Tsunami Fragility estimates for damage quantification

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Traditional vulnerability estimates: Tsunami Fragility Functions (TFF)

- Adapted from seismic hazard analysis conventions
- Quantitative vulnerability models
- Link hazard (demand parameter) to risk (damage exceedance)
- Asset-type specific

Definitions:

Koshimura et al. 2009

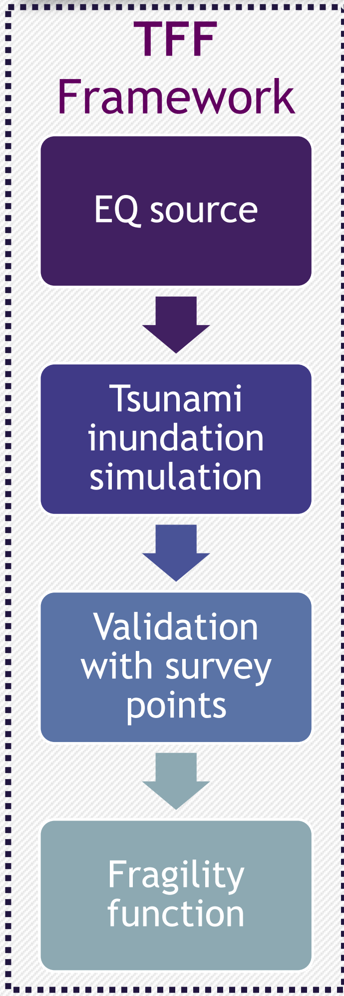
[TFF are] measures for estimating structural damage […] to tsunami attack. [They] are expressed as the damage probability of structures with regard to the hydrodynamic features of inundation.

Reese et al. 2011

[TFF] give the probability of being *in or exceeding* a specific damage state (*DS*) as a function of the demand imparted to the structure by the hazard.

Brief history of TFFs

- Koshimura et al. 2009 introduce fragility functions for tsunamis
- Reese et al. 2011: multi-class TFF using GLM
- Mas et al. 2012: TFFs in areas with low data availability
- Suppasri et al. 2013: TFF for Japan, following the 2011 Great East Japan Earthquake
- De Risi et al. 2017: TFFs accounting for input uncertainty



Use-cases and limitations of TFF

- Use cases:
  - Academic discussion
  - Proposed implementation in PTRA
- Limitations:
  - Not transferrable
  - Demand parameters usually proxies for direct loads
    - inundation height → Hydrodynamic force
  - Aggregated measure
- TFF Applications for disaggregated estimates:
  a) Adriano et al. 2014 (No ground truth)
  b) Rehman & Cho 2016 (No ground truth)
  c) Moya et al. 2018 (Earthquake damage)

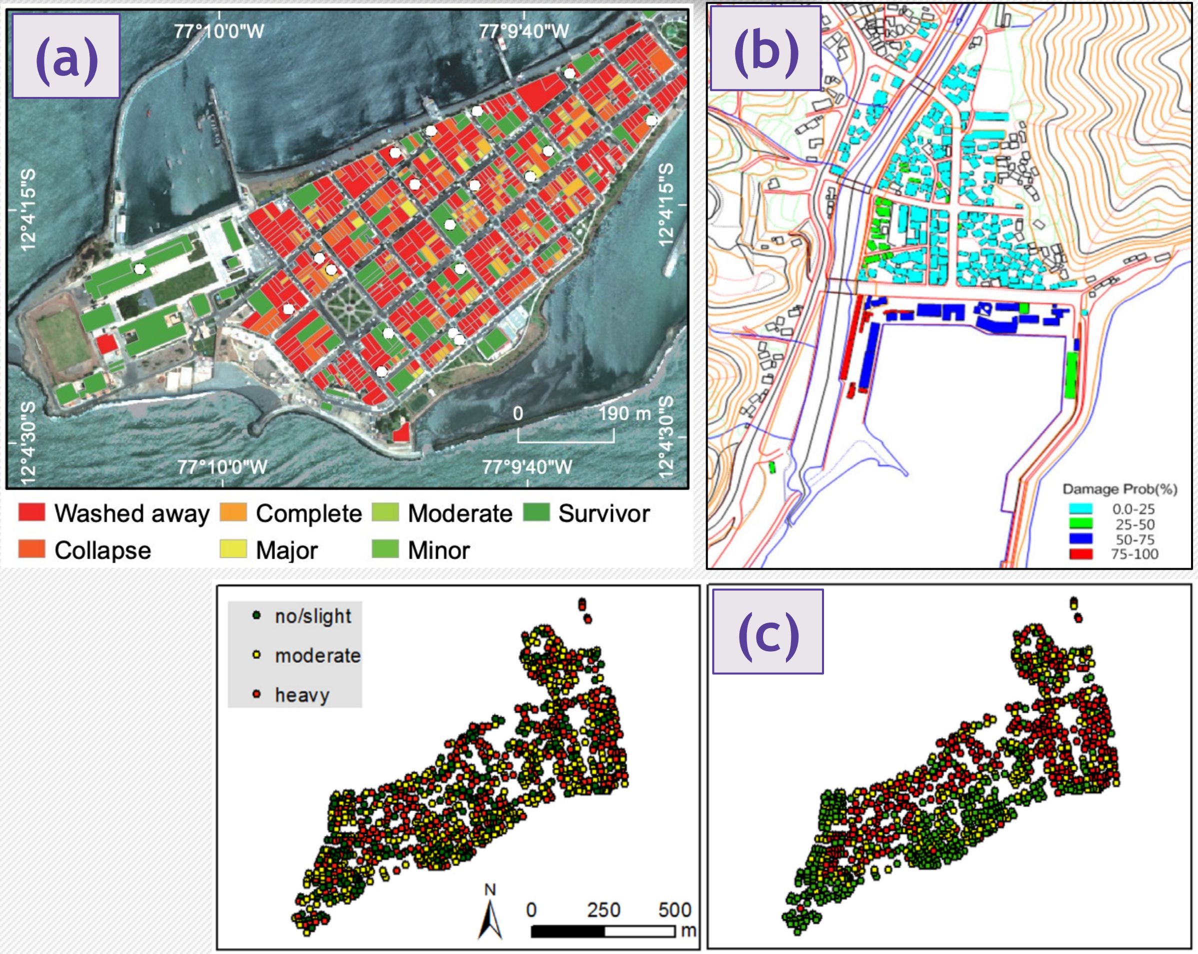


Fig. 8. Left: An instance of a synthetic EBDS. Right: The actual EBDS from field survey.

Tsunami Fragility Functions in context

- Push for standard integrated PTHA → PTRA workflow (AGHITAR, GTM)
- Guidelines for policy & insurance

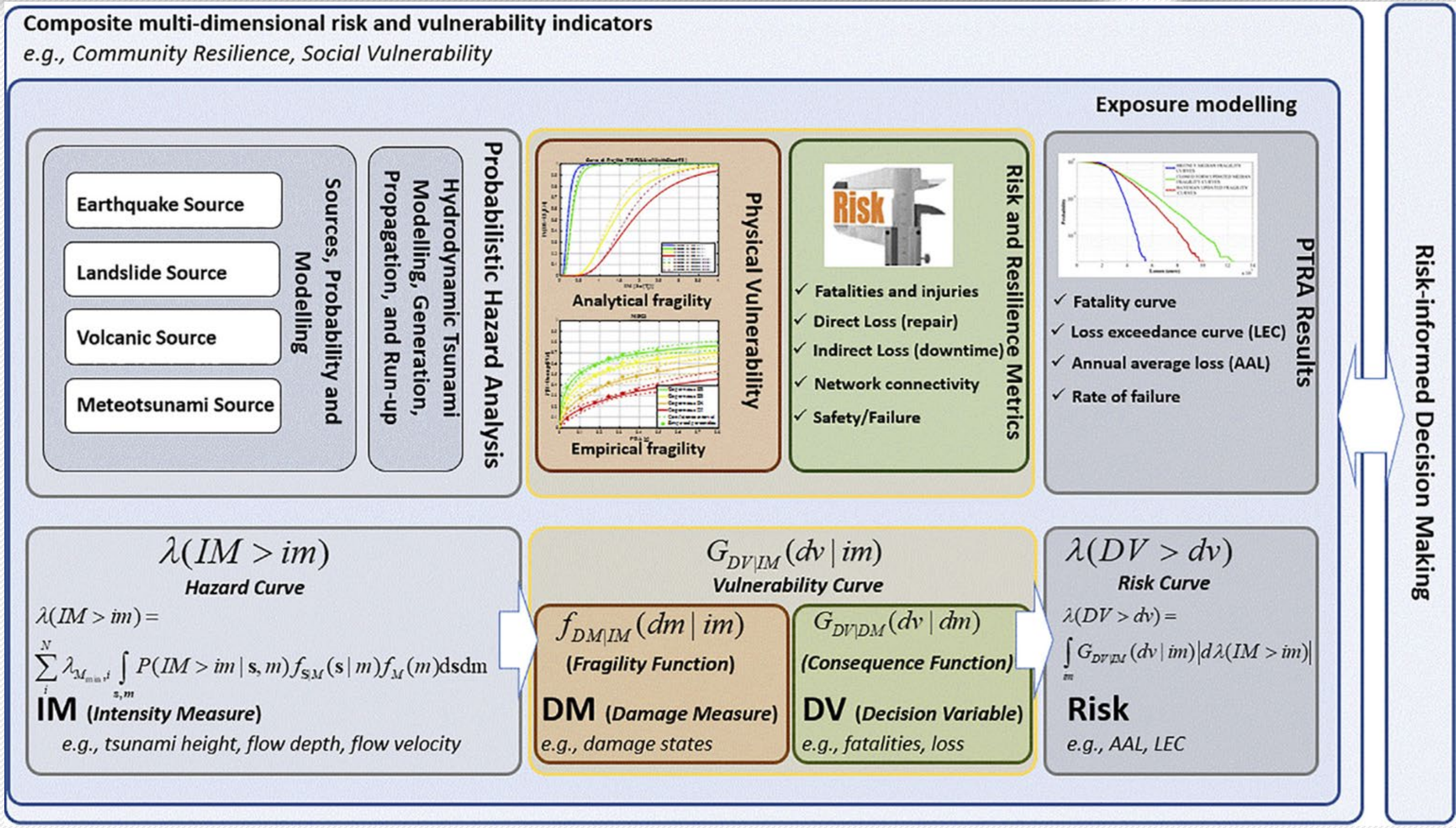


Figure courtesy of: J. Behrens et al., "Probabilistic Tsunami Hazard and Risk Analysis: A Review of Research Gaps," *Frontiers in Earth Science*, vol. 9, 2021.

[1] AGHITAR: Accelerating Global science In Tsunami HAzard and Risk analysis
[2] GTM: Global Tsunami Model

Damage-to-loss

Disaggregated damage estimates require:

- disaggregated inputs ☑
- disaggregated model ☐

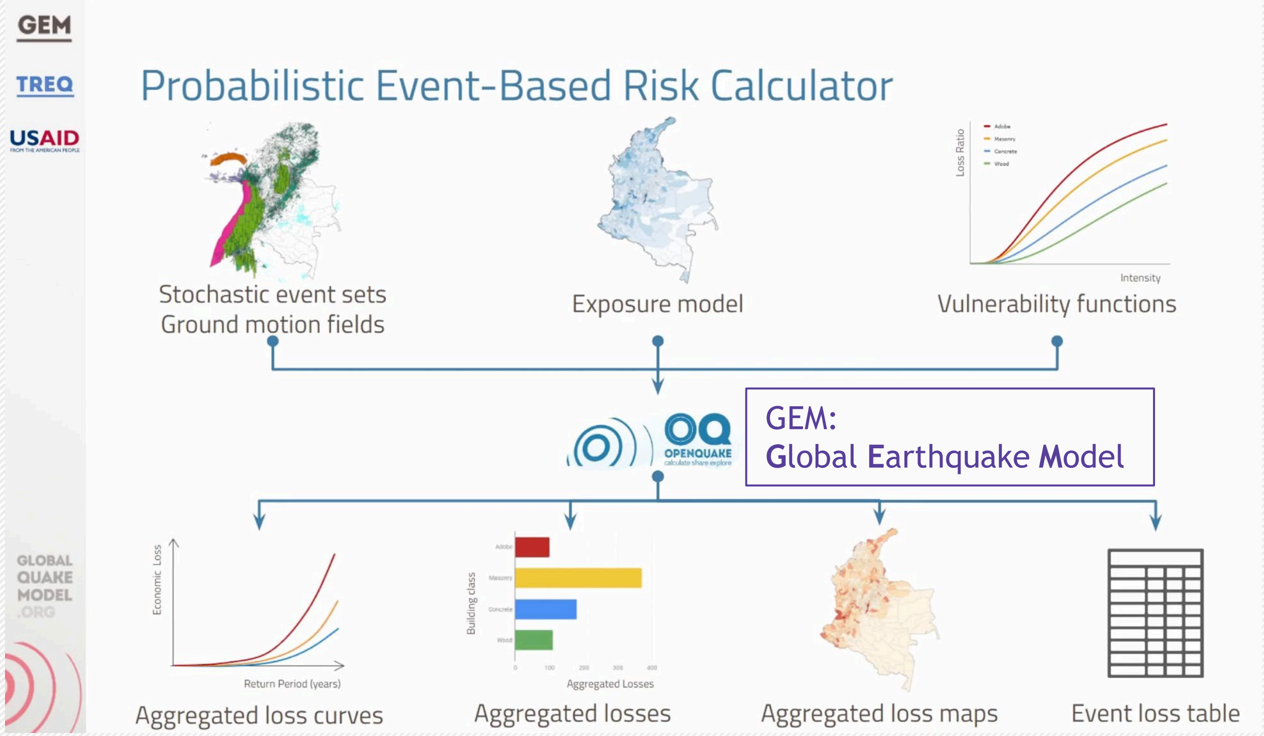
TSUNAMI RISK = TSUNAMI HAZARD X **VULNERABILITY** X EXPOSURE

Tsunami hazard =	The probability of a potentially damaging tsunami occurring at a site within a given period of time.
Vulnerability =	The likelihood of losses (financial and casualty) given a tsunami of a particular intensity.
Exposure =	Quantification of the number of people and buildings at risk.

VULNERABILITY = **FRAGILITY** X LOSS MODEL

Fragility =	The probability of building damage given a tsunami of a particular intensity.
Loss Model =	Probable losses (financial and casualty) for a given level of building damage.

Figure courtesy of: Charvet Iet al. (2017) 10.3389/fbuil.2017.00036



Aggregation dilutes spatial relevance

Figure courtesy of GEM OpenQuake: https://docs.openquake.org/vulnerability/vulnerability/vulnerability_dam2loss_computing_vul.html

Adaptability and uncertainty

- Why are TFF **not applicable** to other areas?
  - Demand parameter → result of inundation model parameters
  - Different areas → different model parameters
  - Different areas → different structural response

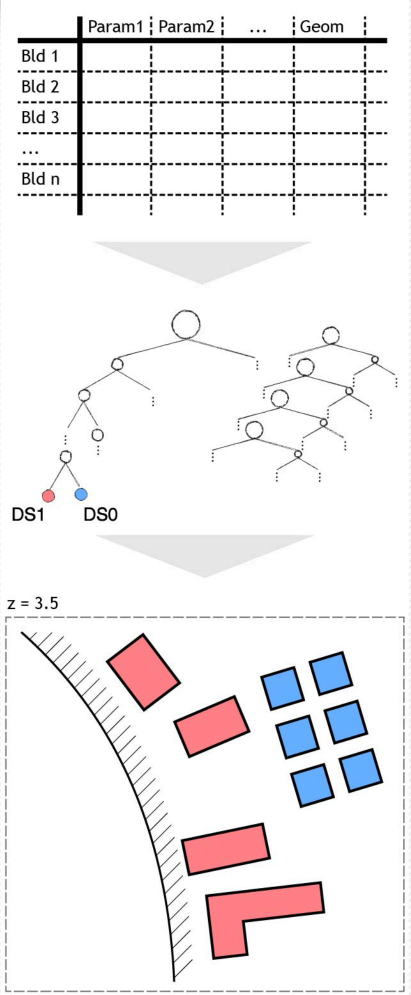
- **Solutions:**
  - Account for input uncertainty around model parameters and structural response
  - Add parametric proxies for influencing factors
    [bld material, bld density, coastal distance, elevation, etc…]

Experiments

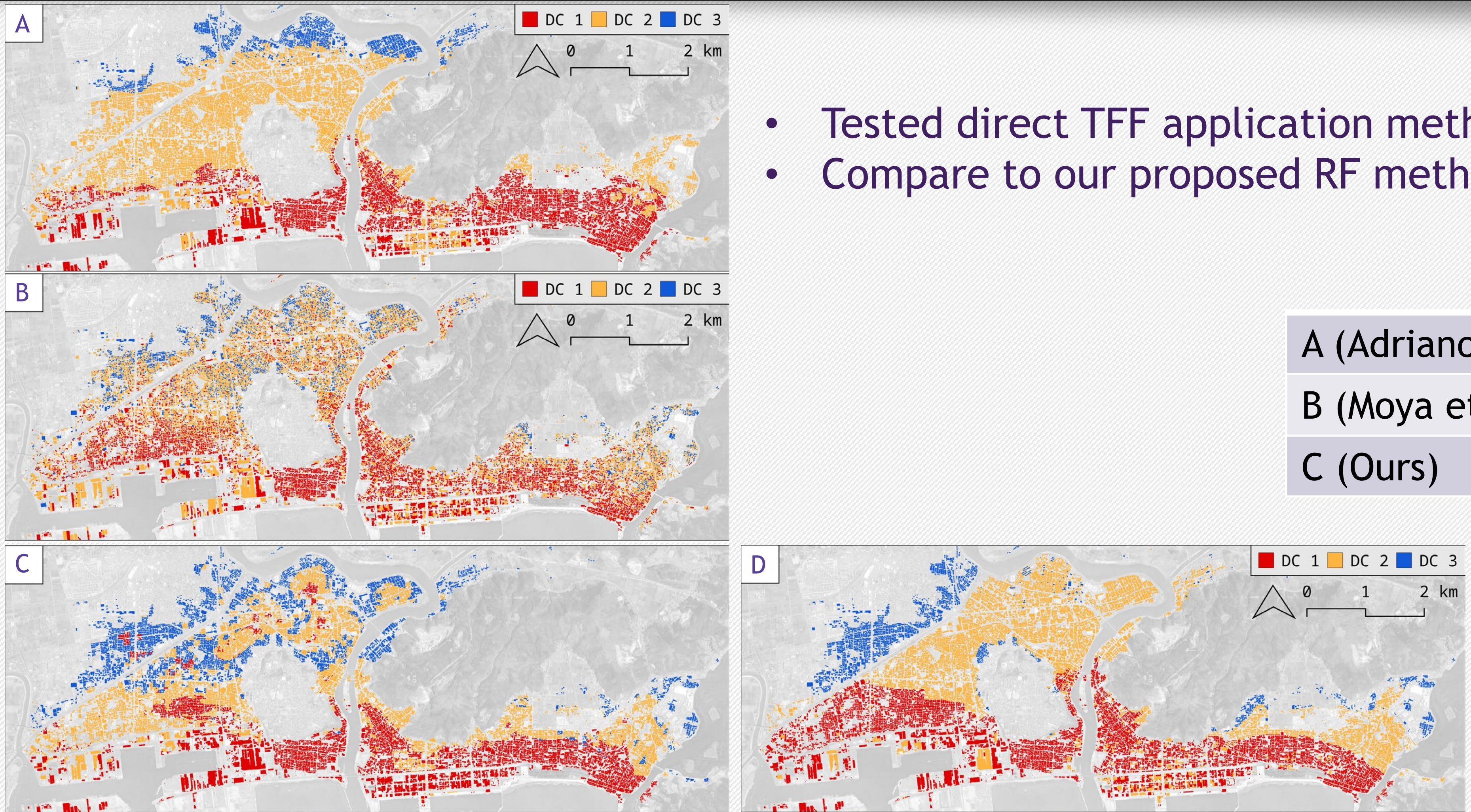
7

Random forests for fragility estimates

Physical demand parameters (intensity, structural, environmental)	→ Control for effect of latent processes
	→ Directly relate physical parameters to building damage
Machine learning classification	→ Learn disaggregated damage estimation
	→ Direct spatial output



Experimental results



- Tested direct TFF application methods (slide 7)
- Compare to our proposed RF method

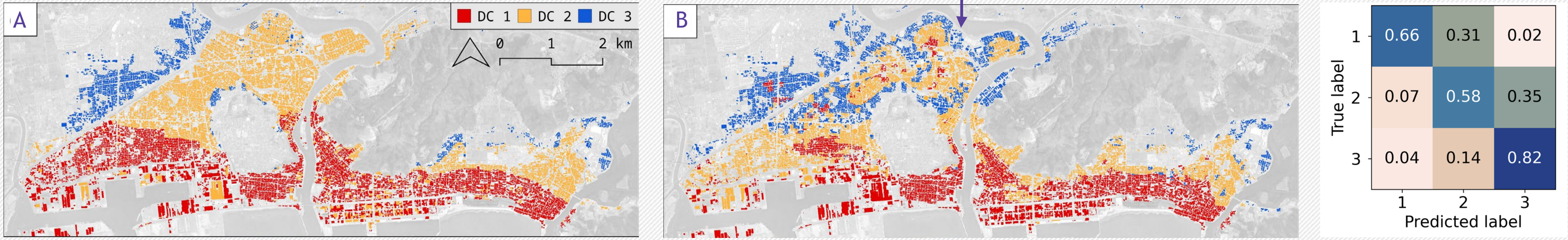
	Average F_1-score
A (Adriano et al.)	0.576
B (Moya et al.)	0.593
C (Ours)	**0.628**

A: Adriano et al. Method
B: Moya et al. Method
C: RF Method (**Ours**)

D: Ground truth

Discussion & limitations

- Results:
  - Damage learned from physical parameterization of tsunami and environment
  - Direct fragility estimates for individual buildings
- Limitations:
  - Performance scales with number of classes (more classes → lower performance)
  - Does not account for inherent class ordering
  - Learns unexpected spatial response



Probabilistic approach – overview

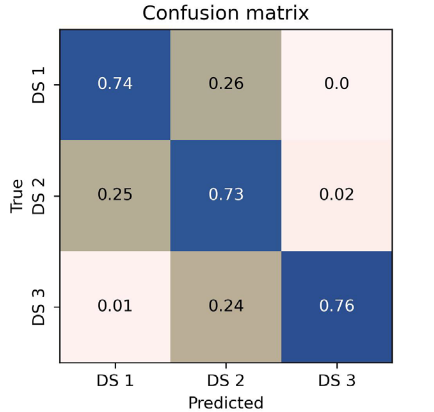
Bayesian decision making toolbox:

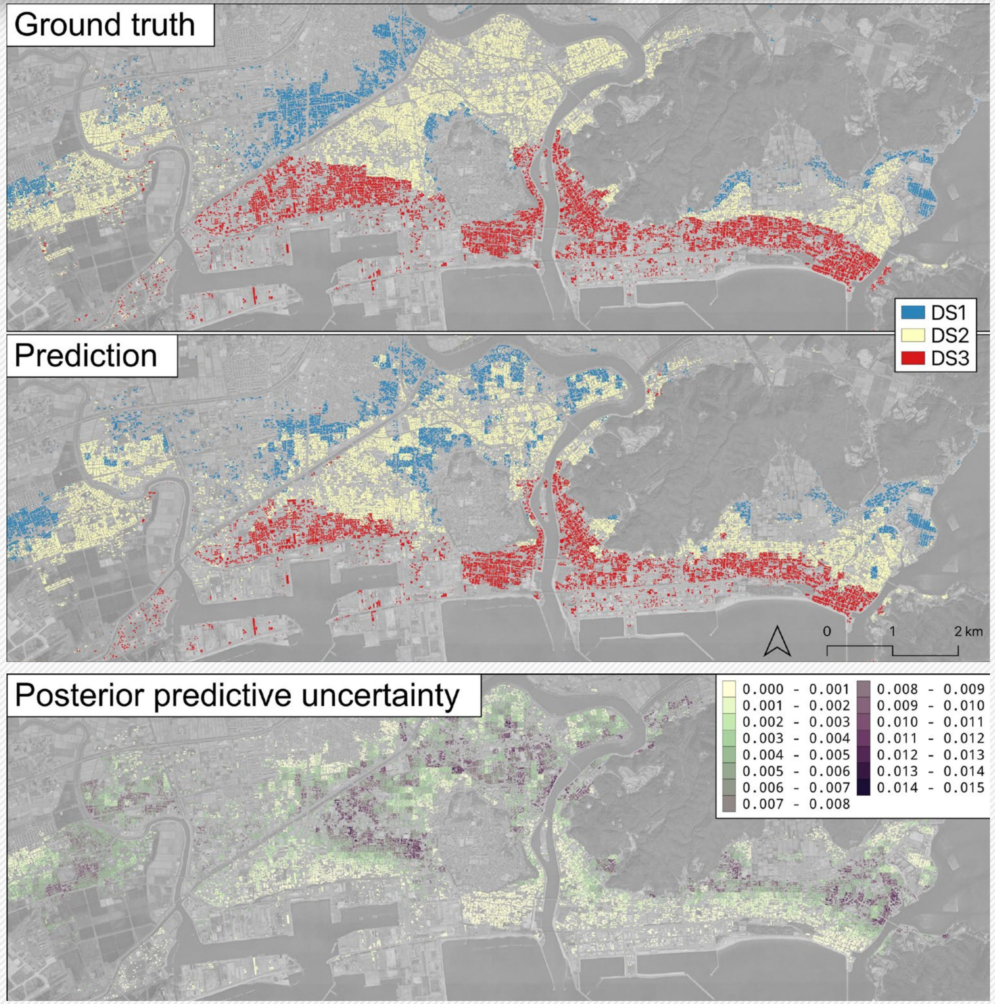
1. Allows us to include more features (than TFF)
2. provides optimization routines, e.g. HMC, VI, etc…
3. Places distribution over parameters → input uncertainty
4. Propagates uncertainty to the posterior distribution → output uncertainty

HMC: Hamiltonian Monte Carlo, VI: Variational Inference

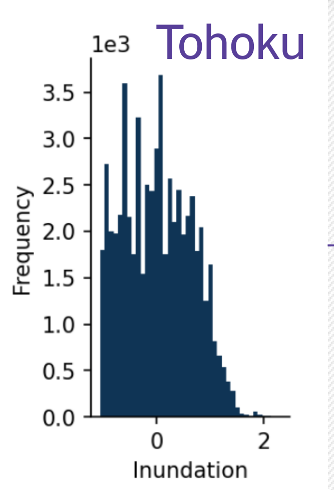
Probabilistic approach – results

- Generally improved results
- Relative low inundation → Greater uncertainty(DS2)
- Hypothesis: earthquake effects are more relevant at lower inundation levels

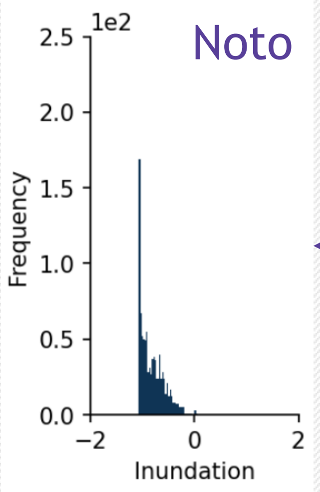


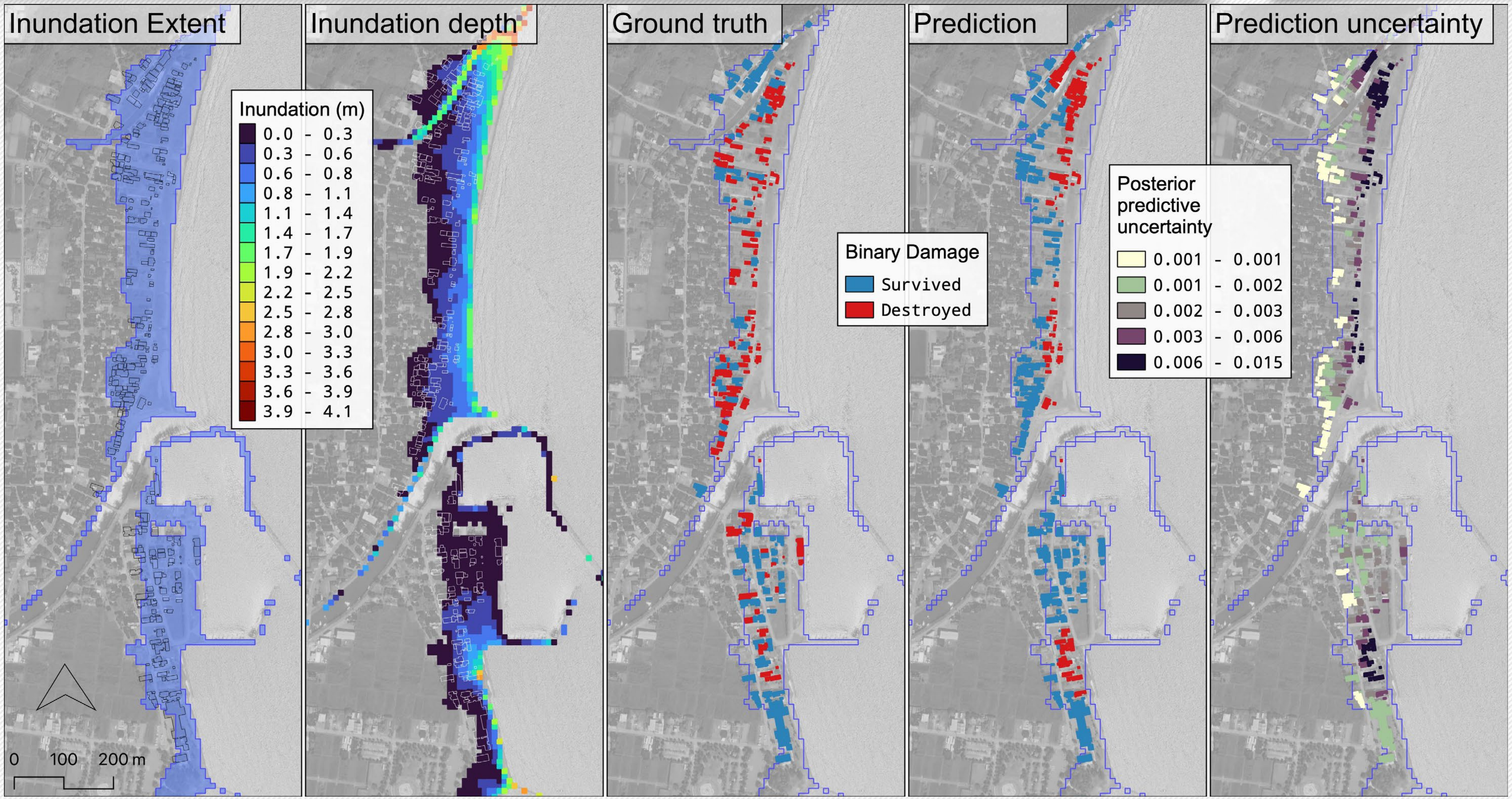


Discussion & Limitations – cont.



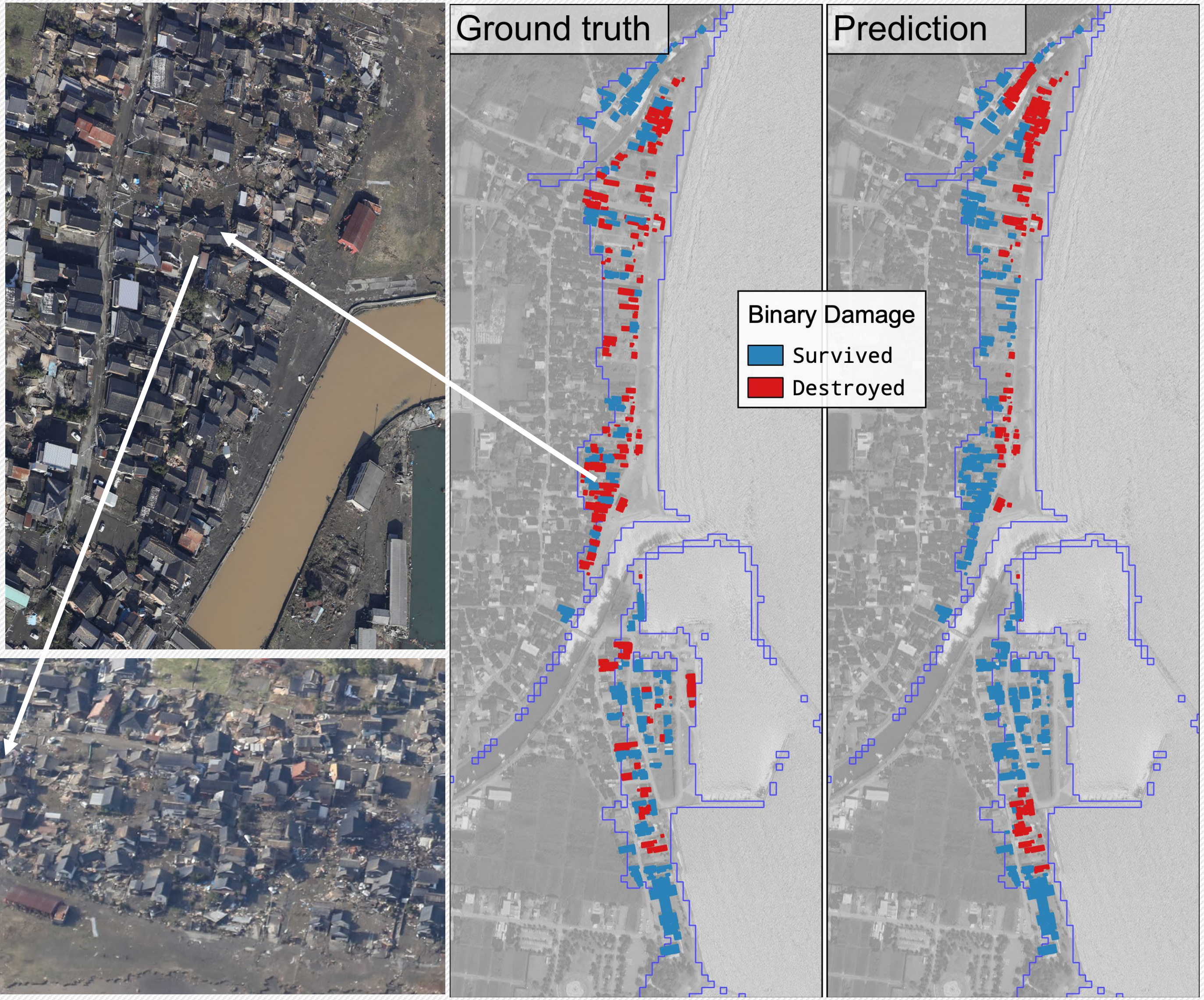
Very low inundation





Inland misclassification correlates with “**pancake collapse**”

In areas of low inundation height, the model has high confidence but has no notion of EQ effects.



Discussion & Limitations

Advantages over previous methods:

- Increased performance
- Spatially consistent (learning better, more interesting trends)
- Appears to generalize **in-distribution**

Limitations:

- Out-of-distribution (Noto case) performance much lower on destroyed class:
  1. Hypothesis: significantly greater influence of EQ impacts
  2. Parameter definition require knowledge of domain (not naïve like random forest)

Takeaway message:

1. We developed a probabilistic method for building fragility estimation
2. Our method performs in-distribution (not necessarily in-domain)
3. Measuring the predictive uncertainty, allows:
    - Identify patterns that are not captured by the parameters (e.g. EQ impacts)
    - Inform decision makers about potential extra risk
4. Fits into the PTHA + PTRA framework → disaggregated estimates