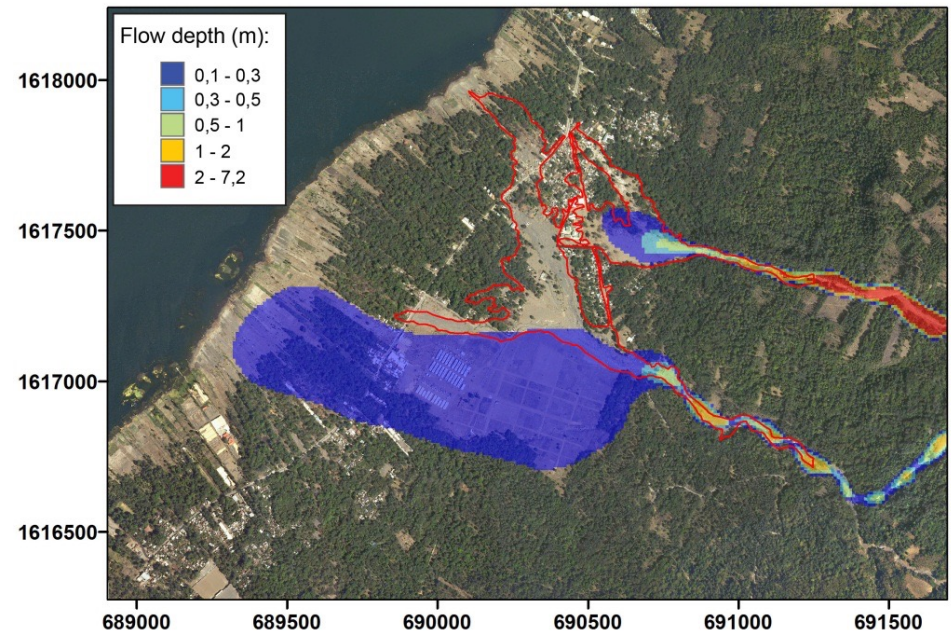


Lahars: dynamics and modeling



Lahars

- **Generation mechanisms:**

1- Triggering mechanisms: rainfall runoff and slope failure (most common), rapid snow or ice melting, overflow from crater lake, volcano-tectonic earthquake

→ may be primary (syn-eruptive) or secondary (post-eruptive or unrelated to eruptions)

2- Generally occur as secondary flows originating from pyroclastic flows, debris avalanches, tephra fallout remobilizations

- **Two-phase transport system:**

water-saturated flow (liquid fraction) + rock fragments up to several meters (solid fraction) → destructive due to high momentum of solid fraction

→ abundant liquid contained in them allows them to flow over gentle gradients and inundate areas far away from their sources

- **3 types of lahars:**

1- debris flows (contain > 50 vol% sediments, bulk densities: 1800-2300 kg.m⁻³)

[Movie](#)

2- transitional flows or hyperconcentrated flows (20-50 vol% sed., bulk densities: 1300-1800 kg.m⁻³)

[Movie](#)

3- muddy streamflows (< 20 vol% sed.)

Lahars



This debris flow on Casitas Volcano, Nicaragua, was triggered by heavy rains during hurricane Mitch in 1998. Casitas is a Holocene volcano with no historic eruptions. This volcano does have an active hydrothermal system, that altered lavas, changing permeability and increasing the likelihood of slope failure.

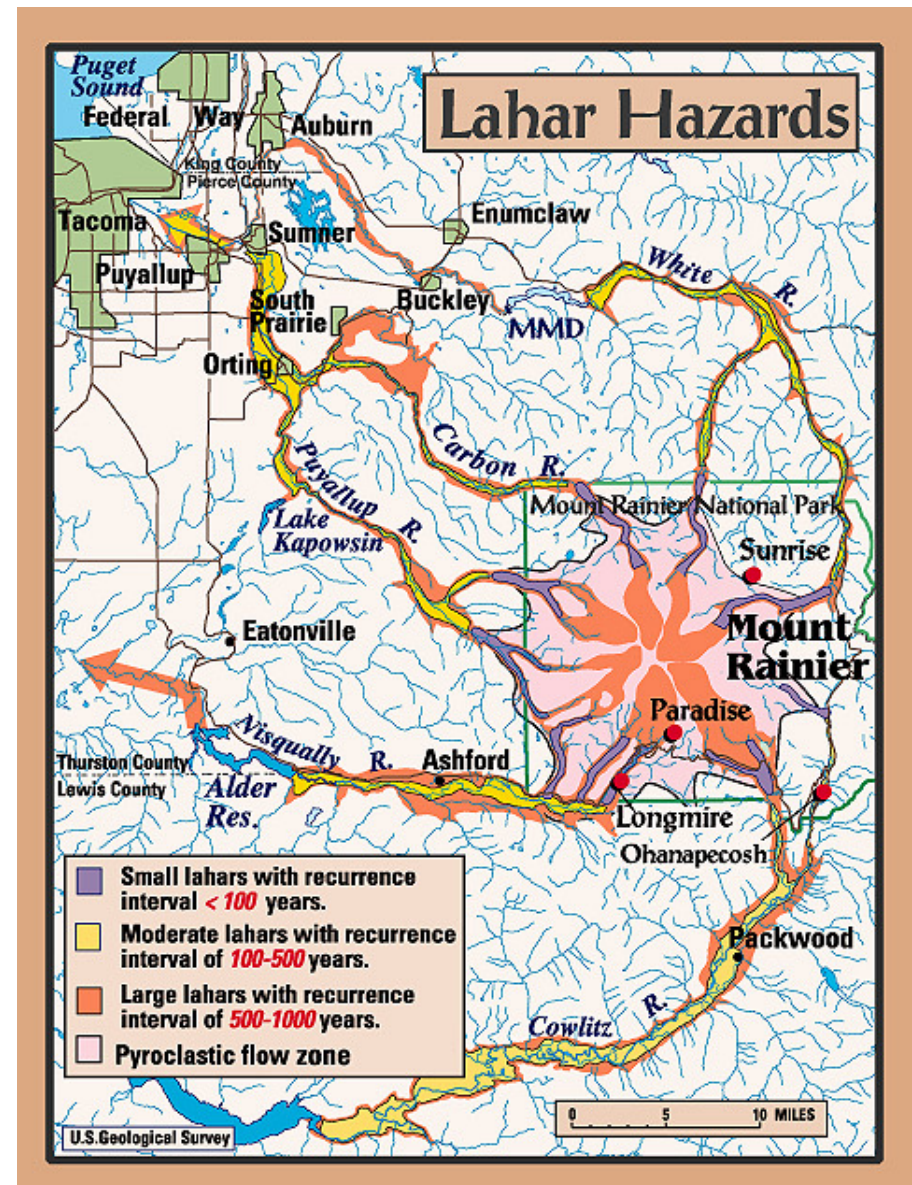
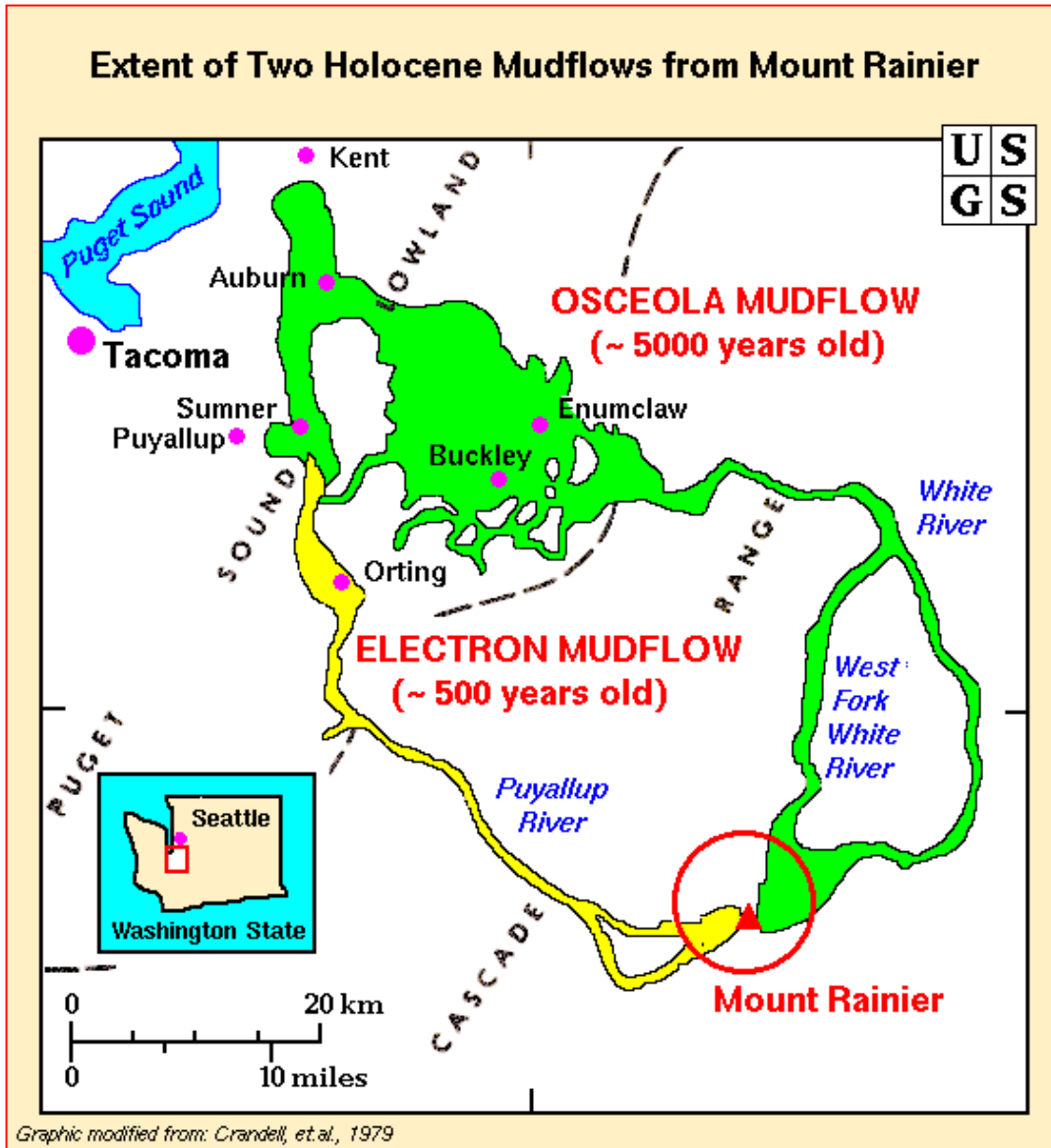


The November, 1985, debris flow at Nevado del Ruiz, Colombia, had a volume of about $4 \times 10^7 \text{ m}^3$ in this river valley (the Rio Azufrado) and runout of $> 100 \text{ km}$! This debris flow killed more than 23,000 people in the city of Armero, located 73 km from the volcano.

Magnitude of debris flows is most often characterized in terms of volume:

- Relatively small debris flows are the most frequent to occur, with $V \sim 10^3 - 10^5 \text{ m}^3$
- The largest debris flows are rare, and have $V > 10^8 \text{ m}^3$

Lahars



Osceola mudflow from Mount Rainier, USA:

→ 3.8 km³ , 140 km runout, 350 km² inundated area, up to 200m thick!

Lahars transport and deposition

➤ Flow transformation during transport (unsteady and non-uniform):

- **Bulking:** The erosion and incorporation of secondary, exotic debris by lahars as they move downstream

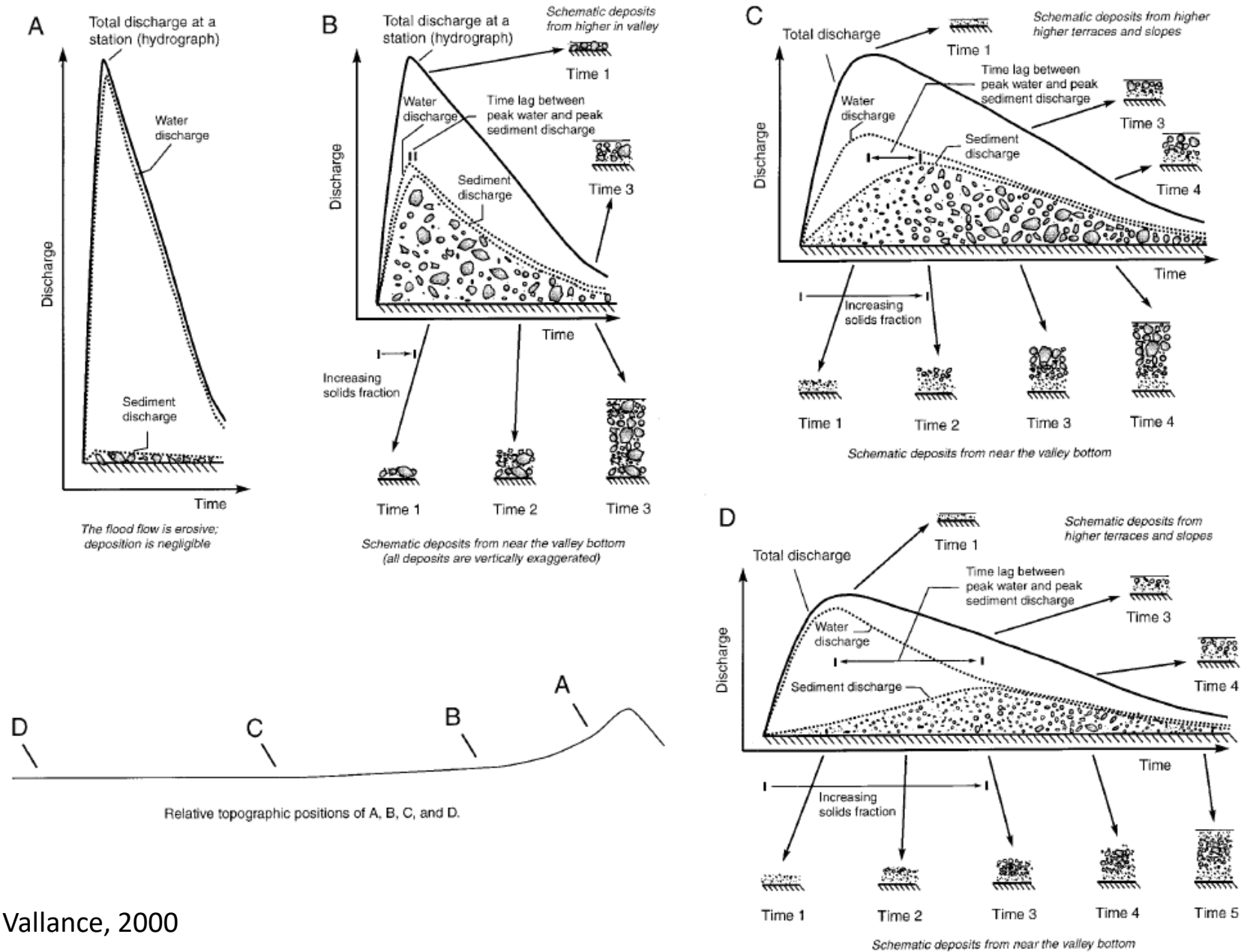
→ apparent bulking factor: $ABF = 1 - (R_f / R_i)(S_i / S_f)$

where R is the proportion of the reference component (or size class) not affected by bulking, S is the proportion of any other component (or size class) of interest, i indicates proximal (initial) value, and f indicates downstream values.

- **Debulking:** A process in which the lahar selectively deposits certain particles, owing to their size or density, as it moves downstream. Debulking differs from the general deposition of bulk sediment in preferentially removing particles, usually large or dense ones, from the flow.

→ apparent debulking factor: $ABF = 1 - (R_i / R_f)(S_f / S_i)$

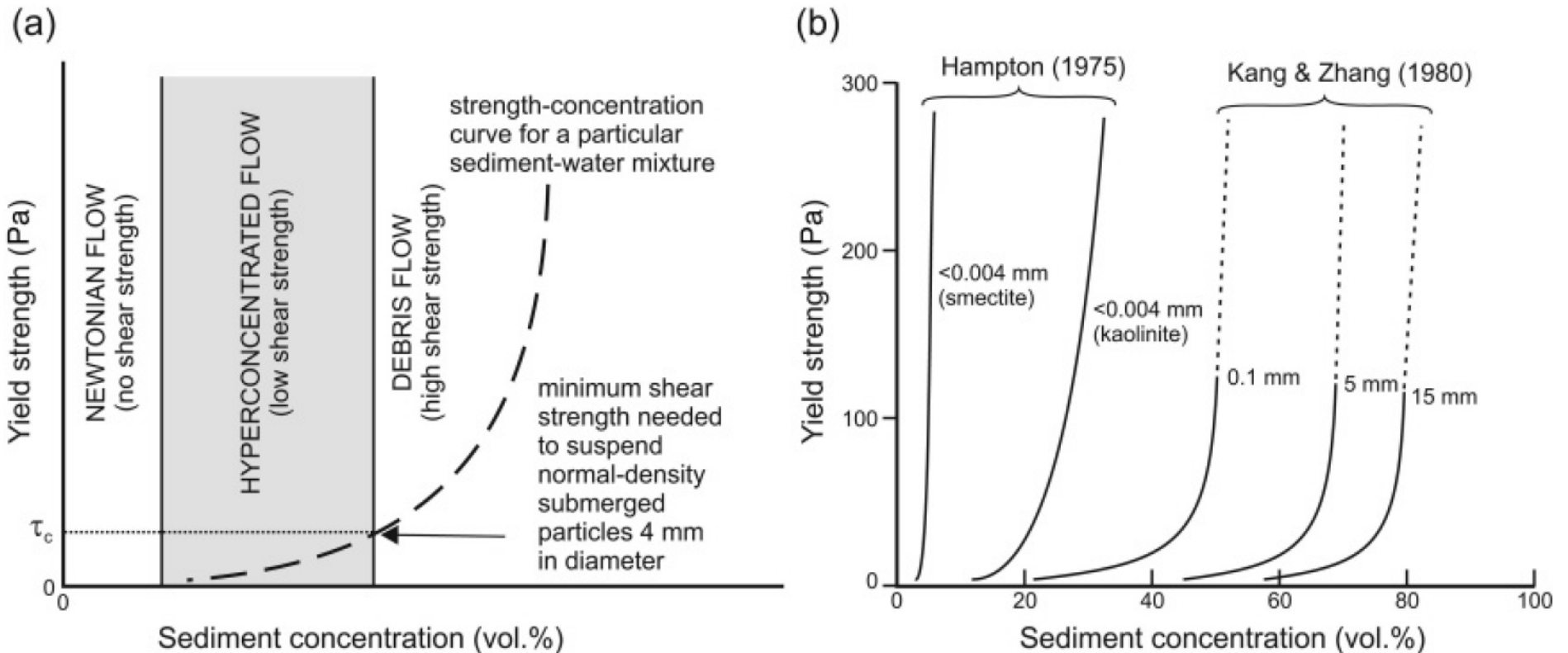
Lahars: transport and deposition



Vallance, 2000

FIGURE 1 Schematic hydrographs showing how lahars beginning with water floods are initiated and behave when they undergo downstream dilution. Flood phase is shown in A, debris-flow phase is shown in B; and transitional phases are shown in C and D. The diagram also illustrates the progressive-aggradation model of inverse grading in C and D.

Lahars: dynamics



Yield strength of sediment–water mixtures as a function of suspended sediment concentration. (a) Definitions of flow type based on an idealized yield-strength–concentration curve for a poorly sorted sediment–water mixture. (b) Measured yield-strength–concentration curves for a range of sediment–water mixtures illustrating the effect of grain-size distributions (curves are marked with the median particle diameter) and compositions.

- Cohesive flows (contain > 5% clay) versus non-cohesive flows (contain < 5% clay) → different flow behaviors, mobility, grain size distribution...
- changes of as little as 2–4 vol.% sediment can produce order-of-magnitude changes in rheological parameters!

Lahars: modeling constrains

- Rheology of such multiphase flows is composition-, scale-, time-, and possibly shear-rate dependent, with a primarily nonlinear and potentially hysteretic (i.e., behavior under increasing strain rate differing from that under decreasing strain rate) relationship between shear stress and strain rate...
 - Flows are neither steady nor uniform
 - Pore pressure is laterally heterogeneous
 - Mobility governed by fluid interiors with lithostatic pore pressures and resistant coarse-grained exteriors
 - There is a range from frictional to collisional grain interactions
- 4 principal components in (physics-based) lahar models:
 - (1) a set of terms that describe conservation of mass and (sometimes) momentum of the bulk flow or its constituent components;
 - (2) a description of channel geometry;
 - (3) a means of quantifying flow resistance;
 - (4) a means of solving the resulting suite of partial differential equations numerically.

Lahars: modeling approaches

- (1) Empirical models based on observed correlations among lahar parameters such as volume, flow velocity, and cross-section or inundation area, but which lack treatment of flow physics
 - (2) simple rheological models that assume a constant stress–strain-rate relationship and composition-independent flow behavior
 - (3) hydrologic models that assume Newtonian behavior but are calibrated to lahars through modification of the flow resistance term
 - (4) sophisticated theoretical formulations that seek to describe the constitutive behavior of multiphase mixtures
 - (5) mass-flow models that seek to combine elements of approaches (3) and (4) with the inclusion of processes such as sediment entrainment and deposition or development of vertical grain-size stratification
- The greatest differences among the more physics-based models lie in their descriptions and treatments of flow resistance and faithfulness to the underlying physics, which commonly represent a compromise between mathematical accuracy and computational tractability.

Lahars: empirical models

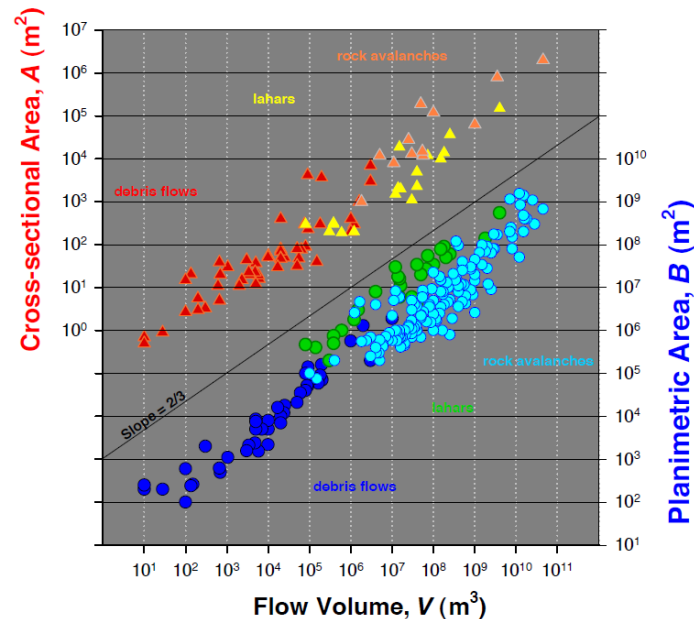
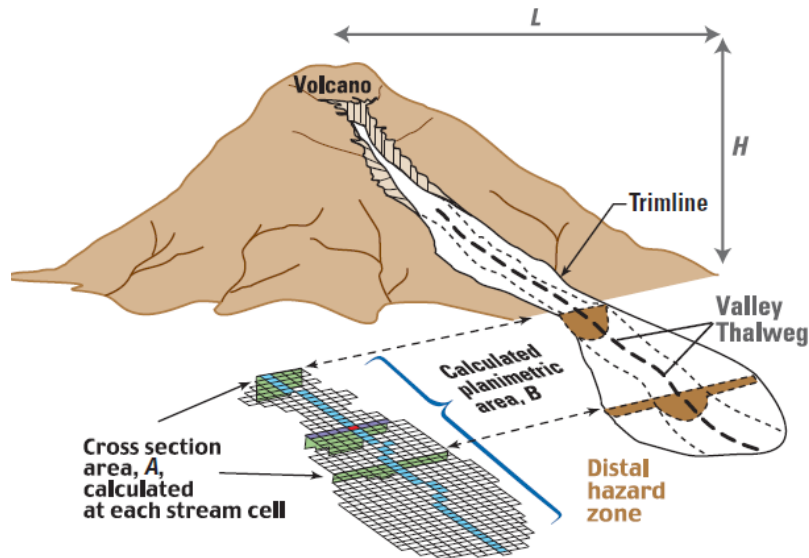
- **LaharZ (Schilling et al., USGS)**

➤ based on historical data, relationships between vertical drop / horizontal travel distance and/or flow volume/ deposited area

+ Rapid, objective and reproducible delineation/estimation of areas at risk, useful during crisis management...

- Do not capture the flow dynamics and variables during runout (velocity, thickness...)

Iverson et al. (1998). GSA Bulletin



$$A = 0.05V^{2/3}$$

$$B = 200V^{2/3}$$

Lahars: empirical models

- **Pierson et al, 1998:**

- predict arrival times $T(x)$ of flows of different near-source peak discharges at distances x downstream from source and a power-law relationship for predicting near-source peak discharge Q_p from lahar volume V :

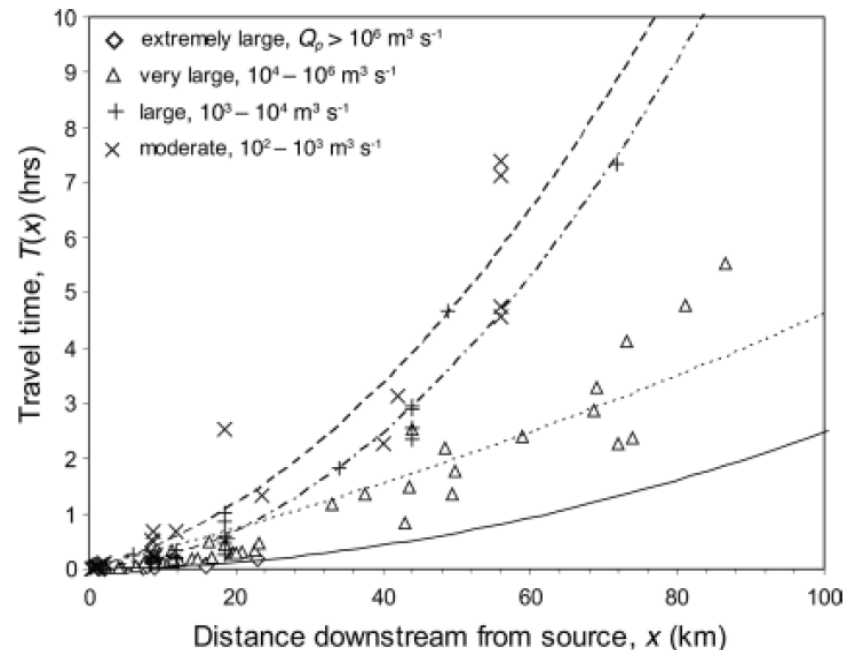
$$T(x) = a_2 x^2 + a_1 x + a_0,$$

$$Q_p = c_1 V^a.$$

- used to forecast proximal peak discharge and consequent travel times to specific distances from source if the initial volume of a future flow can be estimated:

- Different types of flows have different c_1 and a coefficients:

Flow type	c_1	a
Granular debris flow	0.135	0.78
Muddy debris flow	0.0188	0.78
Merapi lahars	0.00558	0.831
Sakurajima lahars	0.00135	0.870
Landslide dambreak	0.293	0.56
Glacial dambreak	0.0163	0.64



Peak discharge, Q_p ($m^3 s^{-1}$)	a_0	a_1	a_2
Extremely large, $>10^6 m^3 s^{-1}$	0.00909467	0.000090487	0.000282666
Very large, $10^4-10^6 m^3 s^{-1}$	-0.271086	0.0378719	0.000110375
Large, $10^3-10^4 m^3 s^{-1}$	0.087511	-0.00889418	0.0015254
Moderate, $10^2-10^3 m^3 s^{-1}$	0.300674	-0.0179581	0.00209817

Lahars: rheological models

➤ **Flow Resistance can be expressed through:**

- **Bingham (viscoplastic) model:**

Assumes a rigid plug, resistance depends on viscosity (μ) and strength (S) of the material:

$$\tau_b = S + \mu \, du/dt$$

- **Bagnold (collisional) model:**

Assumes grain collisions, resisting stress in granular flow is given by:

$$\tau_b = v \, \rho_s \, d^2 \, (du/dt)^2$$

where v is the solids fraction, d is the particle diameter, ρ_s is the density of solid particles, $d^2 (du/dt)^2$ is proportional to the granular temperature.

- **Combination model**

– Coulomb friction plus collisional losses, movement in a viscous fluid with

$$\tau_f = v \, (\rho_s \, g \, h - P) \tan (\phi)$$

where $\tan (\phi)$ is the friction coefficient and P is the fluid pressure. If $P = \rho_s \, g \, h$ the flow is liquefied. At the flow perimeter $P = \rho_f \, g \, h$. In the flow interior, $P = 0.8 \, \rho_s \, g \, h$

➤ **Shear Strength is generally expressed by:**

1) $k = c + \sigma \tan \phi$, with k = shear strength, c = cohesion, σ = normal stress, ϕ = friction angle

2) $\sigma = (\sigma - P)$ with P = pore pressure

Lahars: hydraulic flow models

- Depth-averaged 'shallow water' conservation equation of mass and momentum to calculate a hydrograph that propagates downstream:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0,$$

$$S_f = S_0 - \frac{\partial h}{\partial x} - \frac{u}{g} \frac{\partial u}{\partial x} - \frac{1}{g} \frac{\partial u}{\partial t}, \quad S_f = S_0 - \text{pressure differential} - \text{convective acceleration} - \text{local acceleration}$$

where A is flow cross-sectional area, h is depth, u is depth-averaged velocity, Q is discharge ($=Au$), x is distance downstream, S_f is friction slope, a term taking into account energy dissipation, S_0 is channel bed slope, g is acceleration due to gravity, and t is time.

- The most common resistance terms used in these models are the empirical Manning coefficient n and Chézy coefficient C :

$$n = \frac{1}{u} R^{2/3} S_f^{1/2}, \quad C = \frac{u}{\sqrt{R S_f}}.$$

where the hydraulic radius ($R = A/P$, where P is wetted perimeter) is equivalent to flow depth for wide, shallow channels.

Lahars: Coulomb mixture models

➤ Flow Components:

• Fluid phase

- Frictionless mixture water and fine particles
- Responsible for cohesive strength

• Granular phase

- Coarser particles
- Determines frictional strength

- 1) uses separate equations for the conservation of mass and momentum of the solid and fluid components of a flow of granular material
- 2) couples terms that link the momentum equations of the separate phases (i.e. Darcy's law + Terzaghi stress law)...

- Mass conservation:

$$\frac{\partial h}{\partial t} + \frac{\partial(h\bar{u}_x)}{\partial x} + \frac{\partial(h\bar{u}_y)}{\partial y} = 0,$$

- Momentum conservation in x direction:

$$\rho \left[\frac{\partial(h\bar{u}_x)}{\partial t} + \frac{\partial(h\bar{u}_x^2)}{\partial x} + \frac{\partial(h\bar{u}_x\bar{u}_y)}{\partial y} \right] =$$

$$- \operatorname{sgn}(\bar{u}_x) (\rho g_z h - p_{bed}) \left(1 + \frac{\bar{u}_x^2}{r_x g_z} \right) \tan \varphi_{bed} - 3v_f \eta_f \frac{\bar{u}_x}{h}$$

(basal shear stresses)

$$- h K_{act/pass} \frac{\partial}{\partial x} (\rho g_z h - p_{bed}) - h \frac{\partial p_{bed}}{\partial x} + v_f \eta_f h \frac{\partial^2 \bar{u}_x}{\partial x^2}$$

(longitudinal normal stresses)

$$- \operatorname{sgn} \left(\frac{\partial \bar{u}_x}{\partial y} \right) h K_{act/pass} \frac{\partial}{\partial y} (\rho g_z h - p_{bed}) \sin \varphi + v_f \eta_f h \frac{\partial^2 \bar{u}_x}{\partial y^2}$$

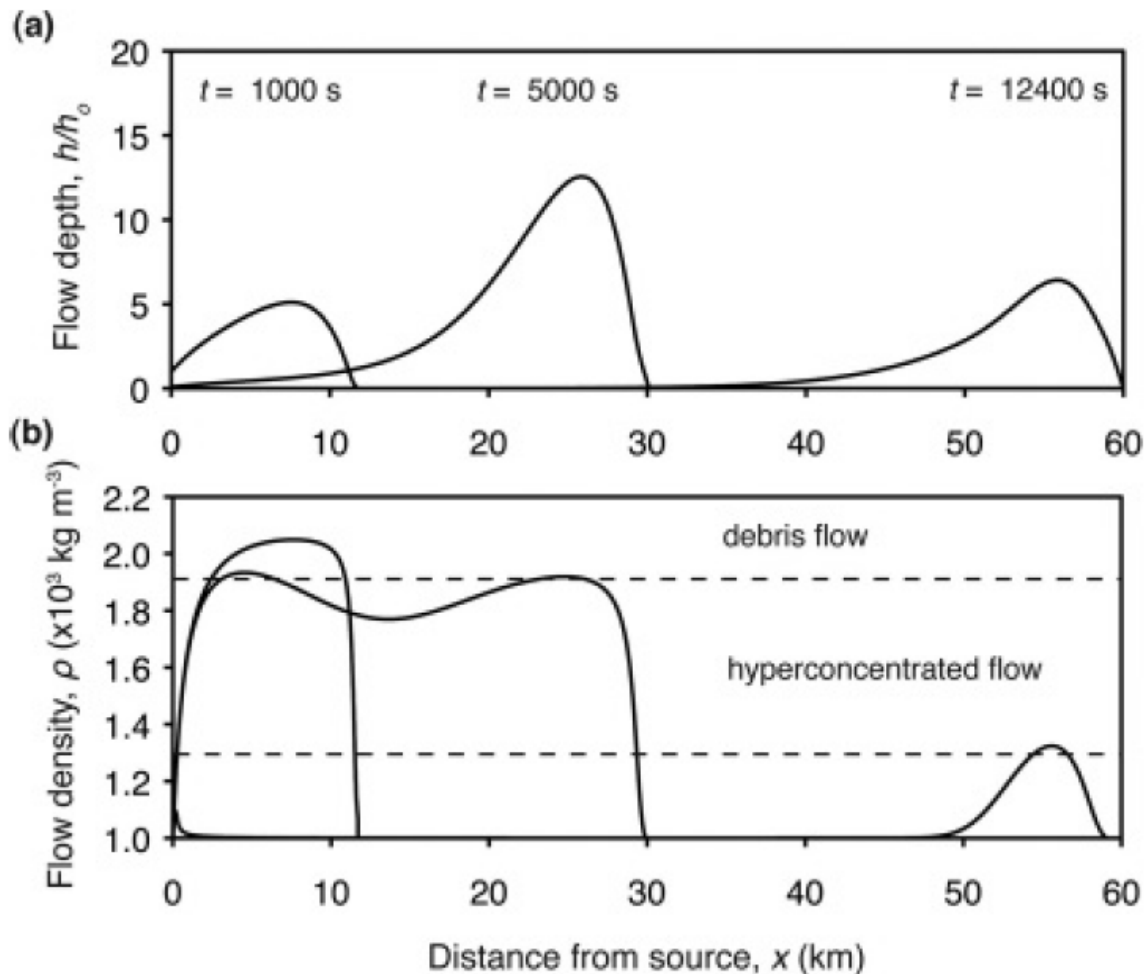
(transverse shear stresses)

$$+ \rho g_x h$$

(gravitational body force stresses)

Lahars: flow transformation models

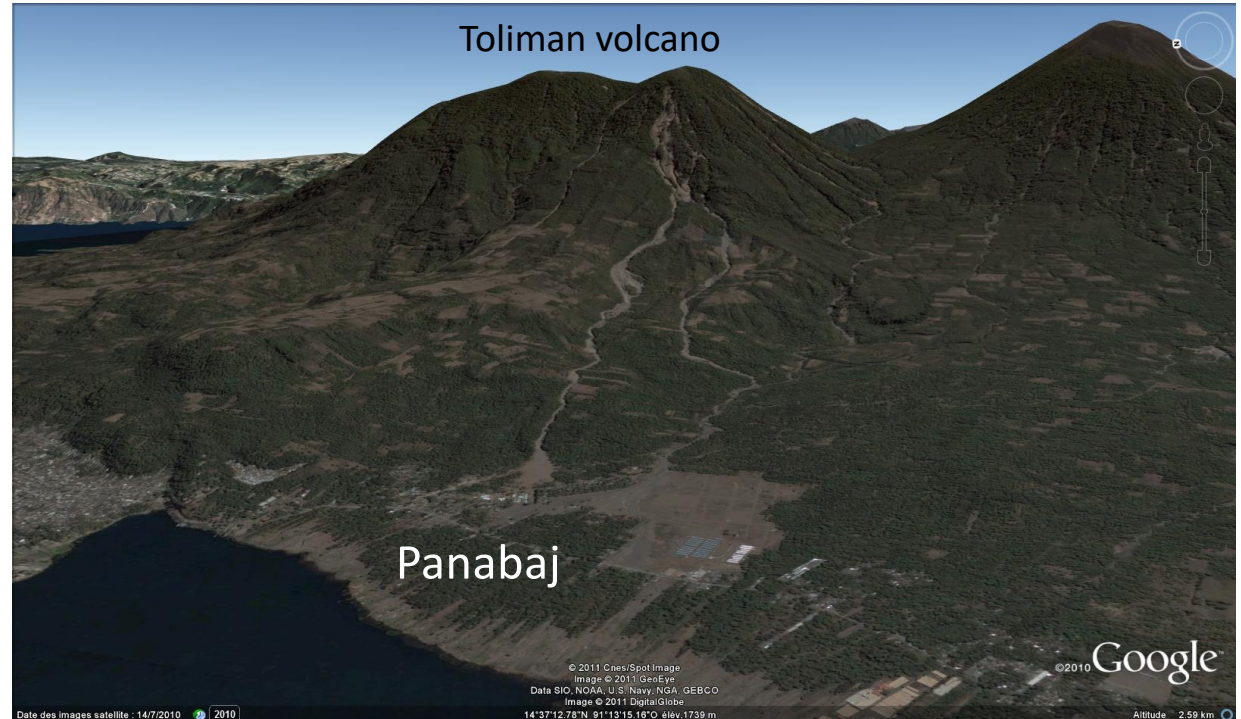
- Fagents and Baloga (2006) developed volume conservation formulations similar to the shallow-water equations but permitted density to vary. Terms representing the addition and loss of volume (mass) were added to the right-hand side of the conservation equations to represent sediment entrainment and sediment deposition by a flow...



The simulated flow starts out as a water flood but rapidly entrains sufficient sediment to become a lahar.

As the flow slows on encountering shallower slopes with distance downstream, deposition of sediment causes the flow to lose sediment and decrease both its depth and bulk density.

Case study: the 2005 Panabaj debris flows



- Heavy rainfall (> 500 mm) over Guatemala in 2-6 October 2005 from tropical storm STAN induced landslides and debris flows
- In the community of Panabaj, Santiago Atitlán, a debris flow of pyroclastic material originating high on the slopes of Tolimán volcano buried much of the community, leaving approximately 400 people dead.

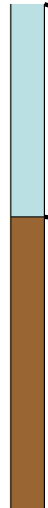
Case study: the 2005 Panabaj debris flows



1.67 m

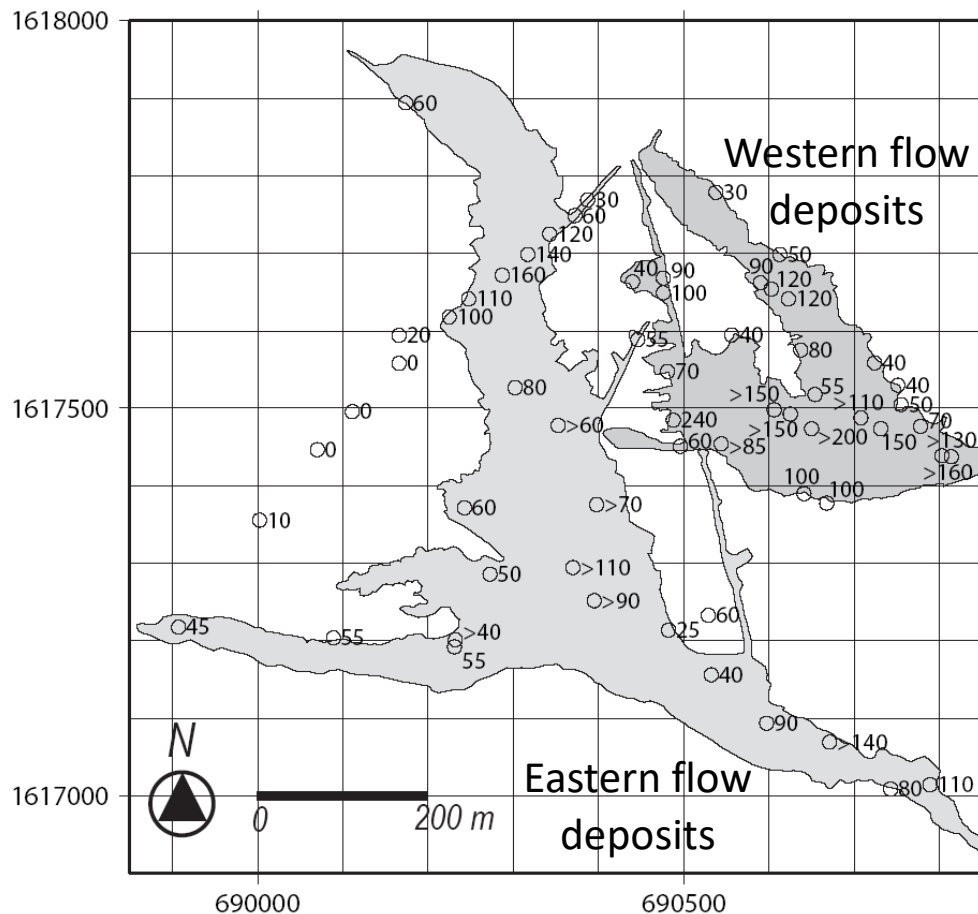
1 m

0 m



Case study: the 2005 Panabaj debris flows

- Field mapping conducted in 2006 by Chuck Connor, Laura Connor (USF) and Mike Sheridan (SUNY at Buffalo) → key flow parameters and recommendations for hazard mitigation plans

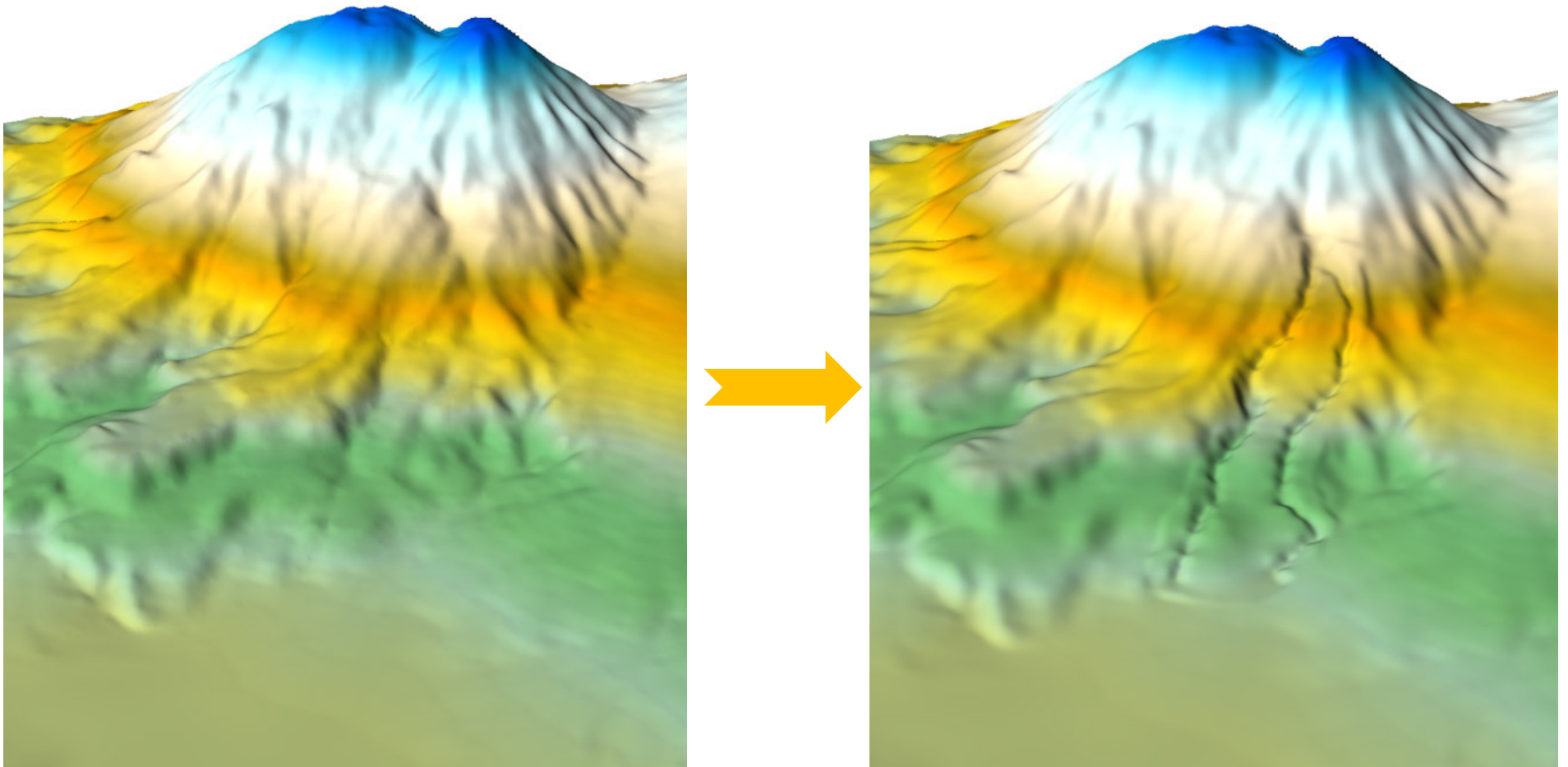


Distribution of the measured flow thicknesses

- ✓ Planimetric area inundated by: Western flow: $\sim 180,000 \text{ m}^2$
Eastern flow: $\sim 77,000 \text{ m}^2$.
- ✓ Thicknesses $\sim 1 \text{ m}$, but $> 1.5 \text{ m}$ in some of the main channels.
- ✓ Hyperconcentrated flows of 10-20 cm thick in distal areas from dewatering
- ✓ High water marks preserved on buildings → up to 40 vol% of water and fine grained sediments
- ✓ Total flow volume $\sim 360,000 \text{ m}^3$.

Case study: the 2005 Panabaj debris flows

- DEM of 10m spatial resolution generated in 2006 from new IGN topo data → poor topographic representation due to smoothing during grid interpolation...



topographic contours of the original DEM adjusted and interpolated from high-resolution orthophotos → new DEM with two main drainages

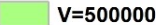
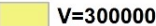
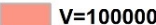
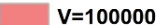
Case study: the 2005 Panabaj debris flows

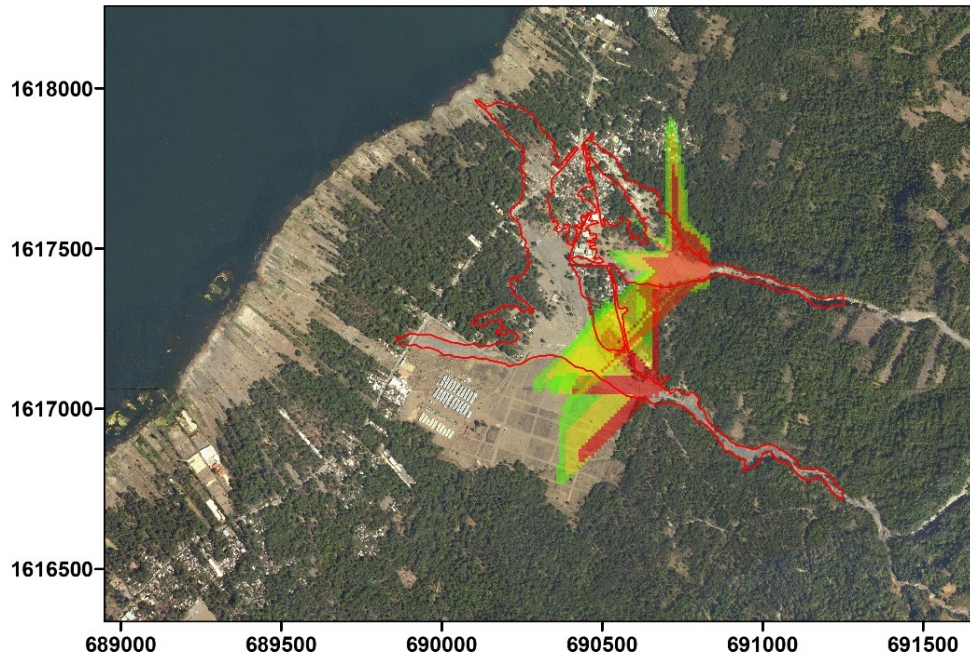
- LaharZ py modeling results

$$A = 0.1 V^{2/3}$$

$$B = 20 V^{2/3}$$

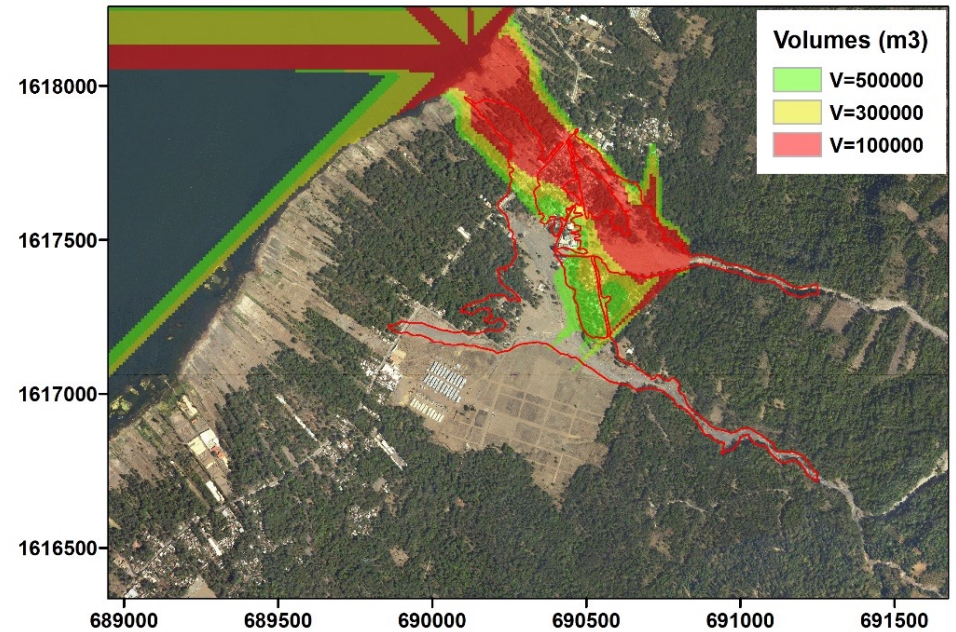
Volumes (m3)

debrisflow_n	debrisflow_s
 V=500000	 V=500000
 V=300000	 V=300000
 V=100000	 V=100000



$$A = 0.05 V^{2/3}$$

$$B = 200 V^{2/3}$$



Case study: the 2005 Panabaj debris flows

Geophysical Mass Flow Models: rheological constraints

➤ TITAN2D and VOLCFLOW: choice of different rheological models

➤ FLO-2D: shear stress relationship using a quadratic solution

Name of the Law	Equation
Coulomb	$\mathbf{T} = \rho h \left(g \cos \alpha + \frac{u^2}{r} \right) \tan \phi_{\text{bed}} \frac{\mathbf{u}}{\ \mathbf{u}\ }$
One angle	$k_{\text{act/pass}} = 1$
Two angles	$k_{\text{act/pass}} = 2 \frac{1 \pm [1 - \cos^2 \phi_{\text{int}} (1 + \tan^2 \phi_{\text{bed}})]^{1/2}}{\cos^2 \phi_{\text{int}}} - 1$
Viscous	$\mathbf{T} = 3\mu \frac{\mathbf{u}}{h}$
Voellmy (Coulomb + u^2 term)	$\mathbf{T} = \rho h \left(g \cos \alpha + \frac{u^2}{r} \right) \tan \phi_{\text{bed}} \frac{\mathbf{u}}{\ \mathbf{u}\ } + \xi \rho \ \mathbf{u}\ \times \mathbf{u}$
Plastic (constant retarding stress)	$\mathbf{T} = T_0 \frac{\mathbf{u}}{\ \mathbf{u}\ }$
Plastic + u^2 term	$\mathbf{T} = T_0 \frac{\mathbf{u}}{\ \mathbf{u}\ } + \xi \rho \ \mathbf{u}\ \times \mathbf{u}$
Bingham (plastic + viscous)	$\mathbf{T} = T_0 \frac{\mathbf{u}}{\ \mathbf{u}\ } + 3\mu \frac{\mathbf{u}}{h}$

^aTerms are ρ , density; h , thickness; g , gravity; α , slope; u , depth-averaged velocity; r , slope curvature; ϕ_{bed} , basal friction angle; ϕ_{int} , internal friction angle; $k_{\text{act/pass}}$, earth pressure coefficient; μ , viscosity; T_0 , yield strength; ξ , Voellmy coefficient.

From Kelfoun (2011)

$$S_f = S_y + S_v + S_{td}$$

where S_f is the total slope-friction and is equal to the sum of the various slope components, the yield slope (S_y), the viscous slope (S_v), and the turbulent dispersive slope (S_{td}). These slope components can be rewritten as:

$$S_f = \frac{\tau_y}{\gamma_m h} + \frac{K \eta V}{8 \gamma_m h^2} + \frac{n_{td}^2 V^2}{h^{4/3}}$$

where τ_y is the yield strength, γ_m is the specific weight of the flow, h is the flow depth, K is an empirical resistance parameter, η is fluid viscosity, V is flow velocity, and n_{td} is the Manning roughness coefficient.

Each of these rheological models can be somewhat calibrated using proxies from field/laboratory data: H/L ratio for the Coulomb basal friction, measure of viscosity and yield strength for the slope-friction model etc...

Case study: the 2005 Panabaj debris flows

	Eastern flow	Western flow
Area inundated (m ²)	77,000	180,000
Bulk volume (m ³)	126,000 ± 29,000	240,200 ± 55,400
Sediment concentration (vol.%)	Between 27% to 44%	Around 31%-32%
H/L ratio	0.32	0.3
A/V ^(2/3)	30.6	46.6
A/L ²	0.0037	0.0085

- Using the values of volumetric sediment concentration, yield strength and dynamic viscosities obtained by O'Brien and Julien (1988) for a mudflow with similar characteristics to the October 2005 Panabaj lahars, two empirical relationships were used for the *uncalibrated* FLO-2D simulation:

$$\tau_y = 0.0345e^{20.1C_v}$$

$$\eta = 0.00283e^{23.0C_v}$$

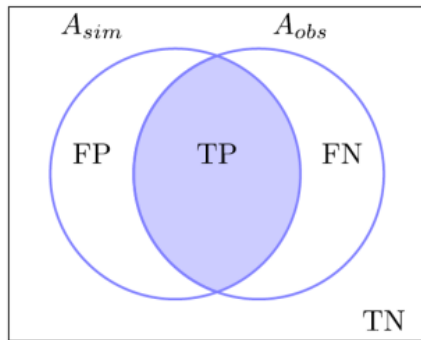
- Brookfield viscometer on a matrix of deposit samples taken at various locations inside the WPF and EPF lobes show two different empirical relationships that are used for the *calibrated* FLO-2D simulation:

$$\tau_y = 0.005e^{32.4C_v}$$

$$\eta = 0.03e^{26.4C_v}$$

Case study: the 2005 Panabaj debris flows

Validation metrics for Geophysical mass flow (GMF) models



TP = True positives
TN = True negatives
FP = False positives
FN = False negatives

A_{sim} = area inundated by simulated flows
 A_{obs} = area inundated by observed flows

- The Jaccard similarity coefficient (R_j) uses TP and the union of areas inundated by observed and simulated flows:

$$R_j = \frac{|A_{obs} \cap A_{sim}|}{|A_{obs} \cup A_{sim}|} \times 100 = \frac{TP}{TP+FN+FP} \times 100$$

- The model sensitivity (R_{MS}) uses TP and the area inundated by simulated flows:

$$R_{MS} = \frac{|A_{obs} \cap A_{sim}|}{|A_{sim}|} \times 100 = \frac{TP}{TP+FP} \times 100$$

- The model precision (R_{MP}) uses TP and the area inundated by observed flows:

$$R_{MP} = \frac{|A_{obs} \cap A_{sim}|}{|A_{obs}|} \times 100 = \frac{TP}{TP+FN} \times 100$$

Case study: the 2005 Panabaj debris flows

Modeling the October 2005 lahars at Panabaj with FLO-2D

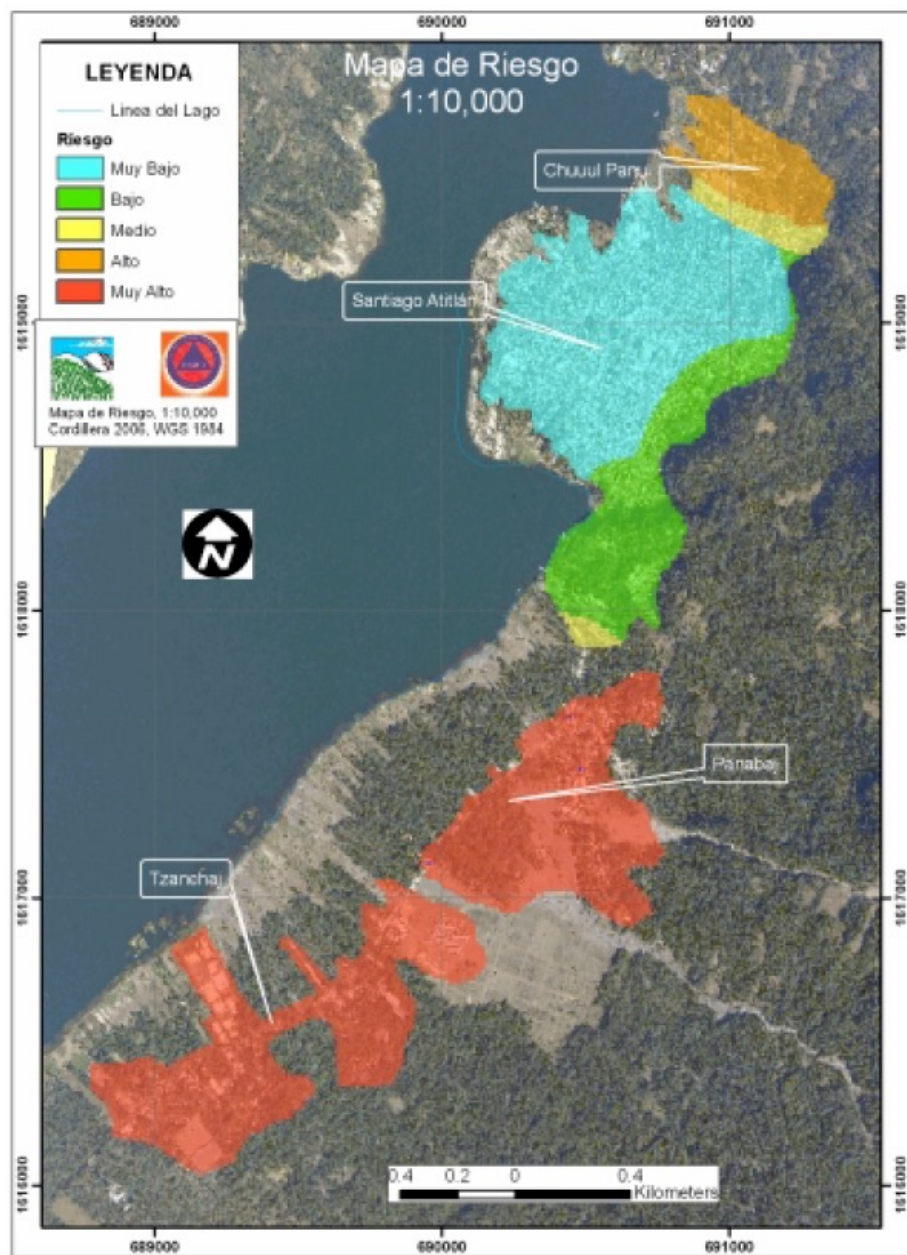


Location	Measured	Simulated
Flow velocities (ms^{-1})		
1	11.0	6.8
2	8.8	4.8
Flow thicknesses (m)		
A	0.9	1.0
B	0.5	0.5
C	1.1	1.0
D	1.3	1.4
E	1.5	0.8
F	0.3	0.3

- model dependence on rheology \rightarrow better performance of the calibrated model with higher R_J , R_{MS} , and R_{MP} than the uncalibrated model and fewer false positives and false negatives.
- In both calibrated and uncalibrated models, $R_{MS} > R_{MP} \rightarrow$ more false positives than false negatives \rightarrow conservative models

Validation metrics	calibrated	uncalibrated
Percent Length Ratio (R_L)	103.0%	96.9%
Jaccard Fit (R_J)	49.6%	32.3%
Bayesian metrics		
Model Precision (R_{MP})	62.2%	40.7%
Model Sensitivity (R_{MS})	74.1%	63.3%

Case study: the 2005 Panabaj debris flows

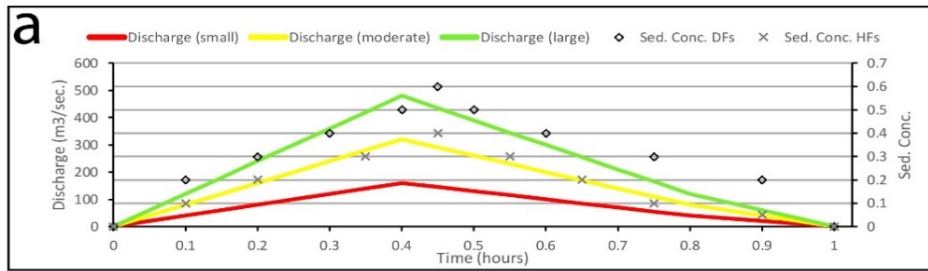


*Debris flow risk map in the Santiago Atitlan area
(Cordillera S.A., 2006)*

Key recommendations for hazard mitigation (OXFAM report, 2006):

- Immediately devote significant resources to public outreach and education → response to future emergencies related to real or potential debris flows.
- Encourage relocation of much of the Panabaj community off of the alluvial fan.
- Develop strategies for mitigating hazards (i.e., construction of levees and/or retainment ponds against small debris flows).
- Monitoring should include rainfall intensity, infiltration, and seismic measurements .
- Incorporate numerical models for debris flows in current hazard assessment.

Case study: the post-2010 Merapi lahars



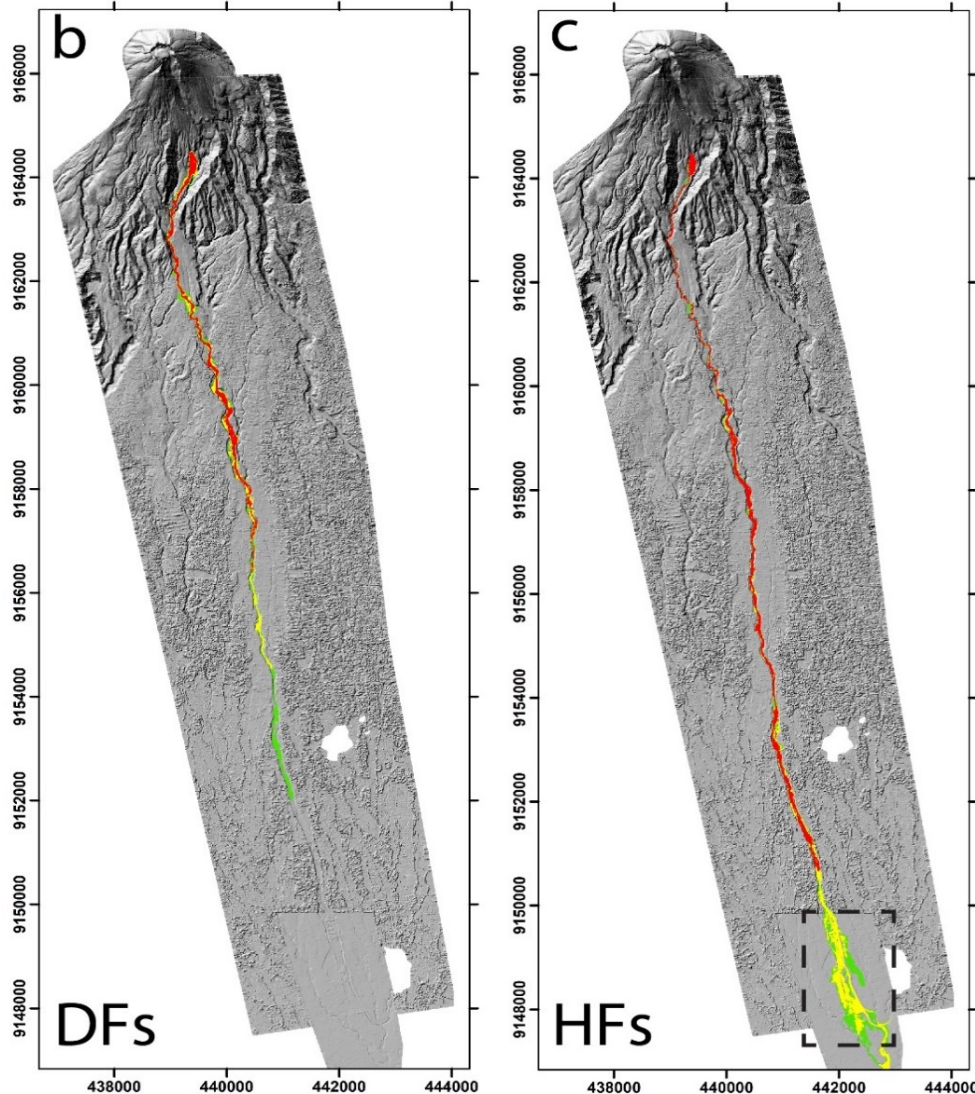
FLO-2D simulation results for the Gendol catchment.

a) Inflow hydrographs for the three lahar events considered: small-volume (red), moderate-volume (yellow) and large-volume (green). Sediment volumetric concentrations for the DF and HF simulations are also shown.

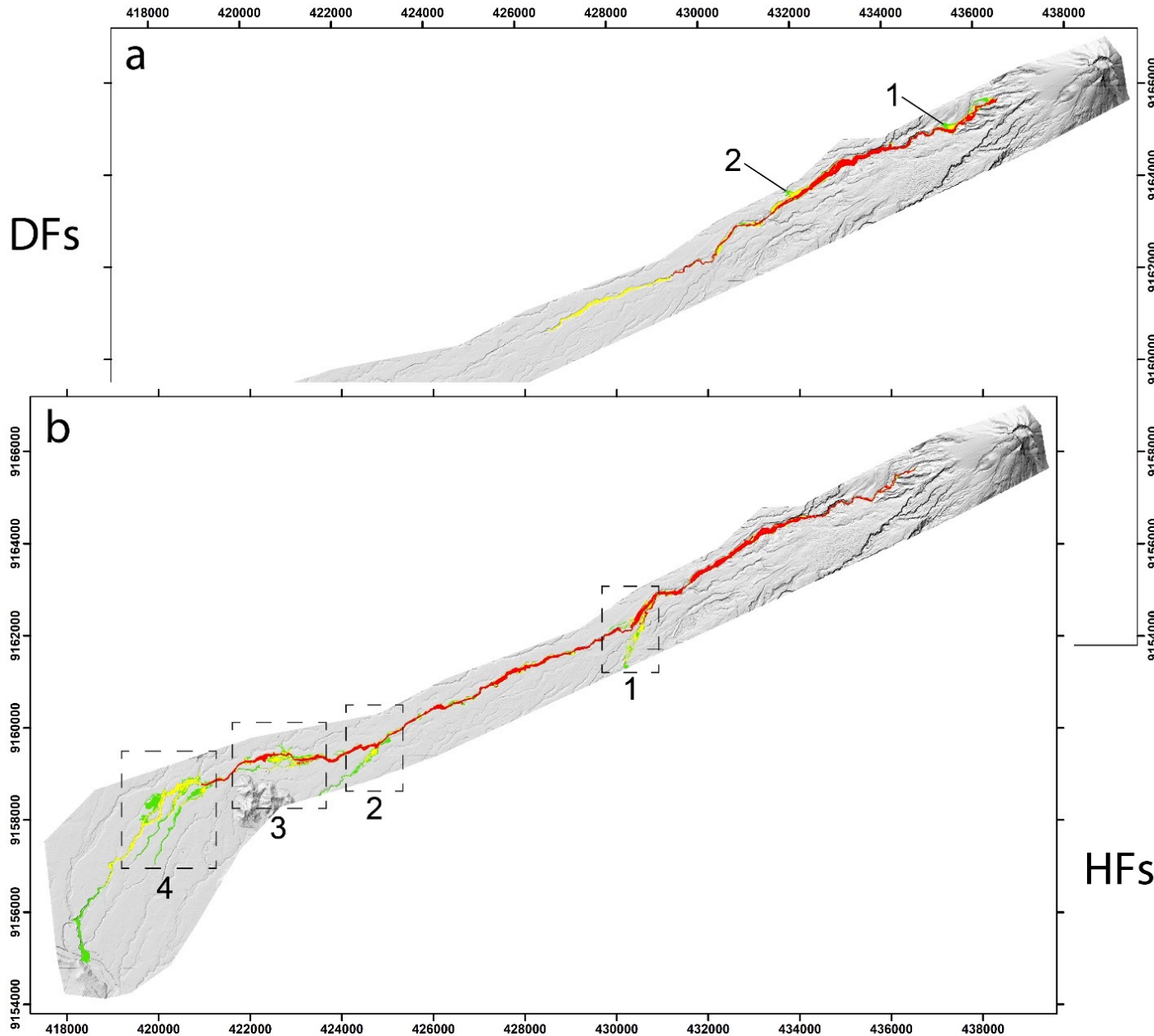
b) Inundation map of the three simulated DFs.

c) Inundation map of the three simulated HFs.

Dashed black rectangle shows the overbank area in the distal part of the Opak-Gendol catchment.



Case study: the post-2010 Merapi lahars



FLO-2D simulation results for the Putih catchment.
a) Inundation map of the three simulated DFs. Numbers correspond to the location of minor overflows.

b) Inundation map of the three simulated HFs. Dashed black rectangles and numbers show the major overbank areas along the Putih catchment