# Changes in Sediment Transport of the Yellow River in the Loess Plateau

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## 1. Introduction

Sediment erosion is a pressing problem throughout the world as it leads to loss of resources such as agricultural land. Soil erosion most commonly occurs as a result of the forces exerted by wind and water. Human induced landscape change can expedite soil erosion due to removal of vegetation, urbanization and rangeland grazing (to name a few). Sediment erosion can lead to increased sediment input to nearby rivers which can alter river channel morphology through increased sediment deposition. Sediment transport in rivers is also important on a global scale as sediments carry organic carbon from the land to oceans via river channels (Ludwig et al., 1996).

River sediment levels depend largely on the surrounding landscape. Areas where the soil is being impacted directly through activities such as cultivation and urbanization will generally contribute large amounts of sediment to a nearby channel. As seen over the last century, high river sedimentation can lead to issues with drinking water quality and engineering structures such as reservoirs. In order to manage the landscape effectively, soil conservationists in the United States developed a universal soil loss equation during the 1950's (Wischmeier, 1976). The soil loss of an area is calculated as follows,

$$A = RKLSCP \tag{1}$$

where A is the computed soil loss per unit area in tons per acre, R is the rainfall factor, as it defines the erosive force of a specific rainfall, K is the soil erodability factor, L is the slope length factor, S is the slope gradient factor, C is the cropping management factor as it defines the rate of soil loss from a field with specific cropping practice and P is the erosion control factor as it defines whether any erosion management factors have been implemented The universal soil loss equation has since been modified a number of times and still acts as a powerful tool to calculate soil movement across a landscape.

Alternative techniques that are applied in the study of sediment transport are the interpretation of rainfall data and watershed area to calculate runoff depth and the use of river discharge data along with sediment level measurement to calculate river sediment yield. Annual runoff is given by the following equation,

$$Runoff\ \ Depth = \frac{Q(365)(24)(3600)}{A(1000)} \tag{2}$$

where A is the drainage area in kilometres squared and Q is river discharge in cubic metres. River sediment yield is given by the following equation,

$$\frac{\textit{suspended sediment flux}}{\textit{drainage area}} \tag{3}$$

The Yellow River in China has long been known for its sediment problems. During the past 50 years, industrial development (hydropower) and urbanization in China have led to drastic changes in topography. Decreases in vegetation cover have led to increased soil erosion through wind and runoff processes. Vast amounts of research have examined the sediment levels of the Yellow River. The purpose of the chapter is to review characteristics of the Loess Plateau region of the Yellow River watershed, examine how sediment transport has changed over the past 50 years and assess whether sediment conservation initiatives have been successful. The chapter is outlined as follows: (a) an introduction to the Yellow River watershed and Loess Plateau, (b) review government policy that has been developed in order to manage soil erosion of the region, (c) an in depth look at research surrounding sedimentation in the Yellow River's Middle Reach, and (d) success in sediment management of the Loess Plateau.

## 2. The Yellow River watershed

The Yellow River, the second largest river in China, and 6th longest in the world is an area of historical significance as it was once the most prosperous region in China. The area is both a place of prosperity and tragedy as over the centuries flooding has caused devastation in the area. The Yellow River headwaters are located in the Bayan Har Mountain region of western China. The river flows east, crossing 9 provinces, and empties into the Bohai Sea. Since the Yellow River watershed is so large, approximately 742,440 square kilometres in area and a channel length of 5464 kilometres, the basin is typically divided into 3 geographic areas: the Upper, Middle and Lower reaches (Figure 1). The Upper Reach originates in China's Qinghai province and travels approximately 3,500 kilometres before the channel turns south in Inner Mongolia. The Upper Reach constitutes just over 50 percent of the total basin area and varies in topography from mountain regions to swamps to grasslands. Much of the Upper Reach channel morphology is dominated by deep canyons and steep channel gradients which make the area suitable for hydro electric power stations

The Middle Reach of the Yellow River begins in Inner Mongolia and stretches approximately 1,200 kilometres to the Province of Henan. The Middle Reach acts as a natural border for the provinces of Shaanxi and Shanxi. The Middle Reach cuts through the Loess Plateau, an area dominated by highly erosive loess sediments. The Loess Plateau covers an area of approximately 640,000 square kilometres. The Yellow River's name refers to the often yellowish color the water has from the high levels of loess. Loess is windblown sediment that contains various levels of sand, silt and clay. Loess grains can be angular in shape which often leads to the formation of loess ridges and banks which dominate the Middle Reach. The Loess Plateau is the main source of sediment for the Yellow River. Due to the large amount of sediment transported from the Loess Plateau into the Yellow River, the Yellow River is considered to be one of the most sediment laden rivers in the world.

The Lower Reach is approximately 790 kilometres long and flow northeast across the North China Plain and into the Bonai Sea. The Lower Reach has little elevation change, the channel widens considerably and river flows are calm and slow. The Lower Reach is an area of sediment deposition as a result of the sediment loading that takes place in the Loess Plateau region. Sediment deposition in the Lower Reach has caused the river level to rise several metres above the surrounding land elevation. As reported by the Chinese Association of Hydraulic Engineering, during the past 50 years the river bed in the Yellow River Lower Reaches has been raised from 1.9 metres to 3 metres. Dike construction in the Lower Reach is important for flood prevention and allows for human settlement. Dike construction, while it helps to prevent flooding it does not eliminate the risk. Historical records indicate that in 1,500 of the past 2,540 years dike breaches have occurred (Shi & Ye, 1997). Dike failure has caused property devastation and loss of human life.

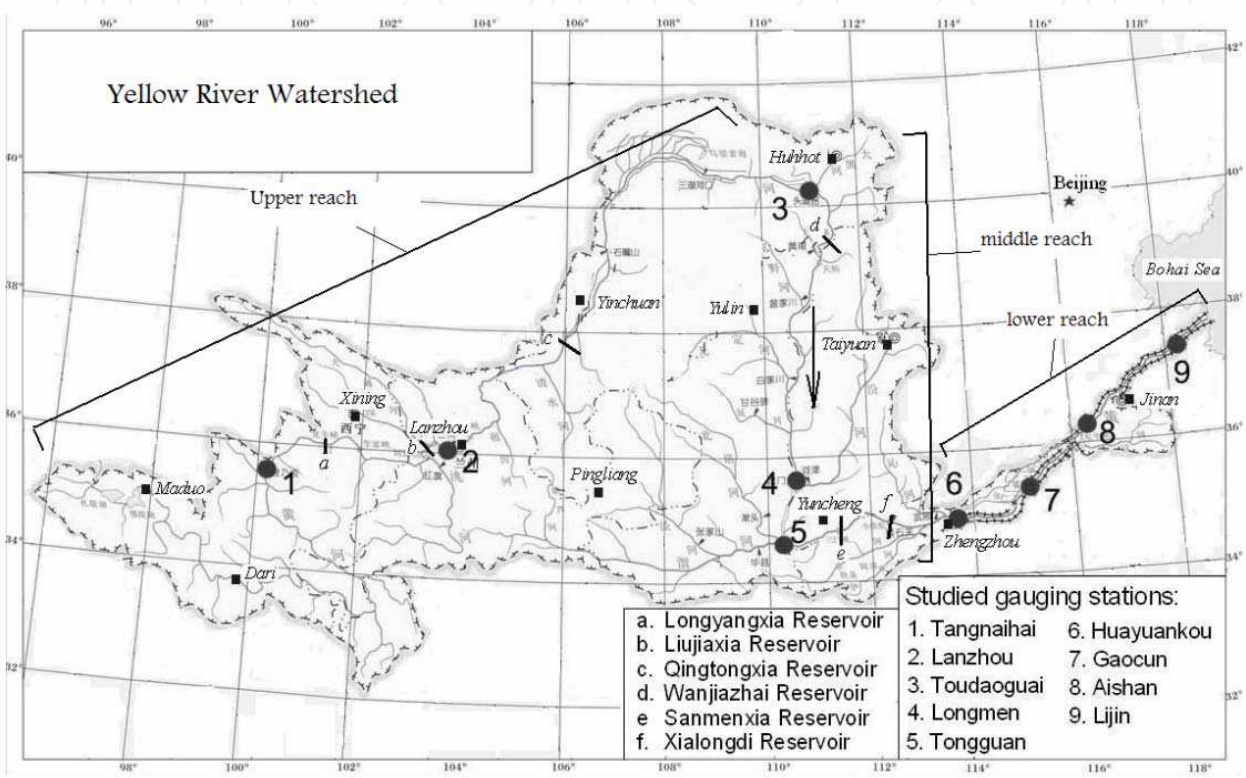


Fig. 1. Yellow River watershed (modified from Lui et al., 2008).

Prior to 1960, no hydropower development existed on the Yellow River. During the 1960's and 1970's, the Yellow River watershed experienced economic prosperity which led to the construction of hydropower stations. As reported by Xu (2003), the Yellow River watershed currently has over 3,300 reservoirs and 17,000 hydraulic structures for water pumping and transferring. There are 9 major hydroelectric stations on the main stem of the Yellow River. The hydropower stations serve not only to provide electricity but are also designed to reduce sedimentation, provide flood control and provide irrigation water supply. Following the extensive hydro development on the Yellow River, soil conservation programs have grown from 8,000 square kilometres in the 1950's to 171,300 square kilometres in the 1990's (Gu, 1994, 2002).

### 2.1 The Loess Plateau

The Loess Plateau covers an area of approximately 640,000 square kilometres, similar to the size of France (Figure 2). It spans the Middle Reach of the Yellow River and is the world's largest deposit of loess. Historically, the Loess Plateau was highly fertile area which contributed to the establishment of ancient Chinese civilizations originating in the region. Due to the angular characteristics of loess sediments, inhabitants of the region were able to construct dwellings in the form of caves. The Loess soil is rich in organic content and ranges from 100 to 300 metres in depth (Cai, 2001). The north and east regions of the Loess Plateau are home to mixed deciduous forests. In the eastern province of Shanxi is the Li Shan Nature Reserve. This nature reserve covers an area of approximately 250 square kilometres, supports a temperate forest and is home to rare species of salamander, deer and pheasant. High sediment levels in the Yellow River are a direct result of erosion from the Loess Plateau. The Loess Plateau is thought to have one of the highest erosion rates in the world (Fu et al., 2000). The annual soil loss from the Loess Plateau is estimated to range from 200 to 30,000 tonnes/square kilometres (Liu, 1985; Zhu et al., 2004). The Yellow River transports approximately 30 times the sediment of the Nile and 98 times the sediment of the

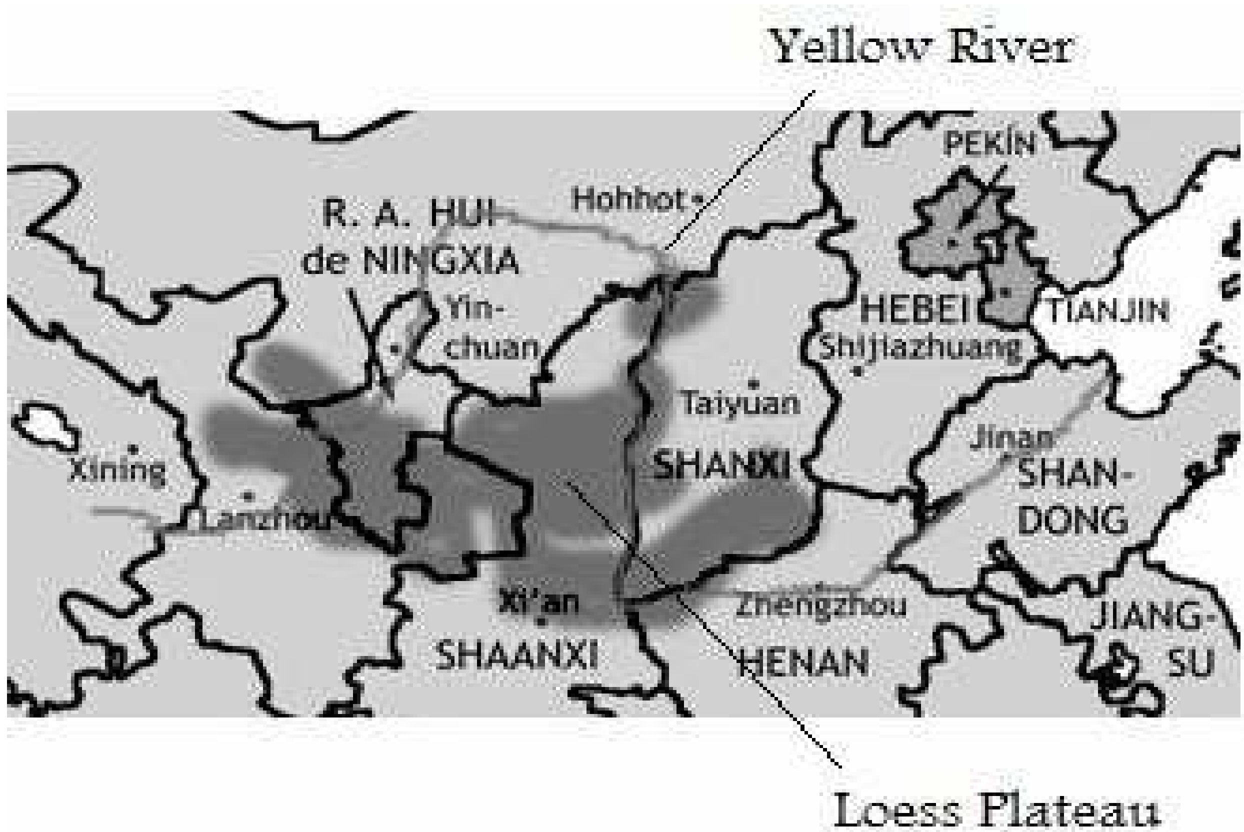


Fig. 2. China's Loess Plateau as indicated by dark grey shaded area.

Mississippi River (Kleine, 1997). The fine sand and silt particles that comprise loess are highly susceptible to wind and water erosion. Loess soils can be eroded at a faster rate than any other soil type (Pye, 1987). Human activity and expansion of farmland have removed a lot of the areas forests and led to increased soil erosion. As China's population grows, the government is planning to intensify agricultural production of the Loess Plateau region.

### 2.2 Loess Plateau Watershed Rehabilitation Project

In 1994, in response to growing concern over desertification of the plateau, the Loess Plateau Watershed Rehabilitation Project was launched and co-ordinated by the Chinese

Fig. 3. Loess Plateau and the Yellow River.

Government and World Bank. The goal of the project was to increase agricultural productivity and income of the area while also decreasing the sediment transport to the Yellow River. After a three year planning phase the following policy guidelines were introduced:

1. Tree cutting banned-people in China were not allowed to undertake indiscriminate tree cutting.
2. Tree planting banned on steep slopes-historical planting of crops on hillsides and gullies was no longer permitted.
3. Land Tenure guidelines-specific rules were set out for farmers designating their rights and responsibilities for each developed terrace and field.
4. Banning of free range grazing-sheep and goats were no longer allowed to wander freely and graze, but rather had to be contained in pens or fenced areas.

In addition to policy implementation, a number of engineering structures were created in order to reduce sedimentation. The most important engineering component was the development of terraces on the loess slopes. This was achieved mainly by bulldozers, where terraces were developed so farmers could plant crops in level fields that would retain a greater amount of water and be less subject to erosion. A second key engineering component of the project was the creation of sediment dams. Three types of sediment dams, key dams, warping dams and check dams were all designed to either intercept sediment or to decrease water flow there by reducing the erosive channel characteristics.

Outcomes of the project according to the World Bank (World Bank, 2003) are as follows:

a. approximately 1 million farmers have benefited from increased agricultural sustainability. Average agricultural income has increased by up to 4 times.

b. grain output from the region has increased 1.5 times and annual fruit output has increased four fold.
c. annual sediment transport to the Yellow River has decreased by approximately 57 million tonnes.

Overall, the Loess Plateau watershed rehabilitation project was the largest of its kind to date. Both the Chinese government and World Bank rated the project as successful as all project targets were met.

## 3. Sediment transport and the Loess Plateau

There are a number of tributaries in the Middle Reach of the Yellow River all with varying topography and drainage areas. When examining sediment transport in any river, it is important to consider not only the river main stem but also the tributaries in order to specify sediment source locations. The following sections identify research done by the authors and others which examine main stem gauging stations, tributaries and reservoirs in the Loess Plateau. Variations in sediment transport under winter ice conditions are also examined.

### 3.1 General trends in sediment transport, Yellow River's Middle Reach, Loess Plateau

This section looks at general sediment characteristics of the middle reach (Figure 4) and how it compares to the Upper and Lower reaches; this section is based largely upon Liu et al. (2008). There are two gauging stations on the Yellow River's Middle Reach. The most upstream station is the Longmen station, and downstream is the Tongguan gauging station (Figure 4). Both gauging stations in the Middle Reach revealed decreasing sediment yields over the past 50 years (Liu et al., 2008). Long term and short term runoff depths are Lower in the Middle Reach in comparison to the Upper Reach. The long term average runoff depths as reported by Liu et al. (2008) have decreased by approximately 40 percent during the past ten years (Table 1). Similarly, annual sediment yield in the Middle Reach has also decreased between 50 to 60 percent in the last ten years (Table 1).

| Station | Drainage area ($km^2$) | Data period | Annual runoff depth Q (mm) | | Annual sediment yield S ($t/km^2$) | |
|---|---|---|---|---|---|---|
| | | | LTA Q | RA $Q_{10}$ | LTA S | RA $S_{10}$ |
| Longmen | 497,552 | 1950-2005 | 53.68 | 32.47 | 1543.65 | 612.48 |
| Tongguan | 682,141 | 1952-2005 | 51.29 | 29.79 | 1631.39 | 766.13 |

Table 1. Long term average (LTA) and recent 10 year average (RA10) runoff depths and annual sediment yield for the middle reach of the Yellow River, as reported by Liu et al., (2008).

Even though the sediment yield is decreasing, the sediment yield in the Middle Reach during the past 10 years is still 4 to 7 times the Upper Reach and 2 to 3 times the Lower Reach (Liu et al., 2008). The Middle Reach, while it accounts for only 15 percent of the drainage area, approximately 90 percent of the sediment comes from this region (Liu et al., 2008). The influence of the Loess landscape definitely has a direct impact on sediment levels in the middle reach. Poor grazing and cultivation practices in the Loess Plateau can lead to soil disturbance. The majority of the precipitation for the region falls between the months of June to September (Cai, 2001); during such time disturbed soils can be transported to the river channel by overland flow. The decrease in sediment yield experienced in the past 10 years may be due to the implementation of terraces and sediment dams throughout the region as part of the Loess Plateau watershed rehabilitation project.

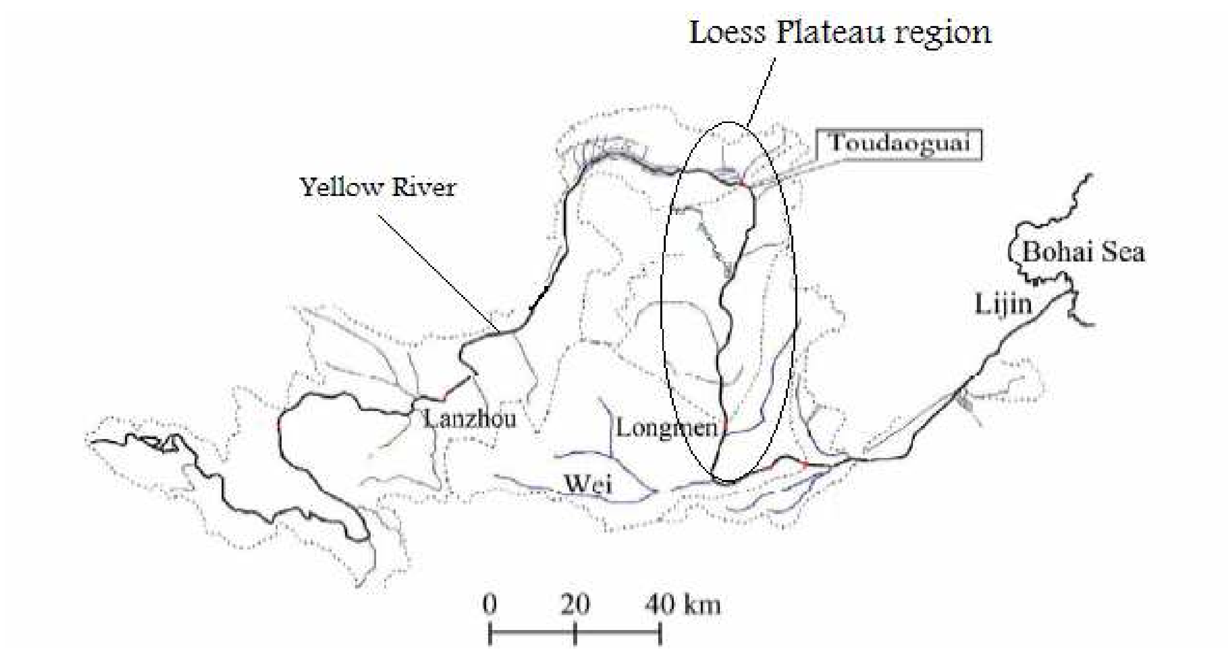


Fig. 4. Loess Plateau region along the middle reach of the Yellow River (modified from Sui et al., 2008).

### 3.2 Sediment transport in the Huangfuchuan watershed along the Loess Plateau

The Huangfuchuan watershed, which is located in the centre of the middle reach in the Inner Mongolia region of China, is an important contributor of sediment to the Yellow River's main stem (Figure 5). The following examination of sediment contributions from the Huangfuchuan watershed is based upon Sui et al. (2008).

The Huangfuchuan watershed covers an area of 3199 square kilometres. The main stem is 137 kilometres long, and the average channel slope is 2.7 percent. The watershed landscape consists of many hills and gullies with the majority of the soil type being loess. The thickness of the loess layers ranges from 20 to 80 centimetres. Three gauging stations are used to examine sediment transport in the Huangfuchuan watershed: (1) the Huangfuchuan station, located approximately 14 kilometres upstream from the Huangfuchuan's confluence with the Yellow River, (2) the Toudaoguai gauging station, located on the Yellow River mainstream, 178 kilometres upstream of the Huangfuchuan River and (3) the Fugu gauging station, located on the Yellow River main stem, approximately 38 kilometres downstream of the Huangfuchuan/Yellow River confluence. The location of the Toudaoguai and Fugu stations provides an excellent opportunity to quantify the sediment contributions of the Huangfuchuan watershed.

The downstream Fugu gauging station, sediment levels are much higher than at the upstream Toudaoguai gauging station (Table 1). It is thought that the Huangfuchuan River watershed contributes sediment to the Yellow River main stem and accounts for the higher sediment concentration downstream. Also, in contradiction to what is expected, the downstream Fugu station has a lower long term annual discharge in comparison to the upstream Toudaoguai station (Table 1). This may be a result of the high amount of water withdrawals from the Yellow River for agricultural, domestic and industrial use.

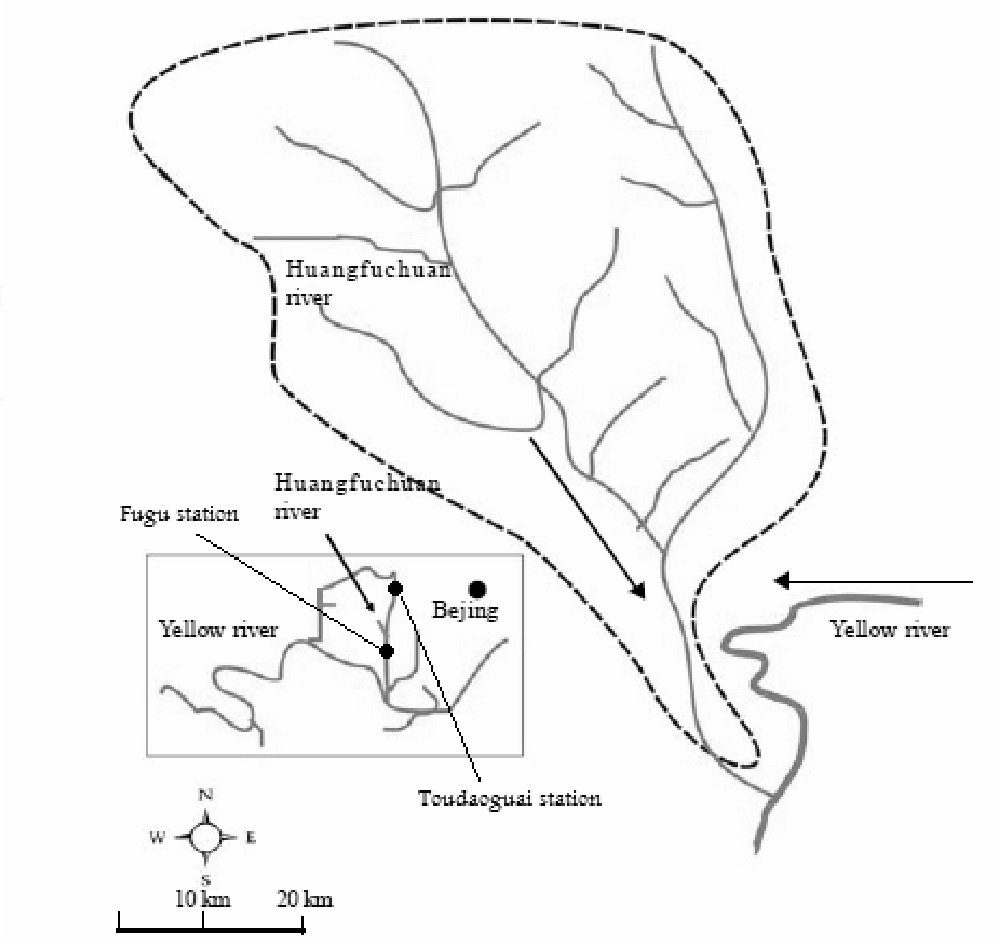


Fig. 5. Huangfuchuan watershed, located in the middle reach of the Yellow River (modified from Sui et al., 2008).

| Long term annual discharge ($m^3/s$) | | | Long term annual sediment concentration ($kg/m^3$) | | |
|---|---|---|---|---|---|
| Huangfuchuan | Toudaoguai | Fugu | Huangfuchuan | Toudaoguai | Fugu |
| 5.23 | 802.47 | 789.18 | 29.47 | 2.98 | 5.24 |

Table 2. Long term annual discharge and sediment concentrations, calculated from Sui et al (2008).

Average monthly precipitation depth was calculated by using data from the Hequ, Yulin and Dongsheng climate stations. As shown in Figure 7, over the last 50 years all three gauging stations exhibit a downwards trend in precipitation. Approximately 80 percent of the total precipitation falls during the months of June to September. Little precipitation falls in this region between the months of November and May. During this time, the soil moisture content is low and it is though that the loess sediment is eroded through wind processes. During the rainy months, June through August, moisture seeps into the soil and less surface runoff occurs.

The runoff depths at the Toudaoguai (upstream) and Fugu (downstream) gauging stations is similar; however the sediment concentration is much higher at the downstream station. This is mainly due to sediment inputs from the Huangfuchuan sub-watershed, located between the upstream and downstream gauging stations. The sediment transport is higher at the Huangfuchuan gauging station in comparison to the Toudaoguai and Fugu gauging stations. Approximately 80 percent of the precipitation and runoff in the Huangfuchuan sub-watershed occurs during the months from June to September; the largest sediment grain size also occurs in the summer when the kinetic energy is highest.

Typically, sediment concentration in rivers increases with discharge due to the increased kinetic energy of the water (Yang et al., 2005). Interestingly, the above relationship between discharge and sediment transport is not consistent in the Huangfuchuan River during the summer months. As shown in Figure 6, the highest monthly average sediment concentration occurring in July is 130 kilograms per cubic metres, while the average monthly July discharge is 16 cubic metres per second. It is thought that the desynchronization of sediment concentration and discharge is related to the antecedent soil moisture of the area. Specifically, little rain falls during the spring months and it is thought that erosion of loess soils in the Huangfuchuan watershed occur through wind transport. By the time summer rain falls in the watershed, the precipitation is absorbed by the loess rather than contributing to surface runoff.

Overall, it appears that the Huangfuchuan watershed is an important contributor of sediment to the Yellow River. Over the past 50 years, runoff and sediment transport from the Huangfuchuan watershed have been decreasing. Climate stations in the area indicate that the average annual precipitation depth has also been decreasing; this may account for the decrease in annual runoff. However, the region has also been subject to various soil conservation initiatives in order to manage erosion. This may also be a contributing factor in the decrease of sediment transport from the Huangfuchuan watershed.

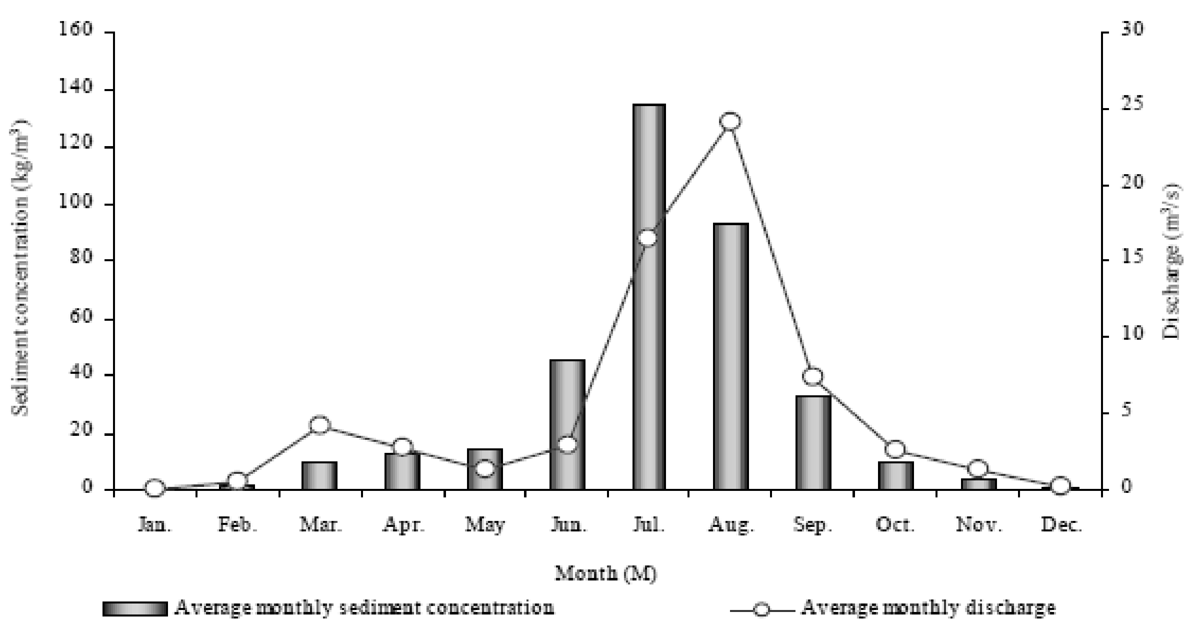


Fig. 6. Sediment concentration and discharge for the Huangfuchuan River station, 1954-1989 (from Sui et al., 2008).

### 3.3 Sediment transport in the Kuye River watershed, Loess Plateau

Similar to the Huangfuchuan watershed, the Kuye River watershed is important tributary located in the Yellow River's Middle Reach. The following examination of sediment transport in the Kuye watershed is based upon Sui et al (2009). The Kuye River watershed is

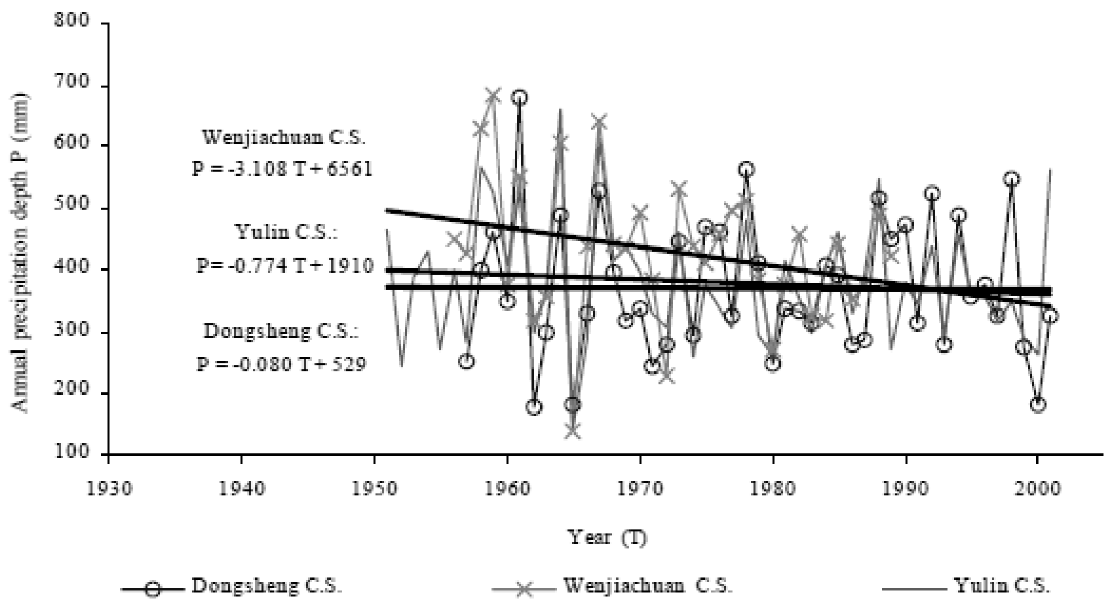


Fig. 7. Annual change in precipitation depth of 3 climate stations around the Huangfuchuan watershed (from Sui et al., 2008).

located downstream of the Huangfuchuan watershed as shown in Figure 8. The Kuye main channel length is approximately 242 kilometres in length and the watershed covers an area of 8,706 square kilometres. The Kuye watershed topography consists of hills, gullies and exposed bedrock; vegetation exists in only 6 percent of the entire watershed.

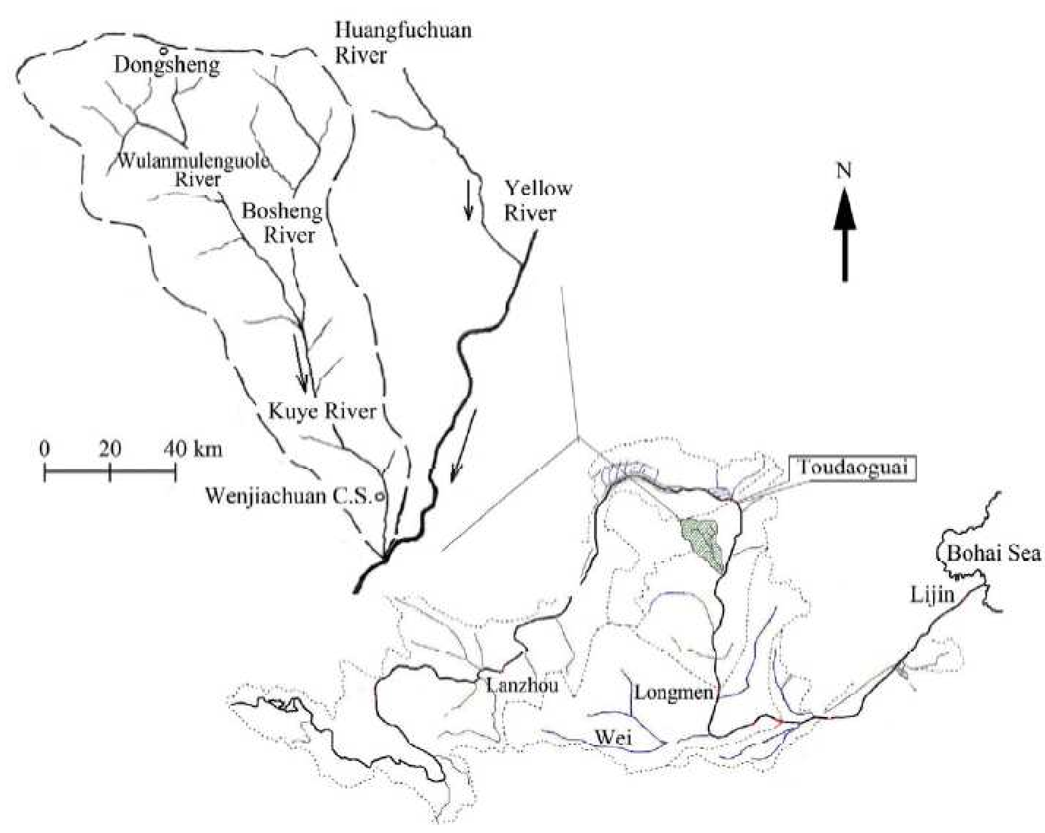


Fig. 8. Kuye River watershed (from Sui et al., 2009).

The loess ranges in depth from 20 to 80 metres. In comparison to the Huangfuchuan watershed, the Kuye watershed is almost twice the size, has little vegetation and the loess layer is much deeper. There is one gauging station on the Kuye River located approximately 7 kilometres upstream of the confluence with the Yellow River's Main Stem. Two gauging stations on the Yellow River Main Stem were also examined in order to study the sediment contributions of the Kuye watershed. The Toudaoguai gauging station is located approximately 302 kilometres upstream of the Kuye/Yellow River confluence (Figure 8). The Longmen gauging station is located 431 kilometres downstream of the Kuye/Yellow River confluence (Figure 8). At all gauging stations, annual discharge and sediment concentration were examined for the period from 1955 to 2006. Precipitation records from the Dongsheng and Wenjiachuan climate stations (Figure 8) were also used in order to calculate runoff depth.

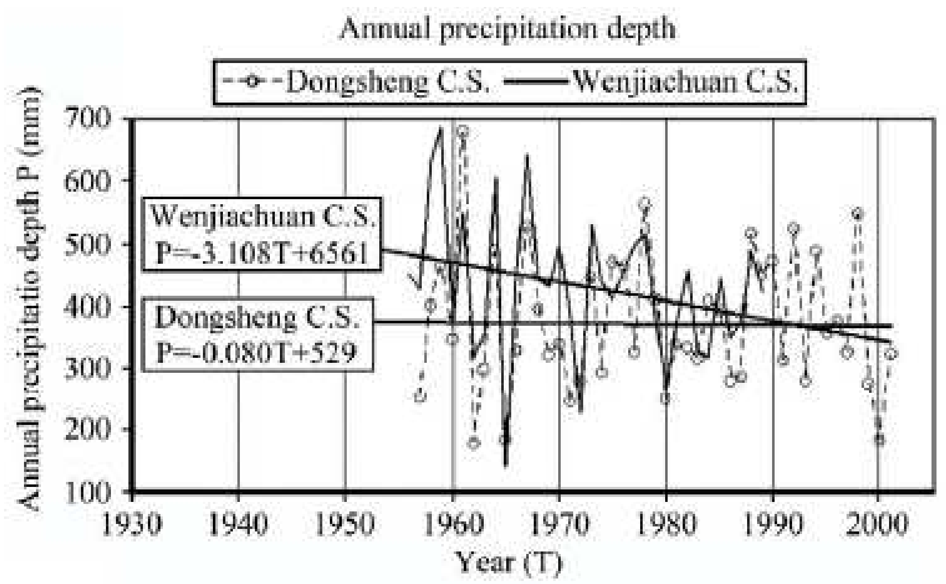


Fig. 9. Precipitation depth at the Wenjiachuan and Dongshen climate stations in the Kuye watershed (from Sui et al. 2009).

The majority of the precipitation in the Kuye watershed falls during the months of June through September. Over the past 50 years the annual precipitation in the Kuye watershed has been decreasing; the Dongsheng station has a slight downward trend (Figure 9). The highest precipitation months are generally July and August, which corresponds to the months with the highest discharge (Figure 10 & 11). Interestingly, similar to the Huangfuchuan watershed, the highest sediment concentration does not occur during the month of highest discharge (Figure 11). In the Kuye watershed the highest average annual sediment concentration of 125 kilogram per cubic metre, occurs in July; the average discharge in July is 43 cubic metres per second. The month of August has the highest average annual discharge, 66 cubic metres per second; however the sediment concentration is 90 kilograms per cubic metre. In the Kuye watershed, this desychronization of sediment and discharge measurements is thought to be related to the intermittent tributaries present throughout the watershed. It is thought that during times of low precipitation the intermittent tributary streams in the Kuye watershed do not have connectivity. The spring season is generally quite windy and high amounts of loess are transported into the tributary reaches; then during months of high precipitation (July and August, Figure 10), tributary channels form connectivity. The month of July is typically dominated by flash flood events where large amounts of stored sediment can be transported from the tributaries to the Kuye main stem and eventually the Yellow River. Even though precipitation and discharge are high in August, it is thought that the majority of the stored tributary sediments are transported during July flash flood events.

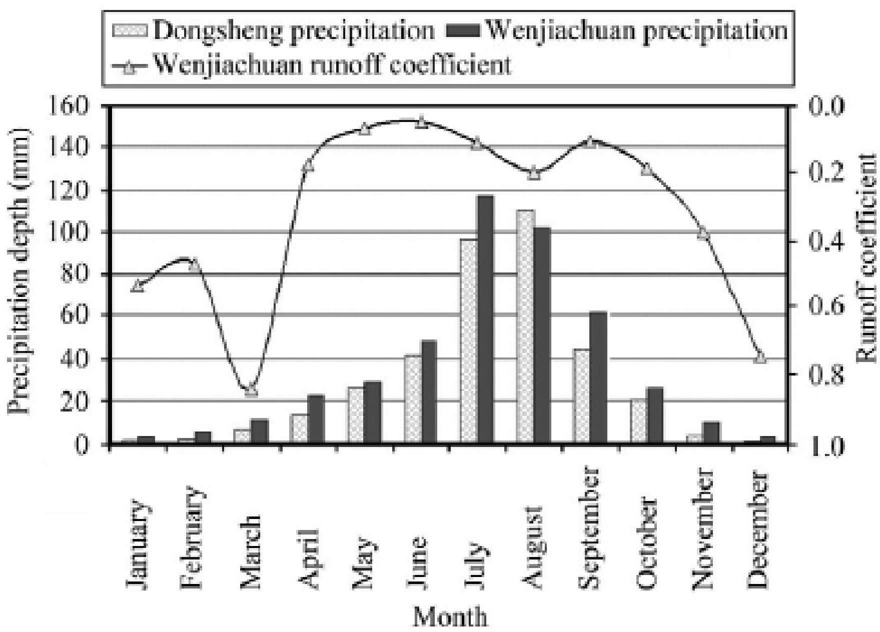


Fig. 10. Average annual precipitation depth and runoff coefficient for the Dongsheng and Wenjiachuan climate stations (from Sui et al. 2009).

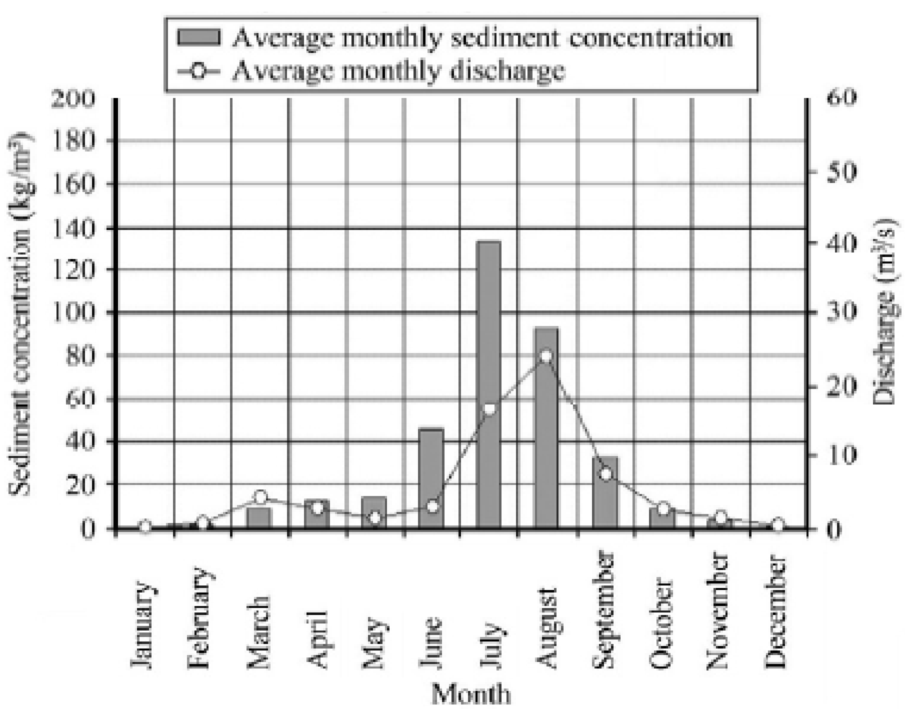


Fig. 11. Sediment concentration and discharge in the Wenjiachuan watershed from 1955 to 2006 (from Sui et al. 2009).

### 3.4 Sediment transport characteristics of a reservoir in the Middle Reach

In general when examining sediment transport and deposition within a reservoir, it is understood that finer, lighter particles will remain in suspension longest and be transported the farthest distance. When a reservoir is located within a river reach, the channel velocity decreases substantially in the transition zone from the channel to the reservoir. This decrease in channel velocity is due to the widening of the river channel into a reservoir. Conversely, larger, heavier particles will be deposited sooner, in the upper reach of the reservoir. Over time, constant sediment deposition will reduce the storage capacity of the reservoir and may eventually fill the area. Sediment removal practices must be undertaken in order to adequately manage a reservoir. Reservoir flushing and sediment dredging are common ways to mitigate sediment deposition.

Typically there are 3 main areas of deposition within a reservoir, backwater deposits, bottom deposits and delta deposits (Figure 12). The backwater region of a reservoir is the region that forms the transition zone between the river channel and the reservoir. Backwater deposits are usually coarse grained sediments. The delta deposition region occurs within the reservoir basin, immediately after the backwater zone. Sediment in the delta region is usually a mix of course and fine grained particles. Sediment deposition in the delta region can occur both across and into the reservoir. Lastly, the bottom deposition zone in a reservoir occurs at the bottom of the deepest part of the reservoir. The sediment located in the bottom deposition zone is fine grained, consisting of silts and clays (Batuca and Jordaan, 2000).

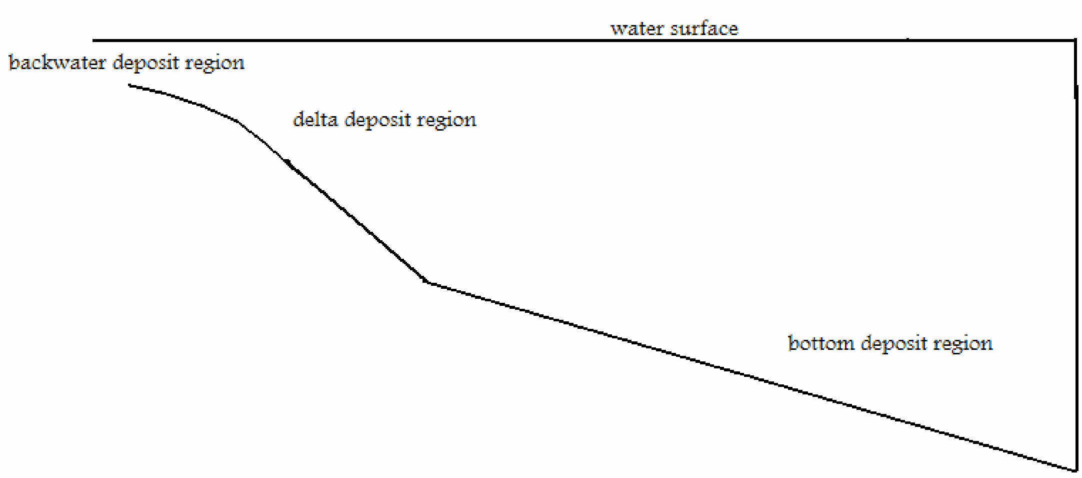


Fig. 12. Typical deposition regions within a reservoir.

Over the past 50 years, a number of hydropower stations have been developed in the main reach of the Yellow River watershed. One of the reservoirs present on the Yellow River main stem is the Tianqiao Reservoir, located just upstream of the Fugu gauging station in the Loess Plateau (Figure 13). The Tianqiao hydropower station was the first power station ever built on the Yellow River and has been in successful operation for more than 30 years. The Tianqiao reservoir consists of two reaches, an upper and lower that form a total reach length of 21 kilometres. The lower reach is 300 metres wide and 12.5 kilometres in length; the upper reach is 600 metres wide and 8.5 kilometres in length.

The water level in the Tianqiao reservoir varies depending on the hydropower operations. Sediment deposition in the Tianqiao backwater region retreats and advances depending on operational water levels. As previously discussed, the upstream Huangfuchuan sub-watershed of the Yellow River is a major source area of loess sediment. Shoals and sandbars development is common in the backwater region of the Tianqiao Reservoir and is likely due to the influx of sediment from the Huangfuchuan watershed (Sui et al., 2005). The relationship between sediment deposition in the Tianqiao Reservoir and the sediment source area upstream is evident when examining historical flash flood events. During 1982 the Huangfuchuan watershed experienced flash flooding during the end of July as indicated by the reported gauging station data (Table 3). Sediment deposition in the Tianqiao reservoir was also high during 1982 (Figure 14). Sediments are primarily deposited in the backwater region of the reservoir as the relatively low flow velocity is unable to transport all the incoming sediment. Over the season, as the backwater region experiences more sediment deposition, the water level of the area rises, which in turn would increase the kinetic flow energy. During the fall and winter seasons, when sediment supply to the reservoir is low, the high flow energy is then able to transport sediments (scouring) from the backwater region into the reservoir (Sui, et al., 2005).

| Date | Discharge ($m^3/s$) | Sediment concentration ($kg/m^3$) |
|---|---|---|
| 29 July 1982 | 1,100 | 1,250 |
| 30 July 1982 | 2,580 | 1,190 |

Table 3. Measured discharge and sediment concentration in the Huangfuchuan watershed, 1982 (as reported by Sui et al. 2005).

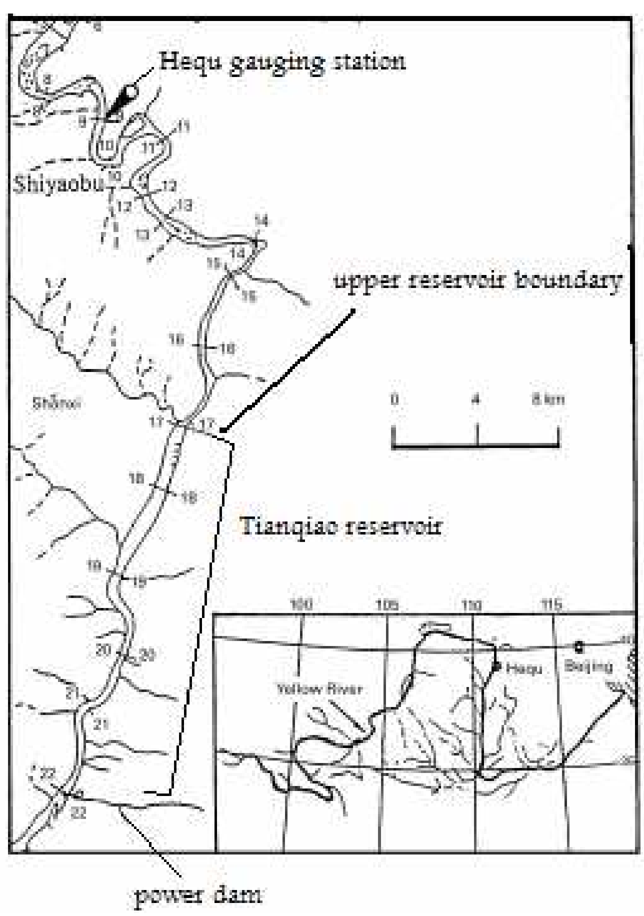


Fig. 13. Tianqiao hydropower station and reservoir along the Yellow River.

Generally, during the summer season when precipitation is high and flooding occurs, the Tianqiao reservoir is in deposition mode. For the remainder of the year, the reservoir is in a scouring mode. Over time the majority of the sediment, approximately 85 percent, becomes deposited in the lower reservoir reach (Sui et al., 2005). Understanding the dynamic relationship between climate, sediment transport and sediment deposition is important in reservoir management. Knowledge of sediment influx is key in development of sediment removal programs, budget allocation and hydropower management.

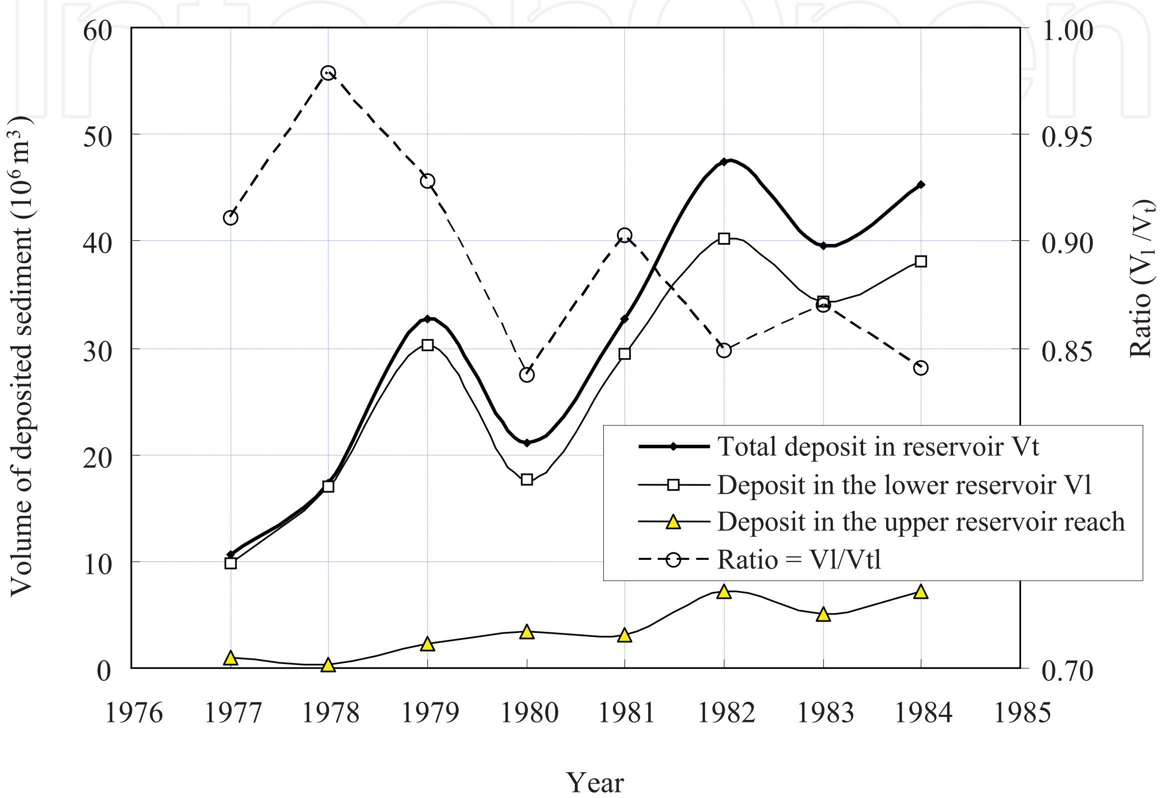


Fig. 14. Volume of sediment deposited in the upper and lower reaches of the Tianqiao Reservoir (from Sui et al., 2005).

### 3.4 Sediment transport characteristics during winter ice cover

While sediment transport in the Loess plateau under open channel flow has been discussed, sediment transport during winter conditions must also be addressed in order to gain a full understanding of the seasonal fluctuations in sediment. Ice cover and jams are frequent along the Yellow River's Middle Reach during the winter season. At the beginning of the Middle Reach is a channel area often referred to as the Hequ Reach; the Hequ reach spans from the Longkou Gorge to the Tianqiao Power Dam as shown in Figure 15. The Hequ reach is approximately 70 kilometres in length with a broad and shallow morphology. Upstream of the Longkou Gorge area, the Yellow River channel is a long, open reach of water; in this area a large amount of frazil ice forms during the winter. The frazil ice is transported downstream, and numerous ice jam events occur in the Hequ Reach. The following is a brief description of the relationship between frazil ice and sediment entrapment as examined in the Hequ Reach of the Yellow River.

In general for open channel flow the sediment concentration of a river depends on the current velocity and the characteristics of the river bed material. The higher the river discharge, the higher the sediment concentration. This relationship becomes much more complicated with the introduction of ice cover and frazil ice. During ice cover, sediment is transported not only through the water but also through attachment to river ice (frazil ice) (Sui et al., 2000). During frazil ice formation, supercooled water is transported throughout the water column promoting ice nucleation. During this process, ice crystals can become attached to pebbles or other sediments on the river bed. In areas of the Hequ Reach in the Loess Plateau, pebbles ranging in size from 0.2 top 0.5 kilograms have been observed in frazil jams (Sui et al., 2000). The upper layer of frazil ice generally has a higher sediment concentration than the lower frazil layers. The highest sediment concentration recorded was 25 kilograms per cubic metres of ice; this is much larger than the highest sediment in water concentration during a jam (7 kilograms per cubic metre) (Sui et al., 2000). During periods of ice jam formation or ice jam breakup, sediment concentrations were found to be higher than during times of stable jamming.

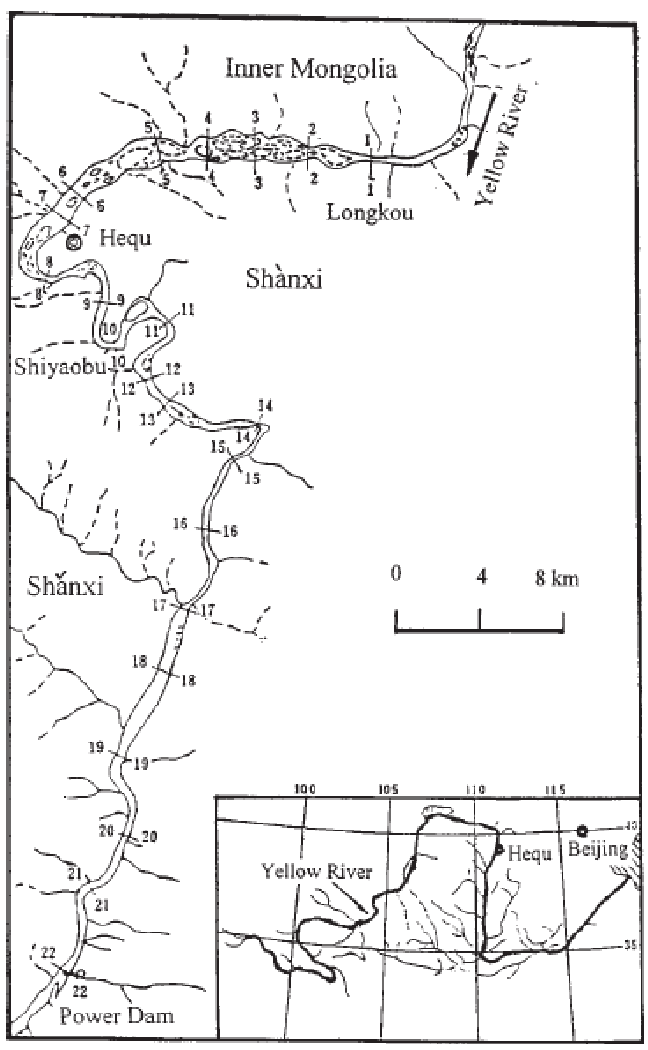


Fig. 15. The Hequ reach along the Loess Plateau region of the Yellow River.

While it has been discussed that the majority of the sediment transport in the Loess Plateau occurs during the summer season, the sediment transport during winter is unique. If ice jamming and frazil ice formation prevail, sediments of large size can be transported down the river reach.

## 4. Success of soil conservation initiatives in the Loess Plateau

In general over the past 50 years, while accounting for human water use and impact, runoff in all reaches of the Yellow River watershed has decreased over the past 50 years (Fu et al., 2004). Changes to land use, global warming, ground water exploitation and human activities (among others) were reported as factors influencing the basin runoff (Fu, et al., 2004). Specific to the Loess Plateau, soil conservation initiatives appear to have had a great impact on the sediment transport to the Yellow River. Large areas of once bare land have been planted with trees and grass and cattle grazing has been forbidden. By the year 2000, the seven provinces that intersect with the Loess Plateau had improved a total of 177,000 square kilometres of eroded land (CERN, 2001). Reclamation to grazing areas appears to have made the largest impact on sediment transport in the Loess Plateau. Local farmers have found drylot feeding more profitable and local vegetation is now protected (CERN, 2001). The implementation of sediment dams also appears to have altered the amount of soil erosion. Sediment dams constructed vary from 2 to 5 metres in height and work to effectively trap eroded topsoil. One a substantial area of topsoil is formed behind the dam, the area can be used as high-yield agriculture plots. The largest reduction in sediment transport can be seen in the Kuye watershed. The long term average sediment transport modulus for the Wenjiachuan gauging station is 10,591 tonnes per square kilometre per year. During the last ten years this values has significantly decreased to 2,805 tonnes per square kilometre per year (Sui et al., 2009)

## 5. Summary and conclusion

This chapter discussed sediment transport within the Loess Plateau region of the Yellow River. The erosion of loess sediments has long been a problem for people residing in the region. Soil erosion has been responsible for loss of agricultural land and significantly altered the lives of many communities residing in the Loess Plateau. There are a number of tributaries in the loess plateau region that contribute significant amount of sediment to the Yellow River's Middle Reach. The Huangfuchuan and Kuye watersheds were shown as sediment source areas with a large amount of sediment transport occurring during the summer flood months. Sediment transport from these watersheds also has large implications for the management of the Tianqiao reservoir. During the 1990's the Government of China implemented a number of soil conservation initiatives as part of the Loess Plateau watershed rehabilitation project. Terraces were constructed throughout the loess plateau, grazing was prohibited and sediment dams were constructed. Sediment concentration in both the main stem of the Middle Reach and in both the Huangfuchuan and Kuye rivers has decreased during the last 10 years. Overall the decrease in sediment levels in the Middle Reach are attributed to implementation of soil conservation initiatives.

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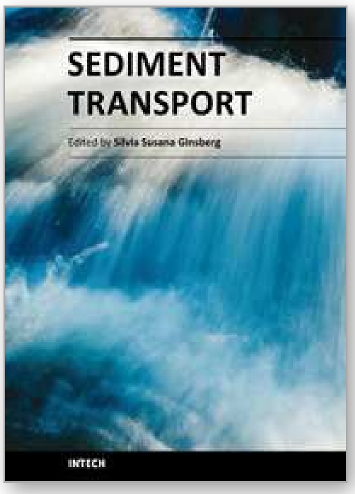


**Sediment Transport**

Edited by Dr. Silvia Susana Ginsberg

ISBN 978-953-307-189-3
Hard cover, 334 pages
**Publisher** InTech
**Published online** 26, April, 2011
**Published in print edition** April, 2011

Sediment transport is a book that covers a wide variety of subject matters. It combines the personal and professional experience of the authors on solid particles transport and related problems, whose expertise is focused in aqueous systems and in laboratory flumes. This includes a series of chapters on hydrodynamics and their relationship with sediment transport and morphological development. The different contributions deal with issues such as the sediment transport modeling; sediment dynamics in stream confluence or river diversion, in meandering channels, at interconnected tidal channels system; changes in sediment transport under fine materials, cohesive materials and ice cover; environmental remediation of contaminated fine sediments. This is an invaluable interdisciplinary textbook and an important contribution to the sediment transport field. I strongly recommend this textbook to those in charge of conducting research on engineering issues or wishing to deal with equally important scientific problems.