

A prediction-oriented hazard assessment procedure based on the empirical falsification principle, application to the Atenquique debris flow, 1955, México

Abani Patra¹, Andrea Bevilacqua², Marcus Bursik¹, E. Bruce Pitman¹, David Hyman¹, Ricardo Saucedo³, and José Luis Macías⁴

¹University at Buffalo

²Istituto Nazionale di Geofisica e Vulcanologia

³Universidad Autónoma San Luis Potosí

⁴Universidad Nacional Autónoma de México

November 21, 2022

Abstract

In this study, we detail a new prediction-oriented procedure aimed at volcanic hazard assessment based on geophysical mass flow models with heterogeneous and poorly constrained output information. Our method is based on an itemized application of the empirical falsification principle over an arbitrarily wide envelope of possible input conditions. In particular, instead of fully calibrating input data on past observations, we create and explore input values under more general requirements of consistency, and then we separately use each piece of empirical data to remove those input values that are not compatible with it, hence defining partial solutions to the inversion problem. This has several advantages compared to a traditionally posed inverse problem: (i) the potentially non-empty intersection of the input spaces of partial solutions fully contains solutions to the inverse problem; (ii) the partial solutions can provide hazard estimates under weaker constraints potentially including extreme cases that are important for hazard analysis; (iii) if multiple models are applicable, specific performance scores against each piece of empirical information can be calculated. We apply our procedure to the case study of the Atenquique volcanoclastic debris flow, which occurred in the State of Jalisco (MX), 1955. We adopt and compare three depth averaged models currently implemented in the TITAN2D solver, available from vhub.org. The associated inverse problem is not well-posed if approached in a traditional way. However, we show that our procedure can extract valuable information for hazard assessment, allowing the exploration of the impact of model flows that are similar to those which occurred in the past, but differ in plausible ways.

A prediction-oriented hazard assessment procedure based on the empirical falsification principle, application to the Atenquique debris flow, 1955, México

Abani Patra^(1,2), **Andrea Bevilacqua**^(3,2,4), Marcus Bursik⁽³⁾, E. Bruce Pitman⁽⁵⁾, Dave Hyman^(3,+), Ricardo Saucedo⁽⁶⁾, José Luis Macías⁽⁷⁾

(1) Department of Mechanical and Aerospace Engineering, UB, Buffalo, NY; (2) Computational Data Sciences and Engineering Program, UB, Buffalo, NY; (3) Department of Earth Sciences, UB, Buffalo, NY; (4) Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Pisa, Pisa, Italy; (5) Department of Material Design and Innovation, UB, Buffalo, NY; (6) Instituto de Geología, Facultad de Ingeniería, UASLP, SLP; (7) Departamento de Vulcanología, Instituto de Geofísica, UNAM, DF; (+) now at CIMSS, UW, Madison, WI.

Paper Number D131B - 0001
Abstract ID: 422430

1. Prediction-oriented modeling

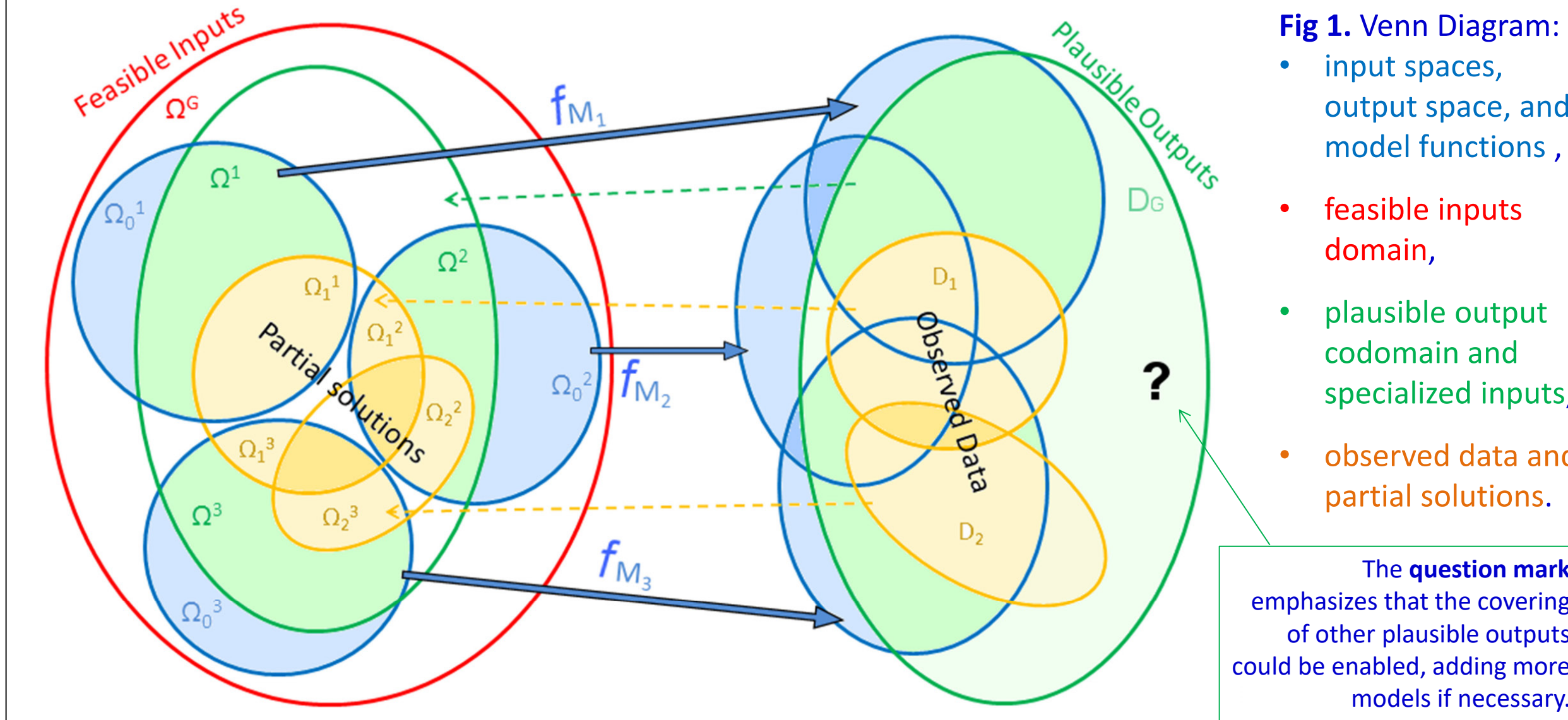
Hazard assessment of **geophysical mass flows**, such as landslides or pyroclastic flows, usually relies on the reconstruction of past flows that occurred in the region of interest using models of physics that have been successful in **hindcasting**. While **physical models** relate inputs and outputs of the dynamical system of the mass flow (Gilbert, 1991; Patra et al., 2018a) this relation is dependent on the choice of model and parameters which is usually difficult for future events.

Choices based on limited data using **classical inversion** is often misleading since it does not reflect all potential event characteristics and even in a probabilistic setting can be error-prone, due to incorrectly limited event space. In this work, we use a **multi-model** ensemble and a **plausible region** approach to provide a more **prediction-oriented** probabilistic framework for hazard analysis.

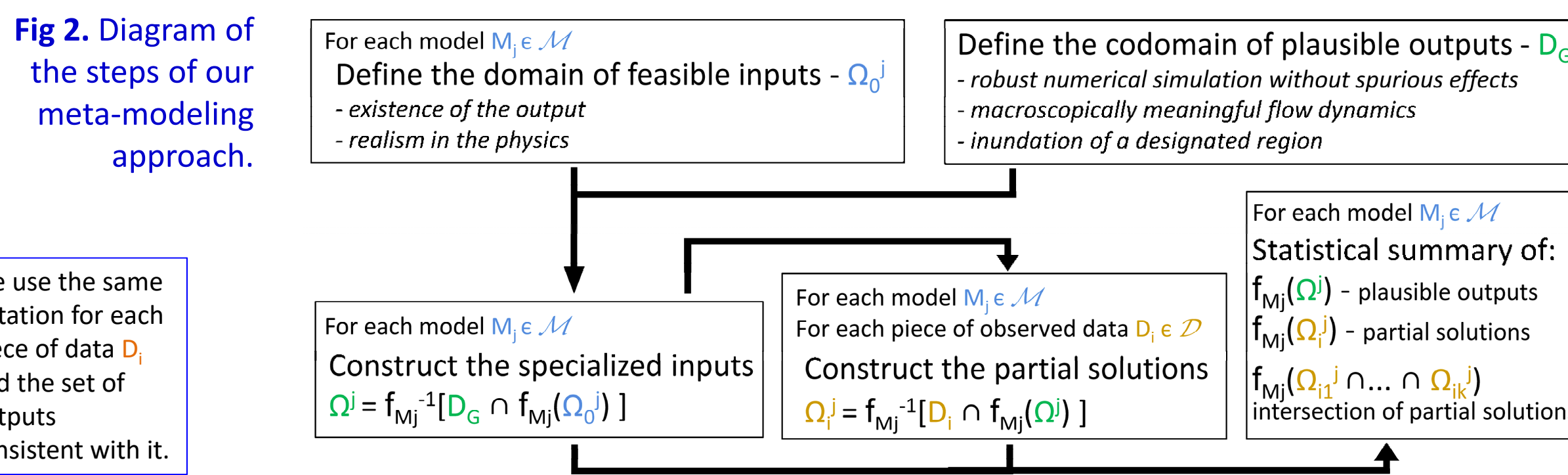
In a **probabilistic framework**, for each model M_i we define a probability measure P_M over the measurable parts of its **input space** Ω_{Q_i} . In the sequel we assume $P_M \sim \text{unif}(\Omega_i)$, where $\Omega_i \subseteq \Omega_0$ is called **specialized input space**.

We represent each model M_i with an **operator**: $f_{M_i}: \Omega_0^i \rightarrow \mathbb{R}^d$. The set of **feasible inputs**: $\Omega_G := \bigcap_j \Omega_0^j$, is a natural meta-modeling framework. Then, we characterize the codomain $D_G \subset \mathbb{R}^d$ of **plausible outputs** - it includes all the outputs consistent with the observed data, plus additional outputs which differ in arbitrary, but plausible ways (see Fig. 2).

So $\forall j$, the **specialized input space** is defined by: $\Omega^j = f_{M_j}^{-1}[D_G \cap f_{M_j}(\Omega_0^j)]$. See Figure 1 and 2. In a similar way, $\forall i$, the **partial solutions** to the inverse problem are: $\Omega_i^j = f_{M_j}^{-1}[D_i \cap f_{M_j}(\Omega_0^j)]$.



The implementation of multiple models is a crucial aspect. Typically, a single model is not able to entirely cover D_G . The question mark indicates that the marking of other plausible outputs could be enabled, adding more models if necessary.

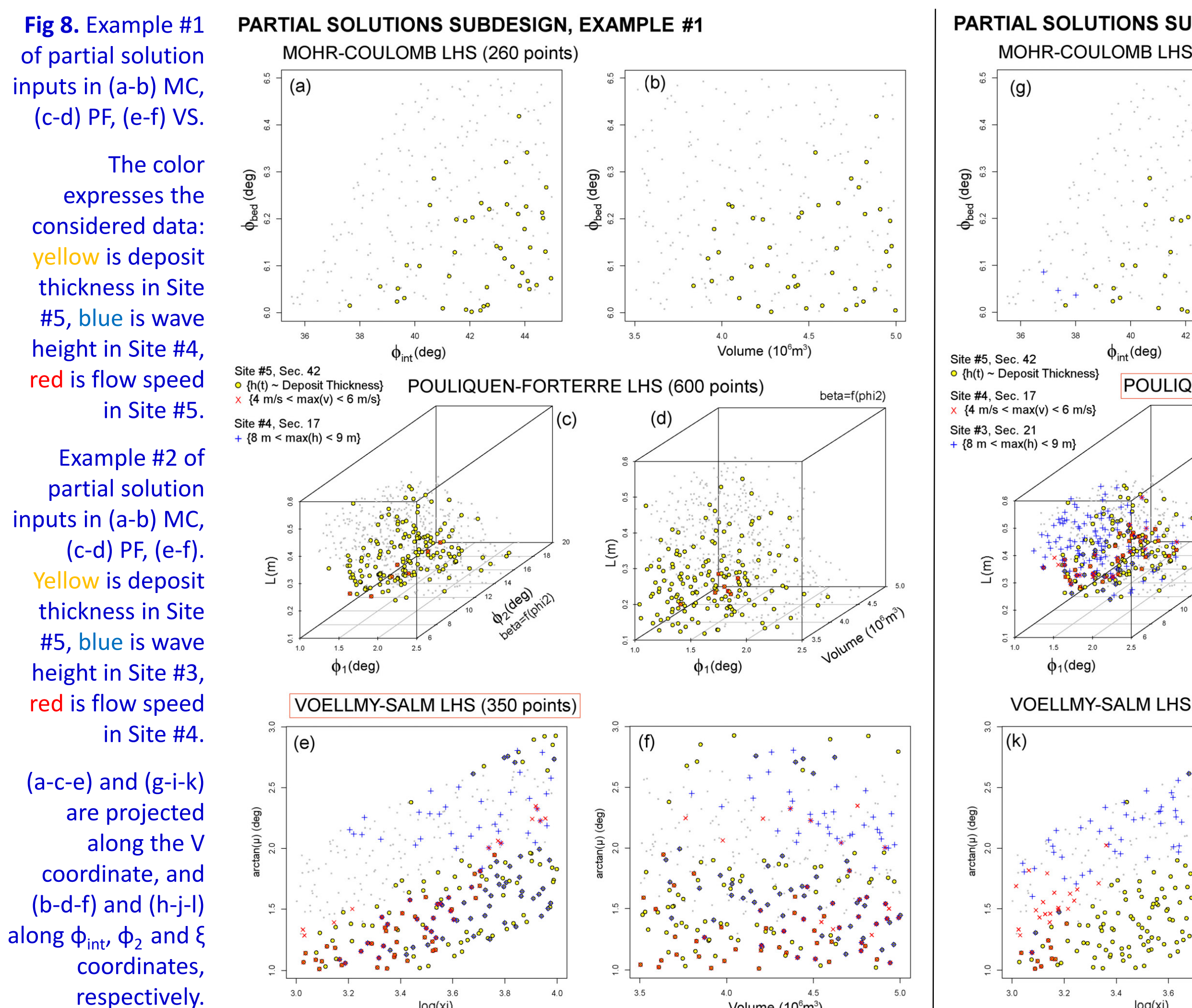


4. Partial solutions in the input space

Figure 7 shows the barplots of **data likelihood**. Model performance depends on the selected **type of data and site**.

- [deposits height] MC performs well at Site #3, while VS at Site #5.
- [maximum flow height] PF and VS can replicate the values at Site #3, and only VS can replicate the values at Site #4.
- [maximum flow speed] PF and VS perform moderately well at Site #4, while only VS at Site #5.

Figure 8 display two examples of **partial solutions** in the specialized experimental design. For each example $n=1,2$ we select a **subfamily of empirical data** $(D_i)_{i \in I_n}$ and define, $\forall j$:



2. Geophysical models and input spaces

We adopt and compare the three depth averaged models **Mohr-Coulomb** (MC) (Savage&Hutter, 1989), **Pouliquen-Forterre** (PF) (Pouliquen, 1999; Pouliquen&Forterre, 2002) and **Voellmy-Salm** (VS) (Voellmy, 1955; Salm, 1990).

Input spaces are explored by **Latin Hypercube sampling** (McKay, 1979; Owen, 1992b; Stein, 1987). The models are incorporated in our large scale mass flow simulation framework **TITAN2D** (Patra et al., 2005; Patra et al., 2018b).

Models are parameterized by:

$$\Omega_{MC}^{\text{MC}} = \{(\phi_{bed}, \phi_{int}, V) \in \mathbb{R}_+^3\} \quad \Omega_{VS}^{\text{VS}} = \{(\phi_1, \phi_2, L, V) \in \mathbb{R}_+^4\} \quad \Omega_{VS}^{\text{VS}} = \{[\arctan(\mu), \log_{10}(\xi), V] \in \mathbb{R}_+^3\}$$

Total Volume: $V \in [3.5, 5] \times 10^6 \text{ m}^3$, i.e. $4.25 \pm 0.75 \times 10^6 \text{ m}^3$.
Input space constraints:
MC - $\phi_{bed} \geq 5^\circ$, $\phi_{int} \in [\phi_{bed}, 45^\circ]$.
PF - $\phi_1 \geq 1^\circ$, $\phi_2 \in [\phi_1 + 6^\circ, \phi_1 + 18^\circ]$, $L \in [0.1, 0.5] \text{ m}$.
VS - $\arctan(\mu) \geq 1^\circ$, $\log_{10}(\xi) \leq 4$.

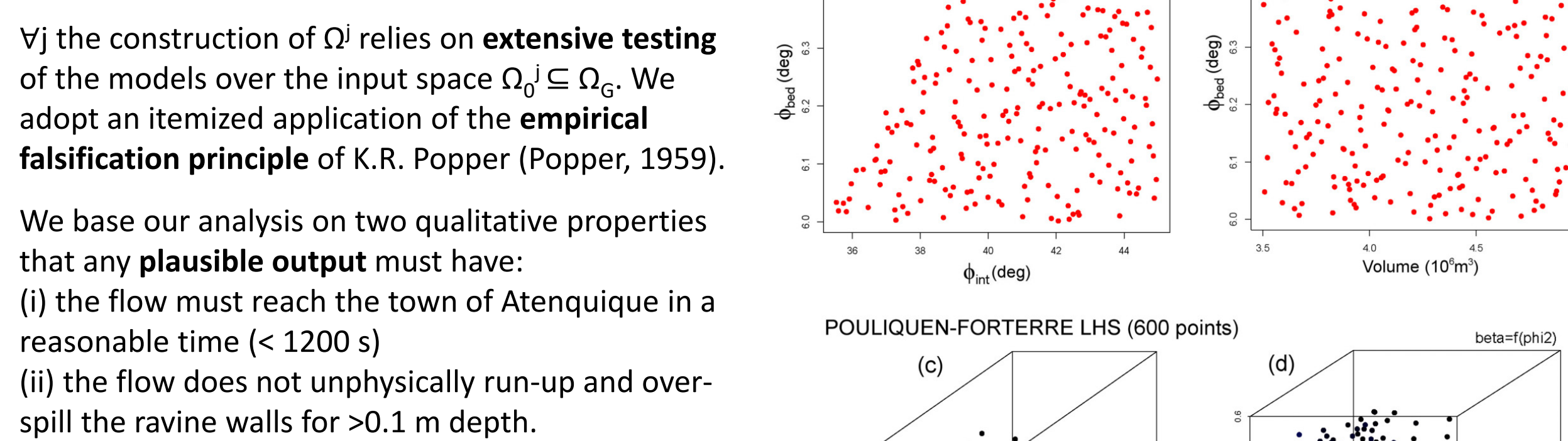


Figure 3 displays the plot of our specialized experimental design.

The existence of **multiple source areas** presents a unique challenge when attempting to model the considered flow (Saucedo, 2003; Saucedo et al., 2008). Based on the work in (Rupp, 2004) we initiate the flow from **five major** source locations, reported in Fig. 4. Piles are paraboloids with unit aspect ratio.

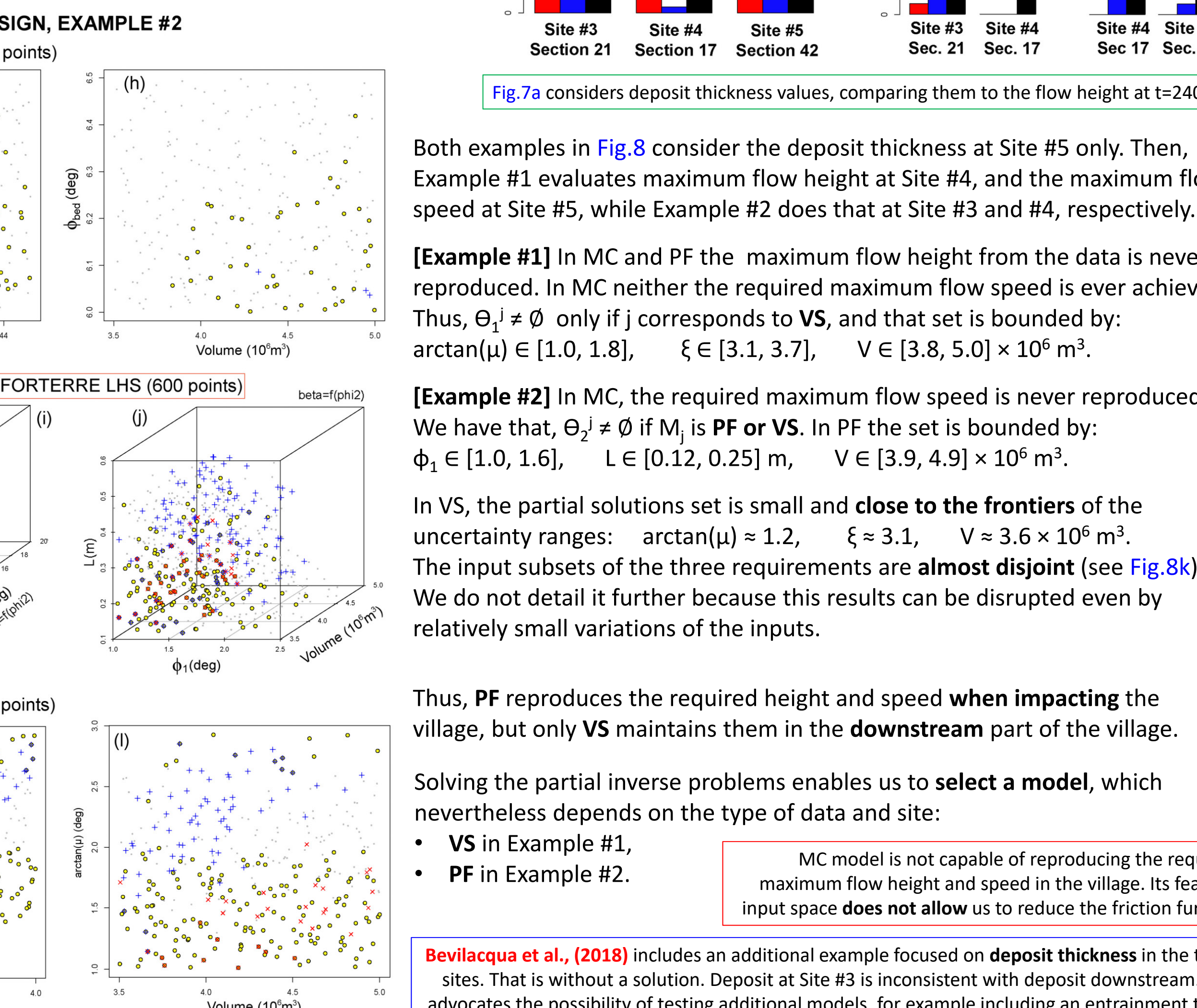
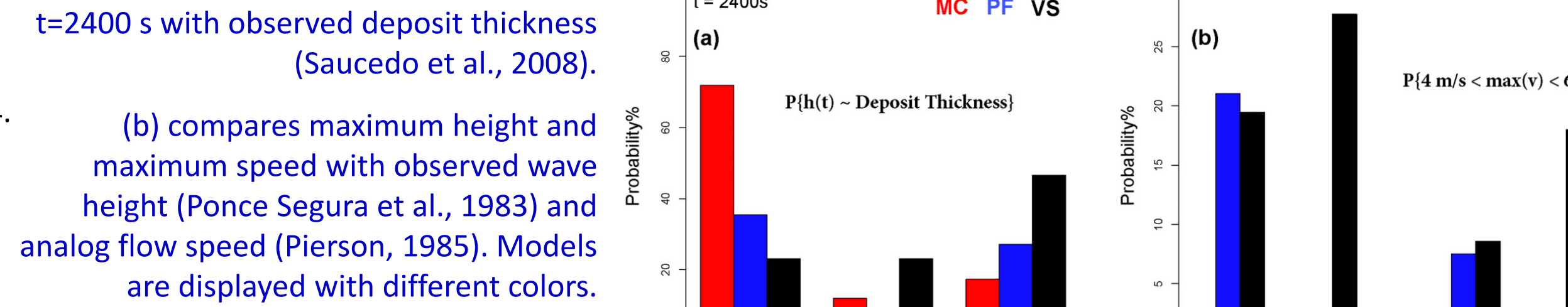
In particular, $\forall k$, $w_k = V_k/V$ is:
 $w_1 = w_3 = w_4 = 19.24\%$, $w_2 = 37.58\%$, $w_5 = 4.70\%$.

This is equivalent to choosing pile radii of 80 m, 100 m and 50 m respectively.

An increase of w_4 , the source in Arroyo Seco, (Fig.4) is not excluded, but would require additional field work to be constrained.

Figure 3. Overview of the specialized experimental design in (a-b) MC, (c-d) PF, (e-f) VS models. (a-c-e) are projected along the V coordinate, and (b-d-f) along ϕ_{int} , ϕ_2 and ξ coordinates, respectively.

7. Barplots of data likelihood in Sites #3, #4, #5. (a) compares flow height at t=2400 s with observed deposit thickness (Saucedo et al., 2008).



3. Geophysical case study and plausible outputs

The **Colima Volcanic Complex** is located in the western portion of the Trans-Mexican Volcanic Belt (small box in Fig.4). It consists of a N-S volcanic chain formed by Cántaro, **Nevado de Colima**, and Colima volcanoes (Allan, 1986; Robin et al., 1987; Luhr&Carmichael, 1990). Nevado de Colima (4320 m.a.s.l.) occupies the central part of the volcanic complex, being the most voluminous of the three volcanoes (Cortés et al., 2010).

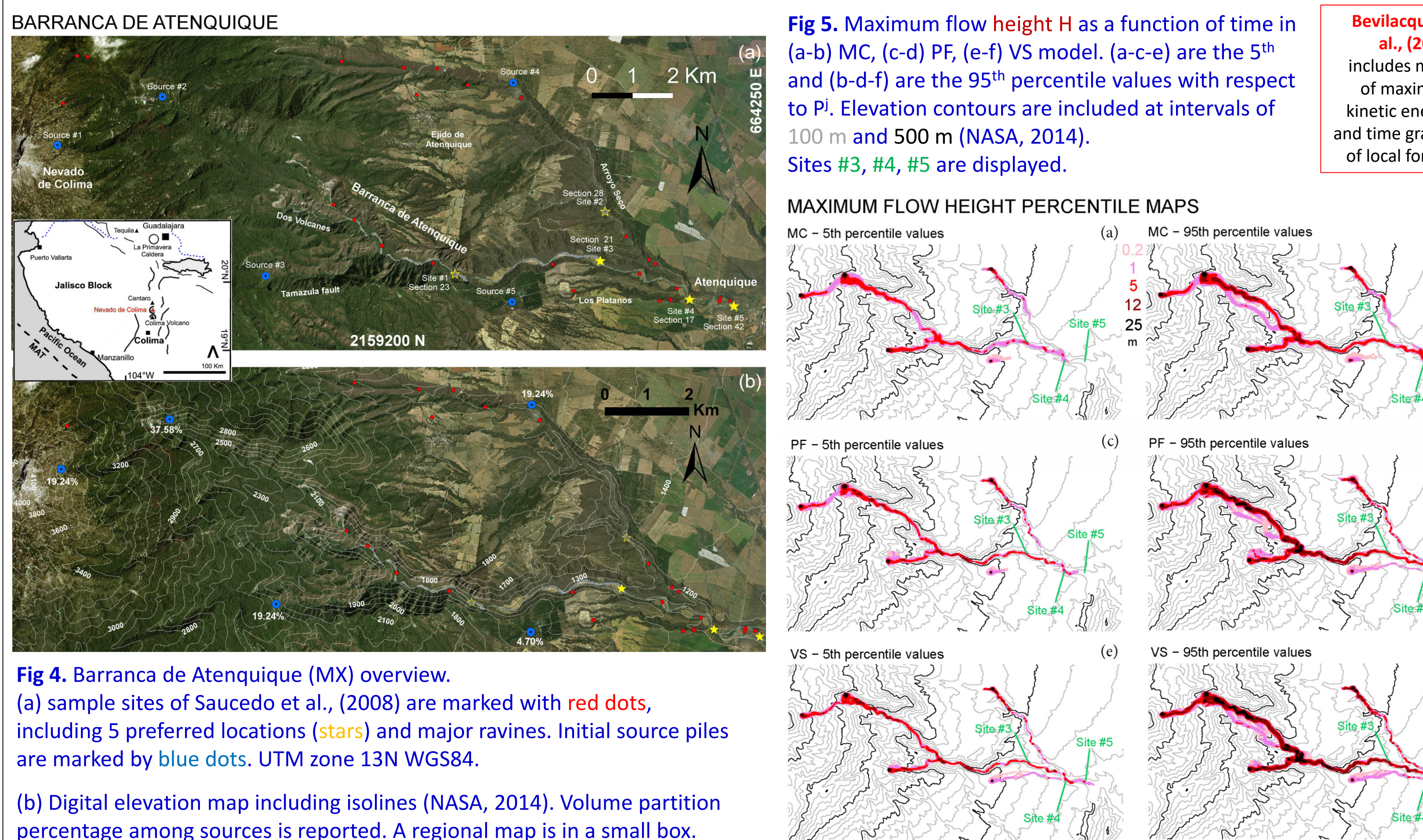
The considered drainage starts at an elevation of **4000 m** on the eastern flank of Nevado, is occupied by **Atenquique river**, and ends at its junction with the Tuxpan River at **1040 m**. On 16 October, 1955, at 10:45 am, the inhabitants of Atenquique were surprised by the sudden arrival of an **8-9-m high** wave carrying mud, boulders and tree trunks. More than 23 people died, and the flood leveled everything but the tower of the church and the upper part of the market place (Ponce Segura, 1983; Saucedo et al., 2008).

Deposits cover a minimal area of 1.2 km², and a minimum volume of $3.2 \times 10^6 \text{ m}^3$ was estimated for the flow. The diluted flow that inundated the village probably had a velocity in the range of **4 to 6 m/s**, obtained by comparison with analogous flows (Pierson, 1985; Saucedo et al., 2008).

$\forall j$ we sample the model M_j input in a **Monte Carlo** simulation, and the output of each sample run is a function $f_j(\omega, x, t)$, where ω is the input, t is the time and x is a spatial element of the computational grid. f_j is a **random function** with respect to the probability distribution P_{M_j} over Ω . The results are summarized in Figure 5 by a family of spatial maps of **maximum flow depth** with respect to time, H .

We display the 5th and 95th percentiles with respect to P_{M_j} .

MC shows the lowest values, while **VS** the **highest**, especially in the distal part of the domain. In MC, the flow in the **tributaries** is not capable of reaching the village, while in the 95th percentile maps of PF and VS, it is. In VS, the flow in Arroyo Plátanos joins the main ravine even in the 5th percentile map. Significant over-spill issues are absent.



5. Examples of conditional results

In Figure 9 we report the spatial maps of mean of maximum in **flow height**, H , and kinetic energy κ . We report the histograms of maximum **dynamic pressure** Q .

$$\kappa := \frac{1}{2} \frac{(h\bar{u})^2}{h} + \frac{(h\bar{v})^2}{h} \quad Q := \max_{t \in T} \frac{\kappa}{h}$$

The dynamic pressure Q and the kinetic energy κ are scaled for a mass with unit density.

In Example #1, $Q \in [0, 150] \text{ m}^2/\text{s}^2$ at Site #4, $Q \in [7.5, 17.5] \text{ m}^2/\text{s}^2$ at #5. In Example #2, $Q \in [8, 13] \text{ m}^2/\text{s}^2$ at Site #4, $Q \in [4, 7] \text{ m}^2/\text{s}^2$ at #5. Typical values of density of **mudflows** are above 2000 kg/m³.

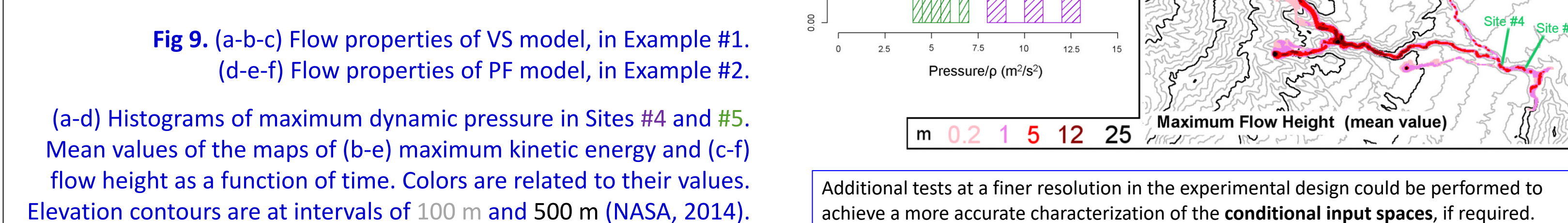
The [4, 6] m/s constraint on maximum flow speed has an **immediate** effect on Q . Imposing it at Site #5, as in the Example #1, or Site #4, as in the Example #2, radically changes the results.

In the spatial maps of Fig.9, PF shows slightly lower maximum flow height, and significantly lower energy than VS, especially in the distal part of the domain.

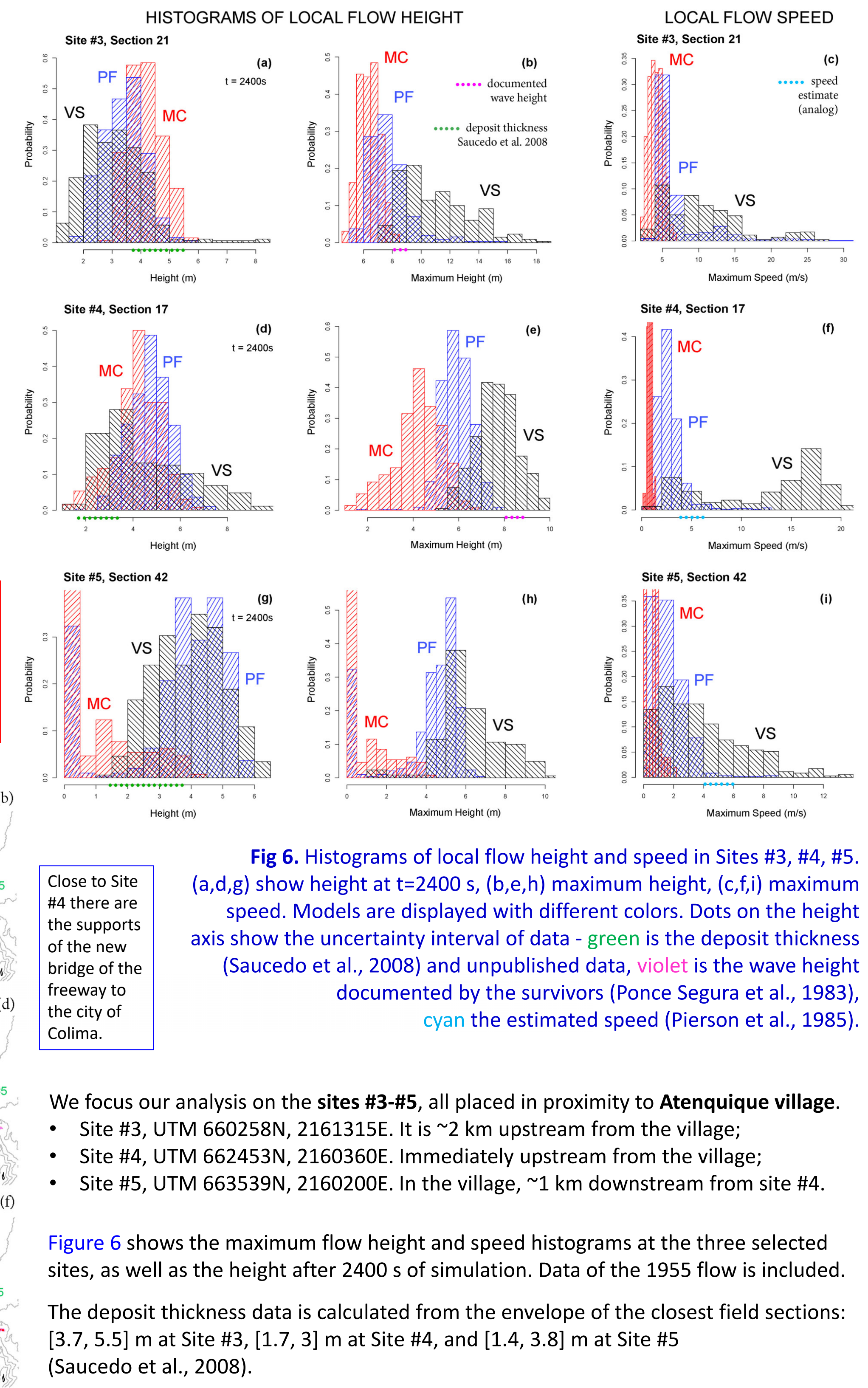
The flow in the **tributaries** can reach the village, except for the smallest flows of Arroyo Plátanos in PF, which however are only tens of meters from the main branch.

Local maxima of flow height are located in the ravine, while the kinetic energy shows a more regular decrease.

These conditional results focus on the replication of specific properties of the 1955 flow. They are enveloped in the wide range of plausible outputs displayed in Fig.5.



Acknowledgements: This work is supported by National Science Foundation awards 1339765, 1521855, 1621853 and 1821311, and by Italian Ministry of Education, University, and Research, project FIS2017 - SOIR. We would like to thank Byron Rupp for his fundamental work on the localization and volume constraints of the Atenquique debris flow (Rupp, 2004), and Ali Akhavan Safaei for the C++ and Python scripts to collect the local outputs and contributing variables on the grid elements (Akhavan Safaei, 2018).



6. Conclusions

We introduced a new prediction-oriented method for hazard assessment of debris flows.

- In summary:
 - We defined a **specialized experimental design** after assuming: the realism of the underlying physics, the numerical simulation robustness, and the meaningfulness of flow dynamics and inundation output. This contains valuable information for hazard assessment and this is a first step towards the development of an objective and **partially automated experimental design**.
 - We calculated the **likelihood** that different model realizations reasonably represented the 1955 Atenquique flow, given **multiple pieces of field data**. The exercise provided useful information in either model selection or data inversion.
 - We constructed **partial solutions to the inverse problem**, conditioning the specialized experimental design to be consistent with subsets of the observed data. We found **model selection** to be inherently linked to the inversion problem.
 - Our results are consistent with **evolution of flow rheology** downstream in the vicinity of the village, from MC above the village, to either PF or VS within and downstream from the village. The meaning may reflect an evolution from inertial to macroviscous debris flow behavior near Atenquique.

References: Akhavan Safaei, A. (2018). Master's Thesis, University at Buffalo. Allan, J. (1986). Geological Society of America Bulletin, 97, 473-485. Cortés, A. et al. (2010). Geological Society of America, Special paper, 464. Ghosh, T. and Krishnamurti, T. N. (2018). Weather and Forecasting, 33, 873-885. Gilbert, S. (1991). Journal of Research in Science Teaching, 28, 73-79. Krishnamurti, T. N. et al. (2016). Reviews of Geophysics, 54, 326-377. Luhr, J. and Carmichael, J. (1990). Geology of the Volcán de Colima, Universidad Nacional de México. McKay, M. D., Beckman, R. J., and Conover, W. J. (1979). Technometrics, 21, 239-245. NASA (PL) (2014). Shuttle Radar Topography Mission (SRTM), Tech. rep. Owen, A. B. (1992a). Statistica Sinica, 2, 439-452. Owen, A. B. (1992b). Journal of the Royal Statistical Society, 54, 541-551. Patra, A. et al. (2005). Journal of Volcanology and Geothermal Research, 139, 1-21. Patra, A., Bevilacqua, A. et al. (2018a). Lecture Notes in Computer Science, 10861, 724-736. Patra, A. et al. (2018b). arXiv.org, 1805.12104, 1-39. Pierson, T. (1985). Geological Society of America Bulletin, 96, 1056-1069. Ponce-Segura, J. (1983). Historia de Atenquique, Talleres Tipográficos Vera. Popper, K. R. (1959). The Logic of Scientific Discovery, Routledge. Pouliquen, O. (1999). Physics of Fluids, 11, 542-548. Pouliquen, O. and Forterre, Y. (2002). Journal of Fluid Mechanics, 453, 133-151. Robin, C. et al. (1987). Journal of Volcanology and Geothermal Research, 31, 99-113. Rupp, R. (2004). Master's thesis, University at Buffalo. Salm, B. (1993). Annals of Glaciology, 18, 221-226. Saucedo, R. (2003). Regional Geomorphology Conference, Mexico City, Mexico. Saucedo, R., Macías, J. L., et al. (2008). Journal of Volcanology and Geothermal Research, 173, 69-83. Savage, S. B. and Hutter, K. (1989). Journal of Fluid Mechanics, 199, 177-215. Stein, M. (1987). Technometrics, 29, 143-151. Tang, B. (1993). Journal of the American Statistical Association, 88, 1392-1397. Voellmy, A. (1955). Schweiz Bauzeitung, 73, 159-165, 212-217, 246-249, 280-285.

Bevilacqua et al. (2018). Probabilistic forecasting of plausible debris flows from Nevado de Colima (Mexico) using data from the Atenquique debris flow. 1555. https://arxiv.org/abs/1805.20124