Available online at www.sciencedirect.com

SCIENCE DIRECT®

Global and Planetary Change 41 (2004) 215–220

GLOBAL AND PLANETARY CHANGE

www.elsevier.com/locate/gloplacha

A river erosion estimate on the Loess Plateau: a case study from Luohe River, a second-order tributary of the Yellow River

Zhu Zhaoyu[a,b,*], Zhou Houyun[a], An Zhisheng[b], Liu Tungsheng[c]

[a] *Key Laboratory of Marginal Sea Geology, Guangzhou Institute of Geochemistry, CAS, Guangzhou 510640, China*
[b] *State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, CAS, Xi'an 710054, China*
[c] *Institute of Geology and Geophysics, CAS, Beijing 100029, China*

Abstract

Based on fieldwork and terrace ages, which were determined using ^{14}C, TL and paleosol stratigraphy, a general model was established for the development of the Yellow River terrace system. The ages for the terraces and valley flats of the Yellow River system are T_6—1.67–0.85 Ma BP, T_5—0.85–0.47 Ma BP, T_4—0.47–0.10 Ma BP, T_3—0.10–0.007 Ma BP, T_2—7.0–0.7 ka BP, T_1—0.7–0.3 ka BP, the higher valley flat—0.3–0.15 ka BP and the lower valley flat 0.15–0 ka BP, respectively. Each terrace or valley flat and corresponding paleo-valley represents a river erosion/deposition cycle. Using this model and selected geomorphic parameters of terraces and paleo-valleys from 10 typical cross sections of Luohe River, a tributary of the Yellow River, an attempt is made here to estimate paleo-river erosion since the Pleistocene on the Loess Plateau.

Keywords: River erosion; Paleo-valley; Terraces; Loess–paleosol series; Luohe River; Yellow River, North China

1. Introduction

Soil erosion is a serious issue in China, with an estimated 15–20% of the total soil erosion areas of the world within China (Wen, 1993). The Loess Plateau is one of the areas in China that is eroded most seriously (Liu, 1985). Every year soil loss from the plateau amounts to $(200–30{,}000) \times 10^3$ kg km^{-2}. About $(16–18.8) \times 10^{11}$ kg of soil is transported into Yellow River each year (Liu, 1985).

What causes the serious soil erosion in the Loess Plateau? How do the eroded landscapes of the plateau form? How will the soil erosion of the plateau develop in future and how can it be managed? Answers to all these questions will provide some information about the ecological and environmental background to the erosion issue and are most important for sustainable development in West China. Soil erosion, which may be sometimes triggered and aggravated anthropogenically, is mainly a function of some physical and geodynamical conditions. There is a long history of research on soil erosion on the Loess Plateau (Zhang, 1981; Cao, 1983; Chen, 1983; Jing and Cheng, 1983; Yuan et al., 1987; Zhu, 1989; Jing et al., 1997; Cai and Wang, 1998; Deng and Yuan, 2001; Zhang et al., 2001). Although some scientists (e.g. Zhu, 1989; Deng and Yuan, 2001; Zhang et al., 2001) focus on the physical background, causes and changes in erosion intensity, the investigations are relatively preliminary. However, more research in these fields

---

[*] Corresponding author. Key Laboratory of Marginal Sea Geology, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, P.O. Box 1131, Guangzhou 510640, China. Tel.: +86-20-8529-0061; fax: +86-20-85290130.

E-mail address: zhuzy@gig.ac.cn (Z. Zhaoyu).

0921-8181/$ - see front matter © 2004 Published by Elsevier B.V.
doi:10.1016/j.gloplacha.2004.01.007

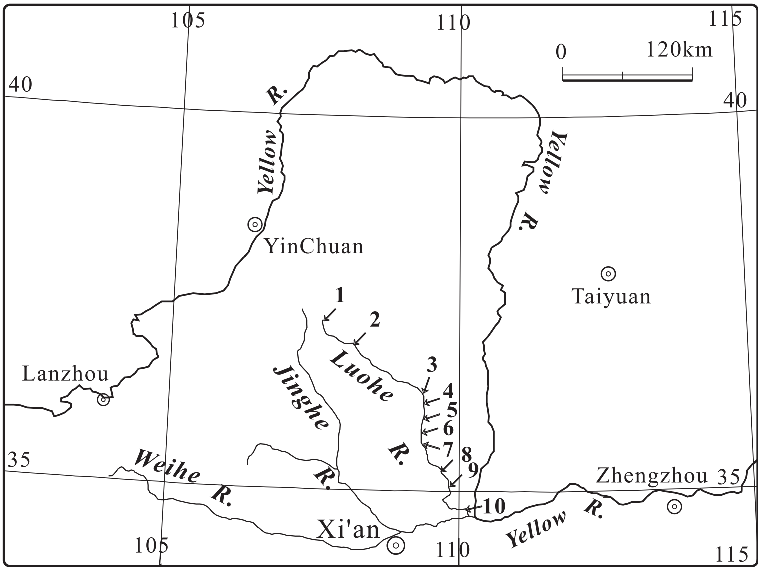

Fig. 1. Location map of Luohe River, North China. Arrows with number 1 to 10 indicate the locations of 10 cross sections: (1) Baiyushan, (2) Wuqi, (3) Ganquan, (4) Fuxian, (5) Luochuan-1, (6) Luochuan-2, (7) Jiaokouhe, (8) Baishui, (9) Yongfeng, (10) Sanhekou.

is essential to understand the patterns of soil erosion and to formulate measures to control it.

Soil erosion on the Loess Plateau consists of surface and river erosion (including incision and lateral erosion) (Zhang, 1981; Cao, 1983; Chen, 1983; Yuan et al., 1987; Deng and Yuan, 2001). Every terrace and corresponding paleo-valley represents a river erosion/deposition cycle (Zhu, 1989). Using the terrace system of the Luohe River, a second-order tributary of the Yellow River, an attempt has been made here to investigate the paleo-incision and lateral erosion of its valley since the Pleistocene (see Fig. 1 for location of Luohe River).

2. Methods

Channel density can be used as an indicator of river erosion intensity on the Loess Plateau (Chen, 1983; Jing and Cheng, 1983). This may be appropriate for estimation of contemporary soil erosion and loss over different areas. If paleo-density of the channels is used to estimate paleo-river erosion, there is a clear need for accurate terrace ages along the length of every tributary channel. Here we select some typical cross sections to study paleo-erosion events of the Luohe River valley. These sections are at Baiyushan, Wuqi, Ganquan, Fuxian, Luochuan-1, Luochuan-2, Jiaokouhe, Baishui, Yongfeng and Sanhekou (for locations of these sections, see Fig. 1). They are selected using the following criteria: the development and age determination of terraces and valley flats, and the spatial distribution of cross sections.

Three steps are taken in the procedure of our calculation: (1) At first, ages of each terrace and tributary channel are determined; (2) selected parameters related to erosion of each terrace and valley are measured. The selected parameters include valley width (W), depth of incision (d), thickness of deposition (h) and incision slope (θ) (for meanings of these parameters, see Fig. 2); and (3) based on the results of the previous two steps, intensities of paleo-erosion events are analyzed and discussed. In the cross section of each erosion/deposition cycle of a river (Fig. 2), the net amount of erosion (D_2), river incision depth (d) and width (w) are used as proxies of river erosion intensity.

2.1. Age determination of channels and terraces of the Yellow River system

The loess–paleosol series on the Loess Plateau has a well-preserved magnetstratigraphy record covering

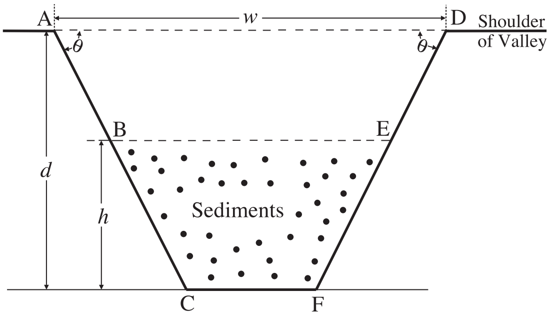

Fig. 2. Sketch map of a cross section of a river with an erosion/deposition cycle. In the cross section, area of ACFD represents total amount of erosion (D_1), while the area of BCFE represents amount of deposition (S), and the area of ABED represents net amount of erosion (D_2) in an erosion/deposition cycle of a river. Here d is the total depth of river incision and h is the thickness of deposition.

the Quaternary (Liu, 1985; An and Ho, 1989). The region has a record which correlates well with the marine isotope stages (MIS) seen in deep sea sediment (Ding et al., 1991). This enables the loess–paleosol series itself to be useful as a dating tool (Ding et al., 1991; Zhu, 1989, 1992, 1995). Based on the many ages which were determined by us using ^{14}C, TL and paleosol stratigraphy, or by others and a comprehensive analysis of nearly 400 cross sections of about 60 rivers on the Loess Plateau, a general model was established for the development of the Yellow River system on the plateau (Fig. 3) (Zhu, 1989, 1992, 1995). According to this model, the formation of the main tributaries and terraces of the Yellow River can be estimated. The formation times of the terraces are T_6—about 1.67–0.85 Ma BP, T_5—0.85–0.47 Ma BP, T_4—0.47–0.10 Ma BP, T_3—0.10–0.007 Ma BP, T_2—7.0–0.7 ka BP and T_1—0.7–0.3 ka BP, respectively. The higher valley flat formed during about 0.3–0.15 ka BP and the lower valley flat during the last 150 years. The Yellow River and its first-, second- and third-order tributary channels formed at the early of the formation of T_6. The fourth-order tributary of the Yellow River corresponds to T_5, the fifth-order tributary to T_4, and so on. This chronology then of the Yellow River, its tributary channels and terraces provides an outline for the development of the Yellow River system.

2.2. Parameters of terrace and valley and river erosion calculation

The Luohe River, which is used in our calculations, is a second-order tributary of the Yellow River, rising in the Baiyushan Mountains, north of the Loess Plateau. It flows across the plateau south–south–eastward and incorporates the Weihe River, a first-order tributary of the Yellow River at Sanhekou. Here we select 10 typical cross sections along the Luohe River to calculate the intensity of paleo-erosion of the Luohe River (Fig. 1). At each cross section, terraces

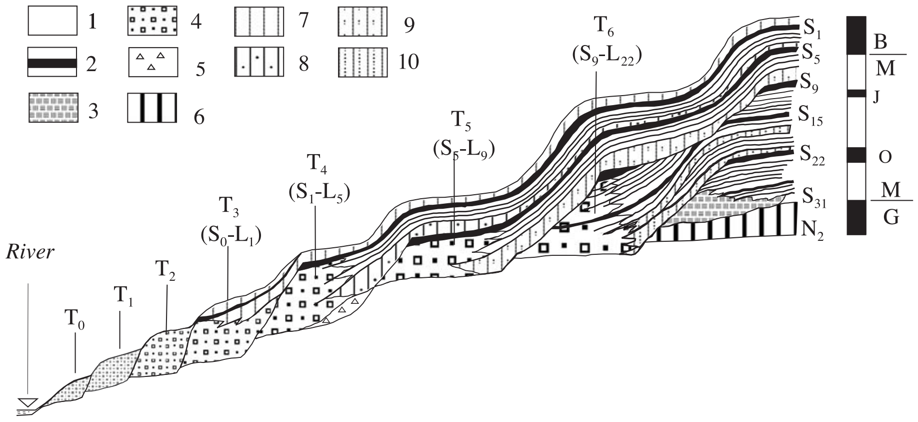

Fig. 3. A general model for the development of the terrace system of Yellow River (modified from Zhu, 1995). (1) Loess, (2) paleosol, (3) lacustrine deposit, (4) fluvial sand and gravel, (5) talus material, (6) red clay, (7) sandy loess L_1, (8) Sandy loess L_5, (9) Sandy loess L_9, (10) Sandy loess L_{18} and L_{22}. Stratigraphy: S—soil, L—loess, T—terrace, N_2—Pliocene red clay; Polarity: B—Brunhes, M—Matuyama, G—Gauss, J—Jaramillo, O—Olduvai.

Table 1
Parameters of terraces and valleys of Luohe River on the Loess Plateau

Terraces	Incision slope θ (°)	Width of valley W (m)	Incision depth d (m)	Deposition thickness h (m)	Time interval t (10 ka)
T_6	28	1500	85	48	59.900
T_5	25	1250	63	38	39.000
T_4	33	925	81	43	36.500
T_3	42	450	47	22	9.000
T_2	44	250	25	10	0.930
T_1	44	150	17	8	0.040
HVF[a]	39	75	9	2	0.015
LVF[b]	14	50	2	1	0.015

[a] HVF—Higher valley flat.
[b] LVF—Lower valley flat.

were well developed and relatively more ages were determined on these terraces. In each cross section, the following parameters for each terrace and corresponding paleo-valley, which represent an erosion/deposition cycle of a river, were measured: incision slope (θ), depth of incision (d), thickness of deposition (h) and valley width (w) (Fig. 2). The time period (t) represented by each terrace and valley flat was obtained from the general model for the development of the Yellow River system (Fig. 3). All the parameters for terraces, paleo-valleys and valley flats of Luohe River are listed in Table 1.

Using these parameters, total amount of erosion (D_1) and deposition (S), net amount of erosion (D_2), deposition rate (a), erosion rate (R), incision rate (γ_1), lateral erosion rate (γ_2) and ratio of erosion intensities (I) are calculated for each erosion/deposition cycle of the Luohe River according to the following equations (Fig. 2; Zhu and Ding, 1994):

$$D_1 = d(W - d\ \mathrm{ctg}(\theta)) \tag{1}$$

$$S = h(W - (2d - h)\mathrm{ctg}(\theta)) \tag{2}$$

$$D_2 = D_1 - S \tag{3}$$

$$a = S/t \tag{4}$$

$$R = D_2/t \tag{5}$$

$$\gamma_1 = d/t \tag{6}$$

$$\gamma_2 = W/t \tag{7}$$

$$I = \gamma_1/\gamma_2 = d/W \tag{8}$$

Here, the erosion rate R, the lateral erosion rate γ_2 and the incision rate γ_1 represent the eroded area, laterally eroded width and vertically incised depth in unit time period in the cross section (Fig. 2), respectively.

3. Results and discussion

Based on the calculation from Eqs. (1)–(8), the results of paleo-erosion for the Luohe River are listed in Table 2.

The results (Tables 1 and 2) indicate that:

(1) Overall, erosion and incision accelerated and valley width (W) was reduced from the Early Pleistocene to Holocene (Tables 1 and 2);
(2) During the Pleistocene (before T_2), incision rate (γ_1) increased steadily but with small increments, while the lateral erosion rate (γ_2) fluctuated and displayed an overall increasing trend. However, both γ_1 and γ_2 have increased dramatically since the development of T_2 (Table 2);
(3) Erosion rate (R) did not change markedly during the Pleistocene. But it increased greatly in the Holocene. During the period from 700 to 150 years BP, the erosion rate increased dramatically to 10–100 times much as elsewhere in the Pleistocene. We are not sure why erosion rate for the last 150 years decreased (Fig. 4) but some recent anthropogenic activity may have contributed to this;
(4) There is a positive correlation between slopes (θ) and erosion rates (R) despite much higher erosion rates in the Holocene compared to the Pleistocene (Tables 1 and 2). Modern measurements elsewhere also suggest a positive correlation between slope and fluvial transportation (Zhu and Ding, 1994);
(5) Incision slope for each terrace or valley flat (Table 1) represents an average from many cross sections. Except the lower valley flat, the high valley flat and all terraces have incision slopes of no less than 25°. Paleosols, however, observed

Table 2
Indexes of soil erosion events over Luohe River drainage on the Loess Plateau

Terraces	Total amount of erosion D_1 (m^2)	Total amount of deposition S (m^2)	Net amount of erosion D_2 (m^2)	Erosion rate R (m^2 year^{-1})	Incision rate γ_1 (mm year^{-1})	Lateral erosion rate γ_2 (mm year^{-1})	Ratio I (γ_1/γ_2)
T_6	114,266	60,389	53,877	0.090	0.140	2.520	0.056
T_5	69,944	39,920	30,024	0.077	0.160	3.210	0.050
T_4	65,024	31,937	33,087	0.091	0.220	2.530	0.087
T_3	18,697	8101	10,596	0.118	0.520	5.000	0.104
T_2	5603	2130	3473	0.373	2.690	26.900	0.100
T_1	193	980	1213	3.033	42.500	375.000	0.113
HVF[a]	580	127	453	3.020	60.000	500.000	0.120
LVF[b]	94	56	38	0.253	13.300	333.000	0.040

[a] HVF—Higher valley flat.

[b] LVF—Lower valley flat.

> during fieldwork have relatively gentle slopes ranging from 6.5° to 13° (Zhu and Ding, 1994), which are smaller than the critical value of 15° for acceleration of soil erosion (Cao, 1983). This indicates that river erosion was relatively weak during periods of paleosol development.

Apparently, the Pleistocene/Holocene boundary seems to be a turning point for the three parameters indicating the intensity of soil erosion, erosion rate (R), incision rate (γ_1) and lateral erosion rate (γ_2). Before this boundary, when T_6, T_5, T_4 and T_3 were developed, no notable change occurred in the three parameters. After this boundary, when T_2, T_1, higher and lower valley flats (HVF and LVF) were developed, all three parameters showed at least a 10 times increase (Table 2). It is yet not clear why this transition occurred. Archaeological studies reveal that since early to middle Holocene there was intensive human activity over the Loess Plateau and Weihe Basin (An, 1987). Perhaps early agricultural activity (An, 1988) made an important contribution to this remarkable increase of soil erosion rate.

4. Conclusions

This study shows that during the time when paleosols developed, incisions of the Luohe River and its tributaries were relatively weak, lateral erosion was relatively strong and the overall erosion rate was relatively small. Whereas while loess was deposited, incisions were relatively strong, lateral erosion rates were relatively weak and erosion rate was relatively higher. Intensive incisions therefore relate most probably to the main glacial epochs.

Of all the indexes of river erosion, erosion rate (R) is the most appropriate to represent the intensity of river erosion. Increasing rate of incision may correlate with relatively strong tectonic movement and cold

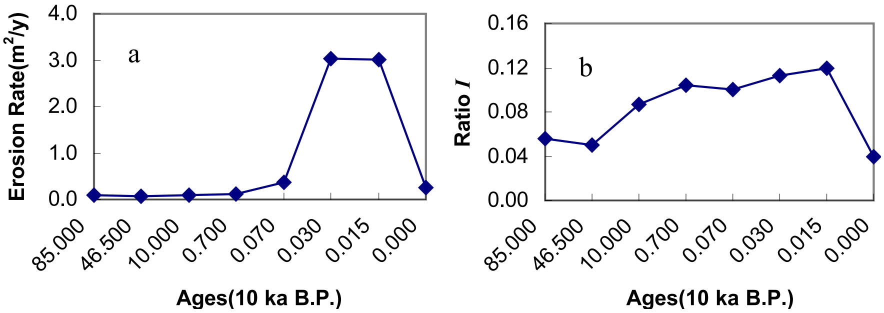

Fig. 4. Erosion rate R (a) and Ratio I (b) for Luohe River for different time periods.

climate, while increasing lateral erosion may correlate with relatively weak tectonic movement and warm climate. If this hypothesis is true, tectonic movement over the Loess Plateau as well as over the Qinghai–Tibet Plateau may have played an important role in the development of the loess–paleosol series and the evolution of soil erosion.

River erosion was significant during the Pleistocene when many valleys and gullies developed on the Loess Plateau. However, river erosion was aggravated in the Holocene. Both human activity (An, 1987, 1988) and physical conditions such as increase of runoff resulted from global warming and strengthening of the Asian summer monsoon (Liu et al., 1996) may have contributed to this aggravation.

The erosion rate estimate presented here is an attempt to study paleo-erosion by the river since the Pleistocene on the Loess Plateau using some parameters of terrace and valley from typical cross sections. The overall model needs to be refined and we hope that our work will act as a springboard to stimulate further investigations.

Acknowledgements

This paper is partially supported by the projects of CAS (KZCX1-10-04, ZCX2-SW-133, KZCX2-SW-118) and “The PEP-II Project” of NSFC (49894170).

References

An, Z.M., 1987. The Neolithic Age in West China. Acta Archaeologia Sinica 2, 133–151 (in Chinese with English abstract).

An, Z.M., 1988. Prehistoric agriculture in China. Acta Archaeologia Sinica 4, 369–382 (in Chinese with English abstract).

An, Z.S., Ho, C.K., 1989. New magnetostratigraphic dates of Lantian homo erectus. Quaternary Research 32 (2), 213–221.

Cai, Q., Wang, G., 1998. The Erosion Processes of Sediment Yield and its Simulation in Small Catchment on the Loess Plateau. Science Press, Beijing, pp. 1–252 (in Chinese).

Cao, Y., 1983. Slope features and soil erosion on the loess region. Geographical Research 2 (3), 19–28 (in Chinese with English abstract).

Chen, Y., 1983. A preliminary analysis of the processes of sediment yield in small catchment on the Loess Plateau. Geographical Research 2 (1), 35–45 (in Chinese with English abstract).

Deng, C., Yuan, B., 2001. Processes of gully erosion and accumulation in the Central Loess Plateau of China since the last interglacial. Acta Geographica Sinica 56 (1), 92–98 (in Chinese with English abstract).

Ding, Z.L., Yu, Z.W., Liu, T.S., 1991. Progress in loess research (Part 3): time scale. Quaternary Sciences 11 (4), 336–348 (in Chinese with English abstract).

Jing, K., Cheng, Y., 1983. Preliminary study of the erosion environments and rates on the Loess Plateau. Geographical Research 2 (2), 1–10 (in Chinese with English abstract).

Jing, K., Lu, J., Liang, J., 1997. Characteristics and Evolution of the Erosion Environments in the Middle Yellow River. Huanghe Hydraulic Publishing House, Zhengzhou, pp. 1–154 (in Chinese).

Liu, T. (Ed.), 1985. Loess and the Environment. Science Press, Beijing, pp. 62–81, 402–412 (in Chinese).

Liu, X., An, Z., Li, X., Kutzbach, J.E., 1996. A study on numeric model of summer monsoon climatic change of China in the last 18,000 years. In: Liu, T., An, Z., Wu, X. (Eds.), Loess, Quaternary Geology and Global Change Part IV. Scientific Press, China, pp. 142–150 (in Chinese).

Wen, D.Z., 1993. Soil erosion and conservation in China. In: Pimentel, D. (Ed.), World Soil Erosion and Conservation. Cambridge Univ. Press, Cambridge, pp. 63–85.

Yuan, B., Ba, T., Cui, J., Yini, Q., 1987. The relationship between gully development and climatic changes in the loess yuan region: example from Luochuan, Shaanxi province. Acta Geographica Sinica 42 (4), 328–337 (in Chinese with English abstract).

Zhang, Z., 1981. Regional geological and morphological characteristics and development of soil erosion in the Loess Plateau, China. Acta Geologica Sinica 55 (4), 308–320 (in Chinese with English abstract).

Zhang, L., Zhu, D., Yang, D., 2001. Research on the relationship of Loess Plateau soil erosion to the evolution of Yellow River Delta since the Late Pleistocene. Scientia Geographica Sinica 21 (1), 52–56 (in Chinese with English abstract).

Zhu, Z., 1989. The sequence of hydrogenic sediments—paleosols in the Loess Plateau and its adjacent regions of China. Chinese Science Bulletin 34 (19), 1629–1633.

Zhu, Z., 1992. Formation of river terraces and evolution of drainage system in the middle reaches of Yellow River. Journal of Chinese Geography 3 (4), 50–62.

Zhu, Z., 1995. A loess–paleosol dating method. GeoJournal 36 (2/3), 243–249.

Zhu, Z., Ding, Z., 1994. The Climatic and Tectonic Evolution in the Loess Plateau of China During the Quaternary. Geological Publishing House, Beijing, pp. 1–225 (in Chinese with English abstract).