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Sediment Problems and Strategies for their Management

Experience from several large river basins

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Sedimen Problems and Strategies for their Management

Experience from several large river basins

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Abstract

The management of sediment in river basins and waterways has been an important issue for water managers throughout history. The changing nature of sediment issues has meant that water managers today face many complex technical and environmental challenges in relation to sediment management. UNESCO's International Hydrological Programme (IHP) launched the International Sediment Initiative (ISI) in 2002. ISI addresses the wide-ranging social, economic and environmental impacts of erosion, sediment transport and sedimentation processes and aims to support the global agenda for sustainable integrated land and water resources management by promoting sound sediment management. Among other actions, ISI has endeavoured to collate and document international experience on sediment problems and their management through the compilation of a series of case studies representative of a broad range of physiographic and socio-economic conditions, which are made available as guidance for policy makers dealing with water and river basin management. Case studies prepared to date include the Nile River Basin, the Mississippi River Basin, the Rhine River Basin, the Volga River Basin, the Yellow River Basin, and the Haihe and Liaohe River Basins. Key experience relating to sediment management drawn from these river basin studies is briefly introduced in this paper, which aims to provide an accessible overview of sediment problems and sediment management around the world and present policy and strategy options to improve the sustainable management of such rivers. Key recommendations for developing management strategies presented in this paper have been extracted from these river case studies.

Keywords: sediment; sediment problems; sediment management; river basin; International Sediment Initiative (ISI)

Introduction

The management of sediment in river basins and waterways has been an important issue for water managers throughout history – from the ancient Egyptians managing deposition of sediment on floodplains to provide their crops with nutrients, to today's problems with siltation in large reservoirs and maintaining river systems as transport arteries. The changing nature of sediment issues due to the increasing human population (and the resulting changes in land use and increased water use), the increasing numbers of manmade structures such as dams, weirs and barrages - as well as the increasing recognition of the importance of sediment in the transport and fate of both nutrients and contaminants within river systems - has meant that water managers today face many complex technical and environmental challenges in relation to sediment management.

The International Sediment Initiative (ISI) was launched by UNESCO's International Hydrological Programme (IHP) in 2002. It addresses the wide-ranging social, economic and environmental impacts of erosion, sediment transport and sedimentation processes, and aims to support the global agenda for sustainable integrated land and water resources management by promoting sound sediment management. The ISI is guided and governed by an Advisory Group and an Expert Group, drawing on the contributions of 15 experts from 14 countries worldwide. The Secretariat for the initiative is provided by the International Research and Training Centre on Erosion and Sedimentation (IRTCES) in Beijing, China. ISI is open to collaboration with all interested international, regional or national institutions, organisations and agencies in the interest of promoting sound and sustainable sediment management policies. Collaborative links have been established with associations and bodies such as the World Association for Sedimentation and Erosion Research (WASER), the International Association of Hydrological Sciences (IAHS), the International Association for Hydro-Environment Engineering and Research (IAHR), the European Sediment Network (SedNet), the International Coordinating Committee on Reservoir Sedimentation (ICCORES), the International Commission on Large Dams (ICOLD) and others. Among other actions, ISI has endeavoured to collate and document international experience on sediment problems and their management through the compilation of a series of case studies representative of a broad range of physiographic and socio-economic conditions. These are made available to provide guidance for policy makers dealing with water and river basin management.

Case studies prepared to date include studies of the Nile River Basin, the Mississippi River Basin, the Rhine River Basin, the Volga River Basin, the Yellow River Basin, and the Haihe and Liaohe River Basins (Abdalla 2008; Julien and Vensel 2005; Spreafico and Lehmann 2009; Golosov and Belyaev 2009; IRTCES 2005; IRTCES 2004). These case studies are available online from the ISI website at: http://www.irtces.org/isi/. The purpose of these case studies is to:

> Increase awareness of erosion and sedimentation issues;

> Increase understanding of erosion, sediment transport and sedimentation processes, and associated sediment problems under different conditions;

> Improve the sustainable management of soil erosion and sediment transport by providing examples of monitoring and data processing techniques, methods for analyzing their environmental, social and economic impacts, and effective management strategies; and

> Ultimately assist in the provision of better advice for policy development and implementation and evaluation of management practices.

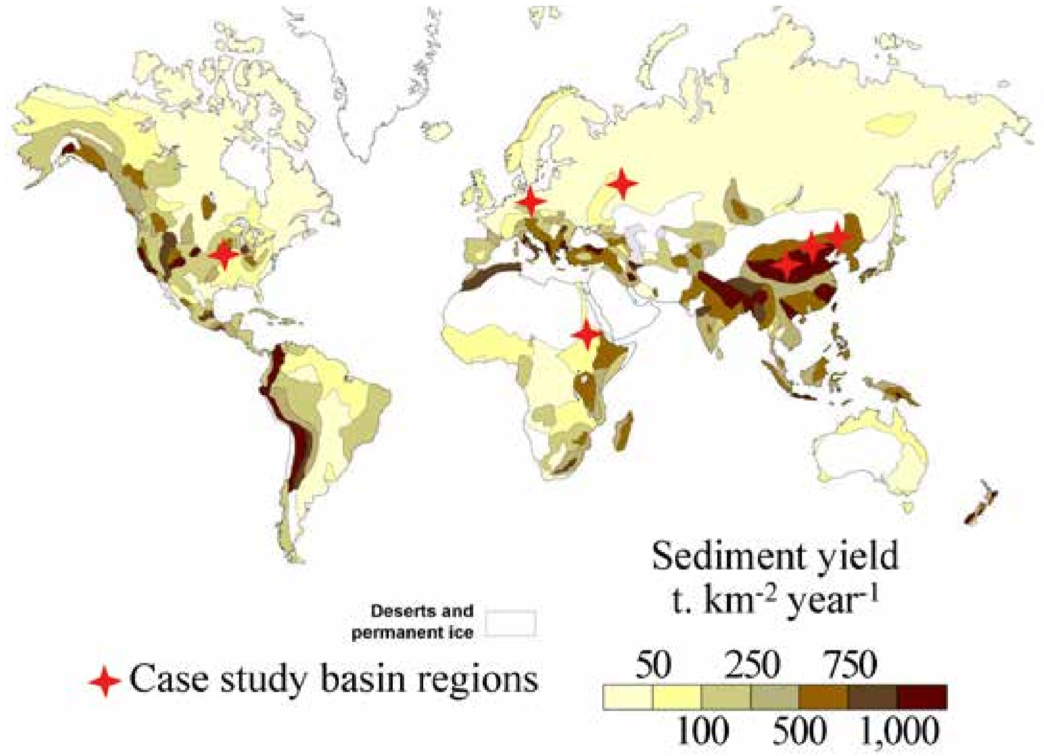
This paper draws on the ISI case studies with the aim of providing an accessible overview of sediment problems and sediment management around the world for water managers and policy makers. Key issues relating to sediment management are explored using examples from several case studies, from which recommendations for developing management strategies have been extracted.

Overview of the ISI case study river basins

Location of the river basins

When undertaking the initial selection of river basin case studies, ISI sought to include a range of basins in different areas of the world that would serve as examples of rivers with both high and low sediment loads, basins with different climatic, physiographic socio-economic conditions, and basins with different sets of sediment problems and therefore requiring different sediment management strategies. The Nile River Basin, the Mississippi River Basin, the Rhine River Basin, the Volga River Basin, the Yellow River Basin, and the Haihe and Liaohe River Basins were chosen in order to provide a representative worldwide perspective on sediment management.

Figure 1. Location of the ISI Case Study river basins. Their location has been superimposed on a generalised map of global sediment yields produced by (Walling and Webb 1983)



Physiographic characteristics of the case study river basins

The most significant physiographic factors include the climate, topography, soil type, and land use of the river basin and its sub-basins. The major components of climate that can affect soil erosion are rainfall and wind. The most marked examples of high erosion rates resulting from climatic conditions are provided by the case study of the Yellow River Basin, where the loess soils are also conducive to high erosion rates. In the Yellow River Basin, 70% of the annual precipitation falls during the period from June through to September, usually in a few large events. For instance, 90% of the annual sediment load recorded at the outlet of the Shejiagou gully in Zizhou County, Shanxi Province, is reported to originate from major storm events occurring during the wet season (IRTCES 2005; Wang et al. 2015).

Within climatically uniform areas with similar soil types, local topography is one of the most important factors responsible for controlling rates of soil erosion. Two main factors associated with topography influencing the rate of soil erosion in a catchment are gradient and slope length. Steep slopes and long slopes commonly experience greater erosion rates because of shallower and more unstable soils and higher flow velocities, and greater runoff volumes and depths, respectively. In both the Yellow River Basin and the Nile River Basin, the areas of each basin that are susceptible to high rates of soil erosion are the areas with steep slopes, reduced vegetative cover and exposed soils, which are also the areas where intense rainfall occurs (IRTCES 2005; Abdalla 2008).

Soil type exerts an important control on the erosion rates and sediment loads of the rivers and their basins discussed in the ISI case study reports. For instance, the highly erodible soils with a high content of loess and sand contribute to large volumes of sediment delivered to the river systems in the Liaohe and Haihe River Basins. The Liaohe and Haihe Rivers are estimated to annually transport approximately 11 million tonnes and 150 million tonnes of sediment, respectively (IRTCES 2004; Liu et al. 2008a).

Land use has a very important impact on erosion and sediment transport by rivers, because it influences the vegetative cover of a catchment. Plants and associated residues protect the soil from the impacts of rainfall, increase infiltration and reduce the volume and velocity of surface runoff. The rates of soil erosion and sediment yield have varied over time in the Volga River Basin, often following changes in land use; greater rates of soil erosion and increased sediment yields were associated with the cultivation of steep hillslopes due to the reduction of arable land during wars or other historical events (Sidorchuk and Golosov 2003).

Socio-economic conditions

The social demands on water management, including water supply, flood control, sediment control, navigation, environmental health and recreational use, are increasing with the growth of human populations around the world. All the ISI case study river basins are among the most heavily populated and economically important areas in their respective countries. The Mississippi River basin has the smallest population among the six basins yet over 30 million people reside in the basin. The Haihe River, Nile River, the Rhine River and the Volga River Basin are regions of great economic significance, with important areas of manufacturing, industry and agriculture. The Rhine River is the most densely navigated shipping route in Europe, connecting a large coastal port, Rotterdam in the Netherlands, with the largest inland port in the world at Duisburg in Germany and the port of Basel in Switzerland. (Spreafico and Lehmann 2009).

Hydraulic works and measures

The construction of hydraulic works such as dams, weirs and levees has played a key role in the development and utilization of water resources, as well as in the protection of the population from the harmful effects of floods and in improving transportation within each of the river basins considered by the ISI case study reports. However, the development of hydraulic works within a river system has the capacity to both affect and be affected by the sediment regime of a river system. The ISI case study reports contain a number of examples of how engineering of the individual river systems has affected sediment transport. Today the Aswan High Dam traps vast quantities of sediment which both reduces the storage capacity of Lake Nasser and results in problems downstream of the dam, including the need for increased fertiliser application to offset the loss of fertile silt formerly deposited by the annual flood, erosion of farmland on the river banks, erosion of the coastline and degradation of the Nile Delta (Abdalla 2008).

In order to provide a generalized comparison of the level of disruption to the natural sediment regimes caused by dams and other hydraulic works in the case study basins, Table 1 includes an estimate of the number of river control structures in each basin and their overall density.

Sediment issues

In many river basins, issues related to sediment are often exacerbated by the influence of reservoirs and hydraulic works. The combination of sediment trapping and flow regulation has dramatic impacts on the ecology, water turbidity, sediment balance, nutrient budgets and morphology of a river basin. Common sediment problems and issues resulting from changes in sediment transport caused by dam construction - as well as from the impacts of excessive sediment loads more generally - are examined in this section. The role of accelerated soil erosion as the main cause of increased sediment inputs to rivers and increased sediment loads is also discussed.

Table 1. Major hydraulic works and reservoirs in the case study basins.

River basin	Large dams/Reservoirs	Small dams	Weirs/ Locks/ Other	Total	Total number of river control structures per km^2
Haihe	25 (Total capacity of 18.1 billion m^3)	1350	–	1375	0.0052
Liaohe	17 (Total capacity of 13.2 billion m^3)	64 medium sized, 607 small sized.	–	688	0.0031
Yellow	22	159 medium sized, 559 small sized.	–	740	0.001
Mississippi	Upper River has 29 locks and dams	–	–	29	0.000009*
Nile	10 (plus two under construction at time of report - 2008)	–	Series of barrages near the delta in Egypt	10	0.000003*
Rhine	10	about 40	about 300	350	0.0018*
Volga	11 (8 large hydropower on Volga, 3 large dams on Kama River)	9 medium-sized, approx 900 small	12 locks	932	0.0007

Note: A 'large dam' is usually defined by ICOLD as one measuring 15 m, or more from foundation to crest, or with reservoir capacity greater than 1.0 million m^3.
* incomplete information in the ISI case study report.- no information is available in the ISI case study report.

Decrease of sediment yield and load after management projects

The sediment regimes of each of the ISI case study river basins have been significantly influenced by urban development, river regulation, and land use practices. These factors have caused changes in soil erosion rates and sediment yields within each of these basins, as well as the sediment loads of the rivers. Table 2 shows that all the river basins have experienced a sharp reduction of both sediment load and yield as well as runoff due primarily to dam construction.

Table 2. Comparison of sediment yields and trends in sediment discharge for the case study basins.

River basin		Mean annual sediment load ($x10^6$/t)	Mean annual specific sediment yield (t/km^2)	Mean annual runoff (volume – km^3)	Mean annual runoff (depth – mm)
Haihe		150	569.5	27	103
Liaohe	Pre Dam	46.4	384	5.8	48
	Post Dam	7.9	65	1.7	14
Yellow	Pre Dam	1243	1653	50	66
	Post Dam	149	198	10	13
Mississippi	Pre Dam	400	134.2	490	158
	Post Dam	145	48.6		
Nile	Pre Dam	120	38.6	80	26
	Post Dam	0.2	0.1	30	10
Rhine		7.3	39.5	74	389
Volga	Pre Dam	26	18.8	254	179
	Post Dam	8	5.8		

* Figures for Nile River sourced from Milliman and Farnsworth (2011); Figures for Mississippi River sourced from Meade and Moody (2010); Figures for Liaohe River (Tieling Station) sourced from Liu *et al.* (2008a); Figures for Yellow River (Lijin Station) sourced from Liu et al. (2013a); Figures for Rhine River sourced from Van Dijk and Kwaad (1998).

The Yellow River Basin has been recognized as having in the past the highest specific sediment yield of all the world's large river basins. Prior to both the construction of reservoirs in the upper and middle reaches of the river and the implementation of extensive soil conservation measures within the Loess Plateau, the mean annual specific sediment yield of the basin was estimated to be as high as 1243 t km^{-2}. The specific sediment yield of some sub-basins within the Loess Plateau exceeded 10,000 t km^{-2} (Liu et al. 2008b).

Measures including the construction of terraces and sediment retaining dams, reforestation and planting of grasses to improve the land cover within the Middle Yellow River Basin since the late 1950s have resulted in the mean annual runoff volume being reduced from 50 km^3 to 10 km^3, and the mean annual sediment load declining from 1243 million tonnes to only 149 million tonnes (Liu et al. 2013a). As a result, the mean annual sediment yield of the basin is currently estimated to be approximately 198 t km^{-2} year^{-1}.

In a similar context, under natural conditions, the Volga River exported large amounts of sediment to the Caspian Sea, with the mean annual load estimated to be approximately 26 million tonnes. At present, however, the trapping of sediment by large reservoirs along the Volga River has resulted in a significant decrease in the suspended sediment load at the mouth of the river to only 8 million tons per year. This has led to wide ranging environmental impacts, particularly in the Volga River delta. The changing sediment load of the Volga River has caused the mean annual specific sediment yield to reduce from 18.8 t km^{-2} to only 5.8 t km^{-2}, the lowest of all of the ISI case study river basins (Golosov and Belyaev 2009; Litvin et al. 2003).

Prior to the construction of the Aswan High Dam in the Nile River Basin, the discharge of the lower Nile River peaked at over 700 million m^3 d^{-1} during the flood season. However, with the construction of the dam, flows were reduced significantly to an average value of around 190 million m^3 d^{-1} distributed almost uniformly through the year. The role of the Aswan High Dam in regulating the flow of the Nile River has resulted in a reduction in the annual runoff volume from 80 km^3 to 30 km^3. By storing and regulating these flows - and also causing the deposition of much of the incoming sediment load - the Aswan High Dam has been responsible for significantly reducing the sediment load that reaches the lower Nile River and the Nile River Delta. Before the construction of the dam, the mean annual sediment load was 120 million tonnes. In recent years, this has been reduced to about 0.2 million tonnes (Milliman and Farnsworth 2011).

Soil erosion and sediment mobilisation

In most of the ISI case study river basins, accelerated soil erosion is a major cause of sediment problems. It results in the loss of valuable top soil, the most productive part of the soil profile for agriculture. The main activities leading to increased soil erosion in the ISI case study river basins include unsustainable agricultural practices and deforestation. Erosion has been further exacerbated by the development of mechanized agriculture which increases soil disturbance and frequently causes soil compaction. Other agricultural practices causing increased soil erosion include farming on steep slopes, the use of pesticides and chemical fertilizers that degrade the soil structure, row cropping, and the use of surface irrigation.

In the Mississippi River Basin, intensive land use - often without proper regard for effective soil conservation measures - was historically responsible for significant increases in the sediment load of the Mississippi and its tributaries. To mitigate the rapidly increasing loss of soil, extensive soil conservation programs were initiated by the United States Government in the 1930s. These included basin-wide efforts to promote contour ploughing, replanting trees and grasses on areas denuded of vegetation, constructing sediment retention dams and stabilizing stream banks (Julien and Vensel 2005; Keown et al. 1986).

Sedimentation in reservoirs and the downstream impacts

Deposition of the incoming sediment reduces the storage capacity of a reservoir over time, and affects the effective management of the structure. In the ISI case study basins, a number of reservoirs suffer from severe sediment problems – in turn posing significant management issues.

While the number of reservoirs within the Nile River Basin is comparatively low, these reservoirs play a significant role in the economic development and water security of the riparian countries within the basin. Severe sediment issues have caused significant problems for a number of the major reservoirs within the basin, such as the Angreb, Khashm El-Girba and Roseires reservoirs. For example, the Khashm El-Girba reservoir in Sudan was constructed in 1964. However, by 1977 the reservoir had lost half of its original capacity due to sedimentation. This loss of capacity caused severe water shortages during periods of drought and a significant reduction in the area of irrigated land (Abdalla 2008).

In the Yellow River Basin, the amount of sediment deposited in reservoirs reached 10.9 billion tonnes by 1989, accounting for 21% of the total storage capacity of all reservoirs on the main stem as well as the tributaries within the basin. For the Sanmenxia Reservoir, problems with severe sediment accumulation became evident immediately after water impounding commenced. The impacts of sedimentation proved so serious that the operating rules for the reservoir had to be drastically changed (Table 3). Prior to the completion of the initial phase of the reconstruction in June 1970, the sediment accumulated in the reservoir totalled 5.3 billion m^3, equivalent to an average annual loss of storage capacity of 0.54 billion m^3 (IRTCES 2005; Wu et al. 2004).

Table 3. Deposition-scouring and sluicing in Sanmenxia Reservoir.

Date	Operation rule	Pool level (m)		Quantity of reservoir sedimentation and erosion (billion m^3)		Sediment inflow and outflow		Bed elevation at Tongguan (m)
		Max	Average	Upstream Tongguan	Downstream Tongguan	Total outflow (billion tonnes)	Total outflow as % of inflow	
1960.09-1962.03	Storing water	332.58	324.02	+0.32	+1.43	0.11	6.8	+4.5
1962.04-1966.06	Before reconstruction	325.9	312.81	+0.36	+1.61	3.39	58.0	+4.4
1966.07-1970.06	Initial reconstruction	320.13	320.13	+1.58	+0.01	7.38	82.5	+5.0
1970.07-1973.10	Further reconstruction	313.31	298.03	+0.38	-0.28	5.93	105	+3.1
1973.11-1978.10	Control operation	317.18	305.60	-0.07	+0.12	6.68	100	+3.1

Notes: '+' represents deposition, and '-' represents scour.

Similarly, the effective operation of the Hongshan Reservoir in the Liaohe River Basin has been drastically impacted by the effects of sedimentation. From 1962 to 1999, the available storage capacity in this reservoir declined by 36.8% due to the significant volumes of sediment deposited in the reservoir. Such problems have also occurred in the Guanting Reservoir in the Haihe River Basin, which was constructed to provide flood protection and water supplies to the cities of Beijing and Tianjin. Due to the large amount of sediment deposited in this reservoir, extensive reconstruction has been required to increase storage capacity (IRTCES 2004).

The downstream impacts associated with the trapping of sediment by reservoirs are quite different from the effects upstream. The problems generally result from a shortage of sediment and the resulting impacts on the equilibrium of the fluvial system and the environment.

A reduced sediment supply can threaten the longer-term stability of river deltas against a background of subsidence and sea level rise (Syvitski et al. 2009). Many other wetland areas are also reliant on a continuous supply of sediment to maintain their ecological functioning and biological diversity. Estuary environments often depend on the deposition of nutrient-rich sediment to support fish breeding. When sediment is trapped in the reservoirs, these ecological assets may be deprived of sediment and nutrients. In some cases, they may eventually cease to function as wetland ecosystems (Julien and Vensel 2005).

On the Mississippi River, the installation of locks and dams in the upper basin reduced the sediment discharge to the lower river and has contributed to the loss of wetlands and estuaries downstream. Dam construction during the 1950s and 1960s on major tributaries such as the Missouri and Arkansas Rivers significantly reduced the suspended sediment load reaching the Mississippi River Delta and the Gulf of Mexico. Estimates of the magnitude of the reduction range from 50% to as much as 70% (Kessel 2003). While wetlands throughout the basin have been affected by this decline in sediment supply, the impact has been especially severe in the marshes and estuaries of the Mississippi Delta.

Another downstream impact associated with reservoir sedimentation involves damage to infrastructure. A reduction in sediment load downstream of dams can encourage accelerated erosion of riverbeds and riverbanks and around structures such as bridge piers. Excessive erosion can undermine and cause damage to these structures. In the Rhine River Basin, investigations of the bed load sediment budget of the Alpine region have shown that river training and bed load excavation have significantly changed the sediment budget and morphology of the river. Increased erosion has also been observed downstream of reservoirs, endangering the stability of bridges and water diversion structures. In the Rhine basin in Switzerland a large number of alpine reservoirs has been built in the past. They serve mainly for energy production but can also be used for flood reduction. Together with the regulated and non-regulated natural lakes they also act as potential sediment retention basins. In the 1950s through to the 1970s, a series of hydroelectric power plants were constructed on the Rhine River on the borders between Switzerland and Germany as well as between Germany and France. The trapping of sediment by these reservoirs led to severe sediment deficit problems downstream and associated impacts on infrastructure in the river channel (Spreafico and Lehmann 2009; Kondolf 1997).

Management strategies

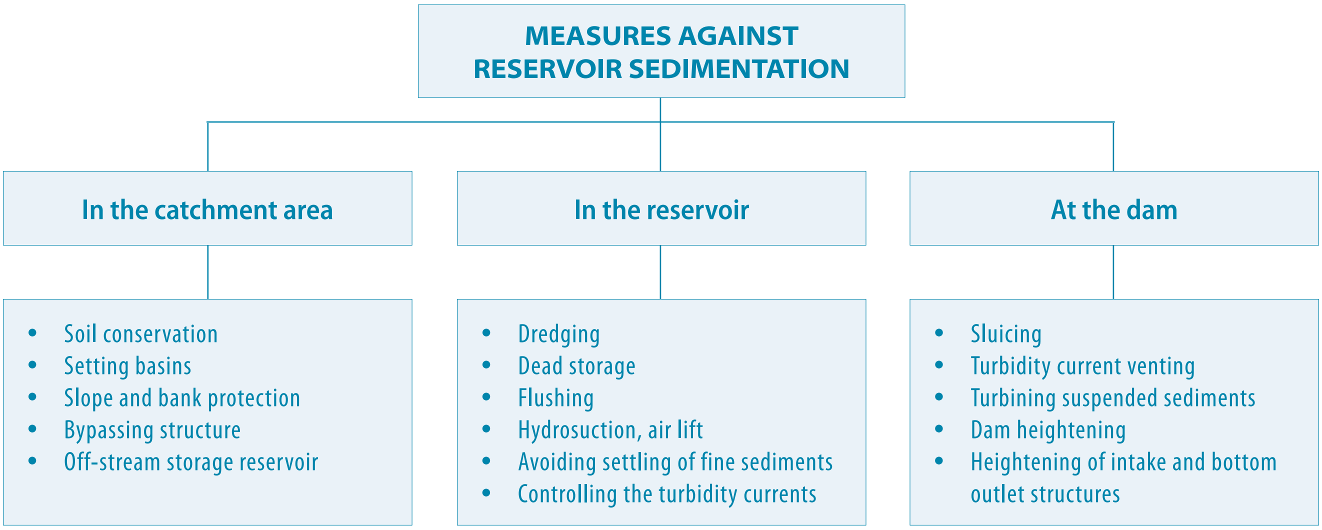
Over the years, many studies have been carried out and many management options have been proposed for dealing with sediment problems.

Technical strategies

Reservoir sedimentation management

It has been estimated that on a global scale, reservoirs intercept up to 25% of the sediment that would otherwise flow to the ocean. Approximately 1% of global reservoir water storage capacity is lost every year through the deposition of sediment. The life of a reservoir is usually limited by sediment accumulation. For existing structures, sustainable sediment management should seek to balance sediment inflow and outflow within the impounded reach, while maximizing long-term benefits. Figure 2 illustrates the different levels at which management efforts can be targeted to reduce sediment retention by reservoirs either by using broad scale land management strategies upstream, or targeting options for managing sediment within the reservoir itself.

Figure 2. Measures for countering reservoir sedimentation (Spreafico and Lehmann 2009).

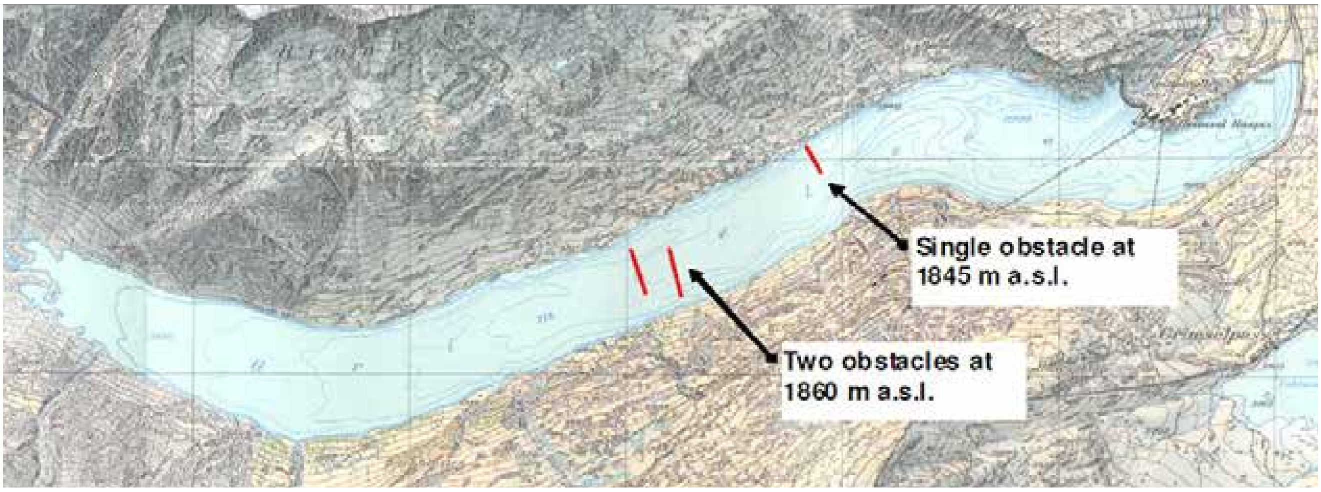


Sediment flushing is a technique whereby sediment previously accumulated and deposited in a reservoir is hydraulically eroded and removed by accelerated flows created when the bottom outlets of a reservoir are opened. In order to address the issue of sedimentation at the Xiaolangdi Reservoir on the Lower Yellow River, two sediment flushing trials were conducted in July 2002 and September 2003. As a result of these two trials, it was reported that 66.4 million tonnes and 120.7 million tonnes of sediment, respectively, were flushed downstream to the sea, considerably reducing the amount of sediment accumulation in the Xiaolangdi Reservoir as well as in the Lower Yellow River channel (Wang et al. 2015). After the trials, 13 further sediment flushing operations were organized, flushing a total of 752 million tonnes of sediment to the sea by 2015 and decreasing the average elevation in the Lower Yellow River channel by 2.03 m.

An alternative to flushing or routing of sediment through a reservoir involves removing sediment by underwater dredging or dry excavation of the deposited material. While this technique can prove successful in some areas, it is generally associated with very high operating costs. In some areas, such as the Roseires Reservoir in the Nile River Basin, dredging is necessary as flushing and sluicing are insufficient to control sedimentation. In addition to the dredging of the reservoir itself, the impounded reach of the river may also require dredging due to the continued accumulation of sediment in the channel, as in both the Yellow River and the Mississippi River Basins. If the sediment is contaminated, its disposal can give rise to further problems.

Another technique for managing the sedimentation of reservoirs is to adopt methods that prevent or reduce the settling and deposition of fine sediments. Such methods include exploiting and controlling turbidity currents. The ISI case study from the Rhine River Basin provides an example from Lake Grimsel in Switzerland, where the construction of submerged obstacles has been used to reduce the deposition of sediment in the reservoir by obstructing the movement of turbidity currents. Results from a high flood event that occurred in October 2000 revealed that turbidity currents develop and propagate in the deepest area of the lake, close to the intake and bottom outlet structures of the reservoir. In such instances, deposits as much as 10 cm thick can be produced by a single event. To prevent sediment deposition, submerged dams that block the flow and deflect a major part of the turbidity current away from the dam wall were constructed (Figure 3). This led to larger amounts of sediment being deposited upstream of the obstacles, and away from the dam wall and intake and outlet structures of the reservoir. It is estimated that the retention of sediment behind these obstacles should continue for at least 20 to 50 years, and provide a valuable contribution to the control of reservoir sedimentation (De Cesare et al. 2008).

Figure 3. The location of the obstacles constructed in Lake Grimsel (based on De Cesare et al. 2008).



Land management and soil conservation techniques

The management of soil erosion has a long history and many different soil conservation techniques have been employed over time. Both engineering or 'hard' solutions involving the construction of terraces, check dams and settling basins, as well as 'soft' measures including forest planting, increasing vegetation cover and improving land management practices (e.g., no-till or low-till agriculture) have proved effective in reducing both soil loss and downstream delivery of sediment.

Applying engineering solutions to manage sediment in a catchment can be very effective. In the Yellow River Basin, extensive engineering measures have been implemented, particularly in the Loess Plateau, to control soil erosion and to reduce the sediment loads of the rivers. One of the most widely applied approaches has been the construction of terraces for agriculture. Constructing terraces enables the slope of the land to be modified, intercepting runoff and reducing soil loss. This also helps to improve soil fertility and increase the productivity of the agricultural areas established on these terraces. In the Loess Plateau, over 20% of all agricultural land is now located on such terraces, equivalent to an area of 380,000 ha. These terraces have been shown to be a highly efficient engineering measure with which to reduce soil loss and improve agricultural viability. Another technique widely used in the Yellow River Basin is the construction of structures to trap sediment within pond and dam systems located in gullies. These structures are known as 'check' or 'warping' dams. Check dams have three functions, namely, 1) stabilizing gullies by preventing gully expansion by retrogressive erosion, bank collapse and scouring, 2) reduction of muddy flood peaks by detaining sediment and 3) trapping sediment to create new agricultural land. After 50 years of management, there are now more than 110,000 check dams constructed in the gullies of the Yellow River Basin, and more than 300,000 ha of new agricultural land have been created (IRTCES 2005; Wang et al. 2015).

Bed load management

In order to maintain the continuity of bed load transport along a river, where it has been interrupted by engineering works, active management strategies such as bed load relocation and artificial bed load supply often need to be implemented. Where the natural transport of bed load has been interrupted, scouring of the river channel can occur. In order to counteract the effects of scouring, artificial supply of bed load material is often adopted as a management strategy. Control of scouring of river channels in the Rhine River Basin has necessitated the artificial addition of bed load material at key locations in Germany. It has been estimated that approximately 260,000 tonnes of sediment are transported annually by barges and dumped into selected reaches of the Rhine River to compensate for the deficit of bed load material (Dröge 1992).

Legal, administrative and organizational strategies

As the pressures on our water resources increase as a result of human impacts and climate change, the need for effective legal, administrative and organizational structures for the management of sediment in river basins is becoming increasingly important. The ISI case study reports present examples of river basins at different levels of development, facing a range of both similar and unique management issues. The legal, administrative and organizational structures adopted by the countries responsible for managing the resources of these basins have a significant influence on their effective management.

In many developing countries, water scarcity disproportionately impacts women more than men (WWAP, 2012). In the Nile River basin sediment problems can impact on domestic water supply. Legal and institutional frameworks should therefore also integrate considerations of gender equality to address the unique needs and challenges regarding access to water by women and girls and to avoid inadvertently exacerbating these negative impacts. Gender has a large role to play in water resource management, and - as such - this issue should be mainstreamed into frameworks for water governance.

Where river basins extend beyond national boundaries, the need for management structures becomes even more pressing, to ensure that the river system is managed cooperatively at basin scale. International organizations such as the International Commission for the Protection of the Rhine and the Central Commission for the Navigation of the Nile seek to promote cooperative management of river systems (Huisman et al. 2000). In the Nile River Basin, the Nile Basin Initiative is a partnership between riparian countries established to encourage the development of the resources of the Nile River in a cooperative manner across political borders. Such organizations and initiatives have helped the riparian countries to build a shared vision and to focus on key actions to improve management of basin water resources.

Conclusion

Water resources are currently under increasing stress in many regions of the world. However, issues concerning sediment management and control often receive less attention in water management policies and programmes. This paper has sought to provide an overview of sediment issues and management strategies by synthesizing the information provided by ISI case studies from the Nile River Basin, the Mississippi River Basin, the Rhine River Basin, the Volga River Basin, the Yellow River Basin, and the Haihe and Liaohe River Basins.

Many rivers around the world are experiencing problems such as declining sediment loads mainly due to the construction of dams and other control structures, accelerated soil erosion and sediment mobilization, and sediment trapping in reservoirs causing reduced storage capacity and further downstream impacts. However, it is encouraging to see that authorities at different levels are now implementing technical strategies for reservoir sedimentation management, soil erosion control and land management and bed load management as well as legal, administrative and organizational strategies to support such initiatives.

The case studies referred to in this paper represent a useful contribution towards the global sharing of knowledge and experience essential for developing a set of best practices in sediment control and management. The hope is that these case studies will encourage further information exchange and sharing of data, and promote international dialogue on sediment control and management issues.

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References

Abdalla A.A. 2008. *Sediment in the Nile River System* [online]. UNESCO-ISI report. Available from http://www.irtces.org/isi/.

De Cesare, G., et al. 2008. *Reservoir Sedimentation. Overview on the problematic of sedimentation and sediment management in Alpine reservoirs*, Rapport No 2. Lausanne.

Dröge, B. 1992. Change of river morphology by controlled erosion and deposition. In *Proc. 5th International Symposium on River Sedimentation, Karlsruhe*: 85-94.

Golosov, V. and Belyaev, V. 2009. *The Volga River Basin Report* [online]. UNESCO-ISI report. Available from http://www.irtces.org/isi/.

Huisman, P., et al. 2000. Transboundary cooperation in shared river basins: experiences from the Rhine, Meuse and North Sea. *Water Policy* 2: 83-97

IRTCES. 2004. *Sediment Issues of the Haihe and Liaohe Rivers in China* [online]. UNESCO-ISI report. Available from http://www.irtces.org/isi/busy-case.asp/.

IRTCES. 2005. *Case Study on the Yellow River* [online]. UNESCO-ISI report. Available from http://www.irtces.org/isi/.

Julien, P.Y. & Vensel, C.W. 2005. *Review of Sedimentation Issues on the Mississippi River* [online]. UNESCO-ISI report. Available from http://www.irtces.org/isi/.

Keown, M.P., et al. 1986. Historic trends in the sediment flow regime in the Mississippi River. *Water Resources Research* 22(11): 1555-1564

Kesel, R.H. 2003. Human modifications to the sediment regime of the Lower Mississippi River flood plain. *Geomorphology* 56: 325-344

Kondolf, G.M. 1997. Hungry water: Effects of dams and gravel mining on river channels . *Environmental Management* 21(4): 533-551.

Liu, C., et al. 2008a. Sediment load reduction in Chinese rivers. *International Journal of Sediment Research* 23: 110-210

Liu, C., et al. 2008b. Changes in Runoff and Sediment Yield along the Yellow River during the Period from 1950 to 2006, *Journal of Environmental Informatics* 12(2): 129-139

Liu, C., et al. 2013a. Changes in runoff and sediment load from major Chinese rivers to the Pacific Ocean over the period 1955-2010. *International Journal of Sediment Research* 28 (4): 486–495

Liu, C., et al. 2013b. Total sediment flux entering the sea from major Chinese rivers and rough estimation for global land-ocean sediment flux. In *Advances in River Sediment Research,* ed. by Fukuoka, S. et al. Florida USA: CRC Press: 201-202.

Litvin, L.F., et al. 2003. Erosion and sedimentation on the Russian Plain, part 1: contemporary processes. *Hydrological Processes* 17: 3335-3346

Meade, R.H. and Moody, J.A. 2010. Causes for the decline of suspended-sediment discharge in the Mississippi River system, 1940-2007. *Hydrological Processes* 24: 3549

Milliman, J.D. and Farnsworth, K.L. 2011. *River discharge to the Coastal Ocean*. Cambridge University Press 2012

Sidorchuk, A.Yu., and Golosov, V.N. 2003, The history of erosion and sedimentation on the russian plain during the period of intensive agriculture. *Hydrological Processes* 17: 3347-3358.

Spreafico, M. & Lehmann, C. 2009. *Erosion, transport and deposition of sediment- case study Rhine*. UNESCO-ISI report, http://www.irtces.org/isi/

Syvitski.J.P.M., et al. 2009. Sinking deltas due to human activities. *Nature Geoscience 2*: 681-686.

Van Dijk, P & Kwaad, F. 1998. Modelling suspended sediment supply to the River Rhine drainage network; a methodological study. In *Modelling Soil Erosion, Sediment Transport and Closely Related Hydrological Processes*. IAHS Publ. no. 249, 1998. IAHS Press, Wallingford, UK.

Walling, D.E., Webb, B.W. 1983. *Patterns of sediment yield*. In: Gregory, K.J. (Ed.) Background to Palaeohydrology. Wiley, Chichester, pp. 69-100.

Walling, D.E. and Fang, D. 2003. Recent trends in the suspended sediment loads of the world's rivers. *Global and Planetary Change* 39: 111– 126.

Wang, Z.Y., et al. 2015. *River Dynamics and Integrated River Management*. Tsinghua University Press, Beijing and Springer-Verlag Berlin Heidelberg.

Wu, B.S., et al. 2004. Yellow River Basin management and current issues. *Journal of Geographical Sciences* 14: 29-37.