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WHY WAS THE AUGUST 2010 ZHOUQU LANDSLIDE SO POWERFUL?

ABSTRACT. On August 8, 2010 in the northwestern Chinese province of Gansu, rainstorm-triggered debris flow devastated the small county of Zhouqu. A modeling study, using a new multiple-phase scalable and extensible geo-fluid model, suggests that the cause is the result of an intersection of several events. These were a heavy rainstorm, not necessarily the result of global warming, which triggered the landslide and followed a drought that created surface cracks and crevasses; the geology of the region, notably the loess covering heavily weathered surface rock; and the bedrock damage, which deepened the surface crevasses, inflicted by the 7,9 magnitude Wenchuan earthquake of May 12, 2008. Deforestation and topsoil erosion also contribute. The modeling results underscore the urgency for a high priority program of re-vegetation of Zhouqu county, without which the region will remain exposed to future disastrous, 'progressive bulking' type landslides.

KEY WORDS: progressive bulking, graded sloping, extreme precipitation, vegetation effects on storm-triggered landslides

INTRODUCTION

Landslides occur irregularly and future research is concerned with developing more accurate predictions about their timing (when), location (where) and size (how big they will be), and in developing procedures that convey risk and warnings to the public to mitigate loss of life and damage to infrastructure and ecosystems [van Asch et al., 2007; Casadei, Dietrich & Miller, 2003]. The storm season of 2010 saw landslides in Zhouqu China (August 8, 2010), Sikkim, India (August 27), and Guatemala (September 3). The question is if these events are a bellwether of an intensified water cycle as a consequence of climate warming [blogs.nature.com/news/thegreatbeyond/2010/08/mudychinafacingmorelandsl.html]? Or does the cause lie elsewhere?

A version of the SEGMENT modeling system, SEGMENT-Landslide [Ren, Leslie & Karoly, 2008; Ren et al., 2009; Ren et al., 2001], is used to investigate the Zhouqu debris flow of August 08, 2010, particularly the cause and possible future preventative actions.

The Zhouqu landslides were preceded by an extreme precipitation event which occurred around midnight of August 7, 2010 (Fig. 1). Both the precipitation intensity of 77,3 mm/hr near 104,42E, 33,78N, and total rainfall amount of 96,3 mm in 24 hours are the highest recorded for the period since the May 2008 Wenchuan magnitude 7,9 earthquake. From a longer perspective, the Zhouqu rainfall event had a 20-year probability of occurrence under the present climatology, considering ongoing, significant climate change. The hills around Zhouqu have been well-known for their long history of landslides [http://news.sciencenet.cn/htmlnews/2010/8/235921-1.shtm; Ma & Qi, 1997; p. 187 of Bolt, Horn, Macdonald & Scott, 1975]. However, this event is unique in its unprecedented magnitude, involving ~ 2,05×10^6 m^3 of sliding material. Because the landslide produced significant loss of life and great economic cost, it has generated intense discussion about the possible cause of the slide: 1. Previous drought conditions caused surface crevasses; 2. Unprecedented intense precipitation; 3. Wenchuan earthquake loosened slopes; 4. Historical earthquakes (century ago) and debris leftover; and 5. environmental consequences as population increases (living to previously un-occupied places). Climate warming often is seen as the major cause, by contributing to the severity

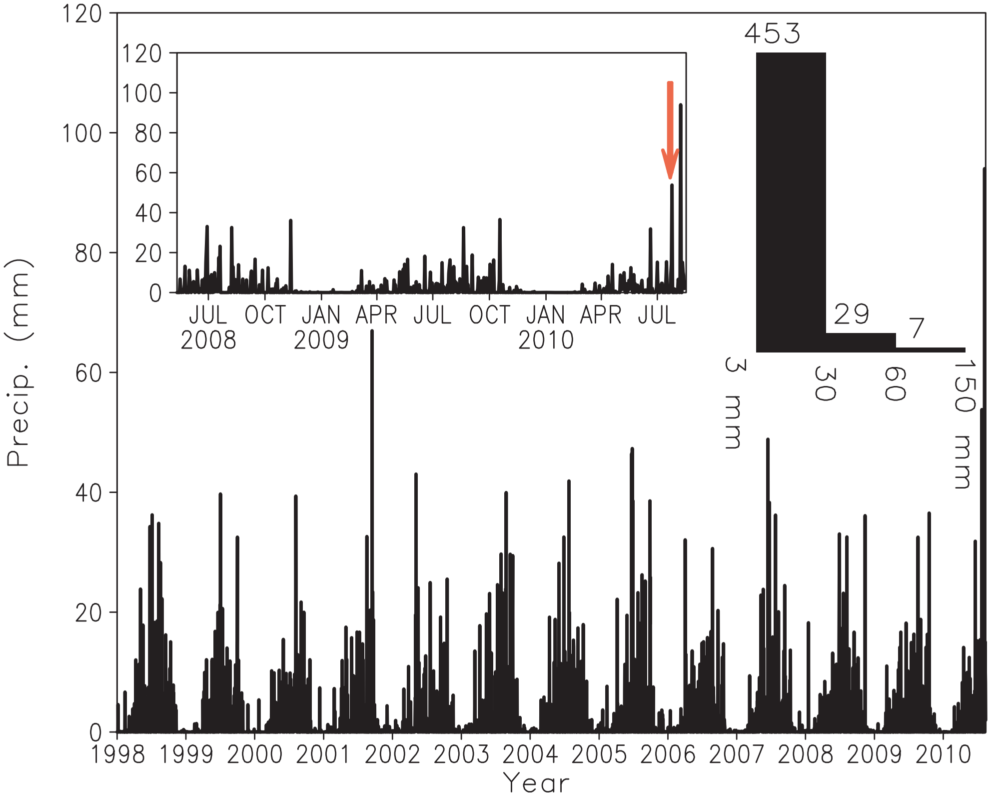


Fig. 1. The daily precipitation time series for Zhouqu (33.875N; 104.375E), for the period January 01, 1998 to August 20, 2010. These are estimated from TRMM (3B42V6, microwave-IR mixed products) 3-hourly precipitation. The last two months are from rain gauge measurements. The left inset is a zoomed-in of the period after the 2008 Wenchuan earthquake. The right inset shows the rainfall histogram based on the landslide triggering rain event analyses proposed by Ren et al. [2010]. Rain events with rainfall totals > 30 mm can trigger significant landslides in the Zhouqu region (see inset histogram). Moreover, in that period, there are 7 events with rainfall totals > 60 mm, which therefore are rainstorms as intense as that which preceded the August 7, 2010 Zhouqu mudslides (the event indicated by the red arrow in the left inset). Thus, extreme precipitation alone does not explain the magnitude of the Zhouqu mudslide

of the rainstorm; others argue that it was the recent drought, which produced cracks in the soil mantle. In addition to its geological uniqueness, because it occurred so soon after the 2008 Wenchuan earthquake, the presence of earthquake-broken bedrock also is cited as a factor contributing to the size of the landslide. A number of factors other than extreme precipitation therefore have been suggested as responsible for magnifying the Zhouqu landslide to its unexpected great size [Ma & Qi, 1997; Yu, Yang & Su, 2010].

To investigate quantitatively the relative importance of the possible causal factors, above-mentioned SEGMENT-Landslides model was applied to the event. SEGMENT-Landslide is a fully three-dimensional dynamical landslide model that incorporates not only soil/rock mechanical properties but also the hydrological and mechanical effects of vegetation on storm-triggered landslides. The model requires a wide variety of input variables, such as land cover, land use and geological data, which were provided by a research group of Beijing Normal University. The digital elevation data were from the Shuttle Radar Topography Mission, SRTM [http://srtm.mgs.gov/], at 90 m resolution. To reproduce historical landslides, we used precipitation forcing from the satellite-based National Aeronautic and Space Administration (NASA) Tropical Rainfall Measuring Mission (TRMM) which has 3-hourly data on a 0,25 by 0,25 degree resolution grid. For surface biomass loading, we used the Moderate Resolution Imaging Spectroradiometer (MODIS) products [Zhao & Running, 2010; Zhang & Kondragunta, 2006]. A team survey of the area also provided a 300 m resolution vegetation mask. To investigate possible mechanisms, we performed several sensitivity experiments with assumed vegetation conditions. Our selected region is 33,66–34,06°N; 104,26–104,66°E. The hilly terrain of this area is composed mainly of metamorphosed limestones, interspersed with altered clay layers. The ground surface rocks range from highly- to completely-weathered. The weathered rocks date from the Paleozoic (primarily the Permian period) and Mesozoic eras, the yellowish inter-bedded sandstone and siltstone date from the Silurian period, and the grey limestones dates from the Triassic period. The infiltration of rainfall through macro-pores, which are well-developed in the soil and rock mass of the Zhouqu region, plays a critical role in slope stability. The hills intersect with canyons in which increased erosion occurs during the highly regular rainy season.

METHODS

Landslides occur irregularly and future research is concerned with more accurate predictions about their timing (when), location (where) and size (how big they will be), and in developing procedures that convey risk and warnings to the public to mitigate damages to infrastructure and ecosystems. Such an effort is critical, particularly in anticipating the effects of climate change on areas prone to instability. Our study is a bellwether in this research direction as it uses a sound physically based predictive technique to assist understanding and informed decision-making. For mudslides, our model will help answer the following key questions. How and when will a particular landslide be initiated? How large will it be? How fast will it move? How far will it travel?

SEGMENT-landslides has been extensively documented by Ren et al. [Ren, Leslie & Karoly, 2008; Ren et al., 2011]. Here we present the governing equations to provide context for the above discussion. For the sliding material, we solved a coupled system for conservation of mass

$$\nabla \vec{V} = 0 \tag{1}$$

and momentum

$$\begin{cases} \dfrac{\partial \sigma_{xx}}{\partial x} + \dfrac{\partial \sigma_{xy}}{\partial y} + \dfrac{\partial \sigma_{xz}}{\partial z} = \rho \dfrac{du}{dt} \\ \dfrac{\partial \sigma_{xy}}{\partial x} + \dfrac{\partial \sigma_{yy}}{\partial y} + \dfrac{\partial \sigma_{yz}}{\partial z} = \rho \dfrac{dv}{dt} \\ \dfrac{\partial \sigma_{xz}}{\partial x} + \dfrac{\partial \sigma_{yz}}{\partial y} + \dfrac{\partial \sigma_{zz}}{\partial z} - \rho g = \rho \dfrac{dw}{dt} \end{cases} \tag{2}$$

under the granular rheological relationship, with viscosity parameterized as

$$v = \left(\mu_0 + \frac{\mu_1 - \mu_0}{I_0 / I + 1} \right) \frac{S}{|\dot{\varepsilon}_e|}, \tag{3}$$

where ρ is bulk density, $\vec{V}$ is velocity vector (*u, v* and *w* are the three components), σ is internal stress tensor, and *g* is gravity acceleration. Here ν is viscosity, *S* is the spherical part of the stress tensor σ, μ_0 and μ_1 are the limiting values for the friction coefficient μ, $|\dot{\varepsilon}_e|$ is the effective strain rate and $|\dot{\varepsilon}_e| = (0.5\dot{\varepsilon}_{ij}\dot{\varepsilon}_{ij})^{0.5}$, I_0 is a constant depending on the local slope of the footing bed as well as the material properties, and *I* is inertial number defined as $I = |\dot{\varepsilon}_e| d/(S/\rho_s)^{0,5}$, where *d* is particle diameter and ρ_s is the particle density. Soil moisture enhancement factor on viscosity is assumed varying according a sigmoid curve formally as Eq. (9) of Sidle [1992] but with the time decay term replaced by relative saturation.

For considered granular material resting on vegetated slopes, the cohesion provided by the roots are implemented in the full internal stress σ's. The root mechanical properties are prescribed according to the vegetation types of the Zhouqu area. There are different ways to decompose the full stress into spherical and deviatoric components. Only the deviatoric part is assumed to proportional to the strain rate through viscosity, which unfortunately depends also on normal pressure.

As a derivative from Eq. (1), the prognostic equation for surface elevation (*h*(*x, y*)) is

$$\frac{\partial h}{\partial t} + (\vec{V}\nabla_H)|_{top} h - w|_{top} = 0 \tag{4}$$

where $X|_{top}$ indicates evaluated at the free surface elevation. In the case with slope movements, Eq. (4) is solved regularly to update the sliding material geometry. It is also from this equation that we estimated the sliding material involved in the simulated landslides (e.g., Fig. 4).

The viscous term in Eq. (2) implies an energy conversion from kinetic energy to heat. To make a full closure of energy, we need the following thermal equation:

$$\rho c \left(\frac{\partial T}{\partial t} + (\vec{V}\nabla)T \right) = k\Delta T + \frac{2}{\nu}\sigma_e^2 \tag{5}$$

where ***c*** is heat capacity (J/kg/K), ***T*** is temperature (K), κ is thermal conductivity (W/K/m), and σ_e is effective stress (Pa). The last term is 'strain heating', converting of work done by gravity into heat affecting the sliding material by changing viscosity or causing a phase change.

For quantitative predictions of storm triggered landslides, a numerical modeling system like SEGMENT is needed. However, some of the requirements of SEGMENT, especially the input and verification data, generally are not available even in modern geological maps. These parameters include vegetation loading and root distributions in soils and weathered rocks. The extension of the SEGMENT landslide model to other regions is limited primarily by the lack of these high resolution input datasets. The landslide features implemented in SEGMENT, if adopted by the relevant community, hopefully will encourage the collection of such vital information in future surveys.

RESULTS

Figure 2a shows the SEGMENT-Landslide simulated unstable areas, as indicated by the maximum obtainable surface sliding speed. Under the current vegetation regime, the most significant scar is that near the Sanyanyu Valley (33,81–33,87N; 104,36–104,42E). The particular sliding is a characteristic "progressive bulking" [Iverson, 1997] type (Fig. 3). The accumulation area spreads up to 3500 m elevation, in a fan shape with the fan "handle" extending down to the Bailongjian River. The surface runoff essentially is clear water above the 3500 m elevation contour, but at lower elevations gradually becomes turbid and entrains small stones and coarse granular material into the slide streams. These creeks are usually dry except during rainy periods. Figure 4 is an enlargement of the Sanyanyu gully, showing

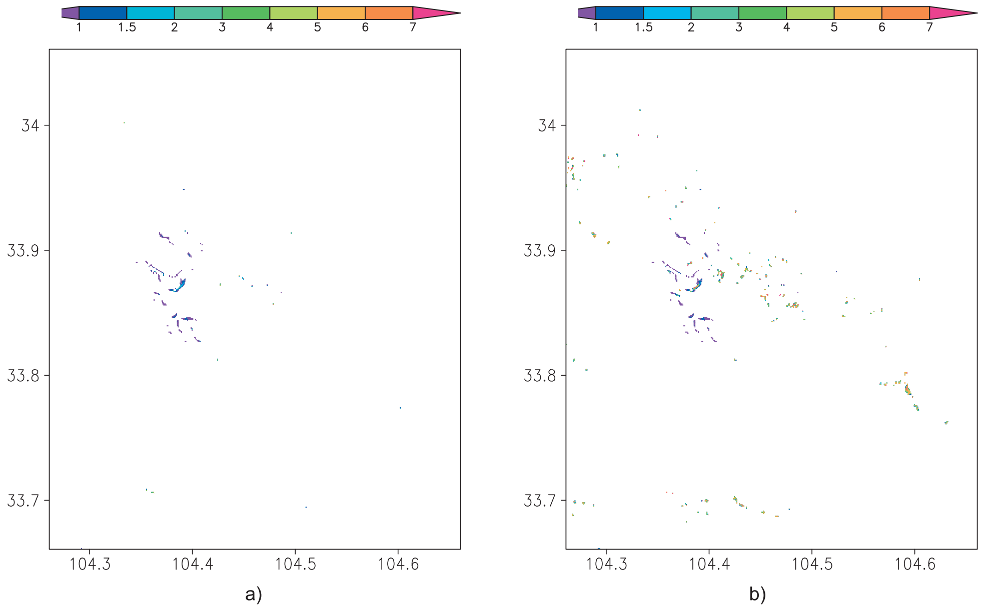


Fig. 2. A detailed comparison of the unstable areas identified by the landslide model. These are areas for which model sliding speeds (m/s) exceeded the threshold value. Panel (a) is with current vegetation. Panel (b) is with vegetation removed. Under current vegetation conditions, only the Sanyanyu area is unstable. When the vegetation is removed, there are many other unstable areas. Moreover, the landslide flow magnitudes are larger than for the vegetated case

the surface elevation changes at two times in the sliding process: the beginning (Fig. 4a) and the cessation (Fig. 4b). At the cessation, the areas indicated by the two red arrows have little elevation change, despite the massive total mass in the slide. They acted like a pathway for the sliding materials at higher elevations. For example, at point A there is a break in the slope where some of the sliding material originated. Over 70% of the sliding material came from the gully banks. Below 2300 m, the solid form of sliding material is continuous in nature and the entrainment effects are so significant that boulders (>50 cm

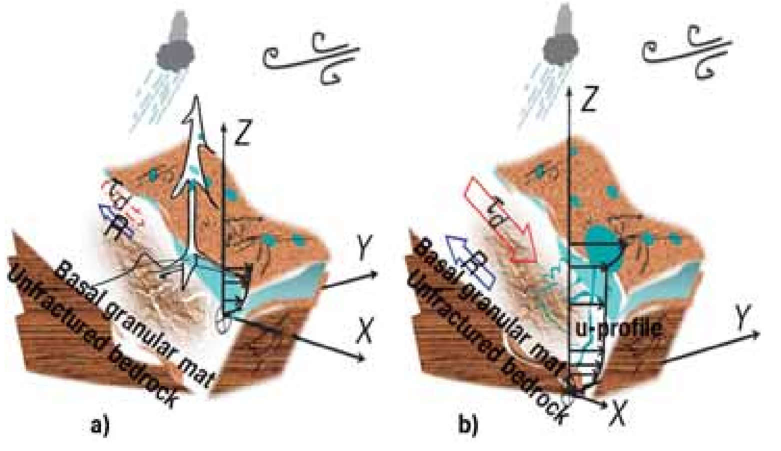
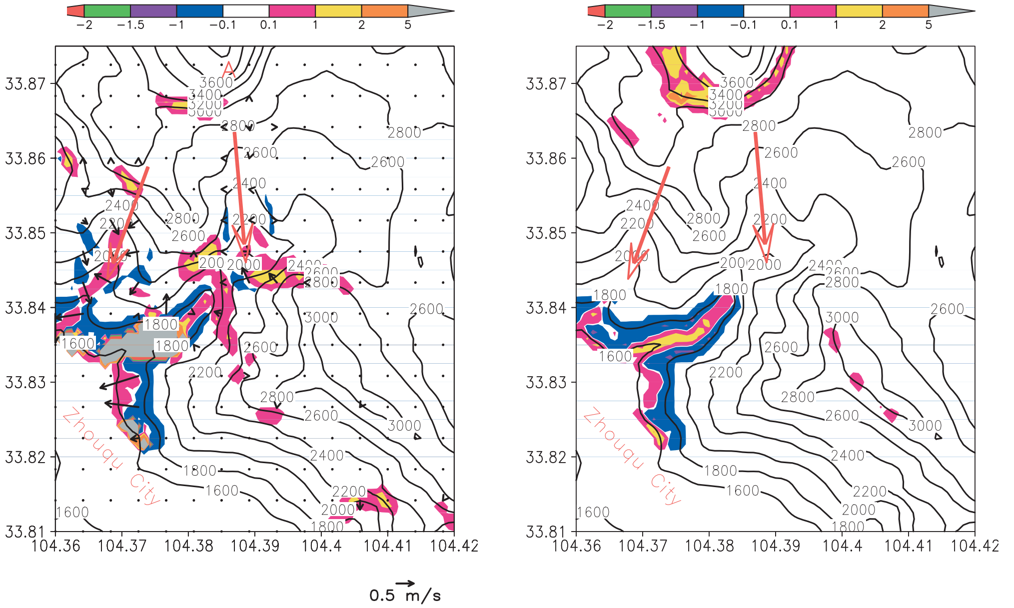


Fig. 3. A characteristic storm-triggered landslide (debris flow). This is a plane view of the entire (solid material) collection basin. The elevation divisions are only for reference. The section with concentrated solid material creeping is only a small portion of the entire area. This means of mass redistribution is referred to as "progressive bulking"



a) b)

Fig. 4. The Sanyanyu gully area. Panel (a) shows the elevation changes (m) in color, at 9 minutes after the August 7th heavy rainfall event. Mud sources are clearly shown in the left panel. Its final deposition is shown in Panel (b) approximately an hour later. The flow has ceased and the deposition is in the Zhouqu city area, via the two parallel gullies. Elevation changes of the creeks (two red arrows) are small and act primarily as pathways for the sliding material. Note the break/failure of the 3400 m elevation contour, indicating the provision of sliding material for the next sliding cycle

in diameter) are relocated down the slope. The thick mud has a viscosity of about 100 Pa•s and the peak sliding speed reaches as high as 2 m/s. A total of 2,05×10^6 m^3 of solid sliding material was involved in this slide and was spread over an area of about 3,2×10^6 m^2.

Figure 4 uses the actual vegetation coverage of the area. If we assume the entire region is bare of vegetation, SEGMENT-Landslide identifies the following “hot-spots” as unstable (Fig. 2b): (33,773N, 104,375E); (33,347N, 104,412E); (33,77, 104,35), (33,79, 104,38) and (33,965, 104,105). In reality, only the Sanyanyu Valley slid significantly. The model makes it clear that the light vegetation cover over Sanyanyu is the main reason for such a large scale outbreak of debris flows. In turn, the light vegetation cover may have arisen from a positive feedback inherent in successive historical landslide deforestation [e.g., Bolt, Horn, Macdonald & Scott, 1975]. Repeated landslides, usually of smaller scale, were investigated in SEGMENT-Landslide simulations using historical TRMM archived precipitation. They show that the rainy seasons of 1998, 2001, 2008 and 2009 all produced landslides capable of destroying the existing vegetation cover. Lighter vegetation cover lowers the criteria for subsequent landslides. This self-propagating mechanism has no lower limit before leveling the slope to below the granular material repose angle.

In the Zhouqu area, the shear zone depth is variable and depends on the quantity of water penetrating into the crevasses. For bare ground (e.g., covered by previous landslide deposits or rockfalls caused by historical earthquakes), runoff readily drains into the crevasses, moistens the granular material and forms a shear zone at the bottom (the lowest reaches of the crevasses). Vegetation cover reduces surface runoff through canopy

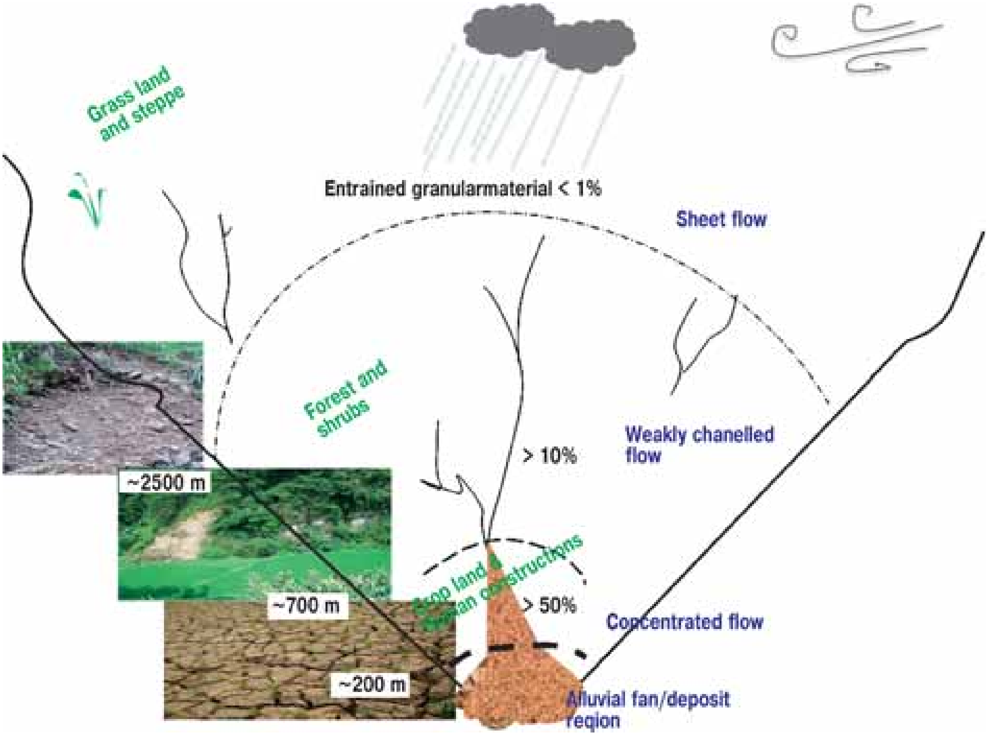


Fig. 5. Diagram showing vegetation effects on storm-triggered landslides. Panel (a) is the case with vegetation and panel (b) is the case void of vegetation. All else being equal, with vegetation, a proportion of rainfall goes into canopy interception (canopy runoff) and runoff and surface ponding are reduced as a consequence. Vegetation also effectively prevents water infiltration into deeper depth. Thus less sliding mass is involved in the vegetated case (the blank arrows show the magnitude of bulk resistive and driving stresses). In the illustration, *R* means resistive stress and τ_d means driving stress

interception. Roots also assist in the retention of water within the rhizosphere. Thus, with vegetation cover, runoff water cannot be effectively channeled into the crevasses and much less sliding material will be involved in the landslide (Fig. 5). The cohesion of the granular particles (loam soil, pebbles from fractured grey lime-stones, and sands) are of the order of 0,1 Kpa, far less than the root strength (~10 Kpa).

The presence of aboveground vegetation introduces the following effects: aboveground biomass loading (gravitational), growing season soil moisture extraction by live roots (hydrological), fortification of the soil within its extension range (mechanical), changing chemical environment of the soils through life processes (e.g., respiration, absorption of minerals selectively and secretion of organic substances) and therefore the bond strength among unit cells (chemical), and wind stress loading (meteorological). The overall effects are the interaction of the above factors and it is difficult to generalize before a detailed analysis is carried out that is specific to a certain situation. For example, the fortifying roots have yield strength larger than dry soils and the existence of roots is commonly thought to increase the resistance of soils. However, the presence of roots, especially when there is precipitation, also facilitates water channelling into deeper depths. After the soil is moistened, the cohesion between soil and the root surface is reduced greatly (to negligible strengths <0,001Mpa, [Lawrence et al., 1996]) and the root strength cannot be effectively exerted. Also, the effect of roots is to 'unify' the soil particles within root distribution range. Once the entire rhyzosphere soil layer is saturated, the fortifying effects will be totally lost.

Table 1. Root strengths of two plants growing in similar environmental conditions [Cartina, personal communication 2012]. Samples are taken at Duron Valley (46° 29′37′′ N, 11° 39′25′′ E) of Italy

	Root type	Diameter (mm)	Failure tensile force (kg)	Deformation ratio (%)	Tensile strength (MPa)
Juniper	Ephe. Absorb	2.9	1.9	3.9	2.87
	Woody trans.	8.6	140	3.7	24
	Structural	12.1	130	2.8	11.3
Swiss Stone Pine	Ephe. Absorb	5.1	21.6	3.6	10.5
	Woody trans.	9.3	120	6.8	17.6
	Structural	12.6	169	2.8	13.5
	Structural	13.9	195	8.8	12.9

Thus, a more accurate statement would be "the reinforcement effects from roots are an effective mitigating factor for shallow storm-triggered debris flows". It is known that shallow interlocking root networks can contribute to mechanical reinforcement to soils [Sidle et al., 1985; Selby, 1993; Lawrence et al., 1996]. For a pasture species, Selby [1993] estimated the 'additional' cohesion ranging from 0,1 to 9,8 kPa, with changes in soil moisture. There are also experimental tests on root strength for a variety of species (Table 1).

In SEGMENT-Landslide, because roots occupy a small fraction of the soil volume, the root reinforcement can be factored in as an added stress over the case of no root presence. As not only tensile strength but also the cross-sectional areas (thickness of roots) are critical, we propose the following 'allometric' approach that uses 'root weight density' and vegetation type to characterize the added tensile strength to the soil medium shear strength and elevated yielding criterion.

$$\sigma^{+} = C_{smc} \sum_{i=1}^{3} \sigma_i F_i(NPP, I_{veg}, Pa, T_{air}) \qquad (6)$$

where σ^{+} is the root mechanical reinforcement (kPa), C_{smc} is soil moisture control (0–1), index i differentiates woody transport roots, woody supporting roots and ephemeral absorbing roots, σ_i (kPa) is a root species-dependent reference value (i.e., tensile strength of xylem of roots, varies from 10 to 30 MPa for most plants), NPP is net primary production (kg/m^2/yr), P_a is annual precipitation, T_{air} is annual mean air temperature, and I_{veg} is species-dependent reference NPP value. F varies from 0 to 1 represents the weight fraction of roots in a unit volume of soil (within range of influence of the roots). Value of F usually is close to 0,2%. The functional form of C_{smc} can be tabulated according to soil type. The modifications from climate conditions are necessary because same plants have very different strategy in allocating biomass when living in different clime zone.

Thus the mechanical effects of the roots also contribute to slope stability. We performed an additional set of sensitivity experiments to further investigate the importance of vegetation in reducing the magnitude of landslides. If the Sanyanyu Basin had been covered 70% by shrub of negligible biomass loading, with root strength of 0,1 Mpa, and coarse root (diameter >1 mm) density of 2 m^{-2} all residing within the top 2 m of soil, the amount of sliding material would be only 1,1×10^6 m^3, or about half the actual volume involved. If there is a closed cover (that is, 1,0 vegetation fraction), the sliding material can be further reduced to 10^4 m^3, and primarily involves only pebbles and protruding boulders at lower elevations. These experiments underline the critical role of vegetation in reducing the magnitude of the "progressive bulking" types of storm-triggered landslides.

Importantly, loss of vegetation has occurred not in recent 10 years and there actually

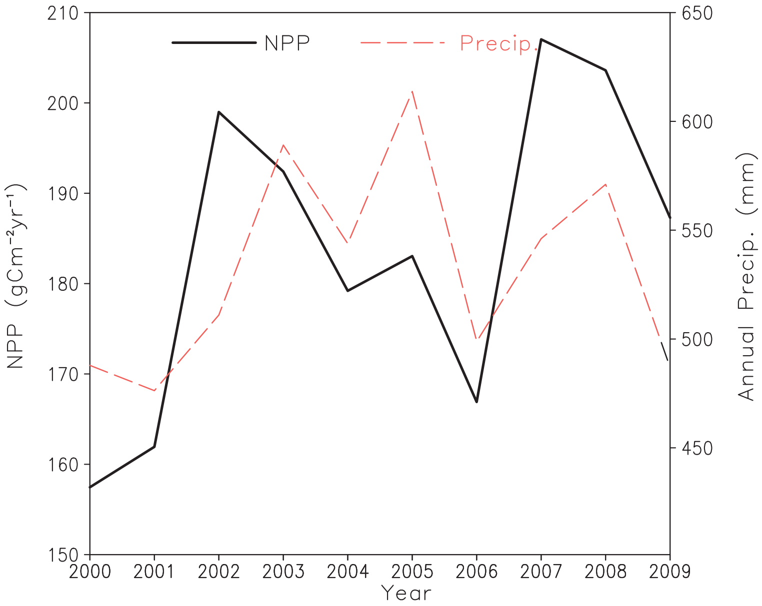


Fig. 6. The annual Net Primary Production (NPP) and precipitation over the past decade for the region of interest (33.66-34.06N; 104.26-104.66E). The 1 km resolution MODIS NPP products are obtained from M. Zhao. Precipitation data is from gauge station near Zhouqu (data obtained from Beijing Normal University). NPP quantifies the amount of atmospheric carbon fixed by plants and accumulated into ecosystem as biomass. Upward trend in NPP indicates a healthy ecosystem (vegetation is getting denser or in growing stage) or climate constraints getting relaxed. As expected, NPP match closely with annual precipitation. Discordances in 2002 and 2008 may correspond to landslide disturbance of the vegetation. The 2008 perturbation possibly is related to the Wenchuan earthquake. In the past decade, the NPP has a rising trend, indicating the vegetation cover is gradually becoming denser

are clear signs that local vegetation cover has been increasing (Fig. 6, also in [Zhao & Running, 2010]). Because the 2008 Wenchuan earthquake has deepened the crevasses within the soil mantle and the bedrock, the criteria for storm-triggered landslides are significantly lowered. Large landslides did not occur before 2008 because, previous storms, although can be equally intense and have even larger total amount (e.g., Sept. 4, 2001), could not infiltrate into deeper shear zone, without the help of the earthquake's tearing of the bedrocks. Large landslides did not occur during the past two years because the threshold precipitation intensity and total was not reached (the past two years are relatively dry as indicated by total annual precipitations: 500 for 2008 and 480 mm for 2009 respectively, see Fig. 6). The landcover in August 2010 therefore was unable to prevent landslides caused by an intense rainstorm, owing to the legacy of the 2008 Wenchuan earthquake. The sealing of the cracks caused and/or deepened, by the Wenchuan earthquake is slow process occurring on a timescale of several decades. Thus, a program of rapid restoration of the vegetation cover over the Zhouqu area is urgently required for re-building that region. The climate of that region, with an annual precipitation over the last 40 years is only 435 mm/yr, suggests the priorities are the restoration of forest on the north facing slope and of a seamless grass cover for the south facing slopes.

The Sanyanyu deep valley has much coarse granular sliding material, particularly stones and boulders, because of a self-accumulation mechanism originating from its specific topographical features and because its loamy soil mantle is more easily dissected by running water. Topographically, the creeks in the valley have 'graded river beds' because the upper parts (near peaks) are steeper than the lower parts (close to the toes).

Thus the upper river bed slopes are larger than the lower river bed slopes. For lighter precipitation events, the stones and pebbles cannot roll directly to the toe, stopping at mid-slope and creating natural barriers to the sliding material that follows (see the red blobs in Fig. 4). These accumulations apply to small slides, typically caused by low to moderate precipitation events. They have occurred at least five times during the past two years: in August, 2008; May, 2009; June, 2009; July, 2009; and September, 2009. However, when intense precipitation occurs, as in August 2010, all accumulated material will be activated and a disastrous event will be generated. Recent studies (Ma & Qi, 1997; Yu, Yang & Su, 2010) indicates that granular material accumulated after the 1879 Wenxian earthquake [Bolt, Horn, Macdonald & Scott, 1975] was involved as the major debris. This supports the progressive bulking mechanism. Because previous landslides, lacked the unfortunate combination of the rainfall intensity, earthquake and poor vegetation coverage, they fail to move the solid material of the Wenxian earthquake to the Bailongjian River.

DISCUSSIONS

On August 8, 2010 in the northwestern Chinese province of Gansu, 1765 people died or lost when a debris flow devastated the small county of Zhouqu. Our modeling study suggests that the cause is the result of an intersection of natural and human-induced events. The natural events include a heavy rainstorm, not necessarily the result of global warming, which triggered the landslide and followed a drought that created surface cracks and crevasses; the geology of the region; and the bedrock damage, which deepened the surface crevasses, inflicted by the 7,9 magnitude Wenchuan earthquake of May 12, 2008. The human contribution was historical (before 1990) deforestation and topsoil erosion. Consequently, Zhouqu became vulnerable to a devastating rainstorm-triggered landslide. The model confirmed the cause of the landslide by producing a rain-triggered mudslide far larger than historical landslides. The landslide was magnified by prior vegetation loss and by water penetration deep into the cracks and crevasses created by the Wenchuan earthquake. The recent findings [Ma & Qi, 1997; Yu, Yang & Su, 2010] that solid granular material from a historical earth quake 130 years ago was involved in the debris flows further confirm our hypothesis. It is not that the rainfall intensity is of 100 year recurrence frequency (it actually is only of 20 year recurrence frequency, according Generalized Extreme Value analysis, a likelihood of 42% occurrence in the upcoming 10 years), but because the combination of strong precipitation with poor vegetation and recent earthquake enhancement of the crevasses is lacking in the past century. Previous debris flows, of smaller scale, fail to transport the granular deposits to stable locations. It also reflects the difficulty in re-vegetating the landslide scarps and even the granular deposits for the region, due to the climate.

The massive Zhouqu landslide of August 2010 was caused by an extreme precipitation event, but was magnified by the Wenchuan earthquake of May 2008 which greatly deepened the pre-existing cracks (either from historical earthquake or more gradual erosion processes) in the ground surface. For such surfaces, intense precipitation events favor the channeling of runoff water to greater depths than usual, creating sliding surfaces at those depths. Thus, more sliding material was involved than for a less intense rainstorm. Vegetation is very effective at holding drainage water in the rhizosphere and reducing drainage into deeper levels, but the severe vegetation loss in the Zhouqu region prevented the vegetation cover from playing a protective role in reducing the critical impact of the hydrological process of deep level drainage.

The modeling results underscore the urgency for a high priority program of re-vegetation of Zhouqu county, without which the region will remain exposed to future disastrous, 'progressive bulking' type landslides. A direct cause of the large magnitude of the 2010 debris flow is the loss of historical deposits and the undercutting of loose gully bed. Re-vegetation of the areas with historical deposits is a priority. Thus, engineering approaches, such as installing check dams, slope protectors, and leveling gullies, should be followed by re-vegetation, because, restoring the current vegetation cover to its natural, much denser state is the most effective long-term approach to landslide mitigation.

CONCLUSION

The Earth's climate currently is in an interglacial period that possibly will continue for another 50 kyr [Berger & Loutre, 2002] without human alteration. Since the 1970s, however, the Earth's climate has steadily warmed and shows no signs of slowing. With the enhanced hydrological cycle [Ren et al., 2011], more extreme weather conditions are expected. The precipitation has a 20-year recurrence frequency, as calculated from projected climate change. A disaster of the same magnitude as 2010 is expected within ~20 years if no effective counter measures are taken.

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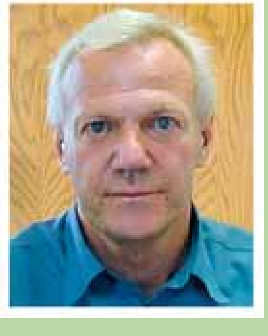

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