Appendix J Rockfall Model Calibration

The stochastic, lumped sum rockfall model Pierre3D was used to evaluate rockfall at The Last Resort (TLR). This appendix outlines the process implemented for calibration of the model to field conditions at TLR.

Initial Model Set Up

The model was set up and tested using the best fit parameters for talus based on the experimental work from slopes near Vaujany, France (Dorren et al. 2005), Preg Quarry, Austria (Preh et al. 2015) Ehime prefecture, Japan (Ushiro et al. 2006) and a natural rockfall site called Tornado Mountain in British Columbia (Wyllie 2014). The model parameters, calibration procedure, and development are discussed in Gischig et al. (2015), Mitchell (2015), and Mitchell and Hungr (2015, 2017). The best fit parameters developed with the model are summarized in Table J 1.

Table J 1. Best-fit parameters for 2D and 3D models after (Mitchell 2015, Mitchell and Hungr 2017).

Parameter	Talus	Rock Face	Quarry Floor
Slope description	Fine to medium, firm talus, residual soil, light vegetation	Rough rock face, strong to very strong, uncontrolled blasting	Quarry floor, compact rock debris
Unit energy for normal restitution (m^3/s^2), $E_{0.5,n}$	15	5	5
Unit energy for tangential restitution (m^3/s^2), $E_{0.95,t}$	50	50	40
2D Roughness scale value, θ_{scale}	0.6-0.7	0.65	0.3
3D Longitudinal roughness scale value, θ_{scale}	1.0-1.5	0.45	NC
3D Tangential roughness scale value, ψ_{scale}	0.9-1.0	0.3	NC
Shape factor for natural rocks, R_{eff}	1.0-1.5	NC	NC
Datasets used for calibration	Vaujany, Ehime, Tornado Mountain	Preg Quarry	Preg Quarry

Note: NC, not calibrated

In this study, calibration of longitudinal and transverse roughness scale values was completed. Unit energies for restitution and the shape factor were not considered.

All simulations used five representative boulder sizes based on measurements collected in the 2015 rockfall deposition area. Pierre3D calculates an equivalent boulder diameter based on user input mass and density. At TLR, density was assigned based on the observed lithology of boulders at TLR ranging from sandstone to brecciated metasandstone. Boulder properties are summarized in Table J 2.

Rockfall release points were assigned to five locations within the main source area of the 2015 rockfall. Building locations were digitized from aerial imagery and field measurement of typical footprints by building type and the approximate locations as measured using an iPad. Sampling windows employed to subsample the data at rockfall impact as part of the assessment of repeatability were assigned in the main rockfall transportation and upper deposition areas (Figure J 1).

Table J 2. Boulder properties used in Pierre3D simulations.

Boulder No.	Measured Dimensions			Density (kg/m^3) [1]	Mass (kg)	Equivalent Diameter (m)
	a-direction	b-direction	c-direction			
1	2.1	3.0	2.6	2650	42572	2.5
2	2.1	3.0	2.6	2650	42572	2.5
3	0.9	1.3	1.1	2650	3411	1.1
4	0.6	1.0	0.8	2650	1272	0.8
5	0.8	1.3	1.1	2650	2894	1.0

1 Density based on reported values for sandstone (Tenzer et al. 2011).

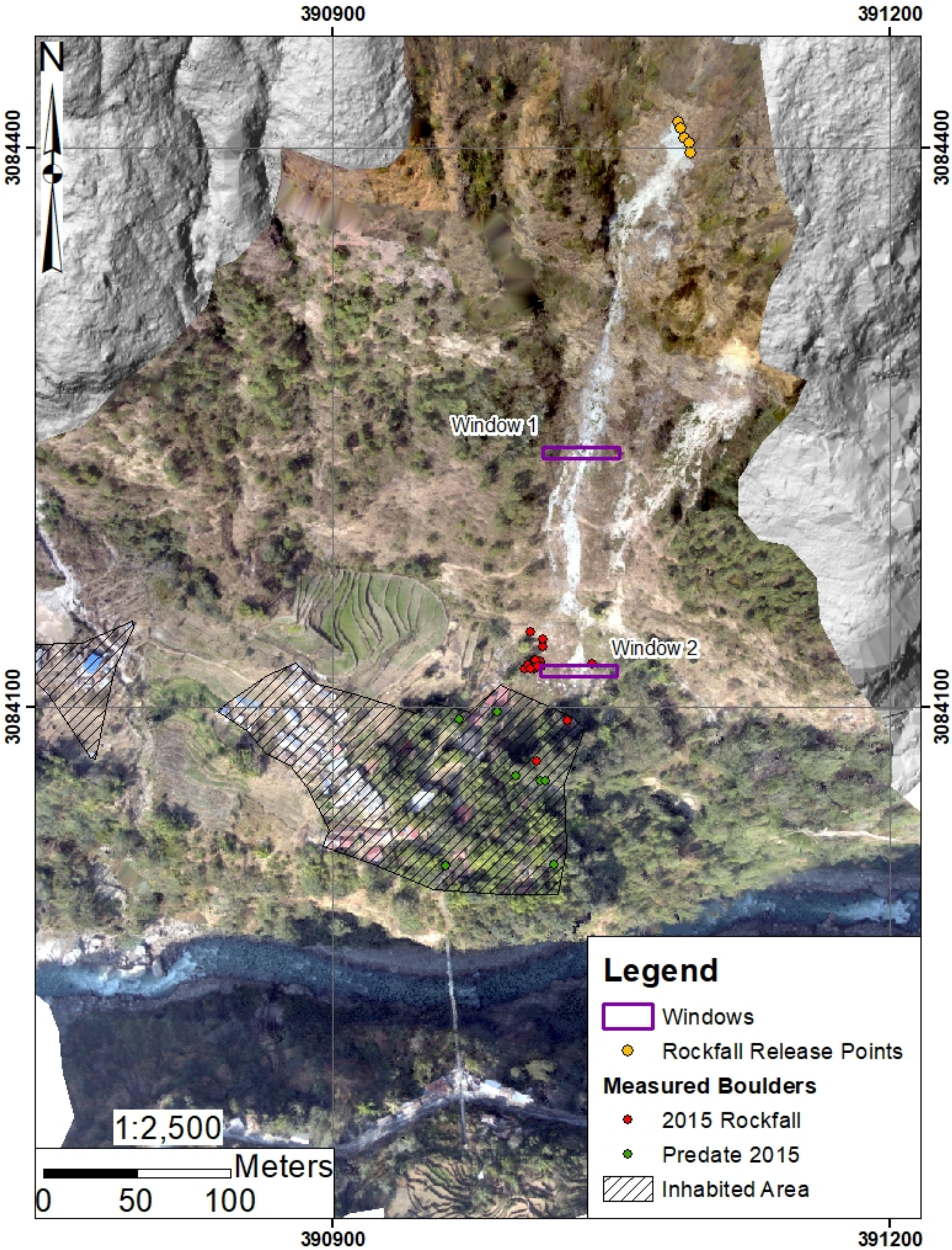

Figure J 1. **Plan view of 2015 rockfall area showing rockfall release points, measured boulders and locations of buildings owned by TLR and the adjacent community. Sampling windows were used to check for repeatability between model runs. Basemap is UAV model (January 2017) underlain by TLS model (November 2017). Coordinates are WGS84 UTM Zone 45N.**

Calibration 1: Single slope material (Talus)

The first set of simulations used a single material model with the calibrated parameters for talus slopes (Table J 1). These parameters led to underestimation of runout and scatter angle as compared with the observed distribution of boulders from the 2015 rockfall by approximately 25 m along slope and 10-15 m laterally (Figure J 2).

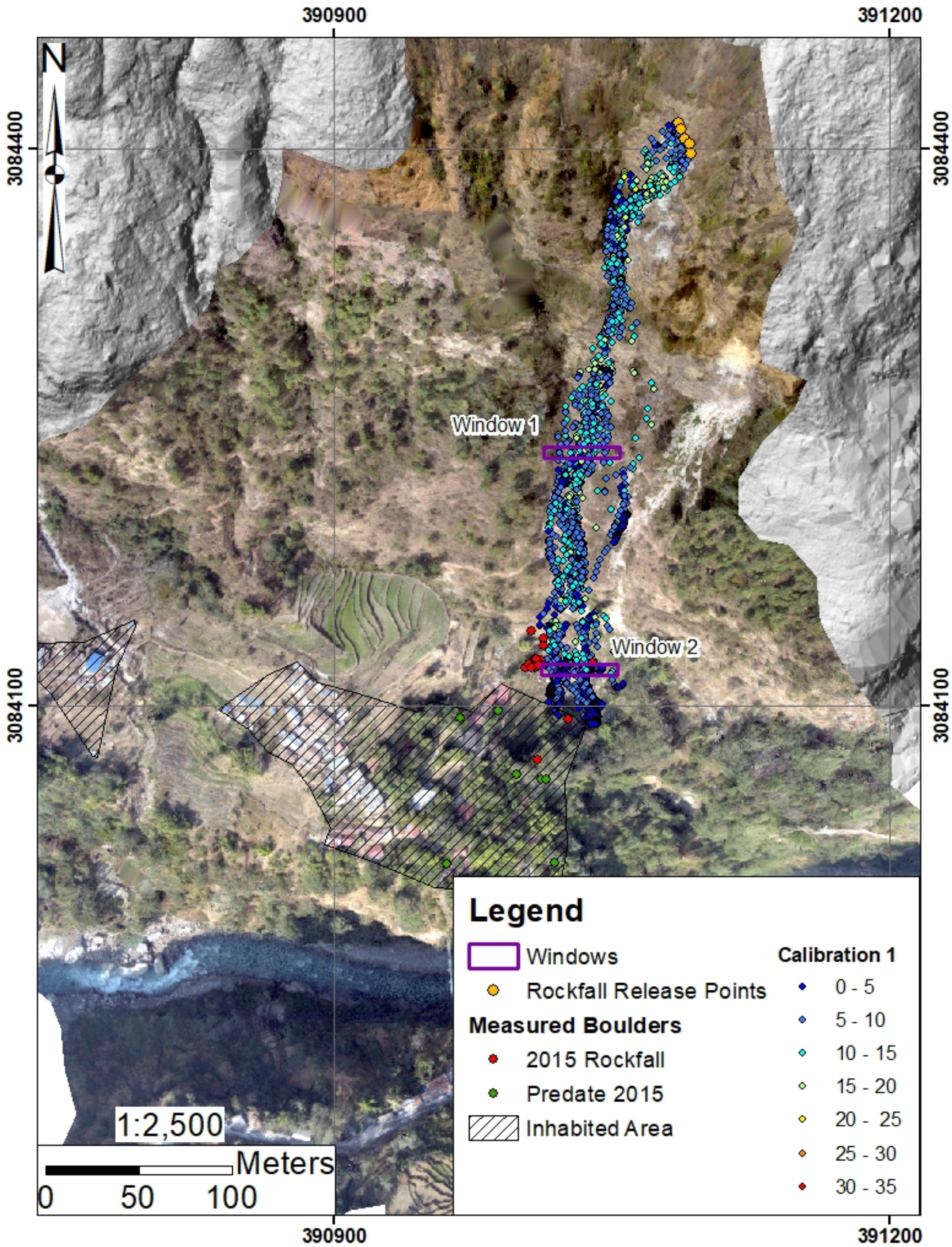

Figure J 2. Rockfall velocity (m/s) based on calibration 1.

Calibration 2: Single slope material

Reduced roughness parameters relative to Calibration 1 were tested ($0.6 < \theta_{scale} < 1.0$, $0.4 < \psi_{scale} < 0.7$ (Table J 7)). Each parameter was varied in increments of 0.1 leading to 20 parameter combinations. For each parameter combination, the five blocks were simulated 10 times for a total of 1000 simulated blocks. The results more closely approximated the distribution observed from the 2015 rockfalls (Figure J 3). As shown, increasing transverse roughness tends to increase rockfall runout for lower longitudinal roughness values (0.6, 0.7). This is interpreted to be partially the result of the increased scatter associated with increased transverse roughness directing blocks towards the main gully below TLR and partially associated with the stochastic nature of the model.

Calibration 3: Single slope material

A subset of best fit parameters ($0.6 < \theta_{scale} < 0.7$, $0.4 < \psi_{scale} < 0.7$ (Table J 7)) was selected from the range tested in Calibration 2 based on visual inspection of fit to the observed distribution of boulders. Each parameter was varied in increments of 0.1 for 8 parameter combinations. For each parameter combination, the five blocks were simulated 100 times to reduce random variation between runs. A total of 4000 simulated rockfall blocks were simulated. Results from these simulations are shown in Figure J 4.

As shown in Figure J 4, the parameters tested all closely match the results indicating that the range of suitable values is $0.6 < \theta_{scale} < 0.7$, $0.5 < \psi_{scale} < 0.7$. For the present analysis, the following were employed based on the best subjective visual fit: $\theta_{scale} = 0.7$, $\psi_{scale} = 0.6$.

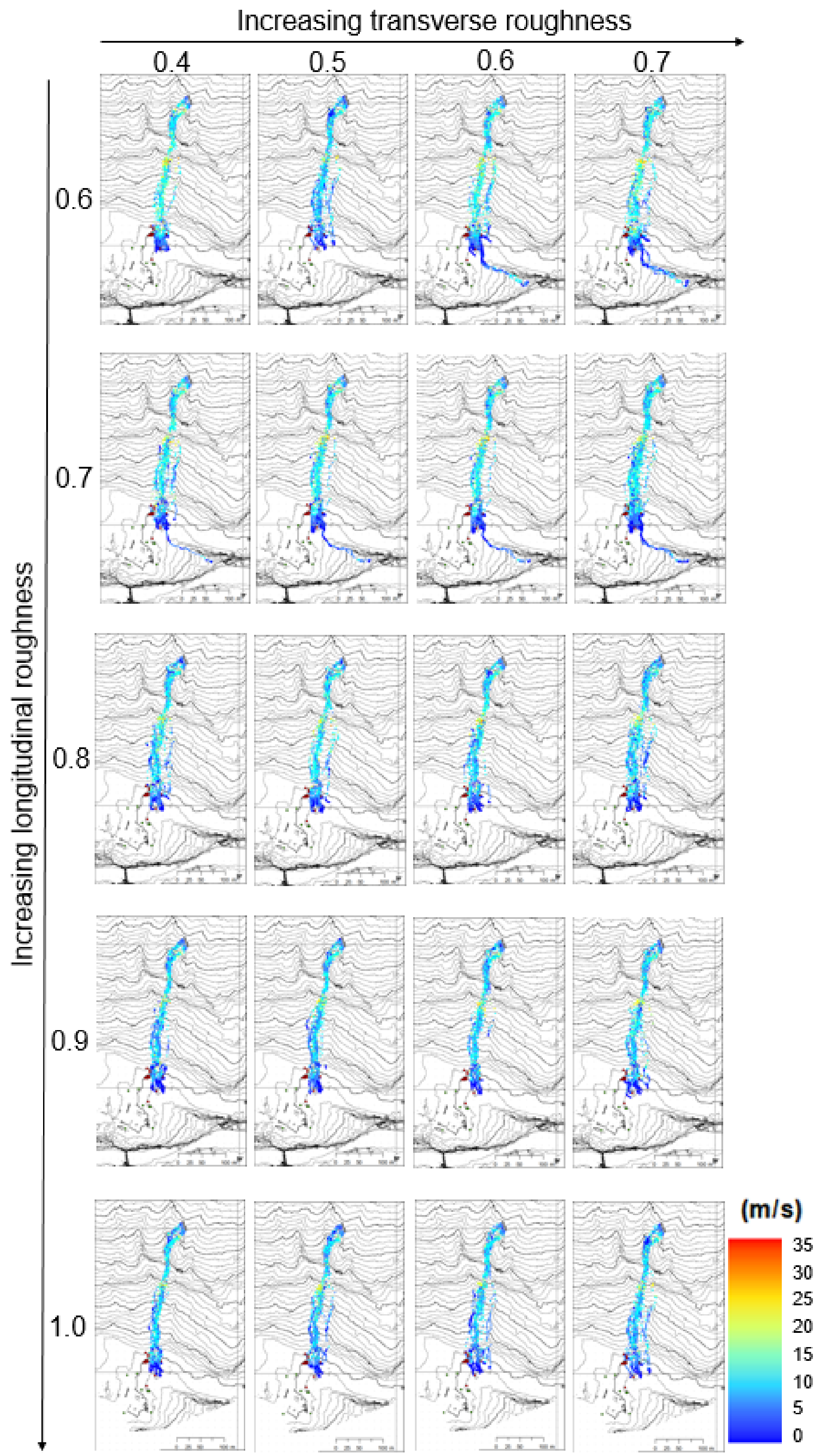

Figure J 3. Calibration 2 (Table J 7) results using a single slope material model. Maximum boulder velocity is shown.

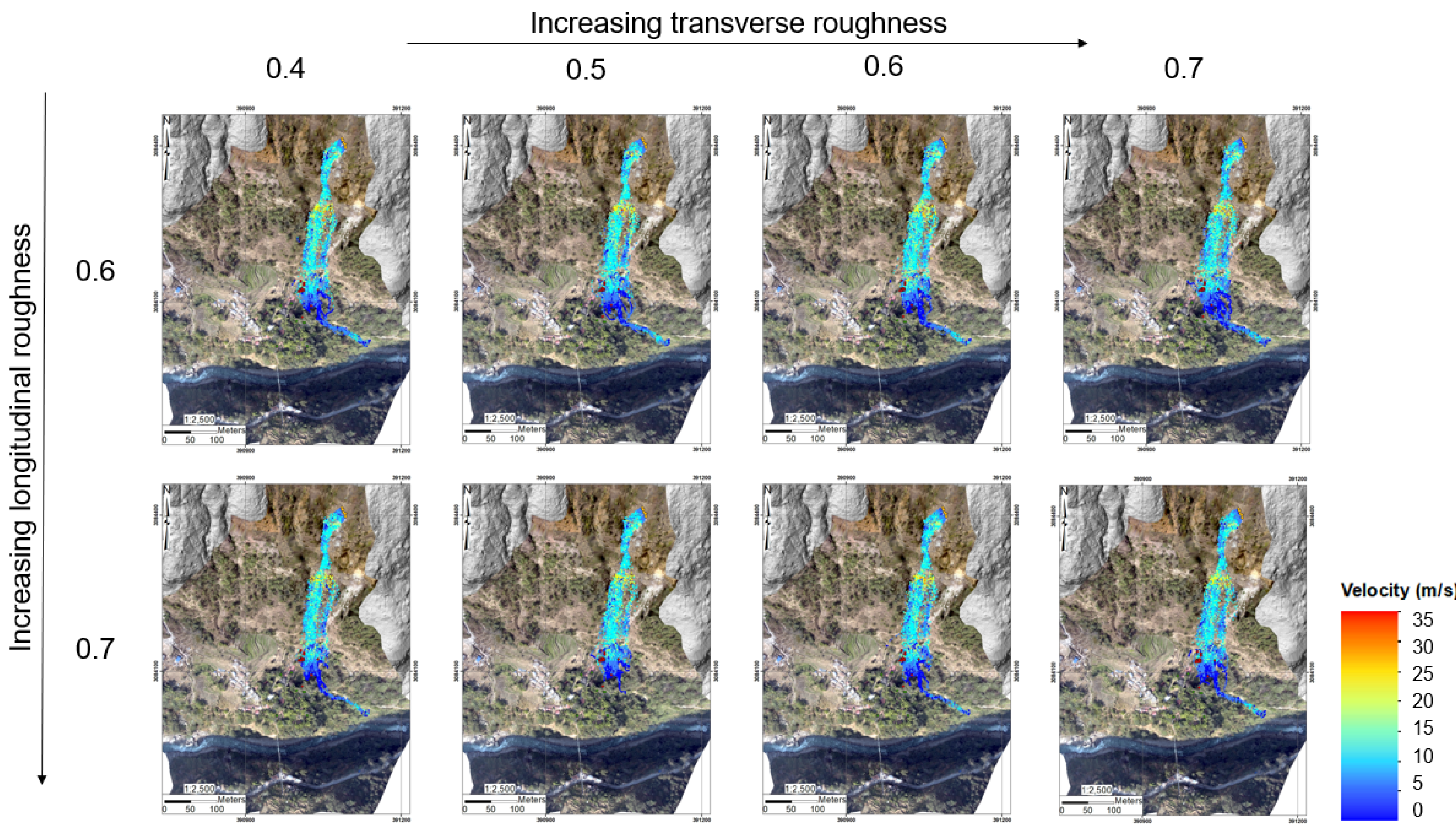

Figure J 4. **Calibration 3 (Table J 7) using a single slope material model. Maximum boulder velocity is shown.**

Assessment of repeatability

In Mitchell and Hungr (2017) at the Vaujany site, 100 blocks were simulated 5 times in order to ensure repeatable results from run to run. At TLR, a similar assessment of repeatability as described in Mitchell (2015) was completed.

Mitchell (2015) used screen locations as the basis for comparison. At TLR, sampling windows arbitrarily located on the slope were used. One window is in the runout path of blocks while the other is in the upper deposition area (Figure J 1). Sampling windows are approximately 40 m wide (perpendicular to slope) and 6.4 m long (parallel to slope) covering an area of 254 m^2. The windows are intended to mimic screens or collector fences that would be used as points to collect data in other rockfall models.

Trial 1: 10 simulations per block

Best fit parameters (θ_{scale} = 0.7, ψ_{scale} = 0.6) were used to simulate each of the 5 blocks 10 times. The model was run twice using the same input parameters and then the results were compared to determine the overall differences. To do so, the results of all impacts within the sampling windows were isolated from the remainder of the impacts and considered individually. The mean and maximum velocity and jump heights aggregated over the 10 simulations were considered (Table J 3 and Table J 4).

As shown, there is significant variability in the jump heights and velocity in window 1 above the deposition area. In contrast, window 2 in the deposition area showed lower variability in the mean and max velocities was (8% and 6% difference, respectively) with the percent difference between the mean and max jump heights higher at 29% and 20%, respectively.

Table J 3. Comparison of jump heights for the selected best fit parameters to determine the effect of the number of simulations.

		Jump Height (m)			
		Run 1 – 10 simulations		Run 2 – 10 simulations	
		Range for Individual Simulations	Simulations Averaged	Range for Individual Simulations	Simulations Averaged
Window 1	Mean	0.88 – 5.39	2.07	1.05 – 1.90	1.52
	Max	1.04 – 5.49	2.28	10.64 – 13.38	11.98
Window 2	Mean	0.30 – 1.57	0.88	0.34 – 1.03	0.66
	Max	0.87 – 3.07	1.39	0.93 – 1.56	1.14

Table J 4. Comparison of velocities for the selected best fit parameters to determine the effect of the number of simulations.

		Velocity (m/s)			
		Run 1 – 10 simulations		Run 2 – 10 simulations	
		Range for Individual Simulations	Simulations Averaged	Range for Individual Simulations	Simulations Averaged
Window 1	Mean	8.56 – 12.88	11.56	8.44 – 9.60	9.25
	Max	8.67 – 13.00	11.97	21.75 – 24.33	22.57
Window 2	Mean	6.32 – 9.62	7.89	5.61 – 8.52	7.27
	Max	8.04 – 10.71	9.71	7.65 – 10.05	9.14

Trial 2: 20 simulations per block

To test if additional runs would improve the repeatability, the same parameters (θ_{scale} = 0.7, ψ_{scale} = 0.6) were again tested twice, in this instance with 20 simulations for each of the 5 blocks. The results of these simulations are summarized in Table J 5 and Table J 6. In this case, the percent difference in the results observed at the sampling windows reduced to <5% at window 1 and <10% at window 2 for both the maximum velocity and jump heights simulated. A comparison of the results for jump height and velocity are plotted in Figure J 5 and Figure J 6, respectively.

Table J 5. Comparison of jump heights for the selected best fit parameters to determine the effect of the number of simulations.

		Jump Height (m)			
		Run 1 – 20 simulations		Run 2 – 20 simulations	
		Range for Individual Simulations	Simulations Averaged	Range for Individual Simulations	Simulations Averaged
Window 1	Mean	1.06 – 2.16	1.59	1.33 – 2.70	1.65
	Max	1.25 – 2.85	1.96	2.49 – 2.84	1.94
Window 2	Mean	0.50 – 0.92	0.63	0.36 – 0.93	0.67
	Max	0.83 – 1.46	1.19	0.95 – 1.53	1.12

Table J 6. Comparison of velocities for the selected best fit parameters to determine the effect of the number of simulations.

		Velocity (m/s)			
		Run 1 – 20 simulations		Run 2 – 20 simulations	
		Range for Individual Simulations	Simulations Averaged	Range for Individual Simulations	Simulations Averaged
Window 1	Mean	10.80 – 14.02	12.81	10.69 – 14.26	12.21
	Max	11.34 – 14.13	13.07	10.69 – 14.55	12.71
Window 2	Mean	6.31 – 8.40	7.38	7.13 – 9.00	7.88
	Max	8.71 – 10.12	9.48	8.90 – 10.41	9.84

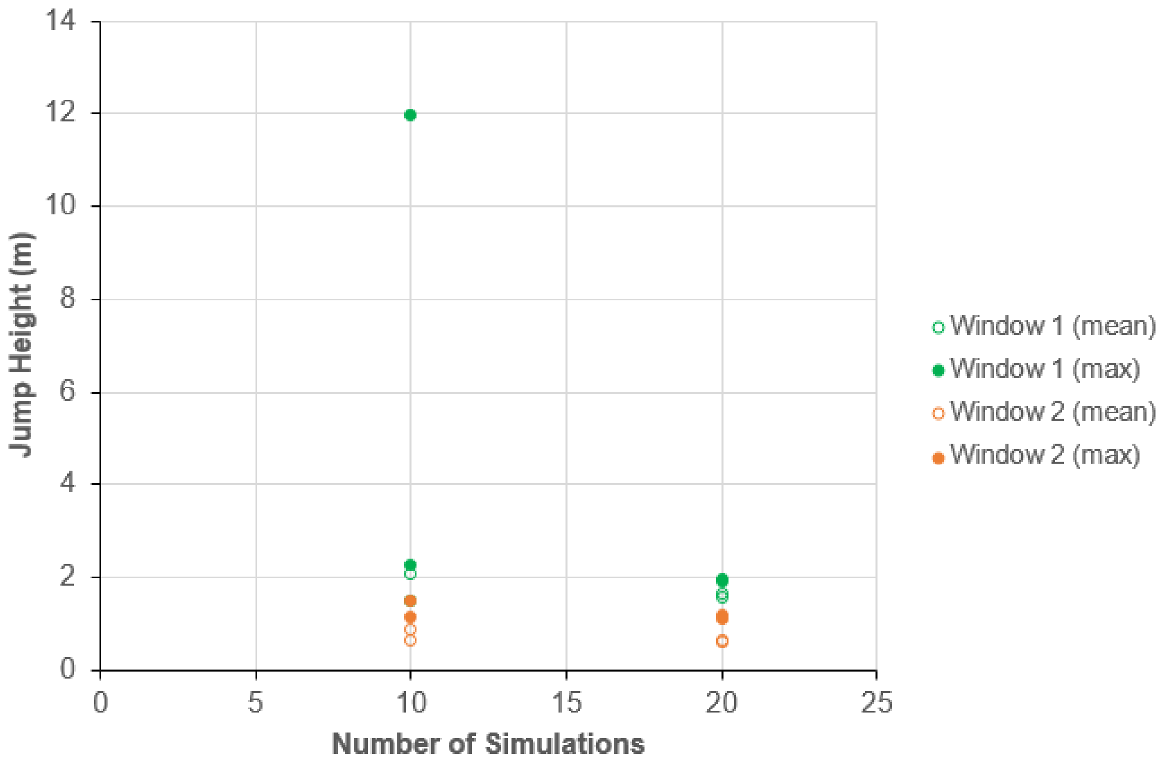

Figure J 5. Comparison of jump height results by number of simulations per block.

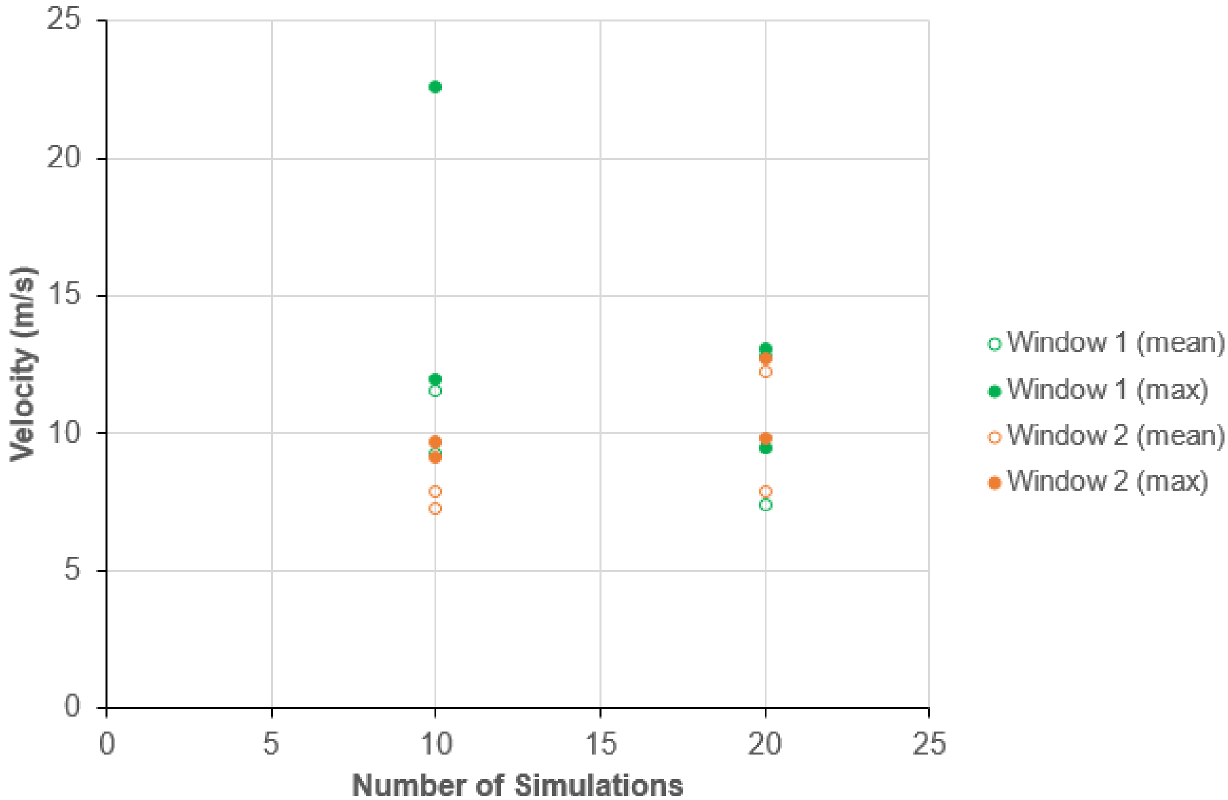

Figure J 6. Comparison of velocity results by number of simulations per block.

Overall, the results indicate that an inherent variability in the model is apparent between repeated runs; however, to maximize efficiency of computing time, 20 simulations per block was designated the minimum criteria for repeatability given the overall agreement of mean and maximum values for jump height and velocity between the sampling windows.

Calibration 4: Two slope material

In the second calibration, two slope materials were employed to represent the differences in behaviour between the main transport area and the shallower angle, vegetated deposition area. The materials were assigned based on slope angle with the division point at 35° (Figure J 7).

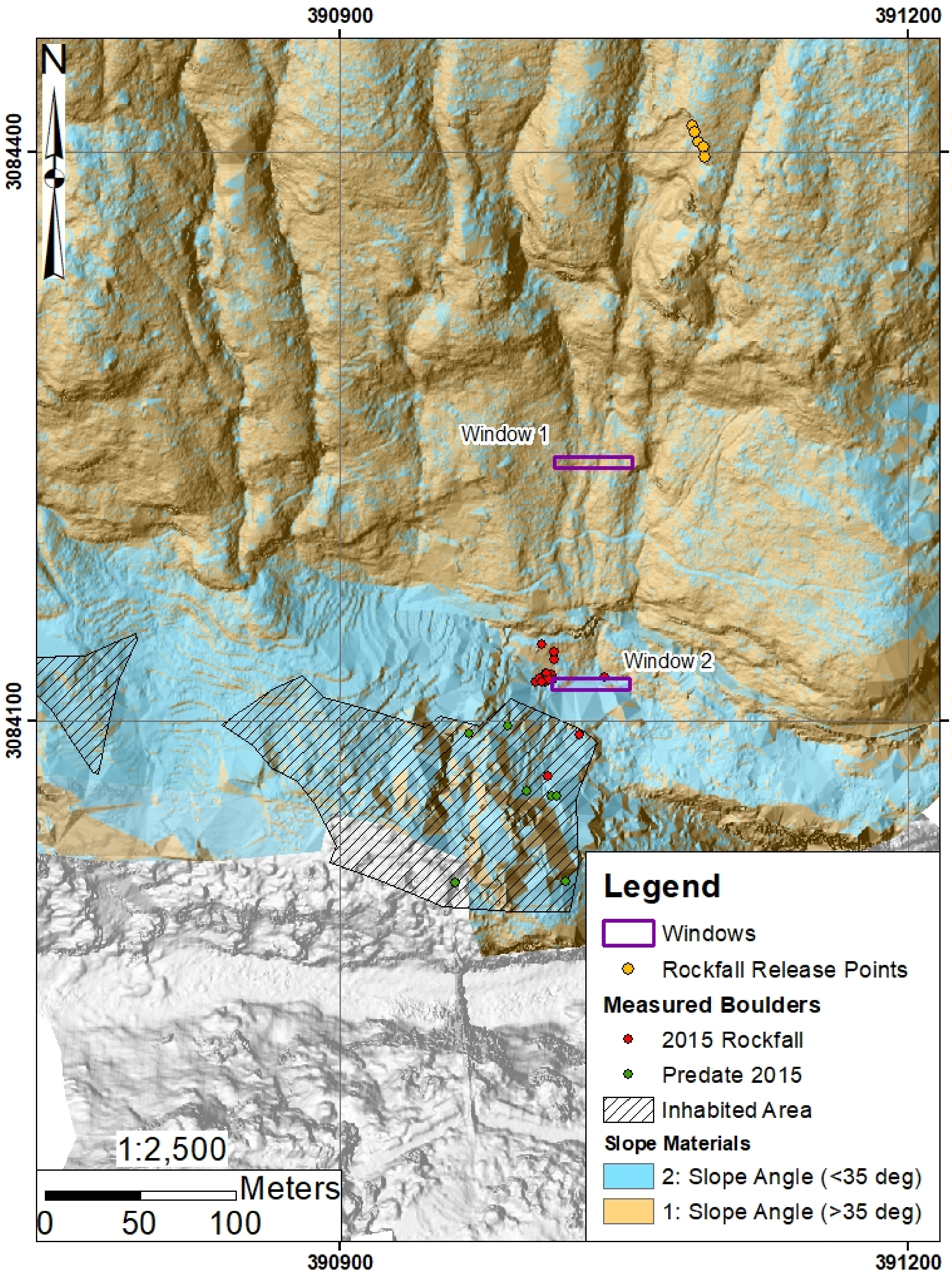

Figure J 7. **Two slope material model based on slope angle. Rockfall release points, sampling windows, measured boulders and buildings all shown. Basemap is combination of UAV model and TLS. Coordinates are WGS84 UTM Zone 45N.**

The second slope material (slope <35°) were arbitrarily assigned as 30% lower for unit energies for normal and tangential restitution and 30% higher for longitudinal and tangential roughness to simulate decreased runout and lateral scatter in the shallower angle, vegetated slopes. These relatively small changes in parameters were used as the single material model already closely matched the trajectory pattern and distribution of boulders observed. Moreover, with limited information beyond visual inspection to calibrate the model, detailed delineation of slope materials was not deemed to be suitable. A comparison of the single and two slope material models is shown in Figure J 8.

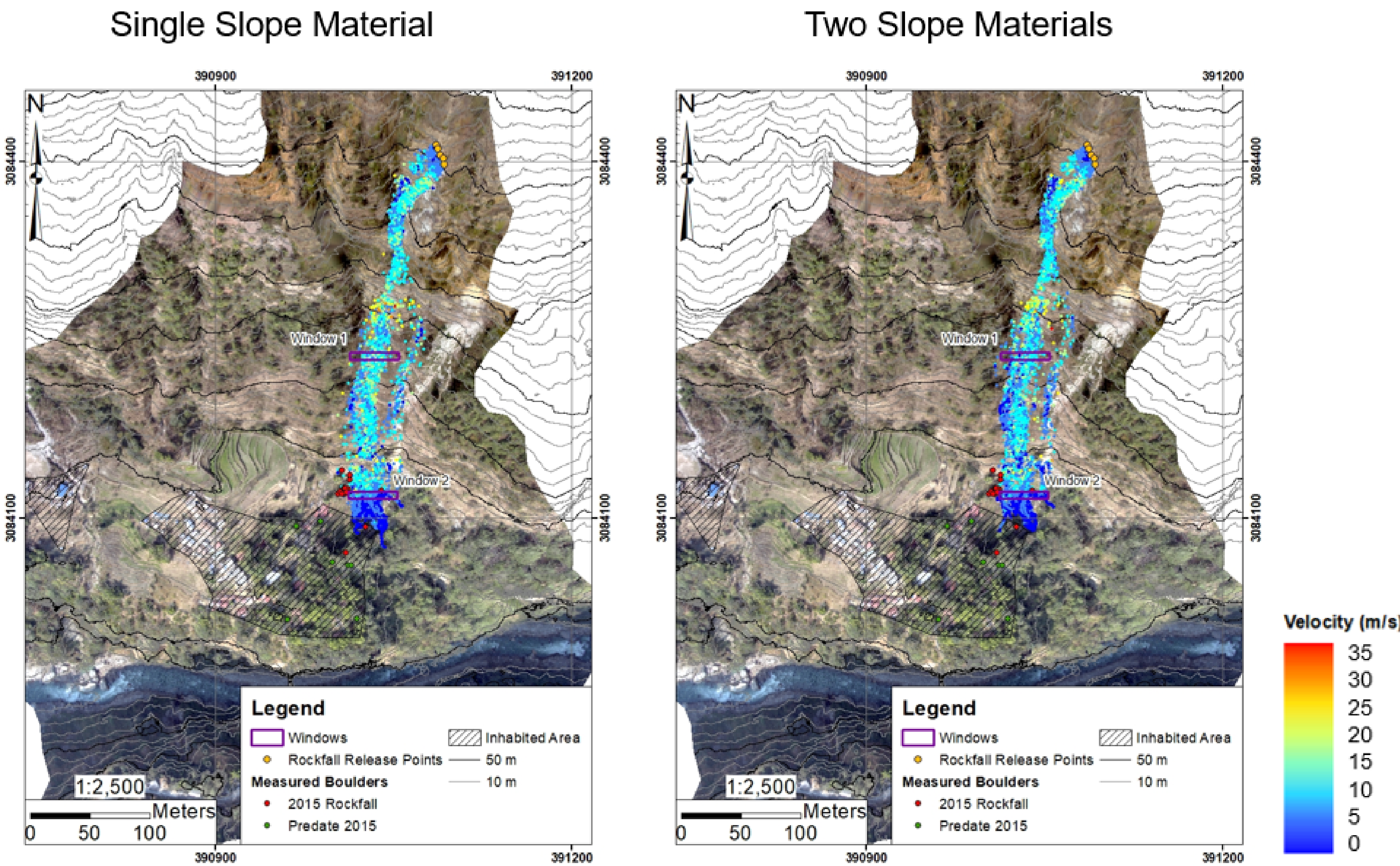

Figure J 8. **Comparison of single and two slope material models simulated using the parameters outlined in Table J 7. Each parameter set was run twice to test for changes in distribution associated with the stochastic nature of the model.**

As shown, the single and two slope material models closely match in terms of runout and boulder distribution Given the anticipated changes in behaviour associated with transitions in slope angle, the two-slope material model with the best fit parameters summarized in Table J 7 was adopted for all future analyses at TLR.

Table J 7. Summary of model parameters tested during calibration.

Parameter	Calibration 1	Calibration 2	Calibration 3	Calibration 4	
Material	Single homogeneous	Single homogeneous	Single homogeneous	Two materials	
Unit energy for normal restitution (m^3/s^2), $E_{0.5,n}$	15	15	15	15	10
Unit energy for tangential restitution (m^3/s^2), $E_{0.95,t}$	50	50	50	50	35
3D Longitudinal roughness scale value, θ_{scale}	1.0 - 1.5	0.6 – 1.0	0.6 – 0.7	0.6	0.8
3D Tangential roughness scale value, ψ_{scale}	0.9 - 1.0	0.4 – 0.7	0.4 – 0.7	0.7	0.9
Shape factor for natural rocks, R_{eff}	Not considered	Not considered	Not considered	Not considered	