A study of the accumulation rate of the lower Yellow River in the past 10 000 years

XU JIONGXIN
Institute of Geography, Chinese Academy of Sciences, Beijing 100101, China

Abstract By using the data obtained from the sedimentological record and ^{14}C dating, the comparison of historical documents and maps, as well as modern hydrological gauging records, this paper discusses the lower Yellow River's sediment accumulation rate in the past 10 000 years. A pronounced tendency of acceleration of the rate is indicated which results from both natural factors and an increase in human activities, with the latter dominant. Accordingly, the concepts of naturally accelerated accumulation and human accelerated accumulation have been put forward to explain the lower Yellow River's sedimentation process. An approximate estimate of the relative proportions of these two are given.

INTRODUCTION

The Yellow River of China is a well-known river, for it has the highest sediment load, suspended sediment concentration and channel accumulation rate of the world. Controlled by natural factors and human activities, the accumulation rate of the lower Yellow River exhibits a very high temporal variability. Geologists and geomorphologists are more concerned with the variation at a long timescale (e.g. 10^3-10^4 years or longer), while hydraulic engineers usually focus their interest on the variation at a short timescale (e.g. 100-102 years). For the purpose of predicting the tendency of the lower Yellow River's accumulation in the future and thereby making some effective and strong counter measures. There is an urgent need to study the lower Yellow River's historical accumulation process from long-term perspectives, and identify its macro-tendency from all superimposing secondary fluctuations. The present paper aims to quantify the Lower Yellow River sediment accumulation since 10 000 years ago.

DATA

In the lower Yellow River, the hydrological measurement was started in 1919, so data are available for only 70 years. Obviously it is far from sufficient to study the channel accumulation longer than 102 years on this basis. For this reason we must make use of some substitutive data to form a data base. In addition to the hydrological gauging records, we have also adopted the following data in this study.

Data obtained from map comparison

Through a comparison of the river channel from topographical maps made in different periods, the change in elevation can be identified, and then the accumulation rate can be calculated.

Data obtained by combined methods of sedimentology, historical documents and archaeology

In history, the lower Yellow River frequently changed its courses, leaving numerous paleo-channels in the North China Plain. Sedimentary sections of these paleo-channels recorded abundant information on the historical accumulation process of the river. Before the Yellow River changed its course to a given area, the surface material there was composed of flood-plain-phase deposits, which are characterized by silt-clay sediment affected by some soil development processes, and possibly contain some historical relics. In contrast the overlying paleo-channel deposits are a set of channel-phase sediments, mainly composed of greyish yellow silty sands. The boundary between these two sets of sediment is pronounced and can be easily determined. Therefore, from the hydrogeological and well core data, the thickness of accumulation by the paleo-channel can be identified. By an investigation of historical documents and archaeological findings, the age of the paleo-channel may be determined, and the accumulation rate can be estimated.

Data based on the ^{14}C dating method

If a set of strati can be determined as the deposits of the Yellow River, and the samples containing carbon can be collected at more than two depths in the vertical section, then the ages of the samples can be determined by ^{14}C dating technique. The vertical thickness between the two depths divided by the difference of their ages then gives the accumulation rate.

TEMPORAL VARIATION IN THE LOWER YELLOW RIVER'S ACCUMULATION RATE

All the data obtained through the foregoing methods are listed in Table 1. The accumulation rate representing the periods 12 000-6000 years before present is calculated based on the strati thickness and the ^{14}C dating data. Through a study on the three phases of the Yellow's alluvial fans formed since the early Holocene (Ye *et al.*, 1982), the accumulation rates for the corresponding three periods ranging from 11 000 years before present to 1194 A.D. were obtained. The data covering the long period from the Han (206 B.C.-220 A.D.) to the Qing (1616-1912 A.D.) Dynasties are worked out by using the sedimentological method in combination with the historical documents and archaeological studies. Afterwards, all the data are based on the map comparison and modern hydrological measurements.

It can be seen from Table 1 that the accumulation rate of the lower Yellow River has been continuously accelerating since 10 000 years ago. To show this tendency more clearly, the accumulation rate in different periods is plotted against time in Fig. 1, where each period is represented by the mid-point of the time-span. the tendency of accumulation rate to increase with the decreasing number of years before present (1990) is very clear, this can be fitted by the following power function:

$$R_a = 92.38T - 0.66 \quad (1)$$

Table 1 Sediment accumulation rate of the lower Yellow River in different periods.

Periods	Mid-point of period (years BP)	Accumulation rate (cm year^{-1})	Location*	Source
12 000 to 9100 ± 150 years before present (BP)	10 550	0.23	The Huangqingzhang paleo-channel zone	Wu & Wang (1982)
9100 ± 150 to 5945 ± 120 years BP	7 520	0.14	The Huangqingzhang paleo-channel zone	Wu & Wang (1982)
5945 ± 120 years BP to 1000 A.D.	3 470	0.20	The Huangqingzhang paleo-channel zone	Wu & Wang (1982)
7000-5000 years BP	6 000	0.30	The paleo-delta of the Yellow Mengchun	Wu & Wang (1988)
9000-5600 years BP	7 300	0.15	Dahechun Relics, Zhengzhou	Calculated based on data from Dahechun Relics Museum
6300-3000 years BP	4 600	0.38	Dahechun Relics, Zhengzhou	Calculated based on data from Dahechun Relics Museum
11 000-6000 years BP	8 500	0.54	Alluvial fan of the Yellow River	Calculated based on Ye *et al.* (1982)
6000-3000 years BP	4 500	0.75	Alluvial fan of the Yellow River	Calculated based on Ye *et al.* (1982)
3000 years BP to 1194 A.D.	1 900	0.66	Alluvial fan of the Yellow River	Calculated based on Ye *et al.* (1982)
602 B.C. to 11 A.D.	2 285	0.44	Yuhe paleo-channel, flood plain	Ye *et al.* (1990)
11-1048 A.D.	1 460	0.20	11-1048 paleo-channel, flood plain	Xu (1990)
Northern Song Dynasty to 1194 A.D.	913	1.92-2.14	Jialu paleo-channel, both channel and flood plain included	Xu (1990)
1271-1580 A.D.	560	2.18-3.13	Jialu paleo-channel, both channel and flood plain included	Xu (1990)
1450-1580 A.D.	475	1.25	Taohuayu, both channel and flood plain included	Xu (1990)
1194-1855 A.D.	466	2.60	Ming and Qing Dynasties paleo-channel, flood plain	Calculated based on Zhang & Xie (1982)
1493-1850 A.D.	318	1.66	Qinhekou-Dongbatou reach, flood plain	Yellow River Commission (1978)
1495-1871 A.D.	315	2.43-3.49	Lankao-Minquan reach, flood plain	Xu (1990)
1752-1855 A.D.	187	1.94-4.24	Shangqiu-Shuining reach, flood plain	Xu (1990)
1875-1890 A.D.	108	5.7	Dongbatou, channel	Lu (1981)
1855-1937 A.D.	94	3.8	Buoxing, channel	Ding & Peng (1983)
1919-1953 A.D.	54	5.9	Huayuankou-Lijin reach, channel	Chien (1960)
1954-1982 A.D.	22	8.2	Huayuankou-Lijin reach, channel	Ye *et al.* (1990)

*Flood plain here refers to land between the two artificial levees.

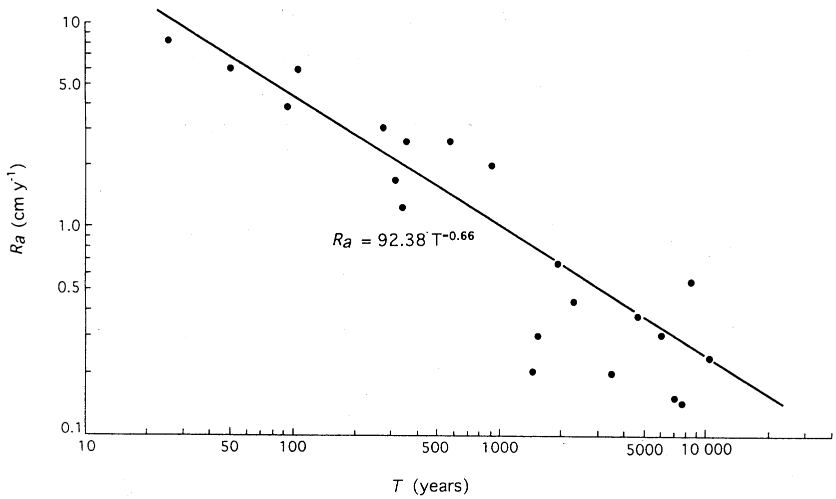

Fig. 1 Plot of the sediment accumulation rate of the lower Yellow River, R_a, against the number of years from 1990, T.

where R_a is the mean accumulation rate of a given period, and T is the number of years before 1990. The correlation coefficient is −0.91, significant at 0.001 level. This equation indicates that R_a is increasing exponentially with time since the Holocene.

The continuing acceleration of the lower Yellow River's accumulation rate results from both natural causes and enhanced human activities. Accordingly, we introduce the concepts of naturally accelerated accumulation and human-accelerated accumulation to explain the relation in Fig. 1.

NATURALLY ACCELERATED ACCUMULATION

Naturally accelerated accumulation can be defined as the acceleration of the sediment accumulation in the channel of the lower reaches, induced by the changing natural factors in the drainage basin. The overall tendency of the climatic changes in the Yellow River basin since the mid-Holocene was favourable to increase the intensity of erosion, which leads to an acceleration of the accumulation rate in the lower Yellow River.

The study (Zhou *et al.*, 1991) on the natural environmental change of the Loess Plateau, i.e. the middle Yellow basin since the Holocene in terms of vegetation evolution showed that the Holocene of this region could be divided into two stages by the time of some 5000 years before present, the former being relatively warm and wet, and the latter cool and dry. Based on the pollen analysis of samples taken from the famous Banpo Relics in Xi'an, Fig. 2 gives the climatic change around this turning point as reflected by vegetation. Towards the end of early Holocene, climate was cool and dry, indicated by a combination of high content of herbaceous pollens and low content of woody pollens. During the early mid-Holocene, climate became warm and wet, with a marked increase in the content of woody pollens and a decline in the content of herbaceous pollens. However, after that period, climate turned to be cool and dry again, with the woody pollen content declining sharply and the herbaceous pollen content increasing. The pollen content of *Artemisia*, an indicator of dry and cool climate, also

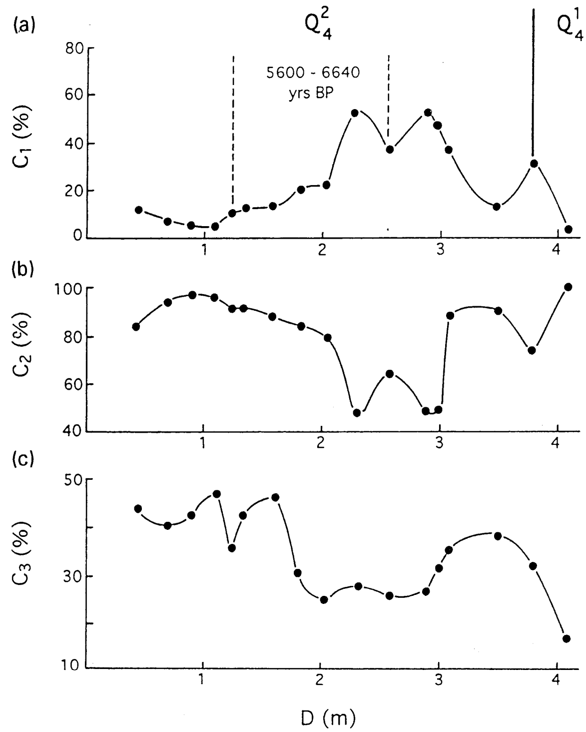

Fig. 2 Pollen content varying with depth from the ground surface, *D*, based on data from the Banpo Relics (plotted based on Zhou *et al.*, 1991). (a) Woody pollen content C_1; (b) Herbaceous pollen content C_2; (c) *Artemisia* pollen content C_3. Q_4^1 and Q_4^2 refer to the early and the middle Holocene, respectively.

indicated a similar pattern. It was determined by ^{14}C dating that the change of climate occurred during 5600-6600 years before present. Naturally, with a tendency towards a drier climate, the drainage basin erosion would be intensified, a process which can be regarded as the naturally accelerated erosion. As a result, the runoff was decreased and sediment load increased in the lower Yellow River, inevitably leading to a naturally accelerated accumulation there.

The study by Ye *et al.* (1982) on the Holocene alluvial fans of the Yellow River showed that the accumulation rate of the fan 11 000 years to 6000 years before present was 0.54 cm $year^{-1}$, and that of the fan 6000 years to 3000 years before present was increased to 0.75 cm $year^{-1}$. This increase provides evidence to support the above mentioned naturally accelerated accumulation rate of the Yellow River, because 3000 years ago or earlier, human ability to intervene nature was negligibly low, thus the deposition in the lower Yellow River was attributable to a natural process.

HUMAN ACCELERATED ACCUMULATION

Human-accelerated sediment accumulation refers to the acceleration of the river's accumulation induced by human impacts and in the lower Yellow River can be attributed to the following causes.

Human accelerated erosion in the middle Yellow basin

The accelerated erosion occurring in the middle river basin means an increased input of sediment to the lower river channel. As a result, the sedimentation there would be accelerated if the river's sediment carrying capacity remains unchanged.

In Loess Plateau in the middle Yellow basin is a well known ecologically critical zone in China. Firstly, the plateau is located in the transition zone between sub-humid, semi-arid and arid climates. After the natural vegetation is destructed, it would be very difficult to recover naturally. Secondly, the plateau is covered by thick loess up to 200 m, the erodibility of which is extremely high. In case the protection by vegetation is lost, erosion intensity would be increased sharply.

The intensity of human activities in the Loess Plateau has increased due to increasing population in this region (Fig. 3). There has been large scale destruction of natural vegetation and associated cultivation started in the Sui (581-618 A.D.) and the Tang (618-907 A.D.) Dynasties (Jing & Chen, 1983). Although the boundary between the agricultural and animal husbandry zones shifted southward and northward occasionally in history due to the climatic change and the changing political conditions, the general tendency was marked towards an increasing higher degree of cultivation and degradation of natural vegetation. Therefore, the man-accelerated erosion there is very high, belonging to the most severe ones of the world.

Many researchers have studied the human accelerated erosion in the middle Yellow basin in relation to natural erosion. For example, Jing & Chen (1983) related the sedimentation in the lower Yellow River to the erosion in the middle Yellow basin, and estimated the erosion amount of the middle Yellow basin in terms of the deposition volume of the lower Yellow fan, channel and delta. The erosion amount during the period 6000-3000 years before present was estimated as 10.75 × 108 t year^{-1}. According to the gauging records, the sediment yield of the Yellow River was 16.8 × 108 t year^{-1} during 1919-1949; it was 16.3 × 108 t year^{-1} during 1949-1980, but another 6.03 × 108 t year^{-1} was trapped by reservoirs. Take the period 6000-3000 years before

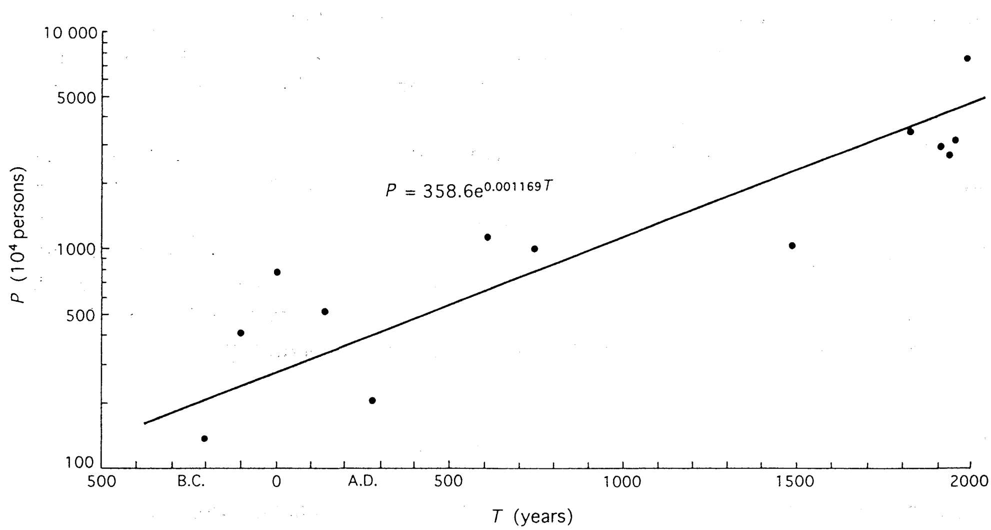

Fig. 3 Population P in the middle Yellow River basin in different periods. T refers to the number of years A.D.

present to represent the natural erosion, and compare it to the period 1949-1980 when the man-induced erosion played a full role. By so doing it can be pointed out that the human activities have increased the erosion amount by 11.58 × 108 t $year^{-1}$, making up 52% of the total, and natural erosion accounts for only 48%. Thus man-accelerated erosion exerts an important control upon the acceleration of sediment accumulation shown in Fig. 1.

Effect of artificial levee construction

The systematic construction of artificial levees along the lower Yellow River was started in the Warring States Period (475-221 B.C.) (Xu, 1993). Before that the Yellow River channel was able to shift freely and the course-change was frequent. Because sediment could be laid down quite uniformly over the vast area of the alluvial fan, the accumulation rate was low.

After the levee construction, if there were no frequent bank-bursts or avulsions, sediment could only be deposited in between the two levees, a factor favouring a much higher rise of the channel. On the other hand, due to the confinement of the levees, water flow may be concentrated in the main channel, and the water depth increases. This would lead to an increased sediment-carrying capacity and ease sedimentation. In fact, the Yellow River regulation strategy of "narrowing the water flow by diking to scour the sediment" proposed by Pan Jixun, a famous hydraulic engineering expert in the Ming Dynasty, was based on this consideration. Therefore, the final effect of levee construction on the channel accumulation rate is dependent on which one of the foregoing two actions is dominant. Study shows that, in general, the former prevails over the latter in a heavily silt-laden river like the Yellow, even under the strategy of "narrowing the water flow to scour the sediment", for a sufficiently long timescale. This will be discussed later.

After the levee construction, the accumulation rate of the outside-levee surface of the alluvial fan became much lower, even under the influence of man accelerated erosion

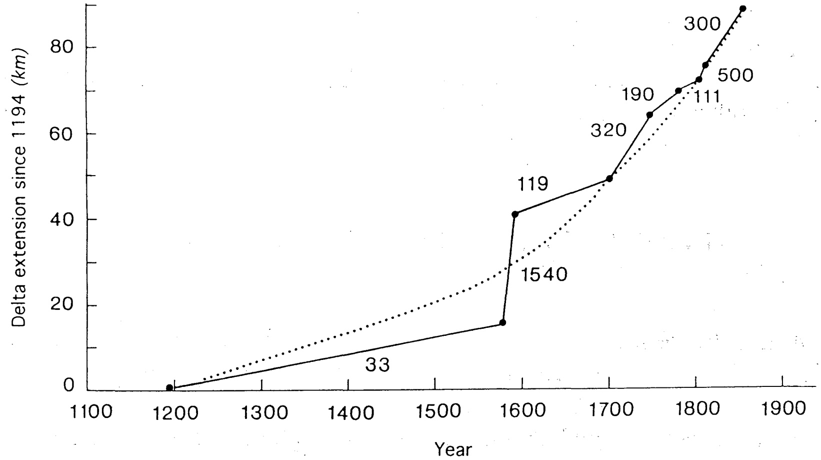

Fig. 4 The delta extension of the Yellow River during 1194-1855 (after Xu, 1993). Numbers refer to the delta extension rate in m $year^{-1}$.

of the river basin. For example, the accumulation rate of the fan formed in the period from 3000 years before present to 1194 A.D. was 0.66 cm year^{-1} (Table 1), lower than that of the fan formed 6000-3000 years before present, which was 0.75 cm year^{-1}. Opportunities for the outside-levee surface to accept sediment became much fewer after the levee construction, leading to the above differences.

The artificial levees would greatly enhance sediment accumulation in the channel and this has been regarded as one of the major causes for the formation of the "hanging river channel" of the lower Yellow (Xu, 1993). When the artificial levees are at high standard and under a good maintenance, the channel accumulation rate may be further increased. After 1949 when the People's Republic of China was founded, the levees have been reinforced three times, and no avulsions have occurred for more than 40 years. Consequently the accumulation rate reaches the value of 8 cm year^{-1}, setting the highest record in history, although the incoming sediment 16.3 $\times$ 108 t year^{-1} is less than that during 1919-1949, which was 16.8 $\times$ 108 t year^{-1}.

Effect of river mouth extending

As a river with the highest sediment load of the world, the Yellow pours 1.2 $\times$ 108 t year^{-1} of sediment into the sea on average. After the levee construction, the huge quantities of sediment from the middle reaches of the river would be redistributed, with much more into the sea. Thus the extending rate of the river mouth became much higher than before. The river mouth extending of the Yellow during 1194-1855 is shown in Fig. 4. The fitting curve is a concave one, indicating an acceleration in river mouth extending. 1578 was the year when Pan Jixun's strategy was put into action; afterwards, the extending rate was increased sharply. The extending of river mouth means a longer river length which makes the channel slope gentler, especially for the near-mouth reach. This will cause a decline in the rivers' sediment-carrying capacity, and thus a regression or backward deposition occurs, gradually upstream from the river mouth. This process will make the channel accumulation rate increase. Here we see a negative feedback mechanism. The narrowing of the channel by the levee construction enhances the sediment transport, then more sediment can be poured into the sea. The river mouth thus extends more rapidly, making a gentler channel slope. Then the river's sediment carrying capacity is reduced. This feedback mechanism explains why the levee construction in a heavily silt-laden river like the Yellow may finally lead to a strong accumulation other than ease it. Therefore, the final fail of Pan Jixun's strategy for Yellow River regulation is not at all surprising, which led to the great course change in 1855.

COMPARISON OF THE MAN ACCELERATED TO THE NATURALLY ACCELERATED ACCUMULATION

During the period 11 000-3000 years before present, the sedimentation of the lower Yellow River can be considered as a natural process without human influence. The accumulation rate of that period was 0.75 cm year^{-1} or less. Afterwards, the acceleration due to human activity becomes stronger through time, and at present the lower Yellow River's accumulation rate is up to 8 cm year^{-1} on average, 58.67 times higher than the early period. However, the present value of 8 cm year^{-1} includes also the result of naturally induced acceleration, and the latter should be separated from the total.

As pointed out earlier, from the period 11 000-6000 years before present to the period 6000-3000 years before present, the accumulation rate was increased from 0.54 to 0.75 cm $year^{-1}$ during a period of about 4000 years. Assuming the annual rate of increase, p, is a constant, then we have

$$0.75 = 0.54\,(1 + p)\,4000 \tag{2}$$

Solution of the equation gives $p = 0.00821\%$.

It took about 3000 years to increase from 0.75 cm $year^{-1}$ to 3 cm $year^{-1}$; during this time span, the natural acceleration rate per year is supposed to remain the same constant, then the accumulation rate induced by the changing climate can be calculated as:

$$0.75\,(1 + p)\,3000 = 0.96\ (\text{cm year}^{-1}) \tag{3}$$

Subtracting this from 8 cm $year^{-1}$, the total, we get 7.04 cm $year^{-1}$. This can be regarded approximately as the result of man-induced accumulation rate. So, it can be calculated out that the ratio of the man accelerated to the naturally accelerated accumulation rates is 7.3:1.

At the first glance, it seems unreasonable to compare the accumulation rate of the alluvial fan with that of the channel. However, because before the levee construction the river was able to shift on the alluvial fan freely and frequently, the difference in the accumulation rate between the fan and the channel was negligibly small for a long timescale. So it can be acceptable to use the fan accumulation rate to substitute that of the channel which is extremely difficult to get.

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