Debris flow susceptibility mapping at a regional scale along the National Road N7, Argentina

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ABSTRACT

A first assessment of debris flow susceptibility at a large scale was performed along the National Road N7, Argentina. Numerous catchments are prone to debris flows and likely to endanger the road-users. A 1:50,000 susceptibility map was created. The use of a DEM (grid 30 m) associated to three complementary criteria (slope, contributing area, curvature) allowed the identification of potential source areas. The debris flow spreading was estimated using a process- and GIS-based model (Flow-R) based on basic probabilistic and energy calculations. The best-fit values for the coefficient of friction and the mass-to-drag ratio of the PCM model were found to be $\mu = 0.02$ and M/D = 180 and the resulting propagation on one of the calibration site was validated using the Coulomb friction model. The results are realistic and will be useful to determine which areas need to be prioritized for detailed studies.

RESUMEN

Se realizó un primer estudio de susceptibilidad a los flujos de detritos a escala regional a lo largo de la Ruta Nacional N7 (Argentina), donde numerosas cuencas producen flujos de detritos afectando la ruta. Se utilizó un modelo de elevación digital con una resolución de 30 m y tres criterios para discriminar las áreas fuentes (pendiente, área de aporte y curvatura del terreno). El recorrido de los flujos de detritos se estimó con un modelo basado en SIG (Flow-R) utilizando algoritmos de probabilidad y de energía. Se eligieron dos de los mejores valores (μ = 0.02 and M/D = 180) para el coeficiente de fricción y el "mass-to-drag ratio" del modelo PCM, estos a su vez fueron validados con el modelo de fricción de Coulomb. Los resultados son coherentes y ayudan a definir las áreas que necesiten un estudio más detallado.

1 INTRODUCTION

The National Road N7 crosses Argentina from East to West, linking Buenos Aires to the Chilean border. This extremely important corridor goes through the Andes Cordillera and meets widely varying terrains and complex geological landforms whose instabilities can impact the highway infrastructure. The study area is located in the Mendoza Province, between Potrerillos and Las Cuevas, next to the Chilean border (Figure 1). Debris flows are one of the most active processes and represent a potential risk for the road-users. The regional commerce suffers significant economic loss when the road is closed for periods that can last several days. In the last century the road and the villages have been affected by several debris flows, which cut the road path, destroyed bridges and hit vehicles.

According to historical records in 1975, 1980, 1998, 2003, 2005 and 2006 debris flows events reached the road in the Río Mendoza valley, even though it doesn't exist good registers for all debris flow events along the highway. Depending on the road stretch, 1720 to 2750 vehicles travel between Potrerillos and Las Cuevas daily (Vialidad Nacional, 2009).

Some previous studies already focused on landslides in this region. An inventory map proposed by Moreiras (2009) shows that 79 % of landslides in the Río Mendoza and Las Cuevas valley are debris flows. Mergili et al. (2010) used their own model for simulating debris flows to some selected study areas along the road. A recent study focuses on the events of January 2005, when heavy rainfalls triggered debris flows near the "Guido station" and swept away a car whose occupants were injured (Wick et al., 2010).



Figure 1. Location of the study area and calibration sites (1-4). Detailed field investigations were performed along the stretches A and B. Modified after ESRI and Google Earth.

The purpose of this study is to perform a regional mapping of debris flows susceptibility along the Road 7 corridor using modern remote sensing documents and numerical models completed by field investigations. The present paper introduces the first results recently achieved.

2 PHYSICAL AND CLIMATIC SETTINGS

The National Road N7 goes through the Río Mendoza valley and crosses three geological units called *Province Principal Cordillera, Frontal Cordillera* and *Precordillera*. Located between 32° and 33° S, this valley is lying above the flat slab subduction segment (Ramos, 1988) which controls the seismic activity in the region. This area includes the highest Andes, with elevation of nearly 7000 m above sea level in Mount Aconcagua.

The *Principal Cordillera* at 33° S latitude is a fold-andthrust belt dominated by thin skinned deformation (Ramos et al., 1996) that was facilitated by the presence of thick gypsum, which localized the detachment of the post-Jurassic cover. The main outcrops in this area are the Jurassic-Cretaceous marines and continental and volcanic units. The continental and marine rocks consist of limestone, shale, clays, sandstone and gypsum. The volcanics rocks are pyroclastites and ignimbrites.

The *Frontal Cordillera* has a complex gondwanic basement structure that has been uplifted almost like a single block during the Andean orogenic time. The older outcrops are Carboniferous marine sediments and, in discordance, the main lithological unit is a Permian-Triassic volcanic-intrusive complex, the Choiyoi group, consisting of basalt, andesite, rhyolite, tuffs, volcanic breccia and ignimbrite.

Between 29° and 33° S, the *Precordillera* constitutes the external zone of the Andes. There, the road crosses Triassic sedimentary rocks consisting of conglomerate, sandstones and limestones.

The relief is a result of fast uplift driven by tectonic of the Central Andes combined with glacial and fluvial incision. Several glacial advances took place during the Quaternary (Espizúa, 1993), reshaping the valley by erosional and depositional processes. At present the glaciers are limited in the cirques above 4200 m. Quaternary glaciations have strongly influenced geomorphic conditions. The Mendoza valley upper part is constituted of steep lateral sides, whereas the secondary basins consist in glacial shaped valleys carved into sedimentary and volcanic rocks. Fragile bedrocks cornices and the seasonal freeze and thaw contribute to the generation of mass movements. The entire valley exhibit a wide range of rock instability processes, including rock avalanches, deep seated gravitational slope deformations, rockfalls and landslides. At present, the valleys are mainly reshaped by fluvial action, mass movement and cryogenic processes. In many cases rock slope instabilities directly feed debris to steep channels. A second major debris source is represented by unconsolidated Quaternary glacial drift, rock glacier and colluvium.

The regional climate is arid to semiarid, although precipitation and temperature vary considerably with altitude changes (Fernández García and Polimeni, 2003). Temperatures range from 20° to -30°, while the total annual rainfall is 142 mm in Uspallata (1884 m) and reaches 359 mm in Cristo Redentor (3832 m), above Las Cuevas. Intense rainstorms occur between 800 and 2000 m during the summer (November to March). The valley and peaks above 2000 m suffer snowfalls in winter (June to September).

3 METHODS

3.1 Data and field survey

The calculations are performed on a DEM (digital elevation model) Aster SRTM available for the entire area (grid 30 m).

Detailed investigations were carried out in two zones (A and B, Figure 1) between Potrerillos and Las Cuevas, representing about 90 Km along the National Road N7. Between these zones, only selected catchments were investigated.

3.2 Triggering areas detection

Sediment availability, water input and slope gradient are criteria relevant for a debris flow initiation (Takahashi, 1981; Rickenmann and Zimmermann, 1993). Thus, potential triggering areas can be detected from the combination of the lithology, the upslope contributing area, and the slope angle. The addition of plan curvature and the land use permit to obtain a more accurate detection (Horton and al., 2008).

The Flow-R model introduced by Horton et al. (2008) detects the potential sources area from the previous parameters on the DEM. A part of the detection is performed through a relationship between the contributing area and the slope. The limit relationship for extreme events (Eq. 1) is based on the observations of Rickenmann and Zimmermann (1993):

$$\begin{cases} \tan \beta_{\rm lim} = 0.31 \cdot S_{UA}^{-0.15} & \text{ if } S_{UA} < 2.5 km^2 \\ \tan \beta_{\rm lim} = 0.26 & \text{ if } S_{UA} \ge 2.5 km^2 \end{cases}$$
[1]

where tan β_{lim} = slope gradient, S_{UA} = surface of the upslope contributing area.

Every point located above that limit is considered as critical.

3.3 Run-out estimation

Flow-R estimates the debris flows spreading by means of a basic energy balance and a probabilistic spreading, merging several GIS and physical approaches. Flow direction algorithms calculate the probability that a debris flow moves from a source cell to the next eight cells. These probabilities depend on the slope and the persistence, which represents the inertia of the debris flow. The model proposes various algorithms, including the one of Holmgren (1994) used in this study (Eq. 2).

$$f_{si} = \frac{\left(\tan\beta_i\right)^x}{\sum_{j=1}^8 \left(\tan\beta_j\right)^x} \text{ for all } \tan\beta > 0$$
[2]

where i, j = flow directions (1..8), f_{si} = flow proportion (0..1) in direction i, tan β_i = slope gradient between the central cell and cell in direction i, x = variable exponent with an optimal value between 4 and 6 for debris flows.

Maximum run-out distance can be calculated using the two-parameter model of snow avalanche motion proposed by Perla et al. (1980) and expressed by Eq. 3:

$$\frac{1}{2}\frac{dv^2}{ds} = g(\sin\vartheta - \mu\cos\vartheta) - \frac{D}{M}v^2$$
[3]

where v = tangential speed ds/dt, s = distance, M = debris flow mass, = slope angle, μ = coefficient of friction and D = a coefficient of dynamic drag.

This model is dependent on the values of μ and the mass-to-drag ratio M/D that need to be calibrated.

Maximum run-out distance can also be assessed using basic energy-based calculations (Eq. 4). The calculation is based on a unit energy balance, a constant loss function and a maximum threshold. This approach constitutes a realistic approximation, but do not represent exact physical processes.

$$E_{kin}^{1} = E_{kin}^{i-1} + \Delta E_{pot}^{i} - E_{loss}^{i}$$
^[4]

where i = time step, E_{kin} = kinetic energy, ΔE_{pot} = change in potential energy and E_{loss} = constant loss.

The energy loss function is a simple Coulomb friction model with a single friction coefficient. This coefficient is approximated using the fan slope angle, assumed to be closed to the friction angle. An upper threshold to limit the debris flows velocity to reasonable values is also added from field data.

More details about the Flow-R model can be found in Horton et al. (2008) and Michoud et al. (2011),

3.4 Classification

The debris flows spreading is simulated first from all the source areas determined in § 3.2 (Run 1). Then, a simulation is performed with the source areas of catchments where evidence of a debris flow activity was observed in the field (Run 2). These second results are manually extended if the deposits observed in the field are not reached.

The classification used for the establishment of the susceptibility maps is a relative hazard scale subdivided in two classes (Table 1).

Table 1. Possible scenarios for the hazard areas classification.

Classes	Spreading area		Field data and testimonies
Proved high hazard	Run 2	or	Yes
Suspected moderate to low hazard	Run 1	and	No
No hazard ¹	None	and	No

¹ i.e. no detected by Flow-R and not observed in the field.

4 RESULTS

4.1 Field survey

Due to the size of the study area, the investigations were limited to a few hundred meters beside the road and no information on source areas was collected. Debris flow evidence was mapped in order to create an inventory that completes the simulations results.

Some catchments present recent activity and endanger the road. This is the case for the calibration sites (Figure 1) chosen for this study. Mitigation measures are inexistent (site 4a and 4b), inefficient (site 3), not maintained (site 1a, Figure 2, Wick et al., 2010) or not terminated (site 2a).



Figure 2. Intersection between the channel and the road on site 1a. The three tubes below the road are partially filled by sediments and debris flows can directly reach the road.

Moreover, numerous pipes below the road are partially or completely blocked off by sediments in the entire study area (Figure 2).

4.2 Triggering areas

Due to the lack of data available in the region, only three parameters were used to detect the potential triggering areas: the slope angle, the upslope contributing areas and the plan curvature.

According to Takahashi (1981), most debris flows occur from slopes steeper than 15° and the data from the debris flows 1987 in Switzerland show that all triggering areas slope angles were below 40° (Rickenmann and

Zimmermann, 1993). Eq. 1 was bounded with these limits and the contributing areas inferior to 1 ha were not considered as potential sources. The choice of a threshold for the plane curvature depends on the DEM grid. Thresholds of $-2/100 \text{ m}^{-1}$ (grid 10 m) and $-1/100 \text{ m}^{-1}$ (grid 20 m) were already successfully used (Horton et al., 2008; Horton and Loye, 2009). Ellen et al. (1997) propose a value of $0.01/100 \text{ m}^{-1}$ for a 30 m grid.

The parameters used for detecting the potential triggering areas are summarized in Table 2.

Table 2. Parameters used for triggering areas detection.

Slope	Contributing area	Plane curvature
> 15° and < 40° 1	> 1 ha ¹	< 0.01/100 m ⁻¹

¹ and above the limiting curve for extreme events determined from Eq. 1 in Horton et al. (2008).

4.3 Run-out estimation

The parameters calibration was performed in four different areas regrouping seven sites prone to debris flows (Figure 1; Table 3).

Previous studies in Pakistan and Switzerland (Horton and Loye, 2009; Jaboyedoff et al., 2010) applied successfully an exponent 6 to the algorithm of Holmgren (1994). The tests on the study area showed no significant difference between both exponents, excepting a slight lateral expansion of the debris flow spreading using an exponent 4 instead of 6. Thus, this smaller value was chosen to remain on the safe side.

The parameters μ and M/D of the PCM model (Perla et al., 1980; Eq. 3) were tested with values ranging from 0.02 to 0.3 for the coefficient of friction and from 20 to 1000 for the mass-to-drag ratio, representing 56 combinations. The best-fit values for each calibration site are enumerated in Table 3.

Table 3. Location of the calibration sites and corresponding best-fit values for the parameters of Perla et al. (1980).

Site	Location	Best-fit values
1a	North Guido Curve	µ = 0.10 ; M/D = 80
1b	North Guido Curve	µ = 0.25 ; M/D = 100
2a	Quebrada Seca	µ = 0.02 ; M/D = 180
2b	Quebrada Seca	µ = 0.05 ; M/D = 180
3	Arroyo Negro	μ = 0.15 ; M/D = 20
4a	East Las Cuevas	- ¹
4b	East Las Cuevas	μ = 0.20 ; M/D = 20

¹No relevant results due to an artefact of the DEM.

The pair μ = 0.02 and M/D = 180 determined on the site 2a is on the safe side regarding to the other sites and is assumed to be optimal for a regional analysis. In order to validate the results of the PCM model, another simulation was performed on the site 2a using the Coulomb friction model. A friction angle of 3° (fan slope on

site 2a) and a velocity limited to 10 ms⁻¹ (based on Wick et al., 2010) were put in Flow-R. The simulated spreading showed a slight lateral expansion but the same propagation distance and thus confirmed the previous choice of the parameters μ and M/D.

4.4 Maps of susceptibility

The combination of spreading simulations and field observations permitted to create a 1:50,000 susceptibility map of the study area (Figure 4). As explained in § 3.4, the hazard classes are relative.

5 DISCUSSION

The field investigations showed that several catchments potentially endanger the road. Detailed studies need to be performed on these places in order to propose adequate mitigation measures, as already presented for the site 1a. There, after the 2005 events, Wick et al. (2010) showed that the road was cleaned without considering the consequences of another debris flow in the same catchment (Figure 2).

Anyway, the results are deeply linked to the DEM resolution and the precision of the maps could be substantially improved using a smaller grid. Due to lack of available data, the source areas detection was performed with only three criteria. Aerial photos will be analysed in the future to map outcrops and thus restrict the potential source areas.

Then, fifty-six pairs of μ and M/D were tested and none was optimal for all the calibration sites. A comparison of the best-fit values to other data calibrated in Switzerland (Figure 3) showed that the best-fit values of calibration sites 1a, 1b, 3 and 4b are comparable to the results of Zimmermann et al. (1997), whereas the best-fit values of calibration sites 2a and 2b have a higher massto-drag ratio.



Figure 3. Comparison between the data of Zimmermann et al. (1997) and the best-fit values of the calibration sites.



Figure 4. Debris flows map of susceptibility along the National Road N7, between Potrerillos and Las Cuevas. Calibration sites (1-4). Satellite imagery ASTER.



Figure 5. Propagation computed by Flow-R on the calibration site 2a. Due to an artefact on the DEM, the simulated debris flow stops a few meters above the road. Google Earth image.

In the main, the debris flow propagations simulated with Flow-R adequately follow the channels, even if some artefacts created incoherent paths sometimes. The calibration permitted to obtain a good general estimation of the maximum run-out at this scale (Figure 5). Although the best-fit values of μ and M/D are different for each catchment, the chosen parameters μ = 0.02 and M/D = 180 allowed creating a coherent 1:50,000 susceptibility map.

6 CONCLUSION

This study is a first assessment of debris flow susceptibility at a large scale along the National Road N7. Despite the lack of data and the low resolution DEM, the results are realistic and will be useful to determine which areas need to be prioritized for detailed studies. Further analysis will be done in the future, especially in order to restrict potential triggering areas detected.

The field survey showed that numerous catchments along the National Road N7 are prone to debris flows. Some are likely to endanger the road-users, often because of the lack of mitigation measures.

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