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Mudflow modeling using Flow-R software: case study of Ras Baalbek basin (Lebanon)

Modélisation de l'écoulement boueux par le logiciel Flow-R : étude de cas du bassin de Ras Baalbek (Liban)

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Résumé: L'écoulement boueux représente un risque de dégradation largement répandu dans les régions montagneuses, arides et semi-arides. Le bassin versant de Ras Baalbek, situé au nord-ouest du Liban, a subi au cours des dernières décennies plusieurs écoulements boueux qui se sont produits particulièrement en printemps ou en automne. Les conditions climatiques spécifiques (présence d'une goutte d'air froid, recrudescence des pluies), les paramètres géomorphologiques favorables (pente forte, sol peu épais et friable, un cours d'eau à régime torrentiel…) et le mode particulier d'occupation et d'usage du sol (rareté du couvert végétal, …) sont, en fait, à l'origine de ce phénomène. Ce phénomène entraîne des conséquences néfastes vu qu'il menace l'environnement et l'économie des villages touchés par cet aléa. Notre étude vise à simuler l'aléa de l'écoulement boueux dans le bassin versant de Ras Baalbek. La méthode suivie repose, en premier lieu, sur la détermination et l'intégration des facteurs les plus représentatifs de l'écoulement boueux (le M.N.T, la pente, l'accumulation du flux, la géologie, et l'occupation du sol) dans un SIG. À l'aide des données spatiales générées par SIG, des cartes de susceptibilité à l'écoulement boueux ont été établies avec le logiciel « Flow-R ». Le résultat est une carte d'aléa de coulée de boue qui tend à délinéer les zones à risque par le biais du logiciel « Flow-R ». Il est nécessaire dans ce sens, d'envisager des mesures d'atténuation pour réduire l'impact d'un tel événement. En effet, de nombreux travaux scientifiques soulignent le rôle important du terrassement, du reboisement des pentes raides ainsi que de l'aménagement du canal d'écoulement pour lutter contre ce risque.

Mots-clés : écoulement boueux, SIG, Flow-R, Ras Baalbek, Liban

Abstract : Mudflow represents a widespread risk of degradation in mountainous, arid and semi-arid regions. The Ras Baalbek basin located in North-East of Lebanon has undergone several mudflows in recent decades, especially in the spring or autumn seasons. The specific climatic conditions (presence of a cut-off low, recrudescence of rain), the favorable geomorphological parameters (steep slope, shallow and friable soil, torrential stream among other) as well as the land cover and land use types (among which is the scarcity of vegetation cover) are all contributing to the presence of this hazardous phenomenon. Mudflow has harmful consequences as it threatens the environment and the economy of the villages affected by it. This study aims to simulate mudflow hazard in the Ras Baalbek basin. The method used consists of the determination and integration of the most representative factors of mudflow (DEM, slope, soil hydrology, flow accumulation, geology, and land cover) in ArcGIS. Using the spatial data generated by GIS, mudflow susceptibility maps were drawn from the results of the mudflow simulations with the "Flow-R" software. In this sense, it is necessary to consider mitigation measures to reduce the impact of such an event. Note that several scientific references emphasize the important role of earthworks, reforestation of steep slopes and the development of the flow channel to reduce this risk.

Keywords: Mudflow, GIS, Flow-R, Ras Baalbek, Lebanon

INTRODUCTION

Mudflow, locally known as "sail", is a mixture of fast-moving water with large amounts of suspended particles, silt and other debris that mix downslope and result in a very rapid flow. They are liquefied when mixed with the large amount of water and the source material (HUNGR et *al.*, 2014).

This type of mass movement mainly occurs on steep slopes characterized by insufficient vegetation cover leading to rapid erosion. Mudflow can be generated in any climatic regime but is frequently related to arid and semi-arid areas where heavy precipitation over short periods can easily erode the source material.

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This phenomenon, mainly occurring in mountainous environments, is considered one of the most dangerous natural hazards affecting built-up areas, infrastructure, and also human lives (RICKENMANN & ZIMMERMANN, 1993; HOFMEISTER et *al.*, 2002).

This paper presents a preliminary assessment of the potential mudflow hazard in Ras Baalbek watershed (North Bekaa - Lebanon) and seeks to delineate the areas under high probability of exposure. Hence, this study's results can be used to propose mitigation measures to reduce the impact of such an event.

STUDY AREA

The study area is located in northern Bekaa (in the north eastern part of Lebanon). It has an area of 307 km^2 and extends from 540 to 2430 m a.s.l. (Fig. 2). The basin is characterized by a semi-arid Mediterranean climate given that the calculated Martonne aridity index is equal to 10.2. It is a dry region receiving 250 to 450 mm/year of precipitation over the period 1989-2016 (TRABOULSI, 2010). However, the basin is affected by late spring and autumn thunderstorms linked to cut-off low at a high altitude (500 hpa) (Fig. 1) causing devastating "sails" (BLANCHET, 1976; TRABOULSI, 2004). An example of such a situation is shown in Fig.1 that reveals the air circulation in the upper layers of the atmosphere (500 hpa) above the eastern Mediterranean basin on August 21, 2006, and June 13, 2018. During these two dates, the study area was under devastating sails.

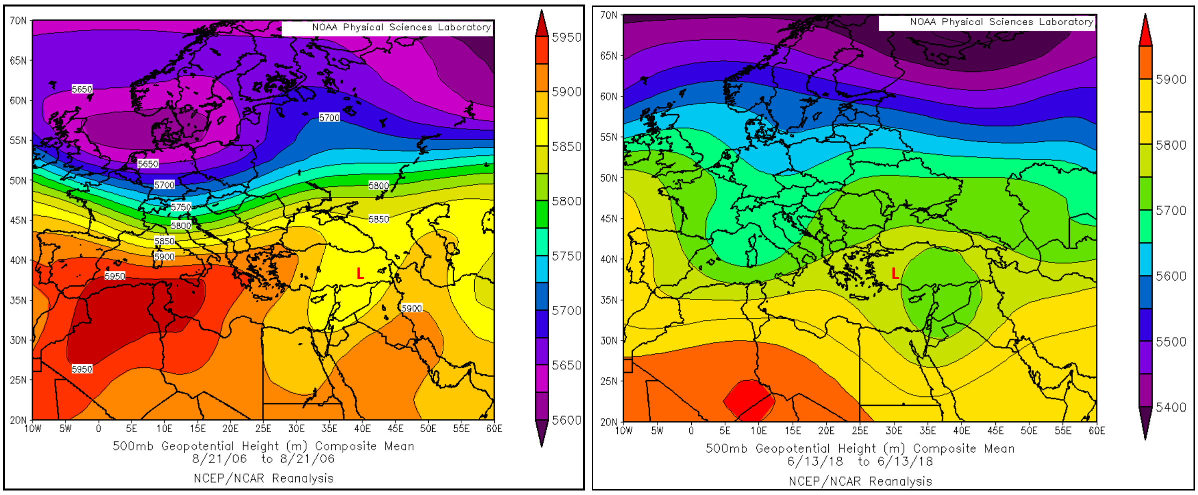

Figure 1.- Air circulation in the upper layers of the atmosphere (500 hpa) above the eastern basin of the Mediterranean that caused the cut-off lows on August 21, 2006 (to the left) and June 13, 2018 (to the right). "L" stands for Lebanon. Data received from NCEP/NCAR Reanalysis.

The basin drains the Oronte River that extends to the west of El Qaa plain (Fig.2). This basin is formed by dry valleys having a temporary and discontinuous flow regime. Its organized network is characterized by the multiplicity of intermittent ravines, due to the concentration of runoff during seasonally late stormy showers. Dry valleys are a dominant feature of the northern Anti - Lebanon Mountain. They are narrow gorges crossing bare limestone outcrops to arrive at their confluence with the Oronte River. The functioning of these valleys is brutal, and their effect is devastating. The slopes' basin is characterized by a particular morphology due to its geological setting:

- In the upper part (1000 m - 2430 m a.s.l.) slopes are steeper than 20° and consist of fractured limestone and dolomitic limestone of Cenomanian (C4) and Turonian (C5) formations. These slopes are often covered by non-consolidated debris varying in thickness between 0.2 and 0.5 m.
- The gentle slopes (1° - 20°) of the lower part (540 m - 1000 m a.s.l.) consist of lacustrine marls and marly limestone dating back to Miocene formation. These slopes are covered by various Quaternary deposits. The latter comprises two types; the first in the plain (El Qaa) is made up of a mixture of silts, sands and gravels, which reflects normal inland deposition among fluvial and slopping (colluvial) depositions; the second is indurated or highly cemented surficial conglomerates occurring at the feet of the mountain slopes.

This geological, structural, and climatological settings promote mass movements (FLAGEOLLET et *al.*, 1999). Moreover, the region suffered from the scarcity of vegetation cover, which increased the torrential activity; grasslands (37%), rocky outcrops (23%) and bare land (15%) form around 75% of the study area. The rest is mainly field crops, fruit trees and urban fabric.

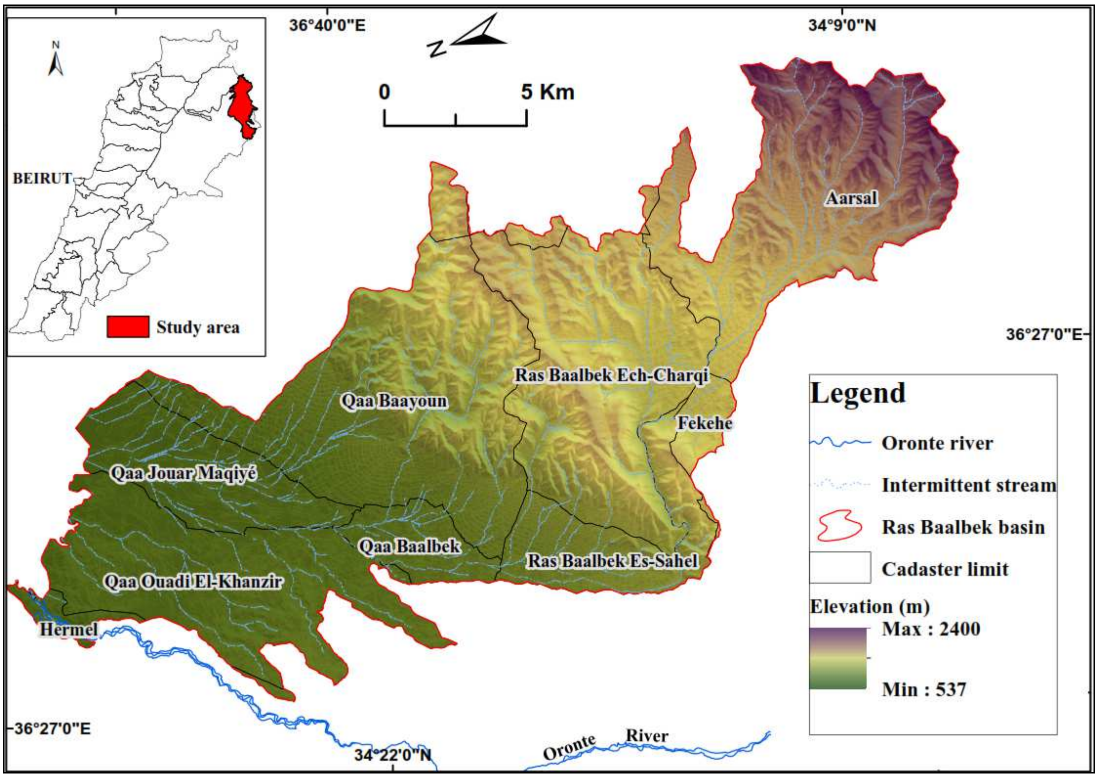

Figure 2.- Hillshade of the Ras Baalbek basin (North Bekaa)

METHODOLOGY

General description

Flow-R (flow path assessment of gravitational hazards at a regional scale) is a disseminated empirical model for susceptibility assessment of mudflow and other natural hazards developed by HORTON et *al.* (2013). This model requires the application of two different steps: (1) the identification of mudflow sources through several morphological, geological and hydrological parameters, and (2) the promulgation and the spreading of these sources through a probabilistic and energetic approach. For both steps, Digital Elevation Model (DEM) with 10m x 10m grid is a crucial component. The flowchart of the applied analysis method is presented in Fig. 3.

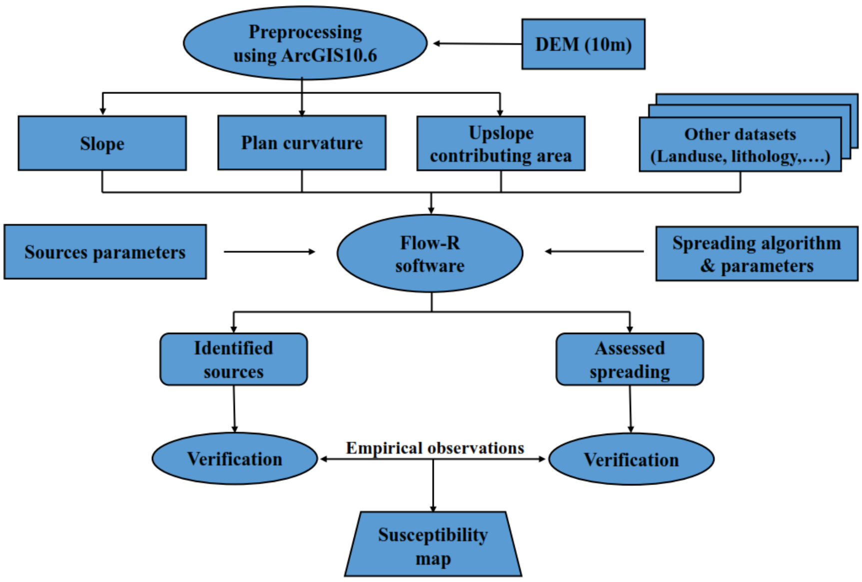

Figure 3.- Schemamtic representation of the adopted methodology

Data sets

The data sets used for the purpose of this study included:

- A 10 m Digital Elevation Model (DEM) covering all of the Ras Baalbek basin.
- Geological maps of Hermel and Aarsal at the scale of 1/50.000 (Dubertret, 1945) covering all the Ras Baalbek basin. The maps contain various lithological units that were digitized using GIS software and validated through site visits and satellite images.
- A land cover map (2016) issued, as a shapefile, by National Center for Scientific Research (CNRSL) which was produced through using SPOT images (1 m resolution).
- World View satellite images from 2018 (resolution of 2.5 m) covering all of Ras Baalbek basin that were used to validate the outcome results.
- An inventory of mudflow events occurring in the basin for the period between 1957 and 2019.
- Topographical maps of Hermel, Aarsal, Ras Baalbek, Sharbine, Al Qasr and Wadi Turkmane at a scale of 1/20.000 covering the study area and having 10 m contour interval published in raster format by the Directorate of Geographical Affairs of the Lebanese Army (DGAG).
- Soil hydrology derived from the soil map of Lebanon issued by CNRSL, 2005.

Source area determination

The mudflow initiation mainly depends on three geo-environmental factors: slope gradient, water contribution and sediment availability (RICKENMANN & ZIMMERMANN 1993). For the purpose of this study, we combined several information layers (Fig. 3): slope, flow accumulation and planar curvature maps originated from DEM, the land cover map, the soil hydrology map and the lithological map.
For each map, we used an index-based approach (GIS-based) and consequently applied the following grid classification: grid cell is equal to (1) when it is considered as “possible source”, i.e., when initiation is possible. Grid cell is equivalent to (2) when initiation is improbable and hence considered as an “excluded cell”. Grid cell is equal to (3) when the decision is uncertain on this parameter. Each cell is considered as “source area” when it is at least once designated as “possible source”, but certainly not “excluded” (HORTON et *al*., 2008). Every dataset was imported to Flow-R in ASCII – grid format and with same resolution and coordinate system.

Slope

The gradient of the slope is a fundamental parameter in triggering mudflow (Takahashi, 1981). The mean slope gradient in the Ras Baalbek basin is equal to 26.5 degrees (with a maximum of 53 degrees and a minimum of zero). In reference to various previous studies such as RICKENMANN & ZIMMERMANN (1993) and TAKAHASHI (1981), most mudflows arise from a topography with a slope gradient greater than 15 degrees. This value will be considered in our study as the lower initiation threshold. Hence, only 30% of the study area will have a direct influence in mudflow triggering.

Curvature

According to DELMONACO et *al*., (2003) and WIECZOREK et *al*., (1997), mudflows occur where curvature is concave. In this study, we used the plan curvature map, which is the curvature where the surface is perpendicular to the slope direction, to identify the gullies. In this map only cells having a plan curvature inferior than -2/100 m^{-1} were considered as possible source of mudflow. This threshold covers 18% of the total basin.

Hydrology

Topography has a variable influence on the runoff mechanism, which increases on concave slopes due to the increase in the kinetic energy of the flows (El Hage Hassan et *al.* 2015; 2019). Mudflows are modeled using the upslope contributing area. The latter was calculated using SAGA-GIS software and defined as the catchment area for minimal water for each DEM cell. For the purpose of this study, the flow accumulation was calculated using $D\infty$ algorithm (TARBOTON, 1997) for which each cell having an area less than one hectare (1 ha) was not considered as potential source (HORTON et *al*., 2008).

Lithology

Mudflow maintains a strong relationship with sediment availability. These sediments were defined by assessing lithological units present in the geological map of the study area at a scale of 1/50000 validated through site visits. The analysis of these units showed that some of them produce amounts of debris due to their weathering characteristics (chemical and mechanical behaviors). Thus, the selection of geological units susceptible to mudflow will only be based on areas previously affected by this phenomenon. These were defined based on the available inventory. According to these criteria, the rocks prone to mudflow ("possible source" in the model) are lacustrine marl, siltstone, non-consolidated debris, sandstone, marly limestone and slope deposits.

Land cover

Climatic aggressiveness depends on the mechanical protection that vegetation can attribute to the soil (EL HAGE HASSAN et *al.* 2018). The physiognomic (rooting, type of foliage, spacing of plants) and phrenoligic criteria (duration of growth) must be taken into consideration in order to determine the degree of soil protection (EL HAGE HASSAN et *al.* 2013; 2016). A vegetation cover is effective when it acts as a hydrological regulator by limiting the velocity of runoff (REY et *al.* 2004) and promotes infiltration. Conversely, the degradation of the plant cover amplifies water velocity. Accordingly, land cover was included in the model to identify certain inaccurate "sources". From the 19 land cover classes, four were included as "possible source" of mudflow. These are rocky outcrops, bare lands, sparse herbaceous vegetation and abandoned farmland.

Soil hydrology

The behavior of the soil with respect to infiltration and runoff must take into account the modification of the surface condition (compaction, cover, opening, and so on), induced by the succession of downpour.

Based on the study conducted by ROSS et *al.* (2018) four hydrologic soil groups (A - B - C - D) were distinguished, defining the soil's associated runoff curve numbers that are used to estimate direct runoff from rainfall. These groups were determined by combining and analyzing three parameters: water transmission soil layer, soil hydraulic conductivity and depth to any water impermeable layer. The hydraulic conductivity of each layer in the soil profile was determined based on several parameters such as texture, organic matter, strength and compaction of soil structure, and clay mineralogy.

A summary of the main characteristics of these hydrologic soil groups and their relation with mudflow' initiation is presented Table 1:

Table 1.- The main characteristics of hydrological soil groups and their relation with mudflow initiation'

Hydrologic soil group	**Soil texture**	**Potential runoff when thoroughly wet**	**Water transmission**	**Possible source of Mudflow**
Group A	10%clay; 90 % sand or gravel; gravel or sand textures. If well aggregated: loamy sand, sandy loam, loam or silt loam.	low	freely	excluded
Group B	10 % and 20 % clay and 50 % to 90 % sand and have loamy sand or sandy loam. If well aggregated: loam, silt loam, silt, or sandy clay loam.	moderately low	unimpeded	ignored
Group C	20 % and 40 % clay and less than 50 % sand and have loam, silt loam, sandy clay loam, clay loam, and silty clay loam. If well aggregated: clay, silty clay, or sandy clay.	moderately high	somewhat restricted	included
Group D	40 % clay, less than 50 % sand, and have clayey texture.	high	restricted or very restricted	included

Runout and spreading modelling

Following the identification of the source areas, data in ASCII files format was imported from ArcGIS to Flow-R software to determine the mudflow runout and spreading assessment. A mathematically based algorithms approach was used, first to calculate the path of mudflow from each potential source area, then to detect their flow direction, and lastly to compute their runout distances (HORTON *et al.,* 2008).

Figure 4 shows the different algorithms used to determine the potential mudflow propagation in the study area.

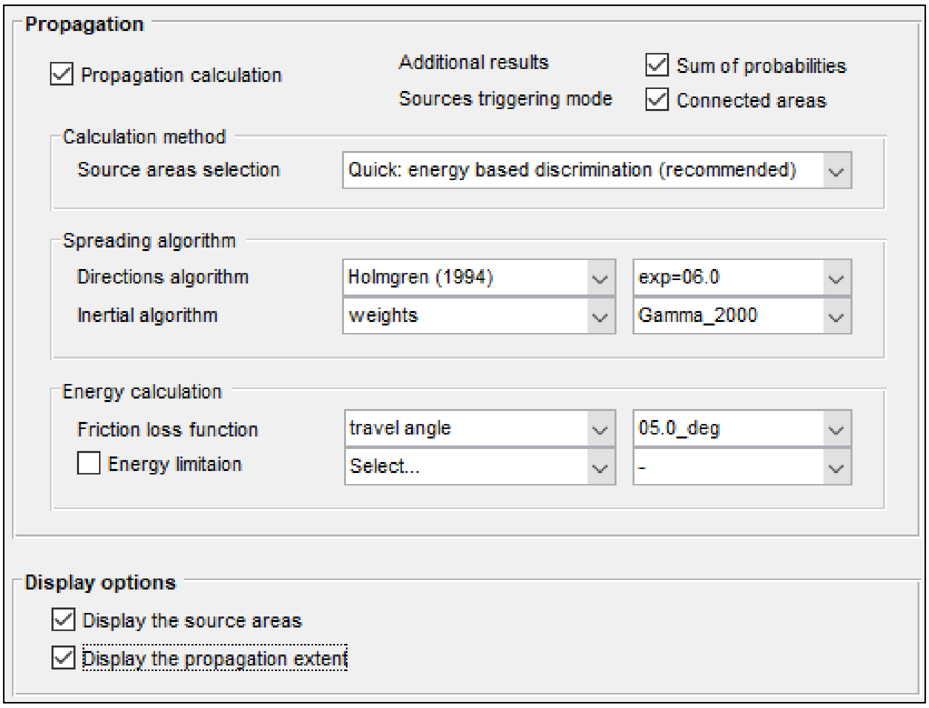

Figure 4.- Screen capture of the applied spreading algorithms to determine the mudflow runout and spreading assessment for the study area

Several Flow direction algorithms were used to model such an event. In this study, we used the Holmgren (1994) flow direction algorithm with an exponent factor equal to 6 (Fig. 4). The latter is considered as the suitable algorithm for the susceptibility assessment of mudflow because it permits the parameterization of the spreading (Horton and *al.*, 2013).

The Holmgren algorithm is calculated according to the following equation:

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

Where i, j = flow directions (1...8) with angular intervals of 45°, f_{si} = flow proportion (0...1) in direction i, tan ($ß_i$) slope gradient between the central cell and cell in direction i and x the variable exponent.

Moreover, in order to define the persistence of the mudflow, i.e., its inertia, a weighting of the flow directions is needed. For that reason, the inertial algorithm done by Gamma (2000) was selected.

The runout distance algorithms consist of basic energy-based calculations. These specify the ability of a mudflow cell to reach another one. In this study, the selected friction loss function for the probable maximum runout was the "travel angle", which is defined as the average slope between the beginning and the end of the mudflow path. Due to the morphological characteristics of the study area, and referring to the empirical mudflow behavior, an average slope angle of 5° was chosen.

RESULTS AND DISCUSSION

The applied model enables the determination of the sensitive sectors to mudflow hazards. The results for the identification of "source" areas are based on the threshold of extreme mudflow events (Fig.5). The spreading zones of all identified sources are combined, keeping the maximum probability values. The result refers to the total surface exposed to the propagation of flows, with an associated qualitative probability, qualifying the potential for susceptibility (Fig. 6 and Fig. 7).

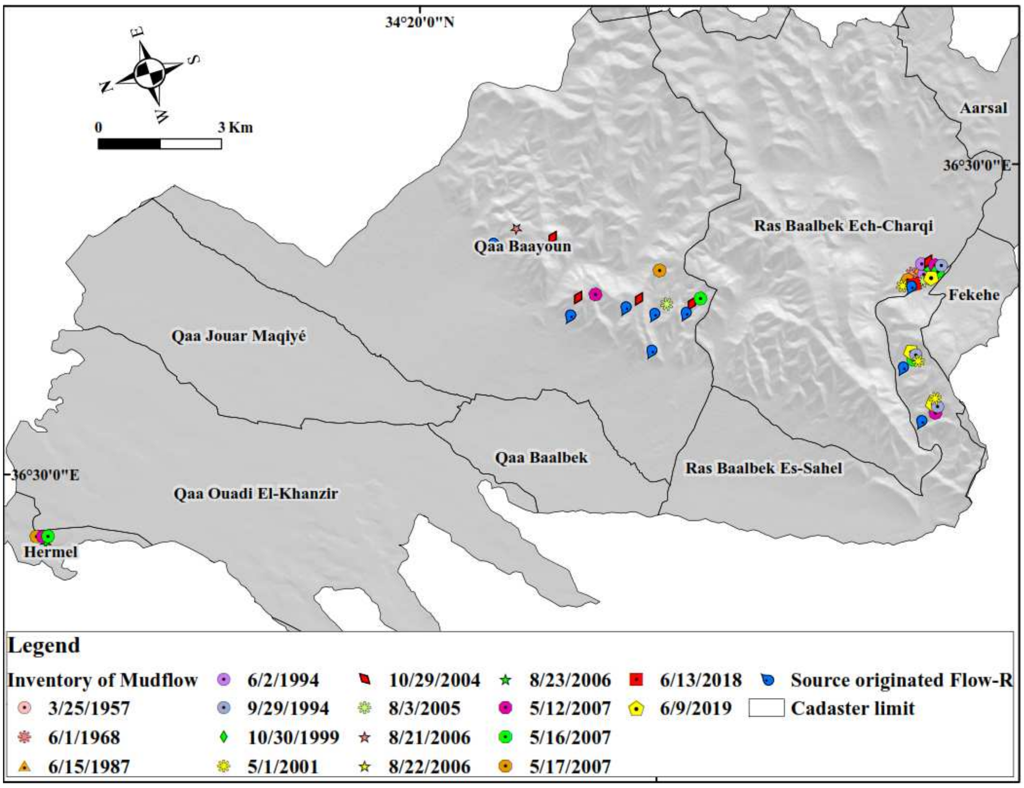

Figure 5.- Probability mudflow source map derived from the flow-R modelling in Ras Baalbek basin and inventory of Mudflow occurred in the basin from years 1957 to 2019

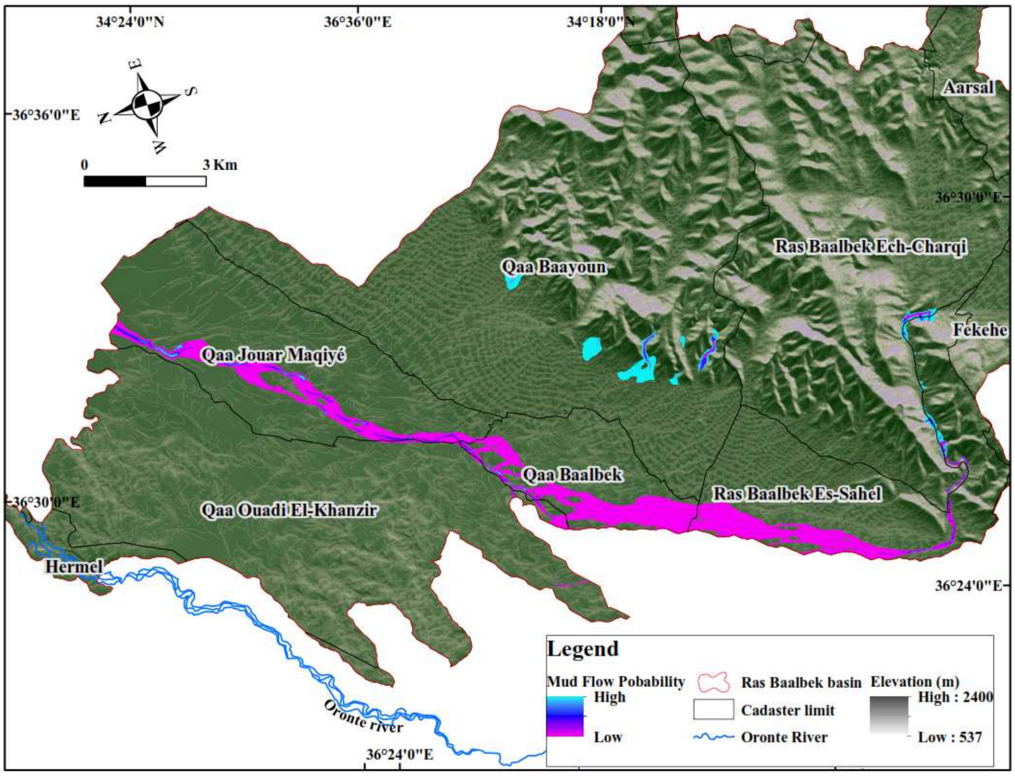

Figure 6.- Mudflow potential hazard map of the study area

The main finding of this model shows that the most threatening hazard arises from Ech Charqi valley, which is an intermittently flowing tributary feeding the Oronte River and crossing the village of Ras Baalbek (Fig. 6 and Fig. 7). Due to the higher velocity of this phenomenon, the “sail” even propagates on very gentle slopes and thus continues its natural route from Ech Charqi valley to Al Qaa plain (Fig.6 and photo 1). Other less frequent mudflows were delimited on the slopes that overlook the El Qaa region (Photo 2).

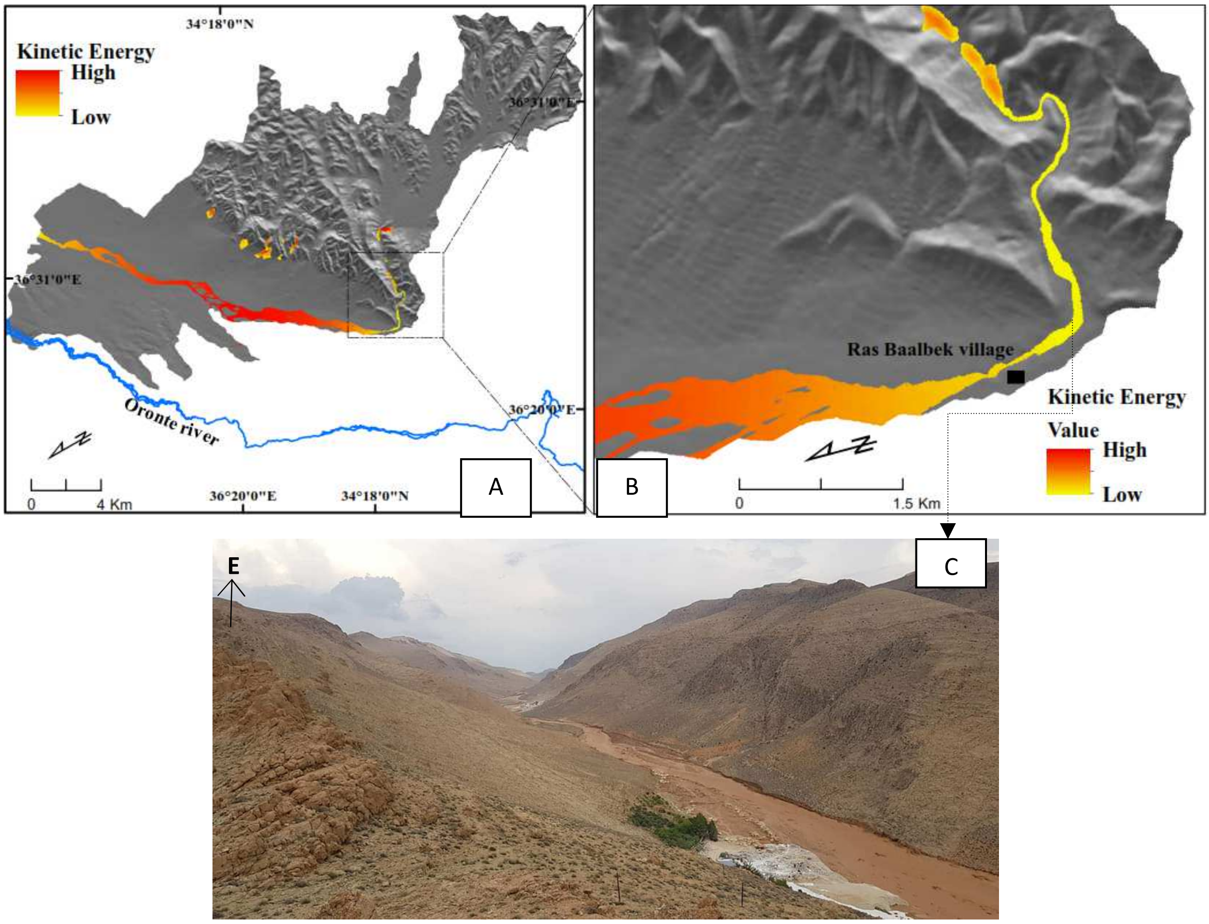

Figure 7.- Kinetic energy map derived from the flow-R modelling. A : kinetic energy map for the whole Ras Baalbek basin. B: view on the kinetic energy of the mudflow in the Ech Charqi – Ras Baalbek valley. C: photo of the sail occurred in Ech Charqi – Ras Baalbek valley on June 13, 2018

Photo 1.- The natural mudflow path (in red) in El Qaa plain

Photo 2.- Slopes overlooking the El Qaa region, sometimes affected by mudflow

These results fully coincide with historical data collected from newspapers, media, technical reports and scientific papers for the period between 1957 and 2019 (Fig. 5). This inventory provides evidence of 21 “sails”. Their spatial distribution shows that about 95% of events were recorded in four villages: Ras Baalbek (Ech Charqi valley), Aarsal, El Qaa and Hermel.

This phenomenon occurs in a rainy context followed by consecutive thunderstorms. The increase in precipitation is accentuated by soil saturation and inadequate rainwater drainage systems. The weakening of the environment by deforestation, amplified by climatic aggressiveness and the rugged topography accentuates the impact of the mudflow. However, the consequences produced by this phenomenon can have an effect on the natural environment and on the socio-economic characteristics (FABRE et *al*., 2017) of the area.

On the environmental level, at the upstream sector, the consequences result in the modification of the surface condition, which will be more sensitive as the rate of vegetation is low (BEN CHEIKHA & GUEDDARI, 2008, CHARBEL et *al.*, 2017). This generates water erosion risk and outcropping of bare rocks. At the downstream sector, where the slope gradient becomes relatively low, a large volume of sediment, mobilized during mudflow, was accumulated. In some cases, these deposits, which may contain fertilizing elements, improve the physical and chemical properties of the soil and offer better yields, especially in el Qaa plain (FEHI, 2014).

Economically, these deposits are indicative of the vulnerability of the study area. In addition to decadence in water quality, there is a sudden change in the landscape by shrouding lands reserved for annual crops and demolition of arboriculture. The impact of mudflow on urban infrastructure and urban fabrics can only be disastrous; overwhelmed by the level of the flow, homes and premises were inundated. Human practices have surely impacted the magnitude of this event. In fact, the extent of artificialized areas at the expense of arable land and perennial crops, linked to the growth in the local population, has favored soils waterproofing. Despite the role of municipal authorities in law enforcement, building standards are not always met.

After the two “sails” of 1994, the Ministry of Energy and Water, with the collaboration of the engineering consultancy company Khatib and Alami, executed the project entitled “protection of Ras Baalbek urban built-up and agricultural lands from the nuisance of the ‘sails’”. Despite the work carried out on Ech Charqi thalweg, to channel the flow, its insertion into the Ras Baalbek urban space had negative consequences by causing submersion of parts of this village.

In June 2018, one of the worst known mudflows was recorded in the Ras Baalbek village. The results left a deep mark on memories. Photos 3 and 4 present a particular view and were used to acquire information and testify the severity of the damages. The death of one person was recorded in addition to the silting up of agricultural lands and urban areas. Additionally, roads were submerged (photo 3.A) and the main channel was partially destroyed (photo 4).

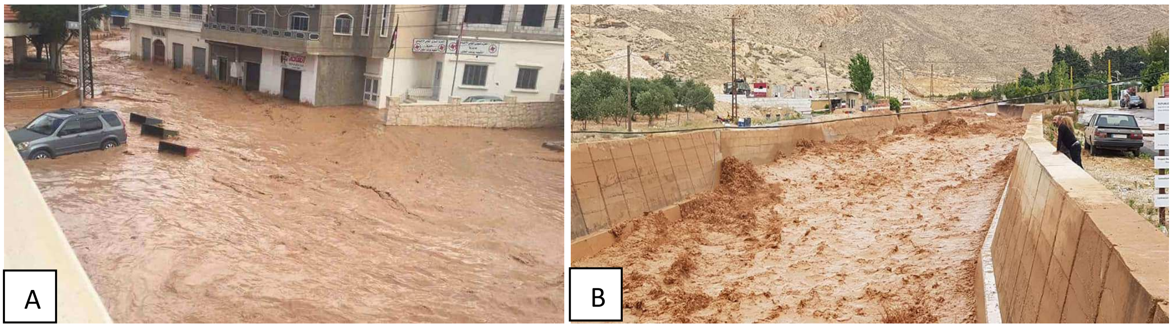

Photo 3.- A: The main road crossing the village was submerged and closed for several hours during the mudflow of June, 2018. **B:** the channel constructed after the sail of 1994 was flooding during the sail of June, 2018

Photo 4.- Roads and buildings affected by the sail of June 2018

CONCLUSION

Mudflow is an essential phenomenon related to erosion and sediment transfer in mountainous regions and represent a significant risk to the population. The recurrence of mudflow accentuates human and material losses and induces changes in the landscape. This hazard is emphasized by increasing human activity. Such a phenomenon requires the examination of the natural and anthropogenic factors that cause risks of such magnitude. Understanding the mudflow behavior in time and space, was possible through the application of a model that maps the vulnerable areas. This model, which incorporates the most representative factors (slope, land cover, flow accumulation, etc.), takes into account the geographic characteristics at local level.

This approach enables to first delineate the most susceptible areas to mudflow and second, to provide scientific knowledge to support the choice and implementation of mitigation measures, and limit future damage related to mudflow hazard.

The chosen method showed realistic results, with an acceptable correlation found between the modelling results (the spreading assessment based on probabilistic and basic energy calculations) and the observed events. Both indicate that Al Charqi valley that overlooks the Ras Baalbek village is the main source of mudflow in the basin. In addition, the Al Qaa plain, the natural outlet of Al Charqi valley, is receiving the highest amount of flood that covers a large part of the plain and adds nutrient sediments (mainly calcium) to the agricultural lands.

Nevertheless, this approach shows some limitations related to the control of the specific site conditions. In addition, the quality of the DEM was very essential because it provided the most important source of information such as upslope area, flow accumulation, curvature, and so on. Consequently, DEM with the highest resolution (5m*5m) may ensure better results. Moreover, this model should be applied to other basins witnessing similar hazards and having similar lithological and morphological characteristics to refine the threshold value for each model's criteria.

At the local scale, especially at the upstream section, mitigation measures should be applied to reduce the hazard of this phenomenon, such as:

- The widening of the channel crossing the village to the size of the maximum flow occurring for the past 70 years.
- Avoiding any additional construction along the "sail" path.

- The construction of two cofferdams located upstream and downstream of Ech Charqi valley to control the flow and regulate the amount of mudflow passing through Ras Baalbek village and El Qaa plain.
- The reduction of steep slopes by terracing to decrease the runoff velocity during thunderstorms. These terraces should be subject to reforestation with native trees to cope with the local climatic characteristics; tree roots preserve the consistency of the soil, reduce soil erosion, and promote permeability. Consequently, the volume of water flowing into the bed of the valleys will be decreased.

This study showed that the Flow-R model can be applied in Lebanon to delineate areas with mudflow hazard with representative results. Also, it is to note that special attention should be accorded to the lithological and morphological characteristics of each site when applying this model.

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REFERENCES

BEN CHEIKHA L. & GUEDDARI M. 2008. *Le bassin versant du Jannet (Tunisie) : évaluation des risques d'érosion hydrique.* M@ppemonde, 90 : 15 p.

BLANCHET G. 1976. *Le temps au Liban. Approche d'une climatologie synoptique*. Thèse de 3ème cycle, Lyon 2, 2 tomes, 447 et 366 pages.

CHARBEL L., EL HAGE HASSAN H. 2017. Modélisation de la perte de sol dans la forêt de Bkassine (Liban sud). *Geo-Eco-Trop*., 41, 31, n.s. : 479-492.

DELMONACO G., LEONI G., MARGOTTINI C., PUGLISI C. & SPIZZICHINO D. 2003. Large scale debris-flow hazard assessment: a geotechnical approach and GIS modelling. *Natural Hazards and Earth System Sciences*, 3 : 443-455.

DUBERTRET L. 1945. *Carte géologique au 1/50000. Feuille de Hermel et Feuille de Aarsal au 1/50.000.* Ministère des Travaux Publics, Beyrouth.

EL HAGE HASSAN H., FAOUR G., CHARBEL L. & TOUCHART L. 2019. Cartographie de l'aléa érosif dans le bassin sud du Litani-Liban. *Revue. Internationale de Géomantique* ; DOI: https://doi.org/10.3166/rig.2019.00072

EL HAGE HASSAN H., CHARBEL L. & TOUCHART L. 2018. Modélisation de l'érosion hydrique à l'échelle du bassin versant du Mhaydssé. Békaa-Liban, VertigO - la revue électronique en sciences de l'environnement [En ligne], 18, 1, mai.

EL HAGE HASSAN H., TOUCHART L., ARDILLIER CARRAS F. & FAOUR G. 2016. Lutte contre l'érosion agricole dans la plaine de la Békaa (Liban).M@ppemonde 117 (2015.1) :17p.

EL HAGE HASSAN H., CHARBEL L., TOUCHART L. 2015. « Cartographie des conditions de l'érosion hydrique des sols au Mont-Liban : exemple de la région d'El Aaqoûra », Physio-Géo [En ligne], Volume 9 | 2015, URL : http://physio-geo.revues.org/4572 ; DOI : 10.4000/*physio-geo*.4572.

EL HAGE HASSAN H., TOUCHART L., FAOUR G. 2013. La sensibilité potentielle du sol à l'érosion hydrique dans l'ouest de la Békaa au Liban.M@ppemonde 109 (2013.1).

FABRE M.S., OLLERO A., MORENO M.L., LOSADA GARCIA J.A., PUERTAS R.S., & NOTIVOLI R.S. 2017. « Évolution hydrologique et inondations récentes dans l'Èbre moyen », *Sud- Ouest européen* [En ligne], 44 | 2017, mis en ligne le 10 janvier 2019, http://journals.openedition.org/soe/3474 ; DOI : https://doi.org/10.4000/soe.3474

FEHRI N. 2014. « L'aggravation du risque d'inondation en Tunisie : éléments de réflexion », *Physio-Géo* [En ligne], Volume 8 | 2014, mis en ligne le 21 mars 2014. URL : http://journals.openedition.org/physio-geo/3953 ; DOI : https://doi.org/10.4000/physio-geo.3953.

FLAGEOLLET J.-C., MAQUAIRE O., MARTIN B. & WEBER D. 1999. Landslides and climatic conditions in the Barcelonnette and Vars basins (Southern French Alps, France), *Geomorphology*, 30 : 65–78.

GAMMA P. 2000. dfwalk-Ein Murgang-Simulationsprogramm zur Gefahrenzonierung, Geographisches Institut der Universitat Bern, Geographica Bernensia, G66, Verlag des Geogr. Inst. Univ. Bern, Bern, Switzerland, 2000 (in German).

HOFMEISTER R., MILLER D., MILLS K., HINKLE J. & BEIER A. 2002. Hazard map of potential rapidly moving landslides in Western Oregon, *Interpretive Map Series IMS-22,* Oregon Department of Geology and Mineral Industries.

HOLMGREN P. 1994. Multiple flow direction algorithms for runoff modelling in grid based elevation model. *Hydrol*. Process, 8 (4): 327-334.

HORTON P., JABOYEDOFF M., RUDAZ B. & ZIMMERMANN M. 2013. Flow-R, a model for susceptibility mapping of debris flows and other gravitational hazards at a regional scale, *Nat. Hazards Earth Syst. Sci.*, 13 : 869-885, doi:10.5194/nhess-13-869-2013.
HORTON P., JABOYEDOFF M. & BARDOU E. 2008. Debris flow susceptibility mapping at a regional scale, in: Proceedings of the 4th Canadian Conference on Geohazards, edited by: Locat, J., Perret, D., Turmel, D., Demers, D., and Leroueil, S., Quéebec, Canada, 20–24 May 2008, 339–406.
HUGGEL C., KAAB A., HAEBERLI W., TEYSSEIRE P. & PAUL, F. 2002. Remote sensing-based assessment of hazardsfrom glacier lake outbursts: a case study in the Swiss Alps. *Canadian Geotechnical Journal*, Vol. 39, (2) : 316-330.
HUNGR O., LEROUEIL S. & PICARELLI L. 2014. "The Varnes classification of landslide types, an update", *Landslides*, 11 (2): 167–194, doi:10.1007/s10346-013-0436-y.
RICKENMANN D. & ZIMMERMANN M. 1993. The 1987 debris flows in Switzerland: documentation and analysis. *Geomorphology*, 8, (2-3) : 175-189.
REY F., BALLAIS J.L., MARRE A. & ROVERA G. 2004. Rôle de la végétation dans la protection contre l'érosion hydrique de surface. *C. R. Géoscience* 336, 8p.
ROSS C.W., PRIHODKO J.Y. ANCHANG S.S. KUMAR W. JI. & HANAN N.P. 2018. Global Hydrologic Soil Groups (HYSOGs250m) for Curve Number-Based Runoff Modeling. ORNL DAAC, Oak Ridge, Tennessee, USA.
https://doi.org/10.3334/ORNLDAAC/1566
TAKAHASHI T. 1997. Estimation of potential debris flows and their hazardous zones: Soft countermeasures for a disaster, *Journal of Natural Disaster Science*, 3 : 57–89 (1981).
TARBOTON D. G. 1997. A new method for the determination of flow directions and upslope areas in grid digital elevation models. *Water Res.*, 33: 309–319.
doi:10.1029/96WR03137.
TRABOULSI M. 2004. *Les précipitations au Proche-Orient : variabilité spatio-temporelle et relation avec la dynamique de l'atmosphère (1960-61/1989-90).* Thèse de géographie, Université de Bourgogne, 233 p.
TRABOULSI M. 2010. La pluviométrie moyenne annuelle au Liban interpolation et cartographie automatique. *Lebanese Science Journal*, 11, 2 : 11-25.
WIECZOREK G.F., MANDRONE G. & DE COLA L. 1997. The Influence of Hillslope Shape on Debris-Flow Initiation. In: ASCE (Editor), First International Conference Water Resources Engineering Division, San Francisco, CA, pp.21-31.