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

Ortega Rengifo[1] y Schneevoigt Nora Jennifer[2]

Recibido: febrero 2011 / Aceptado: junio 2011

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 rio 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

---

1 University of Oslo, Department of Geosciences, Climate and Pollution Agency, Department of Environmental Information, Oslo-Norway. Correo electronico: rengifo.zenon.ortega@klif.no

2 University of Oslo, Department of Geosciences. Oslo-Norway

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, noncohesive 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 northwestern 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 February and August (Berg, 2001; Rojas and Alfaro, 2001), (see Fig. 2).

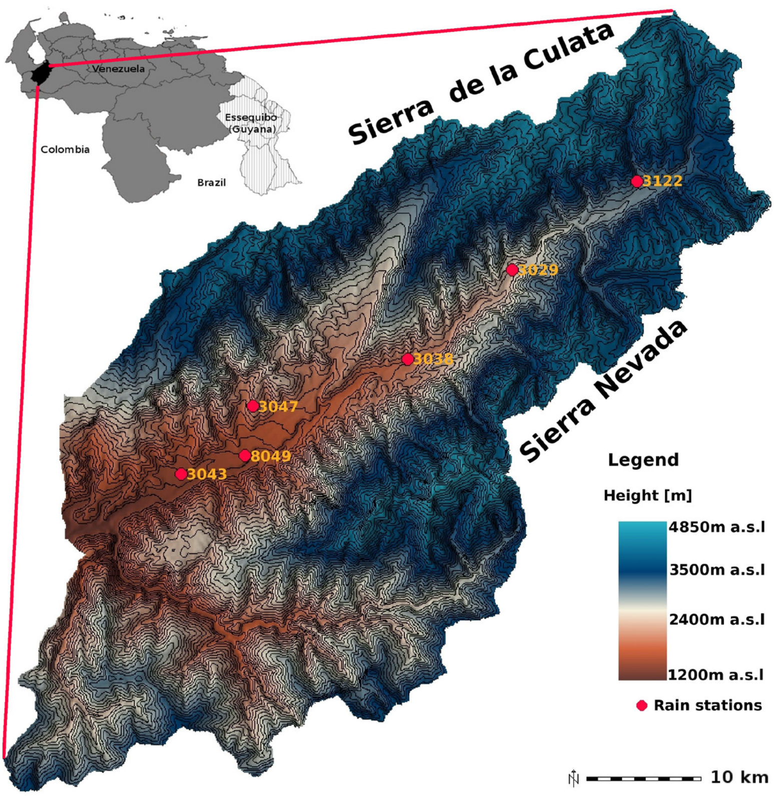

Figure 1. Relief map of the upper Chama River Basin. Relative location map (upper left) modified from Corporación Andina de Fomento (CAF, 2008). The yellow numbers indicate the rain stations displayed in fig. 2.

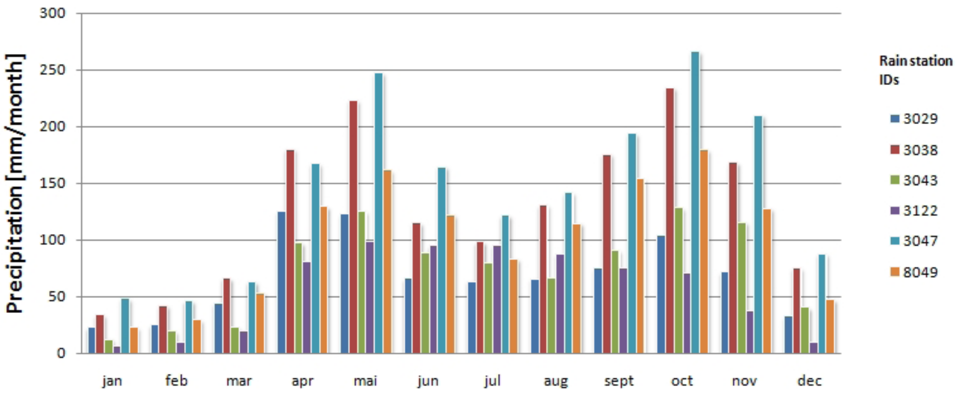

Figure 2. Monthly precipitation along Chama River watershed (MARN, 2006). The locations of the respective rain stations are shown in fig. 1.

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).

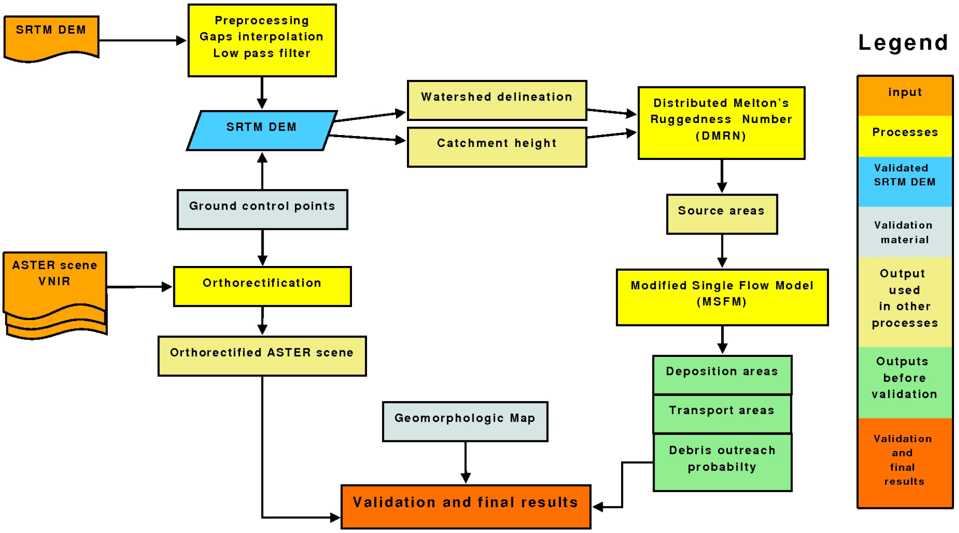

Figure 3. Structure and workflow of the investigation

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):

$$RMSE = \sqrt{(\sum_{i=1}^{n} d_i^2)/n} \qquad \text{[Eq. 1]}$$

where $d_i^2 = Z_{est} - Z_{obs}$. Z_{est} is the DEM value, Z_{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

$$MRN = \frac{H_{max} - H_{min}}{A^{0,5}} \qquad \text{[Eq. 2]}$$

(Melton, 1958)

where H_{max} and H_{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):

$$DMRN = \frac{H_{ave} - H_{c}}{A^{0,5}} \qquad \text{[Eq. 3]}$$

(Marchi and Fontana, 2005)

where H_{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_{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),

$$d_i = \frac{(Tan\beta_i)^f * L_i}{\sum_{j=1}^{n}(Tan\beta_j)^f * L_j}$$ [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; Eisbacher 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. Eisbacher 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 (equivalent to a minimum H/L ratio of 0,19), had to be used. The model also delineates the potential areas to be affected and assign 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-

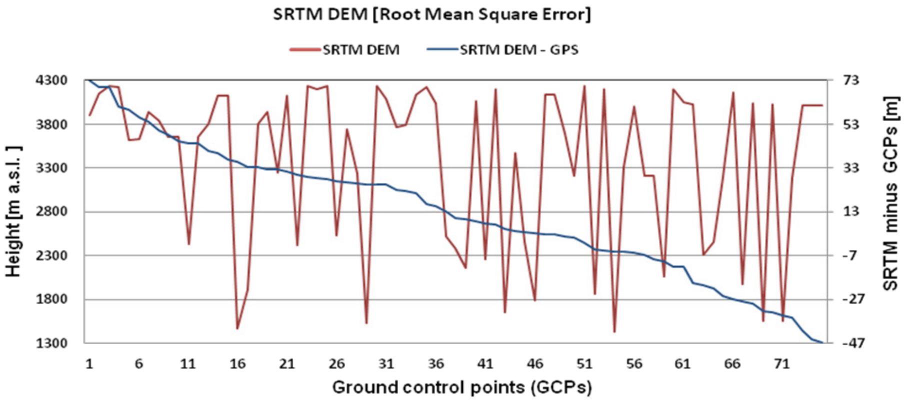

Figure 4. SRTM DEM Root mean square error (RMSE) compared to manually collected GCPs.

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-

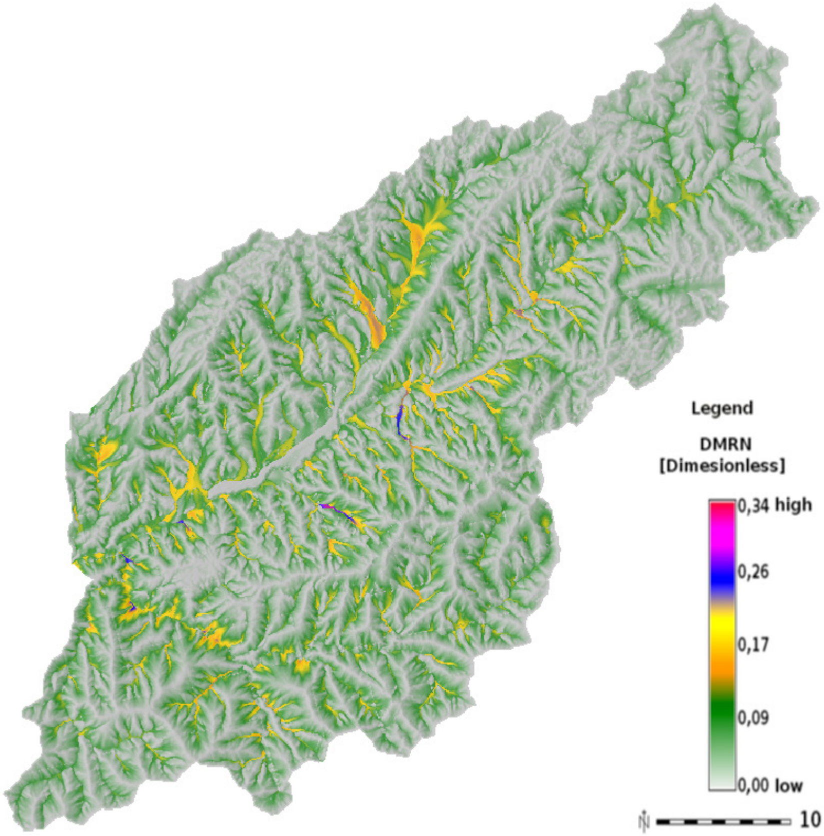

Figure 5: Distributed Melton's Ruggedness Number (DMRN), where 0,34 indicate high and 0,00 low sediment dynamics

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.

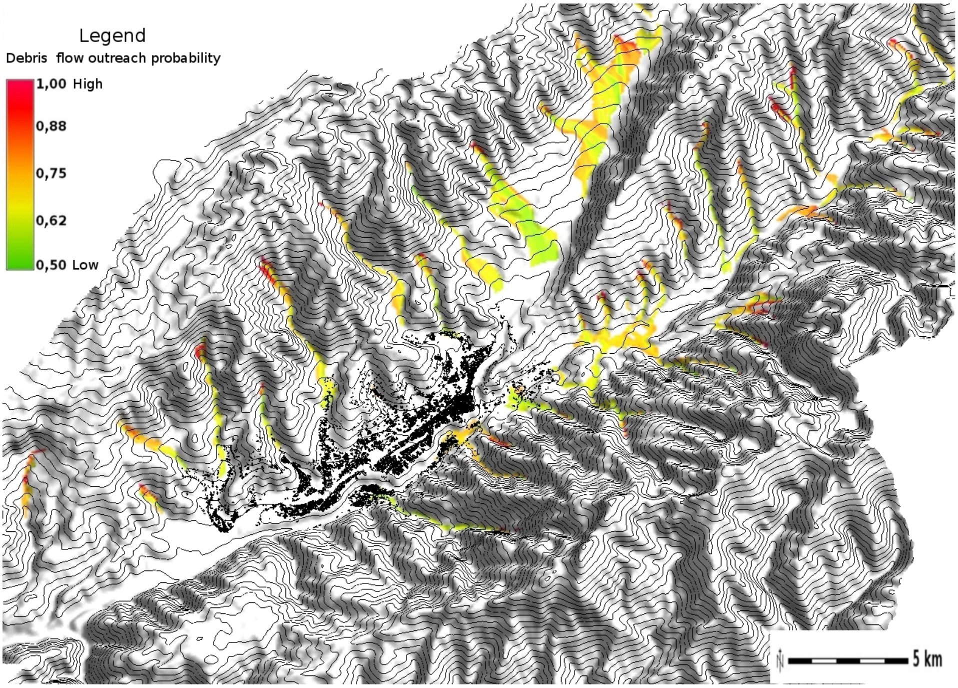

Figure 6: DEM with 100 m contour lines shows modelled debris flows and the city of Mérida (black). 1,0 represents the highest probability and 0,5 the lowest probability for any point to be reached by a debris flow

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-

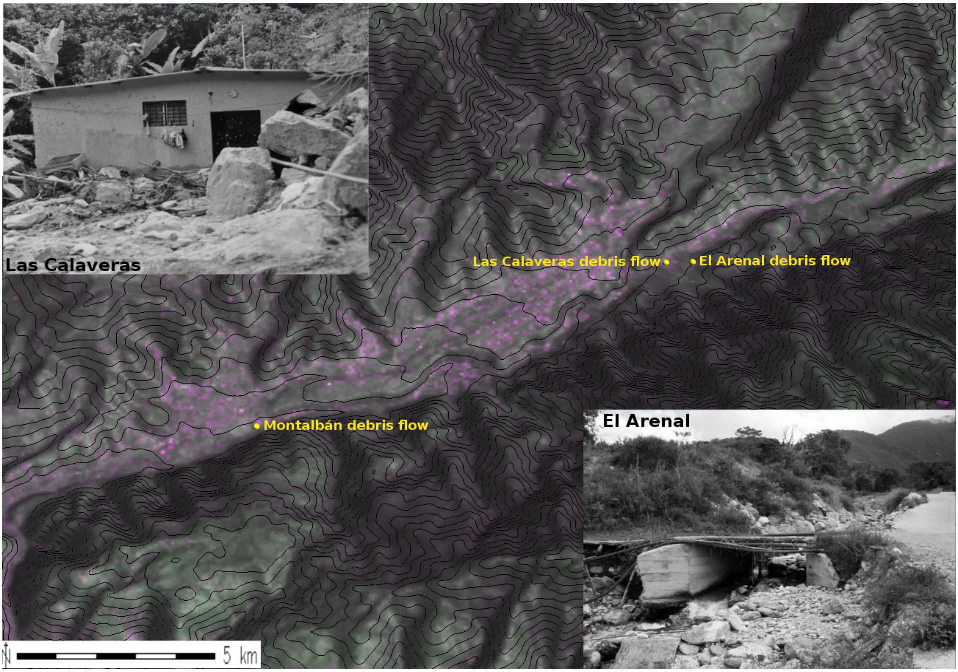

Figure 7: False colour composite ASTER image (Bands 2, 3 and 4), light green represents sparse vegetation and agricultural land, bright purple urban areas/bare soil and dark purple shows densely vegetated areas. Debris flow El Arenal, Nov. 2007 (lower right; photo taken by George Volkhard); debris flow Las Calaveras, Nov. 2006 (upper left). Regarding debris flow Montalbán, Oct. 1947, see fig. 9. The contour line interval is 100 m.

Figure 8: Aerial photo taken in 1947 in the aftermath of the Montalbán debris flow event (Ingeomin, 2006)

sult from the usage of a H/L ratio of 0,19 equivalent to overall slope 11º, 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.

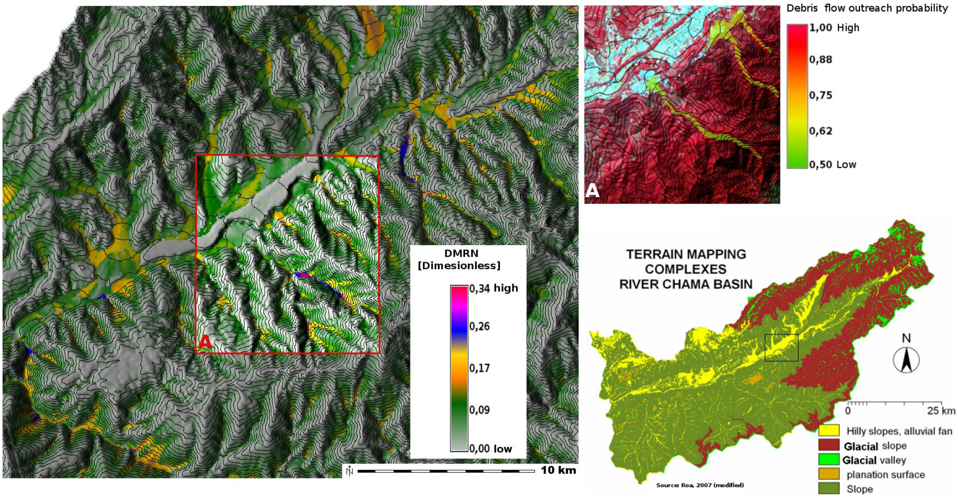

Figure 9: Example of deposition zones as modelled by the DMRN and MSFM, draped over the SRTM DEM (see box A) and the false colour ASTER image (urban areas appear in light blue colour). The contour line interval in both images is 100 m. Lower right, a terrain complexes map of the Chama river Basin depicting the predominant landforms

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-

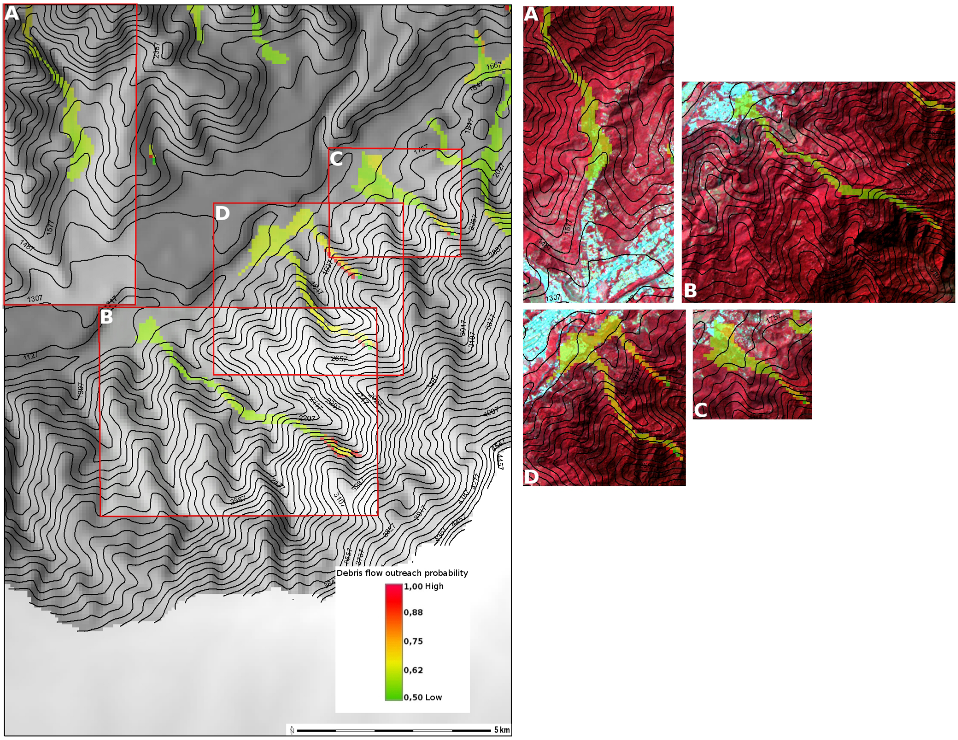

Figure 10: Examples of modelled debris flows reaching alluvial fan areas, e.g. urban areas, draped over the SRTM DEM. Urban areas are shown in black on the DEM (see A, B,C and D). The same area shown in the ASTER image (see A, B, C and D). Ruby colour implies vegetated areas, light blue represents buildings. The contour line interval is 100 m

dy area and coincided with vulnerability and susceptibility studies conducted in recent years (cf. Maldonado, 2007; Roa, 2007; Caritas, 2010).

The following main conclusions can be drawn:

1) The DMRN is useful to determine potential debris source areas in watershed 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 $\leq 11^{o}$, 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.

10. Acknowledgements

We thank Andreas Kääb at the University of Oslo (UiO) for providing guidance, feedback, the ASTER scene and the MSFM script, and the Department of Geosciences (UiO) for financial support. NASA and USGS provided the SRTM DEM, USGS and Japan ASTER Program the ASTER scene. Carlos Pacheco at the Andes University (ULA), Greta Roa and Rigüey Valladares (INGEOMIN), Jaime Laifalle (ULA), Carlos Ferrer (ULA) and Guido Ochoa (ULA) shared their experience and provided important geomorphologic, pedologic and geologic information about the study area. Special thanks to Regula Frauenfelder and Jachym Cepicky for their technical support, George Volkhard for his photos and Bernd Etzelmüller for commenting the paper.

11. References cited

BELLIZZIA, A.; PIMENTEL, N. and M. MUÑOZ. 1981. Geology and tectonics of northern South America. **Geodynamic investigations in Venezuela**. Special publication (9), 79 p.

CABELLO, O. 1966. *Estudio geomorfológico del área de Mérida y sus alrededores*. Facultad de Ciencias Forestales, Universidad de Los Andes. Mérida-Venezuela. 138 p.

CARITAS, 2010. *Zonificación de las áreas suceptibles a procesos hidrogeomorfológicos en el eje 'Vega de San Antonio, urbanización Don Perucho-El Arenal-La Pueblita', municipio Libertador, estado Mérida*. 64 p. (Inédito). [On line] http://www.caritasvenezuela.org.ve/zonificacion.pdf, (last access: November 30, 2010).

CORPORACIÓN ANDINA DE FOMENTO (CAF). s/f. *Sistema de información geográfica Cóndor. Servicio regional de mapas*. [On line] http://www.caf.com/view/index.asp?pageMs=45207&ms=17, (last access: June 15, 2008).

CONTRERAS, A. 2005. *El catastro multiutilitario: Herramienta clave para el análisis territorial y el ordenamiento rural. Caso del Municipio Rangel en el estado Mérida. Mérida-Venezuela*. Facultad de Ciencias Forestales y Ambientales. Universidad de

Los Andes. Trabajo para optar al grado de Magister Scientiae en 'Ordenación del Territorio y Ambiente'.186 p. (Inédito).

DENG, Y.; J. P. WILSON and B. O. BAUER. 2007. *DEM resolution dependencies of terrain attributes across a landscape*. **International Journal of Geographical Information Science**. 21 (2):187-213.

EISBACHER, H. G. and J. J. CLAGUE. 1984. *Destructive mass movements in high mountains: hazard and management*. **Geol. Survey Canada**. 84(16): 12-29.

FERRER, C. 1993. Procesos de erosión de los suelos y los problemas del uso de la tierra en las cuencas superiores de los ríos Chama y Santo Domingo, Edo. Mérida, Venezuela. Guía de excursión. *Reunión internacional. Procesos de erosión en tierras de altas pendientes. Evaluación y modelaje* 1-10. Mérida-Venezuela (16-20 de mayo).

FERRER, C. y J. LAFFAILLE. 2005. *Un estudio de las amenazas múltiples en la cuenca media del río Chama (Andes centrales venezolanos): Caso zanjón El Paraíso*. **Revista Geográfica Venezolana**. (Número especial): 93-117.

GACETTA, P. 1999. *Some methods for deriving variables from digital elevation models for the purpose of analysis, portioning of terrain and providing decision support for what-if scenarios*. CSIRO Mathematical and Information Science (CMIS) unedited http://www.cmis.csiro.au/rsm/research/dems/index.htm, (last access: May 10, 2007).

HOLMGREN, P. 1994. *Multiple flow direction algorithms for runoff modeling in grid based elevation models: An empirical evaluation*. **Hydrological Processes**. 8 (4): 327-334.

HUGGEL, C.; KÄÄB, A.; HAEBERLI, W. and B. KRUMMENACHER. 2003. *Regional scale GIS models for assessment of hazards from glacier lake outbursts: evaluation and application in the Swiss Alps*. **Natural Hazards and Earth Systems Sciences.** 3: 647-662.

HUGGEL, C.; KÄÄB, A. and N. SALZMANN. 2004. *GIS-based modeling of glacial hazards and their interactions using Landsat-TM and IKONOS imagery*. **Norsk Geografisk Tidsskrift.** 58: 61-73.

INSTITUTO NACIONAL DE GEOLOGÍA Y MINERIA (INGEOMIN). 2007. *Efecto social del evento de Santa Cruz de Mora. Emergencia en el Mocotíes*. Encuentro Binacional Colombo-Venezolano en el marco del Proyecto Multinacional Andino: Geociencias para las Comunidades Andinas. Mérida-Venezuela. 64p.

INSTITUTO NACIONAL DE GEOLOGÍA Y MINERIA (INGEOMIN). 2006. *Estudio de suceptibilidad de la cuenca Montalbán-la Ceibita, municipio Campo Elías, estado Mérida*. Mérida-Venezuela. 212 p.

JACKSON, E.; KOSTASCHUK, A. and M. MACDONALD. 1987. Identification of debris flow hazard on alluvial fans in the Canadian Rocky Mountains. In: Costa, J.E. and Wieczorek, G.F. (eds). **Debris flows/avalanches: process, recognition, and mitigation.** Boulder, Colo.: Geological Society of America, 239 p.

LAFAILLE, J. 2005. *Antecedentes de los eventos meteorológicos ocurridos en el valle del río Mocotíes y su impacto geomorfológico*. **Revista Geográfica Venezolana**. (Número especial): 297-311.

LI, Z. Q. and C. GOLD, 2005. **Digital terrain modeling. Principles and methodology**. CRC Press, New York. 323 p.

MCNAMARA, J. P.; KANE, D. and L. HINZMAN. 1999. *An analysis of an arctic chan-*

nel network using a digital elevation model. **Geomorphology.** 29: 339-353.

MALDONADO, R. J. 2007. *Propuesta para la zonificación de vulnerabilidad socio-natural de la microcuenca Quebrada La Resbalosa, Mérida*, 75. (Inédito) http://www.monografias.com/trabajos-pdf/zonificacion-la-resbalosa/zonificacion-la-resbalosa.pdf (last access: December 1, 2010).

MARCHI, L. and G. FONTANA. 2005. *GIS morphometric indicators for the analysis of sediment dynamics in mountain basins*. **Journal Environmental Geology.** 48 (2): 218-228.

MINISTERIO DEL AMBIENTE Y DE LOS RECURSOS NATURALES (MARN). 2006. *Sistema de información hidrológica y metereológica. Datos pluviométricos sobre la cuenca del río Chama* (1947-2001): 1-33.

MELTON, M. A. 1958. *Geometric properties of mature drainage systems and their representation in E4 space*. **Journal of Geology**. 66: 35-56.

MILIARESIS G., C. 2008. *The landcover impact on the aspect/slope accuracy dependence of the SRTM-. Elevation Data for the Humboldt Range*. **Sensors.** 8: 3134-3149.

NETELER, M. and H. MITASOVA. 2007. **Open Source GIS. A GRASS GIS Approach**. Edited by Springer (3rd Edition). 393p.

PATTON, P. C. 1987. Drainage basin morphometry and floods. In: Baker, V.R., Kochel, R.C. and Patton, P.C. (eds). **Flood geomorphology**. New York: Wiley. 503 p.

QUINN, P.; BEVEN, K.; CHEVALLIER, P. and O. PLANCHON. 1991. *The prediction of hillslope flow paths for distributed hydrologic modeling using digital terrain models*. **Hydrologic Processes.** 5: 59-79.

ROA, J. G. 2007. *Identifying landslides hazards in a tropical mountain environment, using gemorphologic and probabilistic approaches, Mérida, 182*. http://drum.lib.umd.edu/handle/1903/7825, (last access: December 1, 2010).

ROJAS, M. y E. ALFARO. 2001. *Influencia del oceano atlántico tropical sobre el comportamiento de la primera parte de la estación lluviosa en Venezuela*. **International Journal of Top, Meteor. Oceonograf.** 7 (2): 88-92.

ROWBOTHAM, D.; D. F. SCALLY and L. JOHN. 2005. *The identification of debris torrent basins using morphometric measures derived within a GIS*. **Geografiska Annaler**. 87 (4): 527-537.

SCHUBERT, C. 1980. Morfología neotectónica de una falla rumbo-deslizante e información preliminar sobre la falla de Boconó. Andes merideños. *Acta científica*. 31: 98-11.

SCHUBERT, C. and L. VIVAS. 1993. **El Cuaternario de la Cordillera de Mérida/ Andes Venezolanos**. Edited by (ULA), Universidad de Los Andes. 345 p. Mérida-Venezuela.

SILVA, G. 1999. *Análisis hydrográfico e hipsométrico de la cuenca alta y media del río Chama; Edo Mérida, Venezuela*. **Revista Geográfica Venezolana**. 40 (1): 9-42.

SRTM FTP Server 2006. *ftp://e0srp01u.ecs.nasa.gov/srtm/version2/SRTM3/South_America/*, (last access: May 20, 2006).

WIECZOREK, G. F. 1987. Effect of rainfall intensity and duration on debris flows in central Santa Cruz Mountains, California. In: Costa, J.E. and Wieczorek, G.F. (eds). **Debris flows/avalanches: process, recognition, and mitigation**. Boulder, Colorado: Geological Society of America. 239 p.