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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;

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 northern 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 $\mathrm{Mg\,ha^{-1}\,yr^{-1}}$ (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 poorest 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 $\mathrm{Mg\,m^{-3}}$. For small cutslope and fillslope failures with estimated volumes > 1 $\mathrm{m^3}$ and < 3 $\mathrm{m^3}$, a volume of 2 $\mathrm{m^3}$ was used; failures ≤ 1 $\mathrm{m^3}$ 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).

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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 con-

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structed 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 ben-

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efits 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 %

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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

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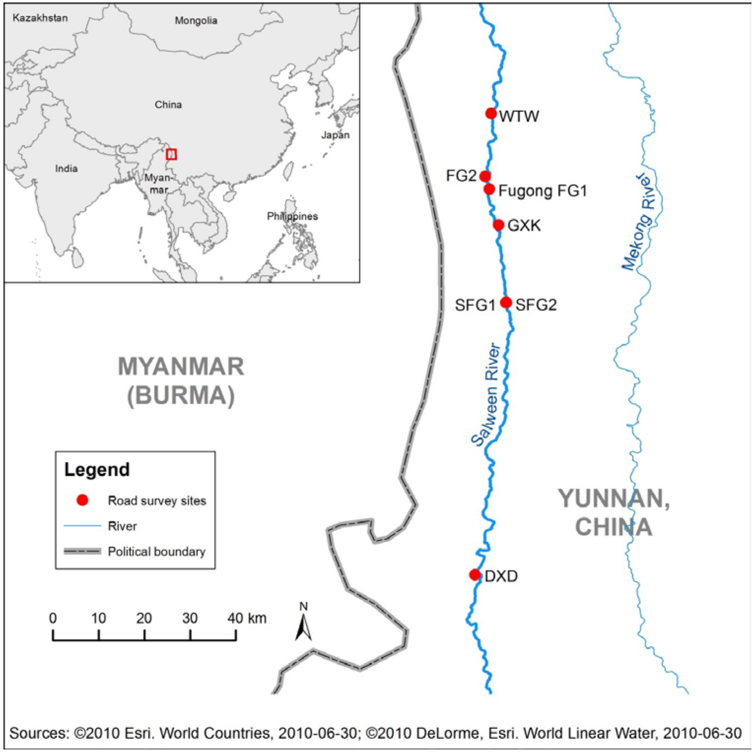

Figure 1. Map showing the general locations of the road survey segments within the Salween River basin. Given the recent construction of these unpaved mountain roads, no road network map is available. Map in the upper left corner shows the general location of the study area within China and the greater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

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.

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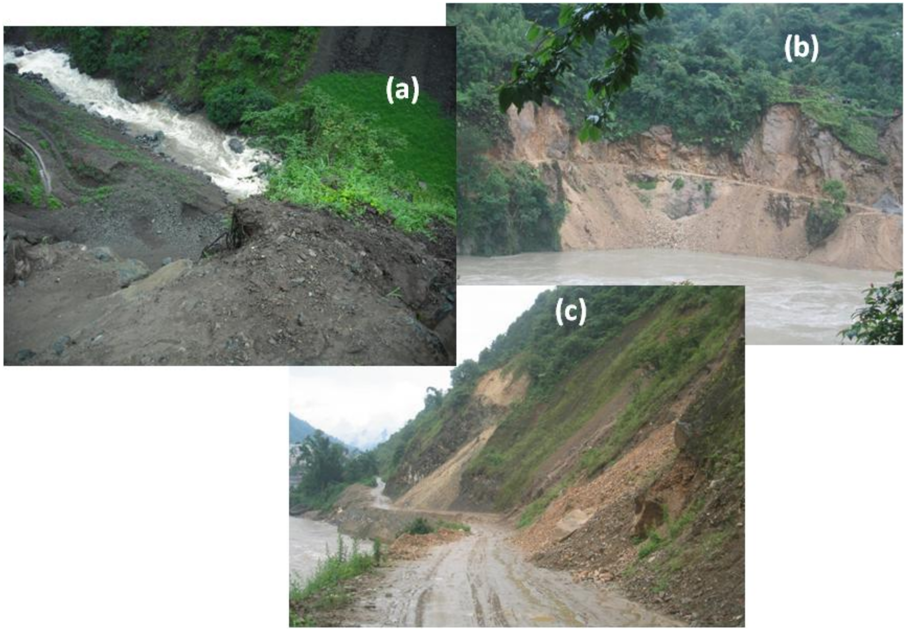

Figure 4. High rates of landslide sediment delivery to the Salween River from the: **(a)** DXD; **(b)** WTW and **(c)** FG1 road segments.

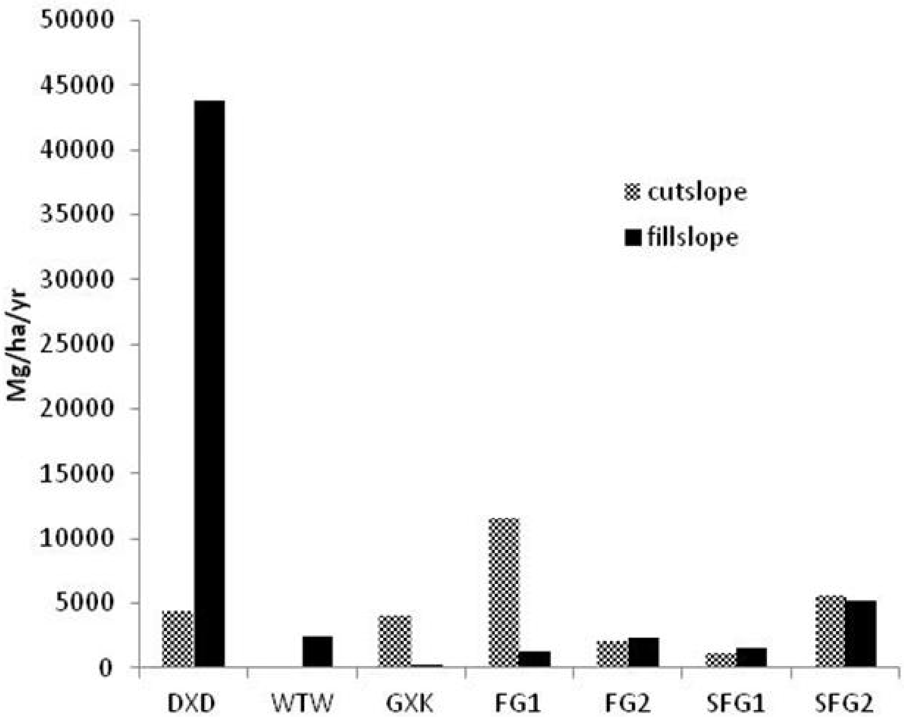

Figure 5. Landslide erosion from cutslopes and fillslopes for the seven surveyed road segments.

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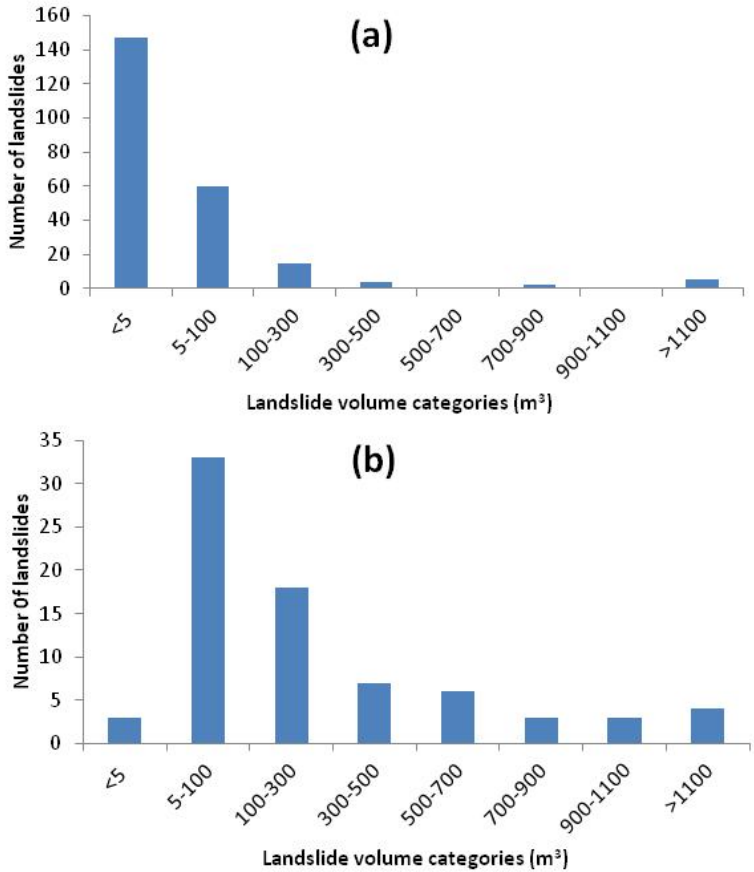

Figure 6. Size distribution for all surveyed landslides from **(a)** cutslopes ($n = 235$) and **(b)** fill-slopes ($n = 77$).

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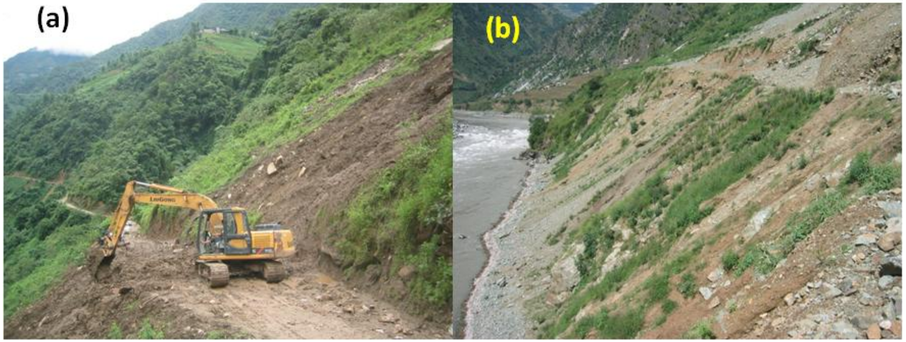

Figure 7. (a) A section of the FG2 road several kilometers north of Fugong that was temporarily closed by a landslide; and **(b)** secondary road to a small mountain village near Daxingdi (not included in our landslide survey) that was abandoned during construction because of excessive landslides.

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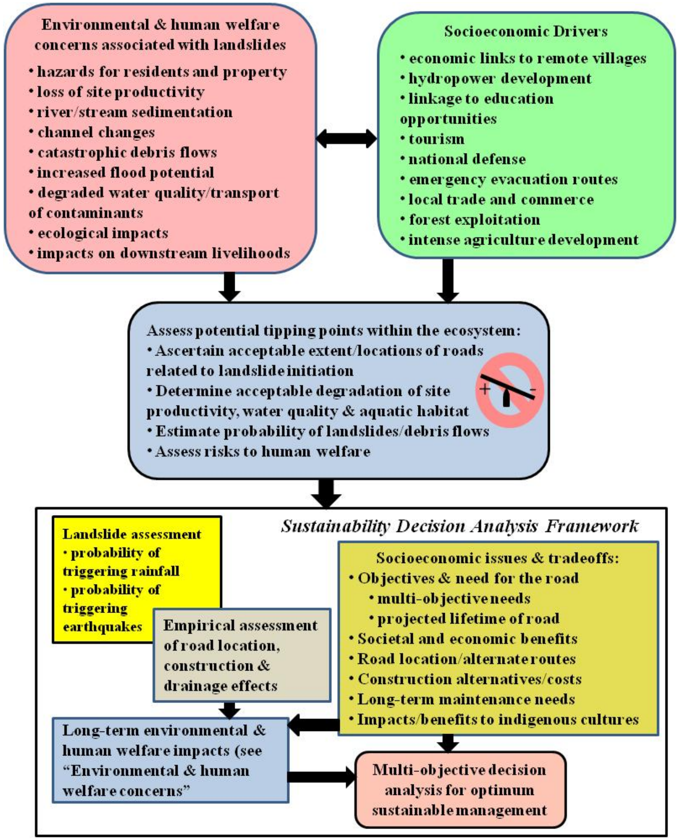

Figure 8. Decision framework for sustainability assessment of mountainous terrain in northwestern Yunnan, China, where extensive road construction is being proposed (modified extensively from Sidle et al., 2013).

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