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Natural erosion rates and sediment delivery ratios in the Hilly Sichuan Basin, southwest China, since the Mid-Pleistocene

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Abstract The present hilly landforms in the Hilly Sichuan Basin above the Three Gorges have developed from the dissection of a large ancient fluvial plain as a result of the incision of the Yangtze River since the Mid-Pleistocene to form the Three Gorges. This paper reports a preliminary assessment of the natural mean annual erosion rate in the Xiaohegou Ravine, a typical small catchment in the Hilly Sichuan Basin, since the Mid-Pleistocene. The mean annual erosion rate is calculated by establishing the volume of material eroded from the zone between the original ancient plain surface and the present land surfaces, using a DEM. This is estimated to be equivalent to a surface lowering rate of 84 mm ka^{-1} or 211 t km^{-2} a^{-1} from the catchment over the last 0.715 Ma. The natural sediment delivery ratio is estimated to be 0.997. The precision of this estimate depends on the accuracy of the elevation data provided by the DEM. The maximum potential error for the estimated natural erosion rates obtained from this study is estimated to be 21.1%.

Key words natural erosion rate; sediment delivery ratio; small catchment; Hilly Sichuan Basin, China; Yangtze River

INTRODUCTION

It is well known that human activity has had a major impact on erosion and sediment delivery within fluvial systems. Reliable information on natural erosion rates and delivery ratios can prove very valuable for qualitative assessment of the magnitude of such impacts in a region. Sediment deposits in lakes and deltas are often used to provide estimates of past erosion rates in the upstream catchment during a given period. For example, estimates of past specific sediment yields from the Loess Plateau in the middle reaches of Yellow River in China have been derived from the sediment deposits in the lower reaches of that river (Ye *et al.*, 1994). An average denudation rate of 16.97 mm ka^{-1} was estimated for the crystalline rock region of the Huangling anticline in the Three Gorges area of the Yangtze River, based on the amount of sediment deposited in the adjacent Jianghan basin. Studies of eroded landforms can also provide useful information on erosion rates during a given period (Zhang *et al.*, 2003). For example, an estimate of the erosion rate on the Luochuan High Plain of the Loess Plateau in the Late Pleistocene was derived from calculations of the volume of loess eroded (Zhang *et al.*, 1988). At a different spatial and temporal scale, the amount of sediment produced during two (19.5 and 33.2 year) periods by 11 (approx. 0.01–0.20 km^2) gullies within a 4 km^2 area in the headwaters of the Waipaoa River basin in New Zealand, was estimated using sequential digital elevation models (Derose *et al.*, 1998). An average glacial erosion rate of 0.021 mm a^{-1} for the entire 2.3 Ma of the Quaternary was estimated by a comparison between glacial and preglacial landforms in northeast Scotland (Neil & Adrian, 1997).

The Hilly Sichuan Basin, one of the important agricultural regions of China, is regarded as one of the severe erosion areas of the Upper Yangtze River Basin. The basin is characterized by typical hilly mesa landforms formed of Mesozoic red sandstones, siltstones and mudstones with horizontal bedding (Zhang *et al*., 2005). Studies of the geomorphological evolution of the area during the Quaternary period have shown that the basin was a large fluvial plain before the Mid-Pleistocene and that it has been dissected to produce the hill landforms since the Mid-Pleistocene, as a result of the downcutting of the Yangtze River to form the Three Gorges (Yang, 1988; Zhang *et al.*, 2004; Zhang *et al.*, 2009). In this paper, the long-term natural erosion rate in a small catchment within the Sichuan basin has been estimated by comparing the surface of the former plain with the present land surface and establishing the volume of material removed.

THE GEOLOGY AND GEOMORPHOLOGY OF THE STUDY AREA

The Changbashan highland with an area of about 10 km^2, a remnant of the ancient fluvial plain that occupied the Sichuan Basin, is located 4 km north of Guobei Town, on the eastern side of the Tuojiang River, while Neijiang City lies on the western side. The margins of the highland are severely dissected by gullies, but the surface of the original plain is well preserved near the Huilong Temple (See Fig. 1(a)). The elevation of the highland surface ranges between 370 m and 407 m, whereas the elevation of the channel bed of the Tuojiang River at Neijiang City is 285 m. The relative relief between the highland surface and the channel bed of the main river varies between 85 m and 120 m. The highland represents Terrace IV of the Tuojiang River, the highest terrace in the area, which is a basal terrace underlain by Mesozoic red sandstone, siltstone and mudstone. The sediment deposits on Terrace IV comprise a gravel and sand layer, 3–10 m in thickness, overlain by a yellow soil silt and clay layer 1–3 m in thickness. The gravels are comprised primarily of hard rocks, such as quartzite, silicarenite, granite, vein quartz and siliceous limestone, which originated from the Longmenshan Mountains in the upper reaches of the Tuojiang River, and contain very little material derived from the local Mesozoic soft sedimentary rocks. Except for the remnant of the high fluvial plain, the deposits of Terrace IV are distributed on the summits of high hills in this region. The highland and hills of Terrrace IV are the highest landforms in the region. Terraces III, II and I are all basal terraces and the relative relief between these terrace surfaces and the river level in the dry season is 55 m, 40 m and 15 m, respectively (see Fig. 1(b)).

Terraces in the Hilly Sichuan Basin and the Three Gorges area have been extensively studied since the 1930s. Those studies indicated that the extensive ancient fluvial plain has been dissected to form the present hill landforms in the Sichuan Basin as a result of the downcutting of the Yangtze River to form the Three Gorges since the Mid-Pleistocene (Liu, 1983; Li *et al.*, 2001). Recent dating of the terrace deposits provide the following absolute ages for the terrace formation (Tian *et al.*, 1996; Xiang *et al.*, 2005): Terrace IV (T4), 0.70–73 Ma; Terrace III (T3), 0.3–0.5 Ma; Terrace II (T2), 0.09–0.11 Ma; and Terrace I (T1), 0.03–0.05 Ma. The hill landforms and the existing river systems, including the Tuojiang River within the Sichuan Basin have clearly been formed by dissection of the ancient plain since the downcutting of the Yangtze River to form the Three Gorges 0.70–0.73 Ma ago (Chen, 1996).

As indicated above, the gravels of the highest Terrace IV are comprised primarily of hard rocks and they contain little of the local soft Mesozoic sedimentary rocks. However, the gravels of the lower terraces contain considerable amounts of the local red sandstone. The gravels of the highest Terrace IV originate primarily from the hard crystalline rocks in the Longmenshan Mountains of the upper reaches of Tuojiang River and with little contribution from the local soft sedimentary rocks, when the ancient plain was not dissected in the Mid-Pleistocene period. As the ancient plain was gradually dissected, the gravels of the lower terraces contain more local sedimentary rocks. The channel bed of the Tuojiang River at Neijiang City has an elevation of 285 m and the highest elevation within the approx. 500 km^2 covered by the 1:50 000 topographic map of Neijiang, is a hill summit at 410 m. This means that the maximum depth of dissection by the Tuojiang River reaches 125 m. Taking 0.715 Ma as the average age for Terrace IV, the average dissection rate of the Tuojiang River at Neijiang City is 175 mm ka^{-1}.

THE STUDY CATCHMENT

The Xiaohegou Ravine is a secondary tributary of the Tuojiang River, lying on the eastern side of the Tuojiang River. It originates from the Changbashan highland and flows to the Qingshuihe River, which flows into the Tuojiang River at Chenjiaba Village. It has two main tributaries, one of which originates from Baiyanggou Village and the other from the Huilong Temple. The Ravine has a drainage area of 10.88 km^2 and channel length of 7200 m with a weighted longitudinal gradient of 1%. Elevations of the ravine in the headwaters and at the mouth are 370 m and 295 m, respectively, and the relative relief is therefore 75 m. In the highlands within the upper reaches of

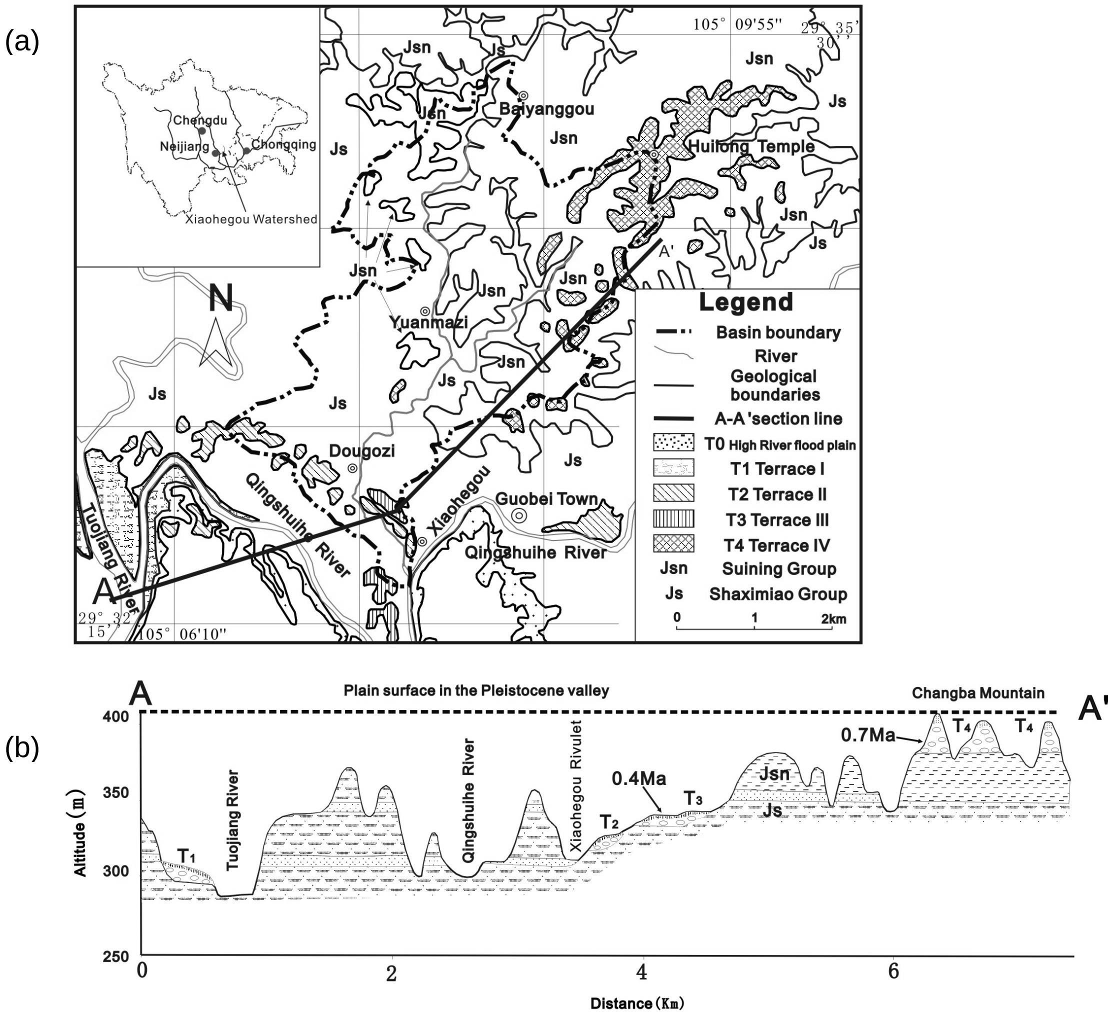

Fig. 1 A geological map of the study area, with an inset showing (a) the location of the study area and the Xiaohegou watershed at Guobei Town near Neijing City within Sichuan Province and (b) a profile across the study area showing the geomorphology, and Quaternary geology

the ravine, there are wide and shallow valleys where channels are small and gentle with a longitudinal gradient of 0.7%. In the middle reaches, from the edges of the highland to the confluence of its two tributaries, the narrow channels are deeply incised into the steep slopes underlain by Mesozoic red sedimentary rocks with horizontal beddings and are characterized by steep slopes with a high longitudinal gradient of 1.5%. In the lower reaches, stretching from the confluence of its two tributaries to Dougouzi Village, there is a relatively wide and gentle valley with very variable widths ranging from 20 m to 200 m. The channels in the valley of the lower reaches have a width of 10–20 m and a longitudinal gradient of 0.3%, and are much wider and gentler than those in the middle reaches. Benches and terraces of <10 m in height exist on the sides of the bedrock channels and they consist of mixed alluvial and diluvial deposits. The valley in the lower reaches has a total area of 0.12 km^2. Taking an average thickness for the alluvial and diluvial deposits of 5 m, the total deposit volume in the valley has been estimated to be 0.6 million m^3. Below Dougouzi Village, the channels become narrow and steep again and Terraces III and II are located on the right side.

In the highlands of the upper reaches, there are Masson pine forests (*Pinus massoniana*), which are rare in the Hilly Sichuan Basin, on the mounds, while paddy rice land is found in the wide and shallow valleys. In the middle and lower reaches, there is cultivated land without irrigation on slopes of <20° and on the terraces in the valleys.

Neijiang experiences a subtropical monsoon climate with a mean temperature of 17.9°C and a mean annual precipitation of 1064 mm, 70% of which occurs during the wet season extending from June to September. According to the second State survey of soil erosion based on remote sensing techniques, the Xiaohegou Ravine catchment belongs to the moderate erosion region with an erosion rate of 3000–5000 t km^{-2} a^{-1} (Ministry of Water Resources, 2000). Hydrologically, the Neijiang area belongs to the zone of the Hilly Sichuan Basin lying between the Dengyingtai and Lijiawan hydrological stations. According to the monitoring data provided by the two stations, the average specific sediment yield of the area was 397 t km^{-2} a^{-1} during the period from 1958 to 1986.

ESTIMATION OF THE VOLUME OF ROCK ERODED SINCE THE MID-PLEISTOCENE

As indicated above, the present hilly landscape of the Neijiang region has been formed by the dissection of the extensive ancient fluvial plain by the Tuojiang River and its tributaries since the Mid-Pleistocene. For the Xiaohegou Ravine catchment, the volume of rock occupying the zone between the surface of the ancient plain and the present land surfaces, was removed from the catchment since the Mid-Pleistocene (Fu *et al.*, 2005).

To quantify the volume of rock eroded from the Xiaohegou Ravine catchment, a DEM of the catchment (see Fig. 2) was generated from the 1:50 000 topographic map (contour intervals of 10 m) by using Geographic Information System software (Yu & Liu, 1998).

The volume of rock remaining above the base level elevation of 295 m, represented by the existing hills within the catchment, can be estimated from the DEM. The volume of rock eroded since the Mid-Pleistocene can be estimated using following equation:

$$A_x = A_o - A \quad (1)$$

where, A_x is the volume of the rock body eroded since Mid-Pleistocene from the catchment (m^3); A_o is the volume of the rock between the plane at 370 m representing the highest elevation within the catchment and the plane at 295 m representing the elevation of the mouth of the catchment; and A is the volume of rock above the plane at 295 m represented by the present hills.

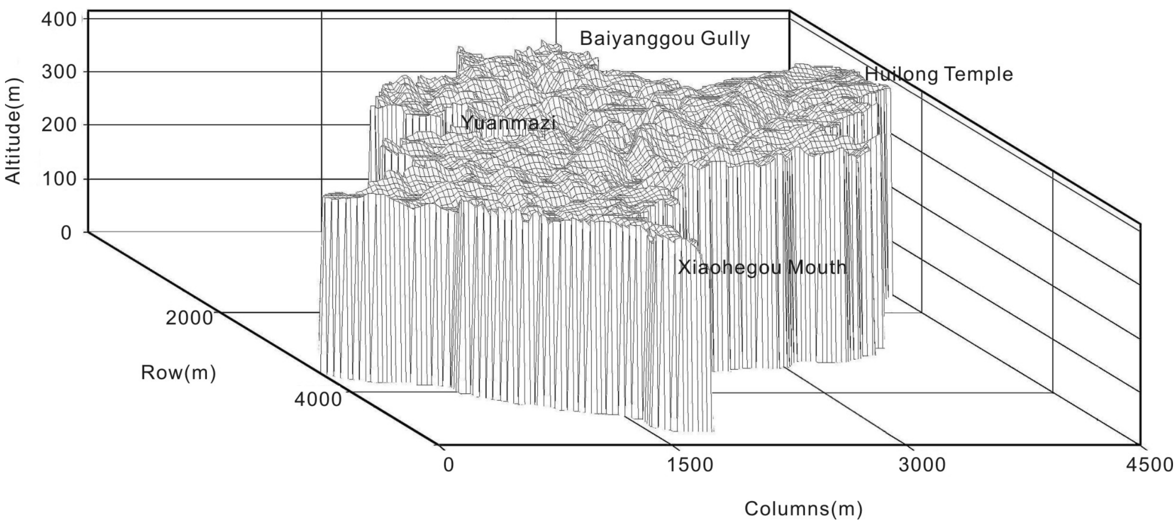

Fig. 2 The DEM of the Xiaohegou catchment.

RESULTS AND DISCUSSION

By using the DEM map, the volume of rock above the plane at 295 m, representing the base level at the outlet of the Xiaohegou Ravine catchment, (A) has been estimated to be 567 million m^3; the volume of rock lying between the plane at 370 m representing the highest elevation within the catchment and the plane at 295 m representing the base level at the catchment outlet (A_o) has been estimated to be 1.224 billion m^3; and the volume of the rock eroded from the catchment over the past 0.715 Ma (A_x) has been estimated to be 657 million m^3.

The accuracy of the estimate of the volume of rock eroded depends primarily on the accuracy of the elevation data provided by the 1:50 000 topographic map. The topographic map has a discrimination accuracy of 1 mm and the related maximum error of horizontal distance is 50 m. The accuracy of the elevation data obtained from the map is related to land steepness, which can be expressed as follows:

$$X = 50 \tan \alpha \quad (2)$$

where, X = the accuracy of the elevation data (m) and α = the slope steepness (°). It is obvious that steep slopes will provide elevation data with a lower accuracy than for gentle slopes. For the average steepness of 10°, the DEM map of the study catchment has an average maximum elevation error of ±8.8 m. As the average height of the catchment is 52.1 m above the elevation of 295 m at the catchment outlet, the related average maximum elevation error is ±17% (8.8 m/52.1 m). The Xiaohegou Ravine catchment has a drainage area of 10.88 km^2. If the study catchment is regarded as a rectangle with a length of about 5 km and a width of about 2 km, the related maximum horizontal distance errors are ±1% (50 m/5 km) and ±2.5% (50 m/2 km), respectively. By integrating the maximum errors in elevation, length and width, the estimated eroded rock body volume has a possible maximum error of ±21.1%.

The average depth of erosion within the Xiaohegou Ravine catchment is estimated to be 60.4 m. This is equivalent to an average rate of surface lowering of 84 mm ka^{-1}, since the Mid-Pleistocene, 0.715 Ma ago. The volume of eroded rock A_x = 657 million m^3 is equivalent to a sediment removal rate from the catchment of 211 t km^{-2} a^{-1}, assuming a bulk density γ of 2.5 g cm^{-3}. It should be noted that the natural erosion rate during the historical period represented by the past few hundred or even thousands of years, may have been different from the estimated natural erosion rate since the Mid-Pleistocene and it may not be representative of the natural erosion rate, because of climate changes and the time-dependent effects of landform changes in the areas upstream of the Three Gorges formed by the downcutting of the Yangtze River.

In addition to the limited terrace deposits, other unconsolidated sediment deposits include the mixed alluvial and diluvial deposits, which occur only in the valleys of the lower reaches of the catchment near Dougouzi Village. The volume of these deposits is estimated to be 0.6 million m^3. The total volume of unconsolidated sediment deposits within the catchment is estimated to be much less than 2 million m^3. Taking 2 million m^3 and 657 million m^3 as the volumes of the deposited sediment and of the eroded rock, respectively, in the catchment for the period representing the last 0.715 Ma, the natural sediment delivery ratio for the Xiaohegou Ravine catchment, a typical small catchment in the Hilly Sichuan Basin, is estimated to be 0.997. This indicates that the natural long-term sediment delivery ratio in the Hilly Sichuan Basin is similar to that for the Loess Plateau in China and close to 1 (Jing *et al.*, 2002).

The estimated natural erosion rate of 211 t km^{-2} a^{-1} is of a similar order of magnitude to the present specific sediment yield of 397 t km^{-2} a^{-1} for the Hilly Sichuan Basin drained by the Tuojiang River. This similarity may indicate that the impacts of human activity resulting in reduced sediment delivery ratios, due to sedimentation in reservoirs, ponds and paddy fields, serve to offset the increased sediment yields associated with accelerated erosion caused by deforestation and reclamation. The increase of the present specific sediment yields over the natural erosion rate may imply that human activities have in general resulted in increased sediment yields within the Hilly Sichuan Basin. However, the low natural erosion rate of 211 t km^{-2} a^{-1} and the high sediment delivery ratio (close to 1) cast doubts on the very high erosion rates of 3000–5000 t km^{-2} a^{-1}, reported by the State surveys.

CONCLUSION

The present hilly landforms of the Sichuan Basin above the Three Gorges in the upper reaches of Yangtze River were formed by the dissection of the large ancient plain that formerly occupied the area, caused by the incision of Yangtze River as it cut through the Three Gorges since the Mid-Pleistocene. The long-term natural erosion rate in the Xiaohegou Ravine catchment has been estimated to be 84 mm ka^{-1} or 211 t km^{-2} a^{-1}, and this is seen to be representative of the past 0.715 Ma in the Hilly Sichuan Basin. The long-term natural sediment delivery ratio is estimated to be 0.997 and therefore very close to 1.

The estimated natural erosion rate of 211 t km^{-2} a^{-1} is of the same order as the present specific sediment yield of 397 t km^{-2} a^{-1} for the area of Hilly Sichuan Basin drained by the Tuojiang River, although this is slightly higher than the former. This lack of a clear contrast between the long-term natural erosion rate and the current specific sediment yield may indicate that the impacts of human activity resulting in reduced sediment yields, such as reduction of the sediment delivery ratio due to sedimentation in reservoirs, ponds and paddy fields, have largely offset the increased erosion rates associated with deforestation and land reclamation. The similarity of the estimated natural erosion rate of 211 t km^{-2} a^{-1} to the contemporary specific sediment yield of 397 t km^{-2} a^{-1} and the high sediment delivery ratio of 0.997 casts doubt on the very high erosion rates of 3000–5000 t km^{-2} a^{-1}, reported by the State surveys.

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