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The recent history of hydro-geomorphological processes in the upper Hangbu river system, Anhui Province, China

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ABSTRACT

This paper describes 20th century climate and human impacts on terrestrial and fluvial systems in the Dabie Mountains, Anhui Province, China, based on analyses of four types of information. Analyses of particle size, mineral magnetism, organic carbon, nitrogen and phosphorus in a sediment core taken from the Longhekou reservoir, built in 1958 AD in the upper reaches of Hangbu River, provide an ~45 year record of fluvial responses, while monitored meteorological and hydrological data provide records of climate and river discharge. Census data compiled for the local Shucheng County provide records of population and land use, complemented with analyses of satellite images. The Xiaotian river delivers over 65% of the total water and silt to the reservoir. Analyses indicate that the fluvial regime tracks the monsoon climate over seasonal timescales, but human activities have a strongly mediating effect on sediment supply, sediment delivery and, to a lesser extent, runoff over longer timescales. Notable periods of human impact on erosion include the Great Leap Forward (1958–1960) and Great Cultural Revolution (1966–1976). A rising trend in precipitation and new land use changes at the present time may be leading to an enhanced flood risk.

1. Introduction

Reconstruction of catchment environmental change has become more significant in recent years as a result of the increasing need to understand and model the relative importance of climate and land use controls on terrestrial and fluvial systems. This is particularly important where information is required over longer timescales than are normally available from instrument records (e.g. Coulthard et al., 2000; Coulthard and Macklin, 2001; Dearing, 2006; Dearing et al., 2006). In this sense, understanding hydro-geomorphological processes over decadal timescales is essential for creating the tools and strategies needed for future sustainable development and the reduction of hazard risk. Without such knowledge there is the risk that key attributes of catchment systems, such as the connection between long term land use and soil loss or the triggers of shifts in flood magnitude–frequency, fail to be incorporated into management plans. The challenge is less one of unravelling the individual effects of either climate or land use drivers of system response and more the understanding of interactions and feedback within a cascading system that may evolve over decades or even centuries (e.g. Dearing, 2008). In China, studies that explore the impact of land use and climate on hydrology and sediment delivery over decadal timescales, either from reconstruction or long term catchment experiments, are with exceptions (e.g. Zhang et al., 2007) uncommon.

The lower Yangtze basin in east China has a typical monsoon climate, one of the densest agricultural populations in the world and a long history of flooding. River discharge levels at the Datong Hydrological Station show that major flood events have increased in frequency since 1990 (Jiang et al., 2008), raising a number of alternative arguments about the roles of climate change, land use and flood storage capacity across the Yangtze basin. The simplest explanation argues for the trend towards more flooding as a direct function of the rising trend in summer precipitation, equivalent to 86 mm more precipitation per decade. This seems to be at least partly caused by a significant shift in the *frequency* of summer rainstorm days (>50 mm/day) between the periods 1961–1990 and 1991–2000 by at least 10 more days/decade, rather than their intensity (Jiang et al., 2008).

Other explanations invoke land use as an important factor determining runoff and flooding (e.g. Yin and Li, 2001). Forest

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clearance in the mountains, possibly by as much as 50% between 1957 and 1986, can be assumed to have increased runoff but the downstream flood effect may have been amplified even further by the reduction in flood storage capacity afforded by riverine lakes. Wetland reclamation on the middle Yangtze floodplain has been estimated to have reduced riverine lake volume by one third (Yin and Li, 2001). These authors argue that this has caused flood peaks on the Yangtze to rise faster and to higher magnitudes, particularly where levées have been constructed to protect increasingly populated rural and urban areas. Chen et al. (2001a,b) claim that water discharge in the lower Yangtze is becoming more extreme as a result of the changing nature of these riverine lakes.

It has also been argued that loss of flood storage capacity is linked to accelerated soil erosion. Sediment yield patterns across China were once considered to reflect essentially regional climate (e.g. Xu, 1994) but growing evidence in the Yangtze system points to the role of human activities, particularly in terms of deforestation and water control projects since the 1960s driven by the needs of an expanding population. Largely as a result of forest clearance, the area of the Yangtze basin affected by surface erosion processes is believed to have doubled since the 1950s and this is linearly correlated with total sediment yield in nine major sub-catchments (Yang et al., 2004). However, recent sediment accumulation rates in riverine lakes in the middle–lower Yangtze are generally stable (Boyle et al., 1999) or only gradually increasing (Xiang et al., 2002) from the 1950s to the 1990s. The evidence points to rates of infilling that are too low to account for significant losses of water capacity. It seems that the increased siltation of Dongting lake (Du et al., 2001), SW of Wuhan, in the middle Yangtze is more likely to have occurred through a combination of 19th century avulsion events, which extended the lake catchment area, and a 40% reduction in the lake area between 1949 and 1983 caused by land reclamation. Besides, actual flood storage in Dongting lake may have actually *increased* from the 1950s to the 1990s because of rising outlet stages caused by increased deposition in the downstream river (Du et al., 2001; Li et al., 2003).

Despite the deposition of ~27% of the Yangtze sediment load in the Dongting lake system, sediment load in the lower Yangtze is actually larger than the middle Yangtze because of increased net erosion and remobilisation of longitudinal bars, the carving of soft alluvial riverbanks, together with additional loads from tributaries to the lower Yangtze (Chen et al., 2001a,b). Although the sediment load in the lower Yangtze remains larger, the analyses of Yang et al. (2002) show that the annual sediment discharge at Datong Hydrological Station has been declining since the 1960s from $\sim 500 \times 10^6$ t/year to $\sim 300 \times 10^6$ t/year, a trend that mirrors the rise in reservoir construction which peaked in the 1970s. An ~9-fold increase in total reservoir water capacity between the 1950s and 1990s has been calculated as equivalent to 22% (Yang et al., 2004) or 12% (Nilsson et al., 2005) of the total annual Yangtze discharge (prior to the construction of the Three Gorges Reservoir) amounting to a total cumulative sediment retention of $>500 \times 10^6$ t/year (Yang et al., 2004), a value that exceeds the amount carried to the coast. The suspended sediment load at the coast is probably lower now than it was in 1900, part of a decadal declining trend since at least the 1960s that has been diverging away from the trend in flooding since the 1980s (Yang et al., 2004).

In many ways, less is known about smaller, low order catchments. Some plot studies confirm the importance of land cover for soil erosion processes in a monsoon climate. For example, un-terraced arable cultivation on 25° slopes at a site in the middle Yangtze increased runoff and soil losses by 300% compared with orchards (Meng et al., 2001). In the lower Yangtze, Zhang et al. (2008) measured annual soil loss rates in a small sub-catchment (8900 m^2) in the Dabie Mountains ranging from 0 to 690 t/km^2, dependent largely on the nature and thickness of organic litter. These erosion rates represent the range of losses between fir forest, pine forest and tea gardens. Micro-plot studies (2×1 m) in the same study showed that soil losses could be ~70 times higher where litter and grass were not present. Although there are studies elsewhere in SE Asia that show how forest clearance in small catchments can increase peak flood discharge and base-flows (Tollan, 2002; Bruijnzeel, 2004), the evidence in small Yangtze catchments is sparse and restricted to the upper Yangtze. There, increased urbanization caused considerable increase in local runoff coefficients (Cheng, 1999), but Lu et al. (2003) found no evidence for an increase in monthly water discharge in major tributaries (14,000–232,000 km^2) in the period 1957–1987, and only increases in maximum monthly or maximum daily in two catchments. The lack of climate data makes it difficult to discriminate between climate and land use effects in these studies.

Information about historical trends in flooding and erosion over decades is limited. For example, in the upper Yangtze there is a tendency for recent sediment yields to increase with the proportion of agricultural land in a catchment (Higgitt and Lu, 1999) but to decrease downstream of reservoirs (Lu and Higgitt, 1998). The authors conclude that the climate and land use controls on erosion and fluvial sediment transport are spatially complex. One of the few lake sediment studies at Taibai lake (SE of Wuhan) describes high sediment accumulation rates (a proxy for erosion) before 1954 correlating with periods of high precipitation, whereas after 1954 the rates are much more closely linked to two periods of land reclamation and intensive cultivation in 1958–1970 and 1983–1993 (Liu et al., 2007). But it is not known whether these observations are site-specific or regional in nature.

Overall, the literature does not yet provide a full picture of how climate and land use combine to affect the hydro-geomorphological links between low and high order catchments within the upper, middle and lower Yangtze basins. Of particular concern is the lack of information for low order catchments, especially those above the highest reservoirs. These catchments need sustainable management strategies not only because they support sizable populations but also because they have the potential to drive significant downstream hydro-geomorphological changes. Thus this paper provides the recent history of hydro-geomorphological processes in lower order Yangtze catchments in the Dabie Mountains that drain via the Hangbu river into lake Chaohu and ultimately to the lower Yangtze river near Wuhu city. The reconstructions are based on analyses of a high-resolution reservoir sediment record covering the past 45 years together with instrumental records, land use and socio-economic archives, and satellite images for the upper Hangbu river system in Shucheng county.

The overarching questions for the research were:

- How have climate and human activities interacted in the past to modify flood and erosion regimes?
- Which specific types of climate event or land use change are key in driving change?
- What is the state of the modern catchment system in terms of its position on trends of process response and recovery?

2. Site and environmental history

The Hangbu River, originating on the north slope of the Dabie Mountains (Fig. 1), is a main tributary of lake Chaohu that ranks the fifth large fresh-water lake in China (2nd in the lower Yangtze). In 1958, a reservoir, Longhekou (also called Wanfo lake) was built with two original purposes. One was to control floodwater and sediment delivery to the downstream fluvial network and lake Chaohu; the other was to establish a new irrigation system for agriculture in the west-central zone of Anhui Province. The reservoir dam wall maintains a water area of ~50 km^2 and a water volume of 8.2×10^8 m^3 (based on the original water level of 70 m a.s.l). The mountainous and deeply dissected catchment area above the reservoir (Fig. 1b), covering 1111 km^2 with a maximum altitude of 1350 m a.s.l (mean 368 m a.s.l), occupies ~56% of the total area of the Hangbu river catchment. The reservoir is maintained mainly

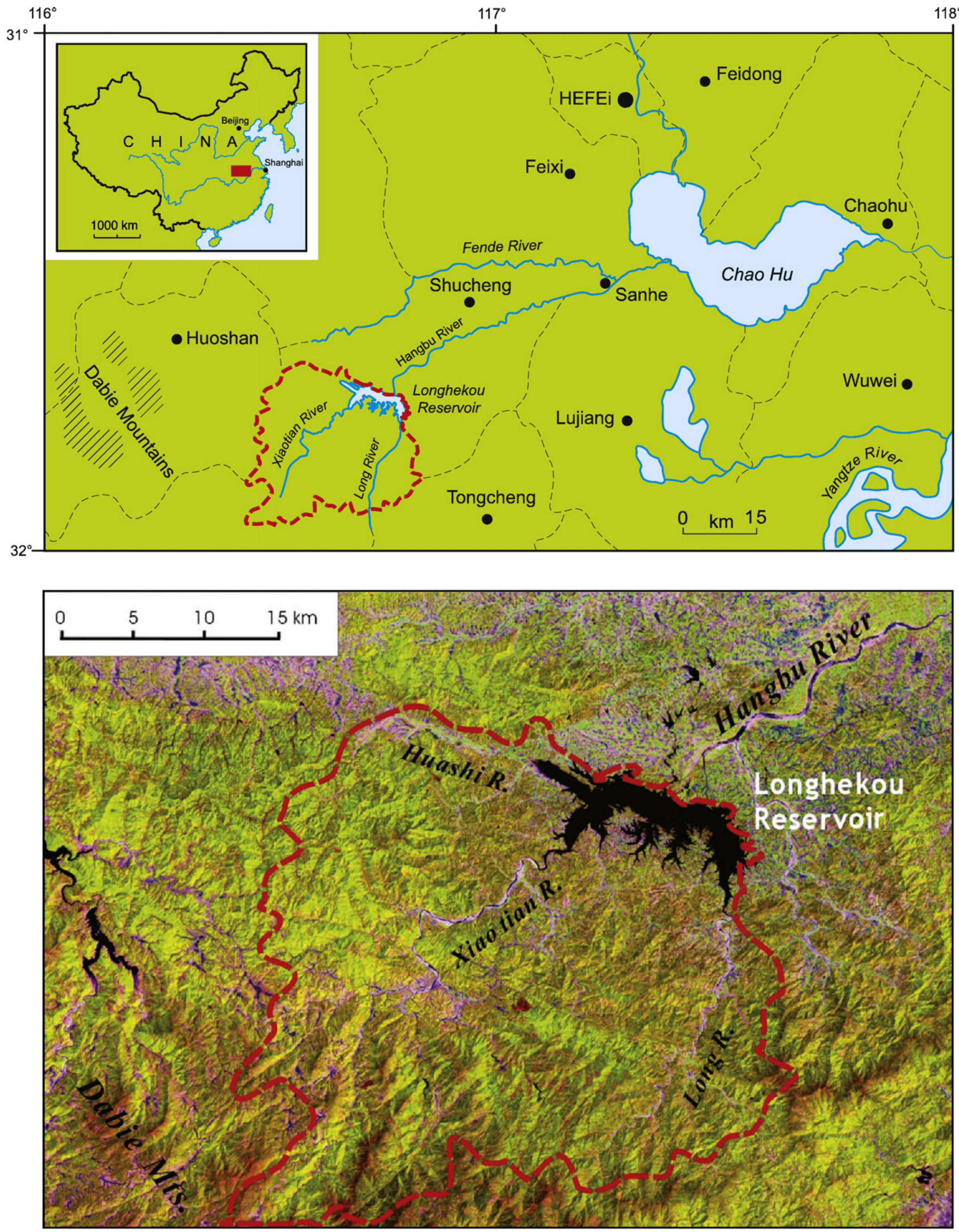

Fig. 1. Site and location: a) Anhui Province, Shucheng county and the Hangbu river system, and b) TM4 satellite image of Longhekou reservoir and its catchment in the Dabie Mountains showing land use (based on false colour) and the three inflowing rivers: Xiaotian, Huashi and Long. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

by precipitation during the rainy/flood season from June to early September. Annual variation between minimum and maximum water level in the reservoir is 1–6 m (Water Conservancy Office of Anhui Province, 1998). There are three main tributaries originating from the Dabie Mountains and the adjacent cultivated hilly lands, of which the Xiaotian river delivers over 65% of the total water and silt into the reservoir. The deposited sediment is believed (by the reservoir engineers) to be undisturbed since its construction, and the rate and extent of infilling have been investigated since 1984.

The Dabie mountains comprise a range of igneous rock types that have undergone multistage migmatization during the last ~2400 Myr. The main Xiaotian and Long tributaries dissect through, in

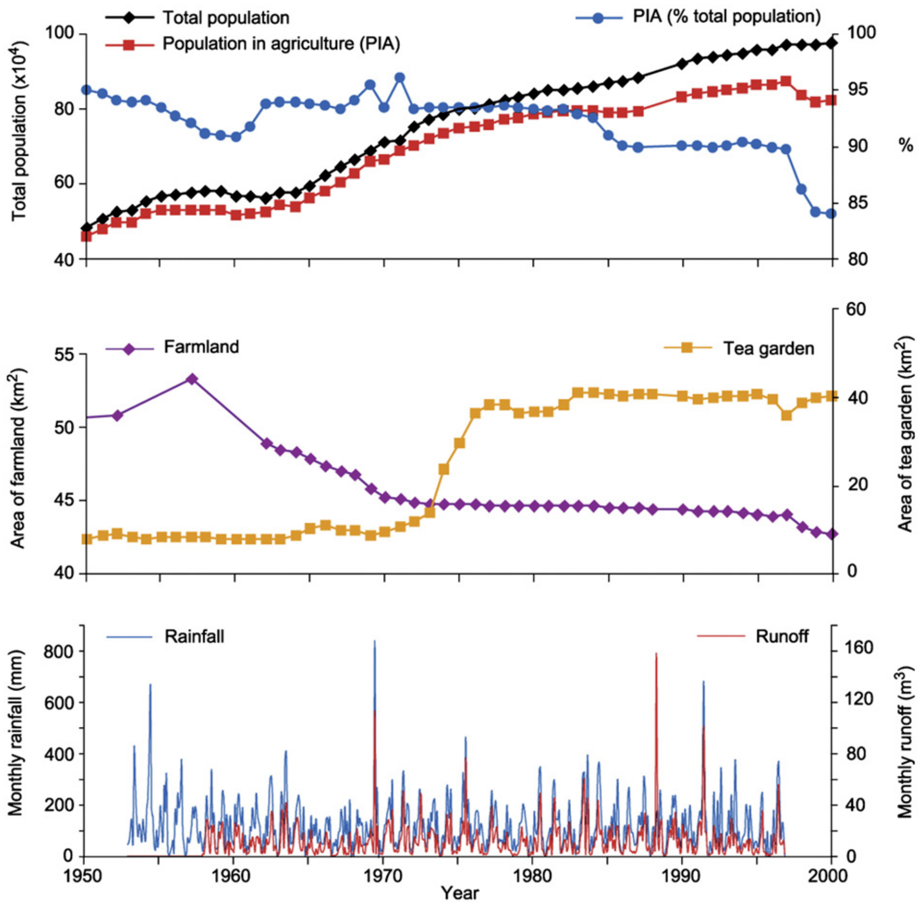

Fig. 2. Selected documented records of socio-economic change in Shucheng county (a and b), and the instrument record of monthly precipitation and runoff at the Xiaotian gauging station (c).

downstream order, migmatic granite/granodiorite, migmatic gneisses and intermediate volcanics/granite. Soils are essentially sub-tropical yellow-brown earths classified (FAO/UNESCO classifications) within a range that varies from thin lithosols in the high mountains to deeply weathered chromic luvisols at lower elevations, with man-made paddy soils in terraced side valleys and main valley floors. Soil properties vary greatly in terms of depth, colour and horizonation over short spatial scales mainly according to the local history of weathering and erosion. The natural biome is sub-tropical evergreen and deciduous broad-leaf forest.

Mean annual precipitation (MAP) amounts to 1425 mm, with a mean annual temperature (MAT) of 15 °C. According to records of climate and hydrology obtained from the Xiaotian gauging station (set up in 1952, 10 km upstream of the reservoir) for the period 1953–1996, MAP shows (Fig. 2c) a slightly decreasing trend with four maxima in 1954 (2249 mm), 1969 (1912 mm), 1975 (1970 mm) and 1991 (2024 mm) and three minima in 1966 (915 mm), 1978 (908 mm) and 1995 (935 mm). For the most recent period 1997–2004, it is likely that the Dabie mountains were impacted by the rising precipitation levels and increased storm frequency measured across the lower Yangtze basin (Jian et al., 2008). Mean annual runoff (MAR) amounts to ~3.6×10^8 m^3. The monthly record of MAR (Fig. 2c) describes annual cycles broadly co-varying ($r^2=0.6$) with monthly precipitation which peaks during the summer monsoon period. During the period 1958–1991, large flood events were recorded in 1969, 1971, 1975, 1980, 1983, 1988 and 1991. For comparison, high summer runoff levels in the lower Yangtze (Datong Hydrological Station ~100 km SE) were recorded 1962, 1964, 1968, 1970, 1973, 1975, 1977, 1980, 1983, 1991, 1993, 1996, 1998 (Jiang et al., 2008), and flooding was also severe in 2002 (no data available). In terms of flood hazard within the Chaohu lake area, the events of 1991 were the most serious as they led to the destruction of Sanhe town in the lower reaches of the Hangbu River (11.5 km upstream of lake Chaohu). The flood hazard in the lowlands is exacerbated when Chaohu fails to drain quickly into the Yangtze River during the rainy season. There has been one serious drought (Water Conservancy Office of Anhui Province, 1998) in 1978, which led to the lowest recorded water level in the reservoir of 48.25 m a.s.l.

Despite the clear links between the incidence of floods, droughts and inter-annual climate variability, the region and its hydrological system has also been under great pressure from human activities, especially since 1950. The documentary records of Shucheng county (Chorography Compilation Committee of Shucheng County, 1995; Yan et al., in press) show that the population of the whole county has doubled, from 489,500 in 1950 to 983,379 in 2000, and most are engaged in farming (Fig. 2a). The total area of farmland across the county has slightly decreased, from 507 km^2 in 1950 to 429 km^2 in 2000, as a result of reforestation mainly since the 1960s. Water conservation was a nationwide activity in China in the late 1950s during which time the Longhekou reservoir was built. In order to build the Longhekou Reservoir it was necessary to inundate 4500 ha farmland and displace 44,000 local residents. From the viewpoint of geomorphological evolution, reservoir construction might be expected to have accelerated the processes of forest damage and soil erosion as agricultural land expanded in the upper reaches, and this seems to be confirmed from forest records. The forest coverage decreased quickly from 60% to 28% and soil erosion is estimated to have reached 2,500,000 t/year (Shi, 2002). On the other hand, human activities have also enhanced soil erosion in recent decades. There have been two severe deforestation episodes in the upper catchment area from the 1950s to 1970s, which were caused by the increasing

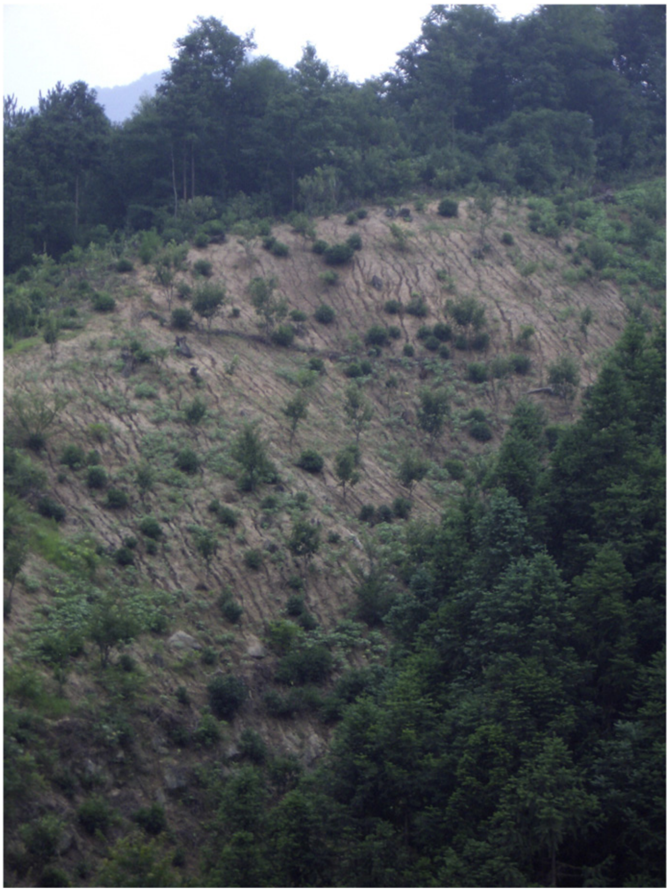

Fig. 3. Tea plantation in the Xiaotian river catchment in the Dabie Mountains showing severe rilling and gullying (Photo J.A. Dearing, July 2006).

need to create more agricultural land and the need of timber and fuel wood. The forest area in Shucheng, for example, dropped from 60% in the early 1950s to 27% in the mid 1970s, and it has been estimated that the area affected by soil erosion has increased to 960 km^2 (63% of the hilly lands). One reason for forest damage was to meet the needs of firewood and subsistence agriculture during the Great Leap Forward (1958–1960). One farmer in the upper Hangbu recalls that before the 1970s the slopes had been cleared for sorghum crops, and reforestation took place in 1976 and 1980. But there was also a four-year transition in agricultural organisation between 1973 and 1976, during which a diverse land use model replaced a single land use model for food production. As a result, it is evident that the total area of tea gardens/plantations (mostly on lower slopes) significantly increased (Fig. 2b). In the modern catchment, tea plantations on steep, lower slopes are clearly linked to the development of rills and gullies (Fig. 3). In 1992, the land use types in the Xiaotian sub-catchment mainly consisted of forests (73%), farmland (9%), tea gardens/plantations (7%), residential area (3%), waters (3%) and unused fields (4%) and roads (0.5%).

3. Methods and techniques

3.1. Remote sensing

We have used remote sensed data from the Landsat 3, 5 and 7 satellites in order to extend the documented regional changes in land use since 1979. Unfortunately, data for the Longhekou catchment and reservoir itself are unavailable. Instead, three images from 1979, 1991 and 2001 (http://www.landsat.org) (Table 1) for a region 10 km SE of the Xiaotian sub-catchment are referred to. Examination of topographic maps, digital elevation models and geological maps indicate that this region is highly similar in relief, geology and land use. For this study we consider it to be an appropriate analogue. From these data, the NDVI (Normalised Difference Vegetation Index) was calculated. The NDVI is a method to compare vegetation 'greenness' between satellite images (Avery and Berlin, 1992), and has been extensively used to observe changes in vegetation in a variety of environments (e.g. Ricotta et al., 1999; Chen and Brutsaert, 1998). The NDVI uses the principle that chlorophyll strongly absorbs visible light (from 0.4 to 0.7 μm) whereas the cell structure of leaves strongly reflects near infrared light (from 0.7 to 1.1 μm). Therefore, by calculating the normalised difference between these two bands (0.4 to 0.7 μm − 0.7 to 1.1 μm)/(0.4 to 0.7 μm + 0.7 to 1.1 μm), comparisons of greenness may be made. NDVI values of less than 0 indicate no vegetation, scaling up to a maximum value of 0.9–1.0 which corresponds to total greenness. Here, we were faced with the difficulties of using three images from different sensors at different resolutions. To enable a comparison, the same wavelength bands were chosen (MSS bands 5, 6 and TM/ETM+ bands 3, 4), and the data were re-sampled to 100 m pixels. The visible bands and the NDVI for the three dates are shown in Figs. 4 and 5. In Fig. 5, we have plotted NDVI values less than 0.1 (water bodies) as black/blue, then three levels of vegetation density increasing from areas with pale tones (NDVI 0.1–0.2 and 0.2–0.3) to areas with dark tones (NDVI 0.3 and above). Unfortunately, we were unable to ground-truth the data, so it is not possible to use these images to indicate exact vegetation types and extents. Therefore, we use the NDVI as an indicator of vegetation density and 'greenness,' but to allow some quantification values greater than 0.3 would indicate that more than 30% of the reflectance from the pixel in question was from vegetation.

3.2. Reservoir sediment and soil sampling

In March 2004, an artificially lowered water level (10 m lower than the mean level) made possible the use of piston and gravity corers in the deep area of the reservoir (Fig. 6). Six cores were sampled, but only one core (ALE: 31°17′47.4″N, 116°46′41.5″E) reached the interface between reservoir sediment and the former riverbed, as evidenced by gravels in the base of the core tube. The core (ALE) is 102 cm long consisting of six stratigraphic units (from top): 0–4 cm sandy clay with black carbonate particles; 4–20 cm dark greyish yellow fine silt; 20–34 cm greyish clay; 34–40 cm grey-green coarse fine sand; 60–80 cm greyish-yellow clayey silts; 80–102 cm clay with unidentified black particles and plentiful plant debris. At the time of sampling, water depths in different parts of the reservoir were measured in order to estimate infilling since 1984 (Fig. 6). Additionally, one hundred and forty soil samples were taken in the three sub-catchments (Xiaotian, Huashi, and Long) (with GPS positioning) in order to construct soil–sediment linkages.

3.3. Sediment and soil analyses

Laboratory analyses of the sediment core comprised magnetic measurements and particle size on 205 samples at 0.5 cm intervals, and organic carbon, nitrogen and phosphorus determinations on 102 samples at 1.0 cm intervals. Soil samples (<2000 μm dry) were measured for their magnetic properties only. Conventional magnetic measurements (Thompson and Oldfield, 1986) were undertaken using a Bartington MS2 dual frequency magnetic susceptibility meter for magnetic susceptibility (χ_{LF}) and frequency-dependent susceptibility

Table 1
Satellite image data.

Satellite	Date of acquisition	Path/row	Sensor	Resolution
Landsat 3	15/6/1979	131/039	MSS bands 5, 6	60 m
Landsat 5	18/10/1991	122/039	TM bands 3, 4	30 m
Landsat 7	1/11/2001	122/039	ETM+ bands 3, 4	30 m

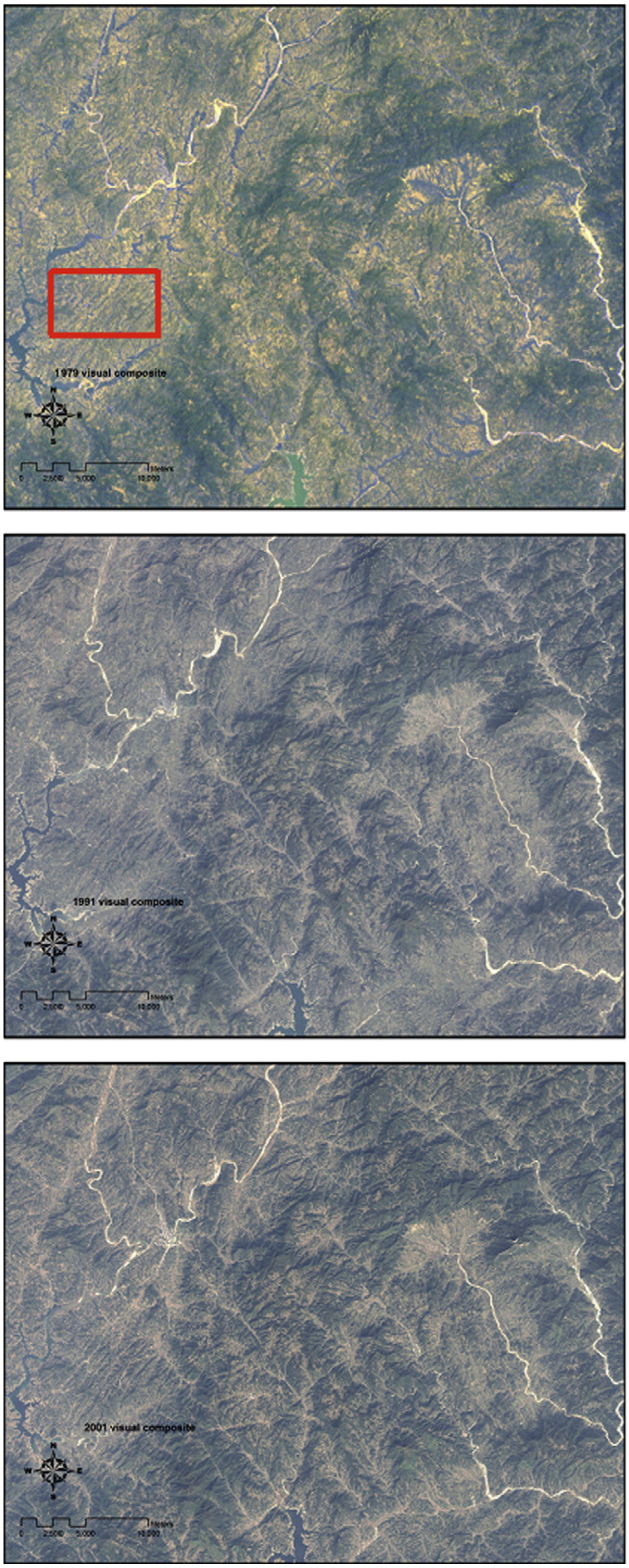

Fig. 4. Landsat composite images of the studied area from 1979, 1991 and 2001. The box on the top image indicates the regions used for analysis in Fig. 7.

(χ_{FD} %); a Molspin Minispin flux-gate magnetometer and pulse magnetizer (0–1 T and 0–300 mT) for (saturated) isothermal remanent magnetization ((S)IRM), and Molspin AF demagnetizer for anhysteretic remanent magnetization (ARM). Particle size analysis was conducted on a Beckman Coulter LS13320 system with a determination error of less than $\pm 1\%$. A method using "oil of vitriol–

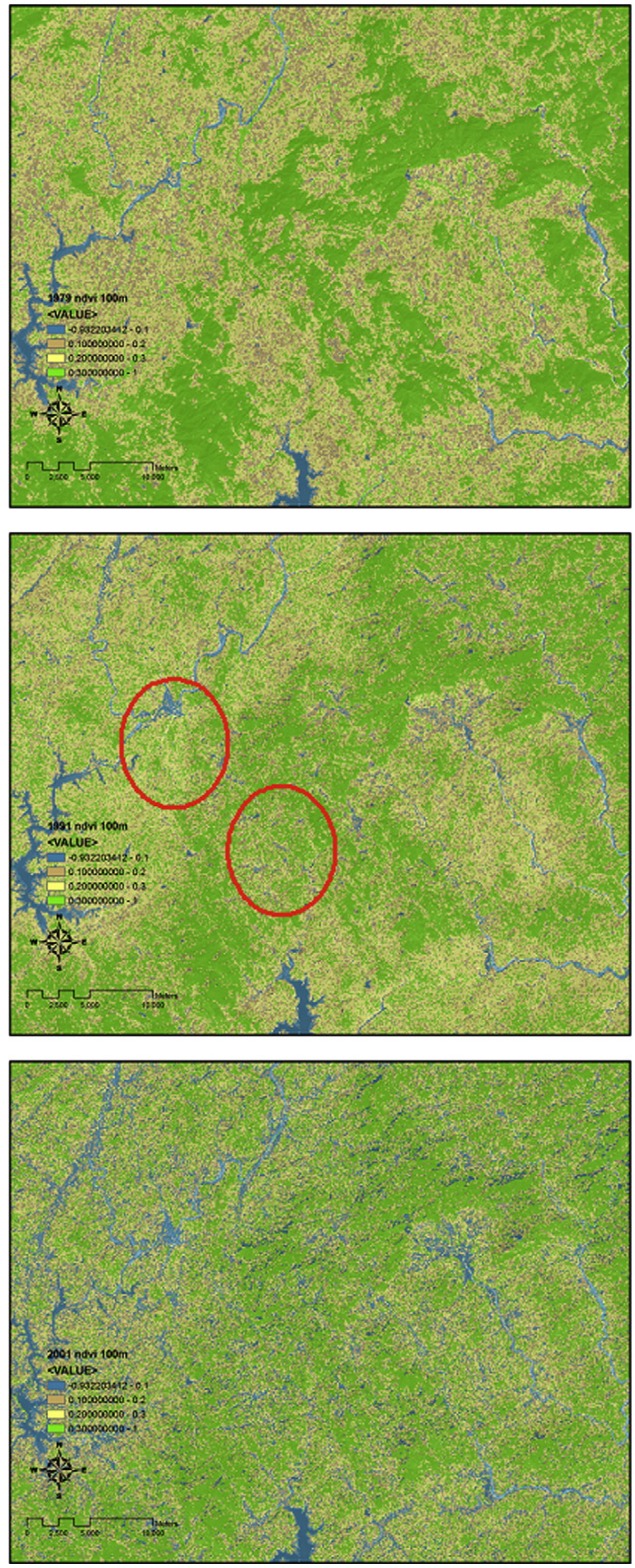

Fig. 5. NDVI indices for 1979, 1991 and 2001 images. The circles highlight examples of lowland change between 1979 and 1991.

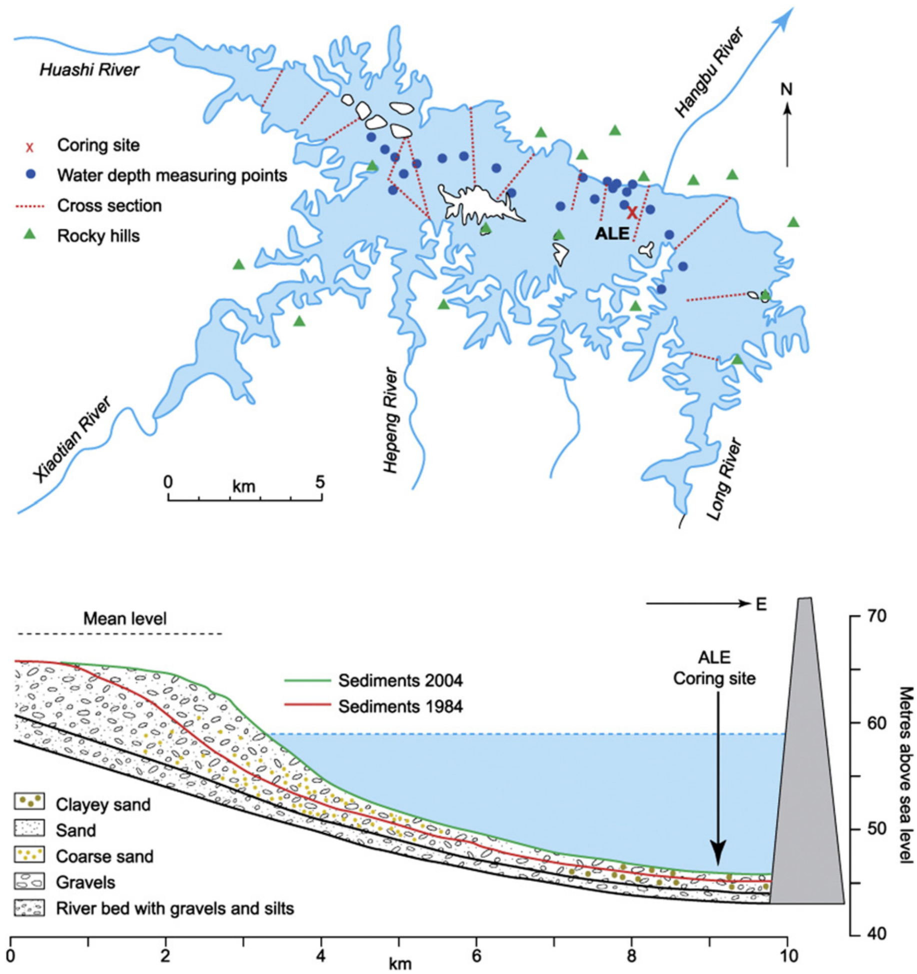

Fig. 6. Longhekou reservoir: a) sampling points and transects, and b) longitudinal section from ALE coring site to the Xiaotian inflow showing infilling since 1958.

potassium dichromate" with extra heating was adopted for organic carbon determination, with an error of less than 5% (Liu, 1996); nitrogen was determined through assimilation by the semi-micro Kelvin method and measurement using an ammonia gas-sensing electrode (Liu, 1996); and molybdenum–antimony colorimetry was used for phosphorus determination (Liu, 1996) on an Analyst 800 Atom Absorption Spectrophotometer (wavelength 700 nm).

3.4. Sediment chronology

Attempts to produce absolute sediment ages from ^{137}Cs and ^{210}Pb nuclide measurements, and spherical carbonaceous particle counts (Rose, 1990; Wu et al., 2005) were unsuccessful due to the diluting effect of high sedimentation rates. The sediment thickness at the ALE site (cross section No. CS5) as measured by reservoir engineers in 1984 suggested a mean wet accumulation rate of ~2 cm/year since 1958. Given the effects of compaction in the oldest sediments, this is highly comparable to the mean wet accumulation rate from 1958 to 2004 of ~2.2 cm/year. We therefore assume a roughly linear accumulation rate (2.2 cm/year) between the sediment–water interface (2004) and the contact with the floodplain gravels (1958), with the constraint that the drought year of 1978 is recorded at 49 cm in the core. At this depth, exceptional maxima in organic, clay and silt fractions (Fig. 8) are consistent with the settling of fines in the water column during a prolonged period of extremely low runoff during the summer monsoon. Comparison of the sample dated to the 1978 drought event with the equivalent date (1981–1982) calculated using an assumption of linear sedimentation throughout the core provides an error estimate of 3–4 years for each sediment date.

4. Results

4.1. Land use change

Comparing the visual images (Fig. 4) shows a clear *increase* in vegetation cover between 1979 and 1991. The tops of hills remain covered in relatively dense vegetation/forest (dark tones) whereas the lower areas and lower gradient slopes show a considerable decrease in uncovered earth (pale tones). This is reflected in the NDVI images (Fig. 5) where there is a general increase in the vegetation index in all of the lower lying areas (the circles in Fig. 5). This change probably reflects the widespread increase in the utilization of these lower slopes for agriculture, especially tea plantations. However, between 1991 and 2001, there are *decreases* in NDVI values, but with less clear spatial changes than shown between 1979 and 1991. From the visual images there appears to be an increase in bare earth — possibly rilling and gullying — between dense areas of vegetation. The distribution of NDVI values for all three images largely support the above findings: there is a general increase in the NDVI values across the whole image (Fig. 7a), and a larger increase within a lowland area (Fig. 7b). There is also a decrease in NDVI values between 1991 and 2001 supporting the observations of an increase in bare values. Interestingly, the increase in lower bare ground values is largely at the expense of mid-range NDVI values (there is a lowering and widening of the curve), which suggests that there has been an increase in both dense vegetation and bare earth.

It should be noted that these images are from different times of year, and the seasonal growth of crops will have an impact on NDVI. The NDVI observations reflect the leaf density and, as such, are indicators of

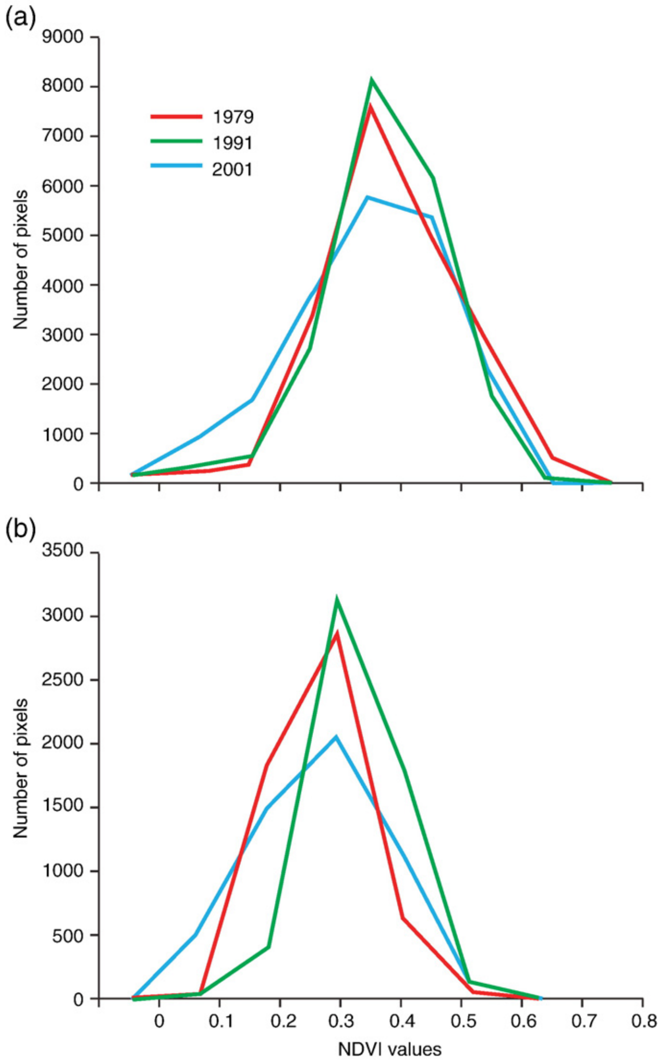

Fig. 7. Distribution of NDVI values for Fig. 4 for 3 years, 1979 (darkest tone/red), 1991 (mid-tone/green) and 2001 (lightest tone/blue): a) for the whole image; and b) for the highlighted section (box). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

process rates — photosynthesis and transpiration. Therefore NDVI values are higher when these process rates are higher as during growth seasons (e.g. Birky, 2001). In this study, if the same crop and extent of crop were growing in 1979 and 1991 a marked decrease in NDVI would be expected because the 1979 images are in the height of the growing season (June) and the 1991 images are considerably later on in the year (late October) when crops and, thus, leaf densities are in decline. However, here we see the reverse, with a considerable increase in NDVI indicating that there was a significant increase in vegetation between 1979 and 1991. When comparing the 1991 and 2001 images these seasonal differences are less marked as there is less than 2 weeks difference between the dates of image acquisition. The 1979 image was from June, at the height of the growing season, whereas the 1991 and 2001 are from late October and November when much vegetation, including rice crops, will have died back. Therefore, it is likely that we are considerably underestimating NDVI values in 1991 and 2001 (in comparison to 1979), so increases in vegetation are probably significantly greater.

There may be issues with comparing images from different satellites. The wavelengths for the bands used are the same for all sensors, but there are some differences in how the sensors were calibrated. This is to an extent negated by using a normalised index (NDVI) that relates differences between bands, as opposed to absolute differences. Vogelmann et al. (2001) showed that whilst there can be clear difference between readings from individual bands, these differences were significantly reduced when the NDVI was calculated. Furthermore, we are not using these results to show absolute changes in vegetation, more to indicate that there have been significant shifts in densities of vegetation and their patterns. These are changes that we feel are apparent from both the visible images and the NDVI calculations (especially between 1979 and 1991).

4.2. Sediment and soil analyses

In general the particle size analysis of ALE (Fig. 8a) defines the sediment as clayey fine sand, with fine clay (<2 μm) ranging 11.4–20.1% (mean 14.6%), coarse clay–silt (2–64 μm) ranging 61–75.7% (mean 70.2%), and sand (>64 μm) ranging 5.6–27.6% (mean 15.1%). The changes in medium silts, coarse silts and sands (16–32 μm, 32–64 μm, >64 μm) show a significant rise from 80 to 90 cm (Fig. 8a). Peak values in the coarse silt and sand fractions are reached at a depth of 50–55 cm, above which there are minor fluctuations about a relatively constant mean. The fine fractions dominate quantitatively below 80–90 cm and through short depth ranges at 45–50 cm, ~20 cm and 0–5 cm. At all other depths it seems that the overall particle-size distribution is normally driven by an absolute increase in the influx of coarse particles.

The trends of organic matter, organic carbon, total nitrogen, total organic nitrogen and total phosphorus are similar (Fig. 8b) suggesting a common source. In the earliest phase, values are fairly constant or gradually increasing before reaching a minor peak ~70 cm and a significant sharp peak at 49 cm. The overall pattern is similar to the curves for the recent sediments that track the peaks in clay and silt fractions (Fig. 8a), with the exception of high values of total phosphorus in the earliest phase of the reservoir's history, at depths 95–102 cm. The C/N ratio shows a more strongly fluctuating curve, with peaks 65–72 cm, 50–55 cm, 42–45 cm and 10–18 cm, values varying between 10 and 18 with a slight declining long-term trend. These values are too low to be explained solely by algal remains (e.g. Kaushal and Binford, 1999), and thus the peak values especially may be interpreted in terms of the inwash from organic-rich soil.

Magnetic parameters (Fig. 8c) describe the changing concentrations and mineralogies of magnetic minerals for which there are several possible types of source. The magnitude of χ_{LF} values (~$1–6.8\times10^{-6}$ m^3/kg) is high for lake/reservoir sediments, which together with the very high sediment accumulation rates argues for a dominance by detrital minerogenic particles from the catchment rather than the effects of atmospheric pollution particles, bacterial magnetosomes or diagenetic dissolution (Dearing, 1999). This suggests that χ_{LF} registers predominantly either changes in sediment sources or particle-size. For most of the core depth, and especially below ~50 cm depth, χ_{LF} values track closely the trend of increasing sediment coarseness (curves for 32–64 μm and >64 μm: Fig. 8a), while above 50 cm depth the association is weaker and restricted to the 32–64 μm fraction. Some magnetic properties track changes in specific sediment sources. In particular, χ_{FD}, χ_{FD}% and χ_{ARM}/SIRM are sensitive to pedogenic magnetite/maghemite that only occur in the biologically active zones of soils, while the back field parameter IRM_{-300mT} is most strongly linked to subsoil or unweathered substrates containing antiferromagnetic minerals, such as hematite.

A scatterplot of χ_{LF} and χ_{FD}% values (Fig. 9) for all soil/substrate (<2000 μm) and reservoir sediments (bulk, hence approximately <1000 μm) supports these inferences. The very wide range of χ_{LF} values ($0.7–25\times10^{-6}$ m^3/kg) is consistent with previously published (e.g. Thompson and Oldfield, 1986) values for soils and sediments in catchments with complex geologies ranging from weakly magnetic granite and migmatite to highly magnetic diabase. Soil samples tend to show higher χ_{LF} values than the local weathered substrate as a result of pedogenic production of iron oxides and accumulation of primary ferrimagnetic minerals (e.g. magnetite) through weathering. The comparison with values for the reservoir sediments is less robust

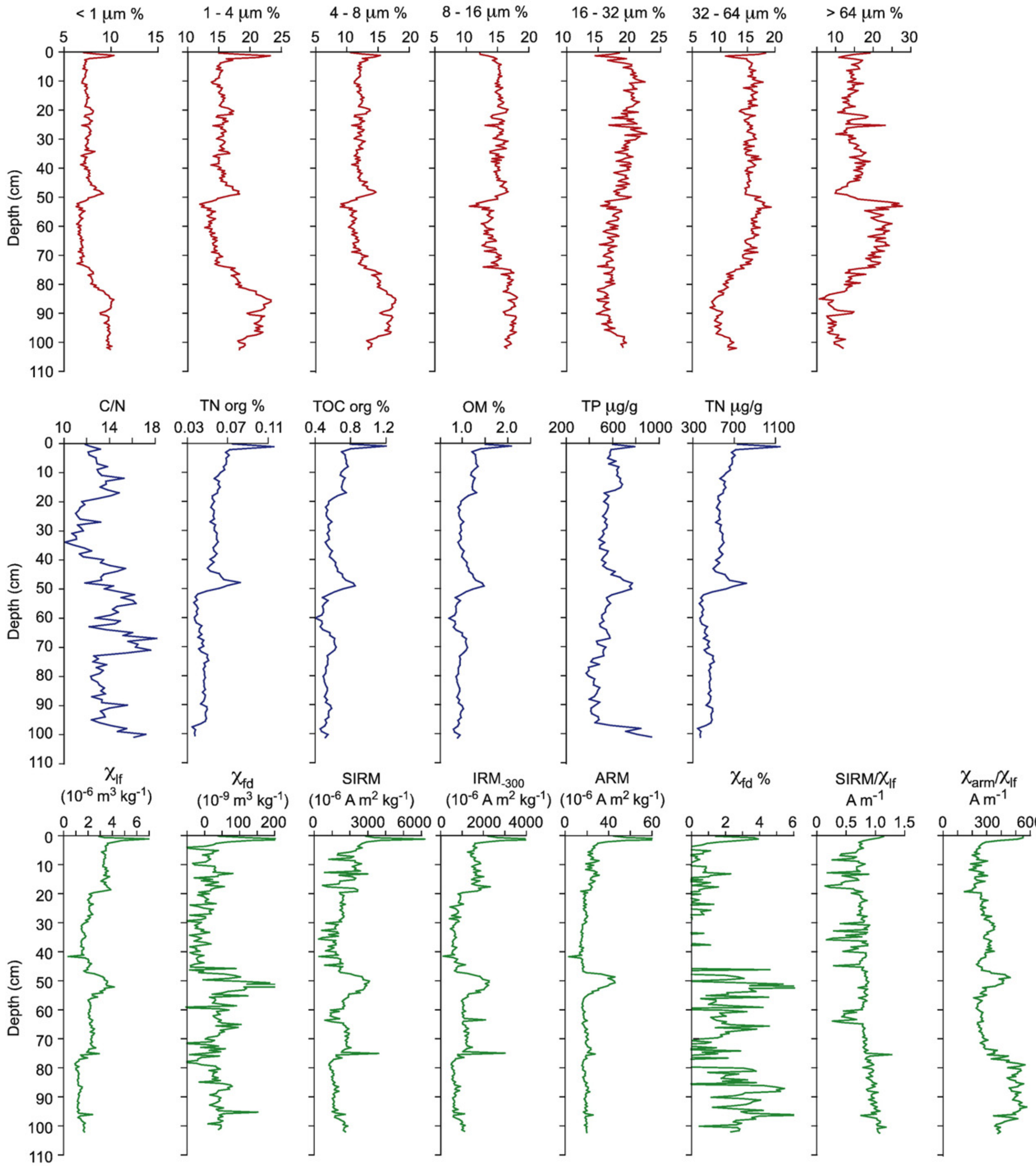

Fig. 8. ALE core analyses: a) particle-size; b) organic carbon, organic matter, nitrogen and phosphorus; and c) mineral magnetism.

because particle-size controls on mineral concentrations are not taken into account. Nevertheless, the range of values on both axes for the soils/substrates is far higher than for sediment suggesting that a constrained range of geological or pedological sources (or mixture of sources) has dominated the sediment supply. The χ_{FD}% values indicate the presence of nanoscale pedogenic iron oxides with superparamagnetic/stable single domain magnetic properties found solely in organic rich surface soils. The limited range of χ_{FD}% values for the reservoir sediments suggests that pedogenic minerals exist within the reservoir sediments but do not dominate the mineral assemblage. Overall, we can deduce that the reservoir sediments are composed of a mixture of minerogenic particles derived from surface and subsurface sources mainly on the weaker magnetic geologies, such as the acidic and intermediate granites located in the Xiaotian catchment.

5. Discussion

5.1. Climate forcings

Hydrological variability in the upper Hangbu catchment over the past 45 years has been strongly controlled by the east Asian monsoon climate, with ~60% of the variation in monthly runoff explained by monthly precipitation. The curve of annual runoff as a percentage of annual precipitation (Fig. 10a) shows relatively higher runoff (>1100 mm/year) in the periods 1962–1964, 1968–1972, 1974–1976, 1980–1981, 1983–1985 and 1990–1991 (no data available after 1996), with a tendency for runoff to be relatively higher with greater precipitation. Comparison of annual (Fig. 10a) and monthly runoff (Fig. 2c) curves suggests that the periods of relatively high annual

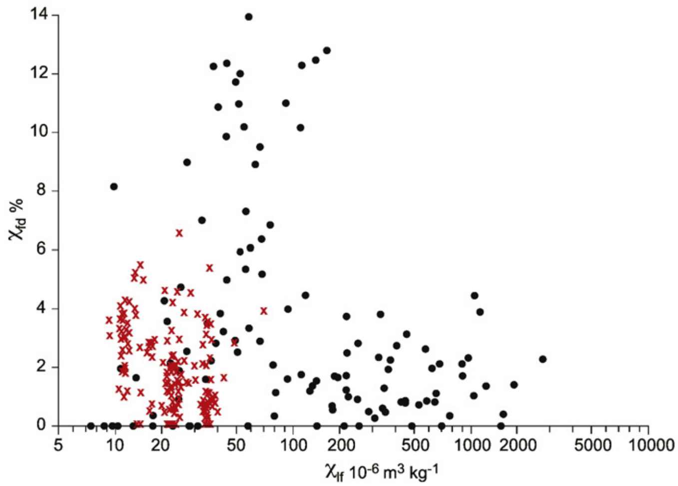

Fig. 9. Log–normal plot of χ_{LF} and χ_{FD} % values for all soil/substrate samples (dots) and reservoir sediment samples (crosses).

runoff are generally associated with years displaying extreme (>2 standard deviations of long term mean) monthly events (Fig. 10b), but that there is also a reasonably constant relationship between the timing of peak floods and large precipitation events.

In the absence of a sedimentation rate curve, the sediment sand fraction is used as a proxy for fluvial competence and sediment loading to the reservoir. It shows 40–50 high frequency variations (Fig. 10c) that appear to register the overall rhythm of annual river flood peaks (Fig. 2c), testifying to the strong influence of the summer monsoon period. However, the curve of low frequency or longer term changes in the sand fraction (Fig. 10c) shows only a weak relationship with precipitation and runoff (Fig. 10a). The periods 1969–1977, 1980–1984 and 1988–1991 with relatively high runoff are equivalent to broad peaks in the sand fraction curve (Fig. 10c), but there is no consistent long term tracking of the meteorological/hydrological curves by particle-size. Indeed, the periods of high sand content in the mid to late 1960s and mid to late 1970s (Fig. 10c) are associated with some abnormally dry years (runoff<750 mm/year; Fig. 10a). It follows that the precise relationship between precipitation, runoff and sediment transport varies greatly over monthly and annual timescales due to changes in precipitation intensity and totals, antecedent hydrological conditions, and seasonal vegetation cover, with the superimposed effects of changes in sediment supply.

5.2. Human forcings

There is some evidence that climate driven signals in the hydrological response may be overlaid with those emanating from human activities that affect sediment supply. Increases in the value of IRM_{-300mT} and χ_{FD} (both mass-specific) in the reservoir sediments may be considered as indicators of erosion: IRM_{-300mT} as a proxy for the hematite-rich weathered igneous subsoils and substrates, and χ_{FD} as a specific proxy tracking the movement of clays derived from magnetically enhanced surface soil (Dearing et al., 1996). These two sediment curves (Fig. 10d) show similarities in overall trend as expected from two erosion proxies, but the relatively higher normalised (*z* score) values of χ_{FD} in the lower half of the core point to significant surface soil erosion, particularly during the period estimated to be 1969–1978. The argument for significant surface soil erosion is further supported by the curves of χ_{FD} co-varying with two other magnetic ratios indicative of pedogenically formed magnetic minerals, χ_{FD} % and χ_{ARM}/SIRM (Fig. 8c) At this time, there are also peaks in the sand proxy for high fluvial competence, C/N ratio values, and to some extent N, P and C % values (Fig. 10e). Together, these data point to increased levels of both fluvial competence and sediment supply from organic-rich surface soil horizons. In contrast, the rise in IRM_{-300mT} from approximately 1993–1994 onwards suggests a stronger contribution from subsoil or channel sources in recent

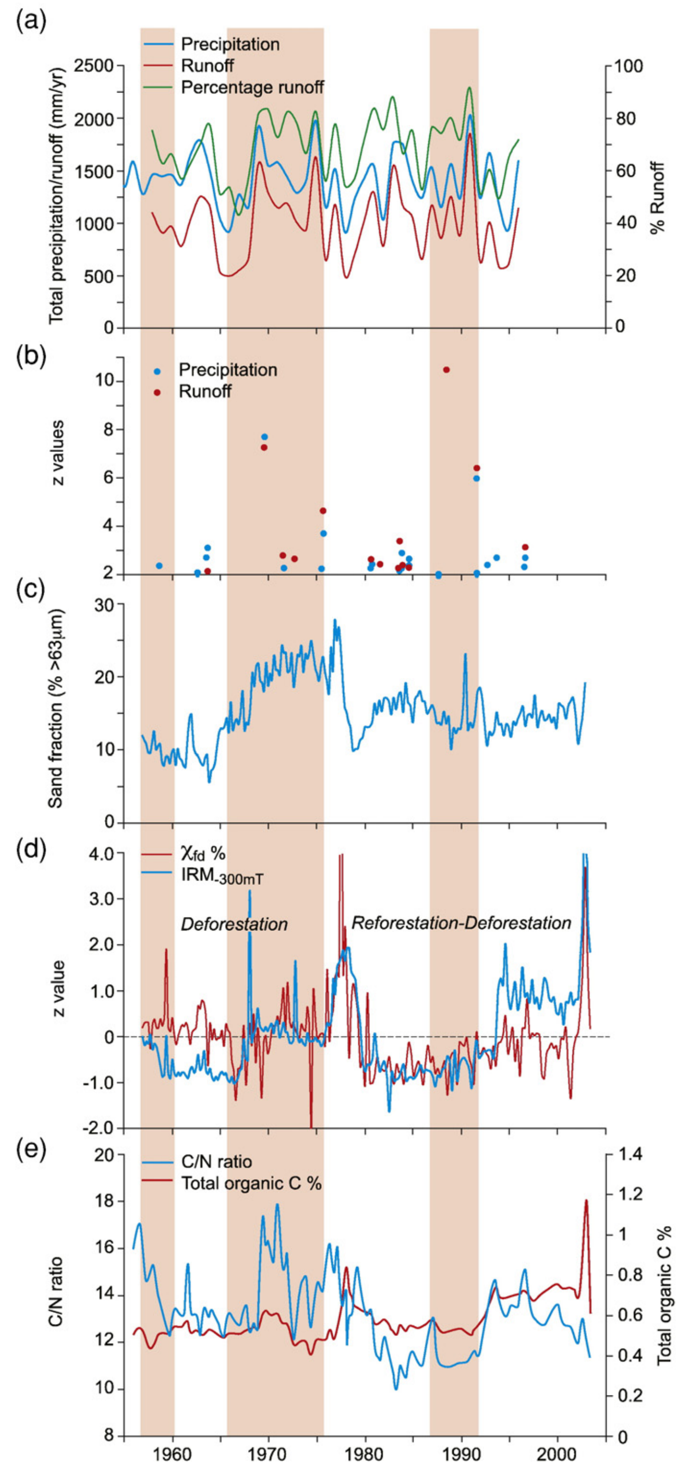

Fig. 10. Compilation of instrumented, documentary and proxy records of climate–human–environment interactions 1958–2003: a) annual precipitation, annual runoff, and annual runoff as percentage of annual precipitation; b) extreme monthly precipitation and runoff (*z* score values> 2); c) reservoir sediment sand fraction as proxy for sediment accumulation rate; d) reservoir sediment magnetic proxies for catchment substrates (IRM_{-300mT}) and surface soil erosion (χ_{FD}), with timings of catchment deforestation and reforestation; and e) reservoir sediment carbon/nitrogen ratio and percentage total organic carbon. The three vertical bars indicate periods of Great Leap Forward (1958–1960), the Great Cultural Revolution (1966–1976) and check dam construction (late 1980s/early 1990s).

decades. If these interpretations in terms of decadal changes in land use are correct there should be strong temporal links between the sediment proxies and documented human activities.

Indeed, the overall trend in proxies for erosion follow the decadal trends in forest clearance and reforestation since the 1950s (Fig. 10c) deduced from documentary, anecdotal and satellite image evidence. The start of the rise in erosion proxies interpreted as dating from the late 1950s to early 1960s correlates with the beginning of the iron smelting movement during the Great Leap Forward (1958–1960) that was followed by the Great Cultural Revolution (1966–1976). Together, these may have led to the clearance of up to 50% of the forest in the Dabie Mountains. The reservoir sediment proxies show highest values for surface soil erosion (Fig. 10d) in the mid to late 1970s which coincide with the end of a seven-year period (1970–1977) in which there was an ~4-fold increase in the area under tea plantations as farming practice diversified (Fig. 2b). Tea plantations are often situated on steep slopes to aid drainage, maintained with no ground cover, and liable to severe rilling (Fig. 3). This record of land use and erosion is paralleled (Liu et al., 2007) in the Taibai lake catchment situated 172 km SW suggesting a regional impact of land use on hydro-geomorphological changes.

The declining trends in erosion proxies after the late 1970s suggest reduced sediment supply, and this may be explained by evidence from satellite imagery for an increase in forest cover between 1979 and

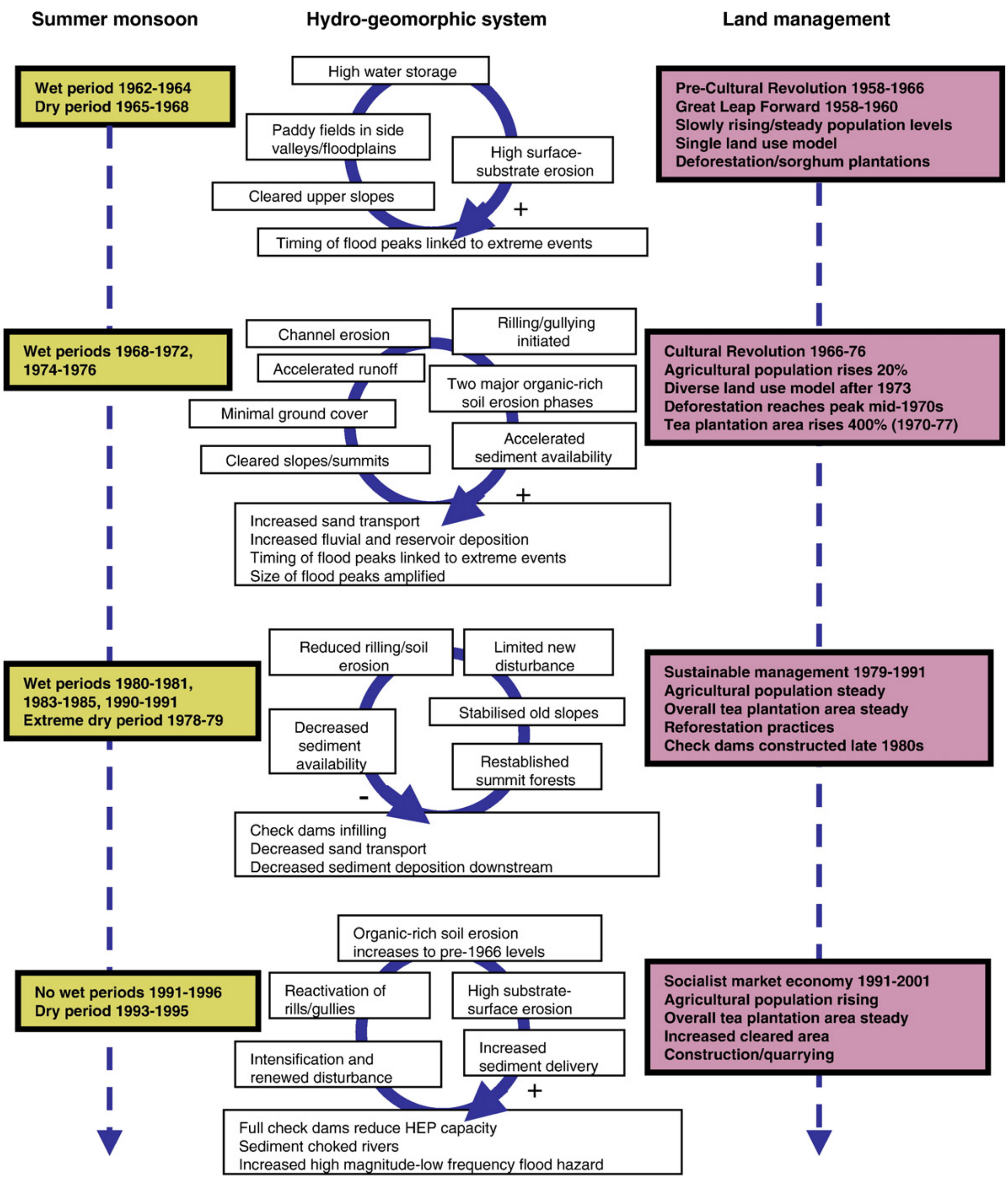

Fig. 11. The sequence of hydro-geomorphological changes in the Dabie Mountains as a result of climate and land use interactions since the 1950s. The scheme shows the instrument/document history of climate (left column), the documented history of land management (right column) and key elements of the cascading fluvial system deduced from reconstruction (centre circles) for four periods from the 1950s (top) to the present (bottom). The circular arrows indicate the chain of links in the hydro-geomorphological cascading system that are either positive (clockwise) or negative (anticlockwise) reinforcing. See text for detailed explanation.

1991. However lower levels of sediment loading to the reservoir were also probably maintained by the construction of several dams on the upper Xiaotian river in the late 1980s/early 1990s, which our observations in 2005 suggest were completely infilled. The significant volumes of trapped sediment may have masked the quantitative effects of potentially higher erosion rates as a result of forest clearance between 1991 and 2001. However the qualitative effect of this phase of deforestation may be seen in the sharp rises in the sediment proxies for subsurface erosion and organic materials, estimated as being 1992–1994 (Fig. 10d). These are associated with suspended sediment fractions and therefore less affected by upstream sediment traps. The sharp rise in clay fractions, magnetic proxies for fine soil particles and organic carbon in the most recent sediments probably dating from post-2000 (Fig. 10) suggests a renewed fine sediment source with both surface and subsurface characteristics, for example road construction and quarrying.

While the links between human activities and erosion are fairly robust, the role of land use in mediating the climate control on runoff is more difficult to infer, especially as the chronology is not tightly constrained. Despite the apparent links between runoff and proxies for increased fluvial competence (coarse particle-sizes), there is little similarity in the trends of percentage runoff (Fig. 10a) and evidence for deforestation (Fig. 10b). This suggests that the two processes are not causally linked. After the 1980s, the associations are even less obvious in the sediment record and, if present, are partly obscured by the effects of check dams on coarse sediment delivery. Comparisons up to the present are made difficult by the lack of hydrological data. Overall, human activities appear to modify sediment supply and source more significantly than runoff and extreme flood events.

5.3. Hydro-geomorphological system dynamics

The combined archives of information from instruments, documents and reconstruction are used to postulate major changes in the dynamics of the hydro-geomorphological system from the 1950s to the present (Fig. 11). In the period 1955–1966, the Dabie Mountains were undergoing forest clearance but established paddy systems in side valleys served to suppress the impact on runoff. As a result the recorded flood peaks were attributable to extreme precipitation events while sediment sources were enriched by surface soil from cleared areas. These positive feedbacks within a cascading system are represented (Fig. 11) by a circular arrow and a plus sign. The time of the Cultural Revolution saw a rapidly rising population and a shift to diverse land usage. It is likely that widespread clearance, particularly for tea plantations, caused headward extension of side valley channels and accelerated sediment delivery from surface and subsurface sources to the main river. The evidence for an amplification of the major flood peaks in 1969, 1971 and 1975 is unclear but overall this period is also represented by a chain of linkages driven by positive feedback. During the 1980s, however, a stable population and reforestation schemes resulted in a more sustainable land use and to some extent a reversal of the accelerating changes observed in the two earlier periods. Reforested summits reduced runoff and erosion levels, and the building of check dams reduced the downstream delivery of sediment to the Longhekou reservoir. In simple system terms, this phase can be described by predominantly negative feedback, as shown by the reversed circular arrow and negative sign. Despite these trends, large flood peaks were recorded in 1980, 1983 and 1988 suggesting that runoff levels in extreme precipitation events may not have been effectively suppressed by the reforestation. In the 1990s, a socialist market economy saw the population rising again with greater levels of urban growth and infrastructural development. There is some evidence for renewed forest clearance, the reactivation of gullies and accelerated soil erosion to the levels observed in the 1960s: check dams and main river systems now appear choked with sediment. The system may be described as having reverted to the previous phase dominated by positive feedback. A major implication for the local population is that, with the regional precipitation trend already increasing since 1997, there must be the risk that downstream areas around the reservoir are vulnerable to an increased flood hazard during high magnitude/low frequency flood events due to reduced flood storage capacity. The reconstructed system dynamics provide the basis to validate catchment process models that can simulate the likelihood of such floods under varying climate and land use scenarios in the future.

6. Conclusions

a) Over the past ~45 years (1958–2004), the history of hydro-geomorphological change in the Dabie Mountains has been affected by climate, particularly the east Asian monsoon, and land use. The timing and, to a large extent, the magnitude of floods are controlled by precipitation events linked to the summer monsoon. But as shown in similar reconstructions from other mountainous areas in Europe (e.g. Foster et al., 2003) and China (e.g. Dearing et al., 2008), the first order controls on the quantitative supply of sediment to the reservoir over the past 45 years are land use and its effect on sediment supply. Factors influencing land use include population increase, forest clearance, enlargement of farmland, and agricultural policies during the Great Leap Forward and the Great Cultural Revolution.
b) Reservoir building for irrigation was a pervasive activity in eastern China during the 1950s. From a landscape management viewpoint, it was therefore an activity that could lead to the expansion or relocation of farming with accelerated land cover change, soil erosion and, consequently, reservoir infilling. The study emphasizes the fragility of the mountain environment in eastern China, especially in terms of the rapid erosional response to removal of forest cover and increased sediment supply. The diversification of food production away from wet paddy in terraced systems and sorghum crops to tea plantations may have had an overall negative impact on the catchment system, necessitating the construction of check dams to suppress the impact on downstream reservoir capacity. In contrast, the direct impact of land cover change on runoff and extreme flooding seems less severe.
c) The database provides detailed information about the interactions between land use, climate, runoff, erosion and sediment transport. With the regional precipitation trend already increasing there is the risk that downstream areas around the reservoir are vulnerable to an increased flood hazard during high magnitude/low frequency events. The reconstructed system dynamics suggest that the mountain catchment systems have moved into a new phase driven by positive feedback. The long term sustainability of these landscapes will, in part, depend on the successful development and application of models, validated against the recent past, which can simulate process-responses under different scenarios of land use and climate.

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