Effects of Sediment Condition on Debris Flow Magnitude in Penticton, BC.

Zhenni Jiang, April, 2016

Abstract

Sediment sizes, saturation degrees, consolidation degree and sediment types all suggest significant impacts on debris flows from different aspects. The study regions are located in Okanagan-Similkameen and Penticton regions, which reflect similar environmental backgrounds dilemmas in terms of debris flows and slope erosions. By using the h/d_e =50 as the divider to operate the two-phase model and Manning's model, conclusions of sediment size work differently under two situations, and other sediment conditions also affect debris flow velocity with different severity.

Introduction

Penticton is situated within the Okanagan Valley between the Okanagan Lake and Skaha Lake. The focus study areas are the surrounding areas of Penticton Creek and the Ellis Creek that originate from the City of Penticton and Okanagan-Similkameen region, which end in the city of Penticton and flow into the aforementioned two lakes. Theses two creeks are both confined by V-shaped valleys that they flow through. The Penticton Creek sources from the Greyback Mountain and passes through the Greyback Lake with a drainage area of 70 square miles, while the Ellis Creek sources from a mountainous region as well (Ferguson et al., 2008).

The weather patterns in both creek areas have changed for the past several decades. In recent years, late spring snowmelt and early spring rain encounter, which make raining on snowpack possible and intensify the convective storms in the summer within the Okanagan basin area. This kind of storm event sometimes exceeds the natural hazard resisting capacity and harder to stay at the steady state level that increases the probability of slope failure.

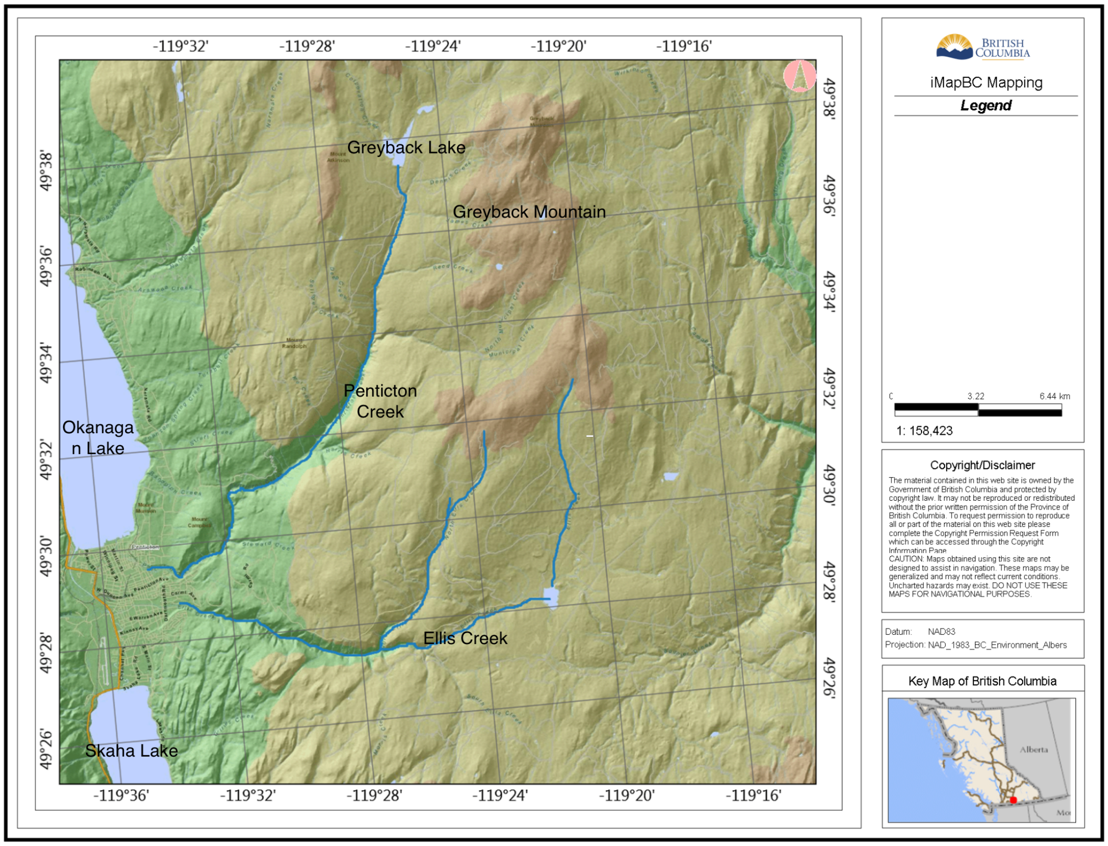


Figure 1. This map delineates the Penticton Creek and Ellis Creek, their flow areas and their source areas. The map is made by using the iMapBC2 with terrain data from DataBC (2016).

Recent anthropogenic activities also abet in increasing occurrence of debris flow and worsening the status gradually. The typical examples are constructions (road building and dam) and logging activities. As figure 2 shows, there is a tremendous amount of logging activities happening around these regions for decades and it has a significant effect on making the circumstance more severe.

In this research paper, I will first introduce the study region and make assumptions, then briefly describe the method I will use and the models I will apply to derive the results. In the end, I will present the conclusion based on the analysis I will make, and discuss the limitations and strengths of this research comparing with other research.

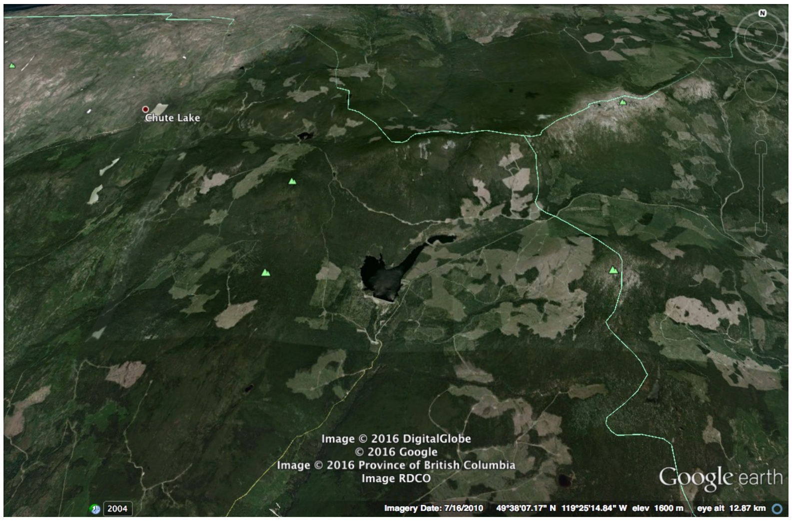


Figure 2. This map image shows clear-cutting scars in the Greyback Lake neighbouring areas. It is retrieved from the Google Earth (2010)

Study Areas and Assumptions

10 debris flow scars along the Penticton Creek (7) and Ellis Creek (3), and 1

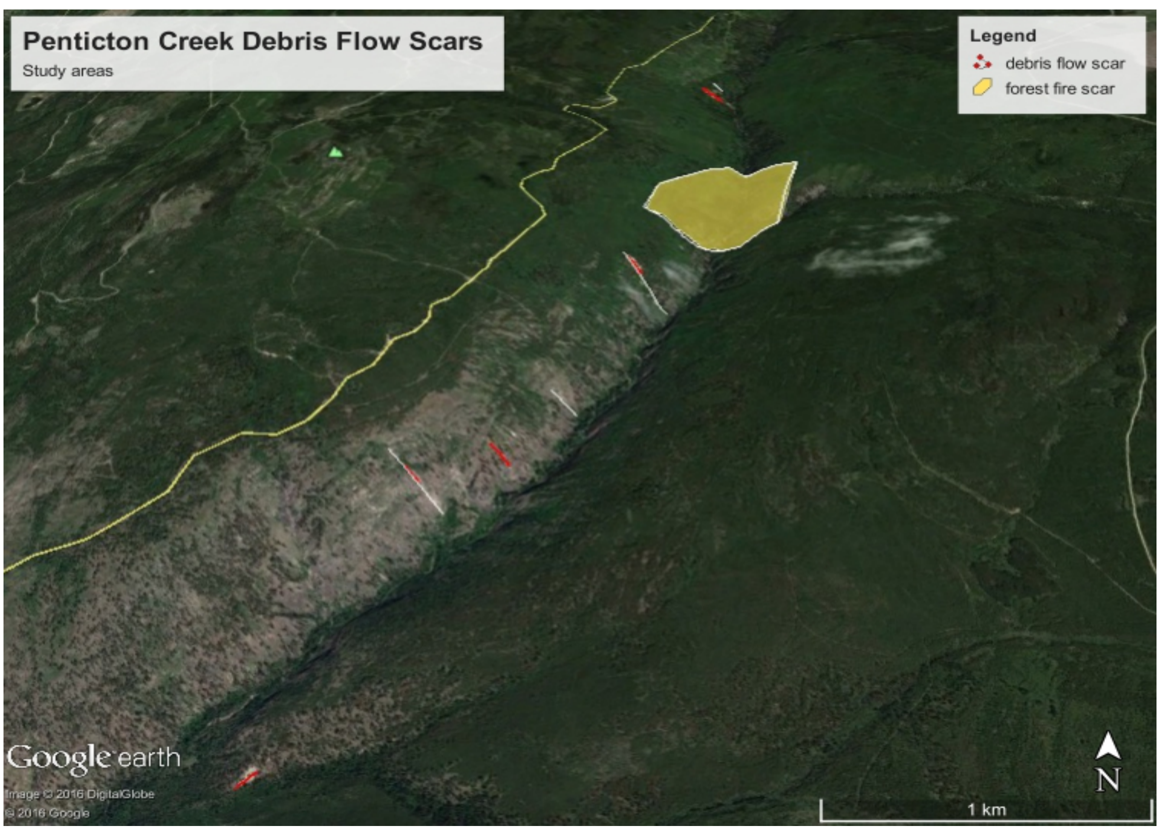


Figure 3. This map shows the Penticton Creek study area and its topography. This map is retrieved from Google Earth (2010).

forest fire scar within Penticton Creek region are chosen for this study. The objective of the research is to find the relationship between sediment condition in terms of sediment size, type, saturation degree and consolidation, and debris flow magnitude based on velocity, run-out distance, flow depth and frequency.

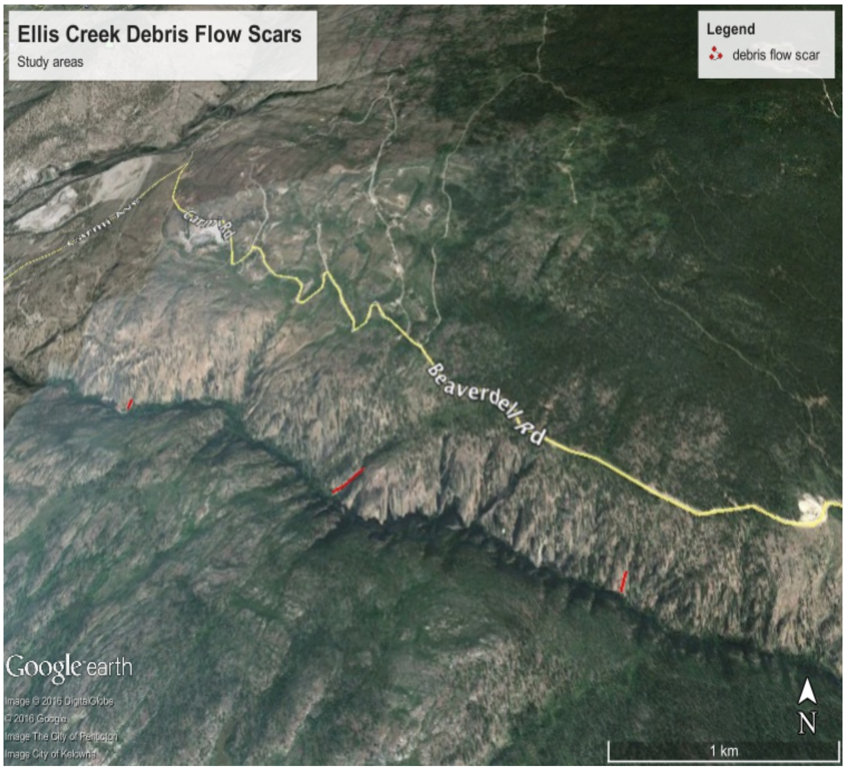


Figure 4. This map shows the Ellis Creek study area and its topography. This map is retrieved from Google Earth (2013).

As the map shows, along the valley margin, road constructions are continuous by the creek and the debris flows happen more frequently on the side where has road passes by. Therefore, I assume that (1) Anthropogenic activities (logging, road building and other constructions) would change the sediment condition and increase the failure chance. (2) The grain size would influence the debris flow magnitude. (3) The sediment saturation degree, sediment consolidation and sediment type would influence the debris flow magnitude.

Method

In order to acquire data of the variables that I will analyze, (a) I download the data from the GEOGRATIS and the DATABC, and input them into the ArcGIS or the iMapBC2 (an open source online map platform) to complete the transformation of data from raw material to visual image; (b) I attain original data from government websites and process them through Matlab by substituting different variables of the following to-be-mentioned model, then apply the processed data into Excel to generate visual graph. Thereby, based on the above procedures and outcomes, final analyses and conclusion can be made. At last, to compare my results and analysis with other published journal articles and survey report, to examine my research and its accuracy, meanwhile, to evaluate the value of the models and whether it can be used for further research.

Model

Researchers deduced that the Dispersive momentum model with rheological equations works appropriately when it is a thin debris flow whereas overestimate the velocity when it gets viscous; the Manning-Strickler Equation works better when it is a viscous and thick debris flow case (Julien, 2010). Therefore, I divide the debris flow into two parts: when the ratio of debris flow depth to grain size is less than 50 and larger than 50. In this research, I will focus more on the first model.

Model 1: Two-phase fluid model (for $h/d_e<50$, h is the debris flow thickness)

This model is designed to reflect the interaction between two phases – solid phase and liquid phase, and to obtain the steady velocity of the debris flow. The composition of the model includes mass conservation equation, momentum equation, the rheological equation of the Bingham flow and quadratic function. It also embodies the buoyancy effect, the surface forces, the internal resistance and fractions between sediment particles.

The model can be written as

Solid phase:

$$Vsx^2 = \{[\varphi\rho_s + (1-2\varphi)\rho_f]gsin\theta + (\tau_B + \mu b)d_0\}\frac{2x}{(2k+1)\rho_s} - \frac{2d_e(1-\varphi)^2}{3k\rho_s}[(2\rho_f - \rho_s)gsin\theta + (\tau_B + \mu b)d_0][1 - \exp(\frac{-3kx}{(2k+1)(1-\varphi)d_e})]$$

Liquid phase:

$$Vfx^2 = \{[\varphi\rho_s + (1-2\varphi)\rho_f]gsin\theta + (\tau_B + \mu b)d_0\}\frac{2x}{(2k+1)\rho_f} + \frac{2d_e(1-\varphi)^2}{3k\rho_f}[(2\rho_f - \rho_s)gsin\theta + (\tau_B + \mu b)d_0][1 - \exp(\frac{-3kx}{(2k+1)(1-\varphi)d_e})]$$

ρ_s is the density of solid particles, ρ_f is the density of the liquid slurry, φ is the solid volume fraction, g is the gravity acceleration, θ is the gradient of debris flow groove, τ_B is the yielding stress of debris flow slurry, μ is the viscous coefficient of debris flow slurry, b is the coefficient of velocity of slurry to y while y is the internal depth of the debris flow body, d_0 is the equivalent radius of control volume, x is the run-out distance in the direction of the debris flow goes, k is the non-uniform coefficient of debris flow body, d_e is the equivalent diameter of solid particles, exp (.) is the exponential function (Guo et al., 2014).

V_{sx} and V_{fx} can then be calculated by utilizing the square root for the above two equations, so as to receive the estimated velocity of debris flow in respect of solid phase and liquid phase. In the above equations, the $[\varphi\rho_s + (1-2\varphi)\rho_f]gsin\theta$ accounts for the volume force of the liquid phase that represents the gravity and buoyancy effects; the $(\tau_B + \mu b)d_0$ represents the turbulence effect and resisting force of slurry in control volume combining with quadratic function, in this study, I assume it to be 100 as Guo and his fellow researchers do; the minuends of the right side equations displaying the total kinetic energy while the subtrahends are on behalf of the influences that the two phases exert on the kinetic energy; by integrating all the elements and omitting the limited influential fractions, the above equations are formatted (Guo et al., 2014).

Model 2: Manning-Strickler Approach (For $h/d_e>50$)

The Manning-Strickler Model is attested by Julien and Paris, relating to predicting the debris flow mean velocity. As shown below:

$$V = 5.75u^{*} log \frac{h}{d_{50}}$$

u* is the shear velocity that can be defined as $\sqrt{ghS}$ (g is the gravitational acceleration, h is the flow depth and S is the slope gradient), log $\frac{h}{d_{50}}$ is the logarithm of flow depth to median grain diameter. (Julien & Paris, 2010).

Therefore, the equation can be rearranged as:

$$V = 5.75\sqrt{ghS} log \frac{h}{d_{50}}$$

By replacing the variables from the equation while keeping others constant, we can get the velocities of the debris flow under different sediment related conditions (grain size, slope degree, the viscosity of sediment bulk).

Result and Analysis:

Velocity changes in different ways with different patterns when assuming everything else constant and only the variables that we presume to alter.

From figure 5, we can observe that as k increases, the velocities of both phases decrease accordingly. This can be explained by the lower degree of material uniformity would increase the frictions among the materials so that increase the material shear strength (SS), hence slower velocity is performed by nonuniform debris flow whereas higher velocity is revealed by uniform debris flow under the same conditions (Seo et al., 2015; Blijenberg, H. M., 2007; Kaitna et al., 2014).

Velocity also decreases as the solid volume fraction increases, which is related to the results of 1. Because the pressure/velocity is a function of k and φ, it can be interpreted that k and φ are positively interrelated (Guo et al., 2014). Furthermore, as the

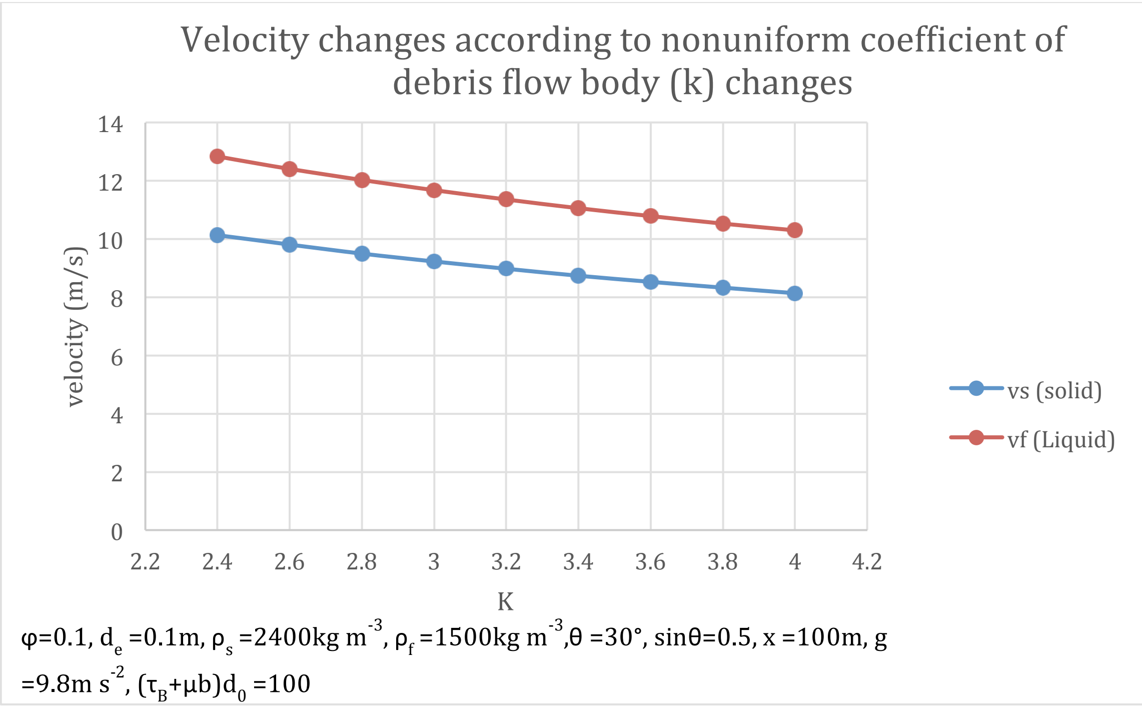
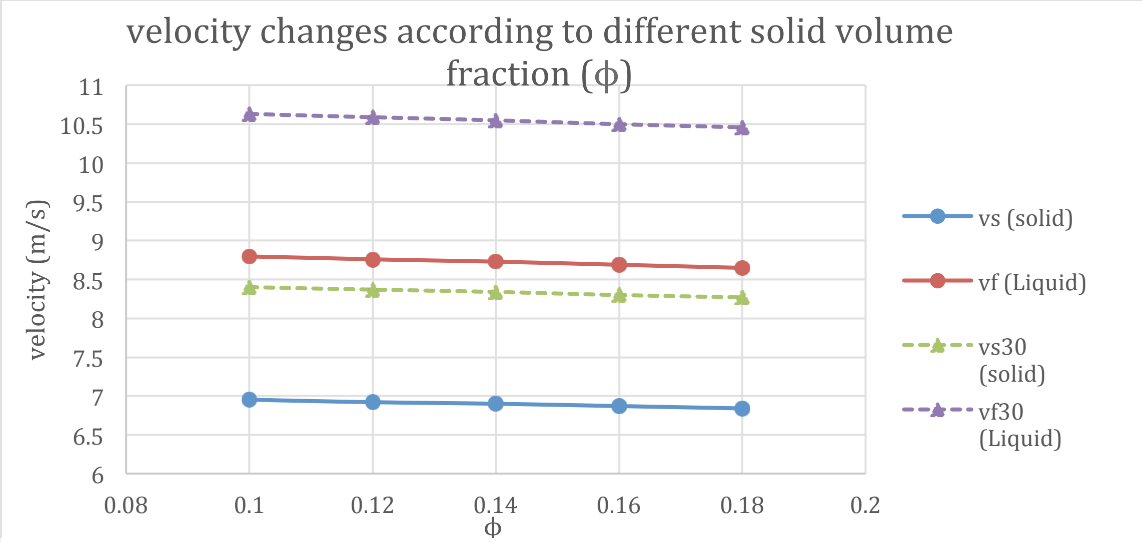


Figure 5. This graph shows the velocity changes as k increases ($k \in (2.4 - 4)$). This result is obtained by applying the Model 1.

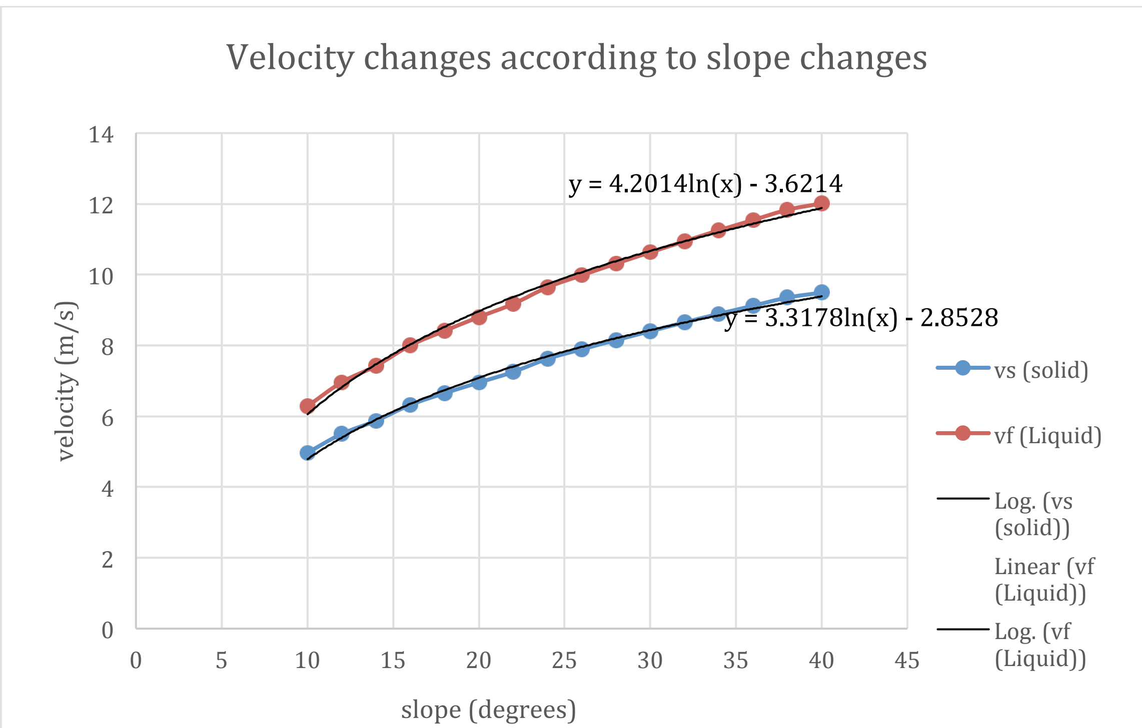
slope increases by 10 degrees, the velocity also increases by 1.5 m/s for solid form and 2 m/s for the liquid phase (figure 6). The reason will be discussed in the following part in detail.

As figure 7 shows, the velocity increases along with the slope raising. Also, as the multiplier of the natural logarithm is larger for liquid phase than the solid phase, it implies that the liquid form of material increases faster as regards to debris flow velocity than solid phase does under the same slope condition. In this case, it signifies that the more viscous the debris flow is, the lower velocity will be (in the setting that the diameter of particles is greater than the critical diameter); in other words, the more saturated the particles are, the higher velocity and liquidity it will reach under the non-Newtonian fluid condition (Guo et al., 2014). This is proved by Chen's research, in which suggests that the critical shear stress is higher for less saturated materials with larger resistance to



vs and vf: d_e =0.1m, ρ_s =2400kg m^{-3}, ρ_f =1500kg m^{-3},θ =20°, sinθ=0.34, x =100m, g =9.8m s^{-2}, $(\tau_B+\mu b)d_0$ =100, k=3.72;
vs30 and vf30: same as above except that θ =30°, sinθ=0.50

Figure 6. It shows the trend of solid volume fraction changes affecting the debris flow velocities. φ ranges from 0.1 to 0.18. This result is obtained by applying the model 1.



ϕ=0.1, d_e =0.1m, ρ_s =2400kg m^{-3}, ρ_f =1500kg m^{-3}, x =100m, g =9.8m s^{-2}, $(\tau_B+\mu b)d_0$ =100, k =3.72

Figure 7. This graph presents the velocity changes according to slope changes. The independent variable “x” of the two trendlines denotes for slope degree, and the dependent variable “y” stands for velocity as the vertical axis represents for. Slope ranges 10 - 40 degrees. This result is obtained by applying model 1.

steeper slopes. Moreover, it proposed that environmental consideration also emphasizes its role in shaping the slope regarding sediment type and by changing the sediment profile referring to saturation degree and erosion rate (Chen, 2005). Such environmental facets include extreme climate events as examples of storms and continuous rainfalls.

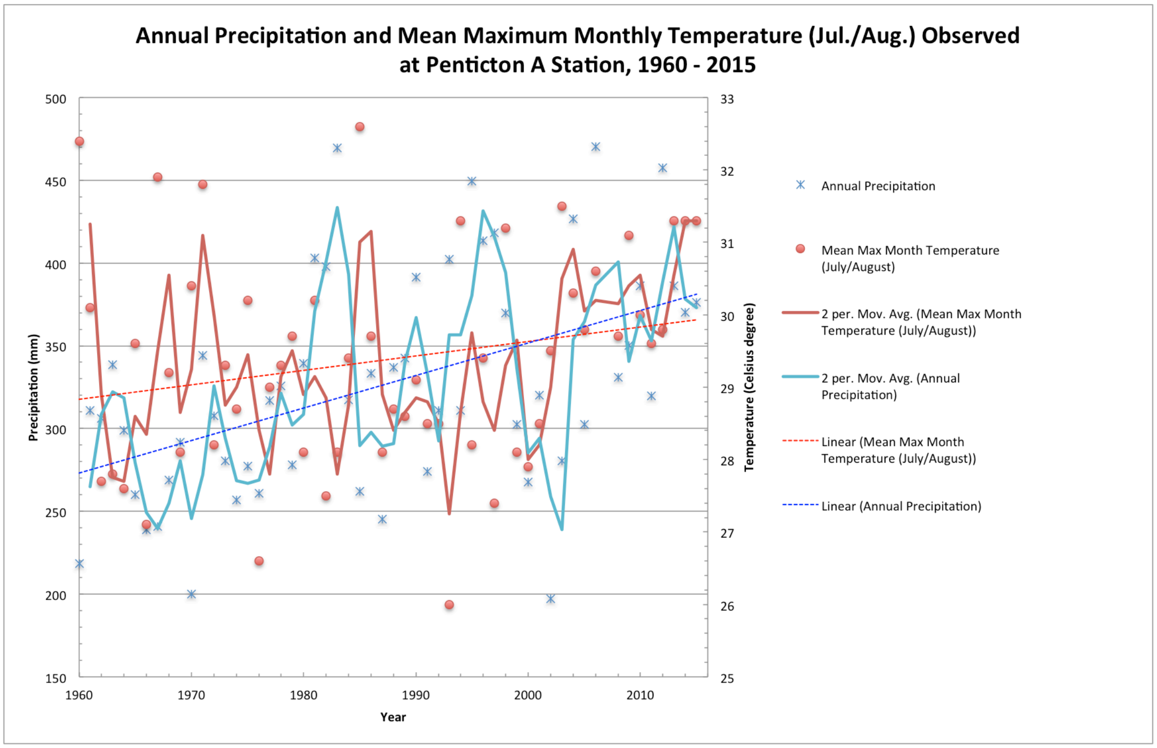


Figure 8. Annual precipitation is calculated based on data retrieved from www.climate.weather.gc.ca (1960-2015); Mean maximum monthly temperature (July/August) data are retrieved from www.climate.weather.gc.ca (1960-2015). The dash lines depict the general trend of both features according to year changes and the moving average curves depict the fluctuation of both features according to year changes.

In the past several decades, records disclose that the climate change has positive feedback on debris flow frequency and magnitude. The annual precipitation and the mean maximum monthly temperature both increase a lot during the 1960-2015 period: the annual precipitation has increased 100 mm while the temperature has increased one Celsius Degrees for the hottest month. Another phenomenon is that both of them are appearing as fluctuating toward the opposite direction at the same time, when the temperature goes up, the precipitation drops down. This raises the number and magnitude of extreme events due to low evaporation with large discharge induced debris flow on one hand, and drought generated low cohesion soil that increases the slope instability on the other hand. Referring to either situation, both deteriorate and change the soil condition in terms of critical shear stress and saturation degree. Another aspect is that the warming trend tends to increase the risk of wildfire, which is highly likely to change the soil profile in short run and threats to yield more sediment than undisturbed areas, and due to this, the plane is more likely and more frequently to suffer from lower magnitude events induced greater magnitude debris flows (Nyman et al., 2015).

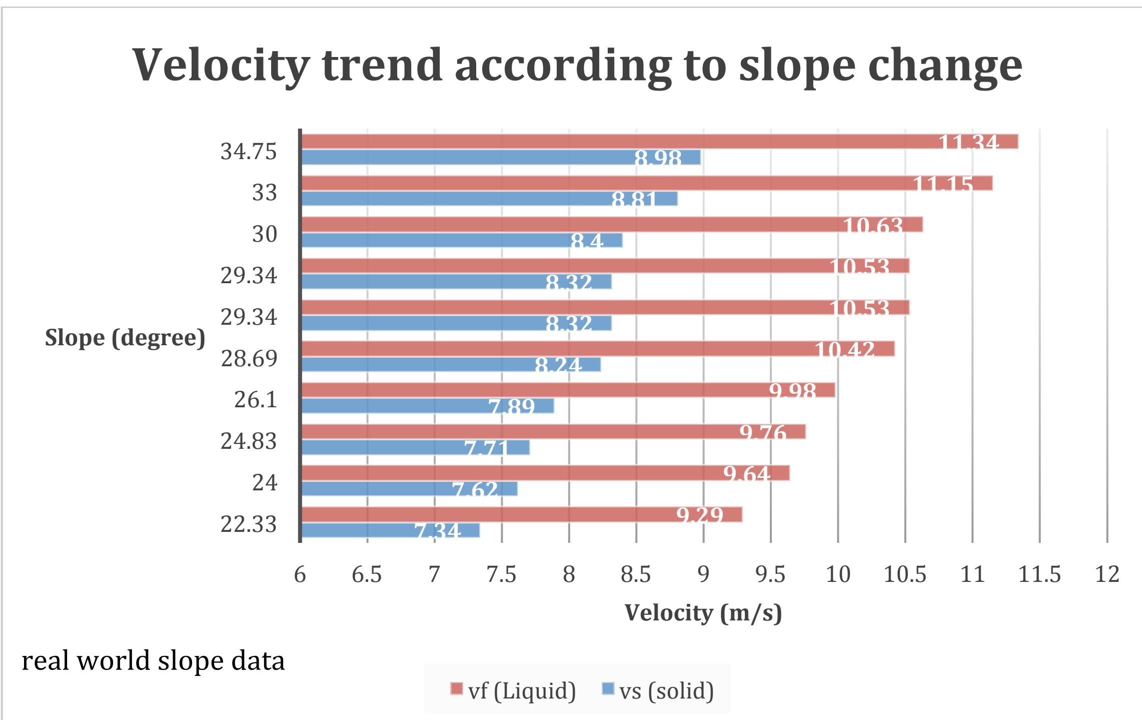


Figure 9. It shows velocity trend according to slope changes. This result is based on the real world data.

From the pie graph, we can notice that debris flows that happened in Penticton areas were mostly occurring on slopes between 26-30 degrees, and secondary mostly on slopes between 20-25 degrees. This phenomenon reveals that debris flows usually happen on steep slopes with 20 degrees and above (figure 9 & 10). As shown in figure 11 and 12, based on figure 1, both Penticton Creek and Ellis Creek have many steep sections and predicted to be unstable. From one aspect, this may attribute to the climate warming and precipitation increase that increase the erosion rate (Zini et al., 2014); from another side, upslope and upstream logging activities may account for the increasing instability of slopes. Besides, the increasing number of debris flows probably has positive feedback on further eroding the slopes that may result in turning the "V" shaped valley into "U" shape (Chen, 2005).

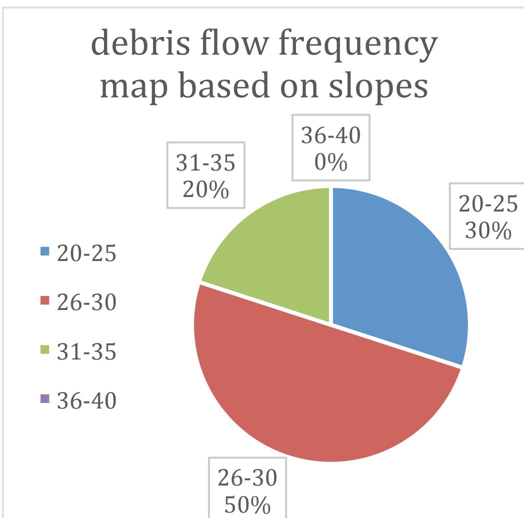


Figure 10. (left) This pie graph shows the debris flow frequency distribution based on slope ranges. This result is obtained through categorizing Penticton study regions debris scars slopes.

Sediment types and bedrock material also influence the erosion rate and the slope stability. In the Penticton and Similkameen areas, soil profile is mainly composed of the morainal material, glaviofluvial material, sand and colluvium based on data retrieved from DataBC. Also, it is present as soft and friable silt loam for depth from 0 to 10'' from the surface and stratified silt, silty clay, clay and very fine sands parent material, which means that this kind of material is easy to get eroded and saturated, meanwhile, the bed material is unstable due to its loose structure and it is easily affected by intensified pore water pressure (figure 13; Kelley & Spilsbury, 1949). Moreover, based upon soil survey that is conducted within the whole Penticton boundaries, over-irrigation for agricultural use and over-withdrawal of tailing water contribute to the collapses of gully sides and

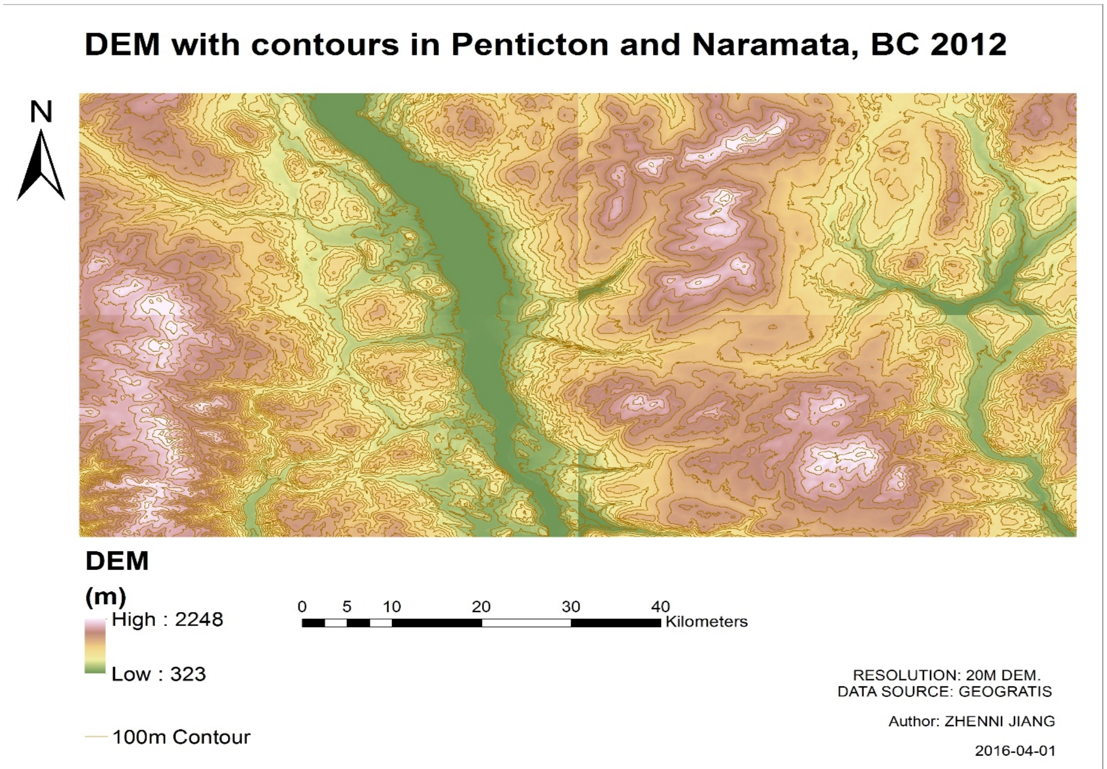


Figure 11. The map above displays the 20m-resolution DEM with 100m-contour around the Penticton and the Okanagan-Similkameen regions. The steep areas are those concentrated with contour lines and the two study regions present as steep on the both sides of the creeks. (2016)

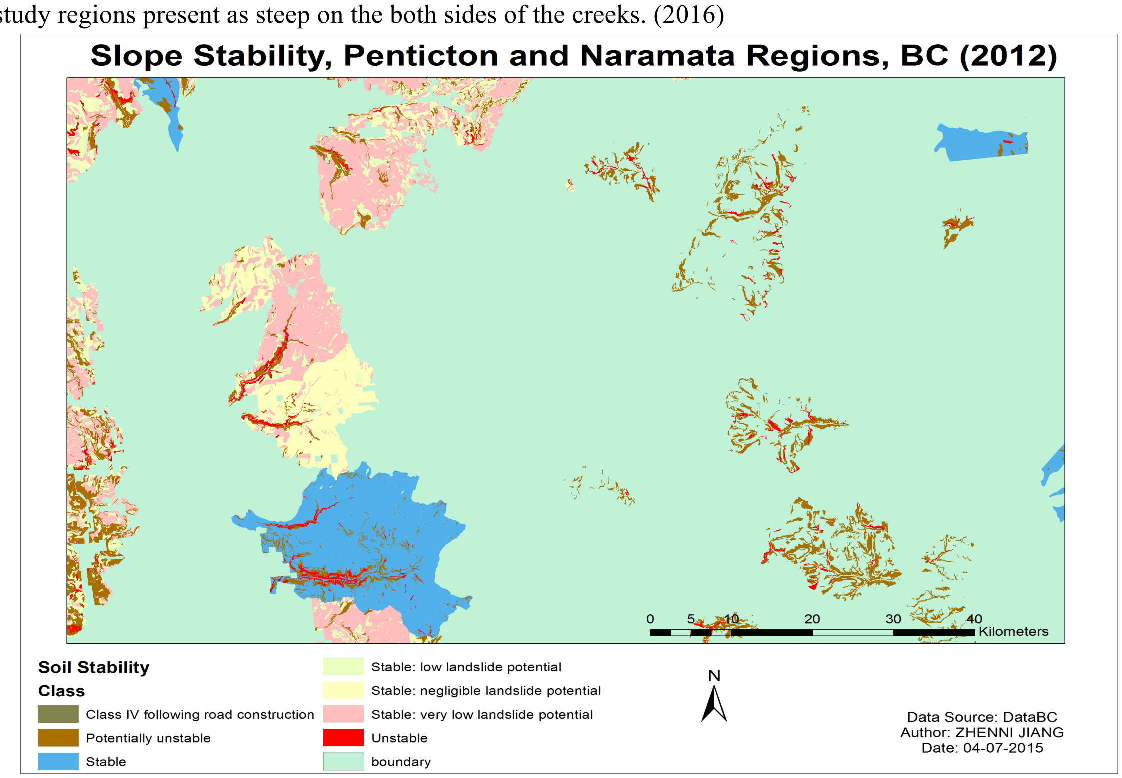


Figure 12. This map highlights the unstable areas based on slope data, their geo-material characteristics and the local environment (precipitation rate, hazard frequency, etc.). The valley areas are shown as unstable (red) or potentially unstable (brown). (2016)

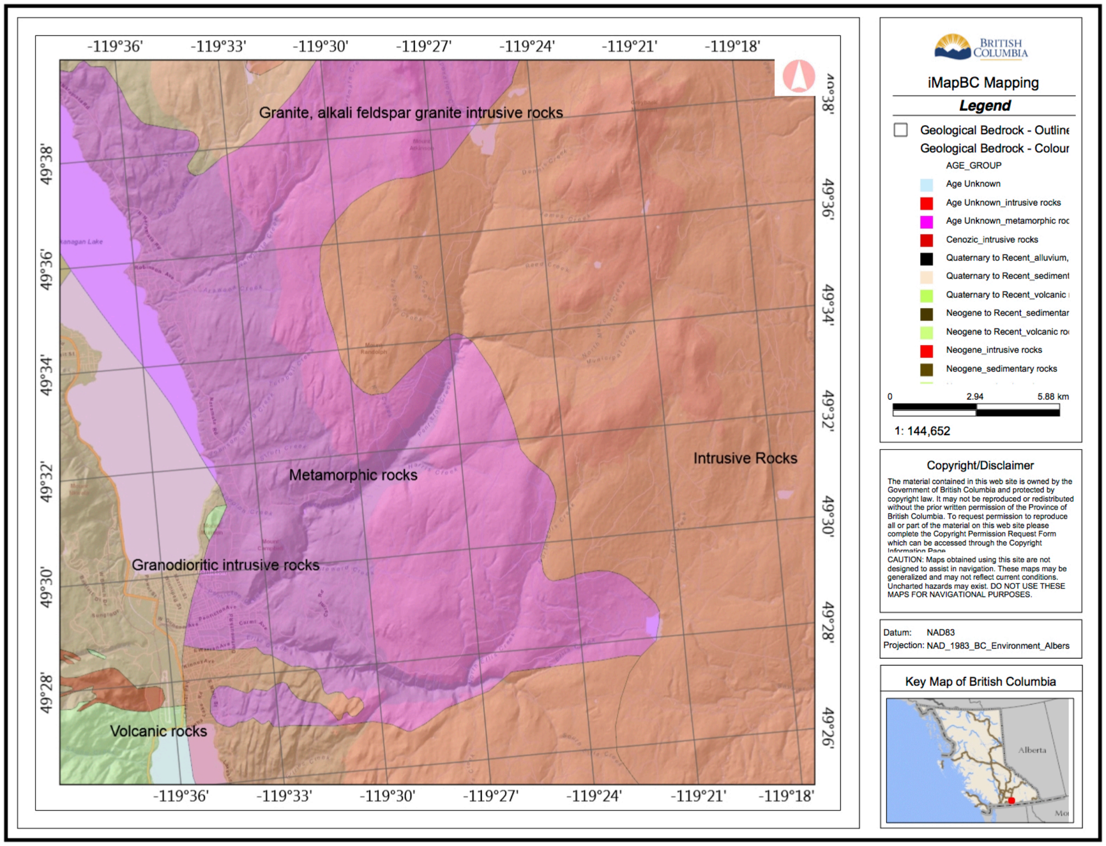


Figure 13. This map shows the distribution of different types of bedrock in the study area. The map is made with iMapBC2.

valley walls (Kelley & Spilsbury, 1949). Thus, take into account of both human intervention and natural influences, worsening sediment conditions to some extent surge up the debris flow frequency and amplify the magnitude degree.

Grain size influence on debris flow varies depending on debris flow types (h/d_e<50 or >50). If debris flows were thin, then the grain size has little influence on the velocity of the flow. In contrast, if debris flows were thick and viscous, the grain size would have the more prominent impact on debris flows. As we can extract from figure 14, the absolute multipliers are both small for the liquid and solid phase that give rise to the barely perceptible influence on debris flow velocity. Nevertheless, the grain size has positive effect on liquid phase, while grain size has negative effect on solid phase hinge

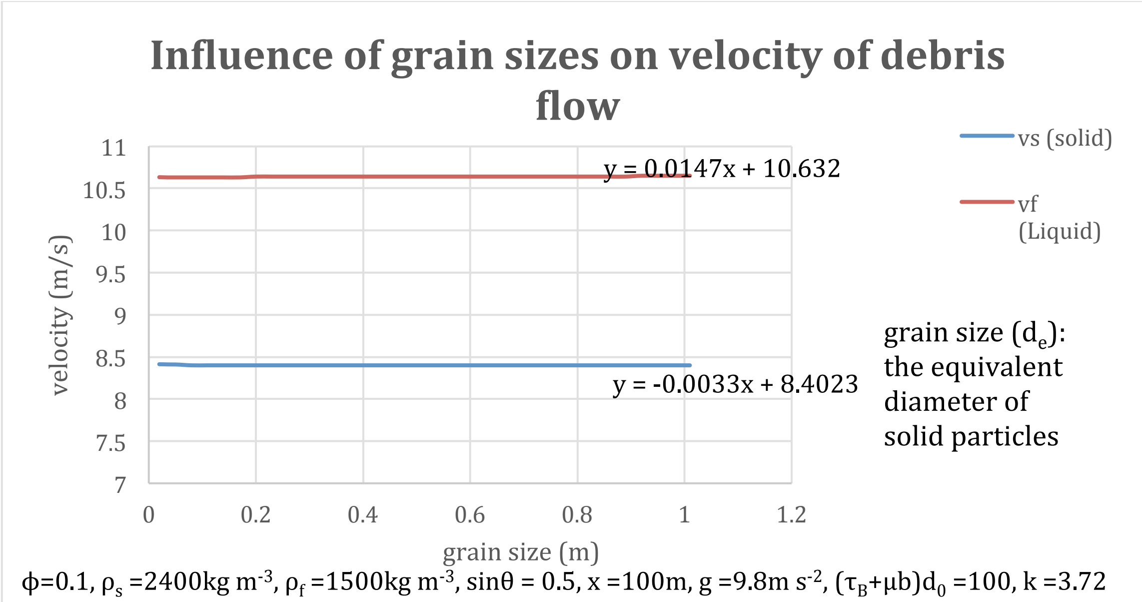


Figure 14. This graph shows the grain size influence on the velocity of debris flows. It uses the Model 1. The equivalent diameter of sediment size is taken as 0.02-1.01 m.

on the figure and the model. As comparing $+\frac{2d_e(1-\varphi)^2}{3k\rho_f}$ - the multiplier stands for liquid phase, and the $-\frac{2d_e(1-\varphi)^2}{3k\rho_s}$ - the multiplier stands for solid phase, we can know that as density of liquid phase is smaller than solid phase (Guo et al., 2014), thereby the divisor for the liquid phase multiplier is smaller than that of the solid phase, so that the absolute number for multiplier of liquid phase is larger than solid phase. Likewise, as the liquid phase uses plus and solid phase uses minus, they explain the positive relationship or negative relationship between the velocity and the grain size. This may be backed up by the increasing grain size would increase the already viscous solid material and if further increased, it would increase the internal fraction of materials and demand relative higher critical stress to entrain it, while for liquid phase, the increasing grain size would increase the traction force due to the weight gain and higher shear stress.

Regarding h/d$_e$>50 debris flows by utilizing the Model 2, the result depicts that when increasing the size of the d_{50}, the velocity would decrease in a logarithm shape.

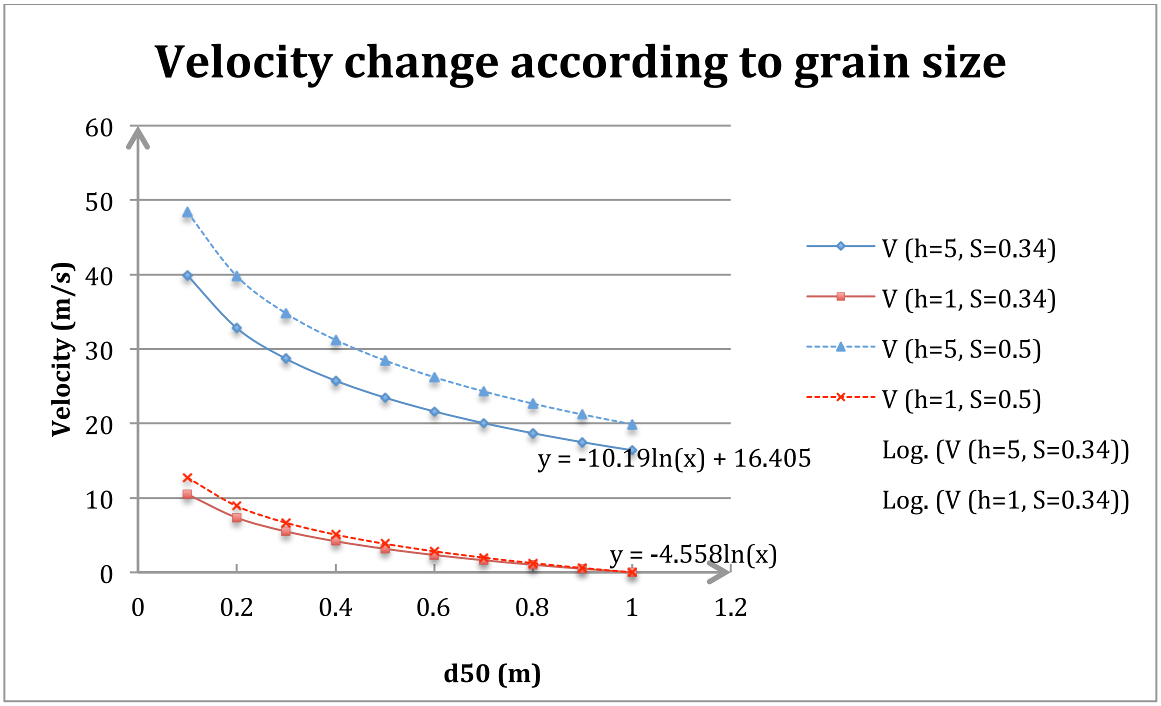


Figure 15. This graph shows the velocity changes according to grain size changes based on Model 2 - Manning's approach. Assuming S = 0.34 as θ = 20 degree for un-dashed line, S= 0.5 as θ = 30 degree for dash line. Blue lines show the flow depth = 1 m and red lines show the flow depth = 5 m.

Also, the finer the median grain size is, the faster the velocity would be. Additionally, when the flow depth is deeper, the faster the velocity would be under the same d_{50}, which gives the proof that the larger scale of debris flow would be with the higher magnitude and may create larger damage as it represents greater energy. Similar to results of Model 1 for slope-velocity, Manning's model also demonstrates that as slopes get steeper, the velocity is higher when others maintain constant (figure 15).

Conclusion:

Through the analyses for models and data/records, the conclusion can be made that (1) Inappropriate and overwhelming human interventions on the local or neighbouring ecosystems would increase the erosion rate and change sediment saturation degrees. (2) When $h/d_e < 50$, sediment size has generally less impact on debris flow velocity but still has positive relations to liquid phase velocity and negative relations to solid phase velocity; when $h/d_e > 50$, sediment size performs negative relations to debris flow velocity. (3) As the sediment saturation degree is higher and less consolidated, the debris flow magnitude would be higher in terms of event scale, frequency and stability. (4) Slope evolution would influence sediment conditions, and as the slope turns to be steeper, the higher possibility of experiencing debris flow is. (5) Higher frequency of extreme natural events (storms, persistent precipitation and forest fire) tends to shorten debris flow frequency intervals and increase its magnitude.

Discussion and further study:

The strengths of the two-phase model are that we can separate the phases into two parts and view the alterations of different variables, it also differentiate the influence of grain size under $h/d_e < 50$ condition on debris flow velocity from the $h/d_e > 50$ scenario. The limitations of the two-phase model are that it only works accurately under the thin layer debris flow yet overestimate the velocities under the viscous debris flows as debris flows are usually presented as heterogeneous while taking the grain sizes as homogenous in the model (Julien, 2010; Iverson & George, 2013), and inefficiency is discovered as the equation includes two many variables. The strength of the Manning's model is that it has been through sufficient examinations and revisions, however quite inaccurate when encountering different and complex cases due to high uncertainties.

According to Burge's survey report about sedimentation analysis of Mission Creek (Burge, 2009). The Mission Creek region, where is also located in the Okanagan valley, is close to the Penticton study areas and presents similar environment background.

They propose that the sediment profile in Mission creek according to D16, D50 and D84 percentile is decreasing in grain sizes as the distance further from the upstream and closer to the downstream (Burge, 2009). Therefore, it might have the potential of undergoing more debris flows in the downstream regions, which could be researched on in the future.

Debris flows originated on steep slopes usually attain high velocities. The impact forces generated by the resultant fast-moving coarse material can be very destructive. The weight is large and the yield strength is high, thus, the frontal wave has an extremely destructive impact on constructions and local morphology. In this case, mitigations have been done to catch the solid material of the frontal wave and thus reduce the risk and magnitude of destruction (Julien, 2010). As in the Penticton Creek and Ellis Creek regions, masses of steep slopes are yielded and developed gradually, protection plans should be designed and mitigations should be taken to prevent severe hazards.

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Data Source:

iMapBC2

GEOGRATIS

DataBC

Google Earth

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