Landslide hazard analysis - Garibaldi at Squamish ski resort project

Garibaldi at Squamish ski resort gets environmental approval - CBC news

The $3.5-billion project is expected to take at least 20 years to be completed

The provincial government has issued an environmental assessment certificate for the project (40 conditions attached)

Controversial project: Objections from locals, environmentalists, negotiations with First Nations as well.

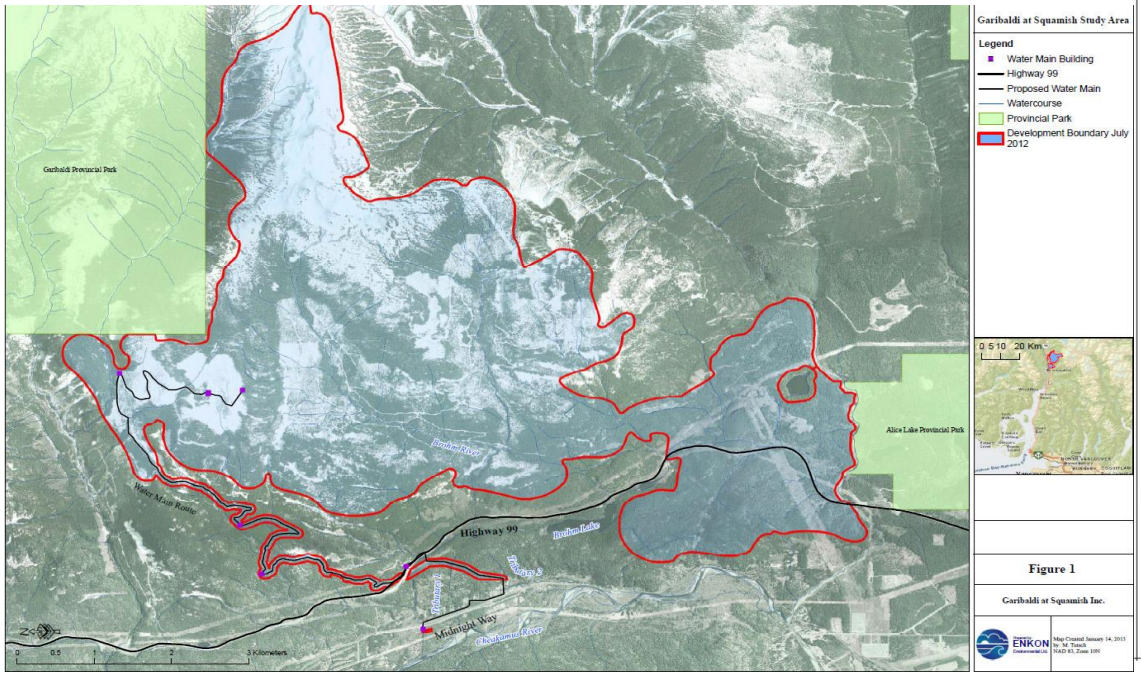
http://www.cbc.ca/news/canada/british-columbia/garibaldi-squamish-environmental-approval-1.3426582

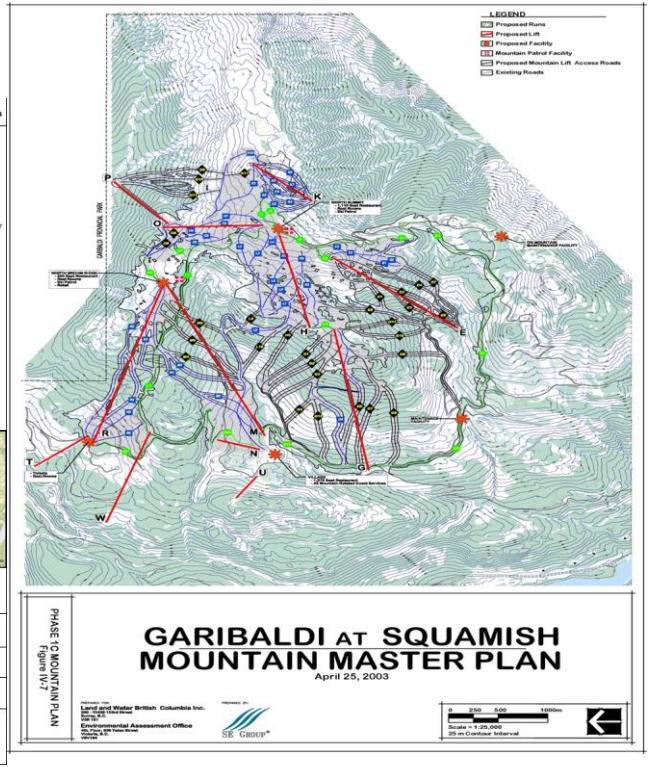
http://a100.gov.bc.ca/appsdata/epic/documents/p404/1454112912193_v2DTWr5ZmpK1NhMGhFdJPN5gQDHS46qTj9bYsDwqqf7sSxqdVn2Y!-1856054728!1454111065584.pdf

Study Area

located at Brohm Ridge, about 15 km north of Squamish

Adjacent to mount Garibaldi





Background Info of Study Area

- Approximate area - 55 km^2

Hilly and rugged terrain

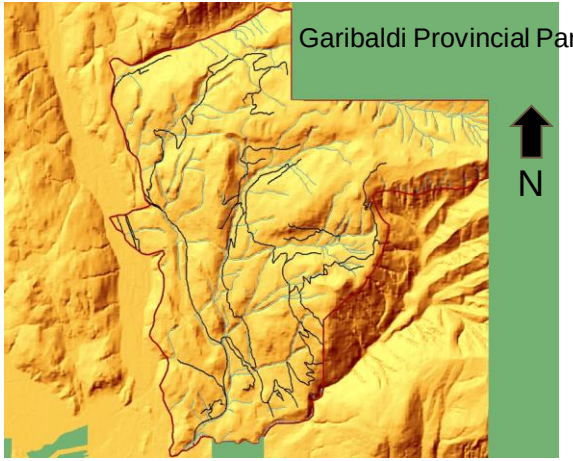
Located along Garibaldi Volcanic belt, part of pacific ranges of the Coast mountains

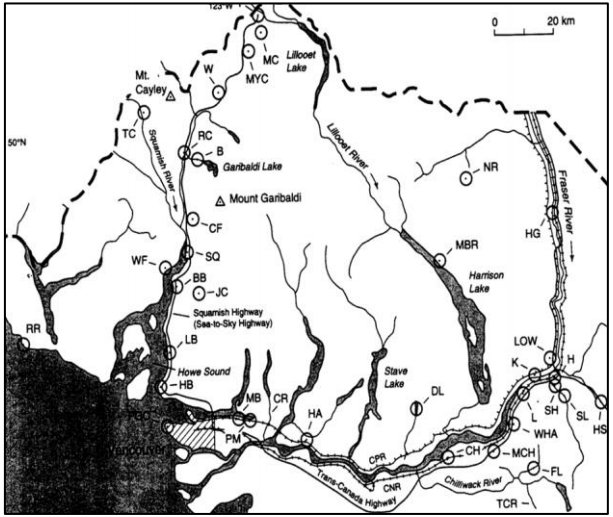
Prone to rapid massive landslides:

Past rockfall/ debris flow (Mount Cayley 1984, Mount Meager 2010)

Tuff sediment: low dry density, relatively impermeable compared with other rock layers in the volcanic pile

sufficient water may accumulate on the tuff layer to fully saturate it, causing strength reduction and buildup of pore pressure.





Research Question/ Goals:

To apply a simple infinite slope model adapted from previous studies (e.g. Montgomery et al. 1994, Zaitchik & van Es, 2003, Loughlin, 1974)

Determine areas that are susceptible to landslides (i.e. FS = <1) within the project area

Determine the influence of the different variables (relative saturation, soil thickness, apparent cohesion) through a Random Analysis Approach

Sensitivity analysis - Potential errors and uncertainties in our study (Cell size)

Validate our model predictions with past records of aerial photography

Methodology

Infinite Slope Stability Model

$$\text{Factor of Safety (FS)} = \frac{C + C_a + (\sigma_n - \upsilon) \times \tan(\Phi)}{\sigma_g \times \sin(\beta)} \quad \begin{matrix}\text{(Strength)} \\ \text{(Stress)}\end{matrix} \qquad (1)$$

$$\sigma_g = \gamma_b \cdot d \cdot \cos(\beta) \qquad (2)$$

$$\sigma_n = \sigma_g \cdot \cos(\beta) \qquad (3)$$

$$d = Z \cdot \cos(\beta) \qquad (4)$$

$$\upsilon = \gamma_w \cdot d \cdot m \cdot \cos(\beta) \qquad (5)$$

$$\gamma_b = m \cdot (\gamma_{sat}) + (1 - m) \cdot (\gamma_{unsat}) \qquad (6)$$

Constants:

$\gamma_w = 10\ kN/m^3$

$\gamma_{sat} = 12\ kN/m^3$

$\gamma_{unsat} = 17 kN/m^3$

C = Cohesion C_a = Apparent Cohesion σ_n = Normal Stress υ = Pore pressure Φ = Peak Friction angle β = Slope angle

σ_g = Vertical Stress m = Relative saturation d = Vertical depth z = Soil thickness

γ_w = water unit weight γ_{sat}= saturated unit weight γ_{unsat}= unsaturated unit weight γ_b= bulk unit weight

Assumed Parameters and Variables

Soil Properties:

-Cohesion: 0 kPa

-Apparent Cohesion due to Root strength: 2 kPa

-Dry unit weight: 12 kN/m^3

-Saturated unit weight: 17kN/m^3

Assumptions based on previous studies e.g. Loughlin(1974), and Cruden (1992) on Mount Cayley, Squamish

Parameters:

-Peak Friction angle: 36°

-Soil Layer thickness: 2m

-Relative Saturation: 0.5

} assumed to be constant throughout the study area

GIS analysis

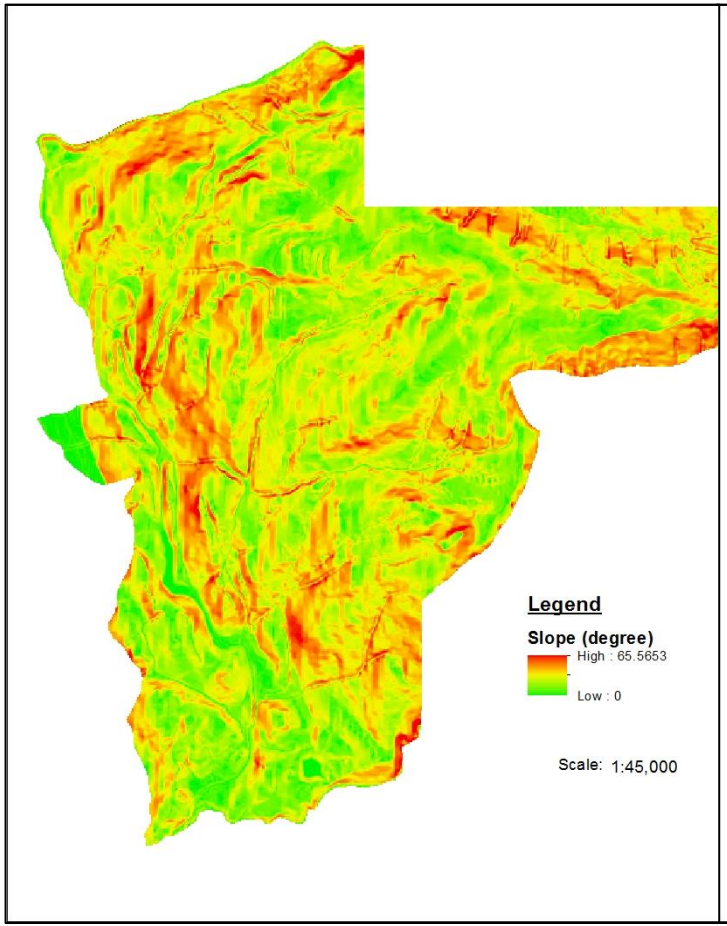
Incorporating our slope model into GIS using Raster Calculator to obtain the rasters for the different parameters and variables

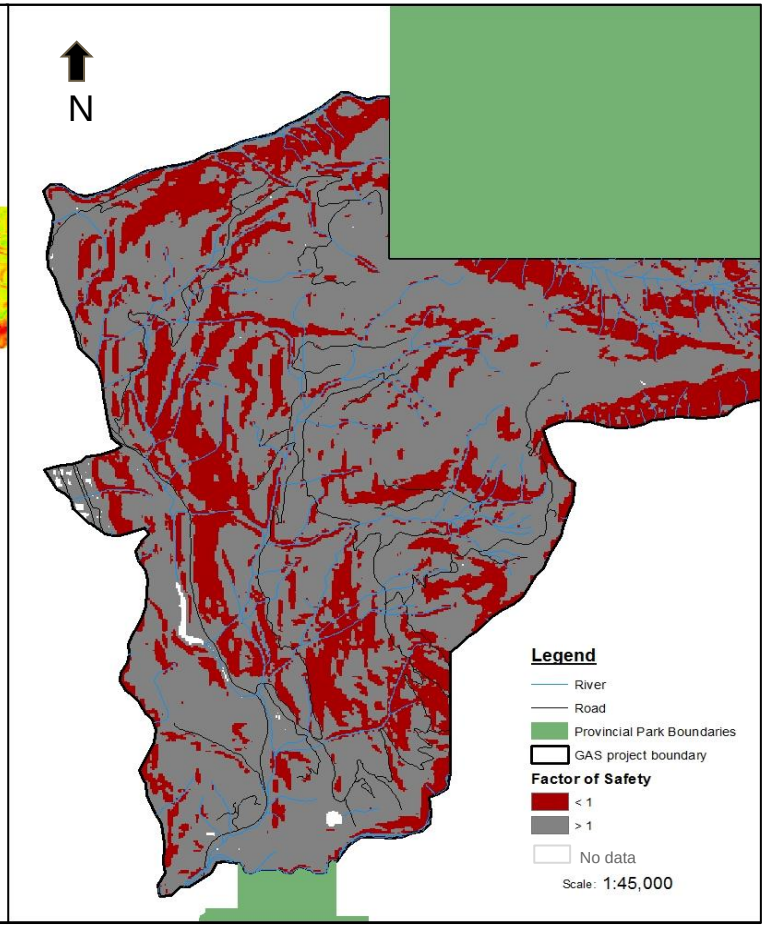
Equations (2) to (6) were used to obtain (1), which determines the areas that are considered to be unstable based on the ratio between Mohr-Coulomb equation and shear stress

FS < 1 = Unstable
FS > 1 = Stable

Results

Determining areas that are prone to landslides (assuming all parameters remain constant)

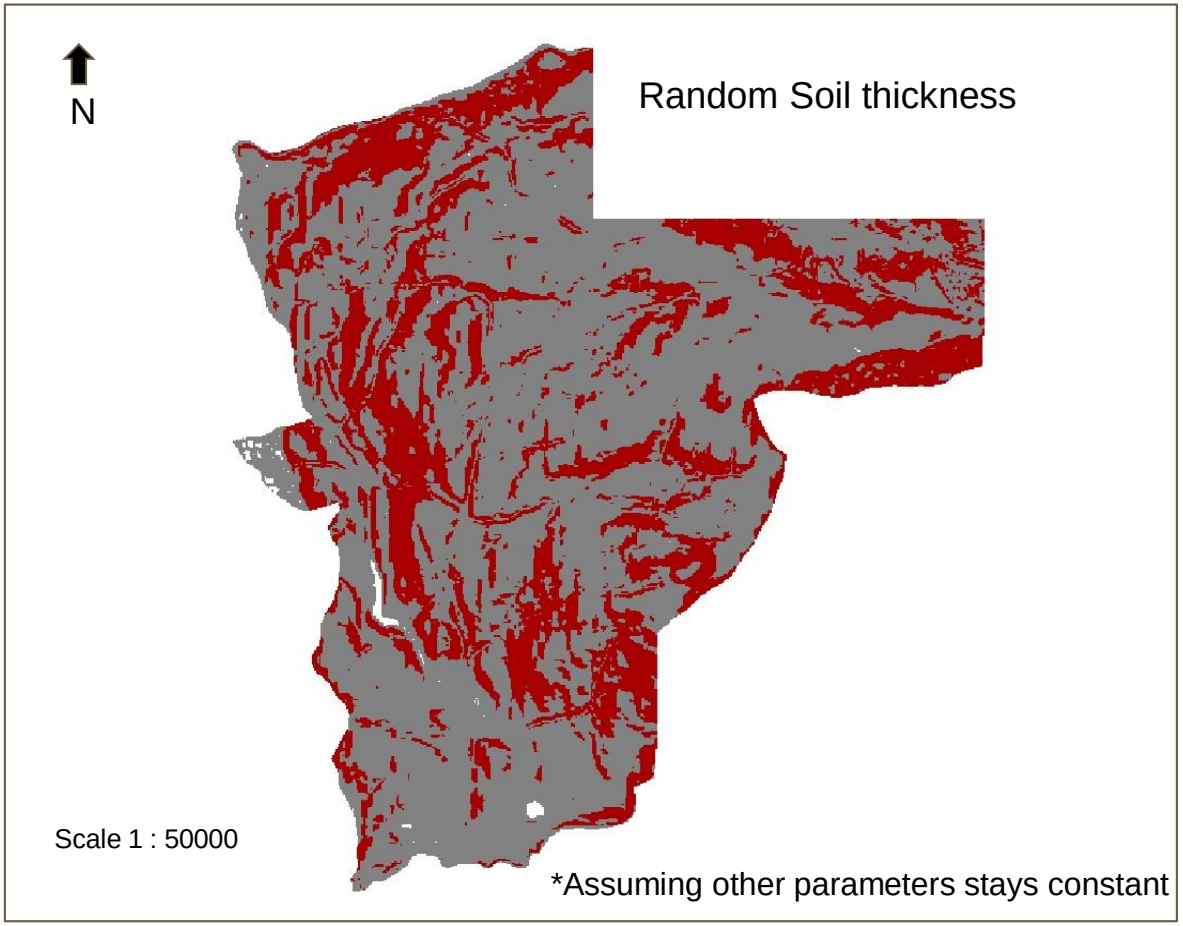




Approximately 30% of study area predicted to be unstable

Random Analysis:

1) Varying soil thickness ranging from **1m to 4m** across the study area



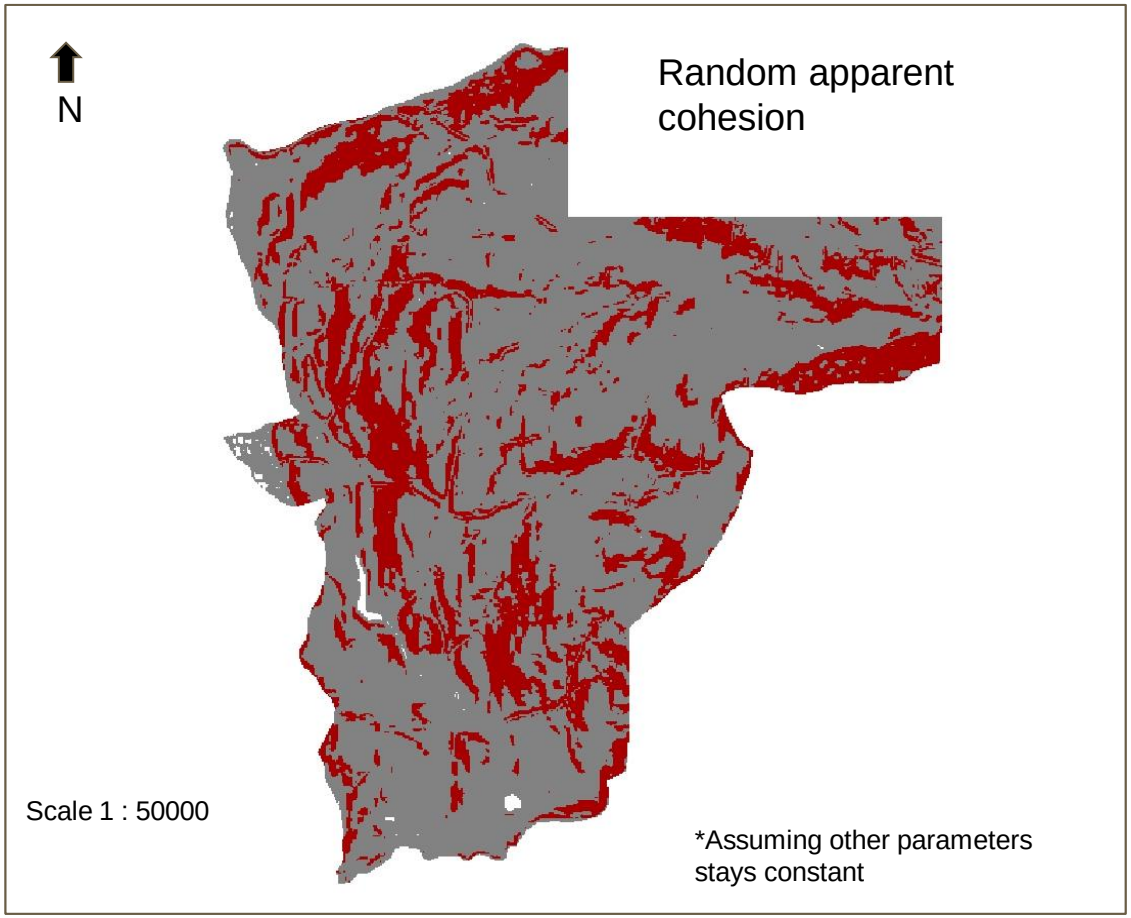
Areas that are considered to be unstable (FS < 1) appears to **increase** when soil thickness is not uniform. Assuming constant soil thickness in such studies might underestimate the areas that are prone to shallow landslides

FS < 1

FS > 1

No data

2) Varying apparent cohesion across study area within **1kPa to 3 kPa**



Areas that are considered to be unstable (FS < 1) appears to **decrease** when apparent cohesion of soil is varied across the study area. The increase in apparent cohesion in parts of the study area might have increased the FS value.

FS < 1

FS > 1

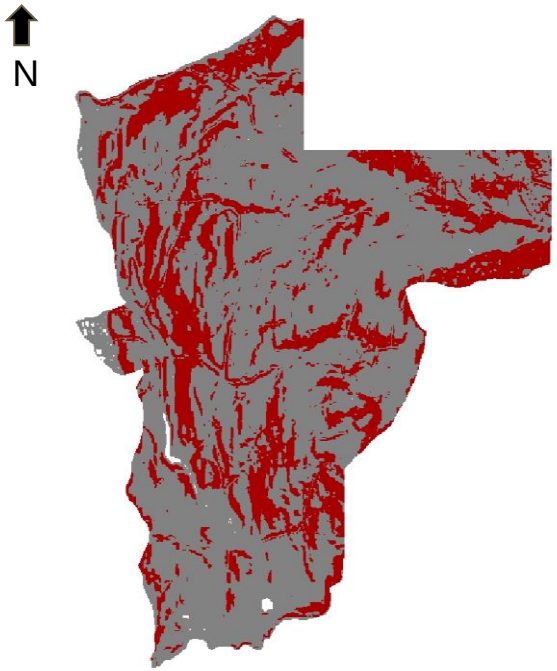
No data

Changing of parameters

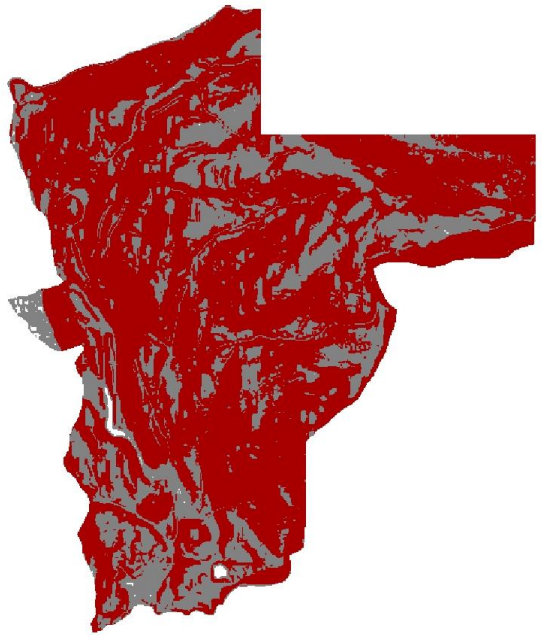
MAP OF FS with changing **Relative Saturation**

(assuming everything else stays constant)

When soil is fully saturated, FS value decreases drastically.



m = 0.5



m = 1.0

FS < 1

FS > 1

No data

Scale 1 : 50000

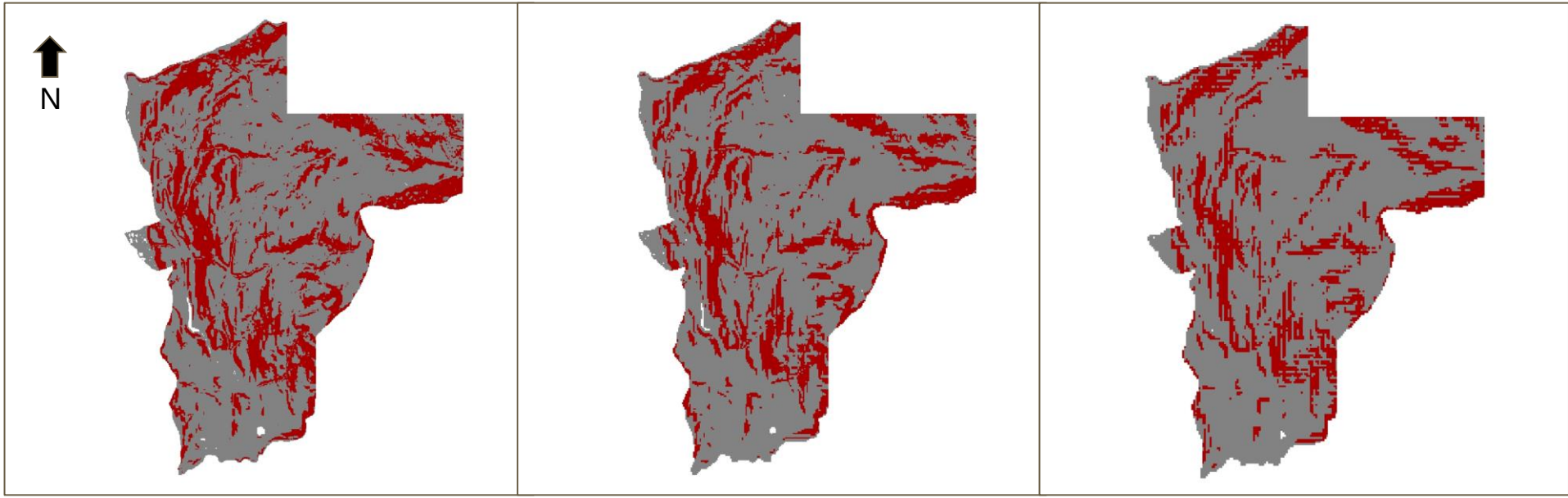
Sensitivity Analysis:

Maps of FS with varying **PIXEL SIZE**

FS < 1
FS > 1
No data

Scale 1 : 50000

18.65m | 35 m | 50m



*Unstable areas appear to decrease with the increase of cell size

Conclusion

This model works when conditions are more or less uniform

Assuming constant parameters (e.g Soil thickness, apparent cohesion) might affect accuracy of the model predictions

More accurate soil data (through soil samples and field studies) is needed to improve accuracy

The use of larger cell size (> 35m) might underestimate unstable areas

Our recommendations

We propose that the development of the new ski resort should avoid areas with low FS value, which are potential to shallow landslides.

Roads that intersect with unstable areas should have appropriate signage

Limitations:

- Uncertain of the actual soil properties of the study area
    - Used estimates from previous studies to make assumptions

- Parameters used were not specific to the study area, but study done in similar areas in the region

Did not take into account the effects of snow / ice accumulation, and rainfall intensity

Made assumptions for some of the parameters (e.g. Relative saturation, apparent cohesion (2 kPa))

Validation - To be completed

We will validate the results of our model to aerial photos from the GIC which dates back to 1950s (Scale of air photo - 1 : 250

Comparing Landslide scars within the study area

Determine how accurate is our model predictions to past landslides within the study area.

Reference

Cruden, D. M., and Z. Y. Lu. "The Rockslide and Debris Flow from Mount Cayley, B.C., in June 1984." *Canadian Geotechnical Journal*. N.p., 7 Apr. 1992. Web. 05 Apr. 2016. <http://www.nrcresearchpress.com/doi/pdf/10.1139/t92-069>.

Loughlin, C. O. "The Effect of Timber Removal on the Stability of Forest Soils." *Journal of Hydrology* 13.2 (1974): 121-34. Web. 5 Apr. 2016. <http://www.hydrologynz.co.nz/downloads/JoHNZ_1974_v13_2_O_Loughlin.pdf>.

Bovis, Michael J. "Rock-slope Deformation at Affliction Creek, Southern Coast Mountains, British Columbia." *Canadian Journal of Earth Sciences Can. J. Earth Sci.* 27.2 (1990): 243-54. Web.

"Landslides in the Vancouver-Fraser Valley-Whistler Region."*International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts* 32.6 (1995): n. pag. Web.

Montgomery, David R. "A Physically Based Model for the Topographic Control on Shallow Landsliding - Montgomery - 1994 - Water Resources Research - Wiley Online Library." *A Physically Based Model for the Topographic Control on Shallow Landsliding - Montgomery - 1994 - Water Resources Research - Wiley Online Library*. N.p., Apr. 1994. Web. 05 Apr. 2016. <http://onlinelibrary.wiley.com/doi/10.1029/93WR02979/abstract>

Wu, Weimin, and Roy C. Sidle. "A Distributed Slope Stability Model for Steep Forested Basins." *Water Resources Research Water Resour. Res.* 31.8 (1995): 2097-110. Web.

THE END

Special thanks to:

Carles Ferrer Boix for helping us with our model

Sally Hermansen for providing the GIS data and info on the Garibaldi at Squamish Project.