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Medium- and Long-Term Changes in Fluvial Discharge to the Sea: The Yellow River Case Study

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Medium- and Long-term changes in fluvial discharge to the sea: The Yellow River Case Study

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A Thesis
Presented to
The Faculty of the School of Marine Science
The College of William and Mary in Virginia

In Partial Fulfillment
Of the Requirements for the Degree of
Master of Science

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by
John J. Galler
August 1999

APPROVAL SHEET

This thesis is submitted in partial fulfillment of
The requirements for the degree of

Master of Science

John J Galler

John J. Galler

Approved, August 1999

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DEDICATION

Mom, for making me realize that life is too short and when a door closes, I'd better find the window that just opened.

Dad, for reminding me that everyday I should learn something and have a good laugh, and to always use my "library card."

Dave P. Thomas, who taught me environmental science's big picture, the forward stroke and the poke check. "Be excellent to each other."

Edward Abbey, "What is life, if full of care, we have no time to stand and stare, eh?" I'm coming to find you, Jack Burns.

Dr. John Milliman for showing me how this science thing is done.

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Go raibh mile maith agat.

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Abstract

The Yellow River has long been known to be one of the greatest suppliers of sediment to the ocean, its load generally cited to be 1.1 x 10^9 t/yr, or about 5% of the global total. Over the past 20 – 25 years, however, the Yellow River's flow of water and sediment has decreased dramatically, and in 1997 both represented less than 1% of what they did in the early 1960's. Two questions arise for this observation: 1) Is this decrease related to natural or anthropogenic causes, and is it cyclical or long-term: 2) How does the decreased flow affect the long-term sediment load?

In terms of the first question, runoff in the Yellow River basin appears to operate on a 65 to 75-year cycle, the previous low-flow period occurring in the late 1920's and early 1930's. Superimposed on this cyclical trend, however, there has been a 15% decrease in Yellow River basin precipitation over the past century. Coupled with these natural occurrences, the rates of water removal have dramatically increases in response to both decreased water supply and greater need for irrigation and other consumptive uses. As a result of all these changes, the 75-year mean for the Yellow River sediment load is estimated to be 0.9 x 10^9 t/yr, the very low recent loads nearly counterbalanced by the very high loads during wet years.

MEDIUM- AND LONG-TERM CHANGES IN FLUVIAL DISCHARGE TO THE SEA: THE YELLOW RIVER CASE STUDY

Introduction

Background

Rivers serve as a critical link between land and the ocean, discharging both fresh water (~35,000 km^3/yr) and eroded sediment (~20 x $10^9 t/yr$) (Milliman 1991; Milliman and Syvitski 1992). Although many rivers supply great amounts of sediment to the oceans, the rivers draining China carry disproportionately large amounts relative to their watershed areas (Figure 1). Of these Chinese rivers, the Yellow River is perhaps best known to geologists and oceanographers. While it is the second largest in China in terms of drainage area (Yangtze is larger) and fourth largest in terms of water discharge (Table 1) (Milliman and Meade 1983), its load (1.1 x 10^9) is the largest in the world, and twice the amount discharged by the Yangtze.

The Yellow River exceeds 5400 km in length, originating at the northern foot of the Bayan Har Mountains, Qinghai Province and running through nine provinces and draining into the Gulf of Bohai, a shallow, epicontinental sea north of the Shandong Peninsula (Cheng et al. 1986; Jinze 1996, Wiseman et al. 1986). The area drained by the Yellow River is approximately 750,000 km^2 (Figure 2) (Milliman et al. 1987; Milliman and Syvitski 1992; Mou 1996).

The Yellow River basin is classified as a semi-arid region, lying between the humid Yangtze River (annual precipitation >1000 mm) to the south and the arid Gobi

Figure 1: Chinese rivers transport an unusually large amount of sediment to the ocean, roughly an order of magnitude more than other global rivers. Data from Milliman and Syvitski, 1992.

World vs. Chinese Rivers

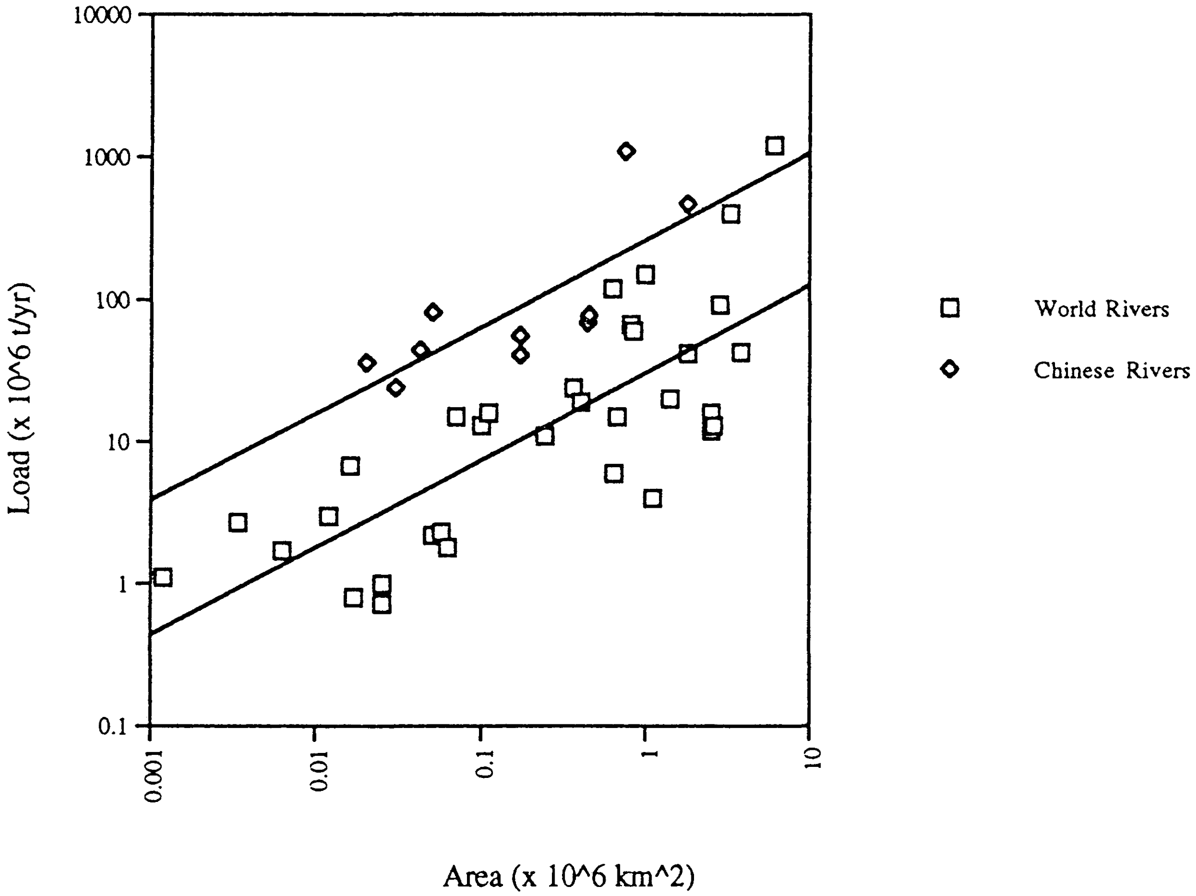
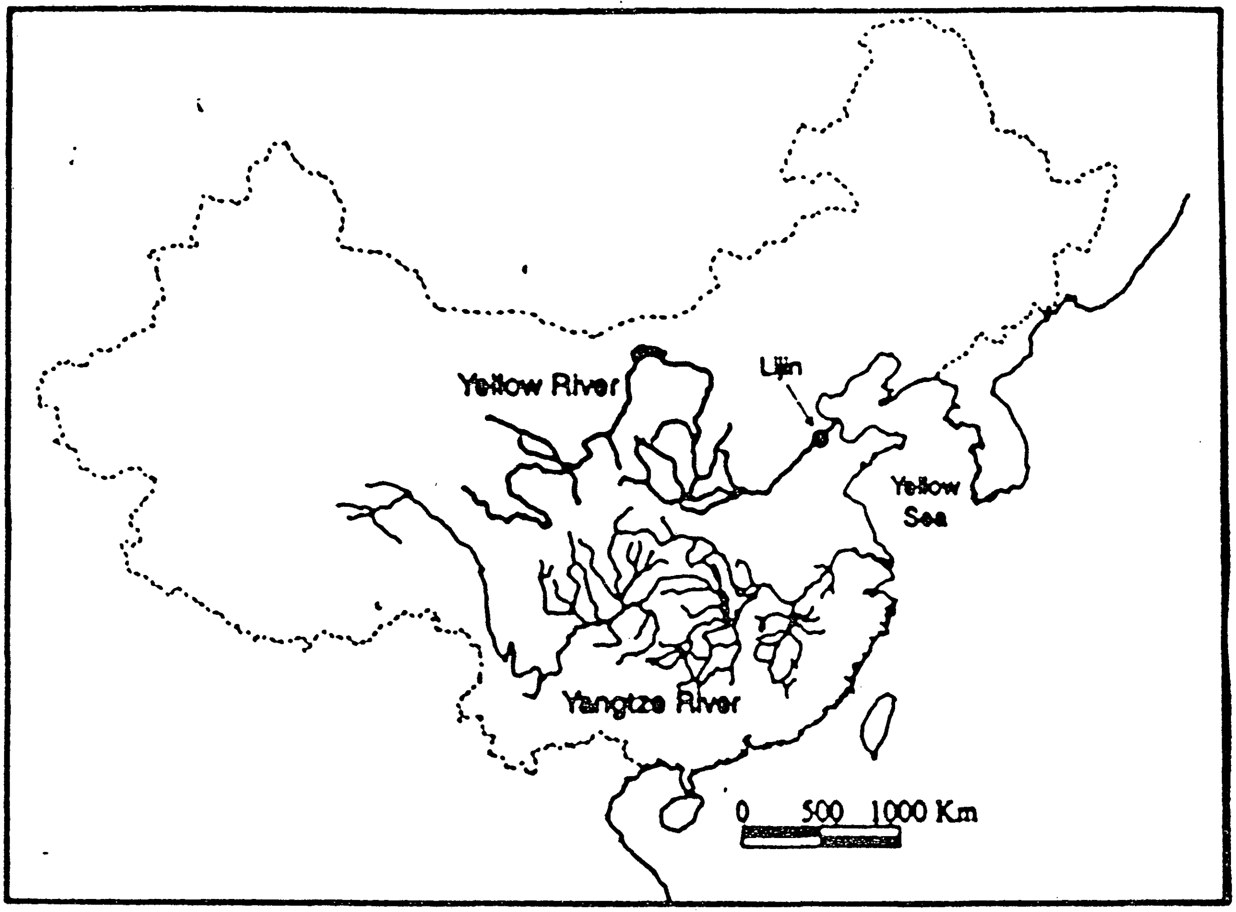


Table 1: Relevant data for the largest rivers in China.

	1	2	3	4	5
	River Name	Sediment (10^6t/yr)	Area (10^3 km^2)	Water discharge (km^3/yr)	Length (km)
1	Yellow (Huanghe)	1100	750	43	5500
2	Yangtze (Changjiang)	470	1800	910	5500
3	Zhujiang	78	450	260	2200
4	Mingjiang	7.7	61	55	580

Figure 2: Location of the Yellow River relative to the Yangtze River. From Yang et al. (1998)


Yellow River
Lijin
Yellow Sea
Yangtze River
0 500 1000 Km

Desert (100 mm/yr) to the north. The Yellow River basin has a mean annual precipitation of 400 – 500 mm (Dai 1988), although some areas have precipitation totals around 100 mm/yr (Figure 3). Of the rain that falls in the Yellow River basin, far less than half makes it into the river. Most of the basin has hydrologic runoff values less than 100 mm/yr (Figure 4). The basin experiences both intra- and inter-annual variations in rainfall. As much as 70% of this rain occurs between July and September, and most of the precipitation falls in the form of heavy rain events with intensities of 5.2 – 18.8 mm/hr. Shorter events have intensities of 1.5 – 3.0 mm/min (Ren and Shi 1986; Gong 1987). This is typical of monsoonal climate areas, such as the Yellow River basin.

The discharge of the Yellow River is subject to great amounts of inter-annual variability. Consecutive years may show a marked change, as much as 3 to 5 times more or less flow.

The most significant statistic about the Yellow River is that it has been estimated to supply 1.1 x 10^9 tonnes of sediment to the Gulf of Bohai yearly (Qian and Dai 1980), although interannual variations are large. While the Yellow River has only 1/8 the drainage area of the Amazon's and 0.7% of its flow and 4.5% of the Yangtze's discharge, the Yellow River's annual sediment load is approximately equal to the Amazon and twice that of the Yangtze (Ren and Shi 1986). Using a more local comparison, the Yellow River carries 8 times more sediment than the Mississippi while draining only 1/4 the basin area and discharging only 8% as much water (Ren 1994). Other than the Yellow,

Figure 3: Isohyet map of the Yellow River basin and surrounding area in mm/yr.
ArcAtlas: Our Earth Cd

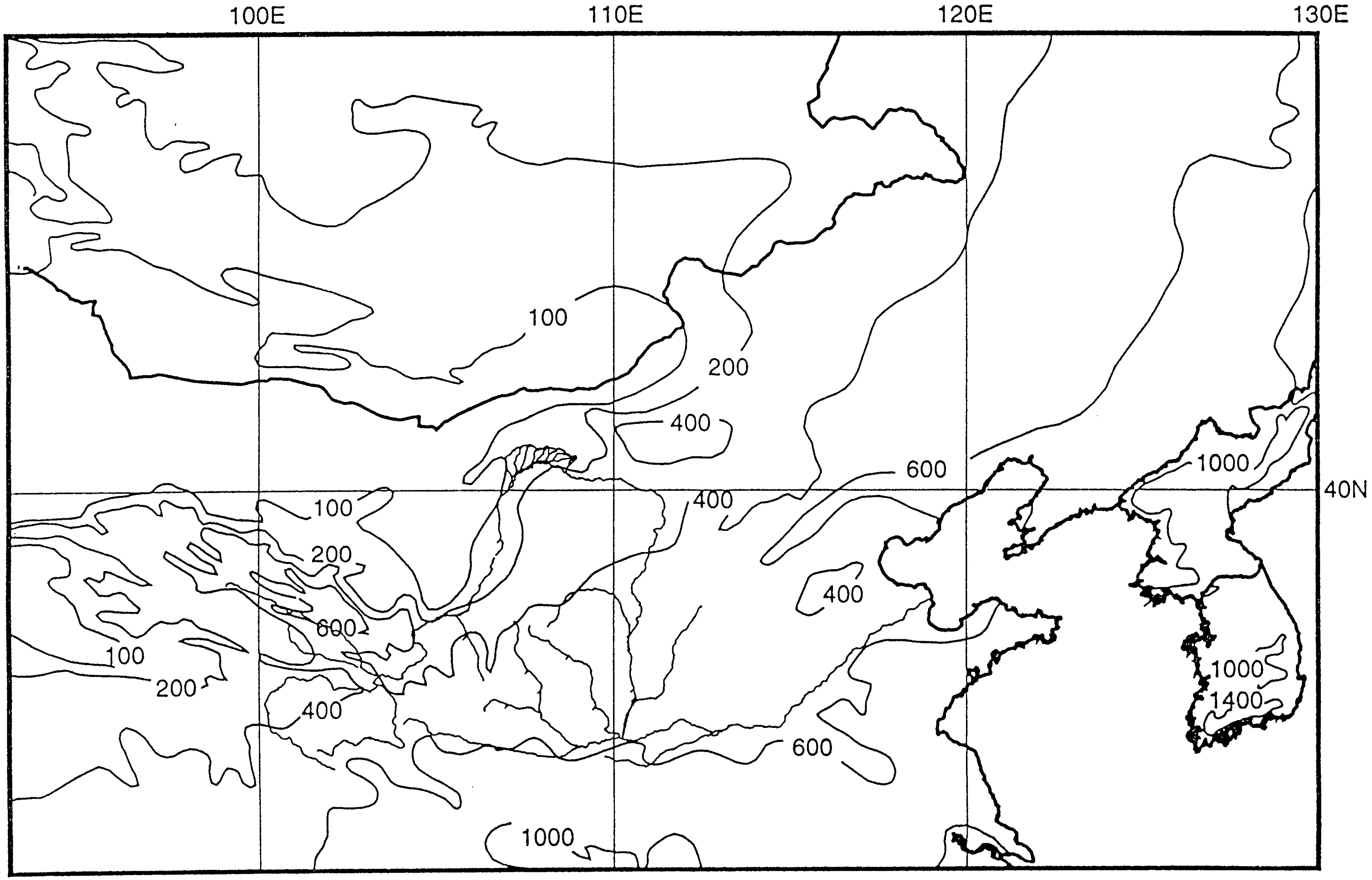
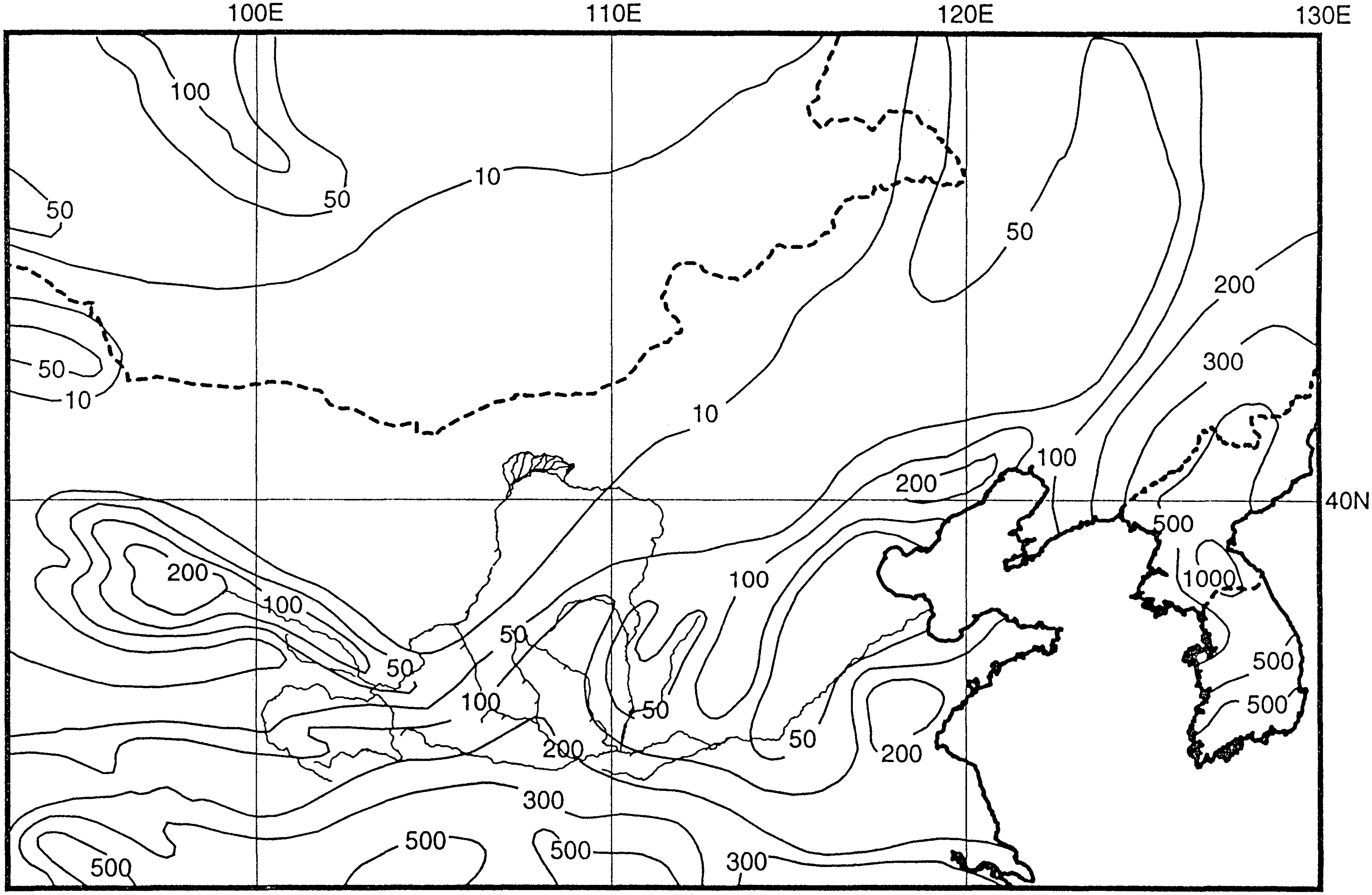

100E
110E
120E
130E
40N
100
200
400
400
600
1000
100
200
600
400
100
200
400
600
1000
1000
1400
1000

Figure 4: Runoff values in the Yellow River basin are typically 10 to 100mm/yr. Constructed using ArcAtlas: Our Earth CD.



Runoff (mm)

Amazon and Ganges-Bramaputra rivers, no river has a sediment load greater than 0.5 x 10^9 t/yr (Yang *et al.* 998).

The large sediment loads of the Yellow River are derived from erosion of the loess plateau on the middle reaches of the river (Figure 5) (Yang et al. 1996, Ren 1994, Dai 1988), its easily erodable nature related to it being fine grained (4 – 20 μm) and non-cohesive. The loess plateau covers an area of 580,000 km^2, about 77% of the total drainage basin (Long and Qian 1986). After major rainstorms, sediment concentrations in the Yellow River can reach 900 g/L (Milliman and Meade 1983, Jinze 1996), and average yearly sediment concentrations have reached 48 g/L, while monthly values can surpass 70 g/L (Milliman and Meade 1983).

Geologic Properties

The loess plateau dates back 2.5 million years to the Late Pliocene, when uplift associated with the formation of the Himalayas and the Tibetan Plateau resulted in the monsoonal climate that characterizes southern Asia. As a result, central China became more arid, aeolian processes increased, and loess began to be deposited (Xing 1980; cf. Xue 1993). In places, the loess deposits reach 200m in thickness (Dai 1988). The loess has a median grain size 0.007mm, and it has a high carbonate concentration and a distinct montmorillonite peak compared to the potassium-rich loess of the Yangtze River to the south (Figure 6a & 6b, Table 2) (Ren and Shi 1986). Table 2 shows a comparison of the

Figure 5: Map of the Yellow River basin map showing the location of the loess plateau. From Mou (1996).

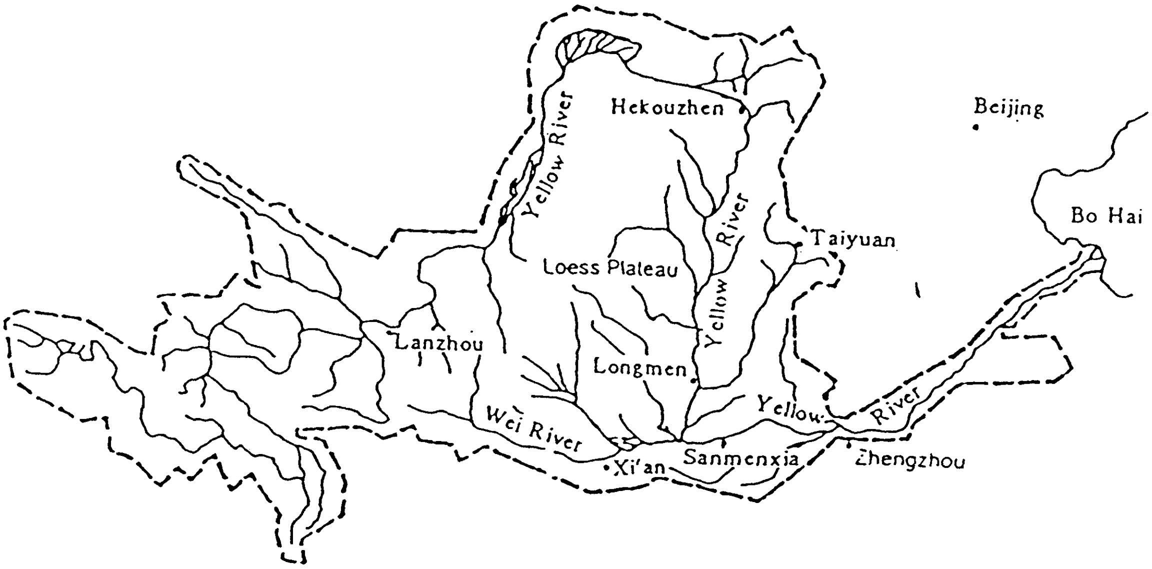
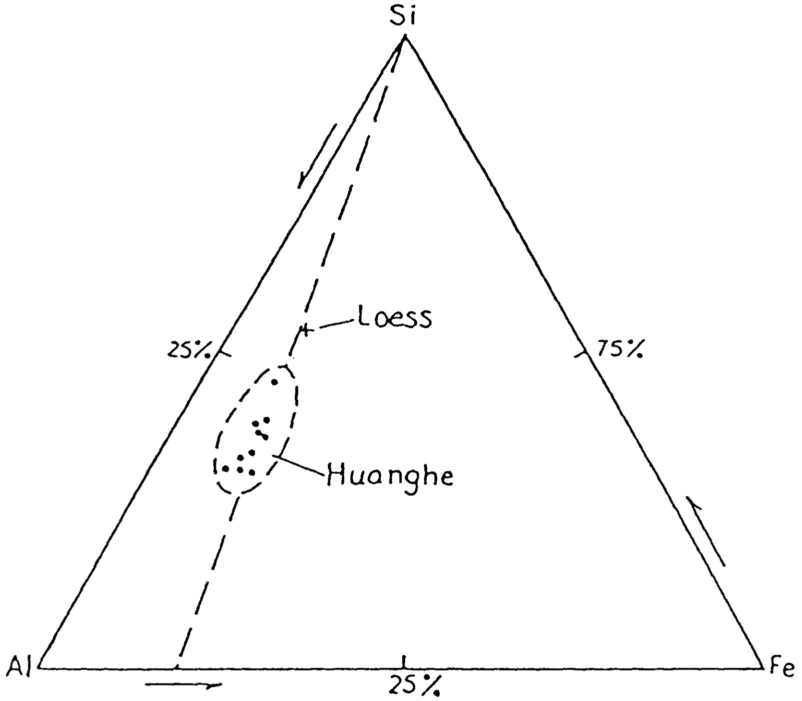

Yellow River
Hekouzhen
Beijing
Bo Hai
Taiyuan
River
Loess Plateau
Yellow
Lanzhou
Longmen
Wei River
Yellow
River
Xi'an
Sanmenxia
Zhengzhou

Figure 6a &6b: Tri-point diagrams of the mineralogy of the Yellow River loess. From Huang et al (1992).


Si
Loess
25%
75%
Huanghe
Al
Fe
25%

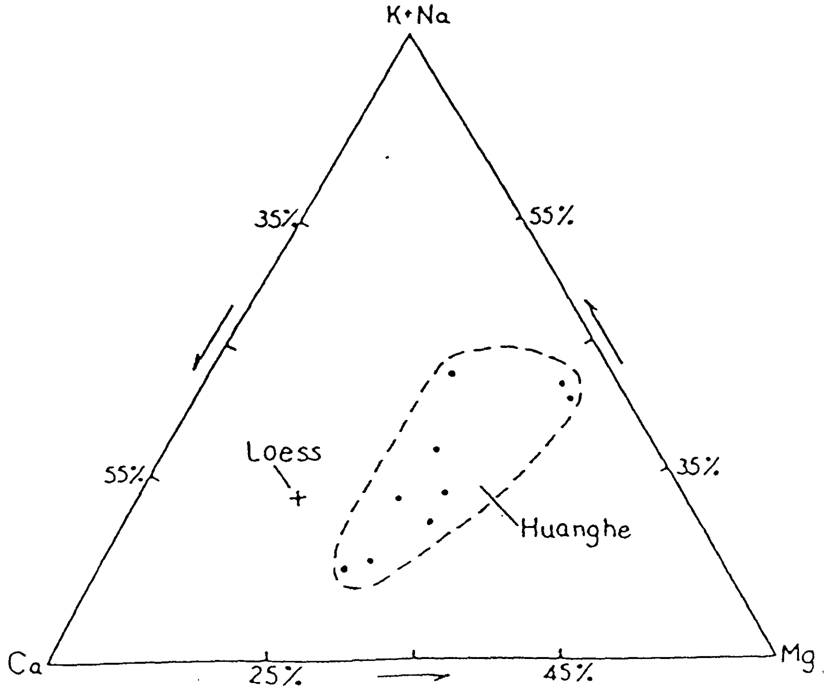

K+Na
35%
55%
Loess
55%
35%
Huanghe
Ca
25%
45%
Mg

Table 2: Mineral content of the sediments from the Yellow and Yangtze rivers. From Ren and Shi 1986.

	CaO (%)	Clay Minerals (%)			
		I	M	C	K
Yellow River Loess	9.63	67	13	12	8
Yangtze River Loess	3.5 - 4.2	75 - 79	2.0 - 4.0	C+K = 19 - 21	

clay minerals found in the sediment of the Yellow River and the Yangtze River (Ren and Shi 1986).

Because of its easily erodable nature, more than 75% of the loess plateau is affected by high rates of soil erosion, with erosion exceeding locally 5000 t km^{-2} $year^{-1}$ on 36.3% of the area, 10,000 t km^{-2} $year^{-1}$ on 77 x 10^3 km^2 and 15,000 t km^{-2} $year^{-1}$ on 33 x 10^3 km^2 (Jinze 1996). The area affected by particularly high rates of erosion often has gully densities of 4.5 – 6.0 km/km^2 (Gong 1987). Much of the loess reaches the Yellow River via gully erosion and gravitational erosion (slope-slides, slumps, collapses and mudflows) (Jinze 1996, Yang et al. 1996, Gong 1987). These high rates of erosion have greatly increased due to poor agricultural practices, which increased the load of the river by roughly an order of magnitude 2000 years ago (Milliman et al. 1987). Prior to 200 BC, the loess plateau was a wooded steppe region supplying relatively little sediment to the river, which was then called "Dahe" or "Great River". It was only after increased farming in loess hills and the associated increase in eroded sediment that the river became known as Huanghe, "Yellow River" (Ren and Zhu 1994). From 60 – 600 AD nomadic tribes invaded the area, and their pastoral society reduced the influence of farming and thus the amount of erosion to half that of present day levels. Following 600 AD, farming returned to this area and sediment loads reached present-day levels (Milliman et al. 1987).

Lower Reaches

Of the sediment eroded from the loess plateau into the Yellow River, much is deposited along the way to the Gulf of Bohai and never actually reaches open water. When the river leaves the loess plateau at Sanmenxia, it has a mean annual load of 1.6 x 10^9 t/yr. In the 500 km distance between Huayuankou (just downstream of Sanmenxia) and Lijin (100 km from the river mouth), an average of 0.5 x 10^9 t of sediment is deposited annually (Ren and Shi 1986, Milliman et al. 1987, Yang et al. 1996, Mou 1996). This large-scale sedimentation caused the bed of the lower reaches of the Yellow River to rise an average of 5 to 10 cm per year between 1955 and 1985 (Long and Qian 1986). Over the long term (100's of years), the channel has been elevated to more than 10 meters above the surrounding land surface (Gong and Xu 1987, Zhao et al. 1989). One result of this elevated river channel is that neither surface runoff nor groundwater flow contributes water to the lower 600 km of the river; in fact, some of the river water actually leaks out from the elevated channel (Yang et al.1998).

Once the water of the Yellow River reaches the mouth, the high sediment concentrations are discharged to the subaqueous delta front via hyperpycnal plumes (Prior et al. 1986, Wright et al. 1986). Of the sediment that reaches the delta, approximately 25% is estimated to be deposited in the subaerial delta and 50% is deposited in the nearshore delta mouth region, with tidal currents being the main redistributing agent of this area (Liu et al. 1998). Of the 25% that escapes the delta, half is estimated to remain in the Gulf of Bohai and the rest enters the north Yellow Sea, with approximately 1% reaching the Southern Yellow Sea (Milliman and Meade 1983; Ren and Shi 1986; Bornhold et al. 1989; Li and Finlayson 1993; Saito and Yang 1994). The annual amount reaching the Yellow Sea, therefore, only amounts to about 0.01×10^9t of the Yellow River's 1.1×10^9t/yr load. However, this still represents more sediment than is estimated to escape from all South Korean rivers combined (Milliman and Farnsworth, in prep).

Recent Trends

Despite this long-term story of high flow, the amount of water and sediment discharged by the Yellow River has dropped steadily over the past 20 – 25 years, such that relatively little sediment may presently reach the Gulf of Bohai (Figures 7a & 7b) (Yang et al. 1998). The first occurrence of no-flow at Lijin (Figure 8) was reported in 1972, and it has increased substantially since then (Pang et al. 1999). Between 1970 and 1990, the number of no-flow days at Lijin seldom surpassed 20/yr, and since 1990, the number increased steadily. In 1997, no water flowed past Lijin for 226 days (Figure 9), with months with the most dry days being April through July (Figure 10). Viewed in another way, annual water discharge prior to 1970 was consistently greater than 25 km^3 /yr and discharges in the early 1960's sometimes exceeded 90 km^3 /yr. However, in the past 12 years annual discharge has been consistently less than 25 km^3 /yr, and in 1997 only 1.8 km^3 flowed past Lijin (Yang et al. 1998).

Figures 7a & 7b: Record of the flow of water and sediment in the Yellow River since 1950. From Yang et al.(1998).

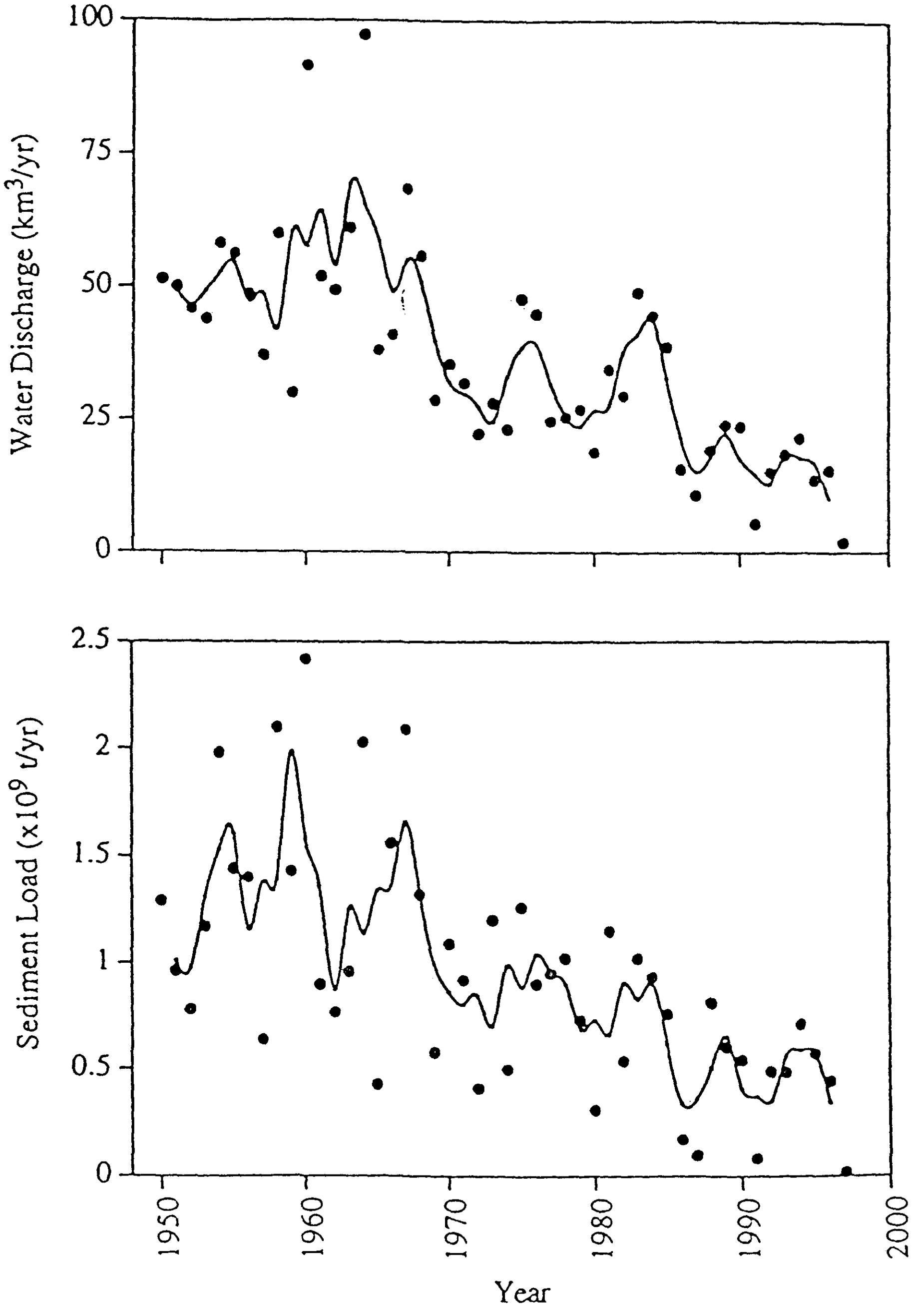

100
75
50
25
0
Water Discharge (km^3/yr)
2.5
2
1.5
1
0.5
0
Sediment Load (x10^9 t/yr)
1950
1960
1970
1980
1990
2000
Year

Figure 8: Location of gauging stations along the Yellow River. Constructed using ArcAtlas: Our Earth CD

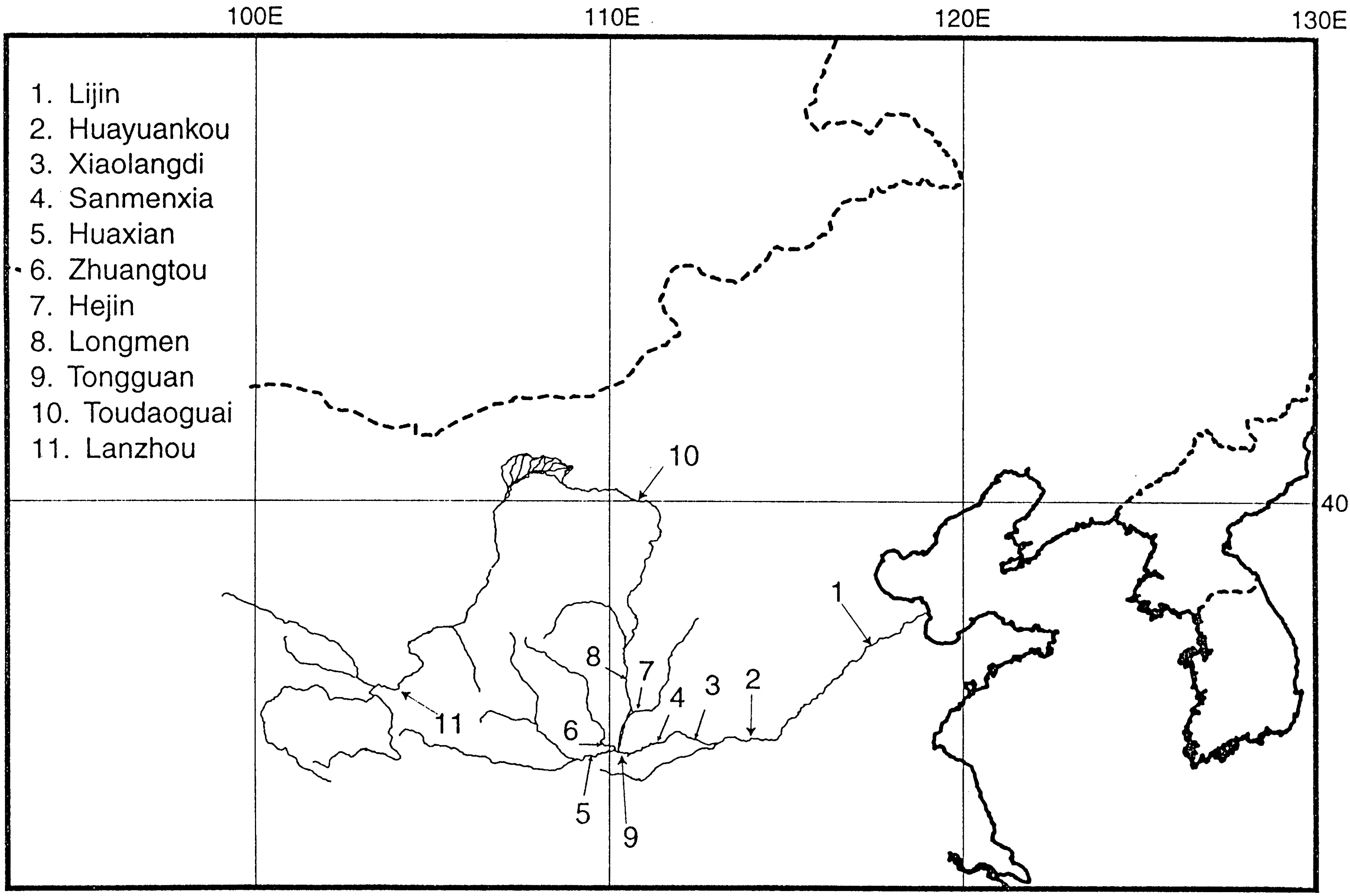
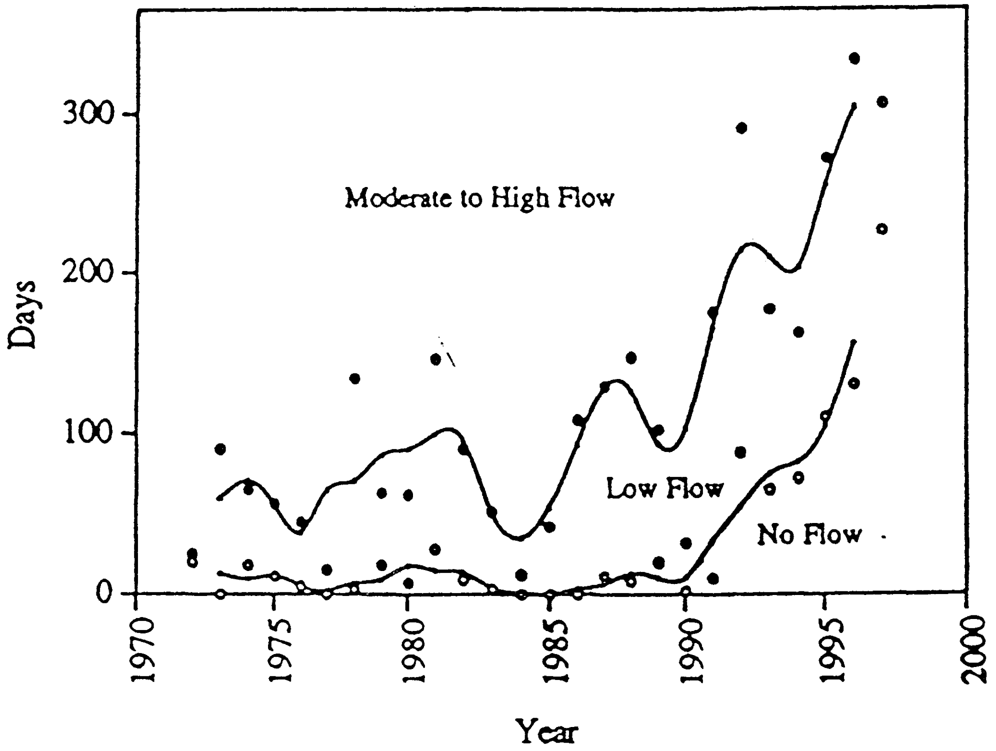
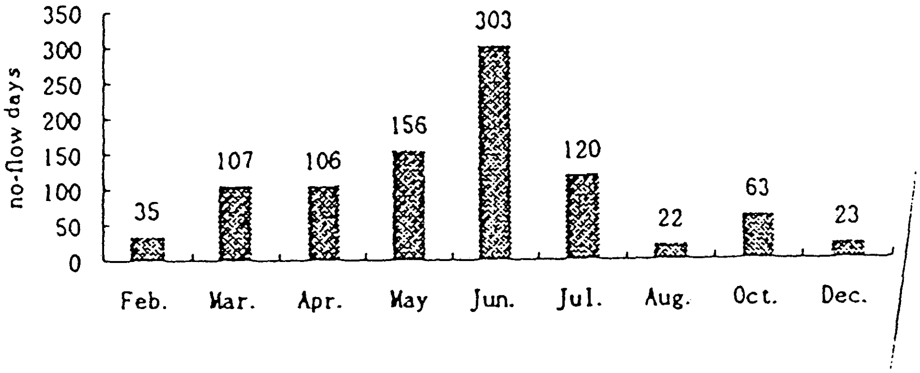

100E
110E
120E
130E
40N
1. Lijin
2. Huayuankou
3. Xiaolangdi
4. Sanmenxia
5. Huaxian
6. Zhuangtou
7. Hejin
8. Longmen
9. Tongguan
10. Toudaoguai
11. Lanzhou
1
2
3
4
5
6
7
8
9
10
11

Figure 9: Days of no flow (open circles), low flow (≤ 200 cms) (low flow + no flow = solid dots) and moderate to high flow (> 200 cms) for the Yellow River at Lijin. Lines represent 3-year moving averages.



Moderate to High Flow
Low Flow
No Flow
Days
300
200
100
0
1970
1975
1980
1985
1990
1995
2000
Year

Figure 10: Total no-flow days in different months at Lejin gauge station from 1972 to 1998. From Pang et al. (1999).



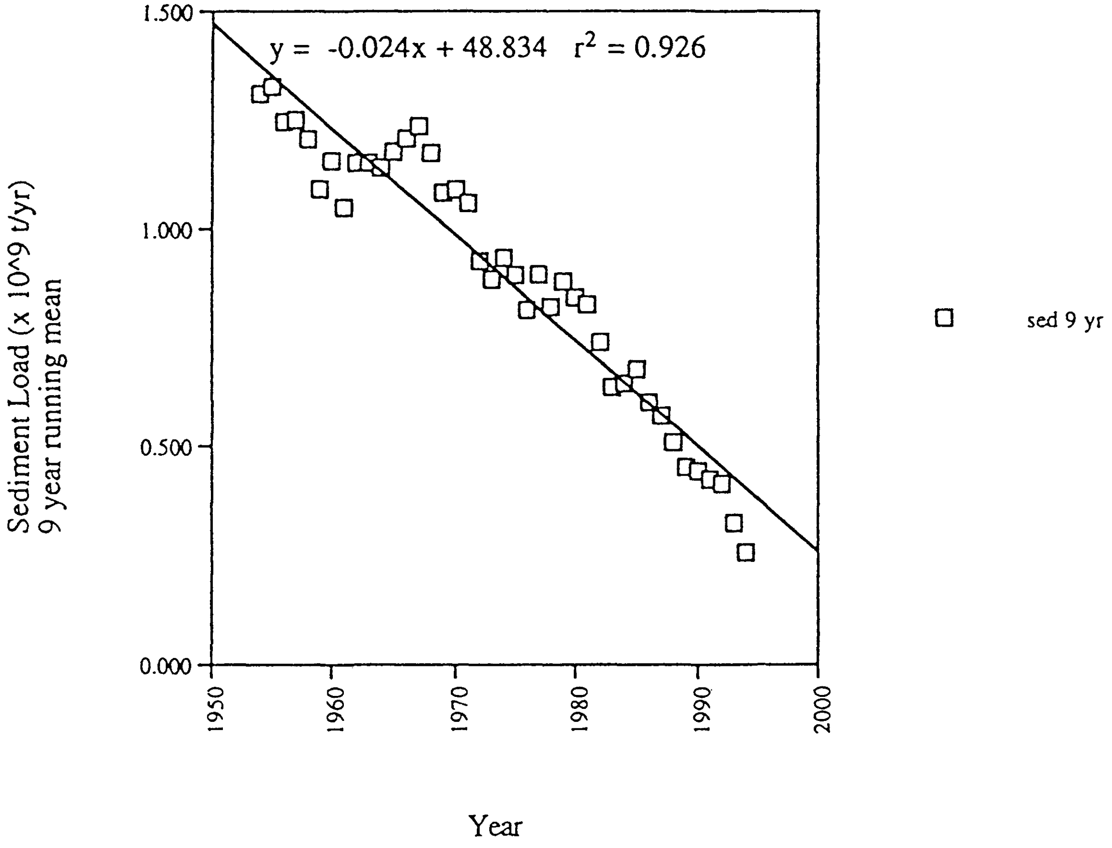
no-flow days
350
300
250
200
150
100
50
0
35
107
106
156
303
120
22
63
23
Feb.
Mar.
Apr.
May
Jun.
Jul.
Aug.
Oct.
Dec.

With the recent reduced levels of water discharge, there is also a corresponding decrease in sediment leaving the Yellow River. In the 1950s and 1960s the annual sediment load at Lejin averaged 1.3 x 10^9 t/yr, compared to less than 0.5 x 10^9 t/yr over the past 10 years. In 1997 the load was only 0.018 x 10^9 t, less than 1% of the annual sediment loads in the early 1960's (Yang et al. 1998).

These recent trends call into question the oft-cited figure of Qian and Dai (1980), who calculated an annual sediment load of 1.1 x 10^9 t/yr. Their estimate was based on data collected between 1950 and the mid-1970s, when flow and sediment loads were generally high, although variable. There may have been no obvious long-term trend apparent in 1980 when Qian and Dai published their paper, but over the past 20 years both water and sediment discharge have dropped drastically (Figure 11). Because the Qian and Dai estimate comes from a period of relatively high flow, one can question the long-term significance of their calculated mean sediment load. This paper addresses a number of questions that arise from this observation. How do these recent changes in flow and discharge change our understanding of the Yellow River's long-term annual sediment estimate? Do we see evidence of the change in river flow being cyclical or long-term, are they natural or do they have an anthropogenic signal?

While the decreased water and sediment discharge are fairly easy to document, the reasons for recent decreases are not yet completely clear. Upstream diversion and dam construction do not appear to play a major role. The Sanmenxia dam, about 600 km

Figure 11: Reduction of Yellow River Sediment Load since 1950 shown in a 9-year running average.



Lejin Sediment Record

upstream from Lijin, was completed in the early 1960s and appears to have had relatively little impact on the sediment load. That dam and other projects upstream probably have resulted in some changes in river flow, but not a major change. It is more likely that the reduced discharge is related to the decreased rainfall and corresponding increased use of the river's water (Yang et al. 1998). By analyzing a century's worth of the watershed's rainfall data, we will attempt to decipher any trends that may indicate decreasing precipitation that could be responsible for decreased river flow.

Methods

In order to conduct this study, it was necessary for the participating American scientists to travel to China and meet with representatives from Ocean University (OU). This occurred on two occasions, March 1998 and July 1998. Through this collaboration, attempts were made to obtain as many data as possible detailing the transport of water and sediment at points along the Yellow River throughout the century. The data that were provided described river flow at 11 stations along the Yellow River dating back as far as 1919. Six of these stations also provided sediment concentrations from 1950 to 1995. Discharge values between 1919 – 1950 were reported as annual totals, and 1950 to the present as monthly values. Values for water flow were reported in terms of km^3 per unit time, while sediment was recorded in 10^9 ton per unit time.

To formulate estimates of the Yellow River sediment discharge data prior to 1950 had to be inferred through indirect methods. Using the water and sediment data from the

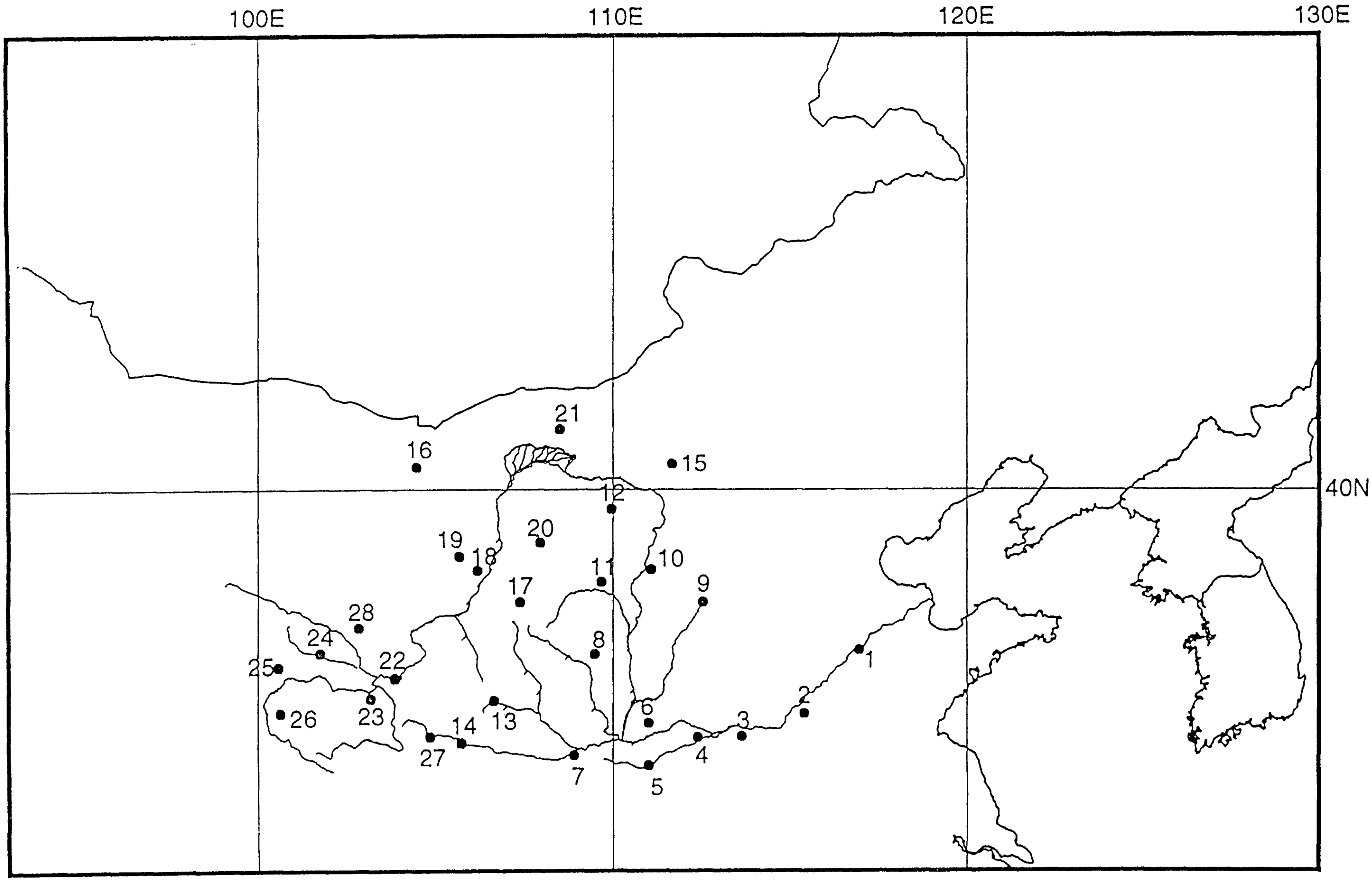
Huayuankou station between 1950 – 1995, a rating curve was developed, which then allowed us to calculate sediment load from water discharge. This rating curve was applied to the water data from 1919 to 1949, and combined with pre-existing data that allowed us to calculate a 77-year record of Yellow River sediment load at Huayuankou. Averaging these years of output gave a new long-term estimate of annual sediment discharge of the Yellow River. By examining the differences in these two estimates an understanding can be obtained as to the reliability of the medium-term estimate compared to the long-term estimate.

While documenting the decrease in water and sediment discharge is fairly simple, the reasons for such a decline are not easily understood. Given that reduced precipitation may be the cause, a thorough investigation was preformed on the rainfall record of the Yellow River watershed. A total of 28 rain gauge stations around the basin gave monthly rainfall totals dating back to the turn of the century (Table 3). These stations were well distributed about the basin, providing coverage for the upper, middle and lower sections of the river (Figure 12). For each month, precipitation for all the stations was summed and then divided by the number of stations reporting, resulting in an average precipitation total throughout the basin for that month. Simple summation of the monthly totals gave yearly rainfall values for 1919 to 1993. Smoothing the data by means of a 9-year running average, trends became more apparent. A non-parametric runs test was preformed on

Table 3: List of stations recording precipitation throughout the Yellow River basin.

Station ID	Lat.	Long	Station Name
1	36.68	116.98	Jinan
2	35.25	115.43	Heze
3	34.72	113.65	Zhengzhou
4	34.7	112.4	Luoyang
5	34.05	111.03	Lushi
6	35.03	111.02	Yuncheng
7	34.3	108.93	Xi'an
8	36.6	109.5	Yan An
9	37.78	112.55	Taiyuan
10	38.5	111.1	Xingxian
11	38.23	109.7	Yulin
12	39.83	109.98	Dongshen
13	35.55	106.67	Pingliang
14	34.58	105.75	Tianshai
15	40.82	111.68	Hohhot
16	40.75	104.5	Bayan Mod
17	37.78	107.4	Yanchi
18	38.48	106.22	Yinchuan
19	38.8	105.7	Alxa Zuoqi
20	39.1	107.98	Otog Qi
21	41.57	108.52	Haliut
22	36.05	103.88	Lanzhou
23	35.6	103.2	Linxia
24	36.62	101.77	Xining
25	36.3	100.6	Gonghe
26	35.27	100.65	Tongde
27	34.72	104.88	Wu Shan
28	37.2	102.87	Wushaoling

Figure 12: Location map of the stations collecting rainfall data throughout the Yellow River basin.


100E
110E
120E
130E
40N
1
2
3
4
5
6
7
8
9
10
11
12
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14
15
16
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18
19
20
21
22
23
24
25
26
27
28

these data to see if any significant changes in the basin's precipitation had occurred over the time period.

Results

Chinese data gave a thorough record of water discharge at 11 stations along the Yellow River. The longest record, 1919 to 1995, came from the Huayuankou station, 500 km from the mouth of the Yellow River (Figure 13) and 400 km from Lijin, the seaward-most station on the river. Huayuankou also has a record of sediment load running from 1950 to 1995, with a mean load of 1.1×10^9 t/yr, less than the 1.6×10^9 t/yr cited by Qian and Dai, since their estimate was based on the high-flow years between 1950 and the late '70's. The measured annual average of sediment load at Lijin from 1950 – 1995 was found to be 0.93×10^9 t/yr. The sediment data from Huayuankou were used along with the water discharge record to construct the rating curve. This curve provides an algorithm by which sediment for years before 1950 can be calculated. This rating curve, which has a r^2 of 0.751 (Figure 14), was then used along with the 1919 – 1949 Huayuankou discharge to calculate the pre-1950 sediment loads at Huayuankou. The 1919 – 1995 calculated and observed data are shown in Figure 15. Because of the marked interannual variations, these data were smoothed into a 9-year running curve (Figure 16). When the years of sediment discharge data from 1919 to 1995 were averaged, a mean load of 1.1×10^9 t/yr was calculated for the entire 77 years. However,

Figure 13: Record of water flow at Huayuankou gauging station from 1919 – 1995.

Huayuankou water flow

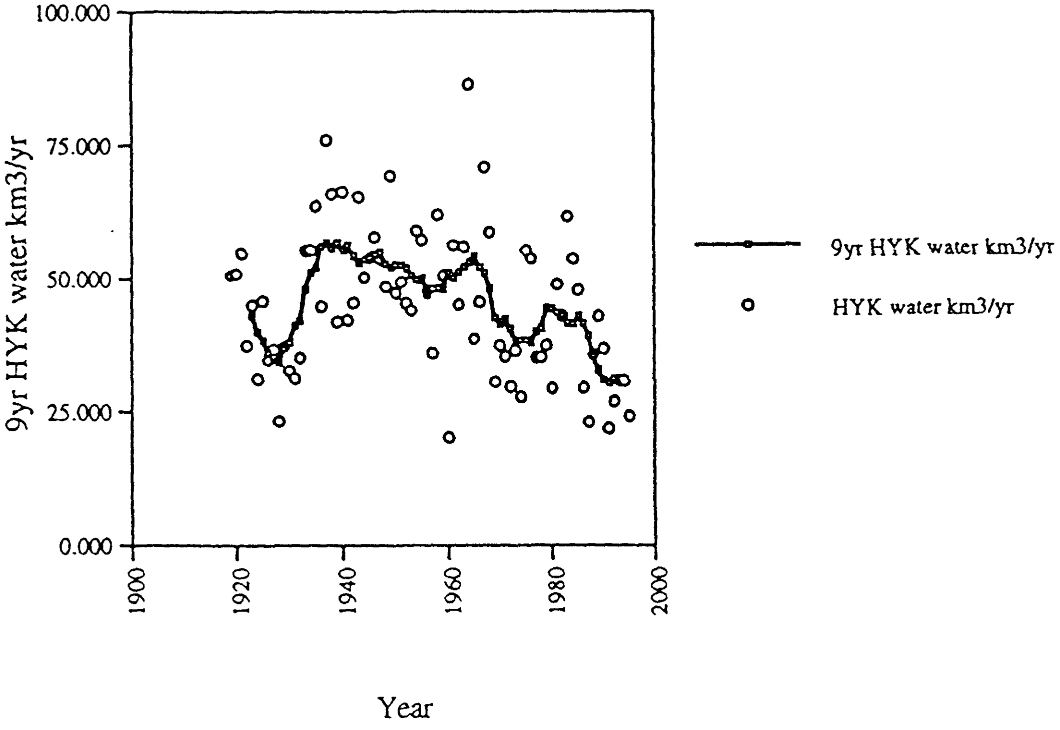


Figure 14: Rating curve used to back-calculate sediment load of Yellow River from 1919 – 1949, when only water flow was recorded.

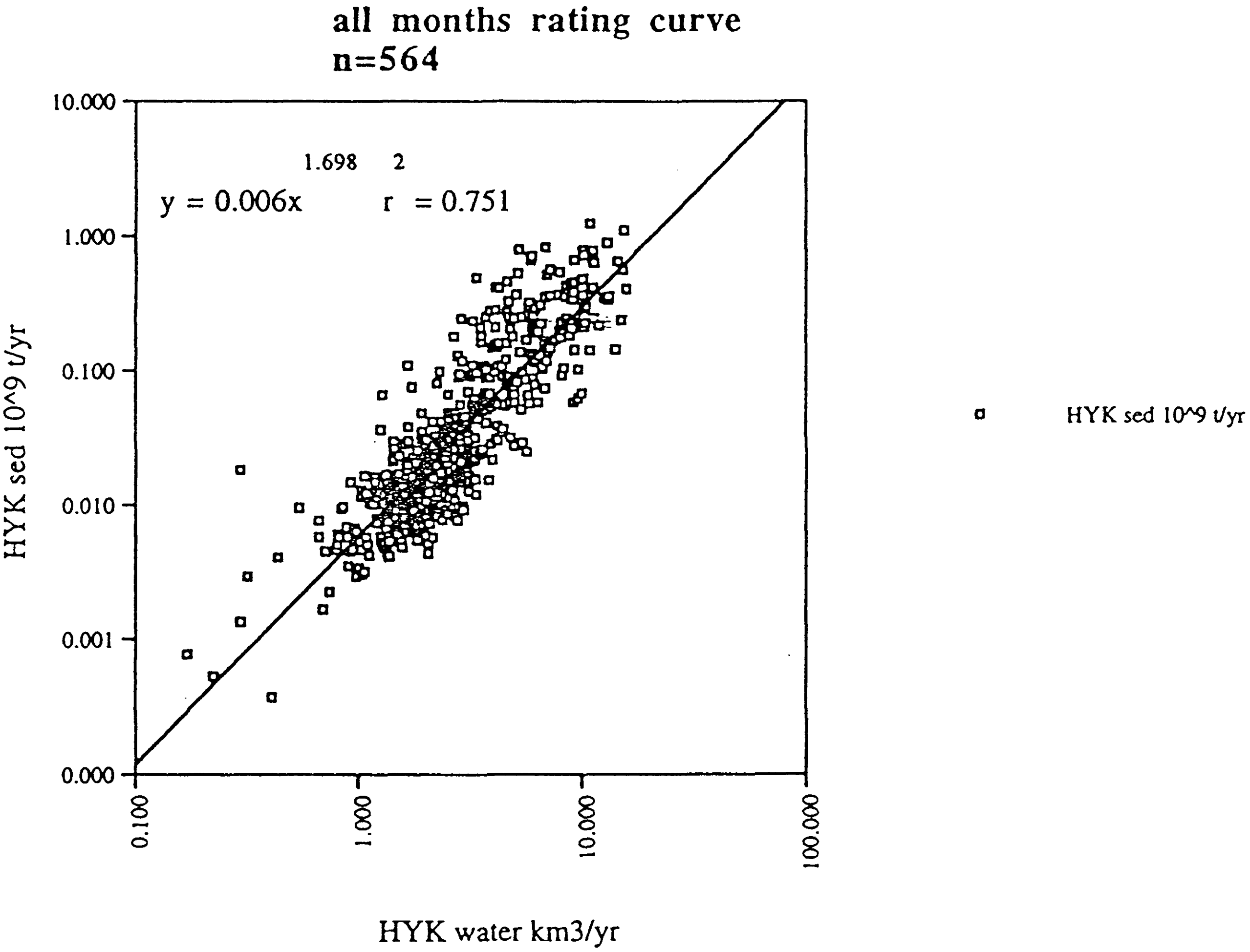

all months rating curve
n=564
y = 0.006x^1.698
r^2 = 0.751
HYK sed 10^9 t/yr
HYK water km3/yr
10.000
1.000
0.100
0.010
0.001
0.000
0.100
1.000
10.000
100.000
HYK sed 10^9 t/yr

Figure 15: Yellow River sediment from 1919 to 1949 calculated by the rating curve in Fig 13 and measured loads from 1950 – 1995.

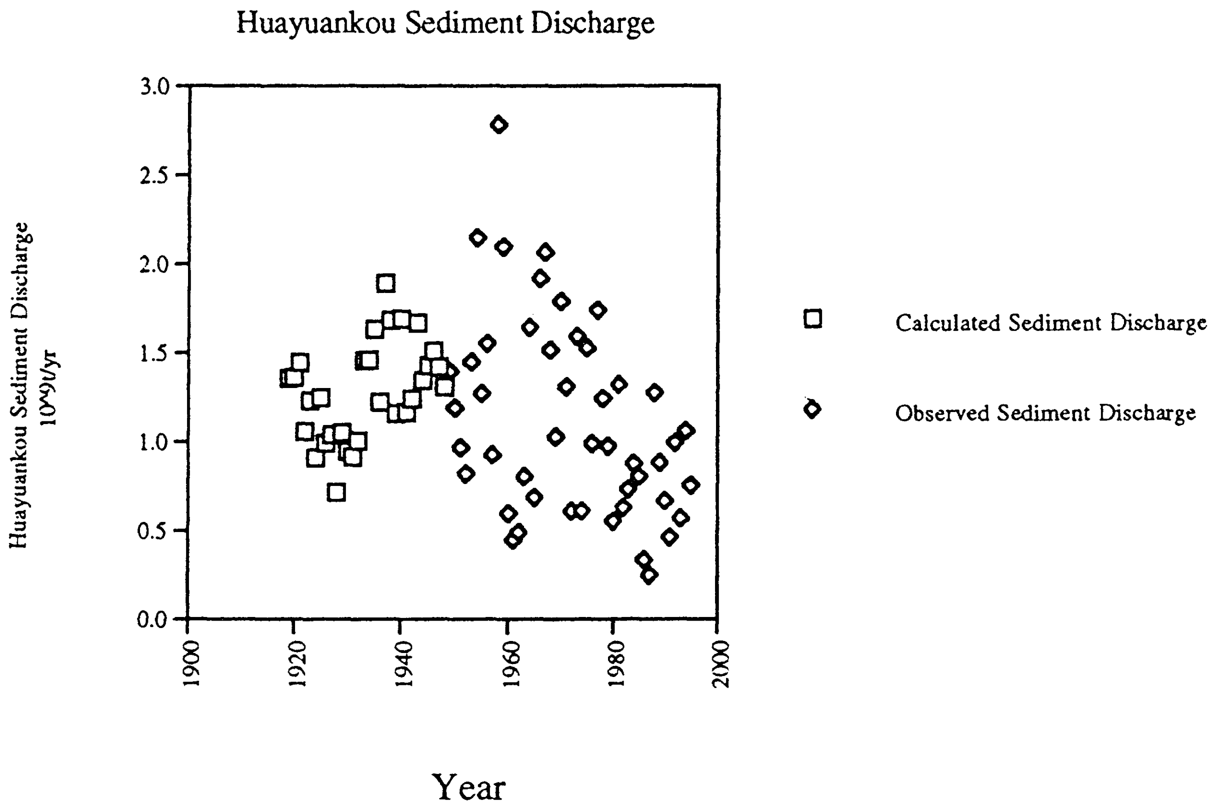
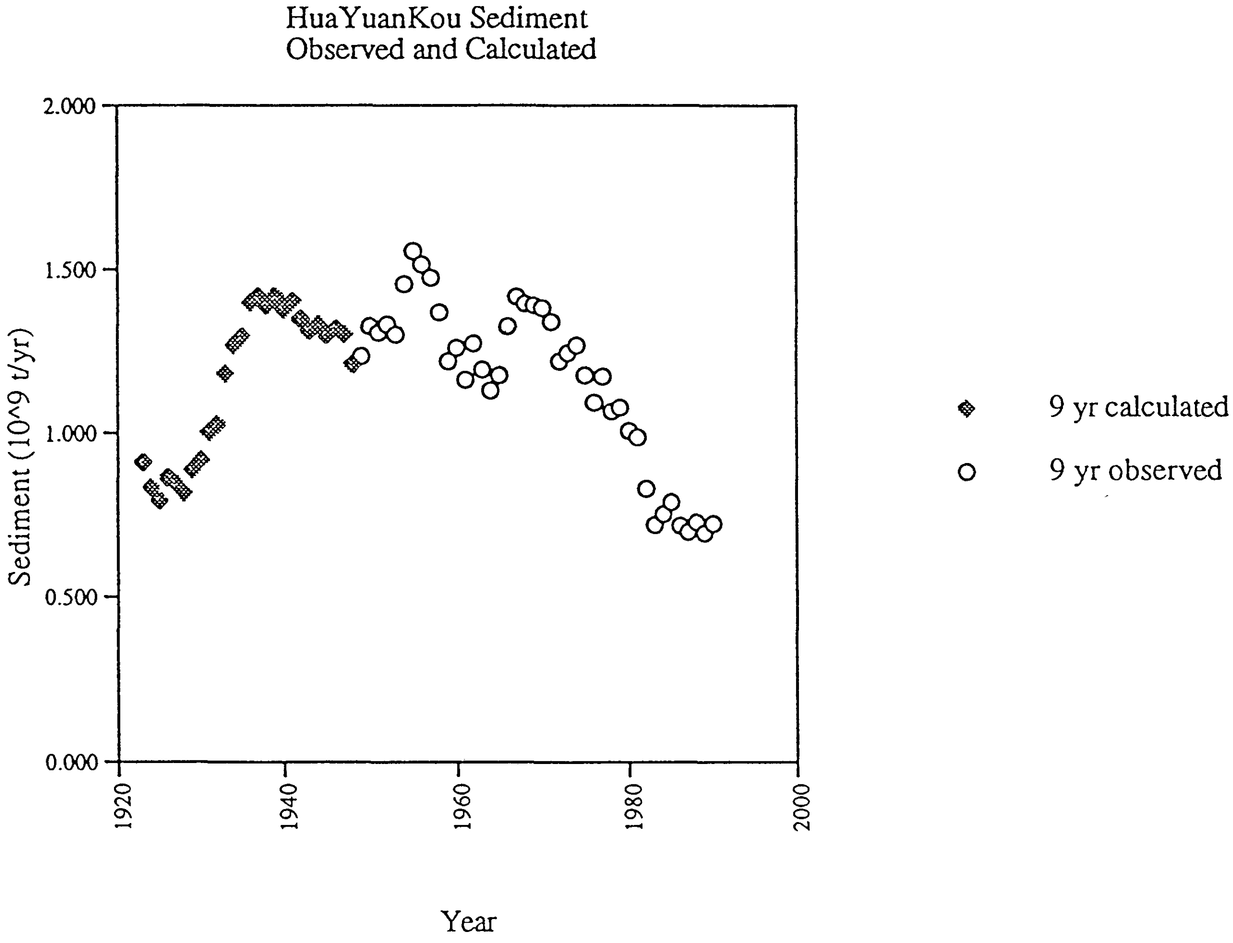
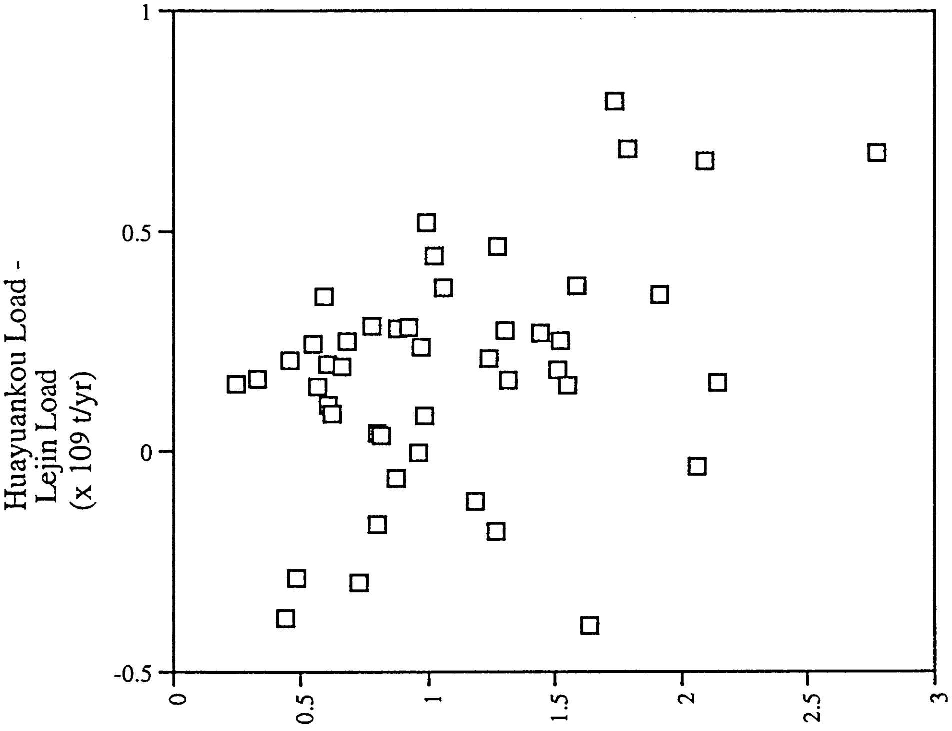

Huayuankou Sediment Discharge
Huayuankou Sediment Discharge
10^9t/yr
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1900
1920
1940
1960
1980
2000
Year
Calculated Sediment Discharge
Observed Sediment Discharge

Figure 16: Nine year running average of sediment discharge data including both the calculated data from the rating curve and the measured data from the Huayuankou station.


HuaYuanKou Sediment
Observed and Calculated
Sediment (10^9 t/yr)
2.000
1.500
1.000
0.500
0.000
1920
1940
1960
1980
2000
Year
9 yr calculated
9 yr observed

it should be noted that this estimate is for discharge passing the Huayuankou station, and the Qian and Dai estimate was for Lijin, and there may be significant amounts of sediment lost between these two stations. However, it can be seen that during periods of low loads, corresponding to low-flow, there is the possibility of increasing amounts of load between the two stations, as a result of the scouring of the channel (Figure 17). For periods when the sediment load at Huayuankou is near 1.1 x 10^9 t/yr, the amount of sediment lost via deposited is likely to be 0.2 x 10^9 t/yr. Therefore, since the long-term annual average at Huayuankou was found to be 1.1 x 10^9 t/yr, the load at Lijin from 1919 – 1995 has been estimated to be 0.9 x 10^9 t/yr (Table 4).

Investigations into the rainfall record of the Yellow River's watershed go back to 1916, extending our records back more than 80 years. Since interannual variability can be great, these data also were smoothed into a 9-yr running average and error bars representing standard error were added (Figure 18). The non-parametric runs test performed on these data reported a total of 12 runs and had an alpha value of 0.000 (Table 5). Percentage decrease in precipitation over this time period was estimated to be as much as 25%.



Load at Huayunakou (x 109 t/yr)
from 1950 - 1995

Table 4: A comparison of the sediment loads at Huayuankou (upstream) and Lijin (downstream) for three different time periods.

	1950-1977 measured values(*)	1950-1995 measured values	1919-1995 calculated and measured
Lejin	1.14	0.93	0.9
Huayuankou	1.64	1.11	1.1

(*) Qian and Dai 1980

Figure 18: Yellow River precipitation index showing a significant decrease in rainfall from 1916 to 1994. The error bars represent standard error. Series 1 is the individual years of data. Series 2 represents a 9-year running average.

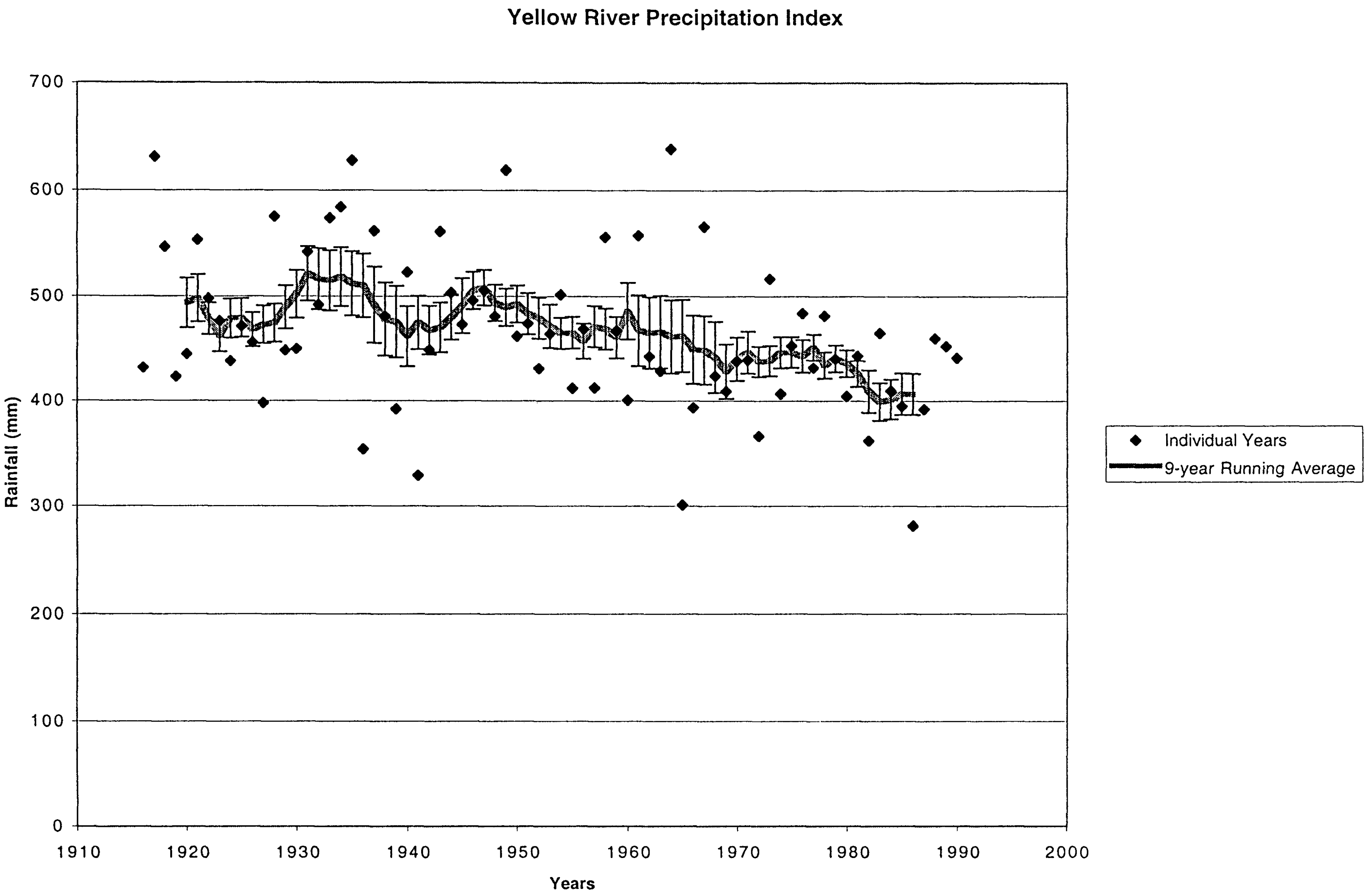

Yellow River Precipitation Index
700
600
500
400
300
200
100
0
Rainfall (mm)
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
Years
◆ Individual Years
9-year Running Average

Table 5: Results of the statistical tests that on the precipitation data for the Yellow River watershed.

NPar Tests

Runs Test

	VAR00001
Test Value[a]	467.5800
Cases < Test Value	33
Cases >= Test Value	34
Total Cases	67
Number of Runs	12
Z	-5.539
Asymp. Sig. (2-tailed)	.000

[a] Median

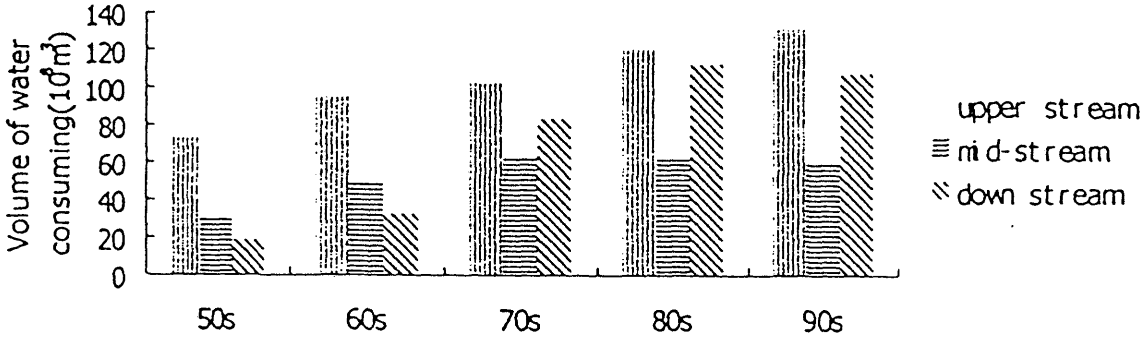
Discussion

The calculated 77-year mean of sediment load of the Yellow River at Lijin, 0.93 x 10^9 t/yr, is 15% less than the 1.1 x 10^9t/yr value given by Qian and Dai in 1980 based on roughly 25 years of data. Qian and Dai's estimate came from a high-discharge period of what appears to be a 65 –75 year cycle. This cycle shows relatively low-flow periods from 1922 to 1932 and also at present. Periods of higher sediment discharge existed in the early 1940s and late 1950s to early 60s, in some years the annual load exceeded 2 x 10^9 t/yr. Our long-term calculation therefore spanned all of these fluctuations of discharge. Besides this longer- term first –order cycle, there also appears to be a second-order cycle of 12-20 years and a third order cycle of 5-7 years. Had Qian and Dai made their calculations 15 years earlier or later with the same number of years worth of data, for example their estimate could have been considerably higher or lower.

While it has been relatively easy to document the decrease in the flow of the Yellow River, determining a cause of this decreased flow is not so simple. Clearly changes in flow reflect long- and short-term changes in rainfall and evaporation as well as changes in human consumption, which to some degree is related to rainfall patterns. One problem is obtaining meaningful temporal and spatial representations of rainfall. Previously published Yellow River rainfall data have been given in decadal averages, which have been thought to have remained constant over the last 45 years (e.g., Pang et al. 1999). Given the strong interannual variations, however, decadal averages may mute any intermediate or long-term trends. By obtaining nearly 80 years of monthly precipitation data from over two dozen stations around the Yellow River watershed, however, a reliable yearly record was created to track precipitation history. This 80-yr record shows a statistically significant decrease in rainfall in the Yellow River basin during this period, perhaps by roughly 20% since 1920. The results of the statistical tests show 12 changes in slope of the precipitation record, emphasizing the oscillatory nature of the rainfall patterns that have been smoothed over and therefore ignored by the previously published decadal averages. The test gives an alpha value of 0.000, which indicates a high degree of certainty of a statistically significant change in rainfall since 1920.

But in addition to decreased precipitation there have been significant changes in anthropogenic activity on Yellow River flow during the last 50 years. From 1949 to 1991 the area of land irrigated by the Yellow River increased 8-fold, from 800,000 ha to 6,300,000 ha, resulting in 300×10^{8} m^3 of water per year being removed from the river (Gu 1994, Ren 1995). This represents nearly 70% of the Yellow River's annual discharge to the Gulf of Bohai, and clearly much of this water ultimately was returned to the river via irrigation ditches. The amounts of water being taken from the river have increased every decade along each stretch of the river (Figure 19). The greatest removal of water has been found to be along the stretch of river from Huayuankou to Lijin, an area that has experienced great population growth and industrial and agricultural expansion over the

Figure 19: Volume of water consumption of the Yellow River Basin in different decades. From Pang et al (1999).



Volume of water consuming($10^8 m^3$)
140
120
100
80
60
40
20
0
50s
60s
70s
80s
90s
upper stream
mid-stream
down stream

Figure 20: Comparison of Yellow River discharge at Huayuankou (upstream) and Lejin (downstream). The difference between these two is water lost or removed, which can be seen to have increased over the past two decades reaching nearly 50% in recent years

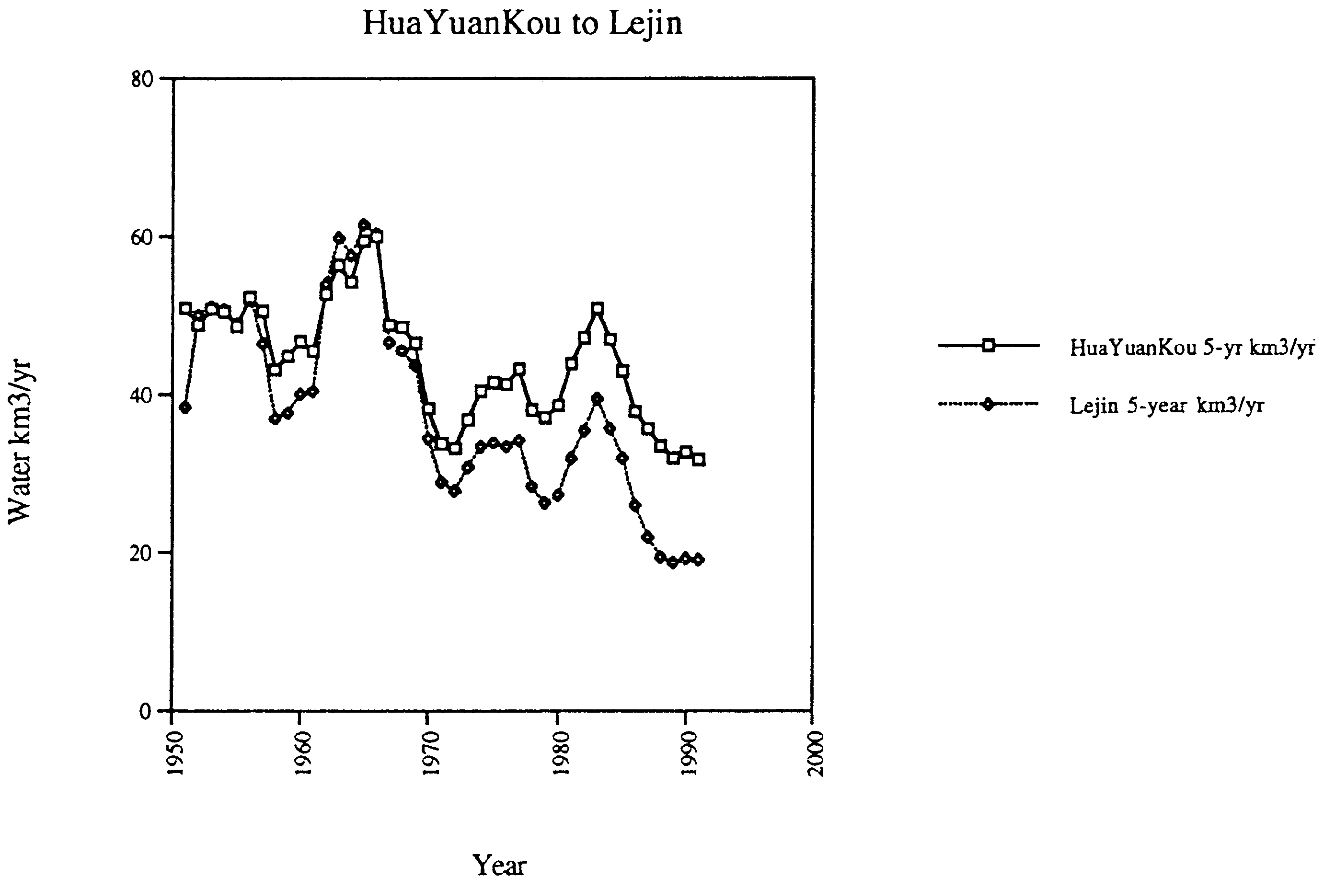
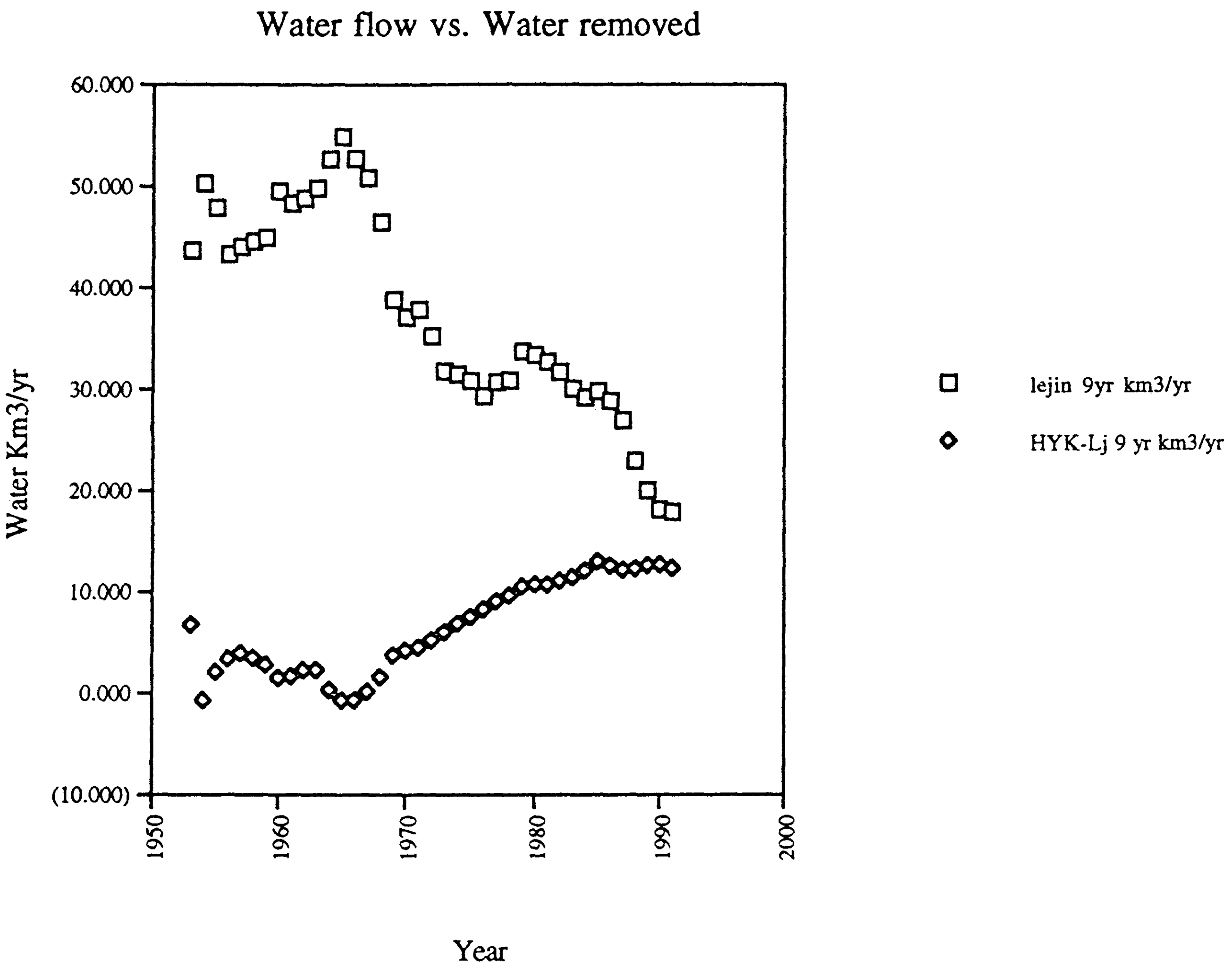

HuaYuanKou to Lejin
Water km3/yr
80
60
40
20
0
1950
1960
1970
1980
1990
2000
Year
HuaYuanKou 5-yr km3/yr
Lejin 5-year km3/yr

Figure 21: Flow at Lijin (upper) and water lost between Huayuankou and Lijin (lower). By the early 1990's roughly half the water passing Huayuankou was lost before reaching Lijin.


Water flow vs. Water removed
Water Km3/yr
60.000
50.000
40.000
30.000
20.000
10.000
0.000
(10.000)
1950
1960
1970
1980
1990
2000
Year
□ lejin 9yr km3/yr
◇ HYK-Lj 9 yr km3/yr

last two decades. As a result, the amount of water lost along this stretch has increased greatly during the last two decades (Figure 20), in part because of decreased river flow, such that almost half of the water passing Huayuankou does not reach Lijin (Figure 21).

This may be due to an attempt to irrigate crops that have not benefited from an adequate rainfall. Ren (1994) points out several examples of anthropogenic activities that will continue to impact the flow of water in the Yellow River: 1) The percentage of natural flow discharging to the sea has decreased from 79.9% in the 1950s to 73.3%, during the 1960s, 54.7% in the 1970s, with flow dropping to 178 x 10^8 m^3 in 1992, thereby causing the Yellow River to become intermittent; 2) Future economic development will cause even more water to be diverted from the Yellow River. In the Shandong Provence alone, the coastal cities of Qingdao, Zibo, Weifang and Yantai are predicted to withdraw a total of at least 20 x 10^8 m^3/yr by 2000; 3) In addition to increased agricultural needs, the Yellow River Commission has estimated that by early in the next century, an additional 230 x 10^8 m^3 of water, or about 50% of mean annual flow at Huayuankou, will be needed for the development of coal mining, thermal power plants and other water-consuming industries; 4) Over the next 20 – 30 years, human activities almost certainly will have a greater impact on river flow than will climate change; 5) To help offset increased water needs in the lower Yellow River, an inter-basin water transfer project currently under construction that will transfer 200 x 10^8 m^3/yr of water from the upper Yangtze River to the upper Yellow River. While this addition of water could nearly balance the growing demand for water in the upper and middle reaches over the next 20 – 30 years, its removal may have substantial impact on the Lower Yangtze in the form of decreased biological productivity off the Yangtze estuary and increased coastal erosion (Ren and Milliman 1996).

During the 15 years from 1950 to 1964, the amount of water flowing past Huayuankou was or 507 x 10^8 m^3/yr. This was a period of relatively high discharge for the Yellow River, especially when compared to present rates of discharge (1990 – 1996 mean = .4 x 10^9 t/yr). In the interim years between the 1950's and the present, there has been a basin-wide increase in the amount of water used for the purposes of irrigation. Increased efforts in reducing the amount of runoff to the Yellow River also have been successful in lessening the flow of the river. These two combine to account for a decrease in flow of 393 x 10^8 t/yr. Compared to this, the amount lost from reservoirs in the form of evaporation, 10 x 10^8 t/yr, appears minor, taking into account these various losses, the lower Yellow River would still have a little more than 200 x 10^8 t/yr of water flowing yearly. However, it has been approved that 230 x 10^8 t/yr can be used for coal mining and the production of thermal power early in the 21st century. Also, coastal cities in the Shandong Province are expected to withdraw 20 x 10^8 t/yr beginning early next decade. Clearly there is not enough water left in the Yellow River to provide for all of these demands (Table 6). Along with the increased need for water is the trend of decreased precipitation in the Yellow River basin (see Figure 18). The Chinese therefore

Table 6: Current and projected removal of water from the lower Yellow River compared with average flow between 1950 and 1964.

Reason for water change	Change in water flow (x 10^8 m^3/yr)	Average flow from 1950 - 1964
Increased Irrigation from 1950 - 1993	- 300(Ren, 1995)	
Coal mining/Thermal Power projected early 2000's	- 230(Ren, 1994)	
Runnoff reducion since 1960	- 93 (Gu, 1994)	
Shandong coastal cities projected early 2000's	- 20 (Ren, 1994)	
Evaporation from Reservoirs	-1.2 (Gong and Xu, 1987)	
	-644.2	507.318(x 10^8 m^3/yr) Measured at HuaYuanKou Station

appear to have plans to use water that most likely will not be available, resulting in continuing extended periods of no-flow of the Yellow River, with little hope for recovery.

Water removal also means that vast amounts of sediment never reach the Gulf of Bohai. This may help to explain the drop off in annual sediment load over the past two decades. Much of this presumably is deposited in irrigation ditches, but there is also a large amount of effort being placed in preventing sediment from eroding into the river. Tens of thousands of silt-trap reservoirs, with a total storage capacity of nearly $9 \times 10^9 m^3$ (only about 10 years of storage capacity, however, at the 1960's sediment discharge levels) have been constructed in the loess plateau region and retard the loss of sediment to the river (Gong 1987). Erosion prevention has been implemented by the planting of trees and grass as well as the construction of level, terraced fields on slopes that were subject to erosion (Gong 1987).

Mou (1996) and Ren (1994) make several points about the status of sediment conservation along the Yellow River: 1) During the 1980s, comprehensive sediment measures reduced the average annual sediment load of the Yellow River by 250×10^6 t; 2) With the water removed for irrigation over the last decade, approximately 1.7×10^8 t/yr of sediment were removed. The projected increased in irrigation in the next decade will therefore remove even more sediment from the Yellow River; 3) Throughout the middle reach of the Yellow River, in the area of the loess plateau, soil conservation reduced the annual sediment load by 170 x 10^6 t, and engineering measures reduced it by 120 x 10^6 t; 4) Construction of gullies accounted for 45% of the sediment reduction, terraces for 24% and reforestation for 24%; 5) In Shandong and Henan Provinces, 6.6 x 10^8 t of sediment have been removed directly from the Yellow River and used to widen and strengthen the 1400 km of dikes along the lower reach of the Yellow River. This task is not yet completed, and an estimated 0.5 x 10^8 t/yr will be removed over the next decade for this purpose; 6) The completion of the Xioalangde Reservoir, scheduled for 2000, will trap 3.3 x 10^8 t of sediment a year from 2001 – 2030; 7) As a result, it is predicted that over the next 50 years, the average annual sediment load of the Yellow River will be reduced by 500 x 10^6 t (i.e. half of the long-term value), although the river water will still remain a sediment rich because of the loess-hill erosion.

While all of the human influences on the Yellow River over the last few decades could possibly be reduced or stopped, reversing the decrease in rainfall can not be engineered. If rainfall continues to decline, an already fragile water resource will become even more fragile. Continued misuse of the Yellow River could have dramatic impact on the enormous population dependent on it.

Conclusion

Due to the reduced transport of water and sediment by the Yellow River in the last 20 –25 years, questions were raised as to the accuracy of the oft-cited Qian and Dai (1980) annual average Yellow River sediment estimate of 1.1 x 10^9 t/yr. Their work focused on a period of 25 years that was thought to be a relatively high flow period, thus causing their results to be an overestimate. This study generated an estimate using 77 years of data from 1919 to 1995, which gave a result of 0.93 x 10^9 t/yr, 15% less than the Qian and Dai study. This study's result averaged two droughts and two periods of high flow and a few stretches of mid-range discharge. Qian and Dai happened to conduct their work during one of the periods of high-to-mid-range flow, thus generating a higher result.

In an attempt to determine any reason for the reduction in flow, precipitation records were investigated and found to show a statistically significant decrease from 1916 – 1995. The decrease may be as much as 25% over this period. This, coupled with increased anthropogenic impacts on the river has resulted in drastically reduced sediment and water discharge over the last 25 years.

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