Numerical reconstruction of the San Carlos de Apoquindo debris flow (Las Condes, 8 October 2026): flow path, volume and uncertainty from public evidence

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Abstract

On 8 October 2026, a mudflow descended from the San Carlos de Apoquindo ravine (Las Condes, Santiago) over a hillside burned nine months earlier. It was reconstructed using a two-dimensional shallow-water model with mud rheology, on terrain with a resolution of 30 m resampled to a 4 m grid with 42,018 buildings, using only public data and an evidence log of every source consulted. Following about 144 mm of accumulated rainfall, and with the 0 °C isotherm reported above the summit of the catchment (10.1 km^2), an independent estimate adopting the reported soil saturation places the mixture volume at about 295,000 m^3, of the same order as that required by the simulated reach. The hypothesis most compatible with observations—main channel, southern branches and rainfall on the hillside—reproduces the Camino El Alba, General Blanche and Quebrada Honda corridors that delimit the official affected area, the reach to Padre Hurtado and about 1 m of mud at Clínica UC Christus, with an exploratory compatibility index of 72/100, which compares hypotheses and does not measure predictive accuracy. A test using held-out observations, defined before examining results, had an unfavorable outcome: the hypothesis reaches 19 of 49 officially affected facilities (39 %, compared with the specified 70 %), because the model leaves parts of the official area without mud. In hypothetical scenarios, flooding of Quebrada Honda is reproduced if the Francisco Bulnes Correa storm-water culvert does not take in the flow calculated at its inlet, of about 65 m^3/s; under those assumptions, a capacity of 30 m^3/s is insufficient. These values do not describe the real structure. The simulated mud extends beyond the official area, for which retention in homes and the coarse load are considered possible explanations, and entry into the Aula Magna of Universidad de los Andes is not reproduced. The results are preliminary.

Scope statement. Independent technical study, not official, based exclusively on public information. Three types of results are distinguished: *observed* (as reported by authorities, the press and official mapping), *calculated* (model outputs under explicit assumptions, such as volumes and discharges) and *hypothetical scenarios* (variants tested, such as culvert capacities). No calculated or hypothetical value is a measurement or an official conclusion; all require independent scientific validation. The study does not evaluate real works whose capacity and condition are not public, or attribute responsibility.

English translation of the Spanish original (11 October 2026); in case of discrepancy, the Spanish version prevails. Figures keep their Spanish labels.

1 Introduction and problem statement

On Thursday 8 October 2026, at about 17:00 (UTC−3), a flow of water, mud and rocks descended from the ravine draining the Andean foothills of San Carlos de Apoquindo (Las Condes, Santiago) and traveled along residential streets for several kilometers: it swept away vehicles and a bus (The Clinic, 2026), flooded homes, a clinic and a university, injured six people and prompted a disaster-area declaration (Interferencia, 2026). According to the press reports consulted, which cite information from Servicio Nacional de Geología y Minería (Sernageomin), the event occurred in an area classified in February 2026 as having a high debris-flow hazard (Chilevisión, 2026a). The catchment had been affected by a fire covering about 1,000 ha between December 2025 and January 2026 (BioBioChile, 2026a; Municipalidad de Las Condes, 2026), and the event followed an exceptionally rainy start to October: more than 90 mm at Quinta Normal so far that month, close to the historical maximum of October 1930 (Rondanelli et al., 2026).

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By the following day, no official mapping of the affected area, discharge measurements or published high-water marks had been located among the public sources consulted. The available information was limited to press reports, the municipality's list of closed streets, an affected-area perimeter and two conflicting explanations of the origin. This work addresses the reconstruction of the debris-flow path, volume and discharge using an explicit physical model and verifiable public evidence. It also estimates flow depth, velocity and pressure in streets and at buildings in the study area, taking the uncertainty of the estimates into account.

2 Theoretical framework

Debris flows and mudflows. A debris flow is a mixture of water and sediment whose behavior depends on the total volumetric solids concentration $C_{v,\mathrm{tot}}$. With $C_{v,\mathrm{tot}}$ between 0.20 and 0.55, the mixture has a yield stress τ_y: it stops when the driving stress does not exceed it. Its density is $\rho_m = \rho_w + C_{v,\mathrm{tot}}(\rho_s - \rho_w)$, where ρ_m, ρ_w and ρ_s are the densities of the mixture, water and solids, respectively ($\mathrm{kg\,m^{-3}}$); ρ_m ranges from $1{,}300\,\mathrm{kg\,m^{-3}}$ to $1{,}900\,\mathrm{kg\,m^{-3}}$. In contrast, the rheological relationships involve the fine-matrix concentration $C_{v,\mathrm{f}}$ (Section 4.3).

Concentration and density ranges in the literature. Mud floods and hyperconcentrated flows contain between 20 and 45 % sediment by volume, with averages of 20 to 35 % and peaks near 45 % in mudflows (FLO-2D Software, Inc., 2021; O'Brien & Julien, 1988); their density ranges from about 1,330 to $1{,}740\,\mathrm{kg\,m^{-3}}$. Above 50 % by volume, the term debris flow is used (Costa, 1984; Zanuttigh & Lamberti, 2007), with solids concentrations of 50 to 80 % and densities of 1,400 to $2{,}400\,\mathrm{kg\,m^{-3}}$ measured in experimental channels and natural samples (Iverson, 1997); about $2{,}000\,\mathrm{kg\,m^{-3}}$ has been estimated for dense surges observed in the field (Zanuttigh & Lamberti, 2007). Table 1 places the mud mixtures tested in this study within that context.

Table 1: Volumetric sediment concentration (C_v) and mixture density according to the literature, and mud mixtures tested in this study. The densities of the tested mud mixtures are calculated with $\rho_s = 2{,}650\,\mathrm{kg\,m^{-3}}$; τ_y and η are the fine-matrix yield stress and viscosity according to O'Brien and Julien (1988).

Flow or mud type	C_v	ρ_m ($\mathrm{kg\,m^{-3}}$)
Mud flood and hyperconcentrated flow (FLO-2D Software, Inc., 2021; O'Brien & Julien, 1988)	0.20–0.45	1,330–1,740
Mudflow, typical values (FLO-2D Software, Inc., 2021)	0.20–0.35 (peaks of 0.45)	1,330–1,740
Debris-flow threshold (Costa, 1984; Zanuttigh & Lamberti, 2007)	≥ 0.50	$\geq 1{,}825$
Debris flow (Iverson, 1997)	0.50–0.80	1,400–2,400
This study: Glenwood 2b ($\tau_y = 6.6\,\mathrm{Pa}$, $\eta = 0.77\,\mathrm{Pa\,s}$)	0.40	1,660
This study: Glenwood 2b with $C_v = 0.43$ ($\tau_y \approx 11\,\mathrm{Pa}$)	0.43	1,710
This study: Glenwood 1 ($\tau_y = 29\,\mathrm{Pa}$, $\eta = 8.8\,\mathrm{Pa\,s}$)	0.45	1,742

Choice of mud mixture and rationale. Three pieces of evidence guide the choice. Sernageomin classified the event as a flash flood that carried a large quantity of sediment (BioBioChile, 2026a); images from the day show a fine matrix with stones, logs and entrained vehicles, rather than boulder fronts; and the observed reach, to Av. Padre Hurtado, requires a mud mixture capable of traveling several kilometers along streets with low gradients. This places the event between the upper end of mudflows and the debris-flow threshold. The reference mud mixture (Glenwood 2b, $C_v = 0.40$) is within that range; a thicker one (Glenwood 1, $C_v = 0.45$) stops before Padre Hurtado, whereas the reference mixture extends beyond the official affected area. Because yield stress increases exponentially with concentration (O'Brien & Julien, 1988), a small change—from 0.40 to 0.43—nearly doubles τ_y; this is why that intermediate value is tested, also representing the additional resistance of the coarse load (stones, logs and debris) not included in the fine-matrix rheology.

Shallow water with rheology. When flow thickness is small relative to its extent, the depth-integrated Navier–Stokes equations reduce to the two-dimensional Saint-Venant equations. The mixture rheology enters as a friction slope S_f, defined in Equation (3). The quadratic closure of O'Brien and Julien (1988) and O'Brien, Julien, and Fullerton (1993), used by FLO-2D (FLO-2D Software, Inc., 2021), sums three terms: yield stress, viscosity, and turbulence plus grain collisions.

Urban representation. In urban areas, flow is channeled along streets and diverted by buildings. These can be represented as raised blocks, impermeable holes or through porosity; the choice affects predictive capability (Schubert & Sanders, 2012).

Mobilizable volume. Debris-flow volume can be estimated from a rainfall–runoff balance. For recently burned catchments, empirical models also relate it to 15-minute rainfall intensity, burned area and relief (Gartner, Cannon, & Santi, 2014). Peak discharge is empirically related to volume (Mizuyama, Kobashi, & Ou, 1992).

Calibration with qualitative observations. When only the extent of the affected area is known, different combinations of volume, discharge and resistance produce similar footprints, i.e., equifinality occurs. The generalized likelihood uncertainty estimation approach (GLUE; Beven & Binley, 1992) proposes accepting all simulations with acceptable behavior and reporting the envelope of their predictions instead of a single best fit.

3 Hypotheses and objectives

Origin hypotheses. Three hypotheses about the locations of flow inflows to the urban area are compared, formulated from sources of differing reliability:

H1 The hypothesis tested is that the conduit carrying the ravine beneath the urban development became blocked on the alluvial fan, at Mons. Álvaro del Portillo, Av. La Plaza and General Blanche, and all the flow traveled over the surface from that point (Chilevisión, 2026a; Interferencia, 2026).

H2 The hypothesis tested is channel collapse or overflow at Francisco Bulnes Correa, where the piped channel crosses the street at the start of Quebrada Honda (BioBioChile, 2026a; Interferencia, 2026).

H3 Inflow is assumed to be distributed among several points where the foothill channels reach the urban development: the main channel (H1), a southern channel crossing the Universidad de los Andes campus (S1) and smaller ravines ending at Av. La Plaza Sur (S2). The hydrograph is distributed in proportion to the area of each catchment.

During the study, H4 (combined outflow at the alluvial fan and at the Francisco Bulnes Correa culvert inlet, plus southern inflows) and H5 (H4 plus direct rainfall runoff on the hillside east of La Plaza Sur) were added as *exploratory* hypotheses formulated after examining the initial results. Two terrain representations (with the linear-park channel carved into the terrain, and a higher-resolution photogrammetric terrain model) and different culvert capacities were also tested. They are reported separately from the initial hypotheses.

Process hypothesis (HP). A two-dimensional shallow-water model with homogeneous-mixture rheology, supplied with a volume compatible with the observed rainfall, reproduces the reported extent: the streets with mud presence and the reach to Av. Padre Hurtado.

General objective. To estimate the debris-flow path and hydrodynamic indicators in streets and at buildings, and characterize their uncertainty from the ensemble of acceptable simulations.

Specific objectives.

1. Construct an urban terrain model with buildings and streets from open data.
2. Implement and verify the mixture rheology in a two-dimensional open-source model.
3. Independently constrain the mixture volume using rainfall and empirical models.
4. Calibrate discharge, volume and rheology using public evidence and compare the compatibility of hypotheses H1, H2 and H3 with observations.
5. Quantify uncertainty and publish the results in a reproducible form.

Links between hypotheses, objectives, methods and results. Table 2 links each hypothesis and objective to the procedure addressing it and the result to be reported.

Table 2: Links between hypotheses, objectives, methods and expected results.

Hypothesis or objective	Corresponding method	Expected result
H1, H2 and H3, evaluated separately	Input sources and calibration criteria (Sections 4.3 and 4.6)	Accepted simulations and metrics by hypothesis (Section 6.9)
HP	Model and criteria for reproducing the extent (Sections 4.3 and 4.6)	Compatibility with observations (Section 6.9)
Specific objective 1	Construction of the urban terrain model (Section 4.2)	Characterization of the domain, buildings and streets (Section 6.6)
Specific objective 2	Implementation and verification (Sections 4.3 and 4.4)	Stopping, restart, convergence and balance results (Section 6.7)
Specific objective 3	Independent volume estimation (Section 4.5)	Volume distributions (Section 6.8)
Specific objective 4	Inverse calibration (Section 4.6)	Acceptable parameters and H1–H3 comparison (Section 6.9)
Specific objective 5	Uncertainty synthesis and publication (Section 4.7)	Maps, ensemble summaries and reproducible materials (Section 6.11)
General objective	Extraction of indicators by street and building (Section 4.7)	Flow path and indicators with explicit uncertainty (Section 6.11)

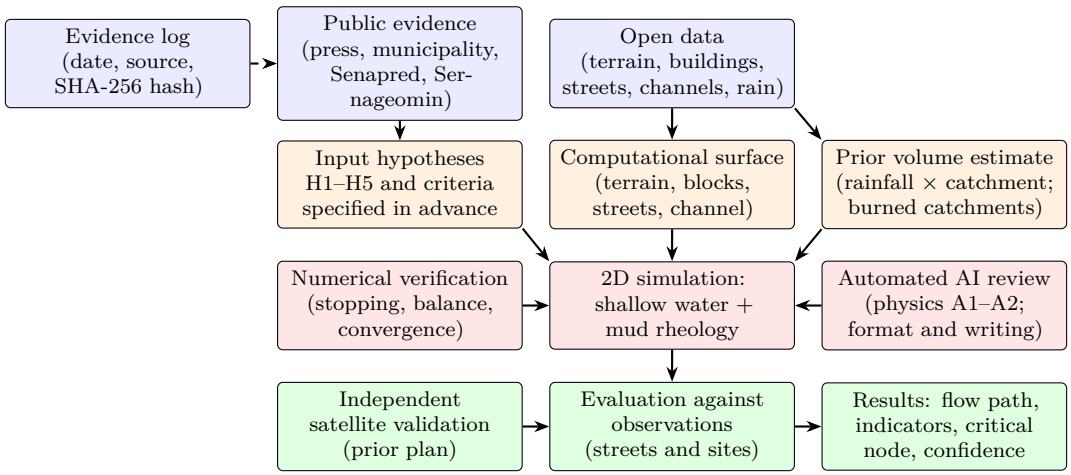

Figure 1: Study workflow. Blue: inputs; orange: preparation; red: computation and checks; green: evaluation and results. Satellite validation was defined before examining the images and is not used for calibration.

Table 3: Inputs to the first model generation; the current version adds Overture Maps building footprints, the official hydrographic network (Geoportal de Chile), the CR2 analysis, Open-Meteo, Sentinel-2 and the official affected area from IDE Chile.

Data	Source	Resolution	Use
Bare-earth terrain	FABDEM V1-2 (Neal & Hawker, 2023)	1 arc second (≈30 m), resampled to 4 m	Ground elevations and catchments
Surface	Copernicus GLO-30 (European Space Agency, s. f.)	30 m	Height of large buildings
Alternative terrain	SPOT 2014 photogrammetry (Hussain, 2021)	0.07 points/m^2 (≈8–10 m)	Sensitivity test
Buildings, streets, channels	OpenStreetMap (Colaboradores de OpenStreetMap, 2026)	vector	1,103 blocks, streets, channel alignment
Rainfall	DMC, station 330019 (Dirección Meteorológica de Chile, 2026)	hourly and synoptic	Prior volume estimate
Observations	Press, municipality, Senapred, Sernageomin	point-based	Evaluation (not a model input)

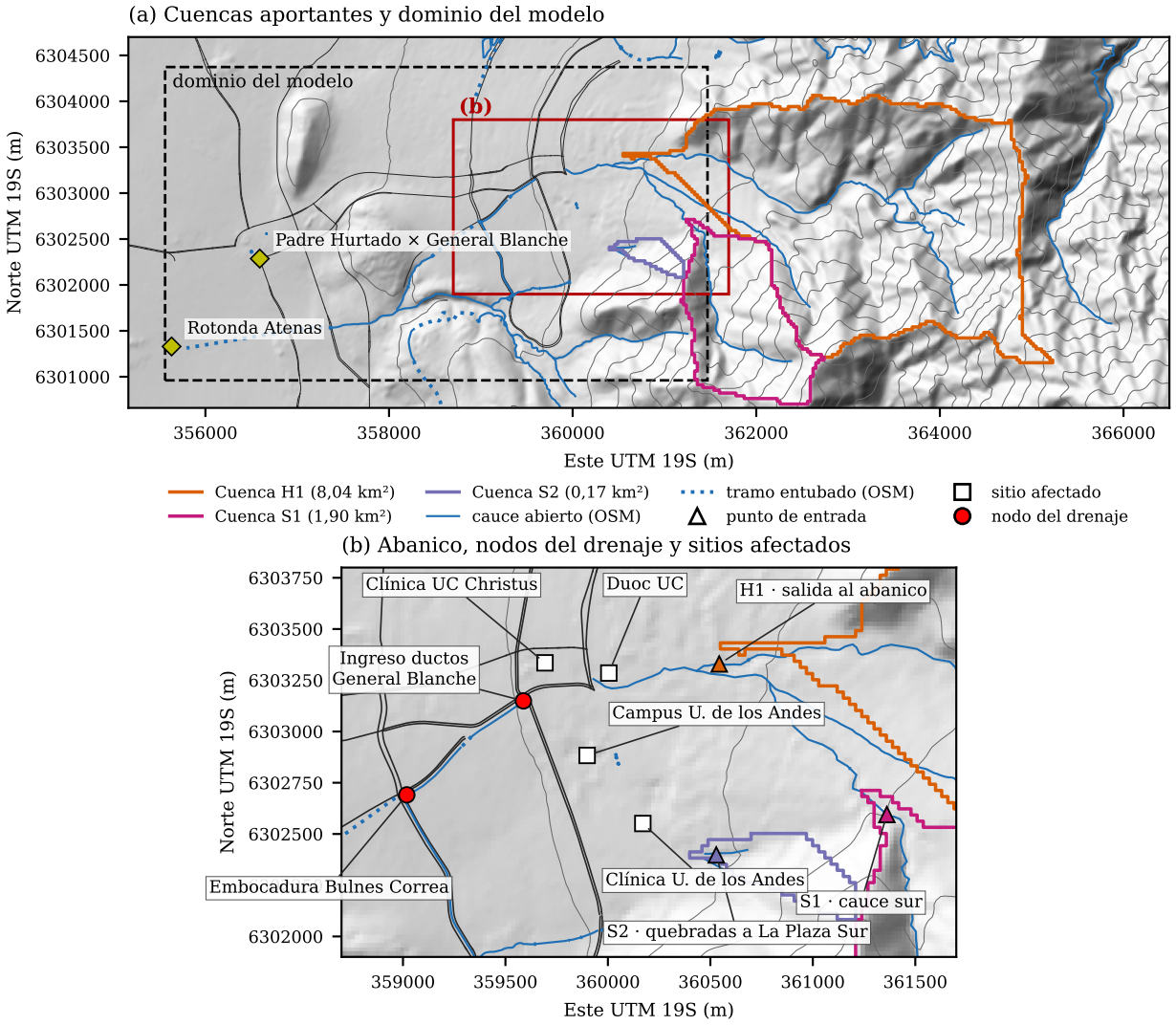

Figure 2: Study area. (a) Contributing catchments delineated from the terrain (H1: main channel; S1: southern channel; S2: smaller ravines towards La Plaza Sur), open channels and piped reaches according to OpenStreetMap, model domain and downstream reference points. (b) Close-up of the alluvial fan: flow entry points, drainage nodes (entrance to the General Blanche conduits and Bulnes Correa culvert inlet) and sites with confirmed impacts. UTM coordinates, zone 19 south, WGS 84.

4 Methodology

4.1 Evidence and evidence log

Every consultation of an external source was archived in an evidence log: UTC date and time, source, extracted data, page capture and SHA-256 hash. This records what information existed at the time of modeling and allows the prediction to be compared later with subsequent observations. Observations were classified according to their physical nature, as recommended in the technical review (see the closing statement on the use of AI tools):

- **Confirmed presence:** streets along which the press reports that the flow "descended": Camino El Alba, General Blanche and Quebrada Honda (La Tercera, 2026b); also Av. La Plaza, where vehicles were recorded being swept away.
- **Municipal closures:** Mons. Álvaro del Portillo and Av. San Carlos de Apoquindo (El Dínamo, 2026). These may reflect precautionary measures or cleanup.
- **Municipal operational perimeter:** El Alba to the north, La Plaza to the east, Quebrada Honda to the south and Padre Hurtado to the west (La Tercera, 2026b). It may include dry areas.
- **Reach:** to the Pueblito Los Dominicos area and Av. Padre Hurtado (La Tercera, 2026b).
- **Sites with presence confirmed by several sources:** the emergency department of Clínica UC Christus San Carlos de Apoquindo, with about 1 m of mud (Cadena 3, 2026); Clínica Universidad de los Andes, at its entrances and outside according to the clinic itself (Radio La Señal, 2026); the Duoc UC campus (BioBioChile, 2026b); and the Universidad de los Andes campus, whose community was stranded (Cooperativa, 2026a). Servicio Nacional de Prevención y Respuesta ante Desastres (Senapred) includes Av. La Plaza Sur among the affected areas (El Dínamo, 2026).
- **Low-reliability evidence, used only to formulate hypotheses:** an image circulated on social media marking several flow sources consistent with the mapped channels.

Rainfall data come from automatic station 330019 (Eulogio Sánchez, Tobalaba) of Dirección Meteorológica de Chile (2026): 34.8 mm on 8 October, 13.8 mm between 15:00 and 21:00 local time, and 49.2 mm between 6 and 7 October. The press reports between 16 and 20 mm in about one hour.

Hydrometeorological information obtained after screening. The mayor reported 144 mm of accumulated rainfall in the area, 20 mm of it on the day of the event, with saturated soil (Interferencia, 2026). The analysis by Centro de Ciencia del Clima y la Resiliencia (Rondanelli et al., 2026) records 42.8 mm at Río Molina station on 8 October, 31.6 mm between 15:00 and 19:00 and a maximum of 10.9 mm in 30 minutes, with the 0 °C isotherm near 2,800 m according to the Cerro Tres Puntas observatory; the same analysis delineates the catchment between 929 and 2,355 m (about 10.6 km^2) and estimates burn severity using the Sentinel-2 differenced normalized burn ratio (dNBR). The Open-Meteo historical hourly forecast (Zippenfenig, 2023) places the isotherm between 2,700 and 2,770 m between 14:00 and 17:00 on 8 October, and gives an accumulated total of about 150 mm over the catchment between 2 and 8 October. Sentinel-2 images (Drusch et al., 2012) from 21 September show no snow in the catchment (normalized difference snow index below 0.4 throughout the cloud-free portion; the white areas were thin clouds), and those from 9 October show 0.09 km^2 of fresh snow, all above 2,000 m. The high Andes did have substantial snow cover: Valle Nevado reported about 1.2 m of fresh snow on 6 and 7 October (Emol, 2026), above 3,000 m.

Comparison with the CR2 analysis. Table 4 compares the catchment and forcing data in this study with those in the CR2 analysis (Rondanelli et al., 2026), published after the hypotheses were formulated.

Later assessments. Senapred updated its assessment to 56 destroyed homes, 40 with major damage, 1,960 with minor damage, 384 people directly affected and more than 1,200 rescued (La Tercera, 2026d).

4.2 Terrain, buildings and streets

This section describes the terrain in the first model generation (1,103 buildings); the version with the full city (42,018 Overture Maps footprints, channels carved according to the official hydrographic network and about 852,000 triangles) is described in Section 6.1. The terrain without buildings or vegetation, i.e., the digital terrain model (DTM), is FABDEM V1-2 (Hawker et al., 2022; Neal & Hawker, 2023), with a resolution of 1 arc

Table 4: Comparison with the CR2 analysis. The difference in area and minimum elevation is due to the outlet location: CR2 places the catchment outlet farther downstream, in the linear park; this study places it where each channel enters the urban development.

Variable	CR2	This study
Maximum catchment elevation	2,355 m	2,355 m (FABDEM and Copernicus GLO-30)
Minimum elevation	929 m	973 to 1,081 m (outlets H1, S1, S2)
Area	10.6 km^2	10.1 km^2
0 °C isotherm	~ 2,800 m (Cerro Tres Puntas)	2,700–2,770 m at 14–17 h (Open-Meteo)
Rainfall on 8 October	42.8 mm at Río Molina	same data
Fire	Sentinel-2 dNBR (28-Dec-2025 and 6-Feb-2026)	not used in the calculation (direction for further investigation)

second (about 30 m), bilinearly resampled to a regular 4 m grid in the UTM system, zone 19 south (WGS 84 datum). Resampling increases point density but does not improve the effective resolution of the elevation model. This limitation must be considered when interpreting the results. A total of 1,107 building footprints from OpenStreetMap (OSM; Colaboradores de OpenStreetMap, 2026) were incorporated as raised blocks. Each block's height is the mean of DSM − DTM, where the digital surface model (DSM) is Copernicus GLO-30 (European Space Agency, s. f.) and the DTM is FABDEM, when the footprint covers at least 900 m^2 and the difference exceeds 2.5 m. Otherwise, the height is the OSM number of stories multiplied by 3 m; without that information, 6 m is assumed. The mean and 95th percentile of DSM − DTM are reported for each block. Four OSM polygons tagged as buildings that correspond to facilities (sports complexes and a shopping center with mean DSM − DTM below 4 m) were excluded because, as solid blocks, they would have artificially diverted the flow. Streets were lowered by 0.15 m, the curb height, with widths based on their category.

4.3 Propagation model

ANUGA version 4.0.1 (Roberts, Nielsen, Gray, Sexton, & Davies, 2026) is used: finite volumes on an unstructured triangular mesh, with the DE1 scheme (second-order Runge–Kutta). For a homogeneous mixture of constant density, ANUGA solves the evolution of unit discharge $\mathbf{q} = h\mathbf{u}$ through the mass-conservation (1) and momentum-conservation (2) equations:

$$\partial_t h + \nabla \cdot \mathbf{q} = S_h, \tag{1}$$

$$\partial_t \mathbf{q} + \nabla \cdot \left(\frac{\mathbf{q} \otimes \mathbf{q}}{h} + \tfrac{1}{2} g h^2 \mathbf{I} \right) = -gh\nabla z - \frac{\boldsymbol{\tau}_b}{\rho_m} + S_h \mathbf{u}_{\text{in}}, \tag{2}$$

where h is flow thickness (m); $\mathbf{u}$, depth-averaged velocity ($m\,s^{-1}$); $\mathbf{q} = h\mathbf{u}$, discharge per unit width ($m^2\,s^{-1}$); z, bed elevation (m); g, gravitational acceleration ($m\,s^{-2}$); S_h, the rate of thickness input ($m\,s^{-1}$); $\mathbf{u}_{\text{in}}$, inflow velocity ($m\,s^{-1}$); $\boldsymbol{\tau}_b$, basal shear stress (Pa); ρ_m, mixture density ($kg\,m^{-3}$); and $\mathbf{I}$, the identity tensor. After dividing by the constant ρ_m, no density factor appears in the pressure or gravity terms. Basal resistance is $\boldsymbol{\tau}_b/\rho_m = ghS_f\,\mathbf{u}/U$, with $U = |\mathbf{u}|$ and friction slope S_f given by

$$S_f = \frac{\tau_y}{\rho_m g h} + \frac{K\eta U}{8\rho_m g h^2} + \frac{n_{\text{td}}^2 U^2}{h^{4/3}}, \tag{3}$$

where τ_y is yield stress (Pa); η, the dynamic viscosity of the mixture (Pa s); K, the dimensionless laminar resistance parameter; and n_{td}, the equivalent Manning coefficient for turbulence and dispersion ($s\,m^{-1/3}$). Yield stress and viscosity are obtained from the rheological relationships

$$\tau_y = 0.1\,\alpha_2 e^{\beta_2 C_{v,\text{f}}}, \qquad \eta = 0.1\,\alpha_1 e^{\beta_1 C_{v,\text{f}}}, \tag{4}$$

where $C_{v,\text{f}}$ is the volumetric concentration of the fine matrix; in contrast, density ρ_m uses the total concentration $C_{v,\text{tot}}$ (Section 2). The sweep simulations adopt $C_{v,\text{tot}} = C_{v,\text{f}}$. The coefficients $(\alpha_1, \beta_1, \alpha_2, \beta_2)$ come from Table 13 of FLO-2D Software, Inc. (2021), where α_1 is expressed in poise and α_2 in $dyn\,cm^{-2}$; β_1 and β_2 are dimensionless. The factor 0.1 in (4) converts both quantities to SI units, so that τ_y is in Pa and η in Pa s. The Glenwood 2 sample appears in three variants in different versions of the documentation and was treated as a sensitivity test. K and n_{td} vary by surface: on paved streets $K = 100$ and $n_{\text{td}} = 0.025$; elsewhere, $K = 400$ and $n_{\text{td}} = 0.050$.

Resistance (3) is applied as a fractional step and solved implicitly in each cell. With $a = \tau_y/(\rho_m h)$, $b = K\eta/(8\rho_m h^2)$, $c = g n_{\mathrm{td}}^2/h^{4/3}$ and $r = (U^* - \Delta t\, a)_+$, the result is

$$U^{n+1} = \frac{2r}{1 + b\Delta t + \sqrt{(1 + b\Delta t)^2 + 4c\Delta t\, r}}, \tag{5}$$

where the asterisk indicates the state before the resistance step; the superscript $n+1$, the state after that step; Δt is the time step and $(x)_+ = \max(x, 0)$. Solution (5) satisfies $0 \le U^{n+1} \le U^*$, preserves direction, dissipates energy and does not modify h. If $|\mathbf{q}^*| \le \Delta t\, \tau_y/\rho_m$, the cell stops and may reactivate in subsequent steps. ANUGA's own Manning friction is set to zero to avoid duplicating resistance.

The mixture enters through a triangular hydrograph with peak discharge Q_p, mixture volume V_m and time to peak of 600 s, with base $T_B = 2V_m/Q_p$. In a circle of radius 14 m, each source adds the thickness increment Δh corresponding to the volume supplied by the hydrograph during the step, together with its momentum: $h^+ = h^- + \Delta h$ and $\mathbf{q}^+ = \mathbf{q}^- + \Delta h\, \mathbf{u}_{\mathrm{in}}$, where superscripts $-$ and $+$ indicate the states before and after the input, and $\mathbf{u}_{\mathrm{in}}$ is oriented along the channel axis. When $Q = 0$, there is no forcing. In H3, each source receives the fraction of the hydrograph corresponding to its catchment area. The mesh has about 4.3×10^5 triangles: 40 m^2 in the corridor between the channels and Padre Hurtado (equivalent side length of about 10 m) and 600 m^2 outside it. Gravitational acceleration is $g = 9.8\,\mathrm{m\,s^{-2}}$ throughout the model. Simulations last T_B + 1,200 s, and the volume balance is recorded in each.

Table 5: Physical and numerical parameters applied in the simulations. Rheological coefficients are from the OBrien and Julien sample table compiled in the FLO-2D manual (FLO-2D Software, Inc., 2021); $\tau_y = 0.1\,\alpha_2 e^{\beta_2 C_v}$ in Pa and $\eta = 0.1\,\alpha_1 e^{\beta_1 C_v}$ in Pa s.

Sample	α_1	β_1	α_2	β_2	τ_y (Pa) / η (Pa s) with C_v =		
					0.35	0.40	0.45
Glenwood 1	0.0028	23.00	0.0345	20.10	3.9 / 0.89	10.7 / 2.80	29.2 / 8.85
Glenwood 2a	0.0648	6.20	0.0765	16.90	2.8 / 0.06	6.6 / 0.08	15.4 / 0.11
Glenwood 2b	0.6480	6.20	0.0765	16.90	2.8 / 0.57	6.6 / 0.77	15.4 / 1.06
Glenwood 2c	0.6480	8.20	0.0765	16.90	2.8 / 1.14	6.6 / 1.72	15.4 / 2.59
Aspen 1	0.0360	22.10	0.1810	25.70	145.9 / 8.23	527.5 / 24.86	1,906.8 / 75.05
Aspen 2	0.0538	14.50	2.7200	10.40	10.4 / 0.86	17.4 / 1.78	29.3 / 3.67
Mixture and constants							
Water density ρ_w / solids density ρ_s							1,000 kg/m^3 / 2,650 kg/m^3
Mixture density $\rho_m = \rho_w + C_v(\rho_s - \rho_w)$, C_v = 0.35/0.40/0.45							1,578 / 1,660 / 1,742 kg/m^3
Gravity g							9.8 m/s^2
Laminar resistance K (streets / elsewhere)							100 / 400
Turbulent-dispersive Manning n_{td} (streets / elsewhere)							0.025 / 0.050 s m$^{-1/3}$
Input, mesh and computation							
Mixture volume V / peak discharge Q_p / time to peak t_p							80–300 thousand m^3 / 100–250 m^3/s / 600 s
Inflow velocity / radius of each source							2 m/s / 14 m
Maximum triangle area (corridor / elsewhere); triangles, first model generation							40 / 600 m^2; ≈430,000
Terrain grid; street lowering; assumed building height							4 m; 0.15 m; 6 m
Courant number (screening / rainfall / final)							1 / 0.5 / ≤0.25
Wetting threshold for evaluation h^*							5 cm (sensitivity 2 and 10 cm)

4.4 Numerical verification

Stopping. On a plane with slope $S_0 = 0.05$, with $\tau_y = 100$ Pa and $\rho_m = 1{,}700\,\mathrm{kg\,m^{-3}}$, depth-integrated Bingham-fluid theory predicts a static thickness $h_c = \tau_y/(\rho_m g S_0) = 0.1199$ m. A block of mixture is released and the simulated deposit thickness is compared with the theoretical static thickness; it is also verified that momentum falls to zero.

Restart. Mixture is added upstream of the stopped deposit, and it is verified that the deposit restarts, stops again and conserves volume.

Temporal convergence. The stopping test is repeated with Courant–Friedrichs–Lewy (CFL) numbers of 1, 0.5, 0.25, 0.1 and 0.05 using the DE1 scheme, and with the DE0 scheme for comparison; the final front reach is compared and the order of convergence relative to the extrapolated limit is estimated.

Volume balance. In each simulation, the cumulative volume supplied by the hydrograph is compared with the volume present in the mesh.

The results of these tests are presented in Section 6.7.

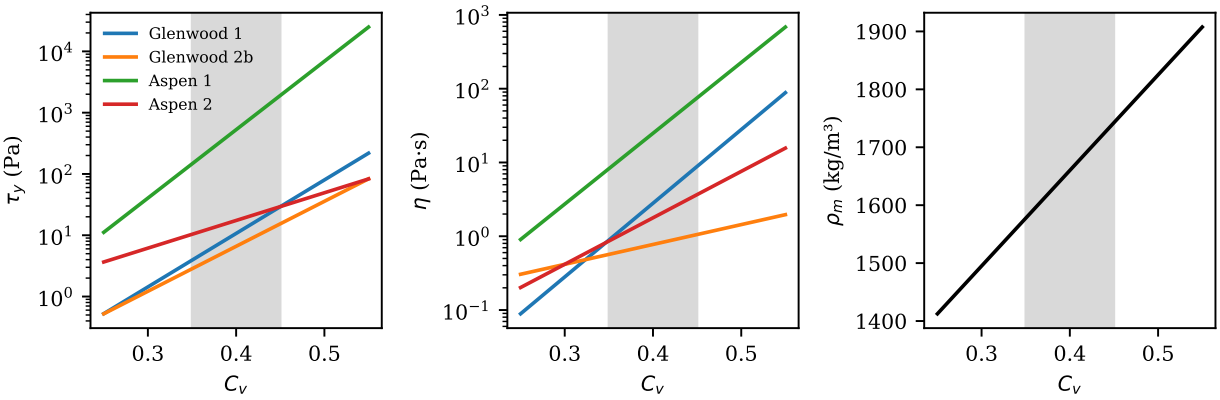

Figure 3: Mixture properties as a function of volumetric solids concentration C_v for the samples tested: yield stress τ_y, viscosity η and density ρ_m. The gray band indicates the range used (0.35–0.45).

4.5 Independent prior volume estimate

Catchments were delineated using flow directions calculated with the eight-direction (D8) method on FABDEM reprojected to the UTM system, zone 19 south (WGS 84 datum), with 30 m cells. A preliminary delineation in geographic coordinates underestimated the area. The outlet of each catchment is the cell with the greatest flow accumulation within 120 m of the point where the mapped channel enters the urban development. The resulting areas are H1 with 8.04 km^2 and relief of 1,376 m, S1 with 1.90 km^2 and S2 with 0.17 km^2: a total contributing area of 10.1 km^2.

Two independent estimates were used, without combining them into a single distribution:

- **Rainfall–runoff balance with water and solids distinguished:** $V_w = f_w PAC$ and $V_m = V_w/(1 - C_{v,\mathrm{tot}})$, where V_w is the water volume incorporated into the pulse; P, accumulated precipitation; A, catchment area; C, the runoff coefficient; f_w, the fraction of runoff incorporated into the pulse; and V_m, mixture volume. The ranges are: event-pulse precipitation P between 12 mm and 35 mm, $C \in [0.3; 0.8]$, $f_w \in [0.5; 1]$ and $C_{v,\mathrm{tot}} \in [0.30; 0.50]$.
- **Empirical model for burned catchments** (Gartner et al., 2014), applied by subcatchment and including its residual error $\varepsilon \sim N(0; 1.04^2)$. This model predicts deposit volume V_{dep}, which is converted to mixture volume using $V_m = (1 - \phi)V_{\mathrm{dep}}/C_{v,\mathrm{tot}}$, where ϕ is deposit porosity. Its applicability outside southern California is a hypothesis.

The distributions are summarized by the median and the 5th and 95th percentiles, and the corresponding peak discharge is estimated using the relationship of Mizuyama et al. (1992). Calibration spans volumes from 80,000 m^3 to 300,000 m^3. Results are presented in Section 6.8.

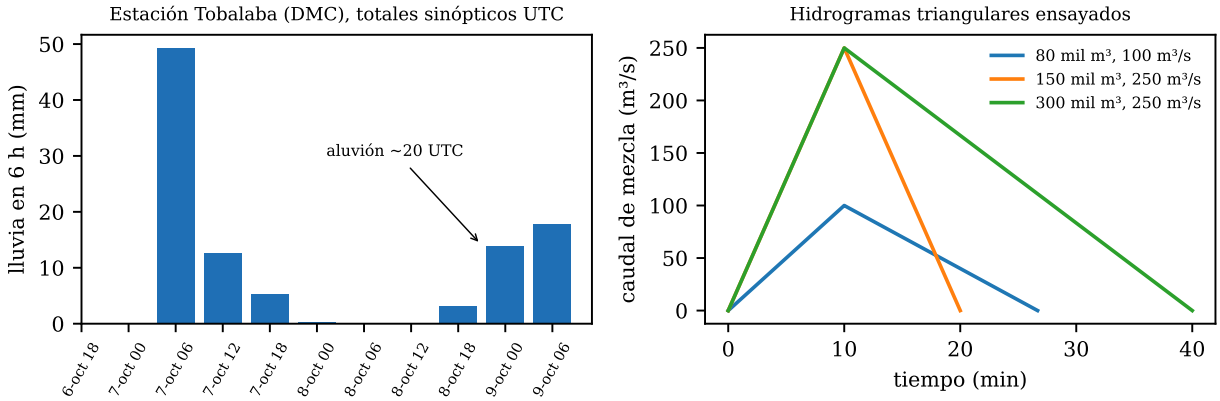

Figure 4: Forcing. Left: rainfall accumulated over 6-hour intervals at the Tobalaba station of Dirección Meteorológica de Chile between 6 and 9 October 2026 (UTC times; the debris flow occurred at about 20 UTC on 8 October). Right: triangular mixture hydrographs tested.

Saturated-soil scenario. With the hydrometeorological information obtained after screening (Section 4.1), a third estimate was added, also without combining it with the previous ones: the relationship between the reported isotherm and the maximum catchment elevation (2,355 m, the same as reported by CR2; an earlier version of the text mistakenly stated 2,775 m, a figure not used in any calculation: D8 delineation and hypsometry were always based on the actual elevation) supports the assumption of liquid precipitation over the entire contributing area, and the soil saturation reported by the authority is adopted as an assumption of the calculation scenario. The ranges used are $P \in [20; 40]$ mm, $C \in [0.6; 0.9]$ and $f_w \in [0.6; 1]$. The snowmelt contribution is bounded above by 50 mm water equivalent over the 0.31 km^2 of the catchment above 2,000 m.

4.6 Inverse calibration and uncertainty

Calibration follows the approach of simulations with acceptable behavior (Beven & Binley, 1992). The criteria were specified before examining the results:

1. fraction R of points on streets with confirmed presence at which $h_{\max} > h^*$, with $R \geq 0.6$;
2. fraction R_{sit} of the four sites with confirmed presence that the flow reaches within 40 m, with $R_{\mathrm{sit}} \geq 3/4$;
3. arrival within 200 m of the intersection of General Blanche and Padre Hurtado;
4. fraction F_{per} of the affected area falling within the municipal perimeter expanded by 100 m, with $F_{\mathrm{per}} \geq 0.5$. Since 11 October, when the official affected area was published (Ministerio de Bienes Nacionales & IDE Chile, 2026), F_{per} has been calculated using that polygon and only for simulated mud in urban areas (within 40 m of a building), to avoid counting hills wetted by rainfall.

The threshold is $h^* = 5$ cm, with sensitivity tests for 2 cm and 10 cm. Each acceptable simulation receives an informal weight $L = R\, R_{\mathrm{sit}}\, F_{\mathrm{per}}$. Streets closed by the municipality are used only as context, because a closure may be precautionary. The Jaccard index relative to the perimeter is reported descriptively, since the perimeter is operational rather than a mapped footprint.

The sweep covers hypotheses H1, H2 and H3; mixture volumes of 80,000 m^3, 150,000 m^3 and 300,000 m^3; peak discharges of 100 $\mathrm{m}^3\,\mathrm{s}^{-1}$ and 250 $\mathrm{m}^3\,\mathrm{s}^{-1}$; and three rheological samples (Glenwood 1, Glenwood 2b and Aspen 2). Screening uses CFL 1; acceptable simulations will be repeated with CFL 0.25 and a fine mesh to constrain the numerical error in reach.

4.7 Ensemble synthesis and indicators by street and building

Three levels of evaluation. A distinction is made between: (i) the *original acceptance criteria*, specified before simulation with a threshold for each (Section 4.6); with the previous terrain, no simulation met all of them, and with the full city the best meets three of four (failing the perimeter criterion); (ii) the *exploratory compatibility index*, defined later, which summarizes the same four criteria on a continuous scale to compare hypotheses; and (iii) *independent validation*, still pending, which requires data not used to formulate the hypotheses, such as post-event satellite images, official deposit surveys or high-water marks.

Exploratory compatibility index. To compare hypotheses, each simulation is summarized by an *exploratory compatibility index* (ECI) with observations, on a scale from 0 to 100: the average of four components, each between 0 and 1, derived from the original criteria specified before simulation (Section 4.6); the index was defined later and the perimeter reference was updated with the official polygon. These components are the fraction of points on streets with observed mud that the model wets (R); the fraction of the four facilities with confirmed impacts that are reached (R_{sit}); reach, equal to 1 if the mud arrives within 200 m of Padre Hurtado and decreasing linearly to 0 at 1,200 m; and F_{per}. The ECI is neither a probability nor a measure of predictive accuracy: it summarizes how well a simulation reproduces a set of qualitative observations, and differences of two or three points should not be interpreted as conclusive evidence that one hypothesis is superior to another. Depths, velocities and pressures by street and building are extracted as the maximum within a radius of 40 m of each point of interest.

5 Model inputs and operation: a guide to application in other catchments

This section describes the method in general terms, without reference to specific products or programs, so that it can be applied to other catchments with the data available in each case. It explains what each input represents, the recommended minimum quality, how it enters the calculation and how its uncertainty affects the result.

How the model works

At every instant and in every cell of a mesh covering the city, the model solves for how much mud is present (thickness), in which direction it moves and at what velocity. It does so using three principles:

1. **Conservation of mass:** mud entering a cell without leaving accumulates as thickness. Mud is neither created nor lost; the balance is verified in every simulation.
2. **Conservation of momentum:** mud accelerates downslope under gravity, according to the slope of the free surface and not just that of the ground, and is slowed by the material's own resistance and friction with the surface. This allows it to flow over a curb if it arrives with velocity, go around a building or pond behind an obstacle.
3. **Material behavior:** unlike water, a dense mixture of water and sediment has a *yield threshold*: if the gravitational driving stress on a layer does not exceed it, the layer stops. This is why mud leaves deposits of a certain thickness instead of draining to the lowest elevation. Above that threshold, the mixture behaves as a highly viscous and turbulent fluid.

The simulation advances in short time steps, of fractions of a second, limited by flow velocity and cell size. Each step first calculates transport and gravity, then material resistance, which can stop a cell or allow it to reactivate if more mud arrives from upstream. During the simulation, maximum thickness, maximum velocity, dynamic loading on obstacles and front arrival time are recorded for each cell.

Input data

Data	What they represent and how they are used	Recommended quality	Effect of uncertainty
Bare-earth topography	Ground elevations without buildings or trees; defines slopes and flow directions.	Preferably 1 m to 5 m resolution; 30 m only reproduces the general direction.	The most influential input: a channel or street unresolved by the terrain changes the flow path.
Building footprints and heights	Obstacles that flow goes around; raised above the terrain.	Complete footprints; height from surveys or number of stories.	Diverts flow locally; little influence on the general path if the footprints adequately represent building geometry.
Streets and curbs	Preferential corridors; lowered a few centimeters relative to sidewalks.	Centerline and width of each street; curb elevation if available.	Determines which streets act as channels.
Open channels and piped reaches	Where the ravine flows on the surface and where underground; transition points are potential overflow locations.	Alignment, cross section and capacity of each reach.	If an open channel is missing, the model substitutes the general slope; if a conduit is missing, its overflow cannot be evaluated.
Contributing catchment	Area and relief draining to each entry point into the city; derived from the terrain.	Terrain of the upper catchment; 30 m is usually sufficient.	Scales expected volume in proportion to area.
Rainfall	Amount and intensity of the episode and preceding days (soil moisture).	Nearby station with hourly or subhourly records; ideally in the upper catchment.	Together with the catchment, constrains volume; short-duration intensity controls peak discharge.
Catchment condition	Burned area, vegetation cover, soil.	Burn-severity mapping.	Increases runoff and sediment load.
Volume and hydrograph	How much mixture enters, at what maximum discharge and over what time.	Estimated from rainfall and catchment, empirical relationships or deposits measured after the event.	Controls reach and depths; constrained through calibration.
Material properties	Mixture density, yield threshold and viscosity, as a function of solids concentration.	Tests on deposit samples; otherwise, ranges from the literature.	Controls when and where flow stops.
Event observations	Affected streets and buildings, reach, depths, times.	Georeferenced points with source and time; high-water marks.	Not model inputs: allow hypotheses to be rejected and calibration to be performed.

Procedure for another catchment

1. **Delineate the exposed urban area** and the points where channels enter the city or change from open to piped. These points are possible flow inputs.
2. **Construct the computational surface:** bare-earth topography, raised buildings, lowered streets and, if possible, open channels with their actual cross sections.
3. **Estimate a volume range** using at least two independent approaches (rainfall times catchment area times runoff coefficient, and empirical relationships for similar catchments), without combining them into a single figure.
4. **Formulate input hypotheses** (the points where flow emerges at the surface and in what proportions) and specify, *before* simulation, the criteria for judging each against the observations.
5. **Simulate every combination** of hypothesis, volume, discharge and material; verify mass balance and numerical stability in each simulation.
6. **Compare with the observations**, retain compatible combinations and report the ensemble as a range of scenarios rather than a single answer.
7. **Repeat compatible simulations at higher temporal and spatial resolution** to estimate the numerical error in reaches and times.

What most improves the result

In this case study, uncertainties ranked by influence were: terrain (resolution and representation of channels and streets), material properties, volume and hydrograph shape, and building heights. A high-resolution survey of the urban area and channel, and deposit samples, are the two improvements with the greatest benefit. For prevention purposes, without an event to calibrate against, the method is applied in the same way, but with volume and material scenarios chosen according to the catchment and with impact envelopes reported instead of a single flow path.

6 Results

Preliminary results (11 October 2026). Sections 6.1 to 6.5 use the terrain with the full city; Section 6.9 retains the initial screening with the previous terrain as a record of the process.

6.1 Simulations with the full city

The terrain version used for the urban results incorporates all 42,018 Overture Maps building footprints over FABDEM at 4 m, extends the domain to Paul Harris, Hospital Dipreca and the Atenas roundabout, and carves three channels that the 30 m elevation model does not resolve: the linear park to the Francisco Bulnes Correa culvert inlet, Quebrada Honda downstream of the inlet according to the official hydrographic network, and the southern branch to the upper part of Av. Monseñor Álvaro del Portillo. The mesh has about 852,000 triangles. Table 6 summarizes the simulations; Appendix A contains the full catalog and a fact sheet with a figure for each key simulation.

Four results stand out:

1. **The city channels the mud.** With all buildings, the calculated thickness around Clínica UC Christus increases from 0.3 to 1.1 m–1.2 m, of the order of the meter reported by the consulted source in its emergency department (a maximum near the facility does not necessarily represent its interior), and reaches 1.9 m next to Duoc UC. Mud runs deeper along the streets and covers less area: about 54 ha within the official area, compared with 93 ha with the previous terrain.
2. **Volume.** With 150,000 m^3, the front stops 348 m from Padre Hurtado; with 300,000 m^3, it comes within 100 m. That volume agrees with the independent estimate assuming saturated soil (Section 6.8).
3. **Selected hypothesis.** The main channel plus the southern branches and rainfall of 35 mm/h on the hillside (z02, v02) obtains an ECI of 72/100 (streets 0.77; facilities 0.75; reach 1.00; official area 0.34): it reproduces flow presence at 77 % of control points on the streets considered, three of the four facilities—including Clínica Universidad de los Andes, with 0.14 m—and the reach, but only one third of its urban mud falls within the official area. Without rainfall on the hillside (v21), Clínica Universidad de los Andes is no longer reached and the ECI falls to 68/100.

Table 6: Simulations with the full city (42,018 buildings). Streets: fraction of points on streets with observed mud that the model wets ($h > 5$ cm); Sites: fraction of the four facilities with confirmed impacts that are reached; dPH: minimum mud distance to the intersection of General Blanche and Padre Hurtado; Perim.: fraction of simulated mud in urban areas falling within the official affected area (IDE Chile); QH: fraction of Quebrada Honda with mud; UCC: maximum thickness next to Clínica UC Christus (about 1 m was reported); ECI: exploratory compatibility index, average of the four criteria (streets, sites, reach and perimeter) on a scale from 0 to 100; it is not predictive accuracy. Mud: G2b, Glenwood 2b ($C_v = 0.40$); G1, Glenwood 1 ($C_v = 0.45$); A2, Aspen 2.

Run	Scenario	V (thousand m^3)	Mud	Streets	Sites	dPH (m)	Perim.	QH	UCC (m)	ECI
z02	channel + southern branches; rainfall 35 mm/h, time step 4× finer	300	G2b	0.77	0.75	15	0.34	0.68	1.13	72
v02	channel + southern branches; rainfall 35 mm/h on hillside	300	G2b	0.77	0.75	15	0.34	0.68	1.13	72
v19	channel + southern branches; rainfall 35 mm/h + official southern branch to Álvaro del Portillo (terrain v6)	300	G2b	0.77	0.75	15	0.34	0.68	1.11	71
v14	channel + southern branches; rainfall 35 mm/h + Álvaro del Portillo ravine	300	G2b	0.77	0.75	15	0.34	0.68	1.15	71
v01	main channel	300	G2b	0.77	0.50	96	0.46	0.68	1.16	68
z01	main channel; numerical check (time step 4× finer)	300	G2b	0.77	0.50	96	0.46	0.68	1.16	68
v15	main channel; Quebrada Honda carved downstream (terrain v5)	300	G2b	0.77	0.50	96	0.45	0.68	1.18	68
v03	main channel; culvert 30 m^3/s	300	G2b	0.77	0.50	96	0.50	0.64	1.16	69
v17	main channel; culvert 30 m^3/s, capture 25 m, Quebrada Honda carved	300	G2b	0.76	0.50	96	0.50	0.62	1.18	69
v05	main channel; culvert 100 m^3/s	300	G2b	0.74	0.50	96	0.53	0.44	1.16	69
v10	main channel; culvert 100 m^3/s, capture 25 m	300	G2b	0.69	0.50	96	0.52	0.00	1.16	68
v18	main channel; culvert 100 m^3/s, capture 25 m, Quebrada Honda carved	300	G2b	0.69	0.50	96	0.52	0.00	1.18	68
v07	main channel	150	G2b	0.72	0.50	348	0.62	0.68	1.09	67
v08	main channel	300	G1	0.74	0.50	396	0.63	0.69	1.16	67
v09	main channel	300	A2	0.77	0.50	151	0.52	0.68	1.14	70
v21	channel + southern branches; official southern branch (terrain v6), without rainfall	300	G2b	0.77	0.50	131	0.45	0.68	1.11	68

4. **Robustness.** z02 repeats v02 with a time step four times smaller and gives the same indicators; z01 does the same for the main channel alone. The very fluid mud mixture (Aspen 2) obtains 70/100; the thick mixture (Glenwood 1) stops 396 m from Padre Hurtado. The ECI of v20 with the normal time step (78/100) depends on 10 cm at a single point on the campus and is not reproduced with a fine time step (v19), so it is not considered.

6.2 Francisco Bulnes Correa culvert capacity: hypothetical scenarios

This section is an analysis of hypothetical scenarios. The actual capacity, cross section and condition of the culvert are not public; the following values do not evaluate the structure or constitute an official conclusion, and require validation with design and inspection information. *Calculated result:* with the full city and the adopted volume hypothesis, the mixture discharge reaching the culvert inlet peaks at about 65 m^3/s, four times that with the previous terrain. *Hypothetical scenarios:* If the culvert captures the entire channel cross section (capture radius of 25 to 40 m), a culvert with a capacity of 100 or 200 m^3/s removes about 93,000 m^3 with a peak of 62 to 66 m^3/s, and Quebrada Honda remains dry (v10, v11, v18). A culvert with a capacity of 30 m^3/s reaches its limit, removes 67,600 m^3, and Quebrada Honda is wetted at 62 % of its points (v17). In these scenarios, the capacity that would have prevented overflow lies between 30 and about 65 m^3/s; that interval depends on the assumed volume, hydrograph and rheology. *Why this changed relative to the first model generation.* With 1,103 buildings, mud spread across the surface and 12,800 m^3 reached the culvert inlet with a peak of 16.5 m^3/s, which a 30 m^3/s culvert would have taken in. With the 42,018 footprints, streets concentrate the flow, increase velocity and deliver about 93,000 m^3 to the inlet with a peak near 65 m^3/s. Both results are calculated and depend on the urban representation; the version with the full city is the current one. A capture radius of 12 m allowed flow to pass beside the sink and produced mud at 44 % of Quebrada Honda even with 100 m^3/s; this was a representation artifact, corrected by capturing the entire cross section. Official hydrographic mapping represents channel continuity from the culvert inlet along Quebrada Honda towards Hospital Dipreca; in the simulations, flow that does not enter the culvert continues along that alignment.

6.3 Comparison with the official affected area

The emergency viewer of Ministerio de Bienes Nacionales, developed by IDE Chile, publishes the affected area (288.5 ha), 2,266 properties and 368 affected street segments (Ministerio de Bienes Nacionales & IDE Chile, 2026). The area is the strip between two corridors: Camino El Alba and General Blanche to the north, and Quebrada Honda to the south, with an extension along El Alba west of Padre Hurtado (Figure 5). Simulated mud runs along these two edges, but leaves the interior of the strip dry and extends beyond it in three sectors: the hills and ravines wetted by rainfall on the hillside, the street network west of Padre Hurtado (8 to 20 ha), and Quebrada Honda downstream towards Dipreca (14 to 26 ha), with thicknesses of 0.3 to 0.4 m. Since the published properties represent the full set within the perimeter rather than properties with verified mud (91 % are inside the area), the fraction of properties touched by simulated mud (717 of 2,266, 32 % in z02) serves to compare simulations, not as an accuracy rate. With this polygon, the perimeter criterion decreases and the ECI of the best hypothesis changes from 74/100 (press perimeter) to 72/100.

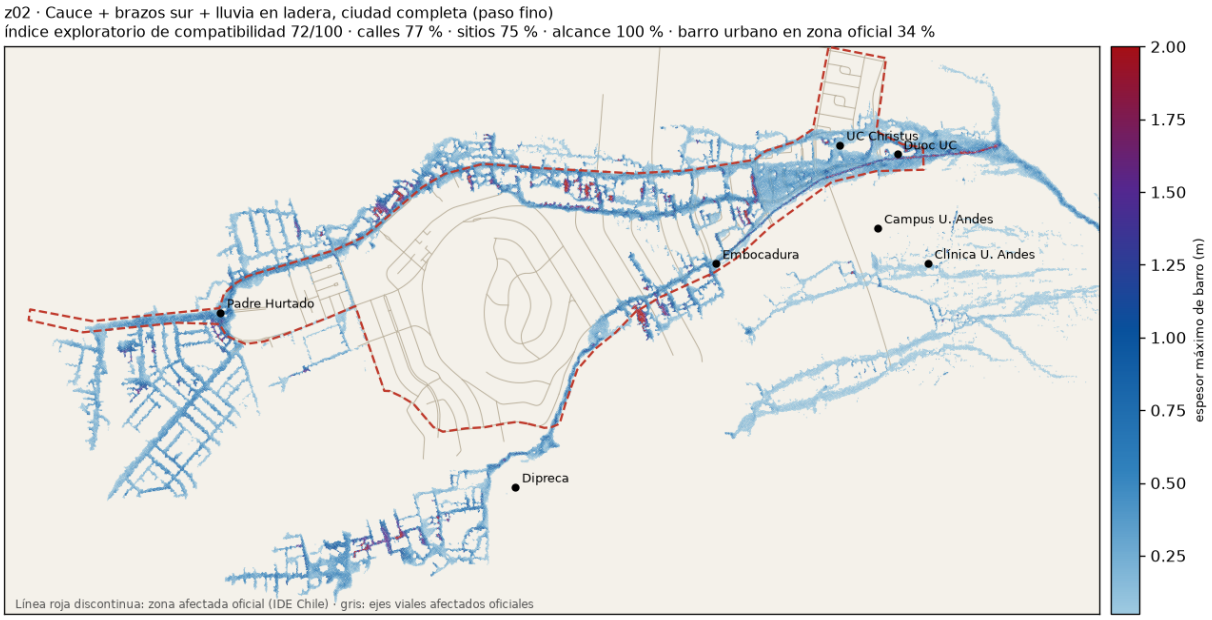

Figure 5: Simulation z02 (main channel, southern branches and hillside rainfall, fine time step) over the official affected area from IDE Chile (dashed red line) and affected street centerlines (gray). Colors: maximum simulated thickness.

6.4 11 October round and test using held-out observations

Tests of extent and double counting. Each test changed one factor in the main hypothesis:

- **Slightly more concentrated mud** (v25, $C_v = 0.43$): does not reduce mud outside the official area (fraction inside the area: 0.346, compared with 0.344 in z02).
- **Greater roughness outside streets** (v27; $K = 800$ and $n = 0.08$): the only test that reduces it somewhat (0.388).
- **Rainfall applied only outside the contributing catchments** (v28): eliminates double counting without changing the indicators. The impact next to Clínica U. de los Andes persists (0.15 m).
- **Rheology by zone** (v29; $C_v = 0.27$ on the lower hillside): does not change the index components.

In all four, the "sites" component reaches 1.00 only because the campus control point exceeds 5 cm with the normal time step (0.06–0.15 m); with a fine time step, that point is at 0.01 m (v19, z02). Under a rule recorded before selecting the candidate (validation protocol, amendment 1), this component is calculated without the campus point. Thus, indices of 78–79 become 72–73. All configurations are tied within three points, and z02, verified with a fine time step, is selected.

Campus microsimulations. Overflows of 20 and 40 m^3/s in the upper part of Álvaro del Portillo were tested, with mud mixtures of C_v 0.25 to 0.40 and 8 m^2 triangles (m20, mk20, ml20, ml40). In all cases, flow runs down the avenue and leaves the domain without reaching the Biblioteca. The overflow point lies outside the Biblioteca's local catchment, about 220 m from its boundary, so with this terrain that flow drains elsewhere. Two explanations remain open: runoff generated within that local catchment (under investigation) and an entry path that the 30 m terrain does not resolve. The available data do not allow them to be distinguished.

Test using held-out observations. The procedure was:

- **Prior reservation and metric.** Before comparison with the model, the 49 affected facilities in the official layer that do not coincide with fitting facilities were held out. The metric was specified: fraction of points with more than 5 cm of simulated mud within 15 m. The favorable criterion was at least 0.70 and exceeding the references v01 (main channel only) and e03 (overflow at the culvert inlet only).
- **Single execution.** The test was run only once on the frozen candidate.
- **Results.** z02 reaches 19 of 49 points (0.39), v01 the same 19 and e03 none.

The outcome is unfavorable. It is reported without modifying the model. In a subsequent diagnosis, which does not change the verdict:

- the median distance to the nearest cell with mud is 32 m;
- 16 points lie more than 100 m away;
- z02 wets about 20 % of the official area's surface and 32 % of its affected properties.

Thus, besides extending outside the official area, the reconstruction leaves substantial parts of it without mud. Some of the unreached points are service facilities whose impacts may have had other causes. The test is only partially independent, because the points are in the area used by the index.

6.5 Universidad de los Andes campus

The university's vice-rector located the overflow in the ravine along the north side of the campus, bordering General Blanche, down which the mud mass descended (Cooperativa, 2026b), and Carabineros located ground zero at Álvaro del Portillo and Av. La Plaza (La Tercera, 2026c); a video circulated on social media shows mud in the Aula Magna (Quinta Conectado, 2026). With the southern branch following the official channel (v19), mud reaches the upper part of Álvaro del Portillo (0.49 m where the channel ends and 0.13 m on the avenue) and runs down it towards La Plaza and General Blanche, consistent with both accounts. However, it does not cross the woodland separating the avenue from the Biblioteca, although the terrain descends from 936.5 to 927.4 m towards a depression next to the building. Three mechanisms are being tested without modifying the main simulations: (i) *inflow from secondary ravines*: the Biblioteca has its own local catchment of 11.3 ha, separate from the contributing catchments, only 57 % of which receives rainfall in the main simulations; (ii) *more liquid runoff on the lower hillside*: campus images do not show stones or urban debris, suggesting a more dilute flow than in the main branch; and (iii) *local redistribution* by embankments, paths and access routes. These are investigated using local microsimulations covering about 800 × 720 m with 8 m^2 triangles, overflows of 10 to 40 m^3/s in the upper part of Álvaro del Portillo, mud mixtures of C_v 0.25, 0.30 and 0.40, and rainfall over the entire local catchment; and a simulation with the full city (v29) with rheology by zone: $C_v = 0.27$ on the lower hillside and $C_v = 0.43$ elsewhere, plus rainfall applied only outside the contributing catchments. Rheology by zone is an intermediate step: it assigns different mud mixtures according to location but does not represent the evolution of concentration along the flow path.

6.6 Previous terrain

The domain covers 5.9 km by 3.4 km with a 4 m grid. It contains 1,103 buildings represented as blocks, with a mean height of 6.2 m and a maximum of 39 m: 82 heights obtained from the difference between surface and terrain, 26 from recorded stories, and 995 assumed at 6 m. Four polygons corresponding to facilities (sports complexes and a shopping center) rather than built volumes were excluded. In the base terrain, the open channel in the linear park between the alluvial fan and Francisco Bulnes Correa is practically flat (cross-channel relief of ±0.5 m). In the 2014 photogrammetric terrain (Hussain, 2021), with an effective resolution of 8 to 10 m, the channel appears as a depression of 1 to 4.5 m relative to its banks. That terrain has a vertical offset of 26.7 m (difference between ellipsoidal and geoidal references) and spurious depressions, which were corrected before use.

6.7 Numerical verification

Deposit equilibrium. Upon stopping on a plane of slope 0.05, the deposit satisfies the yield criterion: the local residual $r = \rho_m g h|\nabla(z + h)|/\tau_y$ has a median and 95th percentile equal to 1.00, with no cells having $r > 1.05$. The theoretical static thickness is $h_c = 0.1200$ m with $g = 9.8\,\mathrm{m\,s^{-2}}$.

Restart. When mixture is added upstream, the front advances 26 m farther than in the control without inflow. However, the control also advances 19 m in 900 s, and the stopped front drifts 6.7 m in the final 300 s. This residual sliding arises from the fractional step and decreases as the time step is reduced.

Convergence. With CFL 0.25, reach converges as the mesh is refined: 354 m, 345.7 m and 341.2 m for cells of 4, 2 and 1 m, with an extrapolated value of about 337 m. With 2 m cells, reach decreases as the Courant number is reduced: 431 m, 374 m, 346 m and 328 m for CFL 1, 0.5, 0.25 and 0.1. This is first-order convergence, with a bias of +30 % for CFL 1.

Convergence in the urban domain. On the terrain with the 42,018 building footprints, the 300,000 m^3 simulation through the main channel was repeated with CFL 0.25. Relative to CFL 1, the difference in maximum thickness has a median of 2 mm and a 95th percentile of 9 mm; 99 % of cells agree on wet or dry status; front arrival differs by less than 20 s; and the minimum distance to Padre Hurtado is the same (96 m). In the city, the front stops because of street and building geometry rather than the residual sliding in the planar test; the urban temporal comparison performed does not show a bias of that magnitude in the indicators examined.

Double counting of hillside rainfall. Hillside rainfall is applied within a polygon of 1.048 km^2 and contributes 36,680 m^3 in addition to the hydrographs. Of that polygon, 74 % lies outside the contributing catchments, whose runoff already enters through the hydrographs; the remaining 26 % overlaps part of S1 (0.096 km^2) and all of S2 (0.172 km^2), double counting about 9,400 m^3, or 2.8 % of the total volume, concentrated around Clínica Universidad de los Andes. Simulation v28 repeats the main hypothesis with rainfall applied only outside the catchments (27,290 m^3) to quantify its effect.

Volume balance. In all urban-domain simulations, the volume in the mesh matches the supplied volume, minus the volume removed by the culvert and that leaving through the boundaries, with a residual below 0.01 %. An earlier version of the outlet boundary generated spurious mass when the front reached the southern boundary, with an increase of up to 20 %; those simulations were discarded and repeated with an outflow-only boundary.

6.8 Independent volume estimate

The contributing catchment covers 10.1 km^2: the main channel (8.04 km^2, relief of 1,376 m), the southern channel (1.90 km^2) and the smaller ravines (0.17 km^2). With the rainfall–runoff balance, the median mixture volume is 151,000 m^3, with 5th and 95th percentiles of 67,000 m^3 and 310,000 m^3. With the model for burned catchments (Gartner et al., 2014), the median is 374,000 m^3, with percentiles of 61,000 m^3 and 2.3×10^6 m^3. For 151,000 m^3, the relationship of Mizuyama et al. (1992) gives $Q_p \approx 230\ m^3/s$.

With the saturated-soil scenario, the median increases to 295,000 m^3, with 5th and 95th percentiles of 181,000 m^3 and 468,000 m^3. Snowmelt contributes at most about 15,000 m^3, less than 5 %: there was no prior snow cover in the catchment and 90 % of its surface lies below 1,800 m. The decisive effect of the high isotherm was the area receiving rainfall: if the snowline is taken to be about 300 m below the isotherm, a 2,000 m isotherm would have left 8.2 km^2 under rain (81 %), an 1,800 m isotherm, 6.0 km^2 (59 %), and a 1,500 m isotherm, 1.7 km^2 (16 %); with the 8 October isotherm, rain fell over all 10.1 km^2. With the same rainfall, a storm with a typical isotherm would have generated between 20 and 40 % less water in the pulse.

6.9 Initial screening with the previous terrain

Table 7: First model generation (9 October 2026), with the previous terrain of 1,103 buildings: fraction of control points with maximum simulated thickness greater than 5 cm, by street, and maximum thickness within a radius of 40 m of each site. All simulations use Glenwood 2b, $C_v = 0.40$ and $Q_p = 250\ m^3/s$, except d03 ($Q_p = 100\ m^3/s$). LP: La Plaza (Portillo–El Alba); GB: General Blanche (San Carlos de Apoquindo–Las Condesas); CEA: Camino El Alba; QH: Quebrada Honda; LPS: La Plaza Sur; UCC: Clínica UC Christus; CUA: Clínica Universidad de los Andes; dPH: minimum mud distance to the intersection of General Blanche and Padre Hurtado.

Hypothesis	V (thousand m^3)	LP	GB	CEA	QH	LPS	UCC (m)	CUA (m)	Duoc (m)	dPH (m)
H3	80	0.87	0.86	0.61	0.00	0.00	0.22	0.00	0.42	1,160
H1	150	0.91	0.92	0.85	0.00	0.00	0.42	0.00	0.55	366
H3	150	0.88	0.92	0.78	0.00	0.00	0.39	0.00	0.53	516
H3	300	0.91	0.93	0.96	0.00	0.00	0.42	0.00	0.54	4
H2	150	0.00	0.00	0.00	0.69	0.00	0.00	0.00	0.00	856
H4, $f_{sup} = 0.5$	150	0.88	0.88	0.57	0.66	0.00	0.26	0.00	0.46	1,007
H4, $f_{sup} = 0.9$	150	0.88	0.91	0.68	0.54	0.00	0.35	0.00	0.52	816
H5 (H4 + rainfall of 20 mm/h)	150	0.88	0.88	0.57	0.66	0.00	0.26	0.06	0.46	1,005
H1, carved channel, no culvert	150	0.89	0.94	0.87	0.55	0.00	0.31	0.00	1.63	338
same, 10 m^3/s culvert	150	0.89	0.94	0.87	0.43	0.00	0.31	0.00	1.63	338
same, 30 m^3/s culvert	150	0.89	0.94	0.87	0.01	0.00	0.31	0.00	1.63	338

Table 7 summarizes the screening simulations. Four regularities are observed:

1. **Alluvial-fan corridors.** La Plaza, Mons. Álvaro del Portillo, Av. San Carlos de Apoquindo, upper General Blanche and Camino El Alba exceed the threshold at 85 to 100 % of their points in all hypotheses with outflow on the alluvial fan, for volumes between 80,000 and 300,000 m^3. Duoc UC and Clínica UC Christus are reached in all of them, with thicknesses of 0.4 to 1.6 m and 0.2 to 0.4 m, respectively.

2. **Quebrada Honda.** This street exceeds the threshold only when flow emerges at the surface at the Francisco Bulnes Correa culvert inlet. This occurs if a source is imposed there (H2, H4) or if the terrain represents the open channel conveying flow to the culvert inlet and the culvert does not take it in. Outflow there of 8 % of the volume is sufficient.

3. **Culvert capacity (previous terrain; superseded).** With the channel represented and only 1,103 buildings, 12,800 m^3 reaches the culvert inlet, with a maximum discharge of 16.5 m^3/s; in that scenario, a culvert of 30 or 100 m^3/s takes it in and Quebrada Honda remains dry (1 %). With the full city, this conclusion changes: the calculated discharge increases to about 65 m^3/s and 30 m^3/s is insufficient (Section 6.2). With 10 m^3/s, about 2,600 m^3 overflows and Quebrada Honda is wetted at 43 % of its points (Figure 6).

4. **Southern sector.** No simulation wets Av. La Plaza Sur or the Universidad de los Andes campus. Only rainfall on the eastern hillside (H5) reaches Clínica Universidad de los Andes, with 6 cm in its surroundings, consistent with the clinic's statement that the impact was outside.

With the previous terrain, no simulation meets the four acceptance criteria specified in advance (Section 4.6). The sites criterion fails in all simulations because the campus is not reached, and the reach criterion fails in all 150,000 m^3 simulations.

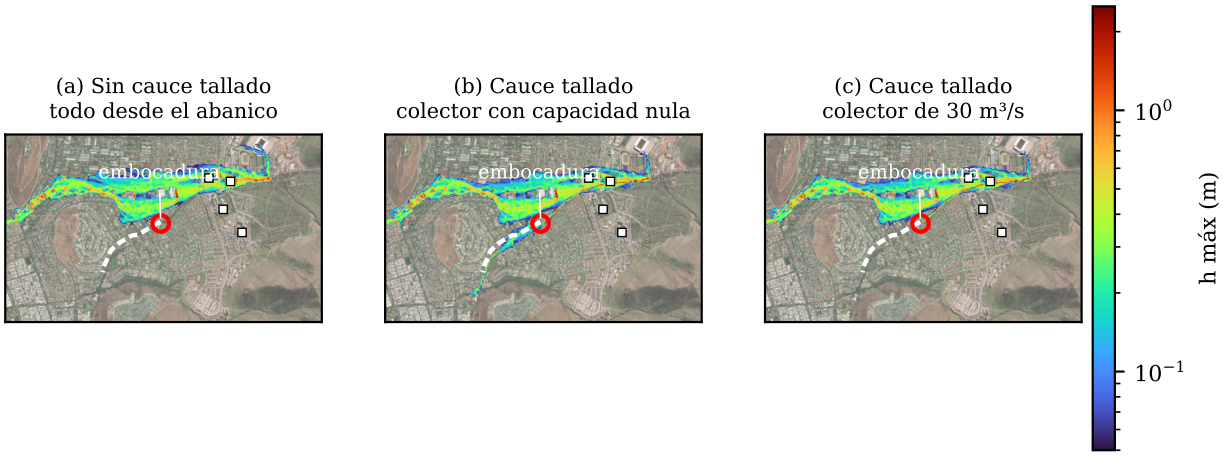

Figure 6: First model generation (previous terrain, 1,103 buildings; superseded by Section 6.2). Maximum simulated thickness with 150,000 m^3 emerging on the alluvial fan. (a) Base terrain: flow does not reach Quebrada Honda (dashed white line). (b) Carved linear-park channel and culvert with assumed zero capacity: flow reaching the culvert inlet through the channel (red circle) overflows towards Quebrada Honda. (c) Same terrain with a 30 m^3/s culvert: the culvert takes in the arriving flow and Quebrada Honda remains dry. Squares indicate affected sites.

6.10 Comparison with information obtained after the hypotheses

Three sources became available after the hypotheses were formulated, allowing a partial comparison, although not independent of the press:

- **Official preliminary explanation** (Rojas Pérez, 2026): the Delegado Presidencial reported that material blocked the entrance to two parallel conduits at General Blanche and that the Bulnes Correa settling chamber collapsed; Carabineros reported channel overflow on that street. This is the combination the model requires to wet both the alluvial fan and Quebrada Honda.

- **Sernageomin technical report on the 31 January 2026 debris flow** (Servicio Nacional de Geología y Minería, 2026): describes a single corridor from Parque San Carlos de Apoquindo, through the Universidad de los Andes sector, to Quebrada Honda at Francisco Bulnes Correa, continuing towards the Apoquindo ravine, Hospital Dipreca and Paul Harris. The channel parallel to Quebrada Honda

appears filled with mud after that event. This matches the channel path that the model needs to represent. The expanded domain of the current version already includes the continuation towards Dipreca and Paul Harris.

- **Press map** (Chilevisión, 2026b): traces the centerlines of Camino El Alba, General Blanche and Quebrada Honda to Padre Hurtado as debris-flow routes. Along those full lines, the best simulation wets 92 % of Camino El Alba, 40 % of General Blanche and 27 % of Quebrada Honda. Lower General Blanche, between Las Condesas and Padre Hurtado, is not reproduced: the simulated flow favors Camino El Alba along that stretch.

More data became available between 9 and 10 October and were compared without modifying the simulations:

- **Locations where mud or water entered.** Senapred includes Av. La Plaza Sur among the three most affected streets; the Universidad de los Andes campus had mud and stranded people, and Clínica Universidad de los Andes had minor water ingress (Cooperativa, 2026b; Interferencia, 2026). On the terrain with buildings, the main-channel simulation does not wet any of these three points. The simulation adding the southern branches and hillside rainfall gives 0.14 m next to Clínica Universidad de los Andes and wets part of La Plaza Sur, but leaves the campus with 1 cm. Both reproduce Clínica UC Christus (1.13 to 1.16 m, compared with about 1 m reported) and the Duoc UC campus (1.9 m).
- **31 January event.** With 75 mm in 1 h 20 min, a much greater intensity than on 8 October, it affected 8 ha, about 4 km of streets and 11 homes (T13, 2026), and the Bulnes Correa culvert "worked very well" according to the mayor (La Tercera, 2026a). The fact that a more intense event was much smaller indicates that antecedent saturation and available material weighed more heavily in October than peak intensity, in line with the saturated-soil scenario.
- **Affected surface area.** The reported 253 ha (Chicureo Hoy, 2026) matches the area of the municipal perimeter published by the press (253.0 ha). It is a safety perimeter rather than a map of mud: simulated mud occupies about 40 ha inside it, because it concentrates in the streets. It is not used to discriminate between hypotheses.
- **Hospital de la FACh.** Water was reported in its emergency department. No simulation reaches that point, about 1.3 km north of the flow path; this is compatible with urban drainage from the day's rainfall and is not used.

6.11 Indicators at critical sites

First model generation (previous terrain, simulation e04; not directly comparable with simulations with the full city). In the simulation with the carved channel and the culvert with assumed zero capacity, maxima within a radius of 40 m are as follows:

- Duoc UC: 1.6 m thickness, 6.3 m/s and 33 kPa dynamic pressure; the front arrives at minute 4.
- Intersection of General Blanche and San Carlos de Apoquindo: 1.4 m, 6.7 m/s and 37 kPa, at minute 7.
- Clínica UC Christus: 0.3 m and 1.6 m/s, at minute 9.
- Bulnes Correa culvert inlet: 1.6 m and 3.9 m/s, at minute 13.

Minutes are counted from the start of the pulse. In that scenario, 170 buildings have mud above 5 cm next to their façades, 46 above 0.5 m and 11 above 1 m; 8 receive dynamic pressure greater than 10 kPa. These values carry the screening bias already noted and have not been compared with measurements.

7 Discussion

What the model reproduces. With the full city, the model reproduces the two corridors delimiting the official affected area—Camino El Alba and General Blanche to the north, Quebrada Honda to the south—the reach to Av. Padre Hurtado, about one meter of mud in the emergency department of Clínica UC Christus, and the impacts on Duoc UC and Clínica Universidad de los Andes. The volume required for that reach, about 300,000 m^3, agrees with the independently obtained estimate from rainfall over a catchment with saturated soil and rain falling across its entire surface. Agreement between estimates obtained through different procedures lends coherence to the order of magnitude, under their respective assumptions; it does not constitute independent validation.

Antecedent rainfall, isotherm and volume. On 31 January, 75 mm fell in 80 minutes and the event was much smaller than the October event, which had lower intensity but occurred after about 144 mm of accumulated rainfall and with the 0 °C isotherm above the catchment summit. Comparison of the two events is compatible with an influence of antecedent saturation and the area receiving rainfall; by itself, it does not establish their relative contribution compared with intensity. Under the calculation assumptions, the upper bound on the snowmelt contribution is below 5 %: no snow was detected in the cloud-free part of the catchment in the Sentinel-2 image of 21 September.

The role of drainage (hypothetical scenarios). In the scenarios tested, the impact on Quebrada Honda is reproduced when part of the calculated flow does not enter the Francisco Bulnes Correa culvert. With the full city, the calculated discharge at the culvert inlet reaches about 65 m^3/s; under the assumptions tested, a hypothetical capacity of 30 m^3/s is insufficient, and the analysis places the capacity that would prevent overflow with full capture near 65 m^3/s. These values do not describe the real structure. Official hydrographic mapping represents channel continuity along Quebrada Honda downstream of the culvert inlet; in the simulations, flow that does not enter the culvert continues along that alignment. The analysis constrains hypothetical capacities under the model assumptions; it does not determine the capacity or condition of the real structure, identify a failure mechanism or allow responsibility to be attributed.

Possible explanations for the simulated extent outside the official perimeter. Only one third of the simulated urban mud falls within the official area, which is a management perimeter rather than a verified mud footprint. The following are considered possible explanations, whose contributions remain to be established:

1. **Impermeable buildings.** In the model, each building is a solid block; in reality, mud entered homes through doors, gates and collapsed walls, and was stored on ground floors and in basements. That retention is not represented, which could intensify channeling along streets. Representation through porosity, commonly used in urban flooding (Schubert & Sanders, 2012), is the alternative (simulation v26).

2. **Coarse load.** Images show stones, logs and entrained vehicles. Fine-matrix rheology does not include that additional resistance; a slightly more concentrated mud mixture ($C_v = 0.43$, between the one that extends too far and the one that falls short) represents it in a simple way (v25).

3. **Vegetation and gardens.** FABDEM removes trees and roughness outside streets is moderate (v27 increases it).

There is also a limitation of the metric: the model does not distinguish rainwater from debris-flow mud, so rainfall runoff in other neighborhoods counts as mud outside the official area and penalizes hypotheses with hillside rainfall.

Sensitivity to terrain. Explicit representation of smaller channels remains the factor that most changes the flow path: the linear-park channel determines whether Quebrada Honda is wetted, the southern-branch alignment determines whether mud reaches upper Álvaro del Portillo, and the representation of the culvert inlet changed Quebrada Honda coverage by 44 %. With 30 m terrain, these corridors must be carved from mapping; the official hydrographic network at 1:25,000 scale proved more reliable than OpenStreetMap for the southern branch.

Campus and Aula Magna. The model produces an overflow on the north side of the campus and its descent towards General Blanche, compatible with reports from the university and Carabineros, but does not reproduce mud entry into the Biblioteca. Three possible explanations are being tested: runoff from the Biblioteca's local catchment (11.3 ha), which only partly receives rainfall in the main simulations; a more liquid fluid on the lower hillside; and local redistribution by embankments, paths and access routes that the terrain resolution might not represent. The available results do not allow a single explanation to be identified.

Test using held-out observations. The only test using held-out observations, defined before comparing them with the model, had an unfavorable outcome: the selected hypothesis reaches 39 % of the held-out affected facilities, compared with the specified 70 %, and does not outperform the main-channel-only hypothesis (Section 6.4). The exploratory index of 72/100 measures compatibility with observations used to formulate the hypotheses; this test shows that such compatibility does not transfer to the fine spatial distribution of official impacts. The model also leaves substantial parts of the official area without mud, as well as exceeding

its extent. This may be due to terrain resolution, building representation, volume or its temporal distribution, unmodeled local inflows, or the fact that official impacts include causes other than mud thickness. None of these causes has yet been evaluated.

Validity. The available observations are qualitative: streets and facilities reported by the press and authorities, and an official perimeter delimiting the management area rather than the area with verified mud. There are no published discharge measurements or high-water marks. The exploratory compatibility index summarizes four criteria specified before simulation and serves to compare hypotheses with one another; it is not a measure of predictive accuracy, and differences of two or three points should not be interpreted as conclusive evidence that one hypothesis is superior to another.

Confidence by result. Instead of reducing results to a single indicator, Table 8 assigns each a qualitative and provisional confidence assessment.

Table 8: Qualitative and provisional assessment of confidence in each result, conditional on assumptions and available evidence.

Result	Confidence level
General mud corridors	Relatively high: compatible with multiple scenarios and the official affected area
Need to represent channels and transitions to culverts	Robust finding of model sensitivity
Order of magnitude of mobilized volume	Conditional estimate, with a wide range (181,000 to 468,000 m^3)
Required capacity of the real culvert	Not determined; only capacities tested in hypothetical scenarios
Exact depth in front of buildings	Exploratory, dependent on terrain and parameters
Velocities, pressures and arrival times	Preliminary indicators, without instrumental validation

8 Directions for further investigation

Seven directions are identified that do not modify the results presented but could change them, and are proposed for further investigation:

1. **Burn severity and speed of runoff concentration.** The fire is mentioned as a precondition but does not enter the calculation: hillside rainfall is uniform and each channel's hydrograph rises to its peak in an assumed time (10 min). Burned, hydrophobic soil allows less infiltration, loses vegetation roughness and concentrates water faster, unevenly according to severity. The Sentinel-2 dNBR between 28 December 2025 and 6 February 2026, the same as used by CR2, would allow runoff to be distributed by severity, the runoff coefficient and the fraction burned at moderate to high severity in the model of Gartner et al. (2014) to be constrained, and the time of concentration of each subcatchment to be estimated.

2. **Higher-resolution terrain on the campus.** Terrain resolution is a possible limitation in representing mud entry into the Aula Magna of Universidad de los Andes (embankments, paths and basement entrances); a local LiDAR or photogrammetric survey would allow that explanation to be tested against the others under investigation.

3. **Separating rainwater from mud.** A passive tracer marking the fluid from the hydrographs would allow the perimeter to be evaluated using only debris-flow mud, without counting urban rainfall runoff.

4. **Porous buildings and coarse load.** Mud retention in homes and resistance from stones, logs and vehicles are being tested in a simplified way (simulations v25 to v27); their calibration requires damage information by dwelling.

5. **Independent validation.** Post-event satellite images, official deposit surveys or high-water marks would allow validation that is currently not possible with qualitative observations.

6. **Concentration as a random variable.** Sediment concentration can be treated as uncertain, for example $C_v = 0.20 + 0.30X$ with $X \sim \mathrm{Beta}(3, 2)$ (mode 0.40 and mean 0.38), and propagated through

the model using Gaussian quadrature at 5 to 7 values to estimate expected values and variances of depth, velocity and pressure, analogously to the propagation of wind speed in structural analysis. Three precautions are anticipated: the distribution, constructed from literature ranges and event evidence, is a belief distribution rather than the actual statistical distribution of sediment, so its results are conditional on it and should be compared with alternatives (uniform, Beta(2,2)); quadrature estimates moments well but not inundation probabilities or extreme percentiles, because wetting and drying introduce discontinuities, which can be handled by interpolating between simulations the threshold concentration at which each cell exceeds a given thickness, or with more simulations (Latin hypercube sampling); and varying concentration between simulations represents uncertainty in a parameter, which is a different level of modeling from the physical evolution of concentration along the flow path.

7. **Evolution of concentration.** Erosion, deposition and incorporation of debris change concentration along the flow path. An input sediment hydrograph (a more concentrated front and a more dilute tail) and a concentration tracer transported with the flow would allow yield stress and viscosity to vary with it. This would distinguish the final deposit from the maximum flow extent, which is currently the only one reported.

9 Conclusions

1. A two-dimensional shallow-water model with mud rheology, built using only public data and with the full city represented, reproduces the main structure of the 8 October 2026 debris flow: the Camino El Alba, General Blanche and Quebrada Honda corridors delimiting the official affected area, the reach to Padre Hurtado, about 1 m of mud at Clínica UC Christus, and the impacts on Duoc UC and Clínica Universidad de los Andes.

2. The selected hypothesis combines the main channel, southern branches and rainfall on the burned hillside: it obtains an exploratory compatibility index of 72/100 with observations (streets 0.77; facilities 0.75; reach 1.00; official area 0.34), measured against the official affected area; its indicators remain unchanged in the temporal comparison performed. The index compares hypotheses; it is neither predictive accuracy nor validation. In the scenarios tested, about 300,000 m^3 of mixture allows the reach criterion to be reproduced, at an order of magnitude consistent with a rainfall-based estimate adopting the reported soil saturation.

3. In the hypothetical scenarios tested, flooding of Quebrada Honda is reproduced when the Francisco Bulnes Correa culvert does not take in the calculated flow at its inlet, of about 65 m^3/s with the full city. Under those assumptions, a capacity of 30 m^3/s is insufficient and a capacity near 65 m^3/s would prevent overflow. These values do not describe the real structure, whose capacity and condition are not public, and require validation with design and inspection information.

4. A test using held-out observations, defined before examining results and run only once, had an unfavorable outcome: the selected hypothesis reaches 19 of 49 officially affected facilities (39 %), below the specified 70 %. The reconstruction reproduces the main corridors but not the spatial distribution of official impacts.

5. The main mismatch is that simulated mud extends beyond the official area, west of Padre Hurtado and towards Dipreca. Possible explanations considered are the representation of buildings as impermeable blocks, coarse-load resistance and vegetation; their contributions remain to be established and are being tested with porous houses, slightly more concentrated mud and greater roughness.

6. An overflow on the north side of the Universidad de los Andes campus is reproduced, but mud entry into the Aula Magna is not; explanations under investigation include the Biblioteca's local catchment, a more liquid fluid on the lower hillside and terrain resolution. Results are preliminary until the ongoing simulations and satellite validation are complete.

Data and code availability

The programs (`prep.py`, `sim.py`, `calibrar.py`, `verif_parada.py`, `cuenca.py`, `volumen_previo.py`), the evidence log of source consultations with their SHA-256 hashes, and the results are available at https://aluvion.hirely.cl/datos.html. The technical review reports are published in full on the same site.

Statement on the use of AI tools

Version control

- **9 October 2026 (first model generation):** previous terrain with 1,103 buildings; screening of hypotheses H1 to H4, carved linear-park channel and initial culvert tests (runs d, e, f, g, k and s). Its conclusions about the culvert were superseded by the version with the full city.
- **10 October:** full city with 42,018 buildings and expanded domain (v01 to v09, z01); volume with saturated soil, isotherm and Sentinel-2; comparison with the press.
- **10 and 11 October:** culvert capturing the entire cross section (v10, v11, v17, v18), Quebrada Honda and southern branch according to the official hydrographic network (v14 to v21), fine-time-step check of the main hypothesis (z02).
- **11 October, morning:** official affected area from IDE Chile as reference, exploratory compatibility index, maximum catchment elevation corrected in the text (2,355 m), citations to the original CR2 analysis, distinction between observed and calculated results and hypothetical scenarios, and appendix of fact sheets.
- **11 October, afternoon (this version):** tests v25 to v29, campus microsimulations, protocol amendment 1 (tie-breaking rule) and test using held-out observations (unfavorable).

The completion date of each simulation is given in Table 9.

Frozen versions, experiment log and held-out observations

- **Frozen versions.** Each published version of the paper and sub-study is preserved as published, with its SHA-256 hash and a version-control tag (`https://aluvion.hirely.cl/paper/versiones/`). The main link points to the latest version without deleting earlier ones. Terrain files are not modified after use: each variant has its own file.
- **Experiment log.** The log includes all runs, including stopped, canceled, failed and discarded runs, with their parameters, terrain, code version and reason. Discarded cases include: the transmissive boundary that created mass, the photogrammetric terrain with spurious depressions, v20 because of a threshold artifact, the 12 m capture radius and v22–v24. As of the afternoon of 11 October there are 71 entries: 48 completed (42 simulations evaluated with the ECI and 6 campus microsimulations), 5 stopped, 3 canceled, 1 failed, 5 discarded groups and 9 ongoing.
- **Separation of observations.** There are three groups:
  - *fitting observations*: streets, facilities, reach and perimeter (press and official area), thickness at Clínica UC Christus and campus accounts. These were used to formulate and select hypotheses, so the ECI measures compatibility, not validation;
  - *descriptive comparison*: affected properties and street centerlines from IDE Chile, and housing assessments. These have already been consulted, but did not enter the index or selection;
  - *held-out observations*: the 49 affected facilities from IDE Chile that do not coincide with fitting facilities, post-event Sentinel-1 images, and future official high-water marks or thicknesses.
- **Preregistered test.** The metric for the facilities test was specified before comparison with the model: sensitivity with $h > 5$ cm within 15 m, and a favorable criterion of at least 0.70 and higher than two references (v01 and e03). The candidate is chosen using only fitting observations and frozen before the test, which is run once and reported regardless of the outcome. The test is only partially independent, because the points lie within the official area used in the index, and does not replace independent scientific validation.

Artificial intelligence tools were used to support technical and editorial review. Two rounds of physics and mathematics review (A1 and A2) and one round of format review (F1) were completed using the gpt-6-astra language model (Codex). The available reports and the changes made are documented alongside the manuscript. Responsibility for the content rests with the author.

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A Appendix: simulation catalog and fact sheets

Table 9 lists all evaluated simulations. Each key simulation then has a fact sheet with its figure: simulated mud (maximum thickness) over the official affected area from IDE Chile and the affected street centerlines, what it tests, what it shows, where it fails and what hypotheses it raises. Tests v25 to v29 and the campus microsimulations are summarized in Section 6.4; v22 to v24 were stopped before completion (experiment log).

Table 9: Catalog of all evaluated simulations, ordered by exploratory compatibility index (ECI). Columns as in Table 6; v20, v25, v27, v28 and v29 are not used for selection with their raw ECI: their "sites" component depends on the campus control point, which exceeds 5 cm only with the normal time step; without that point they obtain 72–73 (protocol amendment 1); Date: day and month when the simulation ended (2026). Terrain: city (42,018 buildings), previous (1,103 buildings), prev.+ch. (previous terrain with the linear-park channel carved) or SPOT 2014.

Terr.	Date	Run	Scenario	V (thousand m^3)	Mud	Streets	Sites	dPH (m)	Perim.	QH	UCC (m)	ECI
city	11-10	v27	channel + southern branches; greater roughness in gardens and trees + rainfall	300	G2b	0.78	1.00	8	0.39	0.68	1.13	79
city	11-10	v20	channel + southern branches; rainfall 35 mm/h + official southern branch (terrain v6), normal time step	300	G2b	0.77	1.00	15	0.33	0.68	1.12	78
city	11-10	v25	channel + southern branches; slightly denser mud (Cv 0.43) + rainfall	300	G2b	0.77	1.00	15	0.35	0.68	1.11	78
city	11-10	v29	channel + southern branches; liquid flow on lower hillside (Cv 0.27) + main branch Cv 0.43 + net rainfall	300	G2b	0.77	1.00	15	0.35	0.68	1.11	78
city	11-10	v28	channel + southern branches; rainfall 35 mm/h only outside contributing catchments (no double counting)	300	G2b	0.77	1.00	15	0.34	0.68	1.13	78
city	10-10	v02	channel + southern branches; rainfall 35 mm/h on hillside	300	G2b	0.77	0.75	15	0.34	0.68	1.13	72
city	10-10	z02	channel + southern branches; rainfall 35 mm/h, time step 4× finer	300	G2b	0.77	0.75	15	0.34	0.68	1.13	72
previous	09-10	f03	arainfalll fan + culvert inlet + southern branches; rainfall 35 mm/h on hillside	150	G2b	0.73	0.75	225	0.39	0.66	0.26	71
city	10-10	v14	channel + southern branches; rainfall 35 mm/h + Álvaro del Portillo ravine	300	G2b	0.77	0.75	15	0.34	0.68	1.15	71
city	11-10	v19	channel + southern branches; rainfall 35 mm/h + official southern branch to Álvaro del Portillo (terrain v6)	300	G2b	0.77	0.75	15	0.34	0.68	1.11	71
city	10-10	v09	main channel	300	A2	0.77	0.50	151	0.52	0.68	1.14	70
city	10-10	v03	main channel; culvert 30 m^3/s	300	G2b	0.77	0.50	96	0.50	0.64	1.16	69
city	10-10	v05	main channel; culvert 100 m^3/s	300	G2b	0.74	0.50	96	0.53	0.44	1.16	69
city	10-10	v06	main channel; culvert 60 m^3/s	300	G2b	0.74	0.50	96	0.53	0.44	1.16	69
city	10-10	v17	main channel; culvert 30 m^3/s, capture 25 m, Quebrada Honda carved	300	G2b	0.76	0.50	96	0.50	0.62	1.18	69
prev.+ch.	09-10	f01	main channel	150	G2b	0.71	0.50	338	0.63	0.55	0.31	68
prev.+ch.	09-10	e04	main channel	300	G2b	0.75	0.50	2	0.46	0.56	0.32	68
city	10-10	v01	main channel	300	G2b	0.77	0.50	96	0.46	0.68	1.16	68
city	10-10	z01	main channel; numerical check (time step 4× finer)	300	G2b	0.77	0.50	96	0.46	0.68	1.16	68
city	10-10	v10	main channel; culvert 100 m^3/s, capture 25 m	300	G2b	0.69	0.50	96	0.52	0.00	1.16	68
city	10-10	v11	main channel; culvert 200 m^3/s, capture 40 m	300	G2b	0.69	0.50	96	0.52	0.00	1.16	68
city	10-10	v15	main channel; Quebrada Honda carved downstream (terrain v5)	300	G2b	0.77	0.50	96	0.45	0.68	1.18	68
city	10-10	v18	main channel; culvert 100 m^3/s, capture 25 m, Quebrada Honda carved	300	G2b	0.69	0.50	96	0.52	0.00	1.18	68
city	11-10	v21	channel + southern branches; official southern branch (terrain v6), without rainfall	300	G2b	0.77	0.50	131	0.45	0.68	1.11	68

Terr.	Date	Run	Scenario	V (thousand m^3)	Mud	Streets	Sites	dPH (m)	Perim.	QH	UCC (m)	ECI
prev.+ch.	09-10	k03	main channel; culvert 10 m^3/s	150	G2b	0.70	0.50	338	0.64	0.43	0.31	67
city	10-10	v07	main channel	150	G2b	0.72	0.50	348	0.62	0.68	1.09	67
city	10-10	v08	main channel	300	G1	0.74	0.50	396	0.63	0.69	1.16	67
prev.+ch.	09-10	k01	main channel; culvert 30 m^3/s	150	G2b	0.65	0.50	338	0.63	0.01	0.31	66
prev.+ch.	09-10	k02	main channel; culvert 100 m^3/s	150	G2b	0.65	0.50	338	0.63	0.01	0.31	66
previous	09-10	d02	channel + southern branches	300	G2b	0.68	0.50	4	0.41	0.00	0.42	65
previous	09-10	d04	main channel	150	G2b	0.63	0.50	366	0.55	0.00	0.42	63
previous	09-10	d01	channel + southern branches	150	G2b	0.60	0.50	516	0.55	0.00	0.39	58
previous	09-10	g01	channel + southern branches	150	G2b	0.58	0.50	592	0.51	0.00	0.38	55
previous	09-10	g03	arainfalll fan + culvert inlet + southern branches	150	G2b	0.60	0.50	816	0.53	0.54	0.35	50
previous	09-10	f02	arainfalll fan + culvert inlet + southern branches; rainfall 20 mm/h on hillside	150	G2b	0.56	0.75	1,005	0.46	0.66	0.26	49
previous	09-10	g02	arainfalll fan + culvert inlet + southern branches	150	G2b	0.61	0.50	947	0.51	0.57	0.33	47
previous	09-10	e06	main channel	150	G1	0.47	0.50	1,686	0.80	0.45	0.59	44
previous	09-10	d03	channel + southern branches; peak discharge 100 m^3/s	80	G2b	0.50	0.50	1,160	0.68	0.00	0.22	43
previous	09-10	e01	arainfalll fan + culvert inlet + southern branches	150	G2b	0.56	0.50	1,007	0.46	0.66	0.26	43
previous	09-10	e02	arainfalll fan + culvert inlet + southern branches	150	G2b	0.52	0.50	982	0.43	0.67	0.23	42
SPOT 2014	09-10	s01	main channel	150	G2b	0.50	0.50	1,188	0.60	0.77	0.37	40
previous	09-10	e03	culvert inlet only	150	G2b	0.08	0.00	856	0.20	0.69	0.00	16

Current hypothesis

z02 · Channel + southern branches + hillside rainfall, full city (fine time step). What it tests: The most complete hypothesis among those tested: mud emerges through the main channel onto the alluvial fan and through the southern branches, with rainfall of 35 mm/h also applied over the burned hillside. It repeats v02 with a time step four times finer to examine sensitivity to the time step. **What it shows:** Calculated: simulated flow follows the two corridors delimiting the official area (El Alba–General Blanche and Quebrada Honda) and comes within 200 m of Padre Hurtado; around Clínica UC Christus it calculates 1.13 m (the consulted source reported about 1 m in the emergency department) and produces flow next to Clínica U. de los Andes. The indicators match those of v02; this numerical check does not validate the event reconstruction. **Where it fails:** Only one third of simulated mud in urban areas falls within the official area: it extends west of Padre Hurtado, along Quebrada Honda towards Dipreca and, because of the applied rainfall, along streets in other neighborhoods. It does not reach the U. de los Andes campus. Part of the applied rainfall (about 9,400 m^3) overlaps catchments already entering through the hydrographs; v28 corrects this. **What it raises:** In z02, hillside rainfall contributes to reproducing flow next to the clinic; its predominance during the event remains a hypothesis. Building representation, coarse load and vegetation are considered possible explanations for the extent outside the official area (v25–v27). **Status:** Highest exploratory compatibility index among the configurations considered after the temporal check: 72/100.

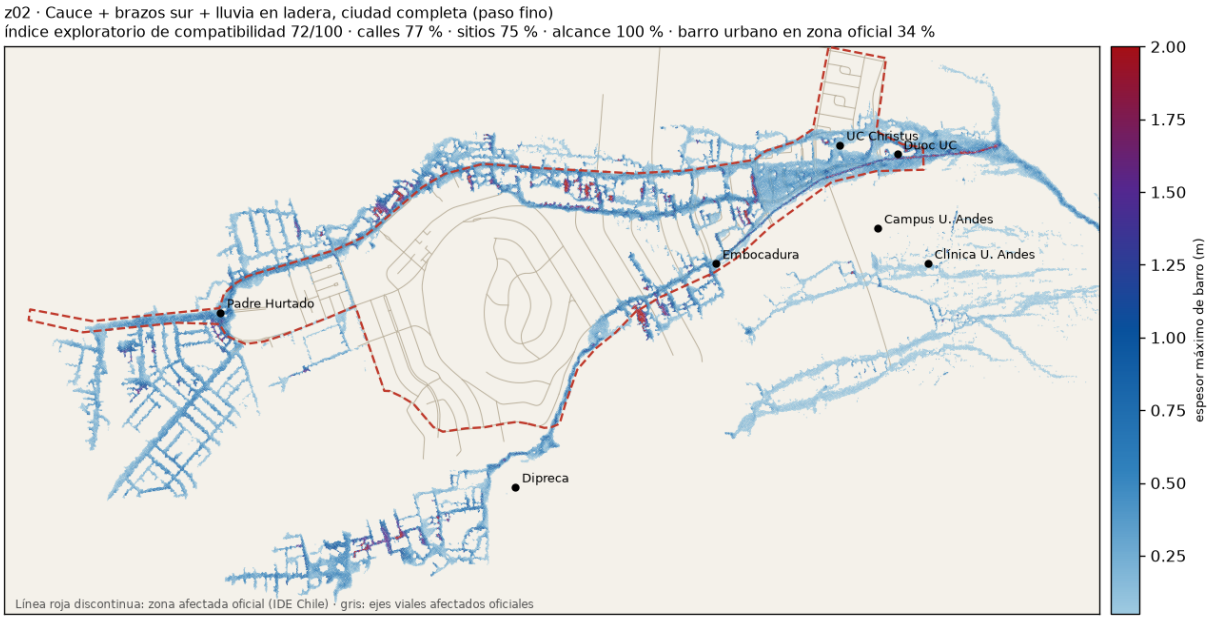

Figure 7: Fact sheet z02: Channel + southern branches + hillside rainfall, full city (fine time step).

Full city

v01 · Main channel only, culvert with assumed zero capacity (300 thousand m^3). What it tests: All mud emerges through the main channel onto the alluvial fan, with the General Blanche conduits and the Bulnes Correa culvert assumed to have zero capacity (hypothetical scenario). **What it shows:** Calculated: with the 42 thousand buildings, flow is channeled along streets; it calculates 1.16 m around UC Christus (0.3 m with the previous terrain), 1.9 m next to Duoc UC, comes within 96 m of Padre Hurtado and wets Quebrada Honda. **Where it fails:** It does not reproduce impacts next to Clínica U. de los Andes, on La Plaza Sur or on the campus. **What it raises:** This configuration does not reproduce impacts in the southern sector. Inflows from that sector are one of the hypotheses considered to explain the discrepancy. **Status:** Reference: ECI 68/100.

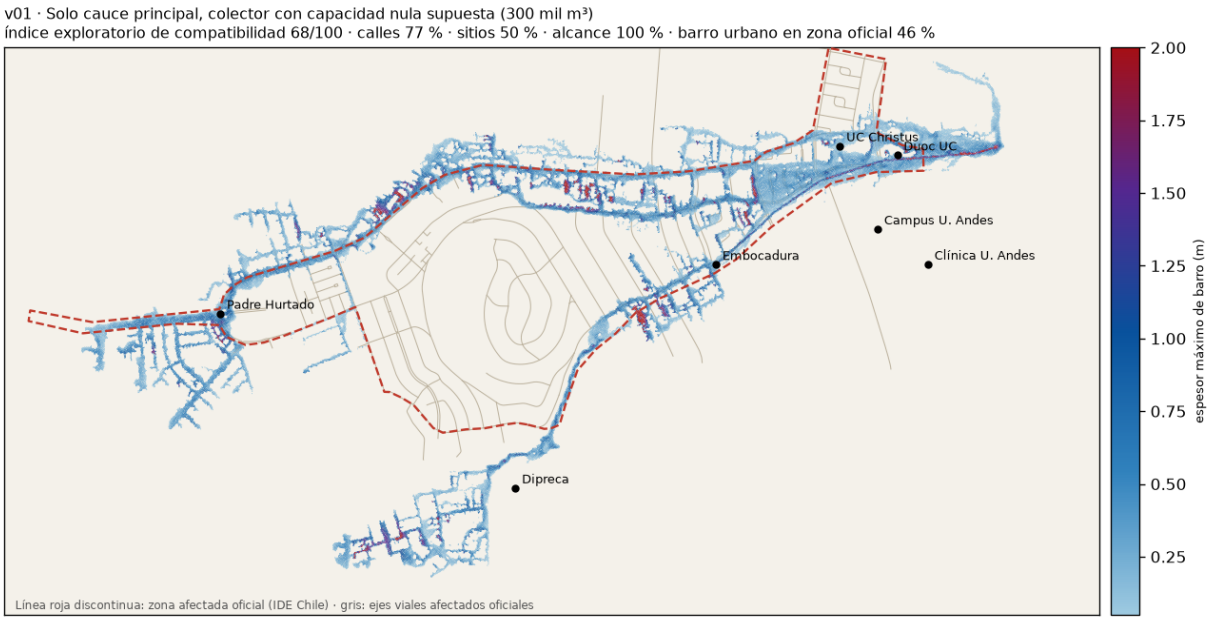

Figure 8: Fact sheet v01: Main channel only, culvert with assumed zero capacity (300 thousand m^3).

v07 · Main channel only with 150 thousand m^3. What it tests: Same as v01, but with half the volume: the central value of the first rainfall-based estimate. **What it shows:** Calculated: the front stops

348 m from Padre Hurtado. **Where it fails:** It does not meet the reach criterion. **What it raises:** In the scenarios tested and under their assumptions, about 300 thousand m^3 allows the reach criterion to be reproduced; that order of magnitude is consistent with a rainfall-based estimate adopting the soil saturation reported by the authority. **Status:** The low-volume configuration does not meet the reach criterion: ECI 67/100.

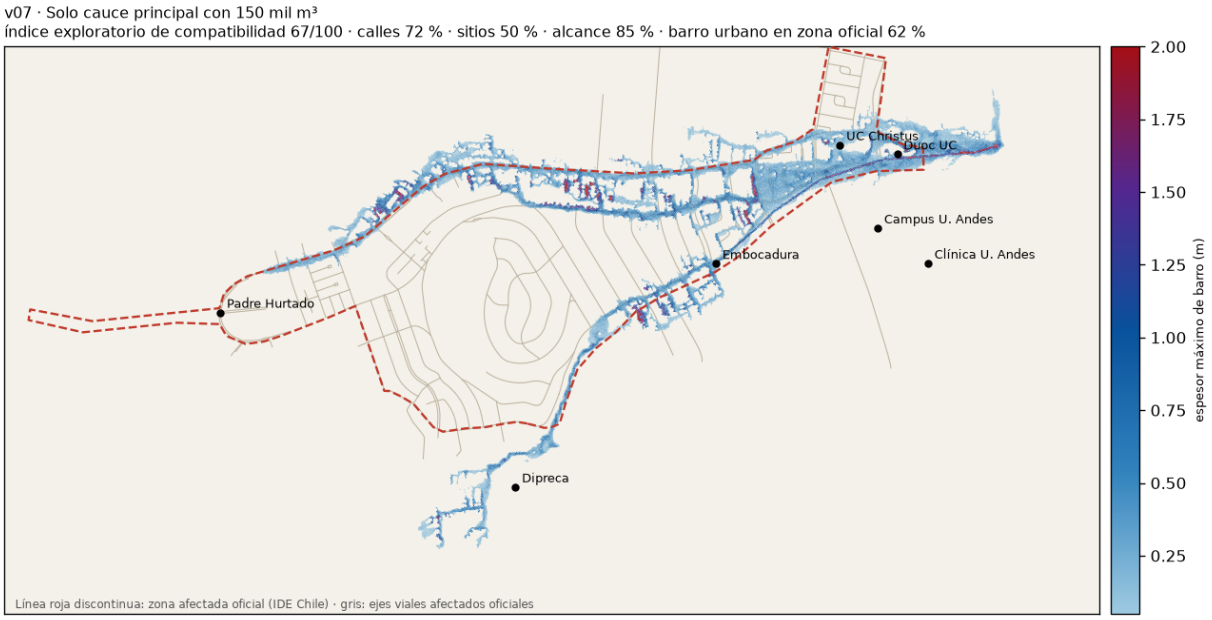

Figure 9: Fact sheet v07: Main channel only with 150 thousand m^3.

U. Andes campus

v21 · Southern branch along the official channel, without hillside rainfall. What it tests: The southern branch follows the official hydrographic network alignment to upper Av. Álvaro del Portillo, where it is cut off to represent the ravine that collapses. Without hillside rainfall, to isolate its effect. **What it shows:** Calculated: mud from the southern branch reaches the avenue (0.48 m where the channel ends) and runs down it towards La Plaza and General Blanche, in a manner compatible with reports from the university's vice-rector and Carabineros. **Where it fails:** Without hillside rainfall, the impact next to Clínica U. de los Andes is not reproduced (0 m) and flow does not reach the Biblioteca. **What it raises:** In the configurations compared, hillside rainfall allows impacts next to the clinic to be reproduced, and the southern branch generates an overflow compatible with that reported on the north side of the campus. **Status:** ECI 68/100.

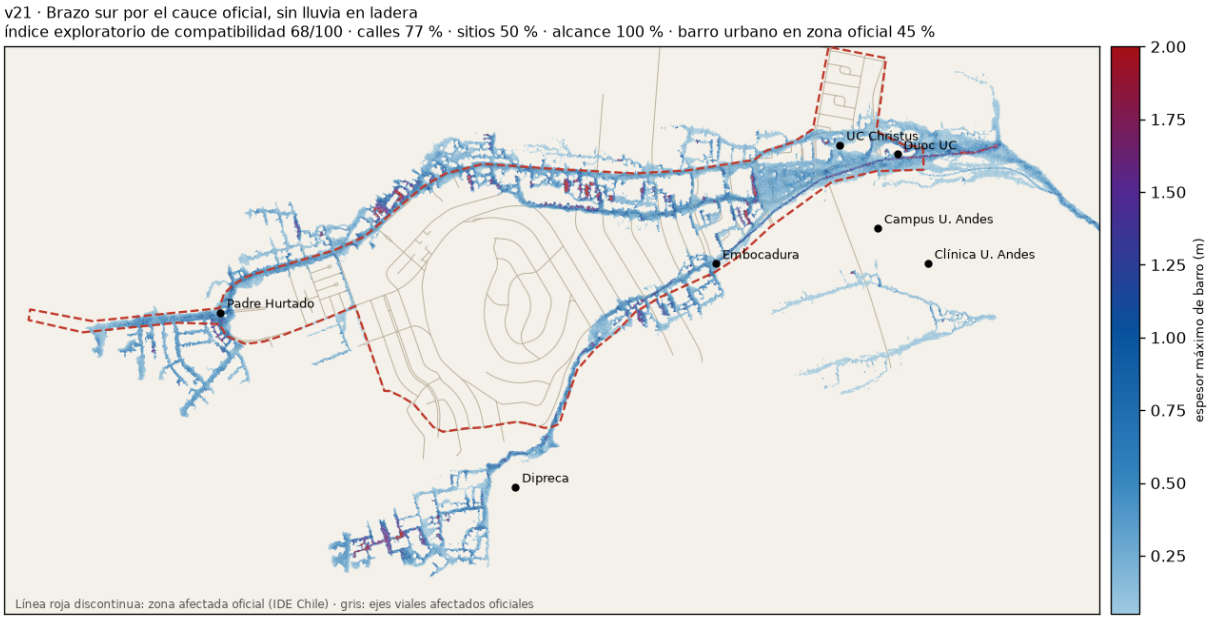

Figure 10: Fact sheet v21: Southern branch along the official channel, without hillside rainfall.

v19 · Southern branch along the official channel to Álvaro del Portillo + rainfall (fine time step). What it tests: The current hypothesis with the southern branch traced according to official mapping, to examine whether flow reaches the campus and the Aula Magna. **What it shows:** Calculated: it reproduces an overflow in upper Álvaro del Portillo and its descent along the avenue, in addition to what z02 achieves. **Where it fails:** Simulated flow continues along the avenue, which is steeper (∼8 %) than the woodland towards the Biblioteca (∼4 %), and does not reach the depression next to the building or the campus control point (1 cm). **What it raises:** Explanations considered include a larger southern-branch inflow (v22–v24), the Biblioteca's own local catchment (11.3 ha), which only partly receives rainfall in this configuration, a more liquid fluid on the lower hillside (v29 and microsimulations), and local relief unresolved by the available terrain. **Status:** ECI 71/100; under analysis.

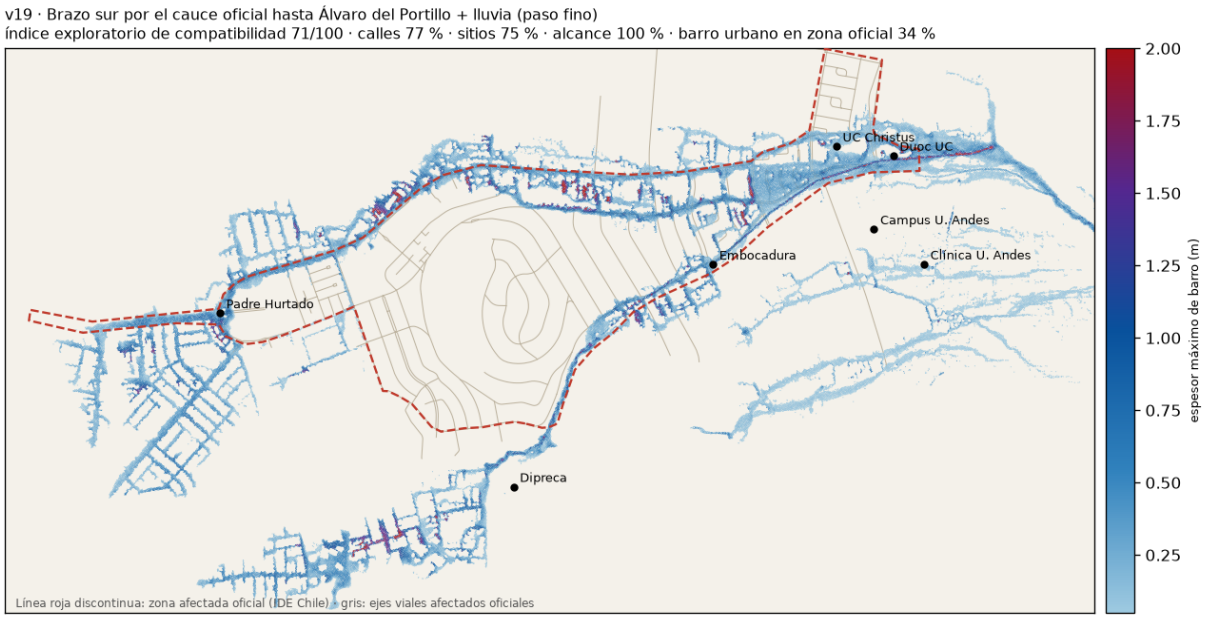

Figure 11: Fact sheet v19: Southern branch along the official channel to Álvaro del Portillo + rainfall (fine time step).

Bulnes Correa culvert (hypothetical scenarios)

v17 · Hypothetical scenario: culvert capacity set to 30 m^3/s. What it tests: Hypothetical scenario with culvert capacity set to 30 m^3/s and capture of the entire channel cross section. The actual capacity and condition of the culvert are not public. **What it shows:** Calculated: the modeled culvert reaches the imposed capacity (removes 67.6 thousand m^3 at 30 m^3/s) and Quebrada Honda is wetted at 62 % of its points. **Where it fails:** — **What it raises:** Under the assumptions tested, a hypothetical capacity of 30 m^3/s is insufficient to prevent flow towards Quebrada Honda. This is not an evaluation of the real structure. **Status:** Lower reference for the interval explored in these scenarios: ECI 69/100.

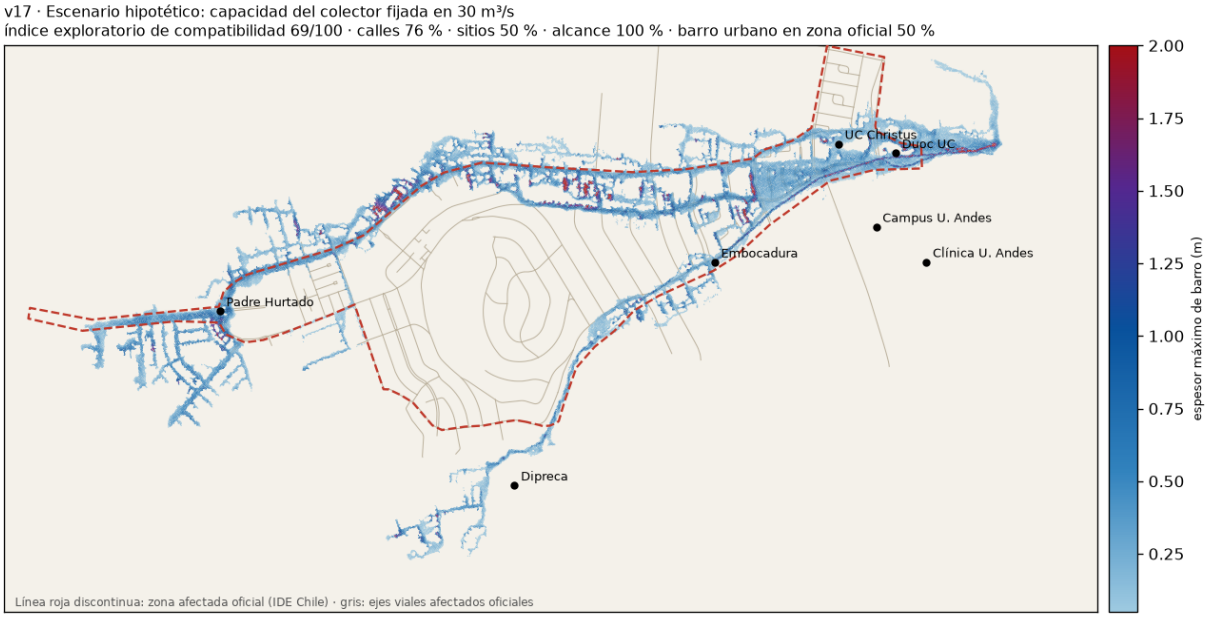

Figure 12: Fact sheet v17: Hypothetical scenario: culvert capacity set to 30 m^3/s.

v10 · Hypothetical scenario: culvert capacity set to 100 m^3/s. What it tests: Hypothetical high-capacity scenario with capture of the entire channel cross section. **What it shows:** Calculated: the modeled culvert removes 94 thousand m^3 with a peak of ∼64 m^3/s and Quebrada Honda remains dry. With 200 m^3/s the result is the same, because calculated arriving discharge does not exceed ∼65 m^3/s. **Where it fails:** The scenario does not reproduce the reported flooding of Quebrada Honda; this discrepancy does not allow the operation of the real culvert to be established. **What it raises:** Under the assumptions tested, the hypothetical capacity that would prevent overflow is near ∼65 m^3/s with full capture. A capture radius of 12 m allowed flow to pass beside the sink: this was a representation artifact, now corrected. **Status:** Upper reference for the interval explored in these scenarios: ECI 68/100.

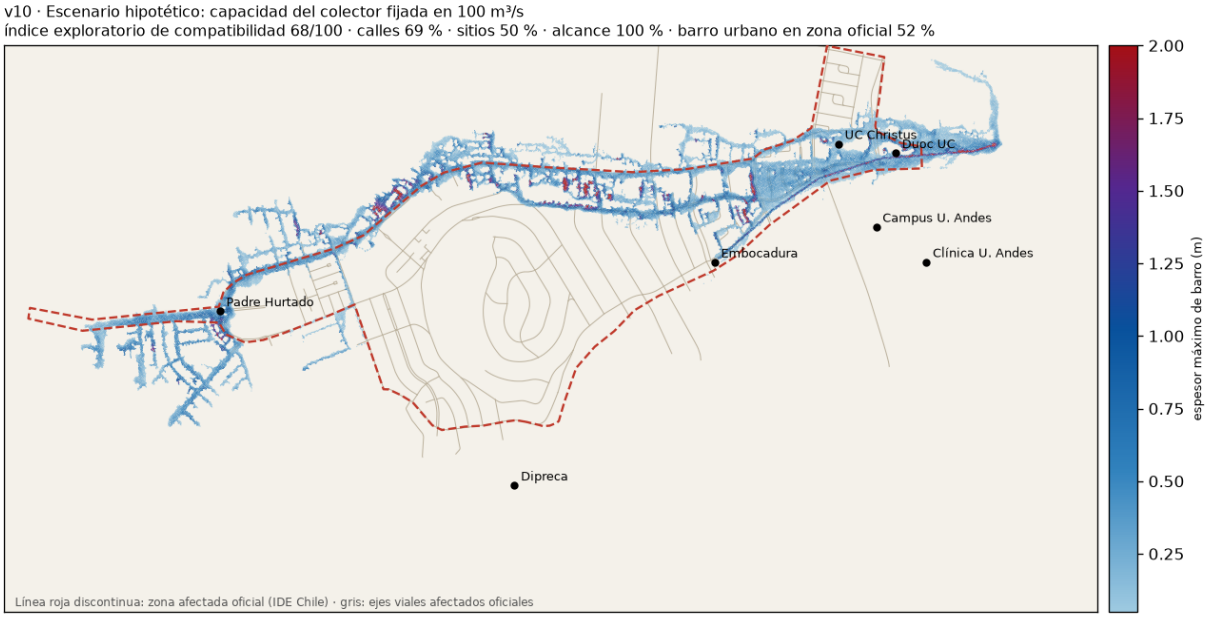

Figure 13: Fact sheet v10: Hypothetical scenario: culvert capacity set to 100 m^3/s.

Mud type

v08 · Thick mud (Glenwood 1, Cv 0.45). What it tests: A more concentrated and viscous mud mixture (1,742 kg/m^3, yield stress 29 Pa). **What it shows:** Calculated: the front stops 396 m from Padre Hurtado. **Where it fails:** It does not meet the reach criterion. **What it raises:** A material intermediate between this and the reference mixture is considered as a hypothesis (Cv 0.43, v25); its correspondence with the event's mud has not been established. **Status:** Thicker variant: ECI 67/100.

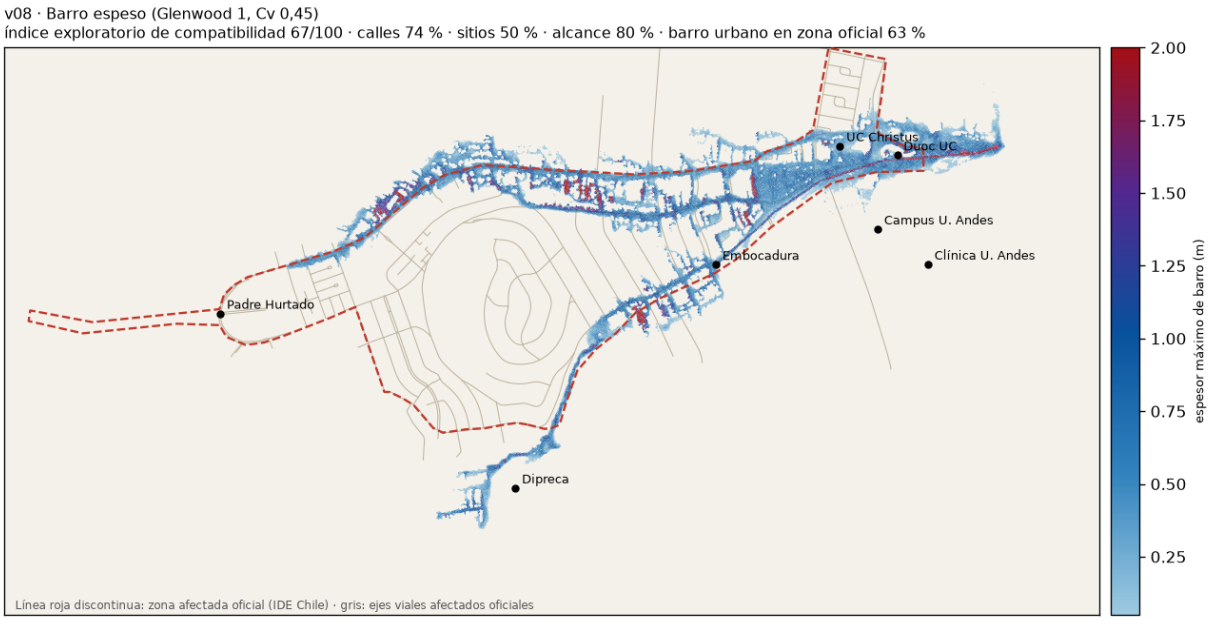

Figure 14: Fact sheet v08: Thick mud (Glenwood 1, Cv 0.45).

v09 · Very fluid mud (Aspen 2). What it tests: A more fluid mud mixture than the reference. **What it shows:** Calculated: a result similar to the reference (ECI 70/100), with somewhat more mud inside the official area. **Where it fails:** It does not reach the southern sector (without southern branches or rainfall). **What it raises:** The ECI varies little between the materials tested; that variation alone does not summarize changes in reach, depth or velocity. **Status:** Index sensitivity to material: low. ECI 70/100.

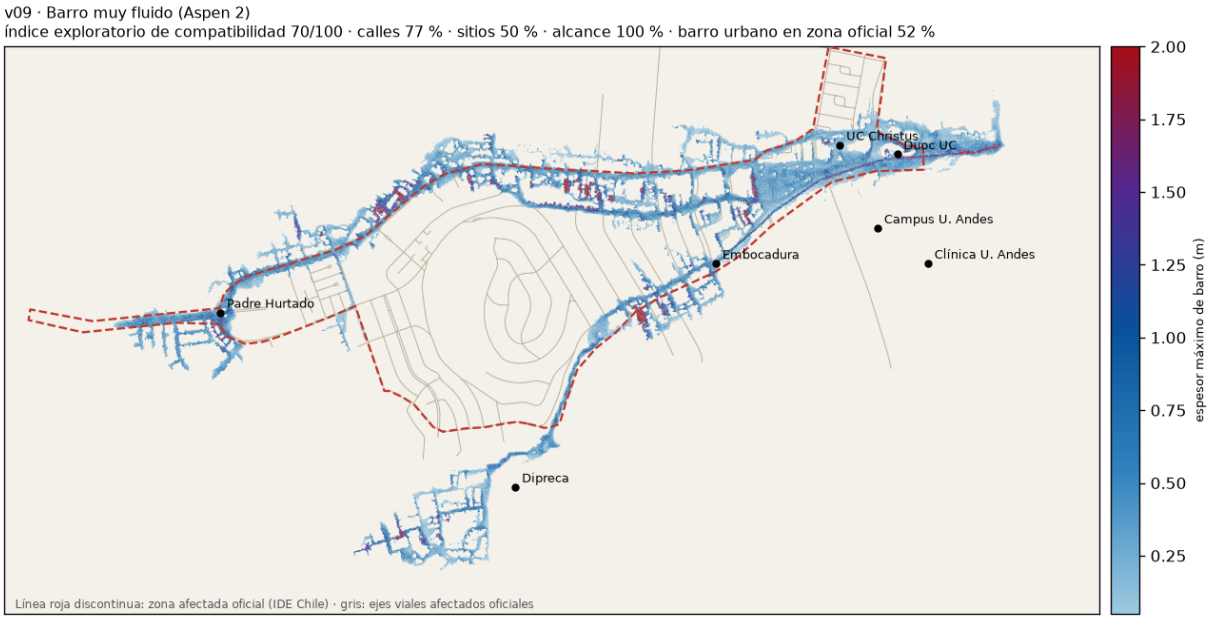

Figure 15: Fact sheet v09: Very fluid mud (Aspen 2).

Previous terrain (first model generation)

e04 · Channel + culvert with assumed zero capacity, terrain with 1,103 buildings. What it tests: The configuration selected in the first model generation (9 October), with only 1,103 buildings represented and the press-perimeter criterion. **What it shows:** Calculated: flow spreads more across the surface (93 ha inside the official area) in thinner layers and reaches Padre Hurtado. **Where it fails:** It calculates only 0.3 m around UC Christus (the consulted source reported about 1 m). **What it raises:** Representing all buildings changed the results; representation as impermeable blocks could intensify channeling compared with one that allows retention in buildings (v26). **Status:** Superseded by simulations with the full city: ECI 68/100.

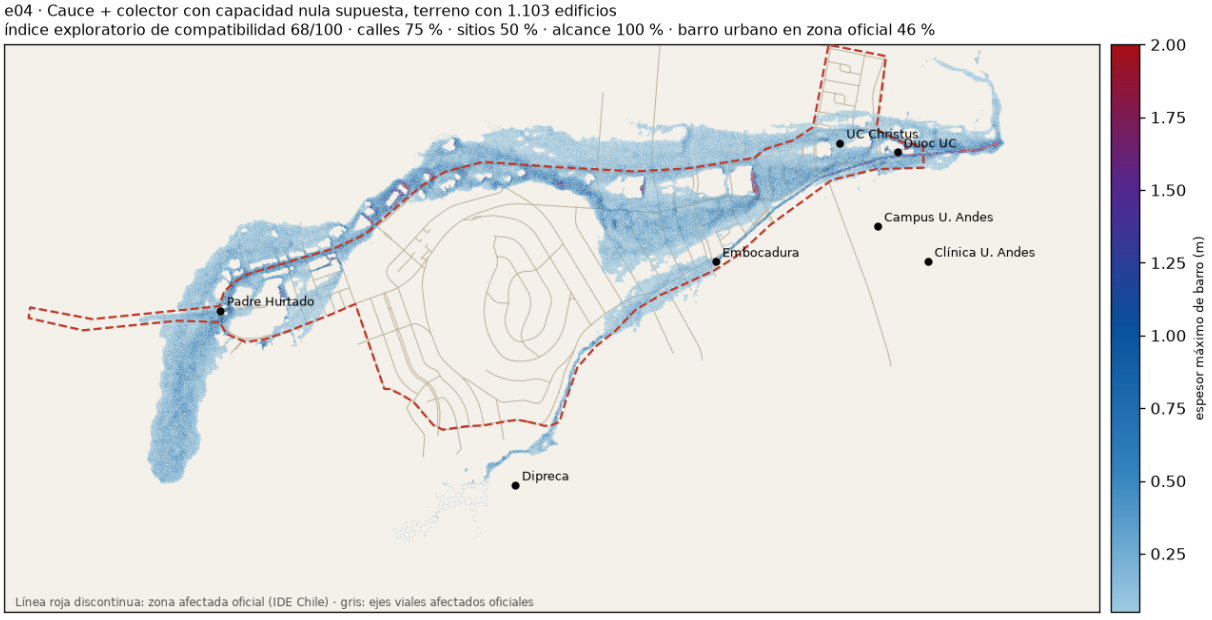

Figure 16: Fact sheet e04: Channel + culvert with assumed zero capacity, terrain with 1,103 buildings.

f03 · Alluvial fan + culvert inlet + hillside rainfall, previous terrain. What it tests: The first simulation with hillside rainfall, using the previous terrain. **What it shows:** Calculated: it was the first to produce flow next to Clínica U. de los Andes and on La Plaza Sur. **Where it fails:** Low thickness around

UC Christus and extent outside the official area. **What it raises:** It led to the current hypothesis (channel + southern branches + rainfall). **Status:** ECI 71/100.

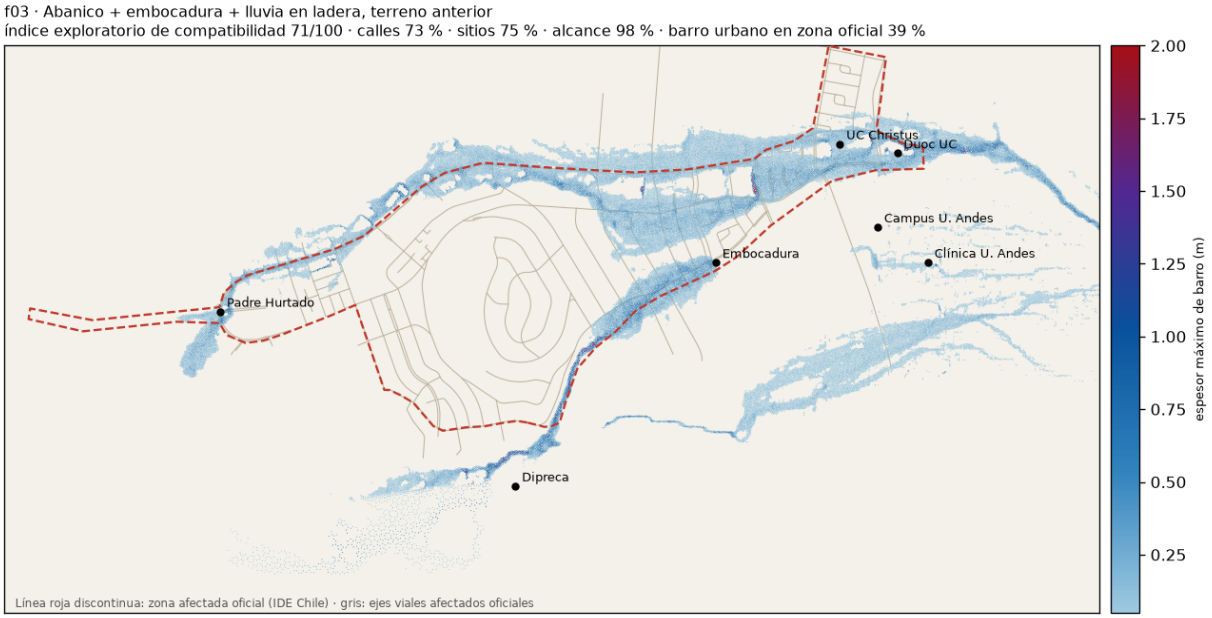

Figure 17: Fact sheet f03: Alluvial fan + culvert inlet + hillside rainfall, previous terrain.

e03 · Overflow at the culvert inlet only (H2). **What it tests:** Whether all the mud emerged from channel overflow at Francisco Bulnes Correa. **What it shows:** Calculated: it wets Quebrada Honda but none of the alluvial fan. **Where it fails:** It does not reproduce General Blanche, Camino El Alba, Duoc UC or UC Christus. **What it raises:** The sources consulted reported an overflow at Bulnes Correa. Simulation e03 alone does not reproduce the full set of observations. **Status:** Does not by itself reproduce the full set of observations under the assumptions and terrain of e03: ECI 16/100.

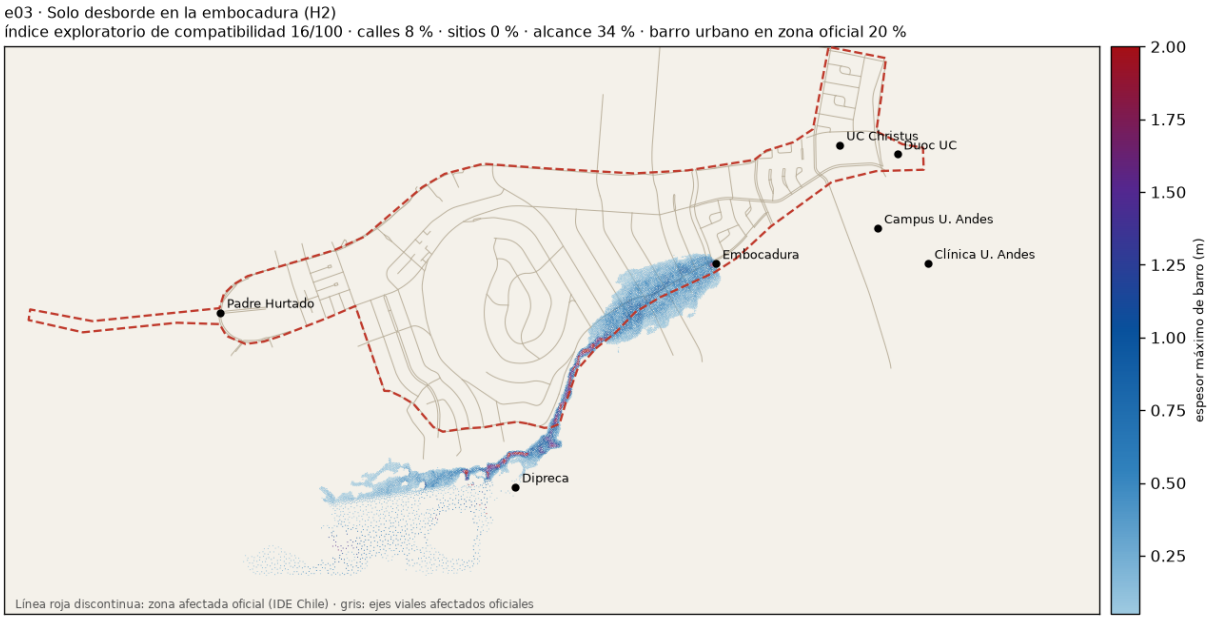

Figure 18: Fact sheet e03: Overflow at the culvert inlet only (H2).