Debris Flow Hazard Mapping Along Linear Infrastructure: An Agent Based Model and GIS Approach

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Abstract. Often linear infrastructure, including rail, highways, and pipelines, span large geographic areas intersecting a variety of terrain, predisposing infrastructure to a higher likelihood of geohazard interaction. Debris flow models can be particularly advantageous in remote hazard and risk mapping along linear infrastructure as runout from susceptible slopes may extend considerable distance downslope to a receptor. In this sentiment, a method is developed using an agent-based model, DebrisFlow Predictor, in combination with geographic information software (GIS), to produce regional debris flow hazard and risk profiles along widespread corridors. Thousands of debris flows upslope of a receptor(s) are simulated in the model environment (i.e., model scenarios). Outputs of the modelled scenarios provide probabilistic spatial attributes of debris flow runout and depth across a digital elevation model at a 5m resolution. The outputs of multiple scenarios are mosaiced and corrected to in-situ temporal and spatial debris flow initiation conditions in GIS. The corrected scenario outputs provide a comprehensive hazard profile along the infrastructure alignment, that in turn can facilitate quantified vulnerability and risk calculations. Thousands of modelled debris flows throughout several physiographic regions of Canada and the United States of America, calibrated to local conditions, provide substantive support for a novel methodology to identify key hazard and risk locations to major linear infrastructure.

1 Introduction

The novel methodology outline by this paper was developed using a specific agent-based model, DebrisFlow Predictor; however, it should be clarified the method is model agnostic, so long as the model has the functionality to provide probabilistic spatial outputs of runout occurrence and depth.

1.1 DebrisFlow Predictor Primer

Often linear infrastructure, including rail, highways, and pipelines, span large geographic areas intersecting a variety of terrain, predisposing infrastructure to a higher likelihood of geohazard interaction. Debris flow models can be particularly advantageous in remote hazard and risk mapping along linear infrastructure [1-3]. DebrisFlow Predictor (DFP) is a shallow landslide runout software that provides probabilistic spatial outputs of deposition and scour along a simulated landslide path. The path, or rather simulated runout, is produced by agents interacting with the topographic conditions of a 5-metre digital elevation model (DEM), and other surrounding agents in the model environment. These interactions are defined by a set of empirically derived distribution curves [4]. As an agent moves downslope through a series of time-steps, it makes decisions to entrain or deposit sediment along its route. Running the simulation from static initiation locations results in probabilistic runout paths, that can be exported out of the model environment to GIS for further analysis.

1.2 Hazard Primer

The definition of hazard varies throughout disciplines, making it a necessity to define the term in the context of its use [3]. The definition formally adopted by the UN Office of Disaster Risk Reduction (UNDRR), '*a process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradatio*n' [5]. In this context and for the purposes of defining hazard ($H_{T,S,R}$) in this paper as it relates to debris flows, the term can be considered as a three-part function, whereby:

$$H_{T,S,R} = H_T \times H_S \times H_R \tag{1}$$

H_T is the probability of landslide initiation per unit of time, H_S is the spatial probability of landslide initiation per unit area and H_R is the likelihood that the hazard will reach a portion of the landscape; H_R is further defined by a function of two factors, that are provided later.

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2 Method and Discussion

2.1 Determining Runout Hazard (H_R)

In consideration of equation (1), modelled outputs are used in combination with GIS to determine H_R. The first step in the process is to define initiation locations for the landslide simulations; in this instance, a grouping of initiation locations run under a similar set of calibration parameters in the model is referred to as a scenario.

To create scenarios, GIS is used to identify susceptible ground and define debris flow initiation locations; whereby susceptible ground is terrain where debris flows may occur. While there are many methods of delineating susceptible ground and probable debris flow initiation locations [6-8], the overall intent of this selection exercise is to provide an adequate spatial density of landslide initiation points upslope of the receptor. The density of initiation locations must be such that the intersecting runout at the receptor can be considered irrespective of the initiation location – this concept is later discussed. To propagate initiation locations for scenarios, a fishnet grid of points is draped across the region, at a defined interval spacing. Those points within the grid that intersect defined susceptible ground are then extracted as initiation locations and used to develop scenarios (***Fig.1***). In most instances, a 150-metre spacing is a good starting point at a regional landscape scale to balance the spatial density and processing expense of the model; however, it is not uncommon to adjust this spacing based on the regional conditions and model capacity.

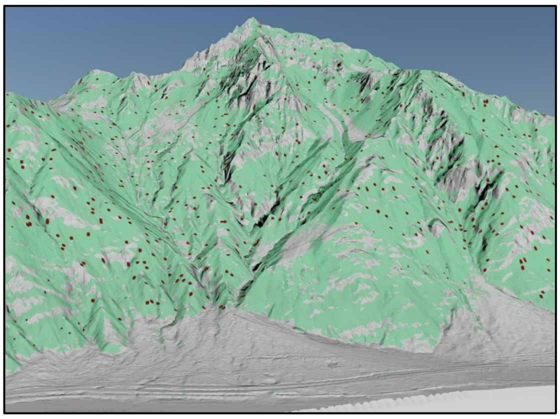

Fig. 1. Example of selected initiation locations (red points) for model scenarios relative to susceptible ground (green).

The selected initiation points are then grouped into scenarios by assigning a random number between a user defined ranged. The range of scenarios should adequately divide the initiation locations into groups that account for the complexity of terrain and landslide processes in the region, with the overall intent of reducing landslide interaction in each individual scenario simulation. This step is often reliant on assessor judgement of in-situ or remote imagery observations of landslide density in individual catchments (i.e., the assessor must increase or decrease the range of possible scenario groupings to better replicate the observed in-situ landslide density and event interaction in each individual scenario).

Once the scenarios are developed in GIS, they are imported into the model environment and run a multitude of times (also referred to as *looping*). The number of loops completed for each scenario is reliant on assessor's judgement to balance the processing expense of the model and assessment goals. Aggregated outputs from each looped scenario, that include the spatial occurrence and depth information, are then exported from the model environment and imported to GIS for further analysis.

Within GIS, modelled debris flow depth results are converted to raster format and averaged using common overlay analysis methods. Average depths can then be later used to facilitate vulnerability, or rather consequence and ultimately risk, calculations along the receptor [9,10].

Determining the average runout, or H_R, requires additional processing steps and is somewhat more abstract. Because multiple scenarios were run from varying initiation points across the region, and in some instances not all scenarios interact at the same location, the probability of the runout occurrence within each discrete scenario and the probability of runout occurrence within the overall modelled scenario space must be reconciled. This can be referred to as the inter-scenario probability (P_{Run}) and the intra-scenario probability ($P_{Scenario}$), respectively, whereby the function of these two probabilities results in the overall runout probability (H_R) of the modelled conditions. This can be expressed as the following:

$$H_R = P_{Run} \times P_{Scenario} \qquad (2)$$

Whereby at any given pixel location in the model:

$$P_{Run} = (\sum Ec)/((\sum Sc) \times Rc) \qquad (3)$$

And,

$$P_{Scenario} = (\sum Sc)/S \qquad (4)$$

Whereby,

Ec = Number of times that a pixel location was intersected by an agent in all model scenarios (e.g., Out of four scenarios run 100 times each, a pixel was intersected fifty times in the first scenario, one-hundred times in the second, three times in the third and no times in fourth. Ec in this example is 153).

Sc = Number of scenarios that intersected the raster pixel, or 'scenario count'. S_C is three using the example above.

Rc = Total number of runs completed for one scenario. Referring to the example, each scenario was run 100 times, so Rc is 100.

S = Total number of scenarios completed. Continuing with the example, S is equal to four.

By these means, H_R at any discrete location is independent of the debris flow initiation location to a degree of uncertainty, that include the model and assessment limitations. Rather, if the assessor was successful in scenario development, a sufficient density of landslides should be simulated upslope of the receptor throughout the course of all scenarios, such that the convergent and divergent topography encountered by the landslide agents as they travel downslope in the model environment, concentrate the variability of runout, and ultimately accommodate for other possible initiation locations within that catchment that were not simulated [11]. This assertion is further bolstered by a Monte-Carlo analysis of runout in the model space, and the necessity for the assessor to balance the number of modelled runs and initiation density of the scenarios to satisfy the accuracy goals of the assessment. Simply, the denser landslide initiation grouping is in each scenario, and the more travel time each agent has in the model, the more reliant H_R results will become.

Fig. 2. Example of $\mathrm{H_R}$ probability as determined from scenario locations depicted in Figure 1.

2.2 Combining Runout Hazard (H_R) with Hazard in Time and Space ($H_{T,S}$) to Determine Comprehensive Hazard ($H_{T,S,R}$)

The means of calculating H_R result in a unitless probability that is ultimately independent of the upslope initiation location. In this respect, H_R determined for the model space, must be corrected to accommodate for the in-situ hazard in time and space, or $H_{T,S,}$, if the assessment goal is to provide comprehensive hazard (i.e., $H_{T,S,R}$).

To accomplish this, the assessor must establish the in-situ $H_{T,S}$ of the study area. This can be completed through many different methods, which are not the topic of this paper, but generally can be facilitated with a landslide inventory or field assessment [12,13]. It should be apparent that $H_{T,S}$, or recurrence interval, requires time and area units (e.g., landslides/hectare/year).

Once $\mathrm{H_{T,S}}$ is determined, the assessor can utilize the binomial probability formula (*eq. 5*) to determine the probability of a discrete landslide initiation scenario. For example, in most assessments it may be important for the assessor to understand the probability of '*at least one landslide*' occurring; however, varying assessment goals may constitute determining other landslide initiation probabilities. Foregoing hypotheticals, the assessor can simply adjust the binomial probability equation as needed for a varying amount of landslide initiations to suit the assessment goals. In an instance where $\mathrm{H_{T,S}}$ probability nears or exceeds one, an exceedance probability should be utilized in lieu of the binomial probability formula; however it is rarely the case to have such a high $\mathrm{H_{T,S}}$ probability in a wide-spread regional assessment. For the purposes of discussion, the binomial probability formula below is defined for at least one successful event, or rather, landslide initiation within a region.

$$P(x\geq1) = P(x=1) + P(x=2) + P(x=3)\ldots+P(x=n) \quad (5)$$

$$P(x) = {}^{n}C_{x}p^{x}(1-p)^{n-x} \quad (6)$$

Whereby,

n = Number of trials, or rather study area size, for which a successful event may occur (e.g., if a study area is 10 km^2, n = 10)

x = The interested number of successful trials, or landslide initiations (e.g., 0, 1, 2, 3, 4…)

p = Probability of success in a single trial, or rather the in-situ $\mathrm{H_{T,S}}$ probability determined by the assessor.

Once the binomial probability is established for a given number of landslide occurrences, that represents the in-situ $H_{T,S}$ condition, the probability must be corrected to reconcile the modelled scenario conditions before multiplying it by H_R. Rather, it is likely that a magnitude, or more, of landslides were initiated in each scenario in the modelled environment relative to the in-situ conditions, and thus, a correction factor must be applied to the binomial probability to ensure the factors of hazard (*eq.1*) are equivalent. This is simply accomplished by dividing '*x*', from equation 5 above, by the average number of agents in all scenarios and multiplying that value by the discrete probability determined for the corresponding '*x*' trials. The corrected probability, now representing the $H_{T,S}$ probability of the modelled conditions, can be multiplied by H_R to determine the comprehensive hazard profile, or $H_{T,S,R}$ (Fig.3).

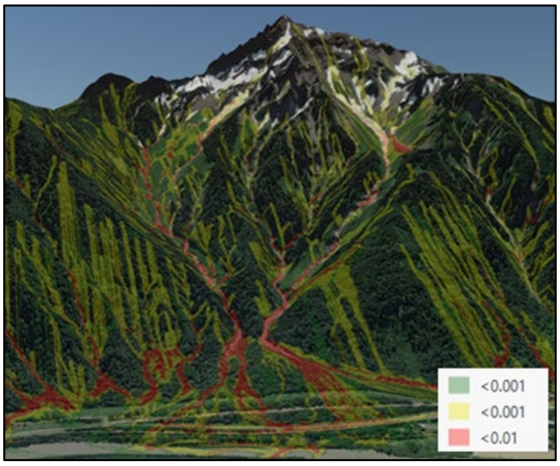

Fig. 3. Example of $H_{T,S,R}$ probabilities following correction to H_R shown in Figure 2. Note, the inverse of the probabilities shown would represent the recurrence interval of hazard.

3 Conclusion

New methods for remotely assessing hazard are becoming available as processing capacity and higher resolution data become readily accessible [14]. The approach of utilizing a novel agent-based model, such as DebrisFlow Predictor, in such a manner has enabled the quantification of probabilistic hazard results across widespread regions with modest limitations and arguably astounding visual aids in support of communicating results. Quantified spatial hazard information also translates to a means for qualified professionals to quantify risk, in most facets, providing communities, government agencies, and industry with quantitative data to make informed decisions on mitigation.

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