Modelaje de flujos de detritos potenciales a partir de un modelo de elevación digital SRMT (Shuttle Radar Topography Mission): cuenca alta del río Chama, noroeste de Venezuela

Modelling potential debris flows from SRTM data in the upper Chama river watershed, northwestern Venezuela

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Resumen
Los flujos de detritos son procesos geomorfológicos comunes en los Andes venezolanos. Estos procesos reflejan la capacidad de transporte de sedimentos de este sistema regional montañoso. En este estudio se presenta un modelo regional de flujos de detritos potenciales en laderas cubiertas de suelo y vegetación en cuencas hidrográficas. El método consiste en la combinación de técnicas de teledetección con parámetros morfométricos e hidrográficos. Para ello se utiliza un Modelo de Elevación Digital (MED) del Shuttle Radar Topography Mission (SRTM) y una imagen proveniente del Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER). El área de estudio abarca la cuenca alta del río Chama, situada en el noroeste de Venezuela. Las zonas origen, el recorrido y las zonas de deposición de los flujos de detritos potenciales se modelan en función de la topografía y la dinámica de sedimentos, mediante la implementación del Número de Rugosidad Distribuida de Melton (NRDM) y el Modelo Sencillo de Flujo Modificado (MSFM).

Palabras clave: Modelaje de flujo de detritos; morfometría; dinámica de sedimentos; rugosidad de cuencas; SRTM; NRDM; MSFM.

Abstract
Debris flows in the Venezuelan Andes are common geomorphologic processes which reflect the sediment supply capacity of this regional mountain system. In this study, a regional model for potential debris flows on soil- and vegetation-covered hillslopes in watershed domains is presented. The method consists of a combination of remote sensing techniques, morphometric and hydrological parameters using a Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) and an Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) scene. The study area comprises the Upper Chama River watershed, north-western Venezuela. Source, runout and deposition areas for the potential

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debris flows are modelled as a function of topography and sediment dynamics, implementing the Distributed Melton’s Ruggedness Number (DMRN) and the Modified Single Flow Model (MSFM).

**Key words:** Debris flow modelling; morphometry; sediment dynamics; basin ruggedness; SRTM; ASTER; DMRN; MSFM.

**1. Introduction**

Hydrologically induced debris flows are the most common mass movement types in the Venezuelan Andes (Laffaille, 2005). They often occur in forested areas of watershed domains, and are usually associated with the seasonal variation of precipitation patterns in this region (Ferrer, 1993; Laffaille, 2005). The debris flow events in the Upper Chama River Basin, north-western Venezuela, are characterised by coarse, poorly sorted, non-cohesive weathered material, including large boulders (Ingeomin, 2007; Roa, 2007). Their source areas are mainly located in the proximity of ridges, e.g. Montalbán debris flow, or close to primary and secondary stream channels, e.g. Las Calaveras debris flow, with slopes ranging from 20° to 40° (Ingeomin, 2007; Roa, 2007). They are caused by intensive downpours over a short period of time and occur mainly at the end of the second precipitation season (October-November). This indicates a relationship between the first precipitation season (April-May), soil moisture conditions, runoff infiltration in hillslopes and the triggering of debris flows in the watershed (Ferrer and Laffaille, 2005). Runouts range from 4 km length, e.g. las Calaveras debris flow, to 11.5 km, e.g. Montalbán debris flow. They differ from place to place as a function of distance between source areas and potential deposition areas, slope and rheological characteristics of the flow (Ingeomin, 2007). The last one is beyond the scope of this study.

In spite of the threat that these geomorphological processes pose for inhabited areas along the Upper Chama River Basin, a regional debris flow hazard assessment has not been proposed yet. Furthermore, the contribution of these natural phenomena to the overall sediment dynamics of the regional river system, and their influence on the torrential behaviour of the Chama River and its tributaries, is poorly understood.

In this study, a regional model for potential debris flows on soil- and vegetation-covered catchment areas is proposed for the Upper Chama River Basin, north-western Venezuela. It models source, run-out and deposition areas for potential debris flows along the Chama River and its tributaries as a function of topography and sediment dynamics. A set of morphometric and geomorphological parameters are applied to determine potential source areas using the Distributed Melton’s Ruggedness Number (DMRN) in combination with primary topographic derivatives.
2. Study area

The area of study is located in the north-western part of the Venezuelan Andes in the Mérida Mountain Range (see Fig. 1). It comprises the Upper Chama River Watershed between 8° 29’ and 8° 53’ N and 71° 19’ and 70° 53’ S, and covers a total area of 1900 km². In the north, it is flanked by the Sierra de la Culata, with maximum heights of 4,800 metres above sea level (m.a.s.l), and in the south by the Nevada South Range reaching 5,000 m.a.s.l (Ferrer, 1993; Bellizzia et al. 1981; Schubert, 1980). Both Sierras are formed by a Precambrian crystalline basement that consists mainly of igneous and metamorphic rocks, and present very distinctive periglacial, alluvial and fluvial landforms (Bellizzia et al., 1981; Ferrer and Laffaille, 2005; Ferrer, 1993; Cabello, 1966; Silva, 1999; Shubert an Vivas, 1993). Regarding precipitation patterns, the study area is characterised by a bimodal precipitation regime, with two maxima in April and October and two minima in February and August (Berg, 2001; Rojas and Alfaro, 2001), (see Fig. 2).

Figure 1. Relief map of the upper Chama River Basin. Relative location map (upper left) modified from Corporación Andina de Fomento (CAF, 2008). The yellow numbers indicate the rain stations displayed in fig. 2.
3. Methods

The methodology employed in this study consists of a combination of morphometric and geomorphological analyses. Their inputs are a Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) collected in C-Band (90 m resolution) and an Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite image (15 m resolution). Their geomorphological assessment involves three distinct parts: DEM optimisation and evaluation, identification of source areas and identification of probable run-out areas (see Fig. 3).
4. DEM optimisation

The information gaps in the original SRTM DEM (SRTM FTP server, 2006) were filled by spline interpolation and the random errors removed using a low-pass filter (Neteler and Mitasova, 2007; Li et al., 2005). The accuracy of the SRTM DEM was assessed with the root mean square error equation (Eq. 1):

\[
RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} d_i^2} \quad [\text{Eq. 1}]
\]

where \( d_i^2 = Z_{\text{est}} - Z_{\text{obs}} \), \( Z_{\text{est}} \) is the DEM value, \( Z_{\text{obs}} \) the field-measured elevation value and \( n \) the number of ground control points (GCPs) collected. For this purpose, 76 GCPs were collected with a hand-held GPS receiver during a field excursion.

5. Identification of source areas using the Distributed Melton’s Ruggedness Number (DMRN)

In this step, the processed SRTM DEM is used to calculate the hydrological parameters, i.e. flow accumulation, flow direction and pour points, required to extract the watershed area extent and catchment height. These DEM derivatives are further used as main input parameters for calculating Melton’s Ruggedness number (MRN) in a distributed form.

MRN is a dimensionless index of basin ruggedness, that normalises the basin relief by areas (Marchi and Fontana, 2005; Rowbotham et al., 2005). Ruggedness is one of the most commonly used morphometric measures to identify debris torrent basins, since it reflects the relief potential of a landscape (Rowbotham et al., 2005). The MRN was also successfully used to differentiate debris flow prone basins from non debris flow prone basins (cf. Jackson et al., 1987), and to identify channels with high versus low sediment transport capacity (Marchi and Fontana, 2005).

For the purpose of this study, the original MRN calculated as a concentrated morphometric indicator from

\[
MRN = \frac{H_{\text{max}} - H_{\text{min}}}{A^{0.5}} \quad [\text{Eq. 2}]
\]

(Melton, 1958)

where \( H_{\text{max}} \) and \( H_{\text{min}} \) are maximum and minimum elevation values within the basin and \( A^{0.5} \) is the drainage basin area, is modified, resulting in the Distributed Melton’s Ruggedness Number (DMRN):

\[
DMRN = \frac{H_{\text{ave}} - H_{c}}{A^{0.5}} \quad [\text{Eq. 3}]
\]

(Marchi and Fontana, 2005)

where \( H_{\text{ave}} \) represents the average height of all upslope cells over each other, \( H_{c} \) the height of the considered cell in the SRTM DEM, and \( A^{0.5} \) the drainage basin area in square metres.

Catchment height \((H_{\text{ave}} - H_{c})\), also referred to as average expected relative altitude of the upslope catchment area (cf. Gacetta, 1999), is obtained by assigning a value equal to the average upslope catchment elevation minus the pixel elevation in the SRTM DEM. This calculation uses an upward recursive method based on
the Multiple-Flow Direction Algorithm (MFDA), (Quinn et al., 1991),

\[ d_i = \frac{(Tan\beta_i)^* L_i}{\sum_{j=1}^{n} (Tan\beta_j)^* L_j} \]  

[Eq. 4]  

(Quinn et al., 1991)

where \( j \) is the total amount number of downhill directions, \( tan \beta \) the local slope, \( f \) a flow apportioning weight, \( L_i \) the contour length weighting factors for each flow direction \( i \), and \( d_i \) represents the flow fraction allocated to each pixel in the direction of \( i \) (Holmgren, 1994). The reason for selecting the Multiple-Flow Direction Algorithm (MFDA) lies in its high ability to capture spatial variability of geomorphological features, when compared to other algorithms, i.e. Single-Flow Algorithms (McNamara et al., 1999).

6. Identification of probable run-out areas

Based on former empirical studies (cf. Jackson et al., 1987; Marchi and Fontana, 2005; Rowbotham et al., 2005; Wieczorek, 1987; Patton, 1987; Eibach and Clague, 1984), the results of the DMRN, local slope calculation and field observations, three criteria were established to delineate potential source areas:

1) Only cells with DMRN values equal or higher than 0.17 were considered (cf. Jackson et al., 1987; Marchi and Fontana, 2005; Rowbotham et al., 2005)

2) Slope values of the considered cells were equal or higher than 20° and lower or equal 40°(cf. Wieczorek, 1987; Patton, 1987)

3) Cells were located in the proximity of ridges and close to expected primary and secondary stream channels (cf. Eibach and Clague, 1984; Patton, 1987; Wieczorek, 1987).

Based on these three criteria, 53 potential source areas containing one or more cells, were selected, and used as input to the Modified Single Flow Model (MSFM). The MSFM is based on a single flow direction algorithm, where the central flow line follows the direction of the steepest descent, and was developed by Huggel et al. (2003; 2004). However, the single flow algorithm (SFA) is unable to adequately simulate the spreading behaviour of debris flows in less steep terrain and unconfined zones (Huggel et al., 2004). To solve this limitation, Huggel et al. (2004) modified the model by integrating a function that allows the flow to diverge up to 45° in unconfined and less steep. This modification enables the model to simulate different characteristics of debris flows in confined channel sections (stream channels) and in flat or convex terrain, e.g. alluvial fans (Huggel et al., 2004).

Modelled debris flows stop when an average slope of eleven degrees (11°) is reached. This last parameter is based on the \( H/L \) ratio (\( H \) is the difference in elevation and \( L \) the path length) and can be modified to fit site specific characteristics, where detailed information regarding the behaviour of debris flows exists. For the study area, this information was not available; so that a average slope of 11°, originally calculated by Huggel et al. (2004) for the Swiss Alps region (equi-
valent to a minimum H/L ratio of 0.19), had to be used. The model also delineates the potential areas to be affected and assigns to each cell the relative probability it has to be affected by a mass movement. It is based on a linear function that defines that the more the flow diverges from the steepest descent direction, the greater becomes the resistance, and therefore the lower the probability for a point or cell to be reached (Huggel et al., 2004). The value of the modelled debris ranges from 0.5 to 1.0 and is expressed as a probability function, where 1.0 represents the highest and 0.5 the lowest probability for a point to be reached by the modelled debris flow (see Fig. 6).

7. Results

7.1 DEM evaluation

The RMSE shows that the SRTM instrument over- and underestimates the terrain elevation of the study area. A subtraction of the SRTM DEM values and the observed values (GCPs) also reveals that the overestimation occurs above 2800 m a.s.l and the underestimation below this elevation. These values vary between +73 m and -49 m (see Fig. 4). Furthermore, the elevation errors of the SRTM DEM also indicate a slope/aspect dependency, which has been already addressed by former studies (cf. Miliaresis, 2008).

In this particular case, the SRTM DEM underestimates the elevation in east-facing slopes, and overestimates it in southeast-facing slopes. However, to determine if the errors found in SRTM DEM are systematic it is necessary to collect more GCPs, which is beyond the scope of this investigation.

7.2 Potential source areas

The 53 potential source areas for debris flows used in this study were delineated with help of the DMRN and the local slope. For this purpose, hillslopes with high relief potential, as a function of rugged-
ness and slope, were determined. Using map algebra, the DMRN map was obtained by dividing the catchment height map by the entire catchment area map (see fig. 5).

In fig 5, the grey colour represents areas, with a very low sediments dynamics, and it is mainly found on ridges and plateaus. The Green colour represents areas with low sediment dynamics and constitutes the transition zones towards areas with medium to high sediments dynamics (yellow and red colours).

In addition, the DMRN map also provided a general overview of the potential hazardousness of the Chama river basin, especially of those hazards that are related to sediments dynamics e.g. sediments mobilisation, erosion on slope and fluvial erosion.

7.3 Modelled run-out areas

48 potential debris flow runouts, out of the 53 source areas were delineated with the MSFM. This represents 91 % of the to-
tal potential source areas. The remaining 5 potential source areas (9%), for which the MSFM did not model the runout, are attributed to the existence of grid cells with slope values below 11º, which is the average slope where the modelled debris stops. The results of the MSFM are presented in Figure 6 which depicts the areas potentially affected by debris flows (relative probability), the potential maximum inundation zones, as well as the flow reach of these events. The relative probability indicates that the more the flow diverges from the steepest descent direction, the greater becomes the resistance, and therefore the lower the probability for a point or cell to be affected. The flow reach component on the other hand, is determined by the H/L ratio used for calculating the MSFM. In this case, a H/L ratio 0.19 (equivalent to an average slope 11º) is used (Huggel et al., 2004). In figure 6, the red areas with a value of 1.0 represent the highest probability and the green areas with a value of 0.5 the lowest probability for any point to be affected by a debris flow.

8. Discussion

Whenever a new model is applied on a theoretical basis, it needs to be validated with respect to its practical applications.
In this case, it is of interest to determine in which extent the DMRN and the MSFM correspond to the reality of the study area. In order to assess the performance of the modelling procedures, the results are analysed qualitatively.

8.1 Qualitative assessment

In order to establish qualitative statements about the performance of the model, a comparative visual assessment was carried out using the following materials: a historical air photo with spatial resolution of 1:40000 (1947), (Ingeomin, 2006), a morphopedological map with a 1:50000 scale (Contreras, 2005) and a 30 meters orthorectified ASTER image. This visual assessment was validated through three fieldwork excursions between Nov. 2006 and March 2007. During these excursions, GPS points were collected and complemented with further imagery, i.e. digital photos (see Figs. 7 and 8).

In general, the MSFM determines the relative probability for a cell to be affected, the potential maximum inundation extent of the modelled debris flows and flow reach of the events. The discrepancies between the model and reality re-
result from the usage of a H/L ratio of 0.19 equivalent to overall slope 11\(^{\circ}\), originally calculated for the Swiss Alps region in Europe. Another source of discrepancies lies in DEM model dependency. The MSFM uses the steepest descent path approach (Single Flow Algorithm) and the H/L ratio to calculate the direction and the outreach of debris flows. Both calculations imply the use of slope as main parameter. In former studies, slope values were found to exhibit variations with the change of the DEM resolution- (cf. Deng et al., 2007), resulting in a systematic decrease or increase of slope values by coarsening or fine-graining DEM resolution.

Regarding the DMRN, the model shows not only areas of the subbasins where sediment transport initiates, but also locations along stream channels suitable for trapping debris material from upstream areas. These areas represent transition zones from debris flows to bedload transport and are very important to predict the flow process at the outlet of the basin.

The DMRN also determines deposition areas, which are consistent with the deposition areas modelled by the MSFM and with the alluvial fans mapped by Contreras (2005) and Roa (2007), (see Fig. 9).

The results of the DMRN satisfy with regard to their function as geomorphologic indicator, i.e. differentiating between areas with high and low sediment transport (cf. Jackson et al., 1987; Marchi and Fontana, 2005; Rowbotham et al., 2005). Besides, they provide a general overview of the distribution of the topographic ruggedness.
Regarding the relative probability being affected, the highest probability (1.0) is found in the proximity of the defined source areas, at the base of steep slopes, while low and medium values of relative probability characterise diverting areas, i.e. alluvial fans. In general, MSFM results indicate that the relative probability for cells or areas to be affected varies from high to low along the entire Upper Chama River Basin with the highest values located in tributary watershed systems (see Fig. 6).

Through a visual assessment of the orthorectified ASTER image, it is estimated that 48 potential debris flows out of 53 modelled source areas will reach an alluvial fan, i.e. farmland or residential areas (see Fig. 10 A, B, C and D). The five remaining potential source areas exhibit a short runout, which can be attributed to overall slope value lower than the threshold of 11°.

9. Conclusions

This investigation demonstrates that the combination of remote sensing data (SRTM DEM) with morphometric and hydrologic parameters is suitable for modelling geomorphologic processes on the regional scale of the study area. Despite the complex characteristics of rugged terrain and the limitations stemming from the structure of the models used and their DEM dependency, the results of the DMRN and MSFM in the Venezuelan Andes are considered to be realistic. They reflect the sediment dynamics of the stu-
Figure 10: Examples of modelled debris flows reaching alluvial fan areas, e.g. urban areas, draped over the SRTM DEM. Urban areas are shown in black on the DEM (see A, B, C and D). The same area shown in the ASTER image (see A, B, C and D). Ruby colour implies vegetated areas, light blue represents buildings. The contour line interval is 100 m.

The following main conclusions can be drawn:

1) The DMRN is useful to determine potential debris source areas in watersheded domains. Furthermore, it provides a general overview of the level of dissection of the watershed based on relief variation, thus allowing to differentiate areas with high sediment dynamics from those with low sediment turnover.

2) MSFM is able to model runout and deposition zones for potential debris flows along the Upper Chama River Basin using a SRTM DEM with a resolution of 90 m. The areas where the potential debris flow model shows a short runout are consistent with the presence of grid cells with overall slopes ≤ 11º, which is the stopping threshold value (H/L ratio) for the modelled debris.
3) MSFM and DMRN render divergent results in some sections of the potential deposition zones on flat terrain, i.e. on alluvial fans. These differences originate from the different flow algorithms used for the calculation of both models.

Regarding the limitations of this model, it is important to mention that both DMRN and MSFM consider neither the volume of the potential source areas, nor the type of material available. This deficiency can however be counterbalanced by extensive surveying in the respective watershed domains or by using advanced models in combination with the model proposed here, e.g. 3D dynamic models. For further studies, a downscaling of this approach is suggested. The inclusions of topographic parameters like curvature and wetness index are recommended, as well as a landcover classification with emphasis on stream channel domains.

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