the volume of sediment trapped in those reservoirs and its growth over the past 70 years, with a prediction through to 2050, based on the reservoirs existing in 2010. If the magnitude of the sediment volumes predicted to be stored in the reservoirs of the different regions in 2050 are considered, Figure 22 shows that Asia stands out as having the greatest volume of sediment accumulated in its reservoirs by 2050. When viewed in relative terms, Asia accounts for a greater share of the total volume of sediment volume deposited in reservoirs than of the total gross storage capacity. For all other regions their share of the total sediment volume is similar to, or less than, their share of the total gross storage capacity. South America stands out as the region with the lowest share of the total sediment volume relative to its share of the gross storage volume. These findings could be seen as suggesting that reservoir sedimentation problems related to loss of storage are greatest in Asia and least in South America.

The data presented in Figures 21 and 22 also provide a basis for predicting when the loss of storage will constitute a major problem in the different regions. In this context, it is useful to distinguish dams used

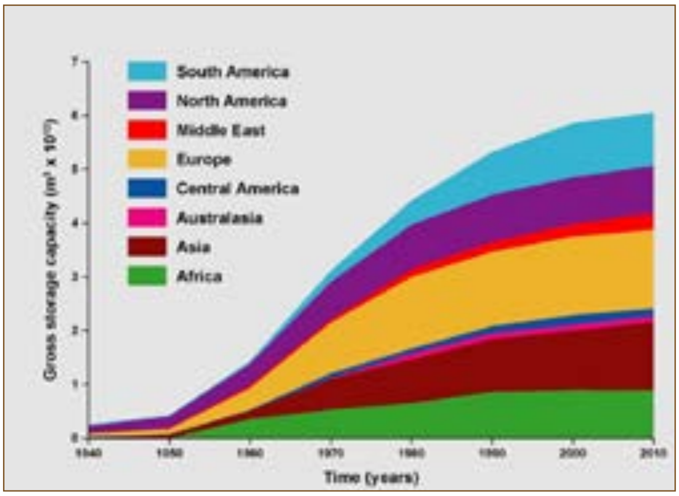

Figure 21. Growth of gross reservoir storage capacity in different regions of the world. (Based on Basson, 2008)

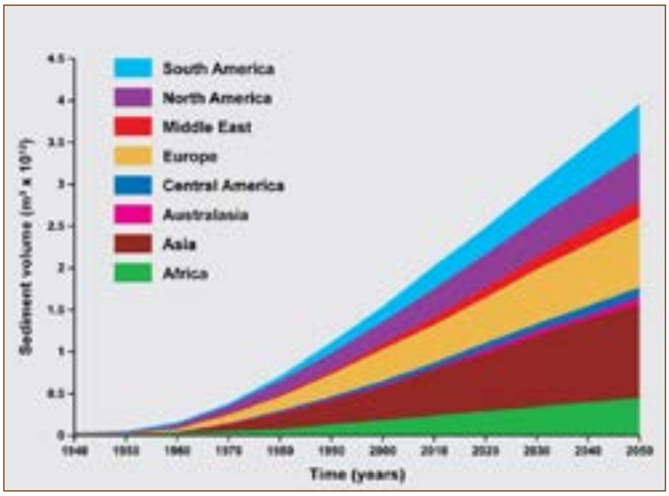

Figure 22. A comparison of estimates of losses of reservoir storage capacity due to sedimentation in different regions of the world. (Based on Basson, 2008)

for hydropower production and those used for other purposes. Basson (2008) indicates that hydropower dams accounted for ca. 82% of the gross storage capacity in 2010. By 2006 ca. 35% of the total storage capacity associated with hydropower dams had been filled with sediment and the proportion of the current total capacity that was likely to be filled with sediment would rise to 70% by 2050 (assuming no further dam construction). The equivalent values for other dams were 33% of the gross capacity had been filled with sediment by 2006 and 62% by 2050. These estimates emphasize the serious implications of sedimentation for the sustainability of the operation of these dams, although they take no account of the additional storage likely to be provided by newly constructed dams after 2006, which would reduce the proportion of total available storage lost to sedimentation in 2050. Basson (2008) suggests that non-hydropower dams become seriously impacted when sediment fills 70% of the available storage. At this point, water yields are likely to be reduced by 40 - 50% and the functioning of intakes is likely to be compromised. In general, hydropower dams can sustain higher losses of storage due to sedimentation than non-hydropower dams, since the primary requirement for the former is to maintain the head required for power generation and a storage capacity sufficient to meet the demand for power. Basson (2008) suggests that hydropower dams will be seriously impacted when 80% of the available storage is lost to sedimentation, whereas the equivalent value for non-hydropower dams is 70%. Table 3 provides estimates of the dates when these critical situations will be reached in the different regions.

Table 3 Projected dates when loss of storage due to sedimentation could reach critical levels in different regions. (Based on Basson, 2008)

Region	Date critical limit reached for hydro-power dams	Date critical limit reached for non-hydropower dams
Africa	2100	2090
Asia	2035	2025
Australasia	2070	2080
Central America	2060	2040
Europe and Russia	2080	2060
Middle East	2060	2030
North America	2060	2070
South America	2080	2060

The dates indicated in Table 3 should be seen as estimates only, since they are associated with considerable uncertainty related to the reliability of the data used and the critical thresholds employed as well as the lumping of data for individual countries within the individual regions. Furthermore, they are based on the gross storage capacity existing in 2010 and its ongoing reduction due to sedimentation and take no account of provision of additional storage through construction of new dams. However, they demonstrate that for hydropower dams, those in Asia face the greatest sustainability problems due to reservoir sedimentation and that for non-hydropower dams those in Asia, the Middle East and Central America face the greatest problems. Hydropower dams in Africa, South America and Europe and Russia have the best prognosis and in the case of non-hydropower dams those in Africa and Australasia are predicted to have the longest lives. Consideration of the individual countries comprising the regions listed in Table 3 permits what could be seen as reservoir sedimentation hotspots to be identified. If

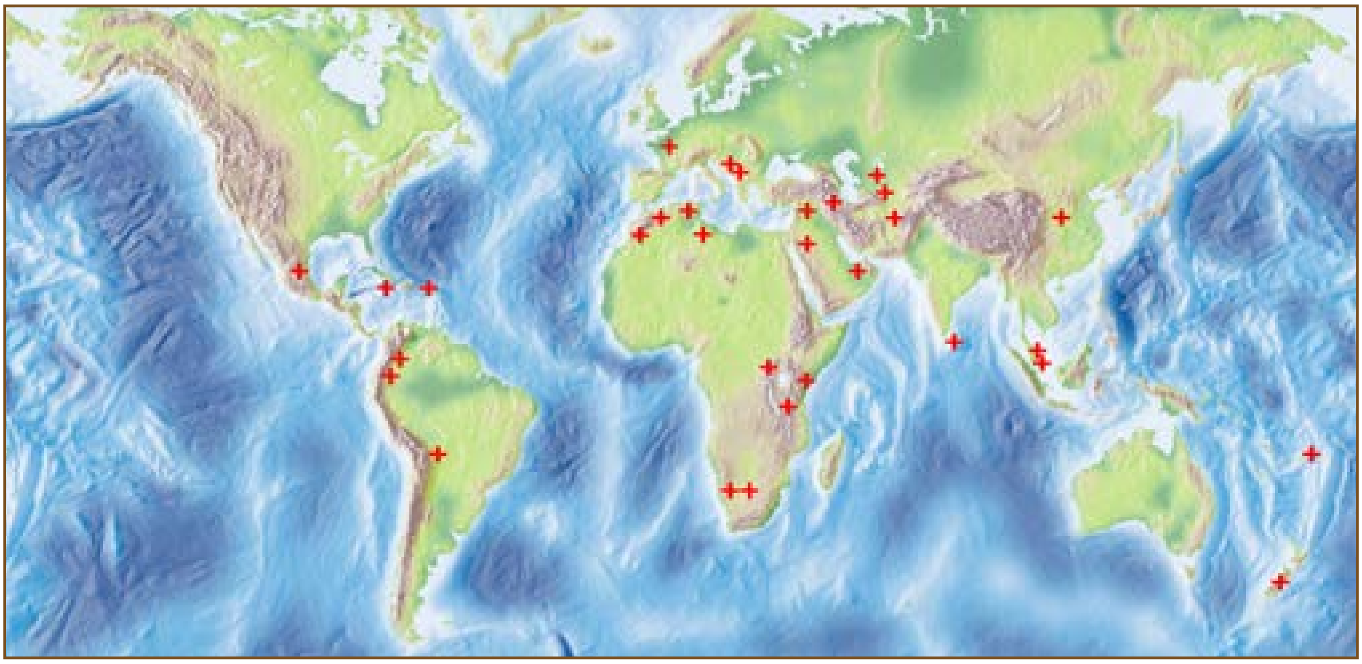

Figure 23. The location of countries where the reservoir storage capacity existing in 2006 is predicted to reach critical levels by 2050 as a result of sedimentation. (Based on data presented by Basson, 2008)

countries predicted to reach the critical level of storage loss as a result of sedimentation by 2050 are seen as representing such hotspots, Basson (2008) identifies 31 countries that merit this designation. These countries are identified on Figure 23. Their distribution reflects in part the influence of engineering or structural controls related to the storage capacity and age of the dams in a particular country, but it also reflects the magnitude of the erosion rates and the sediment loads of the impounded rivers in the countries identified. In this context many of the countries identified are located in areas of the world that have been shown to be characterized by high erosion rates and high specific sediment yields. These include Kenya, Iran, Uzbekistan, China, Malaysia, New Zealand, Fiji, Puerto Rico, Bolivia, Colombia, Morocco, Algeria and Tunisia, and there are clear similarities between Figure 23 and Figure 3 which shows the global distribution of tectonically active areas and Figure 19 which shows the global distribution of sediment yield hotspots.

Table 4 Estimates of the reduction in sediment load of some major rivers of the world as a result of dam construction. (Based on data compiled by Milliman and Farnsworth, 2011)

River	Country	Reduction in sediment load (%)	Load reduction (Mt year^{-1})
Colorado	Mexico	100	120
Nile	Egypt	100	120
Cauvery	India	99	32
Krishna	India	98	63
Asi	Turkey	98	19
Kizil Irmak	Turkey	97	17
Rio Grande	USA	97	19
Indus	Pakistan	96	240
Sebou	Morocco	95	35
Sao Francisco	Brazil	95	14
Moulaya	Morocco	93	11
Ebro	Spain	93	16
Volta	Ghana	92	17
Mahi	India	91	20
Chao Phraya	Thailand	90	27
Drini	Albania	87	14
Limpopo	Mozambique	82	27
Zambezi	Mozambique	81	39
Orange	South Africa	81	72
Namada	India	79	55
Mahanadi	India	74	45
Godavari	India	72	123
Red River	Vietnam	60	60
Mississippi	USA	48	190

As indicated above, sediment trapping by dams clearly has serious implications for the sustainability of their associated reservoirs in many areas of the world. It also has implications for the sediment loads of the rivers on which the dams have been built. Table 4 provides examples of the magnitude of the downstream reduction in sediment load documented for a number of major rivers of the world, where major changes in sediment load have occurred primarily due to dam construction. Reduced sediment loads downstream of dams can result in channel incision and changes in channel morphology as the river adjusts to the reduced sediment loads. Reduced sediment input to the sea at the river mouth can also have important implications for the stability of associated deltas and the coastline more generally. The impact on deltas and their sustainability has attracted increasing attention as a global issue in recent years (Syvitski et al. 2009; Foufoula-Georgiou, 2013), due to their importance as areas of high population density, frequently unique biodiversity and culture, and economic activity, as well as their contribution to food security through agricultural production and fisheries. The close links between delta sustainability and changes in the sediment loads of the rivers at the mouths of which they are located are considered further below.

5 Delta Sustainability

5.1 Background

Syvitski et al. (2009) indicate that the formation and longer-term stability of a delta depends on the interaction of four main factors. The first is the sediment supply and more particularly the aggradation rate, which is controlled by the volume of sediment delivered to, and retained by, the delta; the second is the rate of sea level change, the third is ongoing compaction which reduces the volume of the deposited sediment, and the fourth subsidence associated with isostatic adjustment of the earth's crust to sediment loading and other forces. Three of these factors or controls, namely sediment input, sea level change and compaction are sensitive to human impact. The sediment input can change as a result of human impact and could increase or decrease. A decreased sediment input, such as that caused by sediment trapping by upstream dams (Table 4), could clearly threaten the continuing existence of a delta, if the aggradation rate fails to keep pace with a rising sea level and ongoing compaction and subsidence. Where levees are constructed along the margins of distributary channels, this could further reduce the aggradation rate by preventing the sediment input reaching parts of the delta and thereby reducing sediment retention. Contemporary rising sea levels clearly pose a threat to delta sustainability if sediment inputs are declining and they can also be seen as reflecting human impact through climate change and shrinking of the polar ice sheets. Compaction is in part a natural process, since an increase in the depth of deposited sediment, will cause progressive consolidation of the lower layers and this process will reflect the cumulative deposition over many thousands of years. However, human activities, including abstraction of groundwater, oil and gas extraction and soil drainage and associated oxidation will accelerate compaction and can further increase the problems faced by modern deltas. Syvitski et al. (2009) report that anthropogenically-enhanced compaction rates within the Chao Phraya Delta in Thailand have reached 50 - 150 mm year^{-1} and that more generally human impact can increase compaction rates by an order of magnitude. Figure 24 presents information on the changes in the sediment load of the Indus River in Pakistan during the 20th century as a result of dam construction and diversion of water from the river for irrigation. The reduction of the sediment load of the river commenced in the 1940s with the building of numerous barrages and irrigation channels along the lower river and two major dams, the Mangla Dam and the Tarbela Dam on its upstream tributaries. The annual runoff of the river is now less than about 20% of the original natural flow and the annual sediment load has similarly declined to about 5% of its former value. Information presented by Syvitski et al. (2009) indicates that reduced sediment input to the delta, coupled with a reduction in the extent of the distributary channels by about 80% has resulted in average sedimentation rates within the Indus Delta reducing from about 8 mm year^{-1} in the early 20th century to about 1 mm year^{-1} in the early 21st century. Compaction of the delta deposits has not been substantially affected by water or oil and gas abstraction, but, as a result of the reduced sedimentation, Syvitski et al. (2009) estimate that, the Indus delta is currently experiencing a relative sea level rise of > 1.1 mm year^{-1}. With an area of ca. 4 750 km^2, currently < 2 m above sea level and an area of 3 390 km^2 susceptible to storm surges, the longer-term stability and sustainability of the Indus delta is clearly at risk.

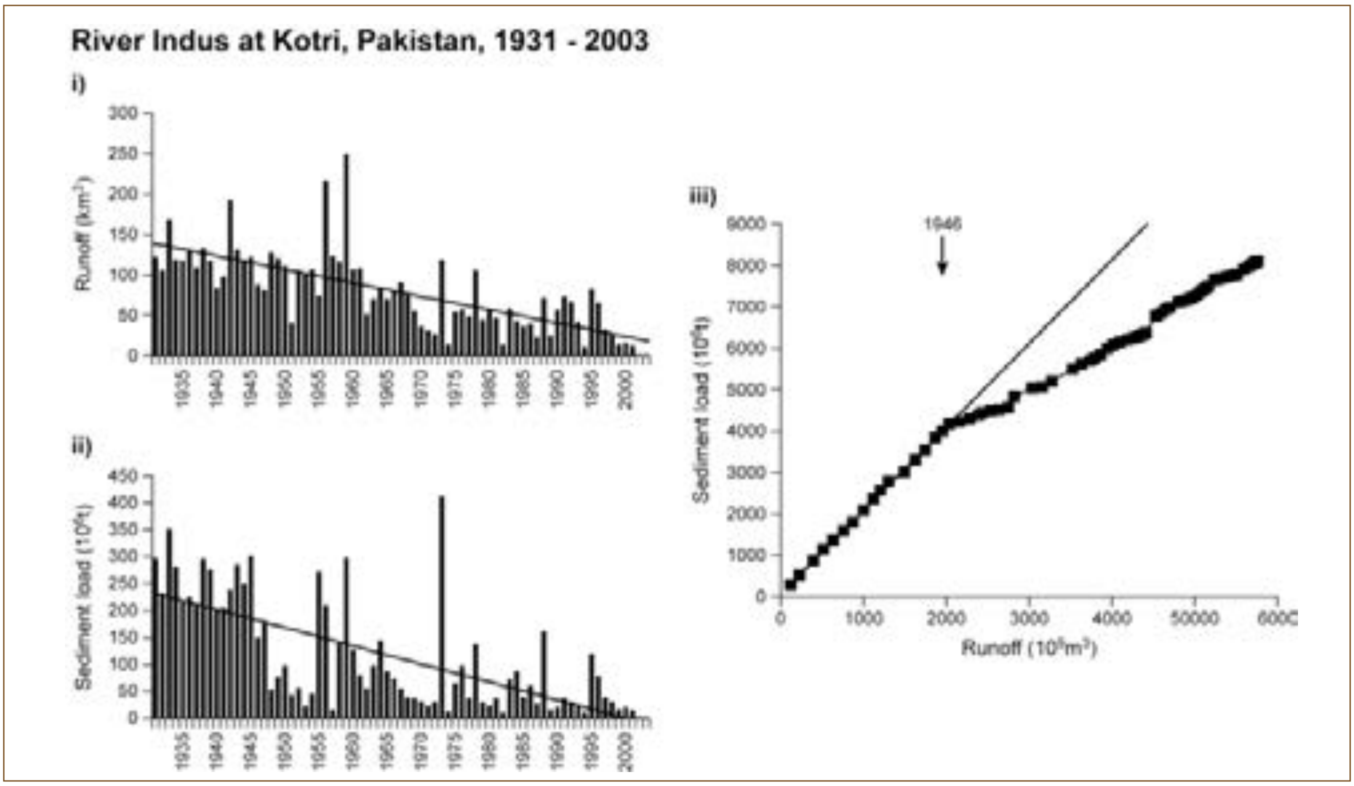

Figure 24. Recent changes in the suspended sediment load of the River Indus at Kotri, Pakistan, as demonstrated by the time series of (i) annual water discharge and (ii) annual suspended sediment load, and (iii) the associated double mass plot. Based on data compiled by Professor John Milliman, Virginia Institute of Marine Science, USA

5.2 The global scene

The current status of individual deltas varies according to the magnitude of human impact and the balance between accretion rates, compaction rates and sea level rise, with the accretion rate and therefore reduction in the sediment load delivered to the delta commonly exercising the overriding control. Deltas where aggradation rates have remained essentially unchanged and human-induced compaction has been minimal, can be seen as facing minimal risk. This is, for example, the situation with the Amazon, Congo, Fly and Orinoco deltas. Deltas which are seen as being at risk and where a reduced sediment load is an important contributor to the problem could be seen as representing sediment hotspots, although in this context the designation 'hotspot' reflects a sediment deficit, rather than an increase in erosion or sediment flux. Syvitski et al. (2009) distinguished four categories of risk of increasing severity. The first category, reflecting the lowest risk, included deltas where aggradation rates had reduced due to reduced sediment input, but still exceeded the relative sea level rise. The second category, representing a greater risk, comprised deltas where the aggradation rates had reduced due to reduced sediment input and no longer kept pace with the relative sea level rise. The third category, designated deltas in peril, comprised deltas where reduced aggradation exacerbated by accelerated compaction due to anthropogenic impact

Table 5 Major world river deltas at risk due to reduced fluvial sediment input. (Based on Syvitski et al., 2009)

River/Country	Area of Delta < 2m above sea level (km^2)	Sediment Load Reduction (%)	Early 20th century sediment accretion rate (mm year^{-1})	21st century sediment accretion rate (mm year^{-1})	Relative sea level rise (mm year^{-1})
Deltas at risk, but accretion rate still exceeds relative sea level rise					
Danube, Romania	3 670	63	3	1	1.2
Han, Korea	70	27	3	2	0.6
Limpopo, Mozambique	150	30	7	5	0.3
Deltas at greater risk, accretion rate less than relative rate of sea level rise					
Brahmani, India	640	50	2	1	1.3
Godavari, India	170	40	7	2	~3
Indus, Pakistan	4 750	80	8	1	>1.1
Mahanadi, India	150	74	2	0.3	1.3
Parana, Argentina	3 600	60	2	0.5	2-3
Vistula, Poland	1 490	20	1.1	0	1.8
Deltas in peril, reduction in accretion rate exacerbated by accelerated compaction					
Ganges, Bangladesh	6 170	30	3	2	8-18
Irrawaddy, Myanmar	1 100	30	2	1.4	3.4-6
Mekong, Vietnam	20 900	12	0.5	0.4	6
Mississippi, USA	7 140	48	2	0.3	5-25
Niger, Nigeria	350	50	0.6	0.3	7-32
Tigris, Iraq	9 700	50	4	2	4-5
Deltas in greater peril, very low accretion and/or greatly accelerated compaction					
Chao Phraya, Thailand	1 780	85	0.2	0	13-150
Colorado, Mexico	700	100	34	0	2-5
Krishna, India	250	94	7	0.4	~3
Nile, Egypt	9 440	98	1.3	0	4.8
Pearl, China,	3 720	67	3	0.5	7.5
Po, Italy	630	50	3	0	4-60
Rhone, France	1 140	30	7	1	2-6
Sao Francisco, Brazil	80	70	2	0.2	3-10
Tone, Japan	410	30	4	0	>10
Yangtze, China	7 080	70	1.1	0	3-28
Yellow, China	3 420	90	49	0	8-23

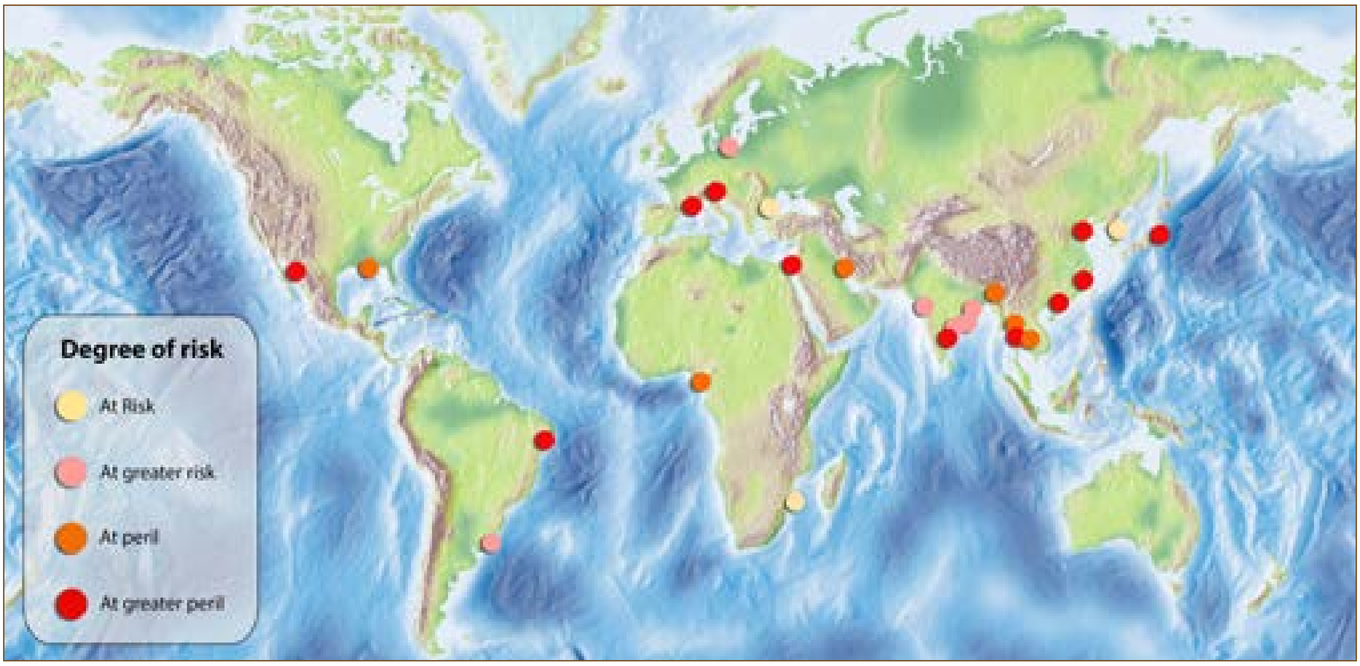

Figure 25. The global distribution of deltas at risk. (Based on Syvitski et al., 2009)

meant that increasing sea level posed a major threat to the sustainability of the delta. The fourth category was designated deltas in greater peril, due to very low accretion rates and/or greatly accelerated compaction resulting in high rates of relative sea level rise. Table 5, based on the work of Syvitski et al. (2009), provides further details of representative examples of the major deltas of the world characterized by a reduced sediment input that are currently at risk or in peril and their categories of risk. Their global distribution is shown on Figure 25. This reflects in part the global distribution of large river basins with substantial annual sediment loads prior to reduction by anthropogenic impacts. However, it is also influenced by the degree of reduction of the sediment load reaching the delta, as well as other factors linked to subsidence and compaction.

6 Perspective

By virtue of the strong links between erosion/soil loss and the sustainability of the global soil resource, soil productivity and therefore food security, an understanding of the global pattern of erosion must be seen as important for ensuring the future sustainability of the Earth system and its social and economic development. Land erosion is the source of much of the sediment transported by rivers and the associated sediment fluxes are an important component of the Earth system. Where the system is disrupted, as with the reduction of sediment supply to deltas and coastal seas, there can be both physical and social and economic implications which need to be recognized and understood. Furthermore, the transport of sediment by rivers necessarily interacts with the development of the water resources of their basins, through siltation of reservoirs and other related hydraulic structures. Again, therefore, a knowledge of the global pattern of sediment yield is an important requirement for sustainable development. This report has attempted to contribute to current understanding of global patterns of erosion and sediment yield and their impacts on the Earth system and its sustainable development, by attempting to identify key hotspots of erosion and sediment yield. In addition an attempt has been made to identify what could be seen as hotspots for contemporary reservoir sedimentation and for the impact of reduced sediment loads of major rivers on their deltas, which frequently represent important centres of population and food production. Identifying these hotspots has served to emphasize the need to recognize the dynamic nature of any assessment of the magnitude of erosion rates and sediment transfer from the land to the oceans. A comparison of contemporary erosion rates influenced by anthropogenic activity with ‘natural’ erosion rates has demonstrated how such activity can both increase erosion rates and thereby intensify erosion hotspots and generate new hotspots. Equally, widespread introduction of soil and water conservation measures can cause reductions in erosion rates and the downgrading of former hotspots. Changes in erosion rates, as well as the trapping of sediment by dams as it moves downstream, can similarly give rise to changes in sediment yields and sediment fluxes, with reduced sediment fluxes being the most common occurrence.

In view of the wide-ranging social and economic implications of erosion and sediment transport, and particularly their hotspots, for sustainable development of the soil and water resources of river basins, the need for effective sediment management as a key component of sustainable river basin management is now widely accepted. There are an increasing number of river basins where both erosion and sediment loads have been successfully managed and thereby reduced by implementing effective soil and water conservation and sediment management strategies (Liu et al., 2017). Scope undoubtedly exists to reduce the magnitude of the rates of erosion and sediment yields associated with at least some of the hotspots identified in this report, although there is a need to accept that where high erosion rates and sediment yields are essentially a product of natural controls, rather than anthopogenic activity, reduction may prove more difficult. The problems facing the world’s deltas have only been recognized relatively recently, since they largely reflect recent changes in the flow and sediment loads of rivers caused by widespread dam construction, sea-level change associated with global warming, and increased subsidence due to recent increases in groundwater abstraction and the extraction oil and gas. Sustainable management of the world’s deltas that are seen as being at risk or at peril (Figure 25) is likely to prove a major challenge. For those deltas where decreasing sediment inputs are a key issue, increasing sediment fluxes is likely to require a new generation of sediment management strategies where emphasis is on increasing, rather than reducing sediment loads, which has been the focus of most previous strategies. Increased use of dams for hydropower, water supply and flood control could prove to be in direct conflict with maintaining sediment inputs to deltas, unless effective strategies for reducing reservoir sedimentation can be developed. Reducing sediment trapping by dams would have considerable benefits in terms of increasing the life of reservoirs and increasing downstream sediment loads and sediment inputs to delta areas.

The need to recognize the dynamic nature of any assessment of changes in the global patterns of erosion and sediment yield emphasized in this report has primarily focused on anthropogenic activity, through, for example, accelerated erosion, soil and water conservation programmes, and sediment trapping by dams. Little attention has been directed to the potential role of climate change in causing further changes in erosion and sediment transport. This reflects in part the difficulty of separating the effects of climate change from the broader impacts of anthropogenic activity and also acceptance that the impacts of climate change will become increasingly important in the future. The need to increasingly take account of the impact of climate change on the global pattern of erosion and sediment yield could be seen as a challenge for the 21st century. Erosion rates and sediment yields are particularly sensitive to extreme events and the potential significance of current increases in the frequency of typhoons, such as that documented for Taiwan, China by Kao et al. (2011) has already been demonstrated.

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