China Erosion and Sedimentation materials

1. Video explaining interactions between the Loess Plateau and the Yellow River:

https://www.youtube.com/watch?v=NQBeYffZ_SI

2. Article and video about human cost of landslides from the Telegraph

3. Blog post about dams on the Yellow River

4. Academic article chronicling the impacts of mountain road development on landslide erosion and sedimentation

China's deadly landslide 'not an accident'

The devastating mudslide in north-west China that has killed more than 1,000 people this week was not a 'natural' disaster but the forseeable consequence of China's cavalier attitude to the local environment, experts have said.

Please watch the accompanying video in addition to reading this article:

By Peter Foster in Beijing

1:20PM BST 11 Aug 2010

http://www.telegraph.co.uk/news/newsvideo/7939420/Rescue-hopes-dwindle-in-mudslide-Chinese-town.html

China's government is under growing pressure over the disaster after it emerged that there had been repeated warnings of the dangers of landslides around Zhouqu following decades of mining, logging and damming rivers for hydroelectric power.

While China's premier Wen Jiabao posed for cameras near rescuers trying to find the more than 600 still missing, local media quoted a growing chorus of experts who warned that the landslide had been "an accident waiting to happen".

A 2006 report by Lanzhou University warned of the dangers presented by the destruction of the forests around Zhouqu for mining and agriculture, causing soil erosion and destabilising hillsides.

"The hills have become highly unstable and easily subject to natural disaster of landslides and mudslides," the report said. "The situation is the result of deforestation, exploitative mining activities, construction of hydroelectric power plants and other development activities."

Zhouqu, once known as the "Shangri La" of Gansu Province, has suffered more than ten major landslides since 1823, but experts said the risk had been increased hugely by the felling of more than 126,000 hectares of forest between 1952 and 1990.

In more recent years, the construction of a highway and more than 40 hydroelectric power dams in the sharp-sided valleys has further destabilised the geology, according to Fan Xiao, a leading Chinese geologist based in Sichuan.

"Local authorities have ignored daunting warnings about the severe consequences of dam-building and viewed dams as their key source of taxation, which contributed 50 per cent of Gannan's revenue according to official statistics," Professor Fan told the South China Morning Post. "Had those warnings been taken seriously, the disaster may have been averted."

Reports from the disaster zone also suggest a growing anger among the inhabitants of Zhouqu that the warnings were not heeded and that a better disaster action plan had not been put in place.

"This has happened before. The government knew it could happen again and did nothing to prevent it," a local farmer Yang, who did not want to give his full name, told Reuters as he searched for five of relatives buried in the mud.

Yellow River Decade: Examining silt at the Sanmenxia Hydropower Station

(blog post from China Green News: http://eng.greensos.cn/ShowArticle.aspx?articleId=579)

Reported by: Lina Wang and Yongchen Wang

We had never expected that on our first visit to the Sanmenxia Hydropower Station, the silt in the Yellow River would put on such a wonderful "show".

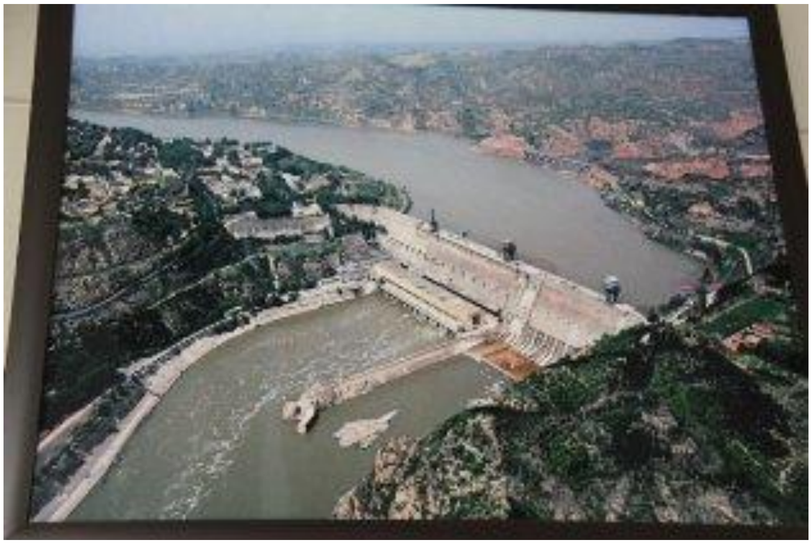
It was 7am on August 15, 2010. As our bus had been having some problems, all 37 passengers disembarked and decided that the focus of today would be to go and check out the Sanmenxia Hydropower Station. From the outset, we had given up on Sanmenxia as we felt that the jury had already delivered its verdict on the project: a fairly unanimous vote of no confidence. In particular, our colleague Qi Pu, senior engineer from the Yellow River Water Resources Council, held firm views on the taming of the Yellow River, insisting that the idea to construct Sanmenxia was fundamentally flawed.

Mr. Qi Pu had also gone to great lengths to contact a guide from the Sanmenxia area with a direct connection to the project to explain it to us in depth.

A map of the Yellow River

A topographic map of the Yellow River Basin

A model of Sanmenxia

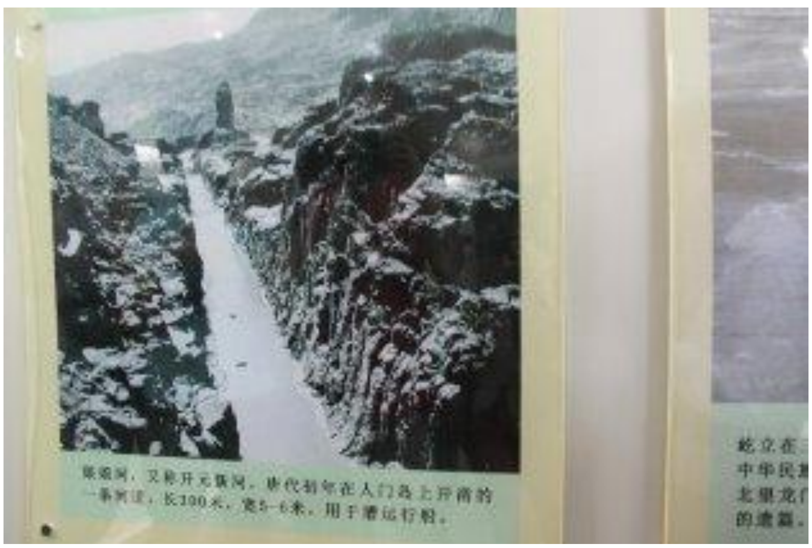


Cut down the middle

The tour guide told us that Sanmenxia Dam was China’s first large-scale water management project constructed on the Yellow River and was now honoured as "The Great Yellow River Dam." The dam is located in the northeast of the Sanmenxia district in Henan province, neighboured to the north by Shanxi Province and to the west by Shaanxi Province, in an area known as "The Golden Triangle." The first ground was broken in April 1957 and in only about four years the bulk of the dam’s construction was virtually complete.

Our guide proudly explained that Sanmenxia was constructed entirely using manual labour, whereas dam construction these days, including the Three Gorges Dam, is all done my machines. She drew our attention to a poem by He Jingzhi called "The Sanmenxia Dressing Table", but explained that she would only recite a couple of lines since it was rather long. One of the lines she chose was written before the construction of the dam while the other was written afterwards. The first was: “The waters of the Yellow River flow from heaven” and the other one was: “The waters of the Yellow River flow from the hands of men”.
In the guide’s view, the construction of the Sanmenxia Dam was simply a testament to the ability of human beings to manipulate the Yellow River.

The “dressing table”, which has since been inundated by water.



The canyon pictured is no more.

These two photos of what was called the Sanmenxia “dressing table” or “dresser ”are extremely rare, as they show the which now rests at the bottom of the reservoir. They are also the sole remaining record of what the area looked like before the dam’s construction. Photos are the only reference we have of the “Goddess River Gorge”, whose sheer cliff faces were also inundated after the dam’s construction.

In this highly biased exhibition centre, surprisingly we did obtain some new information: From the two photographs we learned that the Yellow River floods four times a year, with the silt content rising sharply during flooding months.

Information of the four flood periods of the Yellow River.

Samples of river water.

The four flood periods of the Yellow River are named Spring flood, Summer flood, Autumn flood and Winter Flood. The names of the floods are pretty self-explanatory; however, what wasn't obvious from the exhibition was whether the construction of Sanmenxia Dam had affected the annual flood cycle.

Examining the row of twelve test tubes in this display case, I had an inspiration. Originally, we chose to come on this trip to take a number of water samples and examine the differences in water quality between them. However, several experts we spoke to felt that in reality, this method of fieldwork would not offer any significant insights. This is because there was nothing profound about the sites or periods where we were taking

samples. However, if we were to use the samples collected on this trip to monitor sediment instead of water quality, perhaps we would be able to determine variances in the sediment levels along the entire Yellow River. The realization of new possibilities for our water samples would end up being the most productive result of the day.
The exhibition centre contained so much material that would be considered controversial by today's standards. Touting only the project's triumphs while failing to mention a single word from alternative points of view, the exhibition actually provoked a sense of pity towards it.

Of course, the times are always changing. Thinking back to the past, Tsinghua University water management expert Professor Huang Wanli, and Wen Shanzhang, an intern from the State Administration of Radio, Film and Television (SARFT) put forward a challenging view of the Sanmenxia Dam project. They argued that the use of high dams and large reservoirs to store water and capture sediment was not suitable for the Yellow River with its high silt content, and would lead to numerous problems upstream. However, during that period when the dominant ideology of the times was to build a new China that was bigger, better and bolder, any opposition to the dam's construction was considered almost counter-revolutionary.

The islands depicted in this mural have since been submerged in water

Stepping across two provinces

As expected, the advice of Huang Wanli and Wen Shanzhang, and barely a year into the engineering project, 1.5 billion tonnes of silt had already been deposited into the reservoir. Once the project began generating power, it not only failed to contain the silt, but also created problems on the upper reaches of the Wei River. At this location a dam had been built that steadily raised the height of the riverbed, leading to increased flooding and the salinization of more than 50 million mu (8.3 million acres) of farmland on the Guanzhong Plain.

In 2006, I went to investigate Hua County in Shaanxi Province. Locals showed me one result of the continuously rising Wei River riverbed: a bridge over the river had been buried so deeply by silt that they were forced to build a new bridge where the original bridge had once stood. It had then reached the stage where a bridge on a bridge soon became a bridge on a bridge on a bridge.

When I visited the Wei River the previous year in 2005, the Autumn floods led to the Wei River disaster. By Chinese New Year of the following year, the water had still not receded and victims were still living in emergency shelters.

According to senior engineer Qi Pu , although this project was considered one of the biggest engineering failures since the founding of the Republic, it is undeniable that the lessons it provided were incorporated into the construction of the later projects such as Xiaolangdi Reservoir and the Three Gorges Dam.


The overwhelming force of the silt


Silt in the reservoir.

Regardless of peoples' attitude towards the Sanmenxia Dam Hydropower Station before our visit, all of us could not help but be struck by the sight of the battle occurring before our eyes once we saw the site up close: The Yellow River had morphed into an entirely different form; an awesome sight that was worthy of a painting. In one sense, you could say that the river had been 'sculpted' by manual labour into a form that laid bare the inherent beauty of its raw power.

Yesterday we witnessed the thundering waves of water and sediment being released from the Xiaolangdi Reservoir. And today again the Sanmenxia Dam shook heaven and earth as the reservoir was emptied of silt. Standing above this world of silt, it looked like as if the silt was dancing; just looking at photographs of it causes the mind to wander off into far-away places. I think I speak for most people when I say that the fantastic world of silt had captured my interest far more than the intricate details of hydroelectric generation.

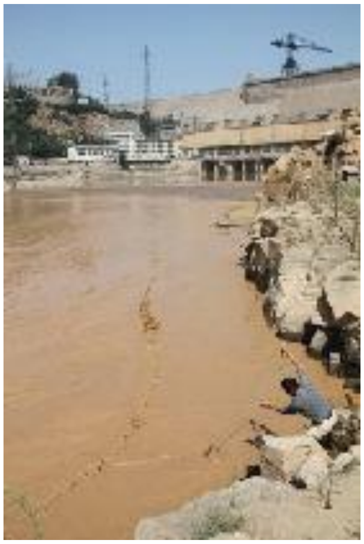
A world of silt

The howling silt

Silt, silt and more silt!

Qi Pu tells us that the process of flushing the accumulated silt out of the reservoir involves draining its contents and then using upstream floodwaters to wash away any remaining sediment. This not only sends the existing build-up of silt further downstream but also brings new deposits of silt from upstream. As a result, the silt discharged from the dam is dense, comprised of both accumulated silt and newer silt from upstream.
Qi Pu has devoted his whole life to understanding the Yellow River, and considers himself a scholar on the topic. In recent years, wherever he goes, he articulates his position on the river's management to our national leaders, to his colleagues and to people in different industries. Even those who don't agree with him entirely have to admire him for his persistence in making his case.


In this photo, the Sanmenxia Power Plant is not generating electricity, but discharging sediment.



Collecting water samples.

A water sample from Sanmenxia Reservoir.

Back on the bus, Qi Pu tells us that the sediment contained within the Yellow River is deposited naturally during the flood season and that these floodwaters ultimately disperse the sediment into the sea, which has far-reaching significance for downstream river management. The large number of reservoirs on Yellow River, the construction of reservoirs on the Yellow River basin in groups, the application of soil and water conservation practices, and the development of irrigation have caused big changes to the underlying riverbed. These changes to the riverbed have dramatically decreased the frequency of floods and reduced the range of the river's peak flow rate. In order to maintain the natural process whereby floodwaters shape the riverbed and transport sediment to the sea, Qi Pu explained that we should cease broadening the river and abstain from trying to limit its peak flow. In recent years, we have adopted a new view of the Yellow River's natural narrow, deep channel and the cyclical floodwaters that transport silt downstream. We are beginning to understand that the downstream waters of the Yellow River have a strong capacity to transport sediment and discharge floodwater, and that silt build-ups are not necessarily related to the river channel's degradation. This sort of thinking is pointing the way for how the lower reaches of the Yellow River can be administered going forward. Until now, it had been thought necessary to construct artificial levees along the river. In the future, however, allowing silt to build up could lead to the formation of natural levees.

According to Qi Pu, after the reconstruction of Sanmenxia reservoir, the principle of storing clear water and discharging muddy water has greatly reduced the silt content of the water. As a result, the upper channels of the River, above the town of Huayuankou are almost clear. Permanent settlements have developed on the Wen and Meng riverbanks around the Xiaolangdi Reservoir. Since the Xiaolangdi Reservoir has gone into operation, most of the banks along the lower river have suffered erosion. There are sections of the river above Gao Village where the river's average flow-rate has increased to more than 5000m3/s. However, in places where the river becomes wide and shallow, the most advanced practices available are urgently needed to restabilize the riverbanks and restore deep and narrow channels. After many years of adjusting the sediment levels of the Xiaolangdi Reservoir, we should be able to restore the natural cycle of silt build-up and discharge that occurs during flood periods, and prevent the main riverbed from rising too high. If the main channel's current can be increased, the flood plain will decrease and the debate over constructing new levees will no longer be necessary. This would be the rational solution to all these problems encountered along the riverbanks. It should be noted that the approach to river management we are currently advocating, in which silt is allowed to accumulate according to natural patterns, applies to wide sections of the river up to the Xiaolangdi Reservoir. It does not account for the unique circumstances of the lower reaches of the Yellow River, downstream of Xiaolangdi Reservoir. As it does not reflect the unique conditions along the entire Yellow River, it should not be taken as such.


An expert in front of Sanmenxia Reservoir.

Recording the roar of the mud.

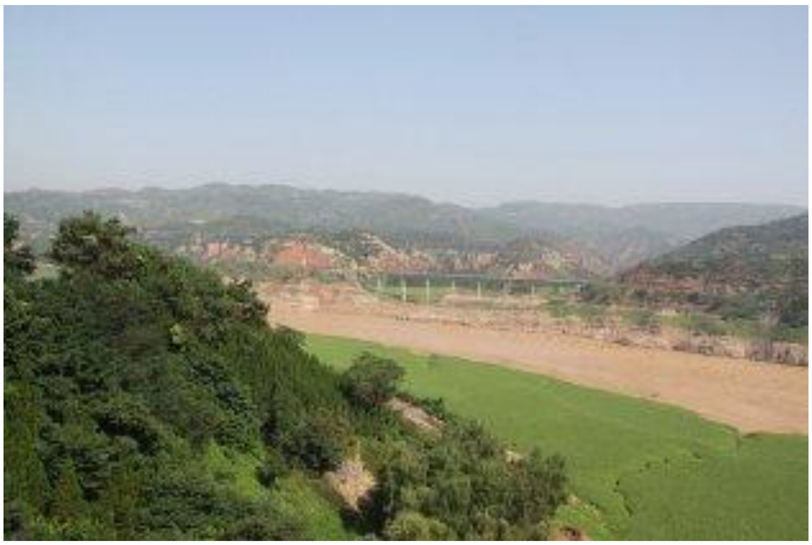
Wang Jian, another expert who was traveling with us, explained how from an ecological perspective the production of hydropower can disrupt the delicate balance of nature. Meanwhile, Luo Kanglong asked why we hadn't seen a single wetland at any of the places we had visited on our fieldtrip. Was it because wetlands had never existed at all, or was it because the 'taming' of the Yellow River had caused the natural surroundings to lose their natural free and wild appearance?

Part of an inscription on the reservoir which reads: “The Yellow River is calm”

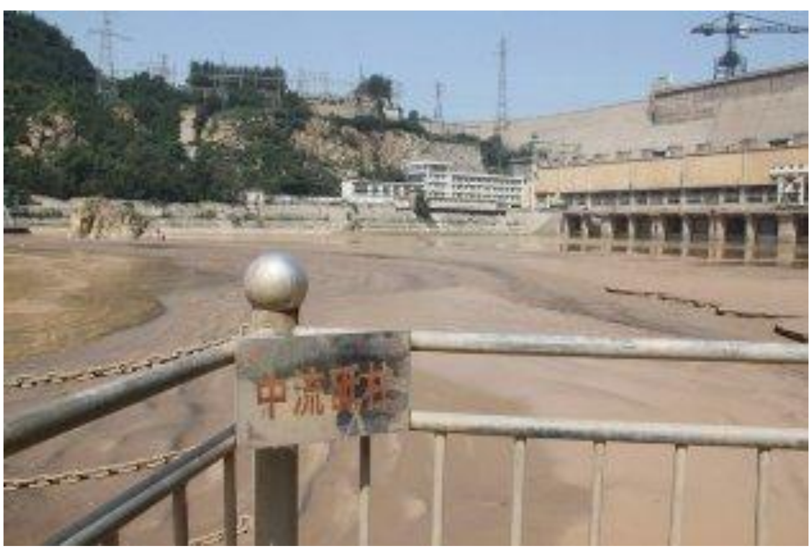
The inscription on the reservoir reads: “The Yellow River is calm, the country is prosperous and the people live in peace”

From an academic perspective, it is hard for those of us with a strong concern for the environment and the health of our rivers to speak with Qi Pu and not feel a strong sense of dismay. However, in recent years, as increased attention has been paid to river management and as our understanding of hydropower has also grown, the question is not whether or not we should build hydropower stations, but where and how to build them in order to avoid future disasters.

Often technical problems are easy to solve. What is difficult is juggling the interests of the upper, middle and lower reaches of the river. While we can use a variety of methods to “tame” the Yellow River, it is pointless to try to change its natural state. In some places the silt will build up, while in others it won't. If we draw too much water here, there will be too little water left there. When we are confronted with problems, perhaps we should take a moment to consider whether it is the river that requires modification or human behavior that requires modification. Perhaps it is possible to reduce our own self-interest and have more consideration for those people who live along the entire Yellow River basin. Maybe when we dream of the huge economic returns that engineering projects and power generation bring, we should also think of the ecological and social consequences of our endeavors.



A view of the entire Sanmenxia Reservoir



The Mainstay Stone, saved by Premier Zhou Enlai.

According to legend, when the Great King Yu (the third of the legendary emperors who created the Chinese state) was managing the country’s waterways, he once came to this site and found a huge stone blocking the river. With two swipes of his sword, he sliced the stone into three pieces: Renmen (Peoples') Stone, Shenmen (Spirits') Stone and Guimen (Devils') Stone. In doing so he created three channels, or gateways for the river to flow through and it is from this myth that the name "Sanmenxia" (Gorge of the Three Gateways) is derived. Nowadays, these three rocks are inundated by water and have become foundation stones.

Anthropologist Luo Kanglong tells us that from the source of the Yellow River to the point at which it reaches the sea, there is evidence of Qi Lu Culture, Zhong Yuan Culture, Jin Shang Culture, Mongolian Culture, and Tibetan Culture following each other in succession. However, with the construction of over 3000 reservoirs of varying size along the Yellow River, we may never know how many other cultures once thrived along the river as we have not had enough time to study and record them.

Nowadays, there still exists a large stone in the water in front of Sanmenxia Dam. Remarkably, though the river has been rising and falling over thousands of years before the dam's construction, this stone has never been inundated by water. For this reason, it is called the Mainstay Stone and has often been taken as a symbol. When the dam was built, some people suggested blowing up the stone, fearing that it would block the current and affect the generation of electricity. However, then Premier Zhou Enlai issued a decree stating that the stone should be protected and the stone proved to have no effect on electricity generation.

Is that a water reservoir or a silt reservoir?

A vista of silt.

From the drainage outlet spews a torrent of mud that looks a yellow dragon struggling to wriggle itself free. The poet Li Bai once wrote of the river: “See how the Yellow River’s waters move out of heaven, entering the ocean, never to return.” It is rare that one would come across such a poetic line these days and generally we can only imagine such a scene.

So it comes as a surprise when, while waiting for the bus to be repaired one afternoon, we visited Shaanxi National Park in Sanmenxia city and were able to witness a section of Yellow River in all its natural glory. Perhaps it is because we had spent the last two days examining the tremendous energy of the artificially-constructed Xiaolangdi Reservoir and Sanmenxia Dam that we felt how natural and untouched the Yellow River appeared here. Moreover, it is rare to see rivers in their natural state these days; such a precious experience that revives the hope of maintaining a harmonious relationship between people and rivers should be treasured.

The natural Yellow River.

Recording the river now to preserve it for future generations

The following day we would go to Tongguan, at the mouth of the Wei River. The ancient County of Tongguan, which had been located in the reservoir area, was entirely relocated after the construction of Sanmenxia Dam. We were going to meet the people that live there now and see how their lives were progressing. There, we would seek out families whose lives on the Yellow River we had been tracking over the past ten years and will continue to track for the next ten.

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Discussions

Epic landslide erosion from mountain roads in Yunnan, China – challenges for sustainable development

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Abstract

Expanding mountain road networks in developing countries significantly increase the risk of landslides and sedimentation, as well as create vulnerabilities for residents and aquatic resources. We measured landslide erosion along seven road segments in steep terrain in the upper Salween River basin, Yunnan, China and estimated sediment delivery to channels. Landslide erosion rates along the roads ranged from 2780 to 48 235 Mg ha^{-1} yr^{-1}, the upper end of this range being the highest rate ever reported along mountain roads. The two roads with the highest landslide erosion (FG1 = 12 966 Mg ha^{-1} yr^{-1} ; DXD = 48 235 Mg ha^{-1} yr^{-1}) had some of the highest sediment delivery rates to channels (about 80 and 86 %, respectively). Overall, three times more landslides occurred along cutslopes compared to fillslopes, but fillslope failures had a combined mass > 1.3 times that of cutslope failures. Many small landslides occurred along road cuts, but these were often trapped on the road surface. Given the magnitude of the landslide problem and the lack of attention to this issue, a more sustainable approach for mountain road development is outlined based on an analysis of landslide susceptibility and how thresholds for landslide trigger mechanisms would be modified by road location and construction techniques.

1 Introduction

Although there is ample evidence of the effects of mountain road development on landslide initiation, only recently has this issue been raised within the context of sustainable development and the potential collapse of certain ecosystem functions (Sidle and Ziegler, 2012; Sidle et al., 2013). In particular, the extent of environmental damage caused by landslides along mountain roads in developing nations is poorly understood. While numerous international donors, non-governmental organizations (NGOs), and environmental advocates have attributed increased sedimentation in rivers and streams in these regions to shifting cultivation and deforestation (e.g., UNESCO, 1974;

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Eckholm, 1979; Volk et al., 1996; Marshall, 1999), more comprehensive investigations and analyses recognize that these land use practices exert much less influence on downstream sediment and aquatic resources than poorly constructed mountain roads (Sidle et al., 2006, 2007, 2011; Wasson et al., 2008; Ziegler et al., 2009). Of course, road and trail systems are associated with shifting cultivation and deforestation, but more recent, rapid expansion of road networks in mountainous terrain of developing nations have been linked to transitions from shifting cultivation to more intense agriculture, increased tourism, economic development, national defense, emergency evacuation routes, and hydropower development (Krongkaew, 2004; Nyaupane et al., 2006; Ziegler et al., 2012; Urban et al., 2013). Rural road development in Southeast Asia has been aggressively supported by organizations such as the Asian Development Bank, the Food and Agricultural Organization of the United Nations, and the World Bank, largely based on perceived socioeconomic benefits (van de Walle, 2002; Balisacan, 2005; Hettige, 2006). In most cases, long-term sustainability assessments that weigh the relative benefits and impacts of rural mountain roads, including socioeconomic trade-offs, have not been conducted (Sidle et al., 2013).

Any road constructed in steep terrain will decrease the stability of the hillslope (Sidle and Ochiai, 2006). Roads cut into steep slopes promote landslides by removing upslope support and oversteepening the cutslope (Megahan et al., 1978; Rice, 1999; Sidle et al., 2006). Fillslopes, particularly when excavated fill material is poorly compacted, are susceptible to failure due to overloading and oversteepening of the slope, as well as when road drainage concentrates on these sites (Burroughs et al., 1976; Douglas et al., 1999; Sidle et al., 2011). As such, midslope mountain roads tend to create the most severe landslide problems because they experience both cut and fill failures including intercepting substantial quantities of subsurface water which often triggers landslides in fillslopes (Wemple et al., 2001; Sidle and Ochiai, 2006). If the terrain below these midslope roads is steep, much of the landslide material can directly reach streams or rivers, contributing significantly to sedimentation (Mills, 1997; Sidle et al., 2011). Because a significant portion of new rural road construction in north-

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ern Yunnan, China, as well as throughout developing regions of Southeast and East Asia, is occurring in steeply dissected mountainous regions, the associated landslides and sedimentation are problematic (Nyaupane et al., 2006; Wasson et al., 2008; Sidle and Ziegler, 2012). However, the effects of rural road development have not been well documented, particularly with regard to sediment sources and delivery.

Structural measures to prevent landslides along roads have been used effectively at vulnerable sites (e.g., Holtz and Schuster, 1996), but are prohibitively expensive in remote regions of most developing countries (Sidle and Ochiai, 2006). Furthermore, little attention has been paid to road location and construction techniques in mountainous Southeast Asia (Ziegler et al., 2004, 2012; Sidle et al., 2006, 2011). As such, landslide issues need to be more carefully considered by the agencies that initiate and control the construction of these corridors in developing nations, as well as environmental groups and international organizations, which are focusing more on widespread land cover changes and hydropower development (Sidle and Ochiai, 2006; Tullos et al., 2013).

One of the first instances of heightened environmental awareness of road-related landslides was associated with sedimentation of streams and resultant impacts on fish habitat in the Pacific Northwest, USA during the 1970's and 1980's. Rates of landslide erosion from secondary forest roads in unstable terrain of Oregon and Washington ranged from 25 to 155 $Mg\,ha^{-1}\,yr^{-1}$ (Sidle et al., 1985). These impacts were believed to be significant enough to severely curtail logging of forests on Government lands in this region. Prior to this time, the major stability concerns with mountain roads focused on road closure, repair costs, and the maintenance needed to retain access (e.g., Bansal and Mathur, 1976; Chassie and Goughnour, 1976; Fleming and Taylor, 1980). Little emphasis has been placed on the impacts of landslides on environmental health and human welfare in developing countries of Asia where secondary mountain road systems are expanding at a rapid pace (Haigh, 1984; Sakakibara et al., 2004; Castella et al., 2005). Within China, the total road length of rural transportation networks increased by 5.5-fold during the 30 yr period from 1978 through the end of 2007 (China Road Construction Report, 2008). A recent study (Sidle et al., 2011) that reported extremely high levels of landslide erosion (1410–33 450 Mg ha^{-1} yr^{-1}) along a recently constructed road in the Mekong River basin of Yunnan, China, as well as observations of similar and prolific landslide problems in the upper Salween and Jingsha River basins of Yunnan Province, encouraged us to examine this issue in greater detail and across a wider range of mountain roads. Herein we present comprehensive landslide measurements at five general locations (total of seven road segments) within the Salween River basin of northern Yunnan, China, as well as estimates of the delivery of landslide sediment to streams and rivers. This study aims to provide a quantitative basis for government and local planning agencies, international donors, and conservation groups to focus their priorities and efforts related to mountain road expansion, location, and construction. Additionally, we show how this information can be used in sustainability assessments for mountain ecosystems subject to these development pressures.

2 Site considerations

The steep Hengduan Mountains of western Yunnan Province are currently experiencing rapid development pressures due to opening access to remote villages, hydropower development, agriculture, tourism, forest exploitation, and other related aspects of economic development. This area includes the north-south trending, deeply dissected gorges of the "three great rivers" (i.e., Salween, Mekong, and Jingsha Rivers) within "The Three Parallel Rivers of Yunnan Protected Areas", inscribed by UNESCO on the World Heritage List in 2003 based on their unique geological history, geomorphic features, ecological processes, and rich biodiversity (UNESCO, 2003). The Salween River (known as the Nujiang River in China) originates in the Tibetan Plateau and winds down steep gorges in northern Yunnan, along the border of southern Myanmar and northwestern Thailand, and eventually discharges into the Andaman Sea off the coast of Myanmar some 2800 km down river. In our study region of northwestern Yunnan, the Salween River follows a major seismic fault. While considered to be one of the poor-

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est regions in China (Su et al., 2012), the rapid anthropogenic change in this area is causing numerous impacts on the landscape and river systems.

The seven road segments we surveyed for landslide erosion are located in five general locations along the Salween River in a region spanning about 120 km from 26°01′ N 98°50′ E in the south to 27°05′ N 98°52′ E at the northernmost site (Fig. 1). All roads were unpaved and unimproved with no drainage facilities, typical of such secondary corridors in this region. From south to north the five survey areas for unimproved roads are: (1) a newly constructed road to access remote mountain villages and a hydropower plant along a tributary of the Salween River just south of Daxingdi village (DXD); (2) two segments of a recently widened road to access remote mountain villages near the Salween River about 40 km south of Fugong (SFG1 and SFG2; lower portion of the road, SFG2, accessed a hydropower plant as well); (3) a relatively new and incomplete road to a small mountain village near Ganxiangke (GXK); (4) two segments of a recently widened road to access small mountain villages near the Salween River several kilometers north of Fugong (FG1 and FG2); and (5) a short road used for sand excavation from the Salween River near Wa Tu Wa village (WTW). All surveyed road segments were at midslope locations requiring excavation into the hillsides. These roads were recently constructed or widened and the approximate dates of the construction were obtained from interviews with residents at each site for corroboration (Table 1). All road segments except for GXK were located within several hundred meters of the river or tributary channels. Except for the very short (0.19 km) road into the sand quarry near Wa Tu Wa (WTW), individual surveyed road segments ranged in length from 0.75 to 0.86 km. Details of the road sites are given in Table 1.

Elevations in the general study area range from about 800 to > 3000 m; elevations at surveyed road sites ranged from about 990 to 1450 m. The region is within an active orogenic belt, where the compression of the Eurasian plate by the underlying Indian plate gives rise to the high mountains, steep and incised gorges, and deeply incised river channels. With progressive uplifting and associated shearing, the Salween River continues to incise creating steep slopes proximate to the main channel and many

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tributaries. To the west of the river, the Gaoligong magmatic belt and high-grade metamorphic rocks are aligned with the north to south trending Gaoligong Mountains. East of the river, gneissic granite with included biotite, amphibolites, and muscovite occur in highly sheared contacts within meta-sedimentary rocks (Song et al., 2007).

Terrain that is undisturbed experiences limited landslide activity as does land cultivated by traditional agricultural practices. Only in the higher elevations on very steep slopes do significant numbers of surficial mass movements occur in relatively unmanaged terrain; these areas are typically remote from active channels. No major earthquakes occurred in the five-year period prior to our field survey. Because of heavy seasonal rainfall, the steep nature of the terrain, the proximity of hillslopes to the Salween River (or its tributaries), and the highly altered bedrock, secondary roads cut into these hillsides are highly unstable. Whilst the types of igneous, metamorphic, and sedimentary rocks vary somewhat among and within the different road sites, the dominant feature that characterized bedrock failures is the highly fractured nature of the exposed rock. Based on our field experience, soil development over bedrock varies in depth from a few decimeters to several meters in some cases, depending on slope position and microtopography.

This part of China is under the influence of the Indian monsoon, and described as a warm-dry climate; a combination of subtropical and alpine climates. Annual mean temperature (average from 1961 to 2010) is 20.2 °C, and mean annual precipitation is 995 mm, the majority of which falls during the monsoon season (May through to October) (Ghestem et al., 2014). Little to no snow accumulates in the lower Salween River valley in our study area. Vegetation above and below road excavations varies from steppe shrub to crops, such as rice, corn, and other vegetables. Prior to the 1950's, most sites supported natural forest cover composed of *Pinus yunnanensis* Franch., *Quercus acutissima* Carr., *Quercus aliena* var. acuteserrata, and *Castanopsis delavayi* (Ghestem et al., 2009).

Based on our field observations, current development in the region appears to be paying little attention to road location or construction methods related to the control of

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mass wasting. Secondary mountain roads are typically constructed by hydraulic shovels, large back hoes, or indiscriminate blasting, and the excavated material is simply disposed onto the side slopes just below the road. The hillsides are characteristically very steep (> 30°) with few if any gradient breaks, thus once a landslide initiates along a midslope road there is little chance of sediment entrapment on the slope, except near the base of the hillside. Smaller landslides along cutslopes are typically trapped on the road, but this material is often later delivered to streams via surface erosion or it can be incorporated into fill material that eventually fails (Sidle et al., 2004, 2011). None of the roads in our study sites had any structural reinforcement except for a recent crude retaining wall constructed on the lower portion of road located several kilometers north of Fugong (FG2). This area was the site of recent mass wasting, just prior to construction, which we documented.

3 Methodology

In June 2010, landslides and related sediment delivery to stream and river channels were assessed along seven road segments within the Salween River basin in northwestern Yunnan, China (Table 1). Lengths and widths of landslides were measured with metric tapes where possible or with a laser distance meter (range finder) when slopes were too dangerous to traverse. Depths around the flanks of landslides on cut and fill slopes were measured directly where possible and otherwise visually estimated to facilitate calculation of landslide volumes. For some of the cutslope failures, it was clear that the entire landslide mass was trapped on the road; thus, dimensions of the landslide deposit were measured instead of the failure area. Numbers of landslides in cut and fillslopes were adjusted for the age of the road and reported as number per km of road per year.

The calculated landslide volumes were converted to units mass using an assumed conservative bulk density of 1.3 Mg m^{-3}. For small cutslope and fillslope failures with estimated volumes > 1 m^3 and < 3 m^3, a volume of 2 m^3 was used; failures ≤ 1 m^3 were

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not considered. Landslide volumes were estimated separately for cut and fillslopes for later comparisons. These data were then calculated per unit area based on the width of the road prism and the length of the surveyed road segment divided by the age of the road (or the last widening of the road) – i.e., sediment mass per unit area of road per year. Based on potential measurement errors in estimating landslide volume, we estimate that our volume calculations are within ±10 % of actual values.

To estimate sediment delivery from road-related landslides, we examined the steepness and uniformity (breaks vs. no breaks) of the slope below each slide, slope distance between the landslide and the channel, evidence of deposition on the slope, and connectivity with the channel. While our visual estimates are somewhat crude approximations of sediment delivery, they are based on geomorphic attributes that control and affect sediment fluxes. At one site (GXK), the channel was relatively distant from the road, thus no connectivity (or sediment delivery) was noted. This does not mean that sediment would never reach a stream; rather it was deposited on the landscape and could be later entrained by surficial processes, similar to surface erosion from widespread land use in the region (Sidle et al., 2006). As such, sediment delivery estimates from roads are conservative. Nevertheless, the direct connectivity of road-related landslides with channels proved to be the most efficient and prodigious conduit of sediment delivery.

4 Results and discussion

4.1 Overview of landslide erosion along the different roads

A total of 312 landslides were measured along about 5 km of unimproved roads at the seven road survey segments in the Salween River valley. Rates of landslide erosion at all seven road survey segments are extremely high by all standards and comparisons (Table 1). The highest rate of landslide erosion (48 235 Mg ha^{-1} yr^{-1}) occurred along a 1 yr old road leading to a future hydropower plant just south of Daxingdi (DXD, Fig. 2).

Based on our knowledge, this is the highest rate of landslide erosion ever reported along mountain roads. The lowest rate of landslide erosion (2780 Mg ha^{-1} yr^{-1}), measured along the upper segment of road located about 45 km south of Fugong (SFG1, Fig. 3), was still 40–50 times higher than landslide erosion rates associated with logging roads in unstable terrain in the Pacific Northwest USA (Sidle and Ochiai, 2006). Within the continuum of landslide erosion rates that we measured, values from the other five road segments ranged from 3458 to 12 966 Mg ha^{-1} yr^{-1} (Table 1). These rates are orders of magnitude higher compared to combined landslide and surface erosion rates (in the order of < 3.5 Mg ha^{-1} yr^{-1}) from catchments with predominantly forest or brush cover and interspersed agriculture in Southeast Asia (including parts of China) (Sidle et al., 2006, 2011). In general, road-related landslides were shallow and occurred on steep slopes – average depths and slope gradients ranged from 0.37 to 1.24 m and 40.2 to 48.6°, respectively, among study sites (Table 1).

Aside from the surveyed segment of the village road near Ganxiangke (GXK), which was remote from streams, the delivery of landslide sediment to the Salween River and its tributaries was > 45 %. Four of the seven road segments had estimated sediment delivery from roads to streams and rivers exceeding 74 % (Table 1). The DXD road with the highest landslide erosion also had the highest estimated sediment delivery (86 %); similarly high sediment delivery rates were estimated at WTW (82 %) and FG1 (80 %) partly due to their proximity to the Salween River (Fig. 4).

The two widest roads (DXD and FG1) had the highest levels of landslide erosion. Wider roads cut into steep terrain disturb a much greater area than narrower roads and tend to destabilize hillslopes to a greater extent (Megahan, 1977; Sidle et al., 1985). Given that all of the roads examined were relatively new (or recently widened), erosion rates reported herein may be higher than longer term averages. Nevertheless, temporal trends in erosion rates along these mountain roads are complicated by the frequent obliteration and extensive blockage of roads during large storm events (including landslides). Such major disturbances either require new road construction or extensive road widening and excavation, thus perpetuating the cycle of active landsliding.

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4.2 Cutslope vs. fillslope landslide erosion

The relative proportion of landslide erosion along cutslopes and fillslopes varied among sites and was strongly influenced by terrain characteristics, depth of road cuts into the hillside, and disposition of fill material. Overall more landslide sediment was produced from fillslopes (38 170 Mg) compared to cutslopes (29 055 Mg) even though cutslope failures outnumbered fill failures by 235 to 77 (more than a 3 : 1 ratio). Three examples stand out as having disproportionately higher cutslope or fillslope landslide erosion. The DXD road had a large number (> 31.3 km^{-1}) and the highest rate (43 789 Mg ha^{-1} yr^{-1}) of roadfill landslides (Table 2; Fig. 5). Of the 27 fill failures that occurred along this road segment, the average gradient below the road was 44.4°. As such, when unconsolidated rock and soil material from the blasting and excavation was deposited on these steep side slopes, it sometimes failed immediately or shortly thereafter during a large storm. In contrast, two other road segments (FG1 and GXK) had significantly higher (about 9 to 16 times higher) landslide erosion along cutslopes compared to fillslopes (Fig. 5). These differences can be partially attributed to the gentler slope gradients immediately downslope of the road which contributed to the low numbers and volumes of fillslope landslides. The GXK road segment had only 2 fill failures with an average volume of 58 m^3, while the FG1 road had 12 failures with an average volume of 124 m^3. The WTW road segment, and especially the FG2, SFG1 and SFG2 segments, each had similar levels of cutslope and fillslope landslide erosion (Fig. 5). The greater than 4-fold increase in cutslope landslide volume in SFG2 (lower segment) compared to SFG1 (upper segment) is attributed the deeper road cuts into fractured bedrock in the lower segment (Fig. 3). Much fewer, but larger (mean mass = 96.6 Mg), failures occurred along rocky cutslopes of SFG2, while more, but much smaller (mean mass = 10.4 Mg) soil failures occurred along cutslopes of SFG1 (Table 2).

The distribution of all cutslope landslides ($n = 235$) was heavily skewed to small failures (< 5 m^3) (Fig. 6a). More than 88 % of all cutslope failures were < 100 m^3. In contrast, fillslope landslides ($n = 77$) followed a more Gaussian size distribution that was only somewhat skewed towards smaller failures (Fig. 6b). About 66 % of all fillslope failures were in the range of > 5 to 100 m^3 and less than 4 % were < 5 m^3. Very large (> 1100 m^3 or > 1430 Mg) landslides along cut and fillslopes comprised only 2 % and 5 % of the respective landslide numbers for these sites (Fig. 6). Nevertheless, the small number of very large (> 1430 Mg) landslides along cut and fillslopes contributed similar sediment mass (16 507–16 645 Mg), constituting 56.8 % and 43.6 % of the total respective landslide mass. All five of the very large cutslope failures occurred along FG1.

Overall the mean mass of individual fillslope landslides was four times higher than cutslope slides; an exception to this trend was FG1 with the five very large cutslope landslides. The widest difference between mean fill and cutslope landslide mass was at DXD – ratio of 11.6 (Table 2). DXD also had the largest mean mass of fillslope failures, partially attributable to the long, steep, and uniform slopes below the road (Fig. 4a). The sites with the smallest mean landslide masses along cutslopes were SFG1 and WTW (Table 2).

Overall there were about three times more cutslope compared to fillslope landslides, and cutslope landslides were more frequent than fillslope failures at all seven road segments (Table 2). SFG1 had the largest number of cutslope failures, but, as noted, these were small and constituted the second smallest landslide erosion rate of all seven road segments; DXD had a rather large number of sizable cutslope failures. WTW and GXK both had high numbers of landslides along cutslopes, but with small to intermediate mean masses (Table 2). Both DXD and WTW had the largest numbers of fillslope failures together with the highest sediment delivery estimates (Tables 1 and 2) – these sites were both proximate to a tributary and the main stem of the Salween River, respectively. Few fillslope failures occurred in FG1 and FG2, and especially in GXK. GXK was situated away from the river and the slope below the road was gentle containing rice paddy fields.

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4.3 Potential framework for sustainable development

As a solution to the landslide and associated environmental damages caused by inadequate attention to secondary road location and construction practices in this region we propose a more sustainable approach that assesses not only the perceived social and economic benefits of these roads, but also the long-term environmental and human welfare impacts. Many of the new roads are inoperable during the rainy season or require extensive excavation or maintenance to remain open (Figs. 2 and 7a). In the worst cases, partially completed roads were abandoned because of persistent landslides leaving a legacy of sedimentation problems with no socioeconomic benefits whatsoever (Fig. 7b). The prolific road-related landslides and associated riverine sedimentation that is occurring within the Salween River basin could push portions of this ecosystem to tipping points where thresholds are breached causing collapse of certain processes and functions. Impacts that could occur in the foreseeable future include: (1) extensive areas of degraded site productivity and altered vegetation due to landsliding; (2) degraded downstream water quality and aquatic habitat; (3) transport of contaminated sediments downstream; (4) alteration of the morphology of tributary streams and the main stem of the Salween River; (5) catastrophic debris flows in sediment-laden tributaries; (6) increased flood potential due to reduced channel transmission capacity; and (7) impacts on livelihoods and economies of water users in communities downstream. Some of these effects are already being realized in this region as documented in a nearby tributary of the Mekong River in Yunnan (Sidle et al., 2011).

Moving forward, there is an urgent need to develop a systems-based approach for more sustainable mountain road development before tipping points are reached in these ecosystems. In northwestern Yunnan, this would include detailed landslide hazard assessments prior to road planning and construction activities. Ideally, such analyses should identify the probability of exceeding landslide trigger thresholds (in this area, largely rainfall) coupled with estimates of decreased slope stability associated with different road locations and construction techniques (Fig. 8). This approach would allow

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for trade-offs between socioeconomic development and long-term environmental and human welfare impacts by articulating acceptable levels of landslide erosion, with an eye towards avoiding tipping points where site productivity, human welfare, ecological attributes, flooding, and aquatic habit are not compromised in the long term. Trade-offs for road development could include alternative locations and construction techniques, assessing "storm-proofing" roads vs. continual widening and maintenance, considering multiple road uses, incorporating climate change impacts, and reevaluating the necessity of the road. In particular, road location strategies can go a long way towards ameliorating landslide problems; these include: (1) optimize the expected lifetime of the road with uses; (2) ensure a balance of minimizing road length and minimizing steep gradients; (3) avoid deep cuts into unstable substrate (especially bedrock dipping parallel to the hillslope); (4) utilize valley bottom and ridge-top roads whenever feasible; (5) avoid seasonally wet areas (e.g., hollows); (6) reduce the width of midslope roads; (7) avoid crossing old landslides, particularly undercutting the toe or loading the head of dormant failures; (8) roll roads to fit hillslope contours and across drainage culverts; and (9) minimize stream crossings (Megahan et al., 1978; Sidle and Ochiai, 2006). Such a systems-based approach that considers all possible road uses and benefits against environmental and human welfare costs (Fig. 8) offers a much more robust and sustainable alternative.

Multi-criteria decision analysis has been applied to similar ecosystem sustainability challenges in which cost/benefit tradeoffs need to be assessed jointly among environmental, economic, and social objectives (e.g., Linkov et al., 2006; Macleod et al., 2007). Throughout much of mountainous Southeast Asia, benefits associated with secondary road development that need quantification include: (1) opening economic markets for goods and services produced in remote villages; (2) tourism opportunities; (3) access to hydroelectric generation facilities; (4) educational opportunities; (5) emergency evacuation; and (6) defense of national borders. Cost assessment associated with mountain road development should focus on: (1) environmental impacts of hydroelectric power facilities, increased tourism, and forest exploitation; (2) direct impacts of road-related

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landslides on settlements, sediment loads in rivers, water quality, and aquatic habitat; (3) loss of site productivity on hillslopes affected by landslides; (4) impacts of relatively clean and contaminated sediments in downstream water supplies; (5) effects on channel conveyance, flooding and potential debris flows; (6) siltation of existing reservoirs; and (7) environmental consequences of unintended forest exploitation (Fig. 8).

Successful implementation of multi-criteria decision analysis related to road development and associated environmental and natural resources planning in this region will require the engagement of diverse stakeholders with government planning agencies, donor organizations, and science experts. An important aspect of this analysis is the need to incorporate landslide risk associated with extreme events – i.e., storms or other triggers like earthquakes. Furthermore some of the consequences associated with ecosystem tipping points (e.g., floods, debris flows, vegetation changes, aquatic habitat degradation) require a probabilistic approach to assessment of risk. Ecosystem goods and services as well as environmental costs should be appropriately valued; in cases where environmental resources have no apparent market value, alternative techniques can be used (Gregory, 2000; Ananda and Herath, 2009). Inherent to the success of such a decision analysis is the concurrent engagement of government planning agencies that deal with road construction, river management, catchment management (including land use), aquatic habitat and biodiversity, and economic development to resolve inter-agency conflicts and consider relevant stakeholder opinions together with scientific expertise and evidence (e.g., Macleod et al., 2007).

5 Summary and conclusions

Our investigations of landslide erosion along seven different mountain road segments in the upper Salween River basin confirm findings from a prior study (Sidle et al., 2011) in a single tributary of the Mekong River near Weixi, Yunnan. The erosion rates measured along these seven unpaved mountain road segments (2780–48 238 Mg ha^{-1} yr^{-1}) are higher than the range documented (1410 to 33 450 Mg ha^{-1} yr^{-1}) along the newly constructed paved road near Weixi, Yunnan, indicating that such epic levels of landslide erosion and sedimentation are potentially widespread throughout the northern Yunnan region (albeit previously unreported). At four of the seven road segments, more than 74 % of the landslide sediment was estimated to be delivered to tributaries or the main stem of the Salween River. Landslide erosion measured along the road segment just south of Daxingdi (DXD; > 48 000 Mg ha^{-1} yr^{-1}) was the highest ever documented along a mountain road corridor.

At all sites, landslides on cutslopes were more numerous, but characteristically smaller than on fillslopes. Where hillslopes were very steep below the excavated road, landslide erosion from fillslopes was greater than from cutslopes. Although few numbers of large landslides (> 1100 m^3) were recorded, these contributed slightly less than half and slightly more than half of the respective total landslide masses from fillslopes and cutslopes. When blasting was used for road construction and when waste rock and soil were pushed onto steep side slopes, resultant fillslope failures routed large amounts of sediments into channels. In many cases, prudent planning and construction measures could have greatly reduced these landslides and the resultant sediment delivery. At most of these sites, road location and layout did not adequately consider avoidance of wet areas, the need for proper drainage, avoidance of deep cuts into unstable bedrock sequences, minimizing road width, and avoidance of steep and unstable slopes (particularly downslope of the road). With respect to construction, careful removal of earth materials with hydraulic excavators can greatly reduce the disturbed footprint of the road and waste material can be disposed at more stable sites or carefully compacted and incorporated into the road prism.

With the high level of road-related landslide sediment already being transported into the Salween River, a more sustainable approach is needed to assess future road system development. A decision tool is needed that includes a rather detailed analysis of landslide susceptibility based on how thresholds for landslide triggers (i.e., rain events) would be modified by various road locations and different construction techniques. In this systems-based analysis, one could assess trade-offs amongst socioeconomic benefits of road networks against costs of protecting long-term human welfare, environmental attributes, and site productivity. Multi-criteria decision analysis could be employed to properly assess the road-related sediment issue in the context of alternative practices and other land uses. This systems-based approach needs to be embraced by local governments, environmental groups, NGO's, and international organizations and donors who seem to be focusing almost exclusively on the socioeconomic benefits of roads in this developing mountainous region. Countries located downstream of China within the Salween River basin (Myanmar and Thailand), as well as the other two major river basins in Yunnan (Mekong and Jingsha Rivers – Thailand, Cambodia, Laos, and Vietnam), need a sufficient supply of clean water to support livelihoods and development. Trans-boundary sediment issues associated with recent road construction in Yunnan pose serious problems for downstream users. Clearly, a paradigm shift is needed to embrace the concepts of sustainability in conjunction with road development in northwestern Yunnan, as well as in other potentially unstable mountain environments.

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Table 1. Geographic information and landslide erosion data for the seven road segments surveyed in northwestern Yunnan.

Road description/ general location	Latitude/Longitude	Average elevation (m)	Road age (yr)	Surveyed road length (m)	Avg. road width (m)	Landslide depth (m)		Gradiate proximate to landslides (°)		Landslide erosion (Mg ha^{-1} yr^{-1})	Sediment delivery estimates
						Range	Avg.	Range	Avg.		
Hydropower road, 1 km south of Daxingdi DXD	26°01′20″ N 98°50′32″ E	990	1	862	7.28	0.3–2.8	1.24	38–71	48.6	48 238	86 %
Sand quarry road near Wa Tu Wa village WTW	27°05′58″ N 98°52′14″ E	1228	1.5	186	5.09	0.2–2.0	0.64	29–68	46.3	3458	82 %
Village road near Ganxiangke GXK	26°50′18″ N 98°53′06″ E	1448	1.5	808.5	4.70	0.15–2.5	0.62	19–57	40.2	4373	0 %
Village road near Fugong FG1	26°55′19″ N 98°52′02″ E	1204	3	783.5	6.49	0.15–3.0	0.70	38–55	45.4	12 966	79.6 %
Village road about 2 km north of Fugong FG2	26°57′07″ N 98°51′34″ E	1285	3	845.5	5.35	0.15–0.7	0.37	35–68	46.0	4502	74.5 %
Upper section of village road 45 km south of Fugong SFG1	26°39′22″ N 98°53′55″ E	1259	1	750	5.15	0.2–1.8	0.70	33–51	42.6	2780	53.3 %
Lower section of village road 45 km south of Fugong SFG2	26°39′22″ N 98°53′58″ E	1162	1	804	5.14	0.07–3.5	0.64	32–66	44.1	10 838	46.4 %

Table 2. Comparison of numbers and mean mass of landslides along cut and fill slopes of the seven monitored road segments.

Road segment	Number of landslides km^{-1} yr^{-1}		Mean landslide mass (Mg)	
	Cutslope	Fillslope	Cutslope	Fillslope
DXD	37.1	31.3	94.3	1099
WTW	35.8	32.3	13.9	39.1
GXG	44.5	1.7	45.7	75.7
FG1	12.3	5.1	612.0	168.1
FG2	15.0	3.5	75.3	360.8
SFG1	64.0	10.7	10.4	72.2
SFG2	29.9	12.4	96.9	215.9
7 Segments combined	33.5	11.8	123.7	495.7

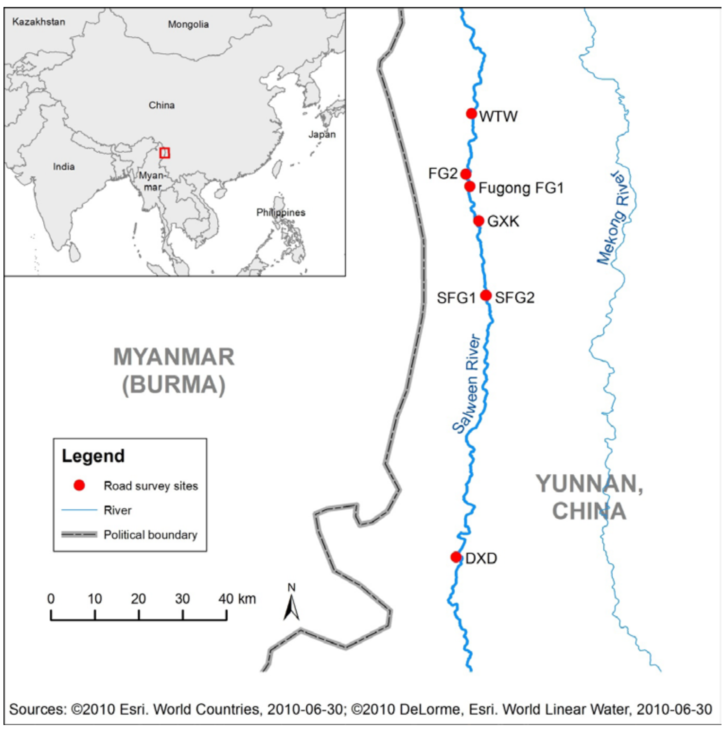

Figure 1. Map showing the general locations of the road survey segments within the Salween River basin. Given the recent construction of these unpaved mountain roads, no road network map is available. Map in the upper left corner shows the general location of the study area within China and the greater Asian region.

Figure 2. The highest landslide erosion occurred along a 1 yr old road (DXD) leading to a remote village and a future hydropower plant just south of Daxingdi, Yunnan, China.

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Figure 3. Road leading to a mountain village on the west side of the Salween River about 45 km south of Fugong. Upper portion of the road had (SFG1) the lowest landslide erosion of all surveyed segments, while the lower portion of the road (SFG2) had fewer numbers of, but larger, cutslope failures. Landslide erosion rates were significantly higher at SFG2 compared to SFG1 – 3.5 times higher for fillslope and 4.4 times higher for cutslope failures. Access bridge across the river is in the lower right corner of the photo.

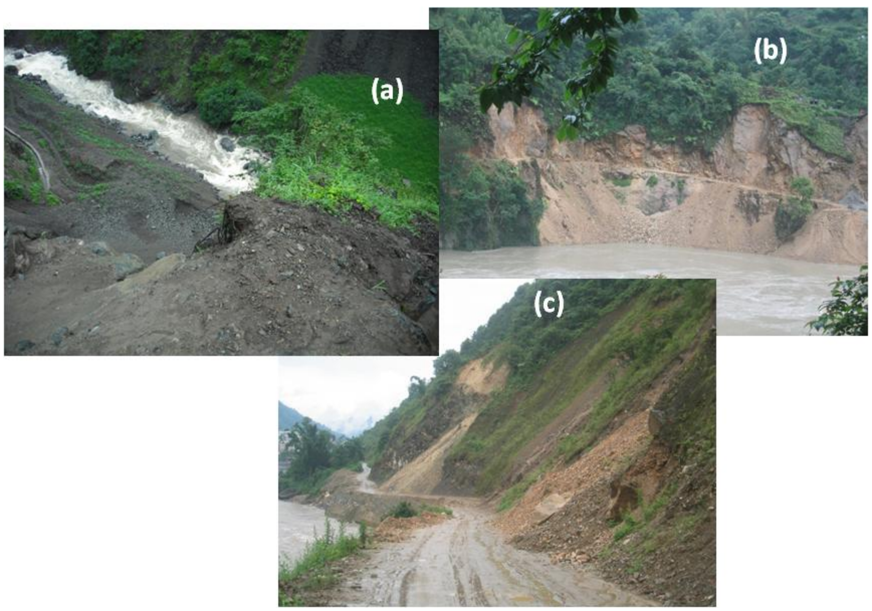

Figure 4. High rates of landslide sediment delivery to the Salween River from the: **(a)** DXD; **(b)** WTW and **(c)** FG1 road segments.

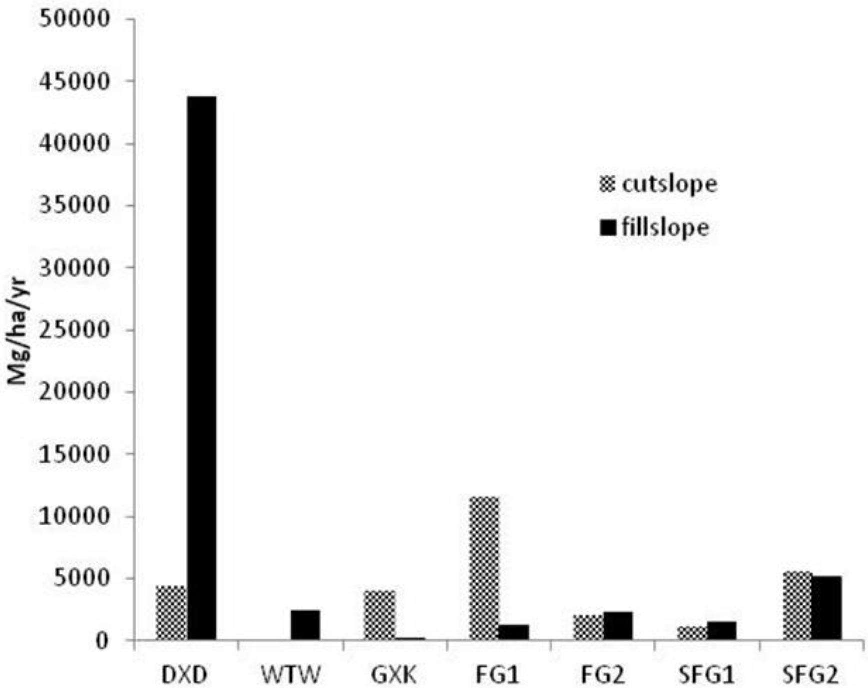

Figure 5. Landslide erosion from cutslopes and fillslopes for the seven surveyed road segments.

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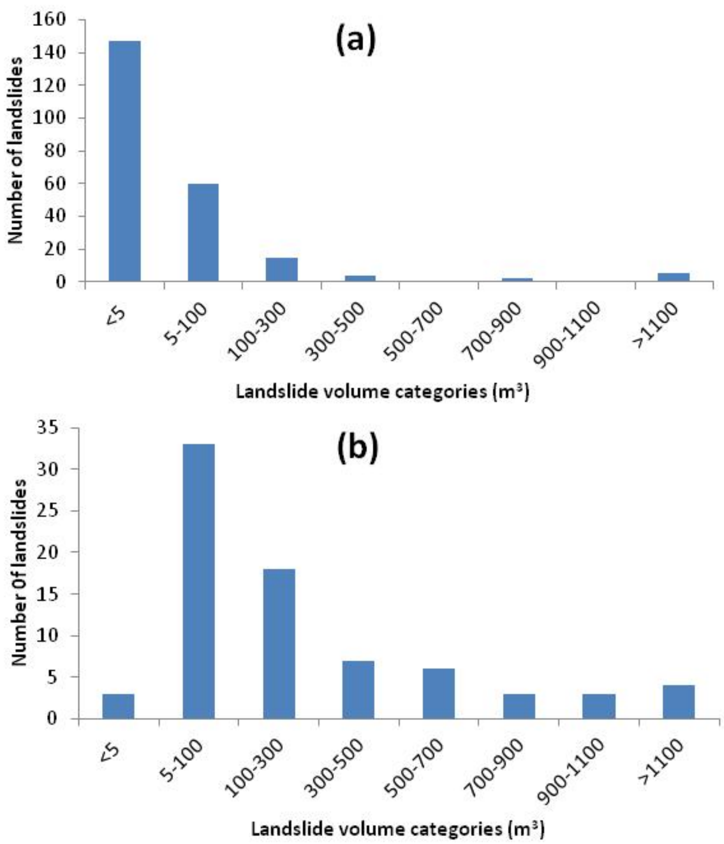

Figure 6. Size distribution for all surveyed landslides from **(a)** cutslopes ($n = 235$) and **(b)** fill-slopes ($n = 77$).

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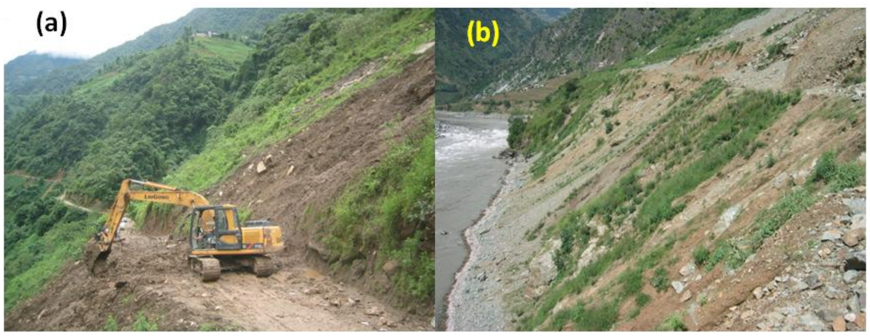

Figure 7. (a) A section of the FG2 road several kilometers north of Fugong that was temporarily closed by a landslide; and **(b)** secondary road to a small mountain village near Daxingdi (not included in our landslide survey) that was abandoned during construction because of excessive landslides.

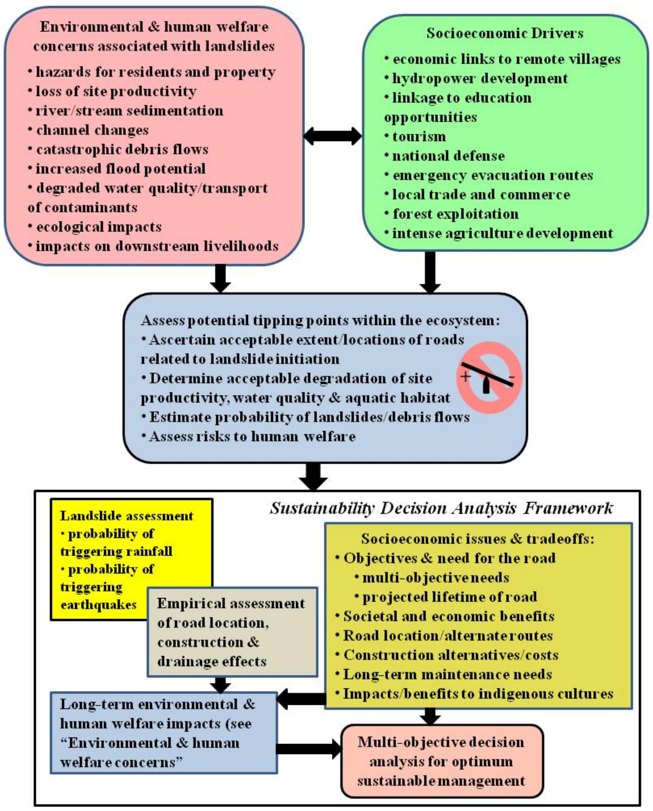

Figure 8. Decision framework for sustainability assessment of mountainous terrain in northwestern Yunnan, China, where extensive road construction is being proposed (modified extensively from Sidle et al., 2013).

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