Review article: Silt and the future development of China’s Yellow River

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Silt loading is a critical problem in the use of the Yellow River for irrigation, domestic, and industrial water supplies. Nearly all of the silt comes in runoff from the immense and highly erodible Loess Plateau. Salinity has a secondary but widespread effect on irrigation development and groundwater quality. Engineering structures and expanded irrigation have reduced the silt load in the lower reach of the river by half over the last 50 years. Still, the level of the river bed continues to rise higher above the surrounding North China Plain. Millions of rural and urban lives are threatened by the possibility that an embankment will break and unleash a horrendous flood, as had happened numerous times prior to 1949. Earthquakes could cause similar catastrophes. Increased populations in cities, expansion of irrigated land, and rapid industrialization have brought about locally severe water shortages. This, in turn, has led to surface and groundwater pollution by salt and heavy metals, lowering of groundwater levels, land subsidence, and salt water intrusion from the Bo Sea. Interbasin water transfers from the Yangtze River in the south to relieve water shortages in the north have been proposed for decades but remain controversial. The high cost of dams, canals, tunnels, pumping, and water control systems needed for the transfer has been a major objection. Other factors have been the adverse environmental impact in both the Yellow and Yangtze river watersheds of transfers and, importantly, the questionable need of the transfers if water conservation practices were used widely and effectively.

KEY WORDS: China, Yellow River, silt, land degradation, floods

The Yellow River (Huanghe) is China’s second largest river, after the Changjiang (Yangtze River). It has long been known as ‘China’s sorrow’ for the lives that have been lost and the damage done by its frequent and violent floods. The river provides irrigation, domestic and industrial water for about 90 million people living within its watershed and for millions more in the North China Plain. Originating in the Qinghai-Xizang (Tibetan) Plateau, the river flows eastwards through central China on its way to the Bohai (Bo Sea) on China’s east coast (Figure 1). In its middle section, it passes through the immense Loess Plateau and picks up a heavy silt load from this erosion-prone plateau. That silt load makes the Yellow River rank first in the world in its average annual silt concentration (Mosely, 1985).

Canal irrigation in China is believed to date from some time before the third century BC, when water was diverted from streams in the vicinity of Xian (Bray, 1984). The first canal having a well-documented history was the Zhengguo, which was constructed in 246 BC (Bray, 1984; Greer, 1979; Will, 1998). It took water from a tributary of the Yellow River in the south to relieve water shortages in the north have been proposed for decades but remain controversial. The high cost of dams, canals, tunnels, pumping, and water control systems needed for the transfer has been a major objection. Other factors have been the adverse environmental impact in both the Yellow and Yangtze river watersheds of transfers and, importantly, the questionable need of the transfers if water conservation practices were used widely and effectively.

KEY WORDS: China, Yellow River, silt, land degradation, floods
on the Loess Plateau remains today the principal impediment to the use of Yellow River water for irrigation, as well as for industrial and domestic purposes.

Silt in the Yellow River is the major problem for irrigated agriculture but soil salinity has become a close second in the upper and lower reaches of the river. It is not the small amount of salt in the river that causes the problem (Ningxia Water Conservancy Department, 1996); rather, it is the combination of over-irrigation and inadequate soil drainage that causes soils to become saline and unproductive (Mei, 1994).

Silt and salt have long been known as the twin plagues of irrigated agriculture. Jacobsen and Adams (1958) described the disastrous effect silt and salt had in ancient irrigated Mesopotamia (Iraq). Their study detailed development and abandonment of canal irrigation east of Baghdad over a 6000-year period. One period of abandonment lasted 1000 years, until the fourth century BC. In the middle of the thirteenth century AD, a near-final end to irrigation came when the Mongol armies of Hulagu Khan ravaged the region. Jacobsen and Adams (1958) contend that siltation of major canals and salinity were the real causes of the cessation of irrigation; Hulagu Khan merely supplied the finishing touches to an irrigation-based society already weakened by silt and salt. Seven hundred years later, Iraq continues to suffer from the salt accumulation that devastated agricultural productivity (Dougramjej and Clor, 1977).

In the four major ancient irrigation societies (Mesopotamia, Yellow River, Nile Valley and Indus Basin), salinity has been a nagging problem since irrigation began (Ghassemi et al., 1995). Canal irrigation ultimately failed in Iraq but the situation was different in the other regions. In the latter valleys, flood-recession irrigation was practiced successfully for millennia. Flood water was collected in basins constructed for that purpose. Silt in the water enriched the soils while the percolating water washed out whatever salts had accumulated in the fields during the previous year (Postel, 1999). Flood-recession agriculture along the Nile in Egypt had been successful for at least 5000 years before 1970. Flood water is still important for agriculture in the lower part of the Indus Valley in Pakistan, but nowadays there is no significant flood-recession irrigation on the Yellow River.
Reliance on flood water diminished in the twentieth century when it became possible to build large water-storage dams to store flood water. In Pakistan, the Tarbela Dam (built in 1976) on the main stem of the Indus performs that function. The controlling Nile dam in Egypt is the Aswan High Dam near the border with Sudan (Abu-Zeid, 1983) which was completed in 1970. Lake Nasser, the reservoir behind the High Dam, can store about two years of the average flow of the Nile. Designers of the High Dam calculated that sediment would reduce the lake’s storage capacity by about 20 per cent in 500 years. Owing to the low relief in Iraq, there are no major storage dams on its section of the Tigris and Euphrates rivers. Large storage dams on those rivers are being built in Turkey as part of the South-eastern Anatolia Project (American Embassy, 1998; Government of Turkey, Ministry of Foreign Affairs, 2000).

Two high dams, Sanmenxia and Qingtongxia, were the first on the Yellow River. They were completed in the 1970s. In this paper, we review the silt and salt problems on the Yellow River, discuss the environmental threats to future development in the Yellow River watershed and the North China Plain, describe proposed south–north water transfers and assess the dangers to human livelihoods.

The Yellow River Basin
The Yellow River watershed (Figure 2) covers about 753 000 square kilometres, practically all of it lying in the upper and middle section of the river (Matsuda and Kubota, 1995; Wei and Zhao, 1983). For administrative purposes, the Yellow River Conservancy Commission in the Water Conservancy Ministry of the central government divides the river into upper, middle and lower reaches. The upper reach, from the river’s source west of Ngoring Lake in Qinghai Province to the gauging station at Hekouzhen in Inner Mongolia drops 3800 metres in elevation. The middle reach, from Hekouzhen to the gauging station at Huayuankou in Henan Province, changes elevation from 1000 to 100 metres above sea level. From Huayuankou to Bohai lies the lower reach which is over 700 kilometres long. Here the bed of the river sits above the surrounding plain, as a result of silt deposition in the river channel, and floods threaten both the lives and livelihoods of people dwelling on the floodplain.

On its journey to the sea, the Yellow River passes through several different geographic regions. From the mountains and broad valleys of the Qinghai Basin, the river becomes entrenched in a series of deep gorges until it comes to the Qingtongxia Dam in Ningxia. Fourteen dams are planned for the gorges above Qingtongxia. Several are already in operation, producing hydro-electric power. Only the Qingtongxia Dam has the dual purpose of generating power and storing and delivering irrigation water. One of the future dams above Qingtongxia, the Daliushu, will also be a multi-purpose dam but its main function will be to allow expansion of the irrigated land and better regulation of flow in the lower reach (Yellow River Conservancy Commission, 1990).
After the river leaves the gorge at Qingtongxia, it flows through the gently-rolling, arid Ordos Plateau, providing water for several large irrigation projects in Ningxia and Inner Mongolia. The combination of hydro-electric power availability, water from the Yellow River and extensive coal deposits have made the upper and middle reaches centres for industrial development (He et al., 1991).

The middle reach, from Hekouzhen to Huayuankou, flows through a severely eroded part of the Loess Plateau where the silt load in the river increases markedly, from approximately

<table>
<thead>
<tr>
<th>Gauging station</th>
<th>Flow volume $10^9 m^3 a^{-1}$</th>
<th>Suspended load $10^6 t a^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lanzhou</td>
<td>31</td>
<td>2</td>
</tr>
<tr>
<td>Qingtongxia</td>
<td>28</td>
<td>3</td>
</tr>
<tr>
<td>Hekouzhen</td>
<td>23</td>
<td>5</td>
</tr>
<tr>
<td>Longmen</td>
<td>30</td>
<td>31</td>
</tr>
<tr>
<td>Sanmenxia</td>
<td>37</td>
<td>40</td>
</tr>
<tr>
<td>Huayuankou</td>
<td>39</td>
<td>35</td>
</tr>
<tr>
<td>Lijin</td>
<td>35</td>
<td>28</td>
</tr>
</tbody>
</table>

Source: Ningxia Water Conservancy Department, 1996, Hong et al., 1991
5 kg\(^{-1}\)m\(^3\)a\(^{-1}\) at Hekouzhen to 40 kg\(^{-1}\)m\(^3\)a\(^{-1}\) at the Sanmenxia Dam (Table 1). At Huayuankou, the river leaves the Loess Plateau and enters the nearly-flat North China Plain (Figure 3), the most agriculturally productive region in China.

Climate
Annual precipitation in the Yellow River Basin generally decreases from south-east to north-west. All of the basin is in the drylands, with a minimum of about 200 mm of rainfall in the Yinchuan area and a maximum around 700 mm in Xian. Precipitation is concentrated between the months of July and September, under the influence of the maritime monsoon coming from the south-east. Frost-free seasons range in length from 200 days in the south-east to less than 100 in the high plateaus in the west. Cold waves are frequent in Winter, Spring and late Autumn across northern China.

Floods are common in the lower reaches of the Yellow River in late Summer, and before 1950, frequently changed the course of the river. From 602 BC to 1950 AD, there were an estimated 1570 disastrous breaks in the river embankments across the North China Plain (Zhao, 1986). Many deliberate breaks were made by Emperors and Warlords who used them as a defence tactic to stop invading armies from the north (Lamouroux, 1998). In fact, the last major break in an embankment occurred in 1938 when the Nationalist Government cut the embankment near Huayuankou in a desperate and futile attempt to halt the advance of the Japanese Army. An estimated 890 000 people died in the ensuing flood (Zhao, 1994). The worst floods on the river originate in the wetter south-east of the Loess Plateau in the vicinity of Sanmenxia Dam (Wu, 1989). Liu and Liang (1989) cite one estimate that an extreme flood would affect 35 million people if it broke the dyke on the north side of the river and 55 million if the break were on the south side. The enormity of such a catastrophe defies comprehension.

Water resources
Shortly after the People's Republic of China was founded in 1949, the government embarked on a vigorous national programme of irrigation development. The objective was to make China self-sufficient in food production. Irrigation was a high priority in meeting that goal. By 1990, irrigated land along the Yellow River had increased nearly 20 times to 6 000 000 hectares, of which 5 000 000 were irrigated from the river and 1 000 000 from wells (Luo and Liu, 1990; Xi, 1997). Of the 6 000 000 hectares, 24 per cent is located in the upper reaches of the river, 33 per cent in the middle reach and 43 per cent in the lower reach (North China Plain).

More than 150 irrigation projects obtain their water by pumping from the Yellow River (Institute of Territorial Planning, 1990). Nine of the completed projects lift the water over 300 metres in multiple stages (Table 2). For the five projects in Gansu Province, the average lift for each project is very high at 600 metres and farmers pay a nominal price for their water, which covers only a small part of the pumping cost, which rises with increasing lift (Clark, 1970). The low price charged is justified by the desire to raise the income level of farmers who have moved from the poverty-stricken loess hills of south-eastern Gansu Province. Poverty alleviation is a major objective of agricultural development projects in the Loess Plateau (Cao et al., 1991; Li, 1991; Shen and Gan, 1992; Wu, 1991).

The Loess Plateau
In and around the big bend in the Yellow River is the extensive Loess Plateau (Figure 3), one of the

<table>
<thead>
<tr>
<th>Province</th>
<th>Project name</th>
<th>Pumping stages</th>
<th>Pumping lift (m)</th>
<th>Designed flow (cumecs)</th>
<th>Area irrigated (designed) (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gansu</td>
<td>Jingtai No. 1</td>
<td>11</td>
<td>472</td>
<td>10.6</td>
<td>20 280</td>
</tr>
<tr>
<td></td>
<td>Jingtai No. 2</td>
<td>18</td>
<td>708</td>
<td>18.0</td>
<td>32 810</td>
</tr>
<tr>
<td></td>
<td>Qinghui</td>
<td>17</td>
<td>595</td>
<td>12.0</td>
<td>17 330</td>
</tr>
<tr>
<td></td>
<td>Yuzhong</td>
<td>13</td>
<td>560</td>
<td>8.0</td>
<td>12 000</td>
</tr>
<tr>
<td></td>
<td>Gaolanxiza</td>
<td>12</td>
<td>653</td>
<td>6.5</td>
<td>10 000</td>
</tr>
<tr>
<td>Ningxia</td>
<td>Xingbuzhi</td>
<td>8</td>
<td>440</td>
<td>6.7</td>
<td>10 000</td>
</tr>
<tr>
<td></td>
<td>Guhai</td>
<td>11</td>
<td>382</td>
<td>20.0</td>
<td>26 670</td>
</tr>
<tr>
<td>Shaanxi</td>
<td>Donglei No. 1</td>
<td>9</td>
<td>311</td>
<td>60.0</td>
<td>64 740</td>
</tr>
<tr>
<td></td>
<td>Dayadu</td>
<td>6</td>
<td>351</td>
<td>6.0</td>
<td>12 000</td>
</tr>
</tbody>
</table>

Source: Institute of Territorial Planning, 1990
largest regions of thick (up to 300 m) aeolian deposits in the world (Guo et al., 1991). The plateau is the ‘cradle’ of the Han Chinese civilization, whose capital was near Xian at the time of the first unification of the nation in 220 BC. Loess is dominantly silt-sized mineral matter which has been deposited by wind. In China, the loess deposits have been accumulating since Pleistocene times, carried by strong winds blowing out of Central Asia. Loess deposits, which are highly susceptible to water erosion (Milliman and Meade, 1983), comprise nearly all of the sediment carried in the Yellow River.

There is no agreement among Chinese scientists concerning the area of the Loess Plateau (Yang and Guo, 1992). Published numbers range from 360 000 km² (Yang, 1989) to 688 000 km² (Jiang et al., 1981). Yang (1989) and Yang and Guo (1992) state that the definition problem is centered on whether the plateau should be defined on physical criteria (e.g. thickness of loess deposits) or on a combination of physical and socio-economic criteria (e.g. loess occurrence and the similarity of development problems). Plateau area estimates cluster around 625 000 km² and 400 000 km². The 623 700 km² figure of the Chinese Academy of Sciences will be used here (Wang, 1991) because most discussions of the plateau seem to refer to conditions in what is called the ‘Loess Plateau and its adjacent regions’, an area about the size of Afghanistan. The projected population of 104 000 000 for the Loess Plateau (Su, 1991) in the year 2000, for example, is more reasonable for the larger area than the smaller one. The 400 000 km² figure apparently refers to a core area where the loess is at least several metres deep.

The North China Plain

The North China Plain comprises the huge delta of three rivers: Yellow, Huai, and Hai. It covers about 350 000 km², is flat, densely-populated with 250 000 000 people, a highly productive agricultural region and is less than 100 metres above sea level (Xu, 1990). Perched as it is above the surrounding plain, the embanked course of the Yellow River now divides the plain into a north part drained by the Hai River and a south part drained by the Huai River. There is no inflow to the Yellow River on its 700-kilometre run across the North China Plain except for a little runoff from nearby hills in the vicinity of Jinan.

Management of the Yellow River must accommodate many interests:

- supplying water to communities, industries, agriculture, and mining operations;
- generating electricity;
- controlling floods;
- limiting water pollution by silt and by chemical and biological substances; and
- scouring the river channel across the North China Plain.

Flood control in the North China Plain, however, demands the highest priority because of the hundreds of thousands of people who could die if the protective embankment and flood detention system fail during the height of a major flood. Floodwater detention basins have been constructed next to the river in the plain to receive storm waters, but their effectiveness has yet to be tested.

A spotless 50-year record of success in containing floods in the river flood plain has led the local people into feeling that there is no flood danger anymore. Complacency and land pressure have persuaded farmers to cultivate land in the flood retention basins and on the flood plain between embankments. No-one knows how many people have endangered themselves by settling in such high-risk areas. Estimates run into a million or more (Mosley, 1985). In the year 2001, that number must now be considerably greater.

The threat to human life mounts steadily as the Yellow River bed rises. Most estimates of the rise are between three to ten centimetres per year (Fu, 1989; Zhao, 1986). Presently, the bed is three to six metres above the plain, on average, and may be as much as 13 metres higher in places (Figure 4). Sediment deposition in the 700-kilometre lower reach is distributed as shown in Table 3.

Environmental degradation

Human-induced environmental degradation in the Yellow River watershed began with the expansion of cropland in the south-east corner of the Loess Plateau at least 3000 years ago. Forest destruction
in the south and overgrazing of the grasslands in the north brought acceleration of a naturally high rate of erosion (Fu, 1989). By the beginning of the twenty-first century, the effect of people was felt virtually everywhere in the Loess Plateau and in the remainder of the Yellow River watershed (McNeill, 1998). Only in the remote reaches of the river in the Tibetan Plateau was the human impact minimal. Even there, overgrazing has become common.

The list of environmental hazards in the Yellow River Basin is long. It begins with silt accumulation in streams, reservoirs, canals and irrigated fields and progresses to salinization of croplands and groundwater. Since the 1950s, rapid industrialization and urbanization have led to severe water shortages in cities and to widespread pollution of surface and groundwaters. In turn, excessive pumping of aquifers has caused declining water-tables, land subsidence and salt water intrusion from the Bohai. Coal burning and toxic smoke from chemical industries, as well as dust storms, have lowered air quality in and around large cities.

Impact of silt control measures

The Yellow River has, at an average 40 kg/m$^3$ a$^{-1}$ at Sanmenxia Dam, the highest silt concentration of any of the world’s major rivers (Mosely, 1985). The Colorado River in the United States is second at 28 kg/m$^3$ a$^{-1}$. Far behind, in third place, is another Chinese river, the Liao, with 7 kg/m$^3$ a$^{-1}$. Silt concentrations in the river rise rapidly between the Hekouzhen gauging station (5 kg m$^{-3}$) and Sanmenxia. That region is the principal source of total sediment and of coarse sand in the river (Mou, 1990; Xie, 1994; Yang and Guo, 1992). Chinese studies have demonstrated that the principal source of silt is an area of about 24 000 km$^2$ in the north-east corner of the big bend, where the middle reach begins (Tang and Zhang, 1991). No significant amount of sediment or water is added in the lower reach. Rather, much deposition occurs in the main channel, flood plain of the river and in canals for the 2.5 million hectares of land irrigated by the Yellow River in the North China Plain (Fu, 1989).

Soil erosion by water, especially, is a severe problem in the Loess Plateau (Zhang, 1992). Native forests (in the south) and grasslands (in the north) have been destroyed. Summer rainfall is intense, loess is highly erodible, and 75 per cent of the 400 000 km$^2$ of deep loess has slopes greater than 3° and 60 per cent are over 15° (Zhao, 1992). Estimated erosion rates over the larger Loess Plateau and its adjacent regions are given in Table 4. On individual fields, water erosion is said to exceed a very high 300 t ha$^{-1}$ a$^{-1}$ (Yang, 1989; Zhang and Hou, 1991). Sheet erosion on deep loess deposits, even though severe, usually has only a slight or moderate effect on crop yields. Gullies are the main source of sediment delivered to the river. Wind erosion occurs primarily in the Mu Us Desert north of the Great Wall in Ningxia and Shaanxi.

Landslides are an annual occurrence on steep slopes. A 1920 earthquake in the Loess Plateau is said to have triggered about 1000 landslides and killed 200 000 people. However, nearly three-quarters of the mass movements are attributed to Summer monsoonal rains (Derbyshire et al., 1991). Eastern China lies in the tectonically active Pacific rim earthquake zone: the 1920 earthquake came before there were any high dams on the river and there were far fewer silt retention dams. Needham (1959) and Zhao (1994) write of a 1556 earthquake in Shannxi Province that must rank as one of the deadliest on record: 830 000 people are said to have died. Zhao also states that a 1976 earthquake in the city of Tangshan, east of Beijing, caused more than 250 000 deaths.

Silt load in the Yellow River

In the 1950s and 1960s the Chinese Government began an intensive programme to reduce silt flow into the North China Plain. Action was concentrated on constructing major dams on the Yellow River (the Qingtongxia and Sanmenxia) and thousands of silt-trap dams on tributaries and in gullies. Table 5 details the change in mean silt load at major gauging stations on the Yellow River over the 40-year period from 1950 to 1989 (Zhou, 1996).

Two important points emerge from an examination of Tables 1 and 5:

1. the abrupt increase in the silt load between Hekouzhen and Longmen; and
2. the generally downward trend in the silt load from the 1950s to the 1980s, at all except the Guide gauging station.

Guide is a major gauging station on the upper reach of the river, in Qinghai Province. For the lowest four stations, a reduction of approximately 50 per cent has been achieved.

Table 3. Percentage of the sediment load deposited in different sections of the lower reach of the Yellow River

<table>
<thead>
<tr>
<th>Location</th>
<th>% of sediment deposited</th>
</tr>
</thead>
<tbody>
<tr>
<td>Huayuankou to Lijn</td>
<td>22</td>
</tr>
<tr>
<td>Lijn to Bohai (delta)</td>
<td>51</td>
</tr>
<tr>
<td>Bohai</td>
<td>27</td>
</tr>
</tbody>
</table>

Source: Long and Xiong, 1981
The first observation indicates that the section of the river producing the greatest amount of sediment is the north-east corner of the big bend in the river. Reducing silt discharge to the river in that section would be more effective than doing so elsewhere.

The second observation is that the efforts to reduce silt flow to the North China Plain have been at least moderately successful and that they may be slowing the rate of rise of the Yellow River bed across the North China Plain. Given the seriousness of the potential consequences of the bed rise, the last implication, if correct, would mean that the Chinese Government’s actions are having a considerable degree of success, even though the river silt levels remain high. A bed rise rate of 3–10 centimetres per year is widely quoted, but no detailed studies have been made of the rate at different places and at different times along and across the flood plain. Deposition and removal of sediment varies greatly over short distances and over various time periods. Along with an apparent decline in sediment loads in the Yellow River since the 1950s, there has been a large drop in the flow of the river at the Lijin gauging station (Xi, 1997; Table 6). There is no obvious reason for the flow decline but its magnitude is disturbing. Many reasons have been given for the occurrence of such a drop, including that given for silt decline – construction of silt-traps and terraces. Without doubt some of the flow decline is the result of expanded irrigation, industrial development and population growth. If the flow remains low, less scouring will occur and additional difficult water allocation decisions will have to be made. Already, there are periods of six months or more when there is no flow in the lower half of the 700-kilometre channel (Brown and Halweil, 1998; Ma, 1999).

Erosion control practices Chinese Government efforts to reduce sediment runoff from the Loess Plateau have, in the past, been directed almost entirely toward erosion control with structures and

| Table 4. Estimated water erosion intensities on the Loess Plateau and its adjacent regions |
|------------------|-----------------|---------------|----------|
| Erosion class    | Erosion intensity (t ha⁻¹a⁻¹) | Erosion area km² | % total |
| Negligible erosion | <5              | 284 000       | 46       |
| Slight erosion   | 5-10            | 47 300        | 8        |
| Moderate erosion | 10-50            | 125 200       | 20       |
| Intense erosion  | 50-100           | 90 000        | 14       |
| Extremely intense erosion | 100-200 | 66 000        | 10       |
| Severe erosion   | >200             | 10 300        | 2        |
| Total            |                  | 623 700       | 100      |

Source: Zhang, 1991

| Table 5. Mean annual silt load at several gauging stations on the Yellow River 1950–1989 |
|---------------------------------|---------------------------------|-----------------|---------------|-------------|
| Guide            | 0.02 | 0.02  | 0.03  | 0.02       | 0.02       |
| Lanzhou          | 0.13 | 0.10  | 0.06  | 0.04       | 0.08       |
| Qingtongxia      | 0.27 | 0.13  | 0.08  | 0.08       | 0.14       |
| Hekouzhen        | 0.15 | 0.18  | 0.11  | 0.10       | 0.14       |
| Longmen          | 1.19 | 1.13  | 0.87  | 0.47       | 0.92       |
| Sanmenxia        | 1.76 | 1.14  | 1.40  | 0.85       | 1.29       |
| Huayuankou       | 1.51 | 1.11  | 1.23  | 0.78       | 1.16       |
| Lijin            | 1.32 | 1.09  | 0.90  | 0.64       | 0.99       |

Source: Zhou, 1996
Table 6. Average annual water discharge of the Yellow River at Lijin gauging station 1950–1986

<table>
<thead>
<tr>
<th>Years</th>
<th>Water discharge ($10^9$ m$^3$ a$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1950-59</td>
<td>48.0</td>
</tr>
<tr>
<td>1960-69</td>
<td>50.1</td>
</tr>
<tr>
<td>1970-79</td>
<td>31.1</td>
</tr>
<tr>
<td>1980-89</td>
<td>28.6</td>
</tr>
<tr>
<td>1990-94</td>
<td>18.5</td>
</tr>
</tbody>
</table>

Source: Xi, 1997

trees. Many soil conservation projects have been initiated, involving terracing, afforestation and silt-control dams. More recently, a new element has been introduced: integrated development combining erosion control with programmes to maximize crop productivity and personal income in a sustainable manner (Jiang et al., 1991; Zhang, 1991).

The objectives of the new approach are to:
- increase yields on the high-potential level farmland;
- replace cropland on steep slopes (more than 25°) with trees, shrubs, and grasses;
- bench-terrace slopes of less than 25°; and
- construct dams to trap sediment in gullies.

Two kinds of dams are built: key dams and silt-retention dams. Key dams are multi-purpose structures located near the mouths of valleys. They are designed for flood control, storing water for irrigation and domestic use, and sediment retention. Silt-retention dams trap sediment and form new, level, high-potential cropland that may or may not be irrigated, depending upon the availability of surface and groundwaters. They are placed in massive gullies in stepping-stone fashion (Plate 1). Silt-retention dams (also called ‘warping’ dams) have been built by farmers for centuries. The new land is prized for producing higher yields than flat lands or the tops of hills or on terraces on steep slopes. New level lands reduce both silt and water flow to the Yellow River.

A comparison between the effects of valley dams and vegetating steep slopes is shown in Table 7. Afforestation and grass planting is done on slopes too steep for terracing. The low level of success in revegetating steep slopes is due to the difficulty in establishing the dense cover of plant litter that is essential for erosion control on steep, highly erodible, loessial soils. Rainfall, even in the sub-humid southern part of the Loess Plateau, at 700 millimetres per year, is inadequate to form a litter layer on the surface that would protect the soil. In the drier middle and northern part of the Plateau, the same limitation applies to establishing a thick grass cover. Grazing exacerbates the situation.

Given that vegetative measures to control erosion on the steep sides of gullies and valleys in the Loess Plateau have not been effective, reliance must be placed on constructing thousands of silt-retention structures in valleys. Theoretically, dam building and raising dam heights could go on indefinitely. As the dams become higher, however, heavy once-in-a-century rains or earthquakes could cause dams to break and do immense damage to people caught in the resulting floods. That possibility is a grim threat that hangs over local people in the Loess Plateau, just as the rising level of the Yellow River bed does in the North China Plain.

Silt-retention dams added an estimated 200 000 hectares of high-quality, level land to the cropland inventory of the Loess Plateau between the 1960s and 1985 (Zhang, 1992). Since the 1950s, it is said that thousands of silt-trap dams and small storage reservoirs have been built. That construction, plus terracing, presumably accounts for the reduced silt discharge at major gauging stations along the river (Table 5). Considering the multitude of gullies and valleys in the Loess Plateau, thousands of additional dams probably will be built in future decades. These will lower the silt load and the flow volume in the Yellow River while allowing for an increase in food production as new cropland is formed.

Clearly, the silt reduction programme the government has undertaken is effective. It will ease – but not eliminate – the overriding concern: a major break of the embankments on the North China Plain.

Natural vs accelerated erosion There are differences of opinion about the causes of Loess Plateau erosion. Wang (1991) and Yang and Guo (1992) state that 30 per cent of the erosion is human-induced, while Zhang (1991) claims that only about 13 per cent is due to accelerated erosion. With about two-thirds or so of the erosion being attributed to natural causes, restoration of the pre-human occupancy vegetation on the steep slopes might reduce present erosion by perhaps one-third. That would slow the rate of sediment build-up, but not nearly enough to eliminate the need to trap silt before it reaches the Yellow River.

A study by Jing (1988) indicated that natural (geologic) erosion was high long before there was human occupancy of the Loess Plateau. He noted that the largest depositional area related to erosion on the Loess Plateau is the North China Plain. That plain, which is the delta of the Yellow River, is both extensive and deep, attesting to the vast amount of
silt that the river has deposited since Pleistocene times.

Sanmenxia Dam The history of Sanmenxia Dam is a story of high hopes and unfulfilled expectations. It carries a warning for the other 11 dams completed, under construction, or planned for the middle reach of the Yellow River. Silt filled the Sanmenxia reservoir in just six years, virtually ending its usefulness for storing water (Long and Xiong, 1981). The present condition of a dam in Ningxia also illustrates the challenge dam-builders face on tributaries of the Yellow River (Plate 2). The dam no longer has a major water or silt storage function. During the six years when silt was accumulating in the reservoir, the Sanmenxia Dam accomplished one of its builders’ objectives i.e. scouring of the river channel across the North China Plain. After the reservoir lost its storage function, build-up in the channel began again.

Presently, the dam generates electricity for only a few months in the Winter, when the silt load in the river is at a minimum (Ma, 1999). Silt continues to pit the blades of turbines and shortens their useful life.

A new dam below Sanmenxia, the Xiaolangdi Dam, was completed in late 1999 and should be fully operational in about two years. It is designed to generate electricity, store irrigation water, help control floods and reduce ice build-up in the river downstream (Zhang, Chinese Academy of Sciences, pers. comm., 2000). It remains to be seen whether it will suffer the same fate as the Sanmenxia Dam. The relatively clear water released from the dam in its first years of operation, at least, should lead to a scouring of the river channel across the North China Plain. The scouring gradually becomes less downstream as the water entrains silt.

Table 7. Erosion control on the Loess Plateau 1974–1986

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Sediment trapped annually (t)</th>
<th>% trapped by treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reservoirs</td>
<td>151</td>
<td>28.4</td>
</tr>
<tr>
<td>Silt-trap dams</td>
<td>217</td>
<td>40.9</td>
</tr>
<tr>
<td>Irrigated cropland</td>
<td>97</td>
<td>18.3</td>
</tr>
<tr>
<td>Terracing</td>
<td>19.6</td>
<td>3.7</td>
</tr>
<tr>
<td>Afforestation</td>
<td>38.1</td>
<td>7.2</td>
</tr>
<tr>
<td>Grass planting</td>
<td>7.8</td>
<td>1.5</td>
</tr>
<tr>
<td>Total</td>
<td>530.5</td>
<td>100</td>
</tr>
</tbody>
</table>

Soil and water salinity

Soil salinity is common on lands in the upper, middle, and lower reaches of the Yellow River. Saline irrigated soils are especially serious in the Yinchuan Plain of the Ningxia Hui Autonomous Region, in the western Hetao area at the north-west corner of the big bend in the Yellow River, and in the North China Plain.

Over-irrigation, poor drainage, and leaky canals are the primary causes of salinization (Li and Zhao, 1991; Zhang, 1995). Salinity has severely hampered agricultural production. Zhang (1995) states that 73 per cent of the irrigated land in the Hetao region at the north-west corner of the big bend is salt-affected. In the Yinchuan Plain, 43 per cent is saline and approximately 16 per cent of the North China Plain’s irrigated land is salt-affected. A combination of improved surface drainage, pumping of drainage wells and lining irrigation canals is needed to lower the water-tables (Zhang, 1988). An extensive open drain system has been installed in Ningxia and the Hetao area and installation of tile drains has begun. Effective ameliorative methods have been developed by research personnel but adoption by farmers is slow.

Despite the fact that salt problems must have existed from the beginning, irrigation in the Yellow River Basin has continued successfully for more than 2000 years (Mei and Dregne, 1999).

Salinity control practices In China, there are well-known, proven, and practical solutions to salinity problems (Mei, 1994; Xu, 1990). Furthermore, the most-needed practice to save irrigation water (greater water use efficiency) also happens to be the first requirement for salinity control. By and large, Yellow River soils are sufficiently permeable to be drained easily. Reducing soil salinity while increasing water use efficiency has the positive

PLATE 2 The sediment-filled lake behind Changshaniou Dam on a tributary of the Yellow River in Ningxia. An aqueduct carrying Yellow River water from the pumping station to irrigated uplands crosses the dam
effect of simultaneously saving water needed elsewhere while increasing crop yields in the process. At present, water use in gravity and pumped irrigation systems of the Yellow River (especially the upper reaches) is wasteful (Zhang, 1995). The reasons are many but include:

- inadequate maintenance of drainage pumps and ditches;
- leaky canals;
- poor land levelling;
- over-irrigation; and
- unused water-saving technologies.

Additionally, hundreds of hectares of fish ponds and thousands of hectares of paddy rice fields require large amounts of water, much of which drains into the subsoil and raises water-tables in adjoining fields.

**Chemical and biological pollution**

Surface and groundwater pollution is the principal pollution problem in the Yellow River Basin and North China Plain (Xu, 1990). Discharge of industrial effluent and untreated sewage from cities and villages is common everywhere. Surface water contamination is becoming increasingly important as water supplies decline and less dilution occurs. While salinity is not a particular problem in surface waters, it is in groundwater. Groundwater contamination by salt, industrial effluents, pesticides, fertilizers and disease organisms has especially severe connotations because cleaning polluted water in most aquifers is practically difficult. Control at the source is essential to avoid groundwater pollution and is highly desirable for protecting surface water and reducing water demand.

**Interbasin water transfer to the Yellow River**

Numerous proposals have been made since the 1950s for transporting water from the Yangtze Basin in the humid south to the Yellow River and the North China Plain (Jones, 1997; Liang, 1998). The long-term flow in the Yangtze is 20 times that of the Yellow River (Zuo, 1983). In the 1950s, interbasin water transfers were planned mainly to open new irrigated lands for food production. Today, agriculture is just one of many competing needs for more water. In 1987, the State Planning Commission began serious consideration of the subject of transferring water from three rivers in the upper watershed of the Yangtze River to the Yellow River (Yao, 1991). Initial plans called for moving 20 billion m$^3$ per year to the Yellow River. That amount of water would allow expansion of the proposed Daliushu Irrigated Area to around 4 000 000 hectares. It would also, importantly, help reduce sediment deposition by providing water to flush the channel of the lower Yellow River.

By the 1980s, three routes had emerged as the most favoured ones. They are known as the east, middle and west routes (Yao and Chen, 1983). The east route generally follows the ancient Grand Canal. It runs along the east side of the North China Plain, ending near Beijing. It would require the pumping of water over the Yellow River. The middle route, also ending near Beijing, would follow along the western edge of the North China Plain and would not, in theory, require pumping along the way. It would be a gravity flow canal 1200 kilometres long, with an elevation at the inlet of 150 metres and of 50 metres at Beijing (Yao and Chen, 1983). Both canals would provide water to increase the irrigated land area, meet domestic and industrial needs, recharge aquifers, halt salt water intrusion and further land subsidence, and minimize drought impacts on rural and urban populations.

The three routes serve different parts of the North China Plain and the Yellow River, and were not intended to be duplicative in their function. The east route has fallen out of favour, principally because of the pumping costs associated with crossing the Yellow River (Liang, 1998). Ever since the idea of transferring water from south China to the north was proposed, there have been opposing views of the necessity for and feasibility of such transfers (Huang, 1983). Some people believe that more efficient use of water would eliminate the need for transfers. Others are convinced that the enormous cost is justified by the water crisis they see developing in north China. Given the controversy, the very high cost, and government preoccupation with the Three Gorges Project, it is likely that several years will pass before full-scale development of south-north water transfers will occur.

Ironically, while preparations for transferring water from the Yangtze to the water-short Yellow River are being made, two projects are under construction to transfer within-basin water from the Yellow River to the Fen River valley and Taiyuan (population 2 million), the capital of Shanxi Province, and to Hohhot (population 1.2 million), the capital of the Inner Mongolia region. The canal system carrying water over the mountains to Taiyuan will be about 300 kilometres long when completed in 2002 (Ma, 1999). Hohhot is to receive its water in 2003 (Brown and Halweil, 1998) along a canal that will run for approximately 75 kilometres. Taiyuan has a metropolitan population of about 2 000 000 people and Hohhot around 1.2 million.
Discussion

The Chinese Government has chosen to emphasize engineering structures as the solution to its environmental problems. Sediment deposition in reservoirs and in the bed of the Yellow River is to be managed by building higher embankments and more dams along the river and by the construction of more silt retention dams in the eroding valleys. Salt damage in croplands is planned to be reversed by installing hundreds of wells to lower water tables. Water shortages are planned to be overcome by long-distance transfers from the humid south or by diverting water from the already-diminished flow of the Yellow River into water-short cities hundreds of kilometres away. South–north water transfers using the favoured middle route on the western edge of the North China Plain is simple in concept but complex in construction. Long tunnels must be constructed, canals must be laid out and rivers must be crossed. When the system is in operation, a collapse of a tunnel would shut down water distribution for weeks or months, as would an earthquake-induced realignment of the canals.

There are substitutes for engineering solutions. The main one is to increase water use efficiency, as many Chinese have proposed (e.g. Zhang, 1995). Perhaps the strongest impetus to increasing efficiency is charging users enough to assure that water will be used efficiently (Brown and Halweil, 1998). The price cannot be raised to a level that is too high for farmers, who are the food producers, but users could be charged differentially, depending upon their ability to pay and the amount of pollution they generate. There are many proven water management practices that can be used in agriculture, industry and homes (Zhang et al., 1992; Zhang, 1995). It is safe to say that unless greater water use efficiency is achieved, there will continue to be a serious soil and groundwater salinity problem. Applying larger amounts of irrigation water to flush out salt only serves to make the need for complementary measures such as drainage wells greater and lowers water quality downstream (Mei, 1994). The idea that dilution is the solution to pollution, which government water planners seemingly subscribe to, places a low value on water. Treatment of domestic sewage and industrial effluent at the source of the concentrated pollutant stops pollution before it can degrade water supplies. Treatment is expensive, but not necessarily more expensive than treating the problems suffered by people living downstream. Raising the price of water for irrigating farmers, urban residents and factories undoubtedly would be less popular than paying for a water transfer project sometime in the future. But, it might well avoid many of the problems of operation and maintenance that engineering structures present. Opportunities to conserve water abound.

Two possible solutions to the threat of the elevated bed of the Yellow River across the North China Plain can be immediately dismissed as impractical. The first is a version of nature’s solution for many millennia: make a new channel. The social and economic cost would be enormous and perhaps impossible for any government to absorb. The second option is to dredge the entire length of the present channel. Again, the economic cost would be very high. Additionally, there would be an environmental cost that could be unacceptable: disposal of the dredged material. Both options are technically feasible. Perhaps one may become socially, environmentally and economically acceptable in the future. A potentially viable solution, if water transfer by the middle route materializes, is to allocate part of the water to scouring the Yellow River channel. Such a diversion would probably be opposed by water users north of the Yellow River unless the proposed flows in the transfer system were increased.

Coping with the salinity and sediment problems in the Yellow River Basin, whether by conserving water or by water transfer, calls for national and provincial governments to play a strong leadership role in planning and executing a viable programme. The task is difficult and the future is uncertain.

Conclusions

China faces the truly daunting task of assuring sustainable development of the resources and economy of the Yellow River Basin in a life-saving and environmentally-responsible manner. Continued beneficial use of water supplies requires finding solutions to two major environmental problems: salinization of irrigated land and high silt loads in the Yellow River. Salinization is a problem for which the technical solution already is well-known. What is needed now is to provide the technical and financial assistance and the incentives to put practices into action. Charging for water is one powerful, if unpopular, incentive to increase on-farm water use efficiency but it must be combined with other actions, such as lining leaky canals, in order to be effective on an area-wide basis. Increasing water use efficiency is essential to controlling salinity and conserving water.

Reducing the silt load responsible for the rising level of the Yellow River bed in the North China Plain and siltation of water storage reservoirs is an intractable problem. There are many expensive short-term treatments that can be employed but no satisfactory long-term solution. The root cause of
the silt problem is the high erodibility of the soils in the Loess Plateau. Engineering measures to capture silt before it enters the Yellow River appear to be needed for the foreseeable future. The Chinese Government is trapped in a troublesome position: expending scarce resources on temporary solutions to a worsening problem.

Control of chemical and biological pollution of land, water, and air in the Yellow River Basin is a subject that must be addressed. Disposal of urban and industrial waste is a steadily mounting problem throughout the country.

The most fearsome threat on the river is that of the rising level of the bed above the adjoining North China Plain. This will turn a minor breach of an embankment into a major break that could cause one of the worst catastrophes in human history—the threat is very real. And, lurking in the background is the possibility of an earthquake destroying a dam such as Xiaolangdi and launching a massive wall of water and mud down the Yellow River.

Editor’s note
The term ‘dike’ has been replaced with ‘embankment’ in this paper to comply with normal UK English usage.

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