THE HISTORY OF IRRIGATION AND WATER CONTROL IN CHINA'S ERHAI CATCHMENT: MITIGATION AND ADAPTATION TO ENVIRONMENTAL CHANGE

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Abstract: This chapter introduces an interdisciplinary methodology that combines the use of archaeological and documentary sources alongside environmental proxy indicators found in sedimentary archives to assess, on a hydrological catchment scale, historical human impacts on hydrology. The advantages and benefits of this technique are demonstrated through the results taken from ongoing work on a case study, Erhai in Yunnan province, China. This approach allows us to increase understanding of local knowledge, vulnerability, mitigation, adaptation, and resilience to local, regional, and globally derived environment and climate change.

Keywords: Erhai, human impact, catchment hydrology, environmental microvariation

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1. INTRODUCTION

Periods of environmental crisis and perturbation in China and Southeast Asia are intrinsically linked to the issue of water control (Elvin et al. 1994). Similar processes are seen throughout the world, and indeed, human activities have altered almost all of the world's river systems with major modifications to hydrological catchment areas. This global and regional problem has been exacerbated by loss of tree cover in watersheds, dam construction, reduced storage times of water in river basins, and increased severity and frequency of flooding. The massive floods (and droughts) in the lower Mekong River basin have been blamed to some extent on widespread deforestation in watershed areas, poor soil management practices, reclamation of flood plains and wetlands, and the rapid expansion of urban areas (Blake 2001). There is also growing international concern about the impacts of large dam schemes in Yunnan Province, China, on the Mekong watershed ecosystem (Lihui 2004). Such concern provides a pressing need to understand natural resource use, in particular water resources, in the large tributaries of the Mekong River in order to assess environmental vulnerability and resilience and to improve environmental security for those people living in these areas. This can only be achieved by understanding the geo-historical context in which contemporary situations have arisen.

Erhai catchment in Yunnan province, China, is a tributary of the Mekong River, with a long and fairly accessible environmental history. It is a region facing new socioeconomic and environmental challenges with large infrastructural development projects being planned, increasing permanent and transitory (tourist) populations[1] and growing concerns over water quality and quantity (UNCRD 1994). It is also a monsoon region threatened by rapid global climate change, which according to various climate models will lead to increased precipitation and more frequent and intense extreme events (Handmer et al. 1999; Arnell et al. 2001; Cubasch et al. 2001) as experienced in China during the summer of 2004 (WMO 2004). Thus, appropriate environmental knowledge and planning are essential if the long-term environmental security of this region is to be assured.

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[1] These population increases are due mainly to the one-child policy not applying to minority nations like the Bai and to some extent to the Go West policy operated by China, which has spurred massive investment in Dali City, formerly known as Xiaguan, and led to increases in migration by Han Chinese to the area.

Our case study investigates the long-term impacts of climate and land use change on hydrology and, in particular, seeks to increase understanding of local knowledge, local community vulnerability, mitigation strategies and adaptation and resilience to local, regional, and globally derived environmental and climate change.[2] The history of irrigation and water control in the Erhai catchment is intrinsically connected to this question, and while the historical record of irrigation and other water issues in the Erhai catchment is fragmented, it nevertheless has value because its long-term perspective highlights some of the emergent issues of environmental change that are not otherwise apparent in shorter term studies. Specific aims of the project[3] relevant here include answering the following questions:

- To what extent have major shifts in hydrological processes and water quality in the historical past been triggered by human activities or climate?
- In terms of runoff and sediment generation, which parts of the landscape are most sensitive to extreme climate or human disturbance?

2. SITE DESCRIPTION OF ERHAI, NORTH AND WEST SHORES

Erhai is found in the Dali autonomous prefecture in Yunnan Province. The lake sits at ~1,970 m above sea level (as measured from Haiphong[4]) with an approximate area of 249 km^2 and a catchment of about 2,565 km^2 (Figure 1). Both the depth and area of the lake have varied during the

[2] Our case-study is part of the IGBP/PAGES Focus 5 initiative on Human Impacts on Terrestrial Ecosystems. The project adopts an interdisciplinary methodology designed to permit global application and draws on documentary and sedimentary archives to investigate the historical impact of humans and climate on water resources in mountainous river basin environments.

[3] See the LERCH website http://pcwww.liv.ac.uk/%7Edcrook/lerch/Erhai/ for details of the wider project.

[4] In general, the Chinese seem to use Wusong as the benchmark for mean sea level (it is located near the mouth of the Yangzi). For this project, it was necessary for the UK research team to use Soviet maps (1970s) of China, which had discrepancies in summit and other heights from the maps used by Chinese colleagues. However, the maps seemed very similar in most ways. It was assumed that the Soviet maps were based on old French maps (the French having been dominant in the Southwest because of their occupation of Vietnam, and a sort of sphere of influence in Yunnan), and that the French had put in heights above MSL that were based on Haiphong.

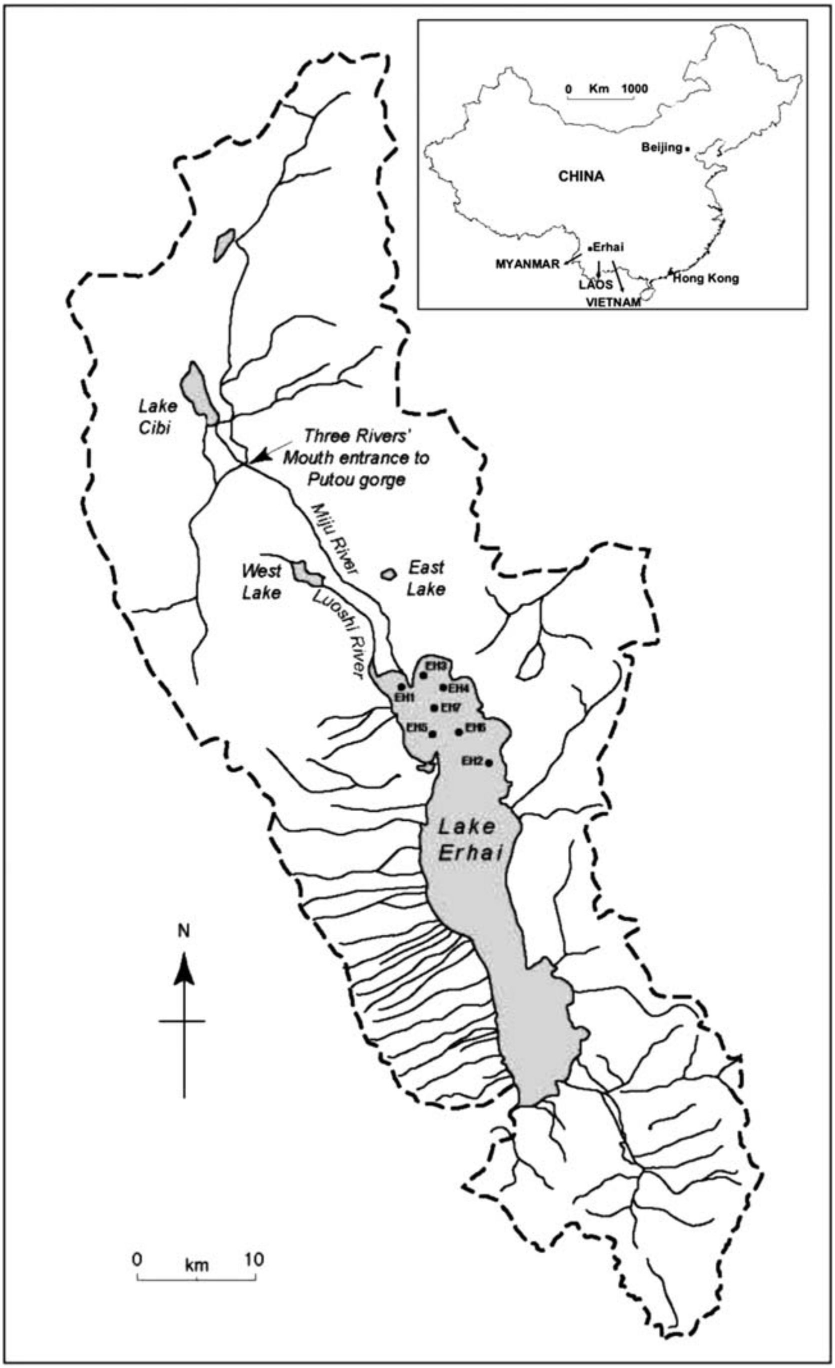

Figure 1: The Erhai Catchment, Yunnan Province, China.

Holocene period (Duan Yanxue 1989). To the north of the lake the heavily embanked and elevated Miju River draws upon an extended northern sub-catchment made up of the lower Dengchuan plain and the slightly elevated Eryuan plain, and the mountain ranges that define the northern catchment. The Miju contributes 5.18×10^8 m^3year^{-1} at the inflow into Erhai via a rapidly aggrading delta. The Miju is flanked by the smallish Luoshi River, which drains the West Lake and the Yong'an River, draining the East Lake on the Dengchuan plain. These "lakes" are not single sheets of water but interconnected groups of small lakes and ponds. The Dengchuan plain is linked to the Eryuan plain by the Putuo gorge. Lake Cibi is located on the Eryuan plain and the upper slopes of this basin form the headwaters of the Miju. The Miju River feeds an extensive river valley offtake irrigation system.

The general climatic pattern is characterized by a dry season from November to May and a rainy season from June to October, during which more than 80 percent of the precipitation falls. The west side has a wet climate with an average annual precipitation of ~1,072 mm, although rainfall rises from 1,000 mm year close to the lake shoreline to 1,800 mm near the crests of the famous Nineteen Peaks of the Diancang mountains, which rise to over 4,000 m. Seasonal snowmelt and springs supply water to an extensive slope offtake diversion irrigation system on the Dali plain, known locally as the famous Eighteen Streams (Xue Lin 1999). These steep gradient streams contribute 2.76×10^8 m^3 of water a year to the lake. Just one of these, the Wanhua Stream, has been estimated to reach a once-in-fifty-years maximum of 158.4 m^3 s^{-1}. Mean annual runoff has been calculated at above 200 mm $year^{-1}$ on the west side, but under 100 mm $year^{-1}$on most of the north side where average annual precipitation drops down to ~763 mm on the Eryuan plain. Seismic activity is frequent, and there are many documentary references to the damage done by earthquakes. The population most vulnerable to these hazards is today mainly centered on the Dali plain, which has 436,000 inhabitants and a density of 299 persons/km^2 in 1990; and on the Eryuan plain in the northern part of the catchment, which has 299,000 inhabitants and a density of 104 persons/km^2 in 1990.

3. METHODOLOGY

It was necessary to adopt an interdisciplinary approach that investigated archaeological, documentary, and sedimentary archives. This was regarded as the best way to deal with varying temporal and spatial scales of enquiry and allow for a full appraisal of a complex system. The north, east, west, and south shores of Erhai have different environmental characteristics as well as varying geomorphological, geographical, and hydrological features (see Elvin et al. 2002). The summarized story from only the north and west sides of the lake are told here because of limitations on the amount of space available. This has the advantage of matching the archaeological and documentary record to the same boundaries and spatial scale as the sedimentary analysis. It also covers the most important hydrological sectors of the catchment. Space limitations also prevented the inclusion of climate and tectonic data into this chapter.

Whilst archaeological sources survive from the Han dynasty approximately 2,000 years ago, the earliest documentary source relate to the early Tang dynasty (~ 628 CE). Documentary sources are fragmented and often not written with the objective of describing the natural milieu or to provide specific environmental information. However, with qualifications arising from a diversity of different sources (Table 1) that reflect the turbulent political history of the area (e.g., Drochon 1866; Litton 1903; Rocher 1904; Wiens 1967), this allowed us to explore social and cultural variables alongside the interactions of technical and environmental factors (see Fitzgerald 1941). The main focus lies in the subset of ecosystem reactions, usually measured as individual events, vigorous enough to be worthy of recording in the historical record, and to analyze their distinctive patterns and probable causes.

Table 1: Archaeological and Documentary Sources Used in this Study.

Type of evidence	Source
Archaeological	Lithics – steles
	Pottery
Documentary	Chinese gazetteers
	Official Chinese documents
	Lists of auspicious and uncanny events
	Minority Nation Ethnographies
	French/British Catholic and Protestant Missionary archives
	French/British colonial consular archives
	Travelogues
	NGO and GONGO reports
Cartography	Pictograms and maps

To access the longer record of prehistory and to observe longer term trends, sedimentary archives were analyzed. Sediment extraction techniques (Last and Smol 2002a) were followed by the principle analytical techniques of pollen, particle size, and mineral magnetics (see Berglund et al. 1986; Thompson and Oldfield 1986; Smol et al. 2002; Last and Smol 2002b). Sediments were collected from Erhai, the Miju River floodplain, and upland areas of the catchment. For the purpose of this chapter we concentrate our analytical attention on one of these cores known as EH2, which was taken from the deepest part of the northern basin at Erhai. It is thought to be representative of the northern part of the catchment as it is located close to the inflow of the main tributary river (Figure 1).

The core chronology is still under construction, but two range finder dates have been obtained based on Carbon-14 dating of the humin and humic organic fractions of the sediment. The two range finder dates are shown in Figure 2.

Thus, the event oriented archaeological and documentary evidence complements the theoretically continuous environmental archives provided by sedimentary archives, providing a reasonably representative chronology of environmental and hydrological change.

4. PRELIMINARY RESULTS FROM THE SEDIMENTARY ARCHIVE

A summary of the sedimentary results from EH2 are presented in Figure 2, which includes a preliminary zonation scheme based on variations in the mineral magnetic and geochemical features distinguished as sediment units 1 to 5. The zonation scheme reflects changing sediment composition up through the core, driven by shifts in the source of sediment to the lake from the catchment. The poor chronological resolution of the results is mitigated somewhat by the serendipitous finding of dateable material at the beginning of the two major inflexions in the magnetic records.

The lower zonal boundary between sediment units 1 and 2 is characterized by a marked increase in χarm (a proxy for magnetic mineral grain size) and iron (Fe) concentration in the sediment from their respective values in ~2650 BP. This trend continues through to the top of the core and appears unaffected by events after 1950 BP. It is further mirrored in the Zr/Ti ratio (a crude indicator of grain size), which appears to show a gradual increase in the clay content of the sediment. This implies that the observed trend may be due to a long-term shift in sediment source and/or supply to the lake. The cause at present is unknown but it is hoped that completion of the sediment analyses will provide the answer. Pine frequencies are seen to fluctuate whilst experiencing an overall decline, which possibly points to the onset of deforestation in the catchment. However, the low values for χfd (a proxy for the presence of magnetic material of a pedogenic origin derived from the catchment through erosion, e.g., Thompson and Oldfield 1986; Dearing 1999) indicate that the supply of topsoil material to the lake during this period was negligible, implying a degree of catchment stability.

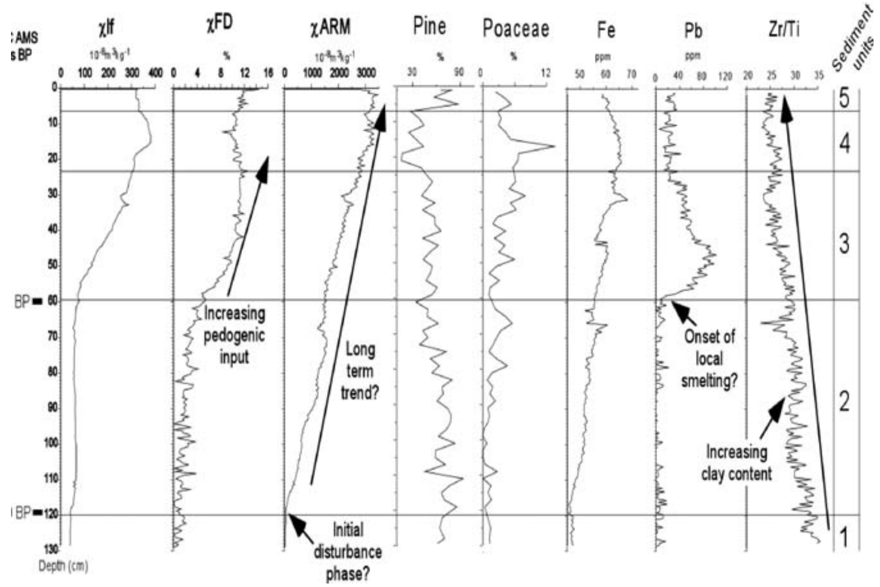

Figure 2: Results from the Sedimentary Archive.

This is clearly not the case in sediment unit 3 which is characterized by a marked and sustained increase in χlf (magnetic susceptibility) and χfd, pointing to the onset of a major period of soil erosion in the catchment at ~1950 BP. Sediment zone 3 is characterized by a marked increase in *Poaceae*, with a greater contribution of grains >37um, which may reflect the presence of cereals (data not shown). *Pinus* values remain high throughout this zone, even increasing slightly at times. Pine would certainly be expected to respond favorably to increased disturbance in the catchment allowing it to out compete previously dominant taxa particularly *Tsuga*. A significant long-distance transported pine component would also be anticipated. A more unequivocal anthropogenic signature can be seen in the geochemistry record, highlighted by the sharp increase in lead (Pb) concentration. With maximum values of ~100 ppm, too high to be simply a local bedrock signature, such a rise in Pb may reflect mining and/or smelting activity in the catchment. The earliest documentary references to silver mines and lead workings that directly relate to the Erhai catchment come from the Nanzhao period, which dates to approximately 649–902 CE.[5] However, earlier direct production of lead near Dali is recorded

[5] When there was an appropriate mixture of lead with the silver in the ore, as was usually the case, the first smelting produced an alloy of lead and silver, the second separated the two, and a third concentrated the silver further, often with the addition of a small amount of

(no clear date) for a lead mine in Heqing (Li Hao, 2002, p. 17), which is outside the border of the Erhai catchment, but nonetheless smelting activities could have taken place in the catchment as they did during the Qing dynasty (editors' note to Li Yiheng 269). The peak in silver mining in the region appears to have occurred during the period of the Dali Kingdom (960–1279 CE) (Li Hao 2002, p. 188). The limited historical data thus make a prima facie case for an upsurge in silver production in the Erhai catchment in or before the seventh century CE, a maximum in the later first millennium CE and the early part of the second, followed by a decline to the point of eventual nonexistence during the eighteenth and nineteenth centuries. This later decline may be reflected in the lead record at the transition zone between sediment units 3 and 4.

It is fascinating to note that such changes appear to be superimposed upon the longer-term trends, which commenced in sediment unit 2. Indeed, the protracted increase in χarm and Fe appears unaffected by the pronounced changes that characterize sediment unit 2, implying we are dealing with two completely separate signals operating on different temporal—maybe even spatial—scales.

A third successive shift in sediment source is highlighted in sediment unit 4, characterized by a marked increase in χlf and a slight decline in χfd. This shift coincides with a major phase of deforestation, with pine percentages falling below 30 percent for the first time in the core. This shift is paralleled by a significant rise in *Poaceae* (<12 percent), possibly pointing to the onset of a major agricultural phase in the catchment. The sustained levels of soil erosion in the catchment throughout this zone suggest that people may have expanded agriculture onto previously untouched areas of the catchment, such as upland slopes. This could also possibly represent a period of increased flood frequency. The upper most sediment unit (5) is characterized by a sharp increase in Pine values to a level comparable to those recorded in sediment unit 1. Such a rise may reflect a major period of reforestation aimed at stabilizing the catchment. Interestingly, despite this χfd values remain high; indeed, the highest values are recorded at the top of the core, which suggests that large amounts of topsoil were still being moved around the catchment at this time. A ^{210}Pb date at the top of the core provides an age of 1960 CE preliminary set at about 6 cm, indicating the observed changes in this zone may be linked to events initiated by the grandiose development campaigns of Mao Zedong, like the Great Leap Forward (see Shapiro 2001).

copper. The lead removed was called "silver-mine lead" and was abundant in Yunnan (Song Yingxing 238, 252).

5. ARCHAEOLOGICAL AND DOCUMENTARY EVIDENCE FOR ENVIRONMENTAL CHANGE

5.1. Early Hydrological Change on the West and North Sides of the Lake

Erhai developed in the late Pleistocene as a result of faulting in a pre-existing river valley. This increased its water levels to those higher than it is today, and which subsequently fell through the early and middle Holocene (Duan Yanxue 1989). First signs of human activity in the catchment appear in the Neolithic with a number of sites found on upper slopes of the mountains, one of which has been Carbon-14 dated to a mean of 3770 BP. The date of the initial clearance of lowland forest and dense undergrowth is not recorded, although it is reasonable to guess some time not later than the first millennium BCE. However, on the west side of the lake permanent settlements have been discovered, with a component of farming, dating back at least three millennia and with evidence of Chinese-style irrigated agriculture from at least the Han dynasty, dated at approximately 2,000 years ago (Yang Dewen 1988). The first recorded administrative unit in the catchment, Yeyu County, was established in the first century BCE by Emperor Wudi of the Western Han dynasty (206 BCE–220 CE).

Further (major) development of the region did not occur until around 745 CE when the independent[6] Southern Kingdom (Nanzhao) was established in the Erhai area (Rocher 1904). Once its lower shores were developed, the western side became the location of a number of political capitals. This was because the western shore provided the conditions for productive irrigated agriculture on a scale large enough to underpin a modest-sized polity and a thriving and urbanizing local economy (Fang Guoyu 1998). This development was accompanied by the beginnings of deforestation and the control of streams and floods. Drainage and breaching of pools and ponds helped turn upland plains into fields and a combined pastoral and irrigated agricultural economy was in operation. The first recorded irrigation system of any substantial size in the catchment, the famous 18 Streams, did not appear until the ninth century CE

[6] After the battle in 745 against the Tang forces, which ended in bloody but absolute victory for the Nanzhao forces, Nanzhao, which could be said to have been under the loose suzerainty of the Tang up to that point, became effectively independent, though for a time reliant on an alliance with the Tibetans. This independence lasted until the Mongol conquest in the thirteenth century.

(see Figure 1). This demonstrated a growing commitment of the state to hydraulic systems during a period when the hydrological regime was possibly greater than today (Elvin et al. 2002, p. 12). Integral to this system was a north-south channel 16 km in length linking 11 of the streams coming down the east-facing slopes of the Diancang Mountains.

The situation on the north shore was different with the land near Erhai, mostly an area of marshland (Li Zhengqing 1998). These marshlands were drained around 737 CE by assembling several tens of thousands of men to cut more than 5 km of channel through Bell Mountain (Yin Ren 1902), which diverted the outflow from West Lake in a different direction to the Luoshi River, eventually to debouch into Erhai (Dengchuan zhouzhi 1854). This act was said to have greatly improved soil drainage and fertility (Zhou Kang 1902). The question posed here is when did these environmental improvements turn into environmental problems?

5.2. The Ming Prelude to Environmental Crisis

An intensifying pressure on resources occurred during Ming times (1368–1644 CE), and maybe earlier (Liu Wenzheng 1991; Li Zhengqing 1998; Duan Jinlu 2000). For example, in the case of the hydraulic administration of the 18 Streams, forcible settling of Ming military colonists alongside the civilian population led to new problems, as pressure on scarce water resources grew. Yi tribesmen also unexpectedly moved into and freshly cultivated the mountains, which required the use of irrigation water. Upstream users thus began applying pressure on downstream users and introduced water quotas. In the area of the 18 Streams on the lower slopes of the Diancang Range, water quotas were allocated between soldiers and commoner–civilians in a total of 35 locations between Shangguan and Xiaguan around 1426–1435 CE (Duan Jinlu 2000). It seems likely that old registers were examined and quotas carved on stone to ensure equity. Shares were temporal, thus ensuring a proportional distribution from an annually variable water source. Except in specially noted cases, this was a daylight share. The old standard for water allocation of 10 days and nights was followed, but occasionally less than 10 shares were allocated, which probably reflects a reduction in the relative quota originally assigned to a collective group of recipients. Government officials ensured compliance and maintained peace through an interventional consultation process between soldiers (the group most under pressure) and civilians, which discussed the scheduling and temporal allocation of water rights through locations and fields as controlled by sluice gates. A ground inspection and enquiry clarified the facts under dispute and infractions of water regulations by offenders were punishable by placing a wooden neck-collar around the offender's neck.

This evidence points and leads to the conclusion that the central part of the Erhai catchment experienced a strategic seasonal shortage of water as determined by the relationship between population pressure, contemporary farming technology, and the quality of natural resources as defined by that technology. During the rice transplantation period this resulted in conflict over a scarce resource. However, human transformation of the environment did not cause acute emergencies until the second half of the eighteenth century, which at that time was part of the catchment in the north.

5.3. Crisis in the North

Late in the sixteenth century a threshold was crossed, with the first clear case of a large ecosystem reaction. The crisis occurred in the northern part of the catchment, in what was then Langqiong county, immediately south of the present-day city of Eryuan (see Figure 1), where the waters of the upper Miju River and the outflow from Lake Cibi, both from the north, the Fengyu River from the west, and the smaller Ning River from the northeast, joined together at or near the Three Rivers' Mouth to flow southwards through the narrow Putuo Gorge, and thence into what was then Dengchuan Department, and finally into the northern end of the Erhai (Elvin et al. 2002; Elvin and Crook 2003). The cross-flow of waters at the entrance of the Putuo Gorge created an obstruction, with the sediments and stones blocking the swift current (Fan Zhaoxin 1830s) and causing water in the Ning River to back up, resulting in drowned paddy and dry fields. This problem was initially resolved in 1598 by clearing and dredging the channel. By 1600 heavy rains led to further flood disasters of an increased severity, which resulted in more dredging of the river and the construction of a subsidiary river. These flooding problems continued into the mid seventeenth century, culminating in the construction of a long dyke designed to control floodwaters (Elvin and Crook 2003).

The flooding problem continued into the eighteenth century, probably because of the opening up of hill lands for cultivation and deforestation. For example, hills in front of and behind Tower Base Mountain, which were opened up between 1757 and 1758, were prone to erosion (Plate 1). Following heavy rain, sediments, stones, and flash floodwaters from these hills emerged from the Baihan Gorge, obliterating the dry cross-dyke and choking the body of the river with flood debris. The result of this was that in 1762, 1769, 1770, 1780, and 1781 disasters were reported, and remission and relief were repeatedly given (Fan Zhaoxin 1830s). Following the flood of 1762, in response to a petition, a low dry cross-dyke several thousands of feet in length was built to prevent flood damage and to replace moribund remedial work at the Three Rivers' Mouth in Langqiong County. After this event minor maintenance was carried out every year and major maintenance every third year. The problem of deforestation may also have become an issue in the western part of the catchment at this time, as it had in the southern part where programs of forest protection and reafforestation with pines were beginning to be put into effect by the 1780s. Scattered evidence for trade in wood within the catchment around this date very possibly reflected growing scarcities elsewhere, and demonstrates an intensifying pressure on resources within the catchment (Elvin et al. 2002).

Plate 1: The Remains of Tower Base on the Tower Base Mountain, Opened Up between 1757 and 1758 by Yi (© John Dearing 2003).

Above Putuo Gorge another subsidiary river was opened in 1771, but flooding remained a problem, returning in 1803, 1806, 1807, and 1808 after heavy rains resulted in the collapse of both large and small dykes, as well as ploughed hills located beside the gorge. In the case of the latter, flood debris caused massive backing up of water into the county capital. More than 1,000 men were assembled to dredge clear sands and muds and split apart huge boulders. With the old cross-dyke destroyed and the old disaster mitigation strategies clearly not working, the authorities looked into new ways of reducing the flood risk. From mountain summits the topography was scrutinized and the decision was made to rebuild a dry cross-dyke 1,100 feet long that was stabilized by willows from the mouth of the gorge to the eastern and western feet of the mountain (Plate 2). Maintenance of this dyke was an ongoing concern with further sectional repairs occurring in 1815 and in 1824. For a while the river flowed freely and peacefully.

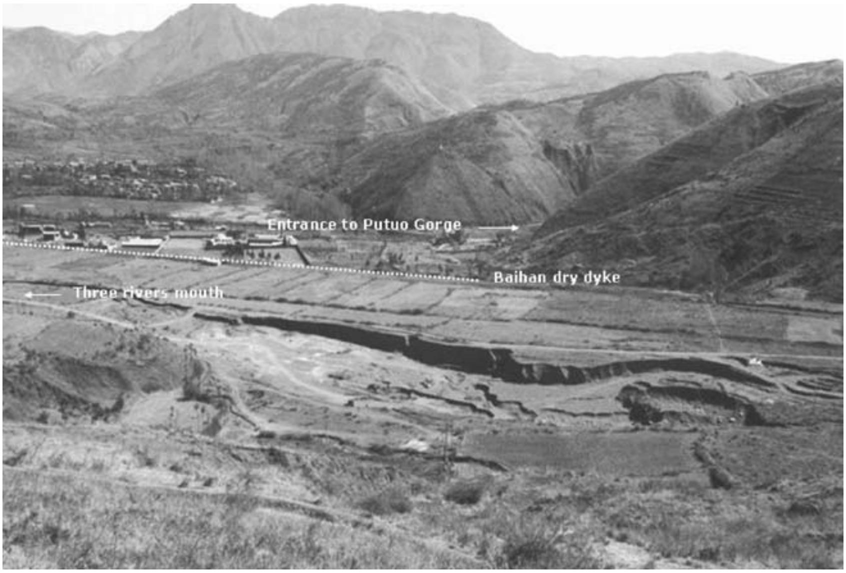

Plate 2: Baihan Dry Dyke and the Putuo Gorge (© Darren Crook 2003).

However, there were problems with the lower reaches in Langqiong, where the earth of the cross-dyke was pared away and made thinner daily and the low willow-dyke failed to survive, thus making the possibility of rupture a real and potentially devastating threat (Fan Zhaoxin 1930s). Four options to mitigate this risk included dredging the lower reaches deeply; building up and repairing the old cross-dyke; opening another diversion channel to reduce channel velocity and diverting the point of impact onto the dyke; and forbidding digging in the mountain gorges where rivers have their sources. With respect to the last point, there were two villages in the mountains, Shachang and Baihe, inhabited by the Yi who dug up the loose, light, and unstable soil on the north facing slopes in the mountain gorges, which were vulnerable to rain splash and detachment processes leading to overland flow and rill erosion. They also initiated some deforestation in this area, driven by a new or much augmented commercial demand for timber during the Daoguang reign-period (1821–1850), which clearly demonstrates an association between development and increased erosion. There is thus a *prima facie* case that the rapid increase in the volume of sediment carried by the Miju and other rivers in the north of the catchment in the later Ming dynasty and the first two-thirds of the Qing dynasty was due to hillslope land being cleared for farming, with or without deforestation,[7] and to an increase in tree-felling.

5.4. Dengchuan Disasters

Flood disasters were not confined to the Eryuan plain. By 1552, the trouble moved south of the Putuo Gorge and continued up to 1849 (Li Zhiyang no date; Hou Yunqin no date). The sudden breaching of the dykes is evident, as is the increase in frequency of repairs. Repairs to dykes carried out by colony soldiers and civilians were first recorded during the Yongle reign (1403–1424), followed by three more records between 1506 and 1521. A local government system in charge of annual repair of dykes was first put into place between 1436 and 1469, but neglect of dyke maintenance led to further crisis in the middle of the sixteenth century (The 1563 gazetteer for Dali). At this point fixed regulations and proportional annual maintenance responsibilities were introduced according to the amount of land owned. Anyone not willing to participate was fined.

A relaxed, community-based maintenance system was replaced by tight bureaucratic control after the flood of 1552. The quantitative details of maintenance work were laid down, with the costs of repair, material and labor, remaining high. The responsibility for specific lengths of dyke was assigned on the basis of taxes paid by landowners and laborers, who normally worked for a month, under official regulation. Organization, including department overhauls, improved periodically throughout the seventeenth, eighteenth, and nineteenth centuries, ensuring a period of stability after the disasters of 1815–1817 (Elvin et al. 2002; Elvin and Crook 2003). The hydraulic engineering above the Gorge at the Baihan may also have played a part.

During the first half of the nineteenth century the population, which was recovering from various epidemics, increased (Benedict 1996), leading to increased pressure on scarce resources. People were forced into the

[7] Not all slopes were forested, but even slopes with scrub needed clearance to make them suitable for farming.

mountains to cut firewood and kindling, which they then exchanged for grain. The clearing of fragile upland slopes adversely affected hydrological conditions and incurred mounting economic burdens, though not for the protagonists. There was a displacement of responsibility. The Yi opened new mountain land above the Baihan Gorge and thus did not have to rebuild the Miju dykes downstream, which is one reason why effects of this type proved so hard to stop. It was estimated that from 1828 to 1843, the riverbed in the upper course below the Putuo Gorge rose by 10 feet in spite of dredging. This was due to land clearance and deforestation upstream, which led to increased sediment loads in the Miju River. At this time river gauges were installed to monitor dredging needs. By the early nineteenth century clearing and dredging required 60,000 men working occasionally for around three months, and half again that number to rebuild the embankments.[8]

The bed of the Miju lay above the land because turbid waters annually transported and deposited silts and sands, particularly during summer and autumn. Some of the sediment remained in suspension until it accumulated at the river débouchement into Erhai, such that with the passing of time, the mouth of the Erhai became obstructed, and the tail end of the river grew congested, preventing boat traffic. For around 30 years prior to 1854–1855, the delta grew by 2.5–3 km, a linear extension rate approaching 0.2 km/year. Thus, the disaster of sediments and stones were endured all the way from the source to the tail. A sharpening awareness of how environmental problems were interconnected occurred as new experiences arose.

5.5. West-Side Hydraulic Degradation

Irrigation systems of the west side fell into a state of administrative neglect, and in some cases allegedly irrecoverable decay during the mid-sixteenth century (*Dali Gazetteer* 1563). At this time almost none of the water supply from the 18 Streams used for farming was under proper control or receiving regular maintenance (Elvin et al. 2002). On the west side over a period of about 100 years, rich soil had turned into sands and stones because of poor water control. In periods where there was a compelling public interest, maintenance work was carried out, but rarely otherwise. Failure to dredge the disaster prevention dyke led to a huge flood some time between 1488 and 1505, which destroyed many houses in

[8] The resolution of the fan/dyke record appears to be multi-decadal and may help in reconstructing an event chronology but this constitutes work in progress.

the walled city of Dali. Thereafter arrangements were made to dredge the moat annually. The same importance was given to the outflow of the Erhai, which was cleared every third year. Failure to dredge channels north of Dali led to 100 *qing* (~ 667 ha) of rich land turning into saline waste, which provides evidence for unsustainable practices.

Increased sedimentation was potentially the result of tree cutting on the Diancang mountains as trees were being felled there at this time. There is a slight suggestion that stocks were beginning to decline, but records imply that trees were still there to be cut in the early twentieth century (*Dali County Gazetteer* 1917). Presumably these trees were even more abundant during the late Ming period.[9] These fragments of evidence leave us with several problems, which are made more difficult by an approximately 300-year gap in the available evidence. An intricate, decentralized complex of small traditional irrigation systems based on the 18 Streams, together with many smaller sources like springs, was still functioning in the early twentieth century, apparently successfully, although this success remains unexplained.

In contrast to the Miju system, the part played by the state in Dali was minimal, as their small scale made community management practicable. People seem to have been content to live with flooding problems rather than trying to control them. Allocation of water was based on what was now a long established legally binding customary rotational cycle. Other groups of villages used similar cycles, whilst still others had inherited rules, working on principles not specified. Judging by the number of names in common, the anthropogenic channel structure of the west-side complex of irrigation systems in 1917 bore little relationship to that of 1563 or that of 1426–1435, just as these latter two had at best only a limited mutual relationship. Whilst the springs, gorges, and main debouchments into the lake remained more or less constant, the manmade conveyance channels of the 18 Streams were slowly but continuously shifted over time by human action across the lower lakeside slopes of the Diancang Mountains. This was done to circumvent the problems created by sedimentation, an observation supported by the decentralized and very slightly anastomotic character of the complex. To open a new channel on the lower slopes of the Diancang channel was not an easy engineering task

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[9] The main period of hill slope deforestation seems to run from the second half of the seventeenth century to at least the later part of the eighteenth (when some remedial reforestation began). This included the reign of the Yongle Emperor (1723–1735). However, we have no direct evidence that any timber from Erhai was used for palace building. (Guizhou would have been a more likely source.)

because strongly corrugated contours on steep slopes and channel seepage had to be overcome. In this difficult terrain a rate of about 33 m a day was thought possible. Thus, we conclude that work of this sort would have amounted to a substantial undertaking, though not a monumental one. In oversimplified terms, while the challenge that developed on the Miju was vertical—namely, to make the dykes higher and the river bed lower—for the 18 Streams it was horizontal, to find a way to relocate laterally. The former required an ever more onerous annual state-run bureaucratic mobilization of labor, resources, funds, and managerial skills; the second needed only intermittent, small-scale excavations.

5.6. Twentieth Century Pressures on Water Resources

The political vacillation of the twentieth century left a large legacy of environmental destruction (Shapiro 2001), which unfortunately remains hard to quantify, as the political sensitivity of this information where it survives is still high. What is clear is that the earthquake of 1925 caused massive disruption to the entire catchment, even causing a tsunami on the lake and adding to the collateral damage brought about by revolution and rebellion (Retlinger 1939). The rest of the century is characterized by increased population (in-migration and natural increase) and development pressure, which over the course of the "Mao era" led to new demands on water, including hydroelectric power (HEP) generation and periods of upland erosion associated with the construction of agricultural terraces and deforestation, which resulted from the need for fuel wood and energy for iron smelting (UNCRD 1994).

The long-term process of land reclamation and drainage on the northern plains continued, with the East Lake all but disappearing. Sediments within the Baihan Gorge cross-dyke increased and grew thicker daily, so that they were almost level with the dyke parapet. Further downstream, it has been estimated that the Miju lacustrine delta vertically accumulated at a rate of just under 50 mm year^{-1} at its mouth from about 1950 to the middle 1980s, a rapid rate in comparison to that found in the Boluo delta (about 2.0 mm year^{-1}) in the south of the catchment. The reduced storage time of water in the Dengchuan Plain may have contributed to the development of this delta. On the western shore about a third of the way down, lakewards of the town of Xizhou and the village of Shacun (sediments village[10]), the Wanhua Stream debouches into the lake

[10] The name of this village refers to a location where sediment from the Wanhua stream regularly aggraded.

(see Figure 1). Since the 1970s this has resulted in the rapid build-up of a striking foreshore spit curved like a fishhook extending into the lake, which is visible on modern maps and remote-sensing images.

Today, water is more strongly regulated both in the Miju (HEP) and on the west shore, where water shortage led to the construction of pumping stations for irrigation from the lake in the 1980s. Water shortage in the north of the catchment led to the construction of a small reservoir (see Figure 1). More irrigation water in particular has been needed to irrigate the large amount of new land brought into production by drainage on the plains and upland terracing. In terms of pollution, the outflow of Erhai named the Xi'er River has become a major source of pollution along the Mekong. The increased use of fertilizers has also created a diffuse source of pollution leading to eutrophication of the lake. A regional development and environmental management plan for the Dali-Erhai Area was drafted in 1994 to deal with these issues. However, aggressive measures to control nutrient and sediment inputs were not taken into consideration until after the first algal bloom appeared in 1996 (Dali EPB 1997). Eutrophication still remains an ongoing concern in Erhai (Jin Xiangcan 2003).

6. DISCUSSION

Our analysis of the Erhai Catchment describes past vulnerability and adaptation to human impacts and climate change and illustrates their effects on hydrology. Using an innovative interdisciplinary methodology many questions have been answered, though some are still left unanswered and the research process has uncovered yet new questions. Thus these results are preliminary and the disentanglement process continues. Before we can come to more confident conclusions about the affects of human activities on water resources, we must integrate both climate and tectonic data to understand the importance of coupling processes and synergy in driving hydrological change.

We start this section by asking whether the initial disturbance phases of human occupation and settlement were significant enough to initiate any long-term environmental trends. Initial landscape disturbance may have started as early as 2650 BP, but methodological constraints make it difficult to draw definite conclusions here. Not until 1950 BP do we see a very strong signal for human disturbance in the catchment in the form of greater amounts of pedogenic material in the catchment, probably topsoil, entering the lake. The timing of this event is in agreement with the documentary record, which shows that around this time Chinese-style irrigated agriculture was introduced. This may not have been ubiquitous throughout the catchment, but most certainly on the western shore, where the lead levels points to a wider development process occurring at this time. In terms of the hydrology, this was a period in history when the control of water became integral to everyday life and livelihoods, producing conditions that led towards a growing commitment to regulating both supply and demand by both individuals and the state, depending on the location. Together, these data point to possible long-term processes initiated by the crossing of important environmental thresholds impacting on present-day conditions in the catchment. This means that contemporary catchment planners concerned with the amount of sedimentation and new land creation in and on the lake may find that their decisions and actions to rectify this problem driven by current Chinese environmental policy may[11] have very little impact on these longer-term trends.

Only rarely do large scale documented events potentially coincide with evidence in the sedimentary records. Indeed, this does not happen again until the eighteenth century.[12] This time it is the pollen evidence that points to a phase of deforestation in the catchment, which is demonstrated by a decrease in *pinus* and an increase in *poaceae* beginning in the transition period between sediment units 3 and 4. This evidence is potentially supported by documentary records, which suggest that people, often minority nations such as the Yi, moved into the uplands to farm partly in response to population pressure on the plains. These actions had severe environmental consequences, supported by evidence found in documentary and sedimentary archives, thus independently pointing to the eighteenth century and the early part of the nineteenth century as a critical period for the onset of rapid environmental degradation in the northern part of the Erhai catchment. This instigated a period of great flooding that initiated the development of the Erhai delta in the north of the lake, which remains an ongoing process, as sediment is slowly transported down the dendritic system. Hypothetically speaking, the dip in χ_{FD}% at this time suggests the mobilization of a different sediment source alongside the already high soil erosion rate, which could reflect a period of high-energy floods.

Analytically, the pattern of spatial connectivity appears to be a crucial determinant in creating the Miju type of acute crisis. Water systems on the west side were marginally anastomotic in places, but predominantly independent of each other; requiring clearing of deposited sediments and

[11] Current government policy to prevent flooding in other parts of Yunnan calls for the land to be returned to the Lakes.

[12] Care must be taken to avoid circular argument because the exact dating of the sediment sequence is not yet available and thus it cannot be certain that these records tally with the documentary records.

restructuring, all of which entailed localized costs. In contrast, the Miju in the north was, for all intents and purposes, a single dendritic system in which perturbations in sediment loading in a multitude of inputs had a cascading effect, as they reinforced each other downstream, which in part is reflected in the different flood records of the upper and lower Miju. The large sub-catchment scale and gradients of the Miju led to this river having a far greater impact on lake hydrology than the comparable Bolou dendritic system in the south of the catchment.

More generally, within the broad framework of the concept of "traditional Chinese irrigated agriculture", it is important to draw significant distinctions between differing degrees of "sustainability," based on contrast and environmental microvariation evident in the two sides of Erhai presented here. A variety of patterns of ecosystem reaction across time characterize pre-modern Chinese-style development, which is notable given that the repertoire of pre-modern farming techniques was for all intents and purposes identical in the two sub-catchments. In the Miju River sub-catchment, a long early phase of relatively widely spaced human innovations to exploit natural opportunities or provide "solutions" to natural problems, with little trouble during the intervening periods, was followed by a dramatically intensifying sequence of crises, with other factors such as upstream stripping of mountain forest and vegetation cover adding to the complexity of causes. The long-term process of land drainage and reclamation of the shallow lakes and marshlands, most evident in the Dengchuan and Eryuan plains of the north, appears to have been an environmentally benign process unworthy of recording in documentation. What this clearly demonstrates is that this level of environmental microvariation must be considered in the formulation of present-day water policy.

Throughout the historical time frame covered by the documentary records, the perturbations and problems associated with the governance and organization of water supply and demand were numerous. The desires for equity in terms of the scheduling and allocation of water rights are apparent from an official perspective, but clearly principles and practice often failed to coincide, particularly when individual motivations and group dynamics were taken into account. Individual apathy, perhaps driven by economic malaise, resulted in periods of moribund irrigation systems and abandonment, particularly on the western shore. Some of these changes constitute part of a dynamic, but others question the long-term sustainability of these systems. The evidence for long-term flexible hydraulic adaptation on the west side of Erhai suggests that even systems with a high degree of relative "sustainability" may not have been absolutely sustainable over the long run (assuming constant technology), except at the cost of periodic restructuring in addition to ordinary maintenance. This leaves open the question of how far can “stability” be reasonably allowed to contain “dynamic” elements, as contributing to any sense of “equilibrium”?

Finally the results demonstrate the advantage of using an interdisciplinary methodology of the type applied here in that they allow an observation of events—such as changes to society and the hydrological system that impact both the competitive demand for and supply of water—over varying temporal and spatial scales. The weight of importance of short-term linear events evident in the archaeological and documentary record is sometimes challenged by longer-term trends (like cyclic and nonlinear events that are apparent in the sedimentary records), such that simple cause and effect relationships are not evident. Clearly non-stationarity is also important and any concept of vulnerability, adaptation, and resilience to changes in the hydrological regime must recognize this dynamic.