HAZARD MITIGATION RELATED TO WATER AND SEDIMENT FLUXES IN THE YELLOW RIVER BASIN, CHINA, BASED ON COMPARABLE BASINS OF THE UNITED STATES

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ABSTRACT

The Yellow River, north-central China, and comparative rivers of the western United States, the Rio Grande and the Colorado River, derive much of their flows from melting snow at high elevations, but derive most of their sediment loads from semiarid central parts of the basins. The three rivers are regulated by large reservoirs that store water and sediment, causing downstream channel scour and, farther downstream, flood hazard owing to re-deposition of sediment. Potential approaches to reducing continuing bed aggradation and increasing flood hazard along the lower Yellow River include flow augmentation, retirement of irrigation that decreases flows and increases erosion, and re-routing of the middle Yellow River to bypass large sediment inputs of the Loess Plateau.

INTRODUCTION

The Yellow River (Huang He) (fig. 1) drains about 750,000 km^2 of northern China, but most of the flow begins as snow at elevations exceeding 2500 m – roughly a fourth of the basin. Similarly, based on records of spring runoff as a percent of total runoff prior to construction of dams and inter-basin diversions, snowmelt probably accounts for two-thirds of the flows in the central reaches of the Rio Grande and the Colorado River, southwestern United States (fig. 2). Each river, the Yellow River, the Rio Grande, and the Colorado River, has an arid to semiarid (<250 and 250-500 mm mean annual precipitation) temperate climate in much or all of the drainage basin lower than 2000 m. Each, therefore, receives sufficient precipitation to cause runoff and erosion, but has sparse vegetation that is poorly effective in preventing erosion.

Owing to climate, geology, and land use, sediment inputs to the middle Yellow River are enormous. Some sediment is stored in reservoirs, reducing their utility, but much passes to the lower Yellow River, where for millennia deposition has increased the levels of the river bed and adjacent lowlands. Conditions of the Yellow River exhibit similarities to problems long recognized in the Rio Grande and Colorado River Basins. Experiences in these two basins provide insight into similar processes of the Yellow River and lead to approaches for mitigating hazards caused by flow regulation, rampant mid-basin erosion, and excessive aggradation in the lower Yellow River channel.

Processes of streamflow, erosion, and sedimentation in the Yellow River Basin generate cultural hazards. Mitigation of physical hazards requires actions for which socioeconomic factors rightly are addressed, but those factors must not be decisive. Reviews (Wang, 1999; Boxer, 2001) of water-policy problems of China have properly acknowledged cultural constraints to hazard mitigation. It is assumed here, however, that physical problems cannot be addressed properly if social and economic considerations significantly hamper corrective measures.

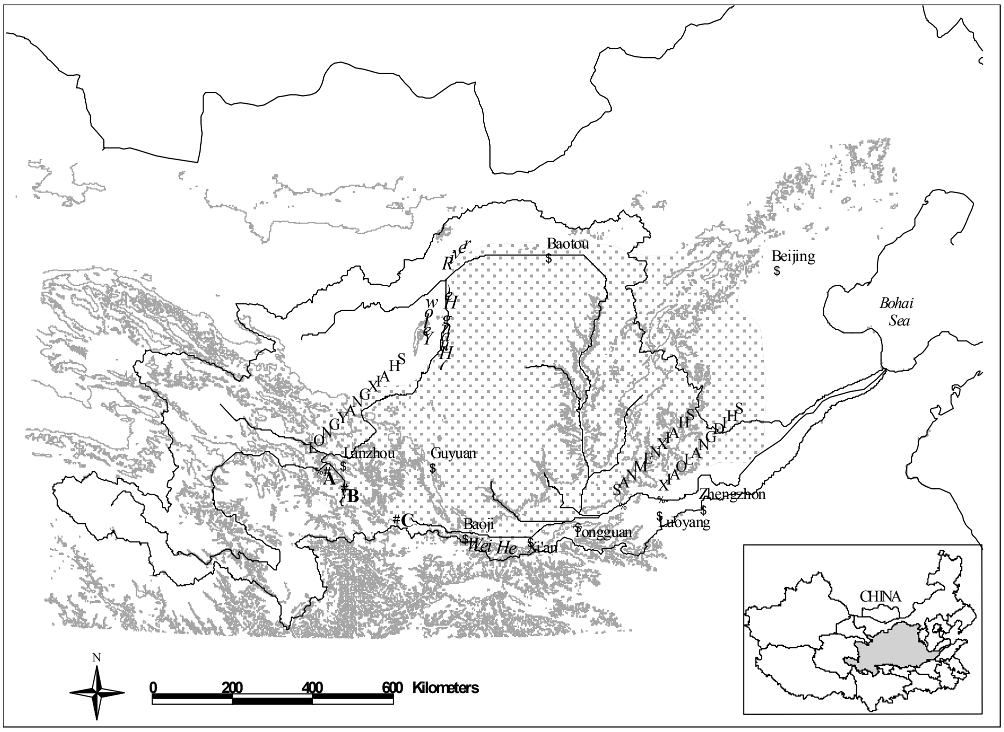

Figure 1. – Map of Yellow River Basin (shaded), with 1000-m contours, showing major streams, the Loess Plateau and related landforms, and selected towns and cities; A is Luijiaxia Hydropower Station, B is Lintao, C is Baoji.

YELLOW RIVER

Annual precipitation in the Yellow River Basin averages about 470 mm; it is nearly 700 mm in uplands of the southern part of the basin and is least, about 200 mm, along northern divides. About 60 percent of runoff is snowmelt from the western basin, where mean precipitation is 300 to 600 mm yr^{-1}, but most floods result from intense summer storms in the Loess Plateau (Li and others, 2002). Flows of the lower Yellow River formerly averaged 1840 m^3s^{-1} (Decun, undated), but ground-water and river withdrawals for irrigation now reduce flows by about 50 percent (table 1). The greatest extractions are from the upper and lower reaches, whereas 11 percent of the natural flow is taken from the middle Yellow River in the Loess Plateau area (Gray and others, 2002).

The Loess Plateau (fig. 1), nearly 60 percent of the Yellow River Basin, has mostly a semiarid climate (mean annual precipitation of 200 to 500 mm), but yields 90 percent of the sediment reaching the lower Yellow River (Gray and others, 2002). Most erosion occurs by failure of steep loess escarpments that lack protection by indigenous vegetation from highly erosive summer rainstorms. Results are high runoff-rainfall ratios and up to 40,000 t/(km^2·yr) (metric tons per square kilometer per year) of sediment from the central Loess Plateau (mostly 34° to 40° N latitude and 105° to 112° E longitude).

Programs to increase food production in the Loess Plateau have included contour farming, terracing, the planting of fruit trees, and drainage-net reduction. Retention dams and stream diversions for conserving water and increasing irrigation also store sediment released by slope failures and other forms of erosion that otherwise would reach the Yellow River. Owing to the extreme loads of fine sediment (clay to fine sand) that enter the Yellow River from the Loess Plateau, erosion-control practices are being installed to reduce by year 2050 up to 50 percent of the 1.6-billion-ton annual sediment load that reaches and is partly deposited along the lower Yellow River (Gray and others, 2002).

Table 1. – Comparison of selected physical features (estimates) of the Yellow River, the Rio Grande, and the Colorado River, and their drainage basins.

	Yellow River	Rio Grande	Colorado River
Basin area (km^2)	750,000	480,000	640,000
Avg. precipitation ($mm\ yr^{-1}$)	470	670	250
Pre-dam discharge (m^3s^{-1})	1840	225	570
Post-dam discharge (m^3s^{-1})	920	200	25
Principal sediment source	Loess Plateau	middle basin	middle basin
Number of large reservoirs	7	4	6
Pre-dam sediment ($t/(km^2 \cdot yr)$)	2130	83	310

COMPARISON BASINS OF THE UNITED STATES

Rio Grande

The upper Rio Grande drainage basin (fig. 2) of southern Colorado (fig. 2) (elevation 2300 to 4200 m) receives mean annual precipitation, much as snow, of 150 mm at lower elevations to about 600 mm at mountain divides. Thus, discharge is largely meltwater. After flowing south through New Mexico, where mean precipitation south of Santa Fe is mostly less than 500 mm yr^{-1}, the Rio Grande (basin area 480,000 km^2; mean precipitation about 670 mm yr^{-1}) enters the Gulf of Mexico near Brownsville, Texas.

Streamflow in the Rio Grande in northern New Mexico averages about 30 m^3s^{-1}, increases to 40 m^3s^{-1} near Albuquerque, and decreases to nearly 10 m^3s^{-1} at Presidio, TX. Downstream of Presidio, inflow from tributaries increases the mean discharge of the Rio Grande to nearly 200 m^3s^{-1} (table 1). Especially downstream from Santa Fe, NM, flow in the Rio Grande during the last century has been reduced about 10 percent by diversions for urban irrigation and use (Lawson, 1925).

The Rio Grande in Colorado and northern New Mexico moves moderate amounts of gravel as bed load. Downstream from Santa Fe, tributaries supply abundant silt and sand, causing a shift from a relatively narrow river to a wide, shallow stream dominated by sand. Sediment-discharge records show that following the closure in 1974 of Cochiti Dam, near Santa Fe, sediment discharge of the Rio Grande downstream of Santa Fe decreased significantly (Meade and Parker, 1984). The sediment load of the Rio Grande between Albuquerque and San Marcial (fig. 2) increases markedly by tributary inputs, particularly by the Rio Puerco, from semiarid lands of central New Mexico. Earlier, however, Lawson (1925, p. 374) reported that sediment transport downstream from Elephant Butte Dam was "…a small percentage of that formerly carried…". Prior to 1925 significant deposition in and along the Rio Grande downstream from El Paso, TX, was noted by Arroyo (1925), who attributed the problem to generally lower flows and reduced flood flows in particular.

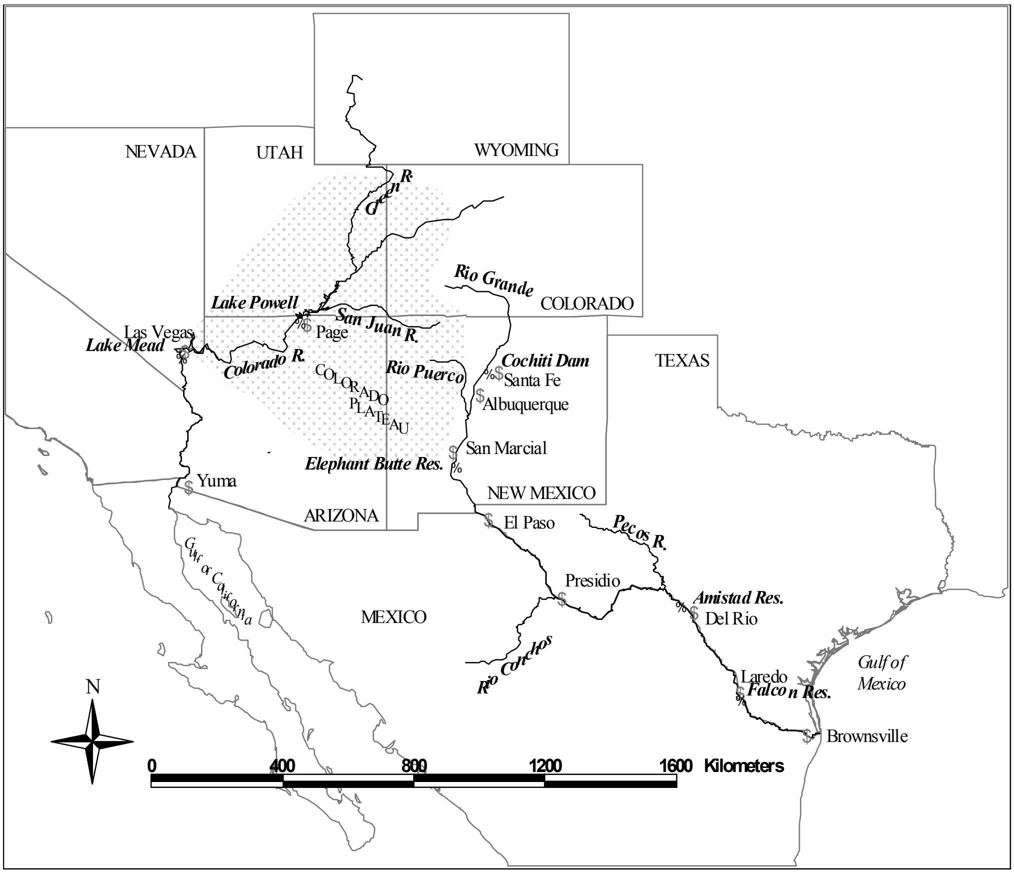

Figure 2. – Map of southwestern United States showing the Rio Grande and Colorado River Basins.

Colorado River

The Colorado River (fig. 2) also heads in the mountains of Colorado, from where it flows generally southwest into Utah and Arizona through areas dominated by relatively soft, erodible beds of shale, siltstone, and sandstone of the Colorado Plateau. The Colorado River enters the Gulf of California from northwestern Mexico, downstream from Yuma, AZ. Mean annual precipitation in the basin ranges from about 700 mm, largely snow, in mountainous central Colorado to 230 mm in western Colorado, 130 to 350 mm or more in eastern Utah and northern Arizona, and 80 mm in the Sonoran Desert of southwestern Arizona.

Discharges of the Colorado River near the Colorado-Utah border average about 100 m^3s^{-1}, increased by tributary inputs to about 470 m^3s^{-1} in northern Arizona (based on flow records of 1941 through 1957) (Andrews, 1991) but, owing largely to evapotranspiration and extractions primarily for irrigation, decrease to 25 m^3s^{-1} or less near the United States-Mexico border. Reflecting snowmelt, the combined mean discharge at three upstream gages on the Green, Colorado, and San Juan Rivers prior to 1958 was nearly 400 m^3s^{-1}, or about 85 percent of the mean discharge in northwestern Arizona. The combined drainage area above the three upstream gages, however, is only 40 percent of the 361,000-km^2 drainage basin above the Grand Canyon gage, northwestern Arizona (Andrews, 1991), demonstrating the disproportionate contribution to streamflow supplied by basin areas of high elevation. Mean daily discharges, based on measurement periods of 11 to 41 years, of the Colorado River at sites 26, 72, and 180 km downstream from large dams decreased 33, 15, and 23 percent, respectively, from pre-regulation discharges (Williams and Wolman, 1984).

Despite the disparate nature of runoff from the upper Colorado River Basin, most sediment is eroded from sedimentary rocks of the Colorado Plateau at lower elevations. The estimated combined mean annual sediment discharge at the upper-basin gage sites on the Green, Colorado, and San Juan Rivers was 27 million tons compared to about 87 million tons at the Grand Canyon gage, northwestern Arizona (table 1). Thus, prior to 1958, the upper basin contributed more than three fourths of the water reaching the Grand Canyon gage, but only about a third of the sediment (Andrews, 1991).

Flow-rate and Channel Changes

Observed changes along the Rio Grande and the Colorado River downstream from and following dam construction have been similar to changes that appear to be occurring along much of the Yellow River. These changes, which are typical of arid and semiarid fluvial systems altered by dams and reservoirs (Williams and Wolman, 1984), generally include (1) reduction of flood peaks, (2) pronounced reductions of sediment loads for long distances below dams, (3) minor to substantial bed lowering during 1 to 2 decades depending on bed-material sizes and potential for armoring in the reach downstream from the dam, (4) increases in bed-material sizes owing to the winnowing of fine sediment during channel degradation, (5) an increase in channel cross section resulting from bed and bank erosion that may decline downstream owing to reduced peak flows and transport capacity, and (6), owing to decreased damage by floods, increased riparian-zone vegetation.

The gradients of alluvial stream channels primarily are dependent on the fluxes – quantities, variation, and timing of peak discharges – of the water and sediment they convey. Prior to basin development, channel gradients of the Rio Grande and the Colorado and Yellow Rivers were dynamically adjusted to the water and sediment delivered to the streams, but flow regulation, reduction of flow volumes by diversions and water extractions, and storage of sediment have altered the adjusted conditions without causing large net change in the relatively slowly responding channel gradients.

The mean channel gradient of the 5550-km Yellow River is 0.00082 ($m\ m^{-1}$). The upper reach of 3470 km has a mean gradient of 0.00100, whereas the middle reach, which receives sediment from the Loess Plateau between Hekouzhen and Zhengzhou, and the lower reach, downstream from Zhengzhou, have mean gradients of 0.00074 and 0.00012, respectively (Decun, undated). The gradient of the middle reach, for a mean discharge of 1800 m^3s^{-1}, is consistent with a wide, sandy, braided channel (Osterkamp, 1978), and the much gentler channel gradient of the lower reach is indicative of lowered flow velocities and reduced transport capacity of the coastal plain, and therefore, deposition of the coarse fraction of the sediment load. The gradient of the middle reach Yellow River may represent adjusted conditions prior to extensive alteration by diversions and impoundments, but the 84-percent reduction in gradient of the lower coastal-plain reach is inferred to be largely the result of reduced flows and partly due to a 120-m increase in sea level, thus base level of the river, during the last 10,000 years (Lambeck and Chappell, 2001).

PROBLEM

Floods and shifts in channel position, due in part to extraordinary sediment loads in the Yellow River, have caused numerous disasters throughout the history of China (Todd and Eliassen, 1940). Withdrawals of water from the Yellow River have reduced flows, particularly in the middle and lower reaches. Deficient precipitation, as occurred during the 1990s, has decreased significantly or eliminated flows reaching the lower part of the Yellow River. Since

1950, moreover, consumptive use of water has increased about 250 percent, about half of the available lower Yellow River discharge (Gray and others, 2002).

In the three drainage basins considered here, dams, reservoirs, and diversions greatly alter natural hydrologic processes by regulating and reducing mean and peak streamflows and by storing fluvial sediment. Most of the large dams and reservoirs of the Yellow River Basin are in the upper and middle reaches of the river. Along the upper Yellow River, mean discharges at the Longyangxia and Lijiaxia Hydropower Stations (basin areas 131,400 km^2 and 137,000 km^2, respectively) are 647 and 664 m^3s^{-1}, whereas mean discharge increases to 865 m^3s^{-1} at the Liujiaxia Hydropower Station (basin area 182,000 km^2). Large dams of the middle Yellow River are at Sanmenxia and Xiaolangdi (basin areas of 688,000 and 694,000 km^2). In the lower Yellow River Basin especially, flow depletion, both natural and imposed, has adversely altered channel conveyance, water quality, agricultural potential, bottomland habitat, and public water supply**.**

Sediment yield in the Yellow River Basin is extreme, about 2100 t/(km^2·yr), a quarter of which is deposited along the leveed 780-km lower reach of the river. Recent sedimentation has caused bed-elevation increases up to a meter per decade (Gray and others, 2002). The effects of reduced flows and flood peaks by diversions and reservoirs in the upper and central basin, accelerated erosion in the Loess Plateau, and sediment deposition along the lower Yellow River (1) degrade both uplands and bottomlands of the Loess Plateau and limit its agricultural potential, (2) reduce the ability, in the central basin especially, to generate hydropower and provide water for irrigation due to sediment storage, (3) decrease food production from lowlands along the lower Yellow River owing to excessive sedimentation, and (4) threaten the safety of farms, population centers, and historical structures due to the potential of major flood and breeching of levees.

The combination of reduced flows from water extraction for domestic and agricultural purposes and flow regulation by dams has induced sediment deposition along the lower Yellow River. Sediment accumulated during 1986 through 1997 at an annual rate of 250 million tons, 70 percent of which was in the main channel. Sedimentation in the lower reach, coupled with reduced conveyance owing to reduced differences between river-bed and flood-plain levels, has halved the channel conveyance to about 3000 m^3/s and prompted lowland inundation by relatively modest floods (Gray and others, 2002). Along the central and lower reaches of the Rio Grande and Colorado River, water extraction is mostly for irrigated agriculture of bottomlands. The extractions reduce discharges of the rivers significantly, but upland erosion and sediment discharges are not greatly increased above background rates owing to a general lack of land-use disturbance.

Reservoirs of the Rio Grande Basin, including Cochiti and Elephant Butte in New Mexico and Amistad and Falcon in Texas (fig. 2), store nearly all of the sediment transported by the upper and middle river (Meade and Parker, 1984). Records of sediment discharge in the Rio Grande at San Marcial, NM, and El Paso, TX, upstream and downstream from Elephant Butte Reservoir, demonstrate dramatically sediment storage in the reservoir. During recent decades, suspended-sediment discharges at El Paso have averaged less than 5 percent of those at San Marcial. Downstream from El Paso, sediment discharge of the Rio Grande increases owing to inflows from the Rio Conchos (from Mexico) and the Pecos River (from Texas). Since closure of Amistad Dam (1969), near Del Rio, TX, and Falcon Dam (1953), near Laredo, TX, most of these inputs too have been stored. Consequently, suspended sediment of the Rio Grande reaching the Gulf of Mexico, which probably approached 20 million tons yr^{-1} before 1940, now averages a few percent of that amount (Meade and Parker, 1984)**.**

DISCUSSION AND APPROACHES TO SEDIMENTATION PROBLEMS

Basin conditions and hydrologic changes to the Rio Grande and the Colorado River are similar to those of the Yellow River. Dams, some nearly a century old, in the middle, sandy reaches of the Rio Grande and Colorado River alter fluxes of water and sediment, causing scour directly downstream and re-deposition of the eroded sediment farther downstream, especially in and directly upstream from succeeding downstream reservoirs. Data from the United States rivers and channel-change data from the Yellow River provide a basis to anticipate continuing accelerated erosion along much of the middle reach, Yellow River, and deposition along its lower reach. If these processes continue, hazards to people, structures, and agriculture in the Yellow River Basin most likely will intensify.

Dams and reservoirs along the upper and middle reaches of the Yellow River have dramatically altered the timing and magnitudes of releases to the lower river. Since 1986, when dams at Longyangxia and Liujiaxia were completed, flood-season releases have decreased about 50 percent, but other releases have increased as much as 55 percent. This aspect of river regulation and sediment-supply disruption optimizes water use in the lower reach, but reduces the high flows capable of entraining stored sediment as well as sediment actively in transport. Without a strategy to reduce inputs of sediment from the Loess Plateau to the middle reach, prevent net deposition of sediment, and remove sediment stored during recent centuries and millennia, bottomland aggradation and related flood hazard along the lower Yellow River will persist, thereby aggravating an already serious problem.

Channel gradients of the Yellow River, the Rio Grande, and the Colorado River remain adjusted to previous conditions of unregulated discharge and unhindered passage of sediment from uplands to the seas. Observations at the three rivers and many others (Williams and Wolman, 1984) show that processes determining downstream channel morphology were greatly altered by dam construction, but, except locally, channel gradient has not been greatly affected. In most cases, regulation and storage of bed load by dams cause scour and degradation downstream from dams, lowland aggradation farther downstream, but little change in mean channel gradient. These tendencies occur along sand-bed reaches of the three rivers discussed here, resulting in continuing aggradation along lower river reaches and a large potential for flood damage.

Owing to drainage-net characteristics and relatively low values of sinuosity, the imposition of meaningful increases in gradient through channel shortening of the Rio Grande and the Colorado River is impractical. Reduction of the on-going problem of storage of coarse sediment supplied by tributaries entering the two rivers may be feasible only by eliminating changes previously imposed – regulation of streamflow, depletion of streamflow, and storage of sediment in reservoirs. Problems of the Yellow River are directly comparable to and, in some respects, more intense than those of the Rio Grande and the Colorado River, but may be more easily addressed by solutions other than those limited to the removal of dams and reservoirs and restoration of natural flow rates.

Population (and cultural and architectural treasures in lowlands), manufacturing, and agriculture of the Yellow River Basin increase with greater mean precipitation down-valley. If the greatest degree of protection for these resources is to be placed on the most populated and productive lowest part of the Yellow River Valley, several possible approaches can be considered to address the short-term (due primarily to floods) and long-term (due largely to channel aggradation) safety of the lower Yellow River Basin:

1. Continue present policies of increasing agricultural productivity in the Loess Plateau, applying erosion-control measures, and storing sediment and flood flows behind large dams of the upper and middle reaches of the Yellow River. This alternative provides

protection against moderate floods, but does not significantly reduce the vulnerability of the lower Yellow River Valley to high-magnitude floods and sedimentation; nor does it alter the processes that presently are steadily increasing sedimentation and concomitant hazards along the lower Yellow River.

2. Divert water from the Yangtze River into the Yellow River, either upstream of the Loess Plateau near Minhsien or downstream of the Loess Plateau near Luoyang or Zhengzhou. Flow augmentation of this sort above the Loess Plateau could cause large increases of sediment transport and deposition in reservoirs of the middle Yellow River. Flow additions to the lower reach would have little effect on human activities in the upper and middle parts of the Yellow River Basin, and would reduce or partially reverse the storage of sediment along the lower Yellow River; ideally, diverted water would transport sediment to the ocean. Potential disadvantages of either approach include ecosystem damage, altered hydrologic conditions in the Yangtze River Valley, importation of inter-basin flows that may be viewed as inadvisable in future decades, and increased flood potential owing to higher ground-water levels in the alluvium of the lower Yellow River Valley.

3. Retirement of agricultural and related land-use practices in the Loess Plateau without changing bottomland activities, including the storage of water and sediment behind dams along the middle reach of the Yellow River. Reversion of lands of the Loess Plateau to natural conditions, combined with revegetation of native species, could significantly reduce sediment yields from uplands of that area, thereby possibly increasing the long-term utility of hydroelectric facilities. This approach may help protect the lower Yellow River Valley from small to moderate floods, but would not substantially reduce the vulnerability to large, catastrophic floods or to continuing channel and lowland aggradation.

4. Retirement of both upland (principally land-use) and lowland (principally water-use) activities in the upper and middle parts of the Yellow River Basin, including the Loess Plateau, would eliminate agricultural production and the generation of hydropower, but would partially restore natural conditions of water and sediment fluxes to the Bohai Sea. Flows in the lower Yellow River would be increased, but the rate of sedimentation would be reduced.

5. Diversion of part of the Yellow River at Liujiaxia Hydropower Station (A, fig. 1), Gansu Province (elevation 1725 m). This would involve re-routing selected flows, especially flood discharges and other flows exceeding mean discharge, up the valley of the Tao He past Lintao (B, fig, 1) into the Wei He Valley upstream from Baoji (C, fig, 1), to its present confluence with the Yellow River (elevation 310 m) upstream of Sanmenxia Hydropower Station. This alternative would maintain low flows in the Yellow River between Lanzhou and Sanmenxia, thereby providing water for urban and irrigated agricultural needs, while considerably reducing sediment transport through the river reach. Between the two hydropower stations, channel gradient would increase about 230 percent, from 0.00074 to 0.0017 ($m\ m^{-1}$). With the construction of appropriate grade-control structures along the Wei He, the increased stream power of flood discharges, coupled with reduced sediment loads, could inhibit lowland deposition between Sanmenxia and the mouth of the Yellow River (channel gradient 0.00065), and possibly would cause bed erosion and thus reduction of flood hazard. This alternative has the possible disadvantage of decreasing agricultural and

hydroelectric outputs of the Loess Plateau. Benefits include an 85-percent increase in mean channel gradient of the diverted Yellow River between Liujiaxia Hydropower Station and the mouth, which, combined with increased flow in the lower Yellow River and elimination of most sediment inputs from the Loess Plateau, would result in an increase of sediment-transport potential through the lower reach. The likelihood of damage by large, infrequent floods may be increased due to bypassing large dams of the Loess Plateau, but this likelihood may be reversed by an increase in channel conveyance through the lower reach as stored channel sediment is entrained and flushed to the Bohai Sea.

Each of the alternatives is associated with disadvantages as well as benefits, and it is emphasized that these alternatives are suggested here only as possible solutions that require more study before a single solution is advocated. The first option, that of continuing present management approaches, may be the least desirable because sediment loads reaching the river will continue to increase, water extractions will continue to decrease flows in the lower reach, lowland aggradation and sedimentation along the lower Yellow River will continue to increase, and the threat of catastrophic flooding downstream from Zhengzhou will become more pronounced each year.

Proposals to modify or induce flooding in the lower Yellow River date from at least the 1960s (Qi, 1997). The general concept of controlled flows to rehabilitate river lowlands, such as controlled releases to the Colorado River from Lake Powell (fig. 2), can be an effective management tool for any large river (Marzolf and others, 1999). A benefit of approach 5 is that releases from Liujiaxia Hydropower Station can be based on Yellow River flow, consumptive needs in the middle basin, and the need to reduce bed elevation along the lower reach of the river. During periods of low runoff, for example, most flow would discharge from Liujiaxia Hydropower Station into the Yellow River, whereas during times of higher flow, and especially during flood, much of the flow would be diverted through the Tao He into the Wei He to maximize scour in the lower reach of the Yellow River. Use of adaptive management, therefore, could not only continue to provide adequate flow to the middle Yellow River, but also could reverse bed aggradation in the lower reach.

The net long-term advantages for the well-being of the people and agricultural production of the Yellow River Basin may be greatest if approach 5 is considered. This approach seems most likely to offer lasting protection for life and resources of the lower basin while minimizing adverse effects of the upper and middle basin. Importation of water from the Yangtze River has the same advantage of flushing stored sediment from the lower Yellow River Valley, but may include negative features, such as future economic (political) imbalances of water distribution and disruption of regional ecological systems.

SUMMARY

Runoff entering the Yellow River, the Rio Grande, and the Colorado River is mostly meltwater from high elevations, but most of the sediment carried by the rivers comes from central, semiarid parts of the drainage basins. Bottomlands of the lower Yellow River have been aggrading for millennia owing to streamflow insufficient to transport all of the sediment supplied to the river, but flow reductions in recent centuries and increases in sediment supplied to the river owing to land-use stresses have increased the sedimentation problem and related hazards markedly. As with the Rio Grande and the Colorado River, regulation of flow along the Yellow River reduces mean discharge and flood peaks, affects channel gradient, and through winnowing alters the sizes of bed material, thereby causing transport-limited conditions for sediment transport.

Evaluation of advantages and disadvantages of several options to reduce the hydrologic imbalances of the Yellow River Basin, supported by observations of similar problems in the Rio Grande and Colorado River systems, indicate that at least three basic considerations are needed to reverse sedimentation problems and hazard of the Yellow River. Most importantly, either delivery of sediment to the river must be decreased or the river needs to be re-positioned to avoid the transport of sediment through the middle basin. Flows need to be great enough to transport both the sediment supplied to the river and to entrain over time sediment stored along the lower reach. Channel gradient needs to be increased to provide the energy required to entrain and transport sediment loads of the Yellow River.

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