Effects of Water Use Diversion Regulation and Conservation on Sediment Transport in China's Yellow River with Comparisons from the United States

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1 Introduction

Too much sediment and too little water are related problems in China's Yellow River Basin. Sediment yield in the basin averages about 2,100 t/(km^2·a), greatest is of the world's large rivers although the Yellow River ranks 31st in mean flow. A quarter of the sediment deposited in the 780-km lower reach, causing bed levels to rise an average of a meter per decade wang and other. Sediment aggradation along this reach is concentrated between dikes, resulting in average river-bed elevations 5 m higher, and at Xinxiang as much as 10 m higher, than surrounding bottomlands. The dikes, which have breached nearly 1,600 times in the last 24 centuries, reduce the threat of flooding for 85-million people on 120,000 km^2 in five provinces of northeastern China (Decun, undated). This paper addresses some environmental and social factors related to this problem, and provides descriptions of two United States rivers that exhibit some analogous responses, albeit not to the extent of those associated with the Yellow River, "China's Sorrow".

2 Background

China's centrally located Loess Plateau, comprising 60 percent of the 750,000-km^2 Yellow River Basin, has the world's largest loess deposit, and yields 90 percent of the sediment reaching the lower Yellow River. The loess supports sparse vegetation that provides little protection from highly erosive summer rainstorms. A result is high runoff rates delivering up to 40,000 t/(km^2·a) of Loess Plateau sediment from localized areas to the Yellow River.

The Chinese Government has promoted Loess Plateau forestation, terracing, contour farming, drainage-net reduction, and construction of retention dams and diversions to increase food production through water conservation while reducing erosion and sediment discharges to the Yellow River. For example, Shaanxi Province plans a 34-percent increase in forest area, and erosion reduction in 63 percent of its vulnerable lands by 2005 (China Daily Newspaper, 2001). Reductions in Loess Plateau sediment transport are considered central to attaining the goal of nearly halving the 1.6-billion tonne annual sediment load of the lower Yellow River, and for cessation and eventual reversal of bed aggradation in the lower reach.

3 Flow, sediment transport, and aggradation

Persistent Yellow River flow depletion resulting from natural and human-induced processes has had deleterious effects on channel conveyance capacity, water quality, ecology, agriculture, and public water supply, particularly in the lower reach. The mean annual water consumption from the river in the 1950's was 12.2 billion m^3; in the 1980's and 1995's, consumption averaged almost 30 billion m^3 annually, of which 90 percent was used for irrigation (Fig.1). A combined 4,250 m^3/s can be diverted from the lower Yellow River via 137 flow-control structures. Consumptive withdrawals from the river are as high as half of its mean annual 58-billion m^3 discharge.

Withdrawals have resulted in reduced flows in the river's lower reach, particularly over the last

decade during which precipitation in the Yellow River Basin has been deficient. For example, the Yellow River in Shandong Province had no daily flow for about 11 percent of the days from 1972 through 1998, probably the result of the combined effects of climatic variability and increased water consumption. During recent centuries droughts have averaged two per decade. Since 1950, annual water consumption has increased by about 2.5-fold and now totals about 30 billion m^3.
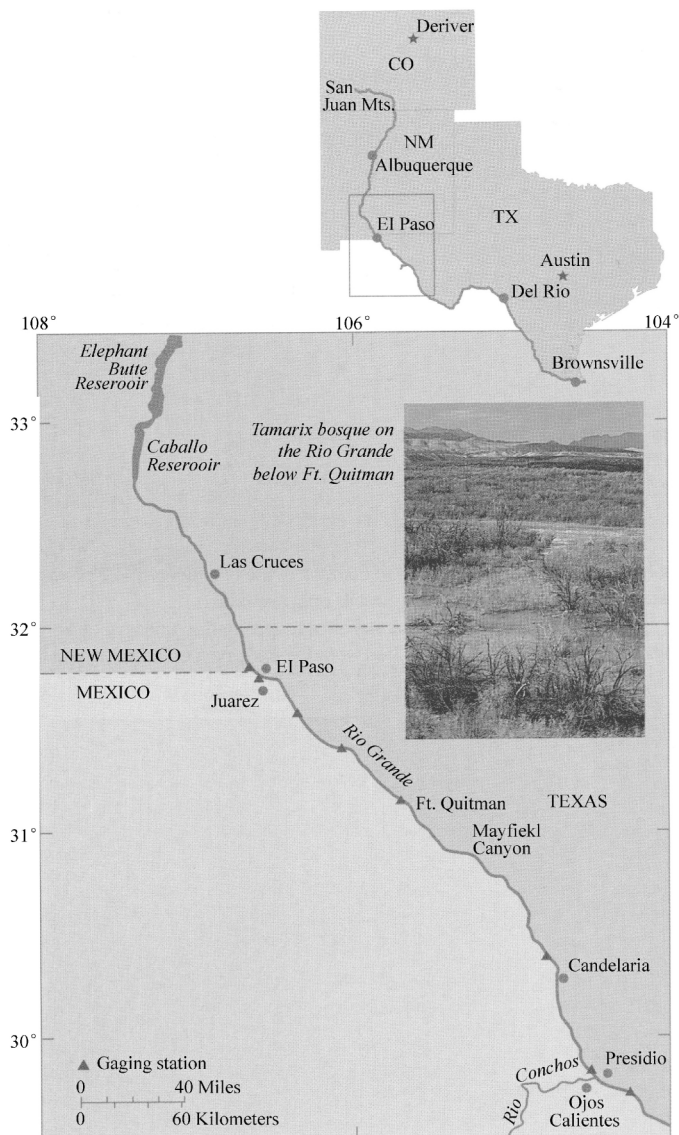

Fig. 1 The Rio Grande Between Elephant Butte Dam, New Mexico, and Presidio, Texas (from Collier, Webb, and Schmidt, 2000)

Table 1 Mean annual industrial and agricultural water consumption in the Yellow River basin (units are billions of cubic meters)

Yellow River Reach	1950—1959	1960—1969	1970—1979	1980—1989	1990—1995
Upper	7.34	9.52	10.3	12.1	2.3
Middle	3.00	4.94	6.34	6.21	6.41
Lower	1.89	3.31	8.35	11.3	10.1
Mean Annual Water Consumption	12.2	17.8	25.0	29.6	28.8

Since 1986, when dams forming reservoirs at Longyangxia and Liujiaxia in the river's upper reach began operation, the timing and magnitude of releases to the lower Yellow River have changed. Flood-season releases were reduced from 60 percent to 45 percent, whereas non-flood season releases were increased from 40 percent to 55 percent. This water-release strategy has the advantage of minimizing flow depletions in the river's lower reach, but the concomitant disadvantage of reducing the higher flows that are most efficient for transporting sediment.

The substantial increase in water use coupled with flow regulation has further exacerbated the already serious problem of sediment aggradation in the lower Yellow River. The average annual rate of sediment accumulation from 1986 to 1997 in the lower reach was 250 million tonnes, of which about 70 percent collected in the main channel. Sediment deposition in the lower reach, coupled with reductions in conveyance due to the reduced elevation differential between the river bed and flood plain, has halved the bankfull discharge to about 3000 m^3/s. This has resulted in comparatively high peak stages during relatively modest floods. For example, a peak discharge of 7,600 m^3/s at Huayuankou Hydrometric Station in August, 1996, generated a stage that was 0.91 m higher than that for a 1958 flood with almost triple the discharge.

The Yellow River is but one example of a river that suffers from channel aggradation due to insufficient streamflow to transport the sediment reaching the main channel. Transport-limited conditions, for which discharge, gradient, and sediment sizes largely control particle entrainment, are common in regulated streams. Examples of transport-limited conditions in two western United States rivers are presented to demonstrate the common geomorphic response to reduced streamflows from water withdrawals and (or) regulation.

3.1   Rio Grande United States

The Rio Grande drains about 440,000 km^2 of northern Mexico and the southwestern United States, flowing 3000 km from the San Juan Mountains of Colorado to the Gulf of Mexico (Collier and others, 2000) (Fig.1). In northern New Mexico, a mean daily flow of 20 m^3/s derives principally from snowmelt. Near the Gulf of Mexico, mean daily flow is 70 m^3/s. Between the Texas cities of Ft. Quitman and Presidio, however, this sand-bed river can be dry, a result of water withdrawals for agriculture. Inadequate flows combined with tributary streams adding water and sediment to the Rio Grande have had undesirable consequences for those living near the river's middle reach. Decade of predominantly dry years through 1904 caused the Rio Grande periodically to cease flow, leaving the river unreliable for agricultural uses. Elephant Butte Dam, midway between Albuquerque, New Mexico, and El Paso, Texas, was completed in 1916 for water supply. The initial capacity of Elephant Butte Reservoir was 3,200 hm^3, enough to store almost three years of the river's average flow, thus converting the Rio Grande into a dependable year-round source of water for irrigation of 81,000 hectares of southern New Mexico and western Texas.
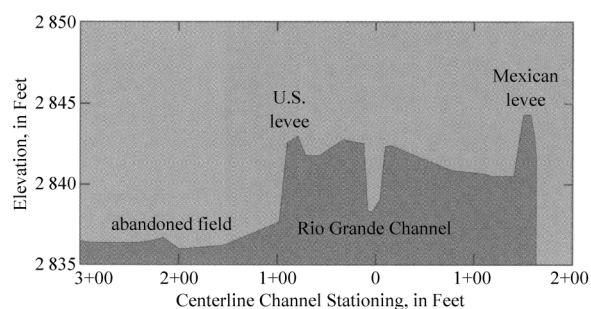

Fig. 2   A cross-section of the Rio Grande 2 km downstream from Candelaria, Texas. 1974
(from Collier, Webb, and Schmidt; adapted from Everitt, 1993)

A consequence of this dependable water was that peak spring runoff downstream from Elephant Butte Dam, averaging 125 m^3/s prior to dam construction, was reduced by 70 percent. Clear-flow releases caused 0.7 m of scour between the dam and Las Cruces, New Mexico, during the first 15 years of dam operation. Tributary-derived sediment, plus material eroded from the channel downstream from the dam accumulated downstream near El Paso, Texas, where the river gradient flattened. From 1907

through 1933, the river bed aggraded almost 4 m through El Paso. A Rio Grande flood in 1942 peaked at 200 m³/s, about 30 percent of that for the maximum flood measured in 1904. This comparatively modest flood, which would have remained confined to the pre-dam channel, caused flooding in the lower reaches of El Paso. By 1974, the channel had aggraded so much near Candalaria, Texas, that the bed of the dike-confined channel was higher than its floodplain (Fig.2).

3.2   Green River

The Green River drains a 120,000 km² basin in Wyoming, Colorado, and Utah (Collier and others, 2000) (Figure 3). Its main source is the Wind River Range of western Wyoming, 1,200 km upstream from its confluence with the Colorado River in Utah. High mountains and plateaus rimming the Green River Basin contribute most of the river's annual flow, though they comprise but a small part of the basin area. From 1895 through 1962, the mean annual peak flood of the Green River at Green River, Utah, was 910 m³/s. Flaming Gorge Dam, closed in 1962, was constructed primarily for power generation. Flaming Gorge Reservoir first filled in 1966. Although the annual volumes of water released from the dam since 1966 are not significantly different from those before the dam was closed, the timing of flows has been radically altered – releases from the dam have increased winter flows and the spring flood has nearly been eliminated.
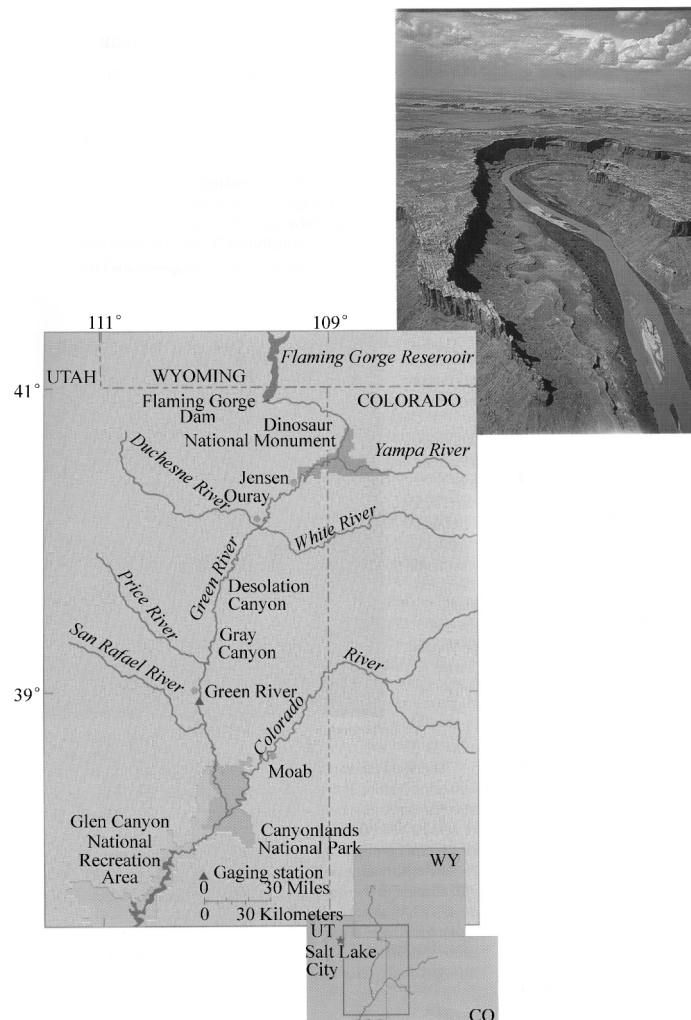

Fig. 3   The Green River from Flaming Gorge Dam to its Confluence with the Colorado River in Utah (from Collier, others, 2000)

Flaming Gorge Reservoir intercepts and stores almost all sediment conveyed to it, and therefore water released from the dam is devoid of the sand and silt characteristic of the natural sediment load. Between the dam and the mouth of the Yampa River, the rate of sediment replenishment by tributaries has not equaled the rate of sediment scour by the nearly sediment-free Green River, and in response the channel has degraded. Since the dam was closed, the Yampa River has delivered most of the 2.9-million tonnes of sediment that the Green River carries annually past Jensen, Utah. Through the 160-km reach between Jensen and Green River, Utah, the sediment budget of the Green River is in approximate adjustment, the bed exhibiting neither aggradation nor degradation. Downstream from the town of Green River, sediment contributions to the river by desert tributaries accumulate in the Green River channel. Deprived of the spring floods capable of moving the sediment, the river in this lower reach has aggraded and narrowed.

4   Different continents, common water-management and sedimentation problems

The Rio Grande of southern New Mexico and western Texas, and the Green River downstream from Jensen, Utah, are transport-limited sedimentary systems. Rainstorms on the high Chihuahuan Desert locally cause floods in ephemeral tributary streams, transport large quantities of sediment into the Rio Grande, and form alluvial fans at the mouths of the tributaries. Before regulation for water consumption, the Rio Grande maintained a dynamic equilibrium with these sediment deposits. The channel would aggrade next to tributary fans, and flood-plain deposits would accumulate during moderate overbank floods. Larger, less frequent floods would deepen and widen the channel, redistributing the tributary fan sediment downstream. Lacking the previous peak flows to move sediment, there now is no natural mechanism periodically to scour the channel of tributary-derived deposits.

The Green River channel downstream from Jensen, Utah, is less affected by water withdrawals than by regulation, but the hydraulic mechanisms are the same as in the Rio Grande – lowered peak discharges lack the stream power to remobilize main-channel sediment derived from tributaries. Consequently, the channels of these streams have aggraded, as have those of many other regulated streams in the American Southwest.

Flows in middle and lower reaches of the Yellow River, like those of the example reaches of the Rio Grande and the Green River, are transport-limited. Bed material of the Yellow River is largely sand and finer sediment that is easily entrained by moderate or larger Yellow River flows. Due to the higher channel gradient in the middle reach, the transport capacity at a given discharge exceeds that of the lower reach. The result is a reduction of sediment-transport capacity and bed aggradation in the lower Yellow River's lower reach.

If the aforementioned conservation measures initiated by the Chinese Government are successful, runoff volumes and peak flows in streams draining the Loess Plateau will be generally reduced. Even reduced runoff, however, will remain transport-limited with relatively high concentrations of sediment – particularly for flows of small recurrence probability. Reductions in Loess Plateau runoff, coupled with water withdrawals in the Yellow River Basin, will decrease further river discharge and sediment-transport capacity. Cessation or reversal of aggradation in the lower reach is unlikely under this scenario.

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