Probabilistic infrastructure damage, debris forecasting, and community resilience analysis for CSZ earthquake and tsunami applied to Seaside, Oregon

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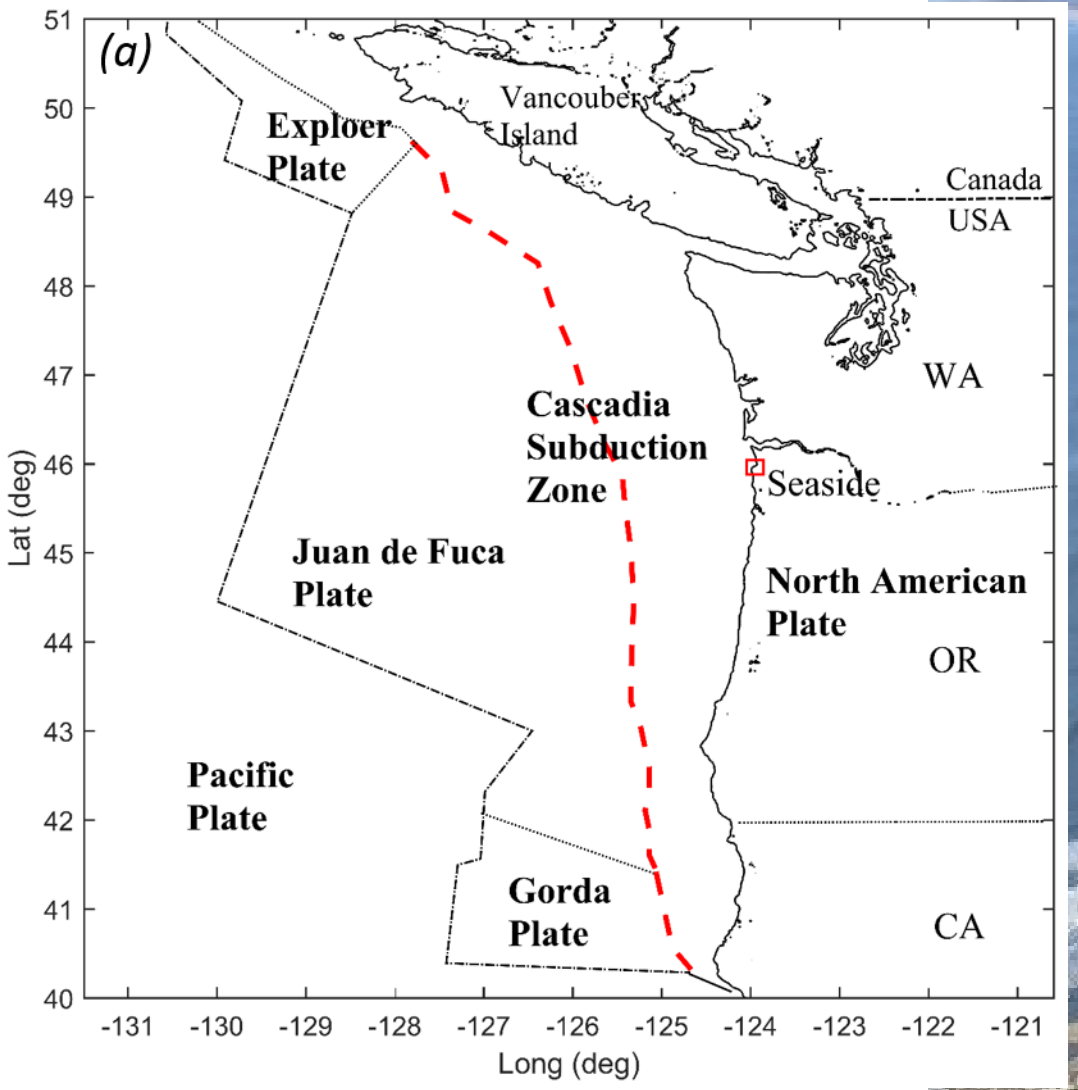
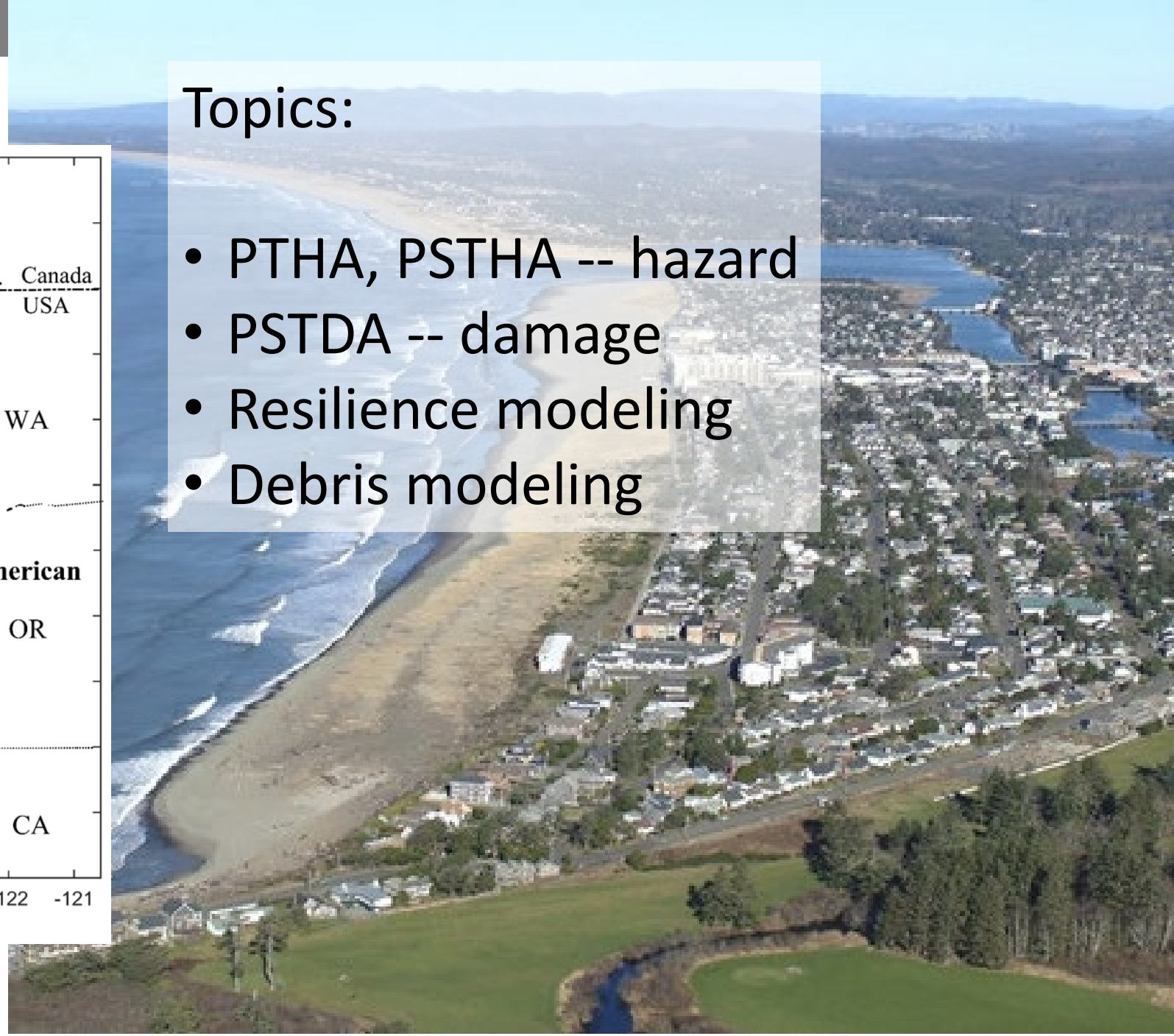
Andre Barbosa, John van de Lindt (CSU)

Center for Risk-Based Community Resilience Planning
A NIST-funded Center of Excellence

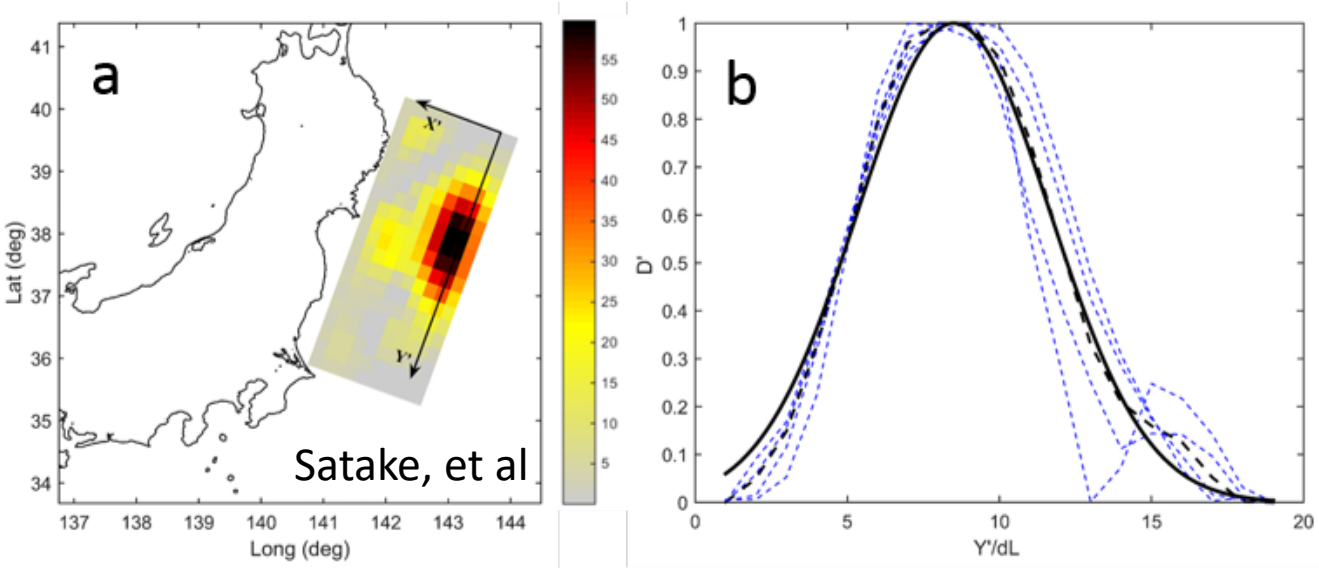




Topics:

- PTHA, PSTHA -- hazard
- PSTDA -- damage
- Resilience modeling
- Debris modeling

1) Inversion model results



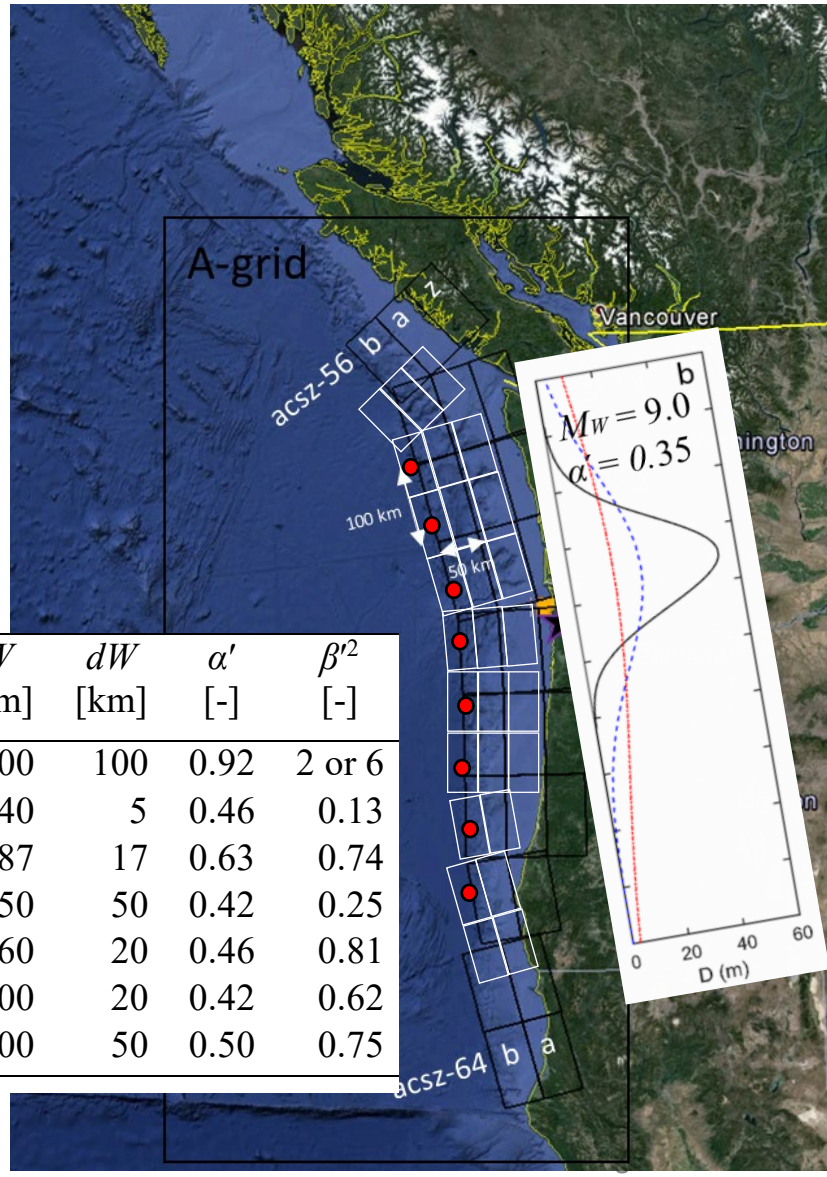
2) New tsunami slip model using a Gaussian distribution

$$D' = f\left(Y'/dL \mid \alpha, \beta\right) = \frac{1}{\beta\sqrt{2\pi}} \exp\left(\frac{-\left(Y'/dL - \alpha\right)^2}{2\beta^2}\right)$$

α (Epicenter) , β (Slip shape)

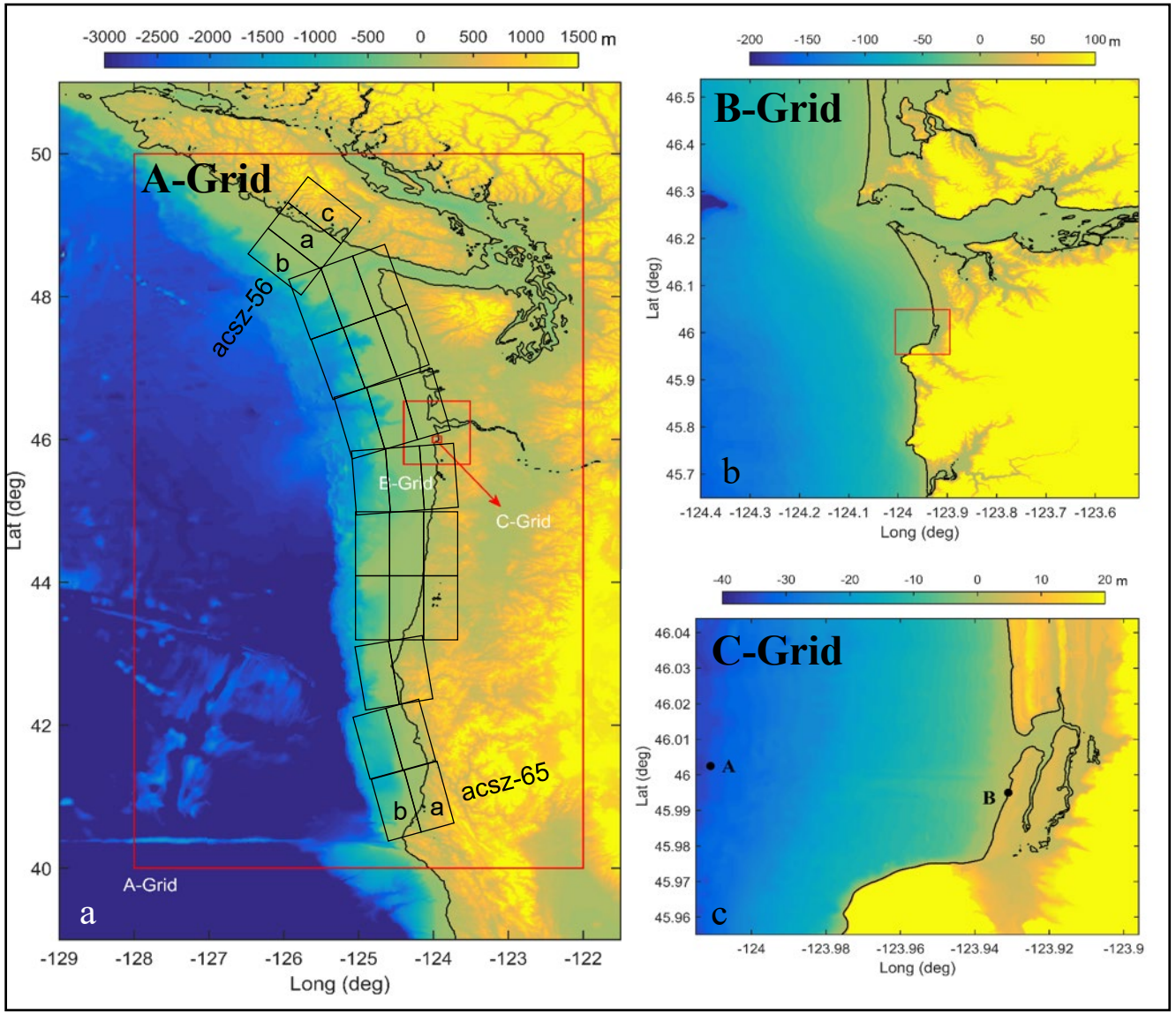
Name	M_W [-]	D_P [m]	L [km]	dL [km]	W [km]	dW [km]	α' [-]	β'^2 [-]
2004 Indian Ocean	9.3	30	1400	100	200	100	0.92	2 or 6
2007 Kuril	8.1	20	200	8	40	5	0.46	0.13
2010 Chile, v1	8.8	13	600	50	187	17	0.63	0.74
2010 Chile, v2	8.8	22	600	50	150	50	0.42	0.25
2011 Tohoku, v1	9.0	32	600	25	260	20	0.46	0.81
2011 Tohoku, v2	9.1	59	500	25	200	20	0.42	0.62
2011 Tohoku, v3	9.0	69	550	50	200	50	0.50	0.75

4) Applying as input sub-faults in model



Park, H. and Cox, D.T. (2016) "Probabilistic Assessment of Near-field Tsunami Hazards: Inundation Depth, Velocity, Momentum Flux, Arrival Time, and Duration Applied to Seaside, Oregon," *Coastal Engineering*, 117, 79-96

Nested models for tsunami generation, propagation, inundation



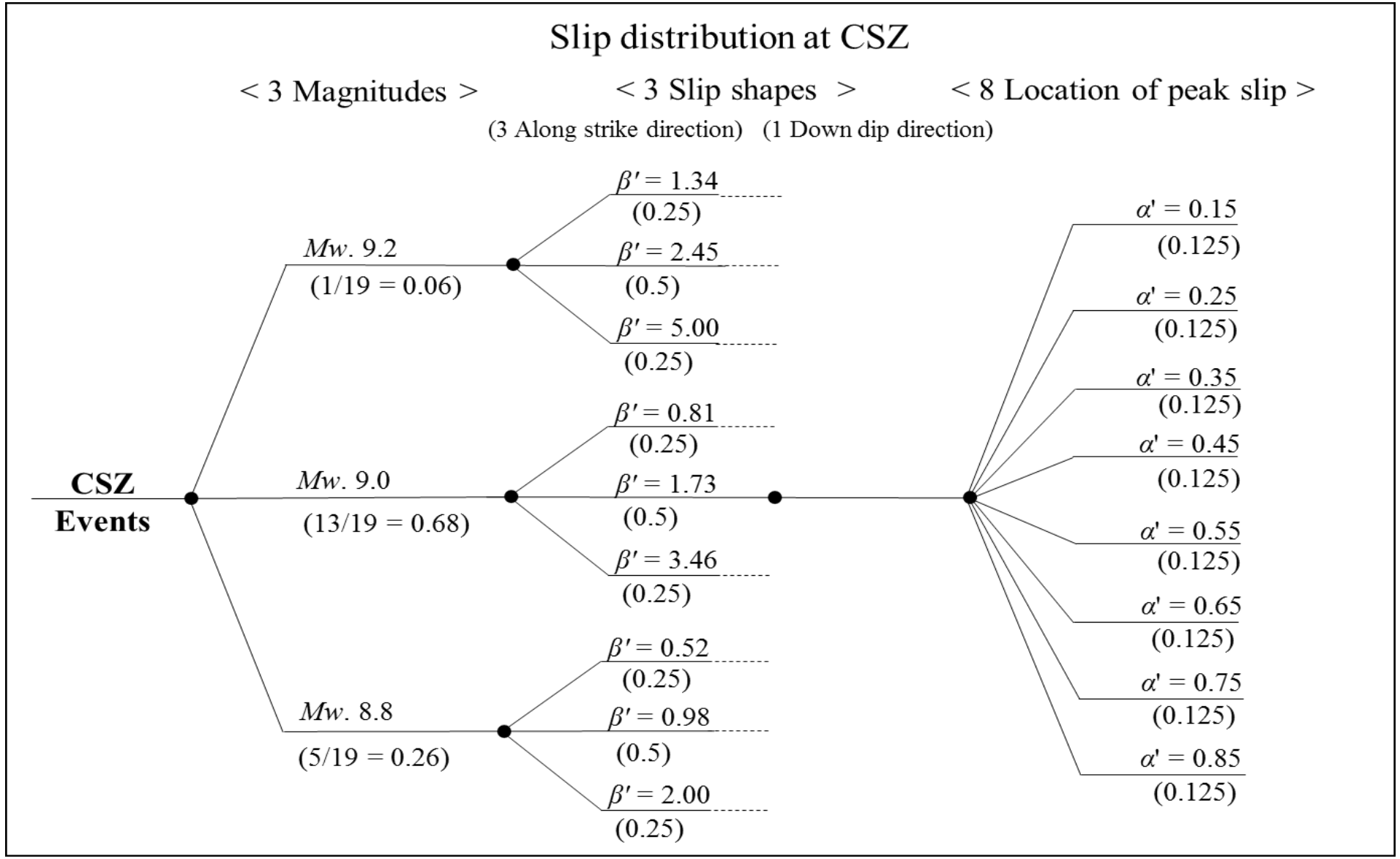
- ComMIT/MOST(NOAA) } A & B-Grid
- COULWAVE } Only C-Grid

Grid	Mesh number / size	Models
A-Grid	400 × 400 / 1 min	ComMIT
B-Grid	800 × 800 / 3 sec	ComMIT
C-Grid	416 × 390 / 24 m	COULWAVE

- Following default setup for each models
- Default friction, n = 0.03.

- Perhaps a bit too coarse. . .

Logic tree model

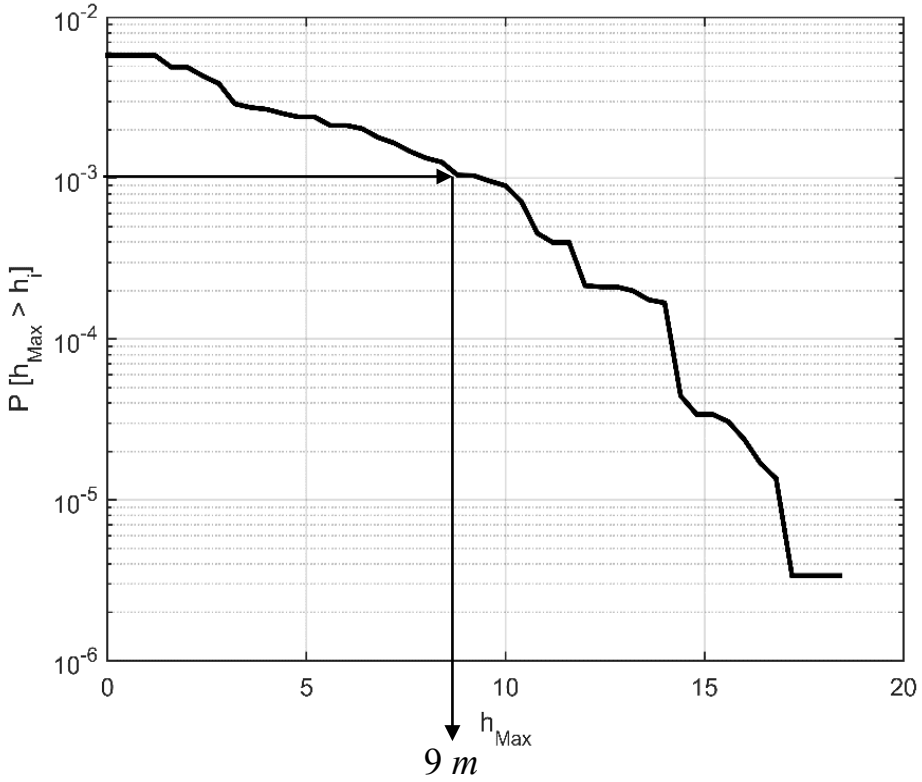


Calculating annual exceedance probability (AEP) of IMs

AEP = 0.001 ~ 1,000 yr

Poisson arrival process (Cornell, 1964) with average occurrence rate of *v*

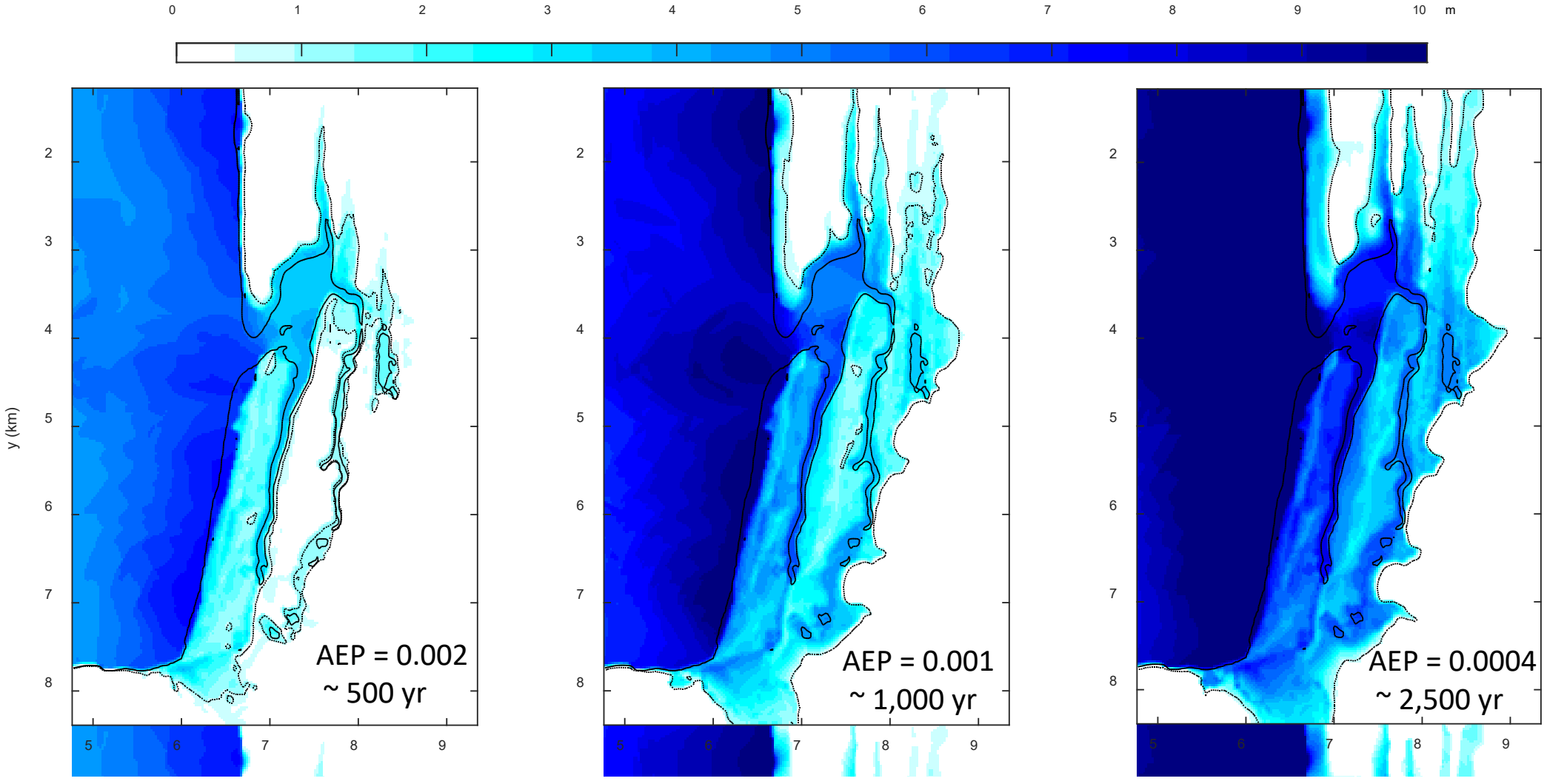
$$P\,[h_{Max} > h_i] = 1 - e^{-vt}$$



(4) Hazards map

Hazards map at Seaside, OR

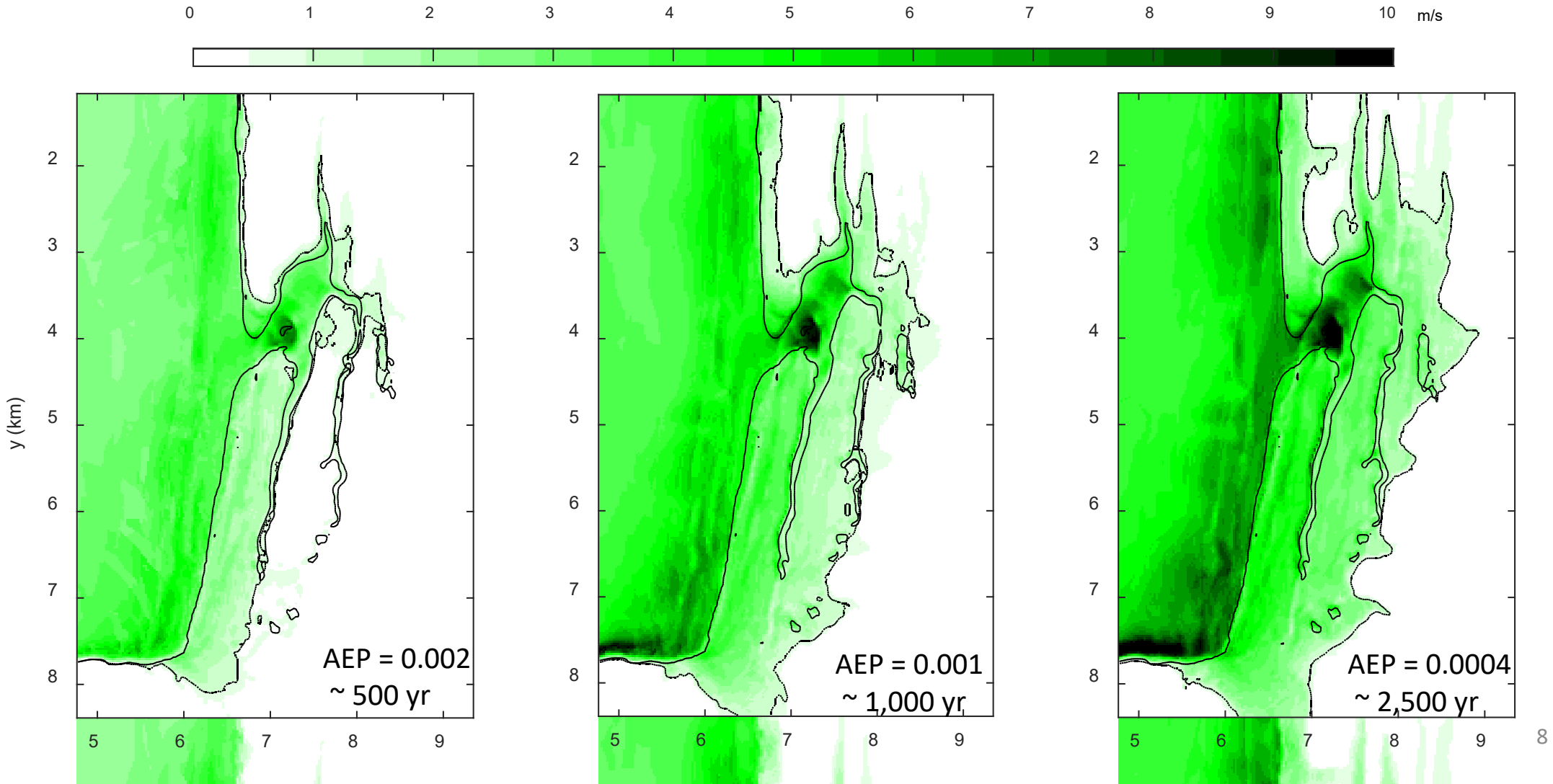
Example: Max. Flow depth (h_{max})



(4) Hazards map

Hazards map at Seaside, OR

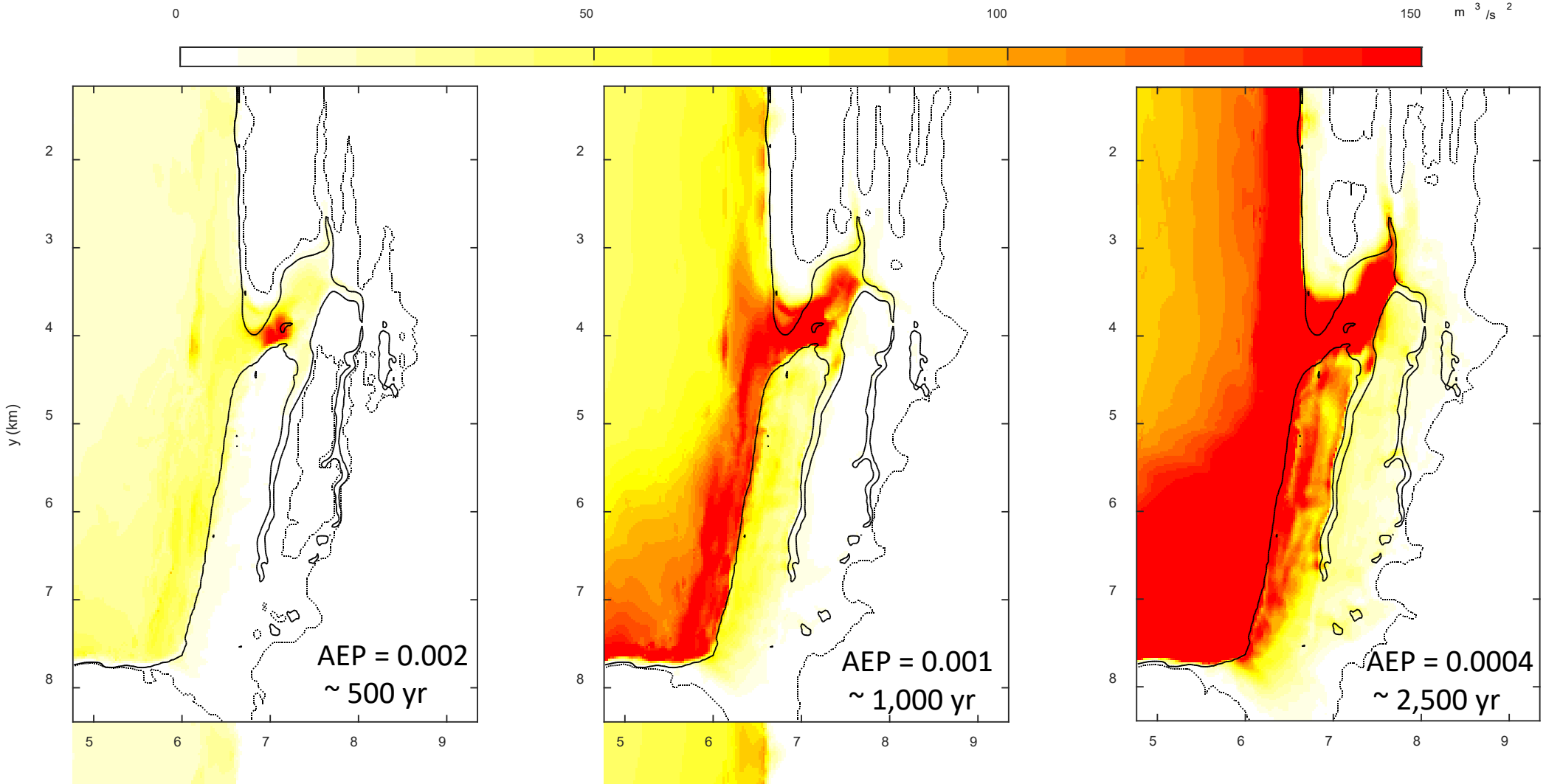
Example: Max. Velocity (V_{max})



(4) Hazards map

Hazards map at Seaside, OR

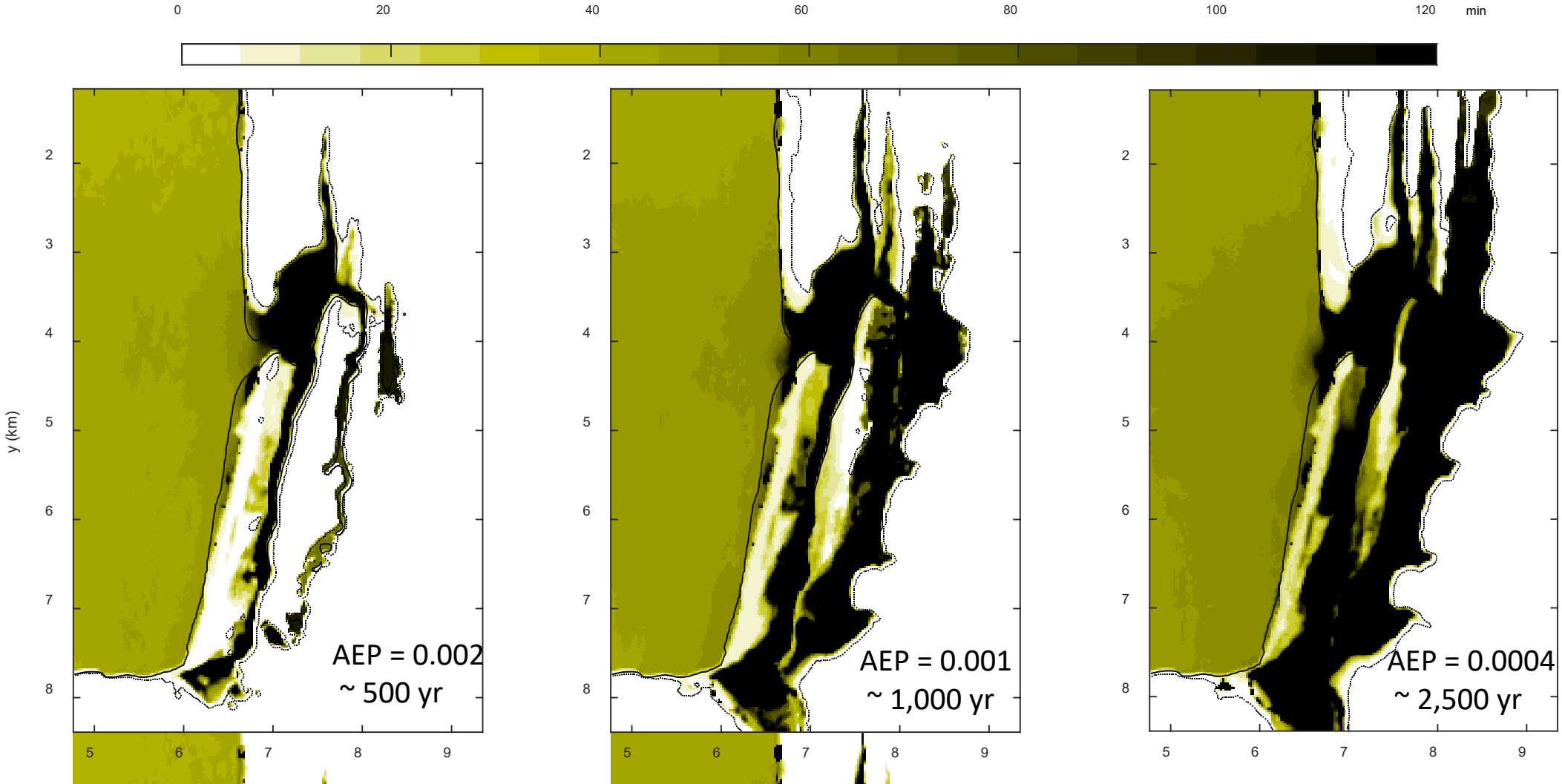
Example: Max. momentum flux (M_{max})

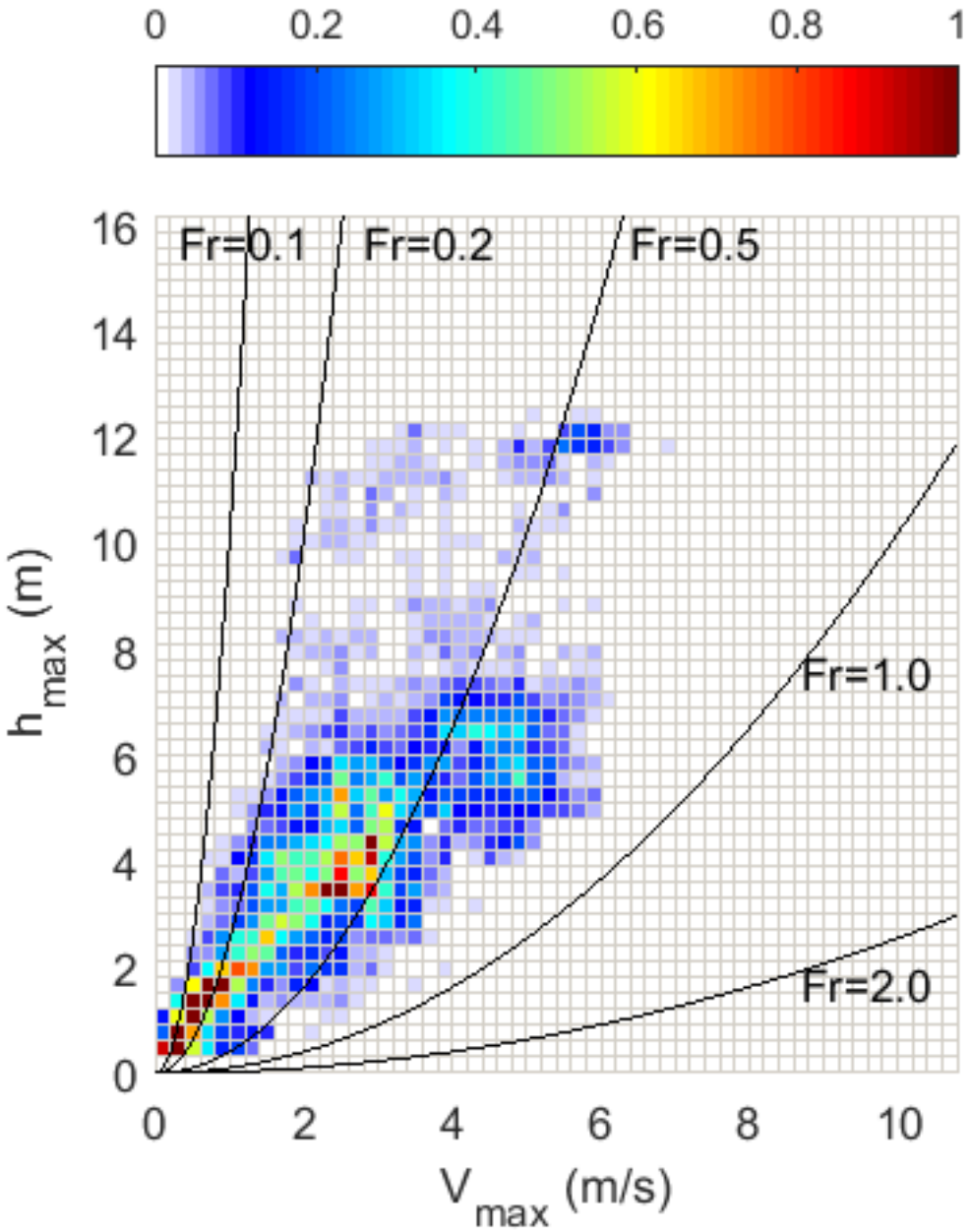


(4) Hazards map

Hazards map at Seaside, OR

Example: Duration time (T_D)

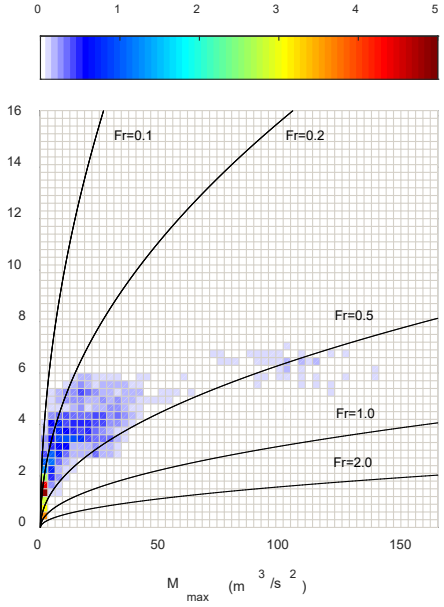




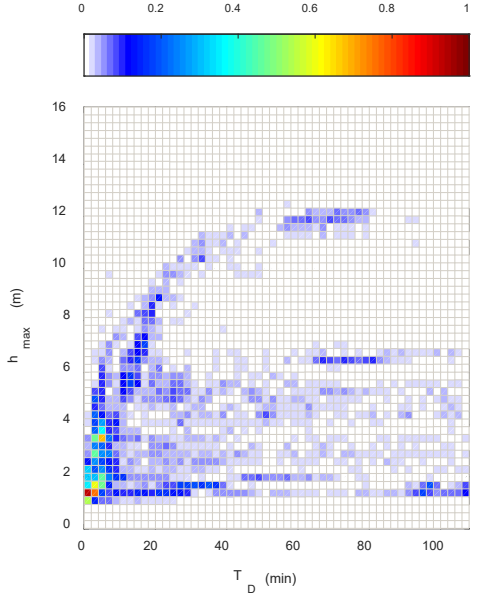
Joint Distribution of Tsunami Intensity Measures?

Correlation of maximum flood depth with other IMs

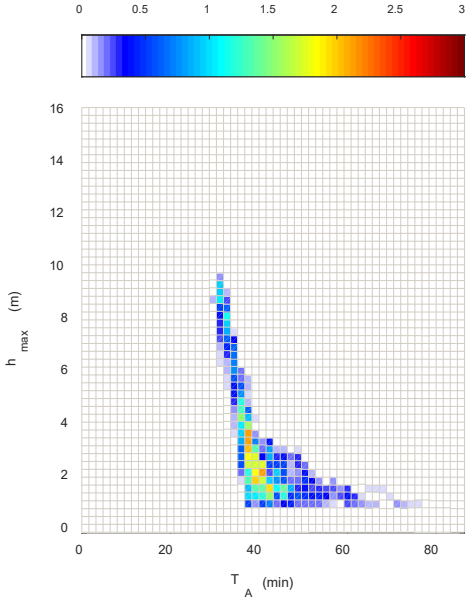
Momentum Flux



Flood Duration

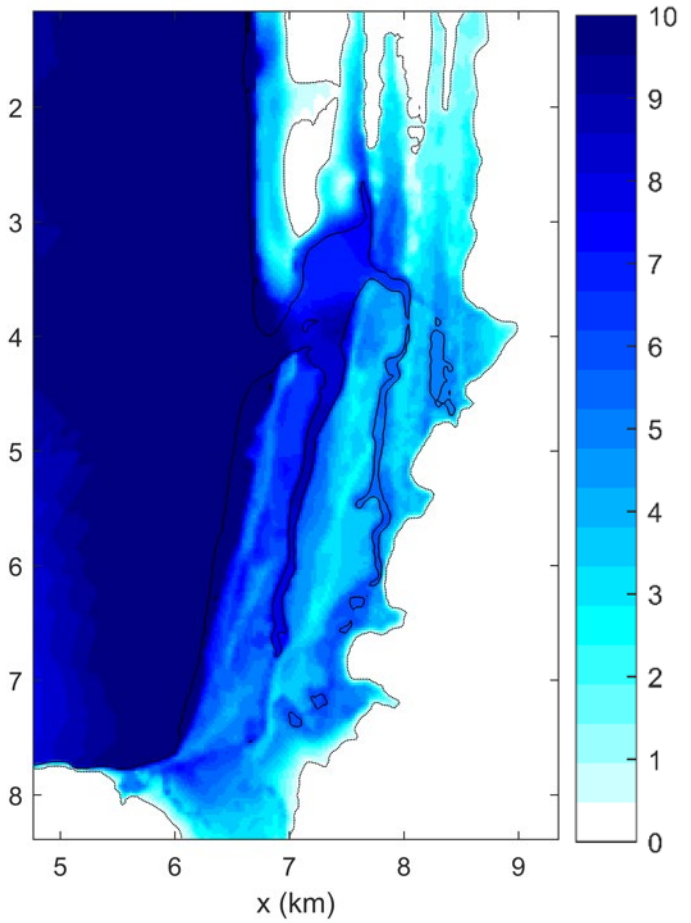


Arrival Time



PTHA Comparison for Seaside, Oregon

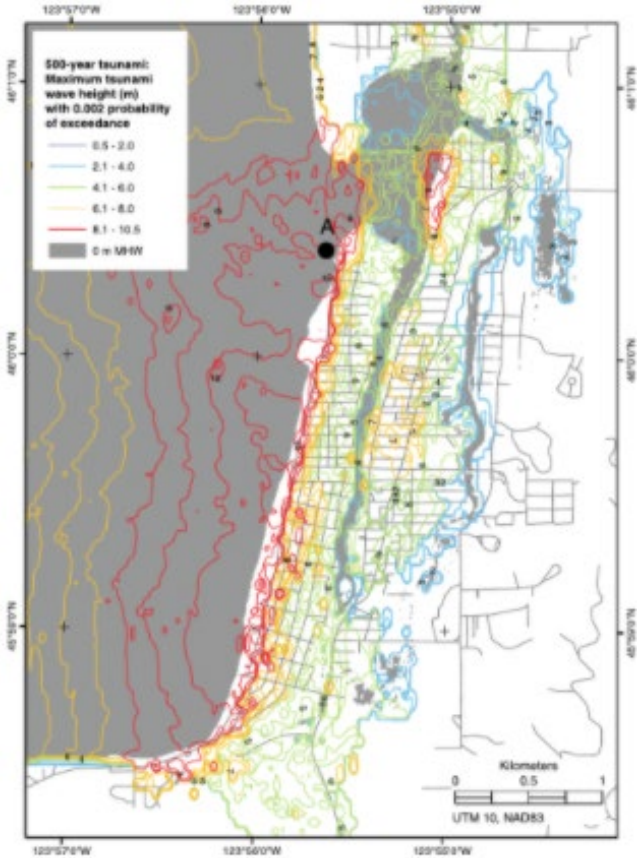
Park and Cox, 2500-yr



ASCE 7-16, 2500-yr

DOGAMI "M"

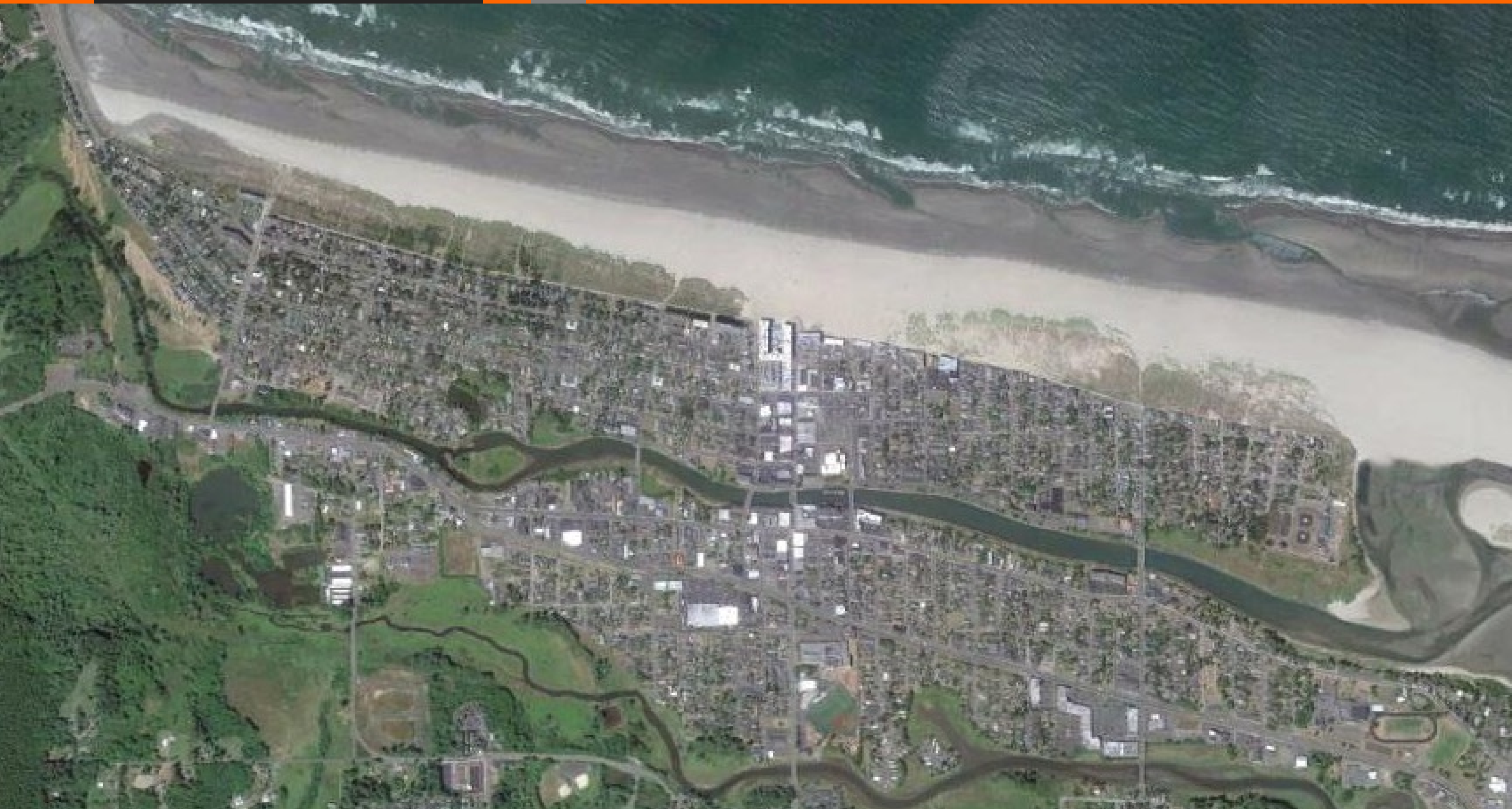
Gonzalez et al. 500-yr



❖ Much more work needed for PTHA, joint PSTHA, joint IMs, spatial correlations, . . .!!

Tsunami Damage Assessment

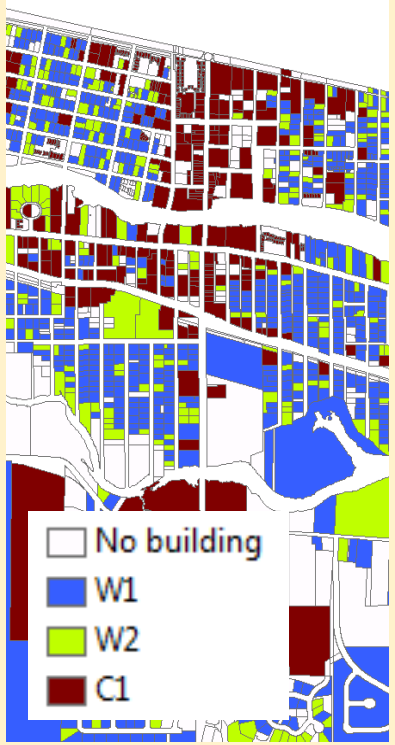
Description of the Built Environment



Seaside Building Layers

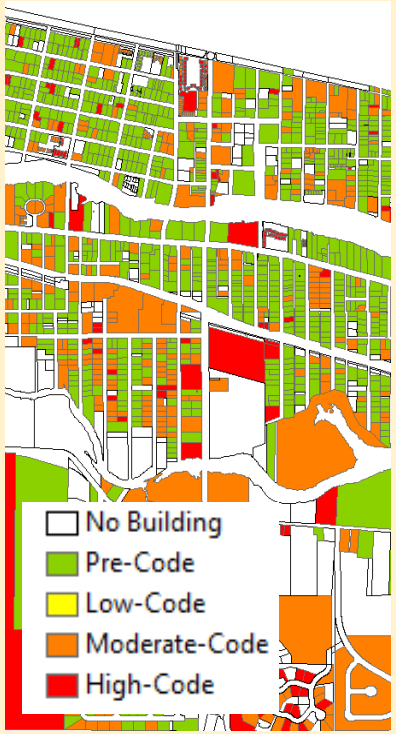
Parcel-level description of the buildings

Construction Materials



Number of Floors

Year built / Seismic codes

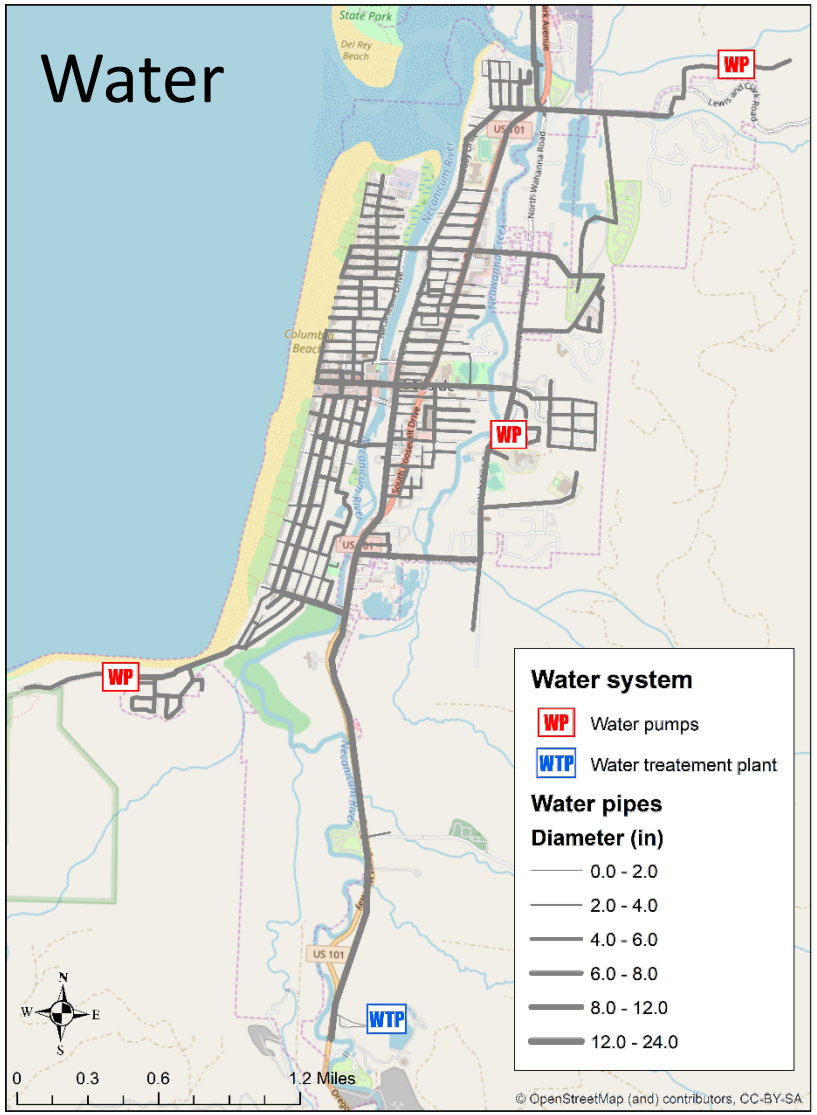


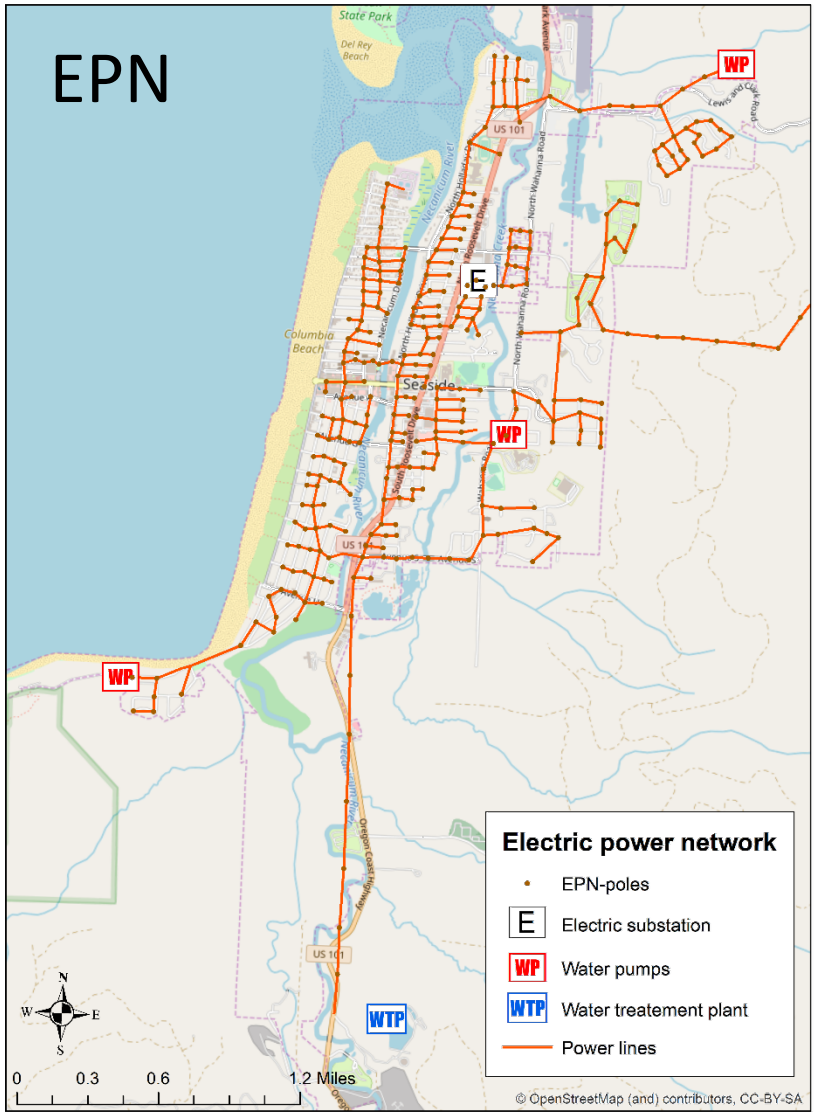
- Description of buildings by construction material, number of floors, date (seismic code)
- Building data inferred from tax data and verified by Google Street view and Rapid Visual Screening for some buildings

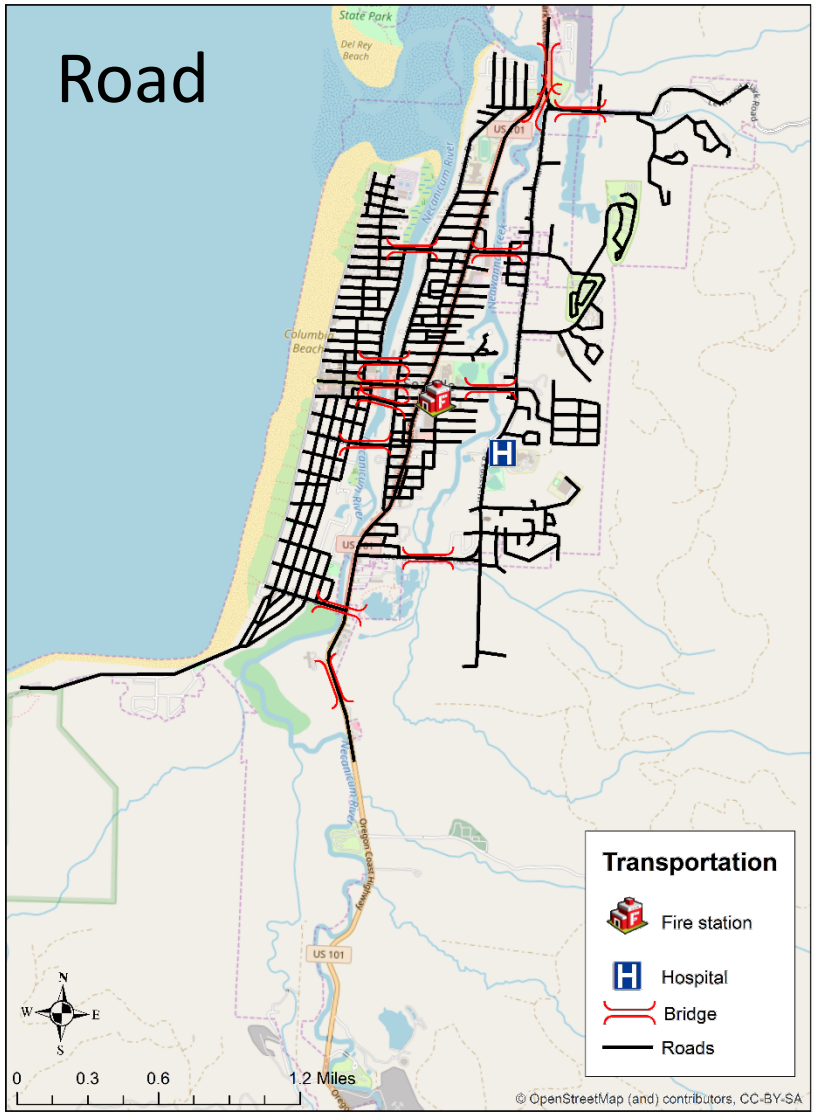
- Critical Facilities Identified
- Public schools relocated ($100M bond, 2016)

Park H, MS Alam, DT Cox, AR Barbosa, JW van de Lindt (2019) “Probabilistic seismic and tsunami damage analysis (PSTDA) for the Cascadia Subduction Zone applied to Seaside, Oregon,” *International Journal of Disaster Risk Reduction*, 35, 101076, doi.org/10.1016/j.ijdrr.2019.101076

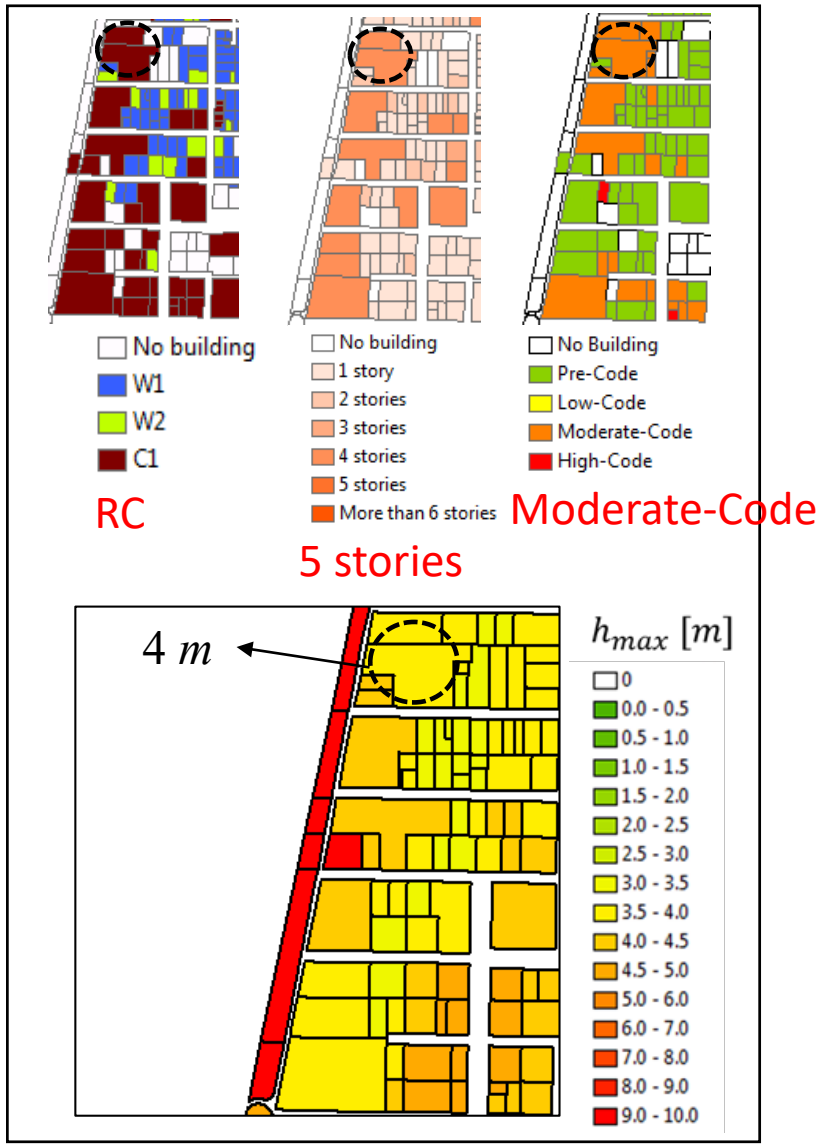
Critical (lifeline) infrastructure networks







Example of Building Damage Assessment (at AEP = 0.001)



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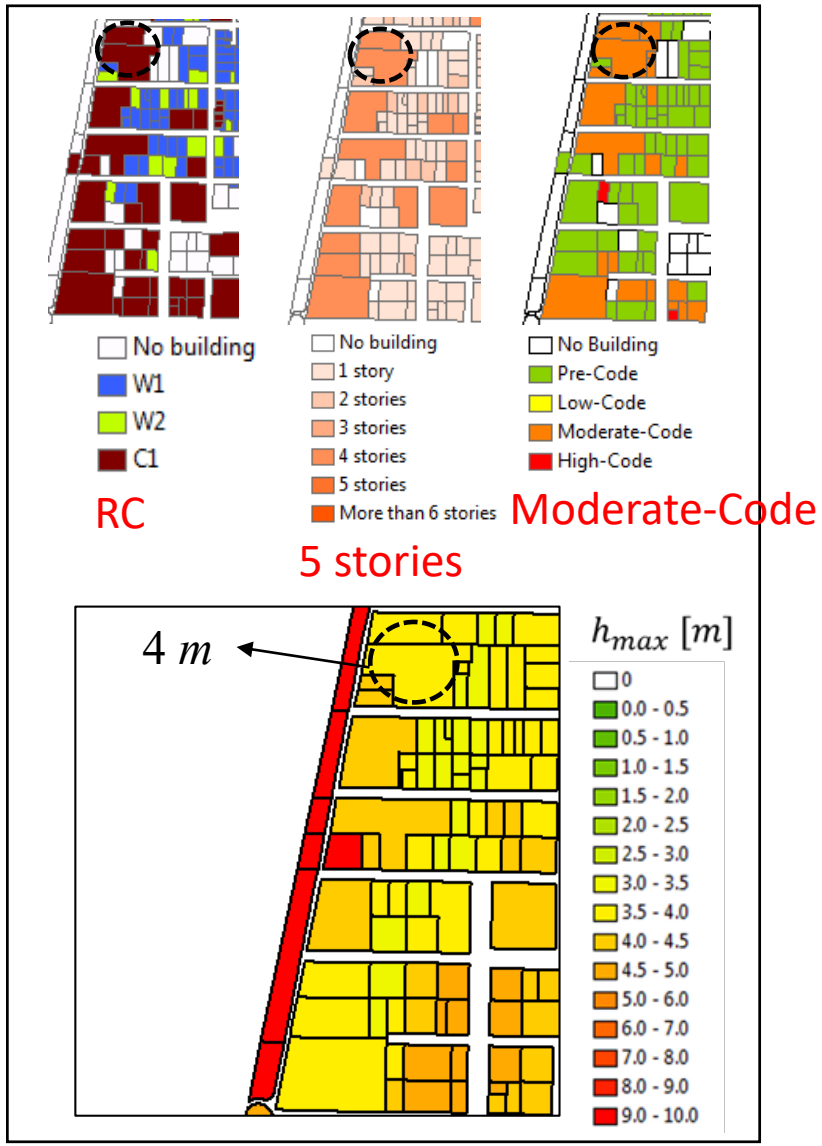
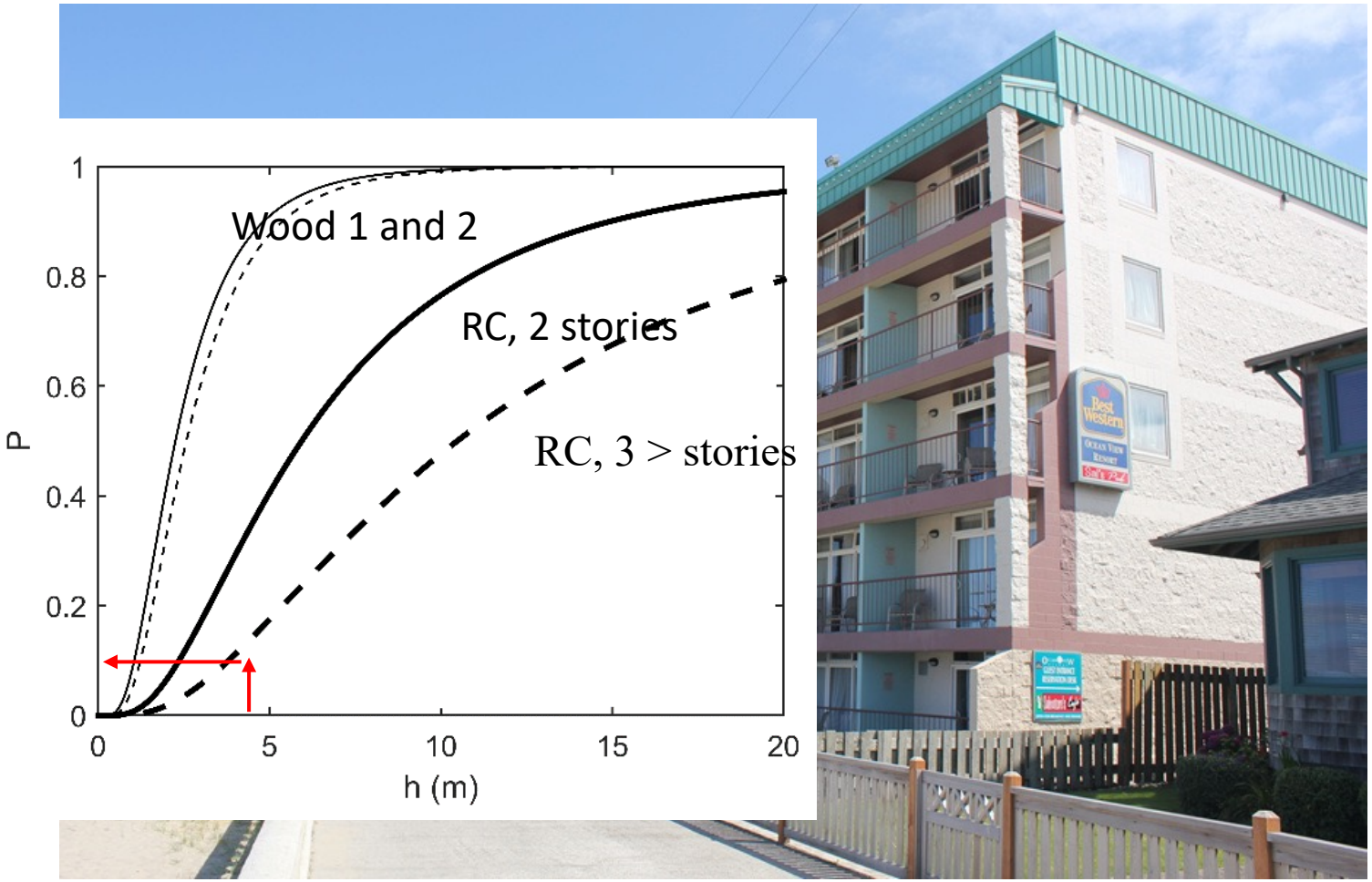
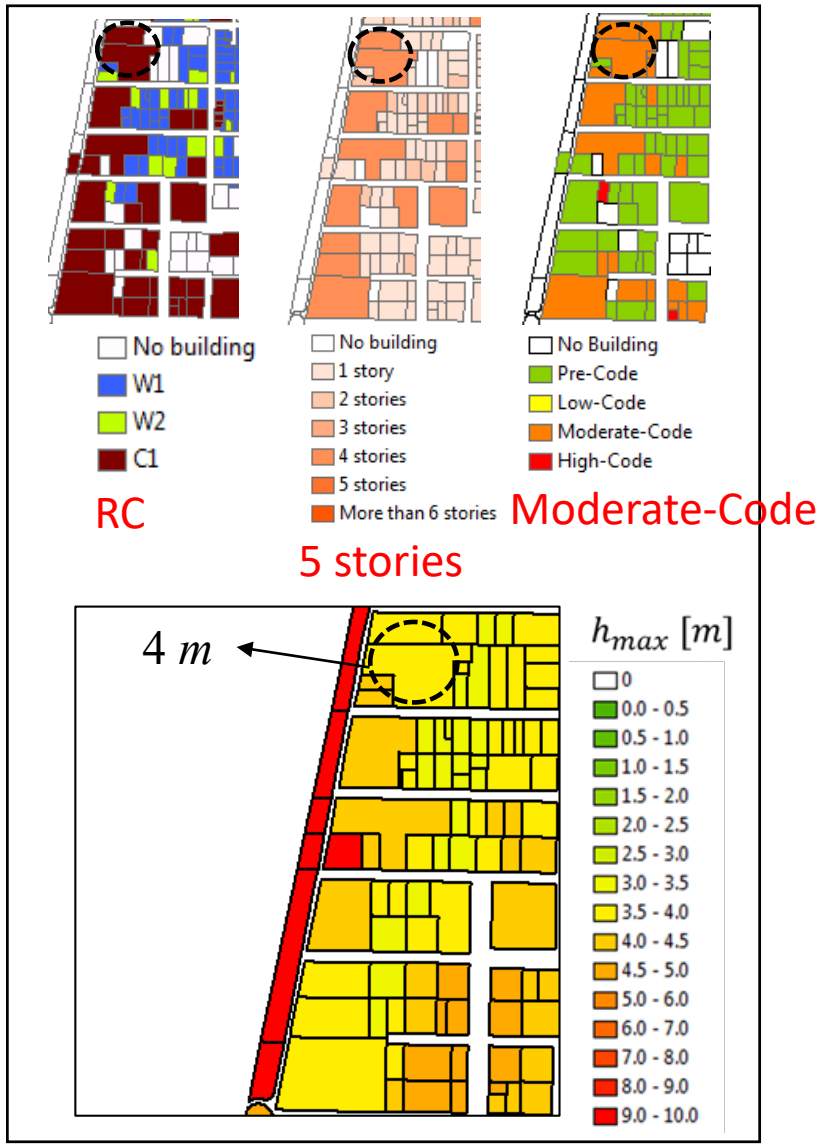
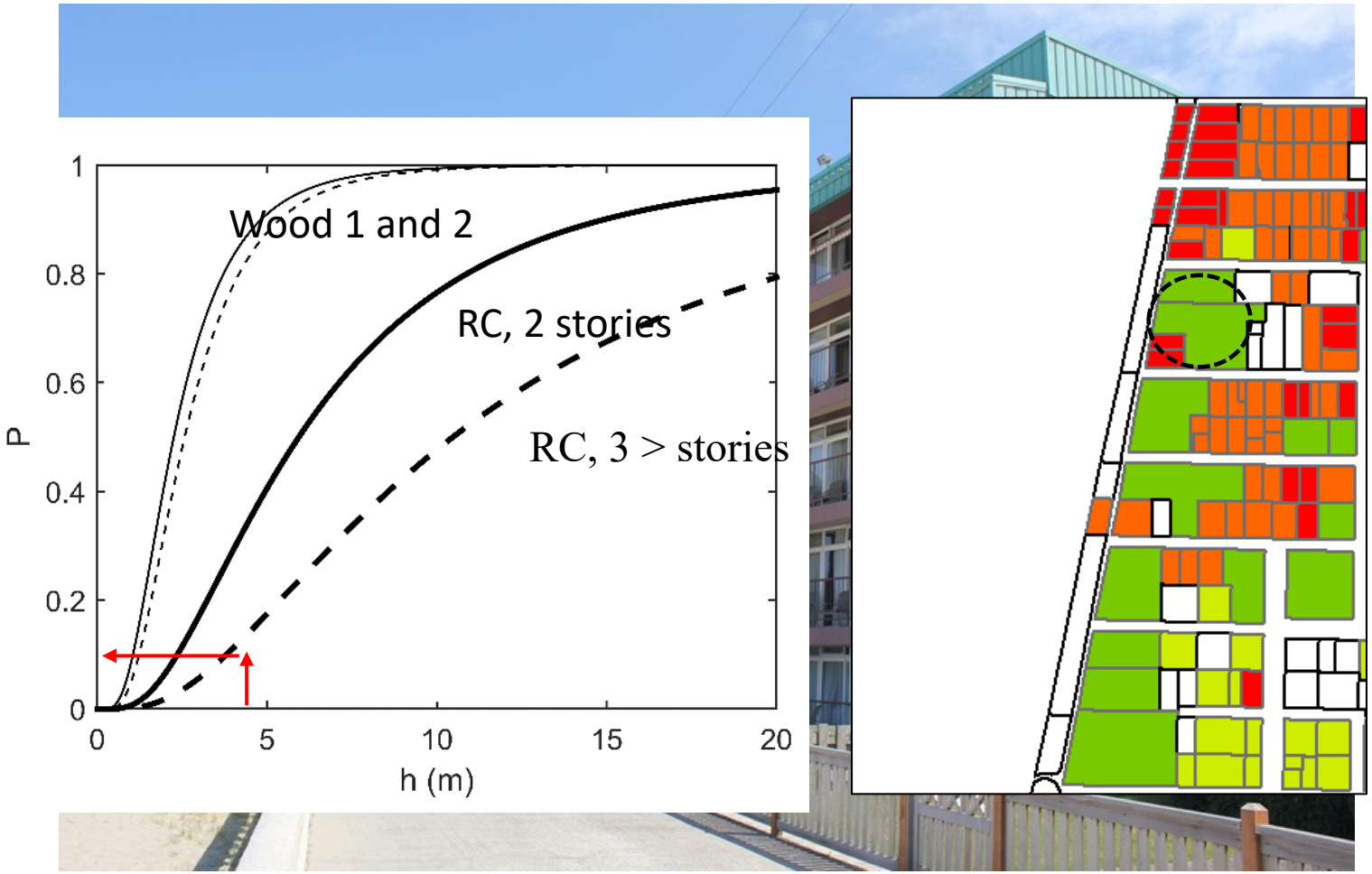




Fragility curves (Suppasri et al., 2013) for collapse damage

Example of Building Damage Assessment (at AEP = 0.001)





Fragility curves (Suppasri et al., 2013) for collapse damage

Example of Building Damage Assessment (at AEP = 0.001)

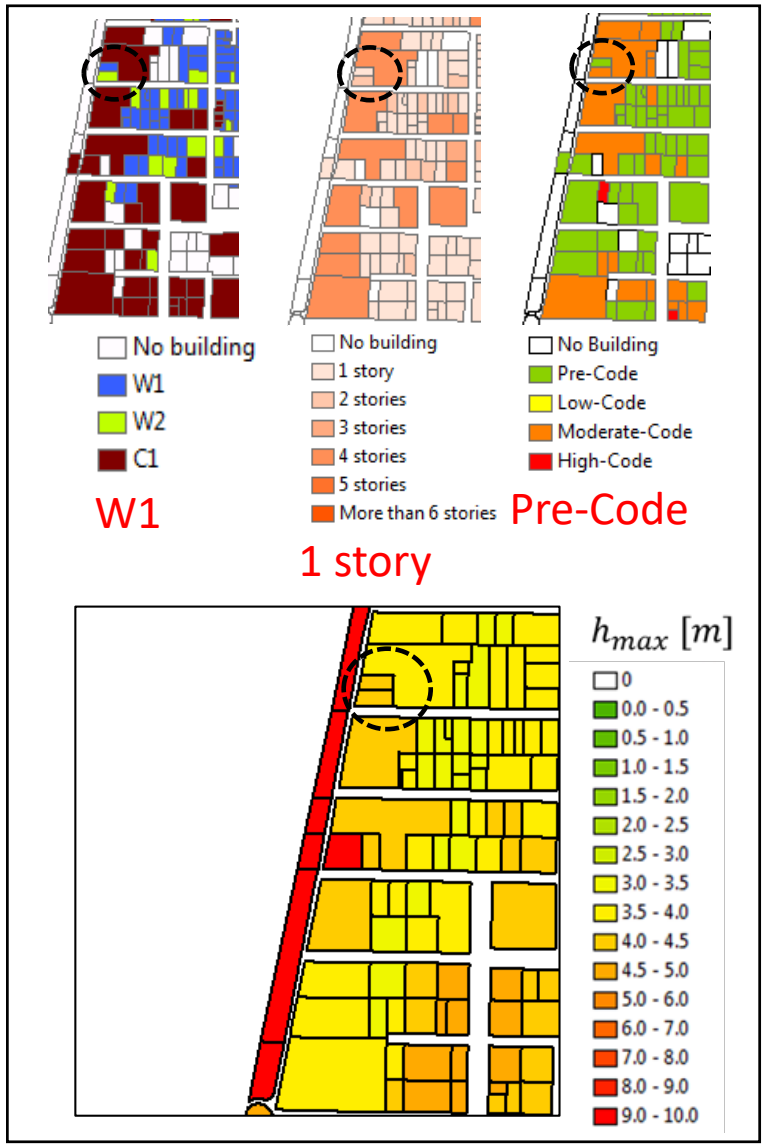
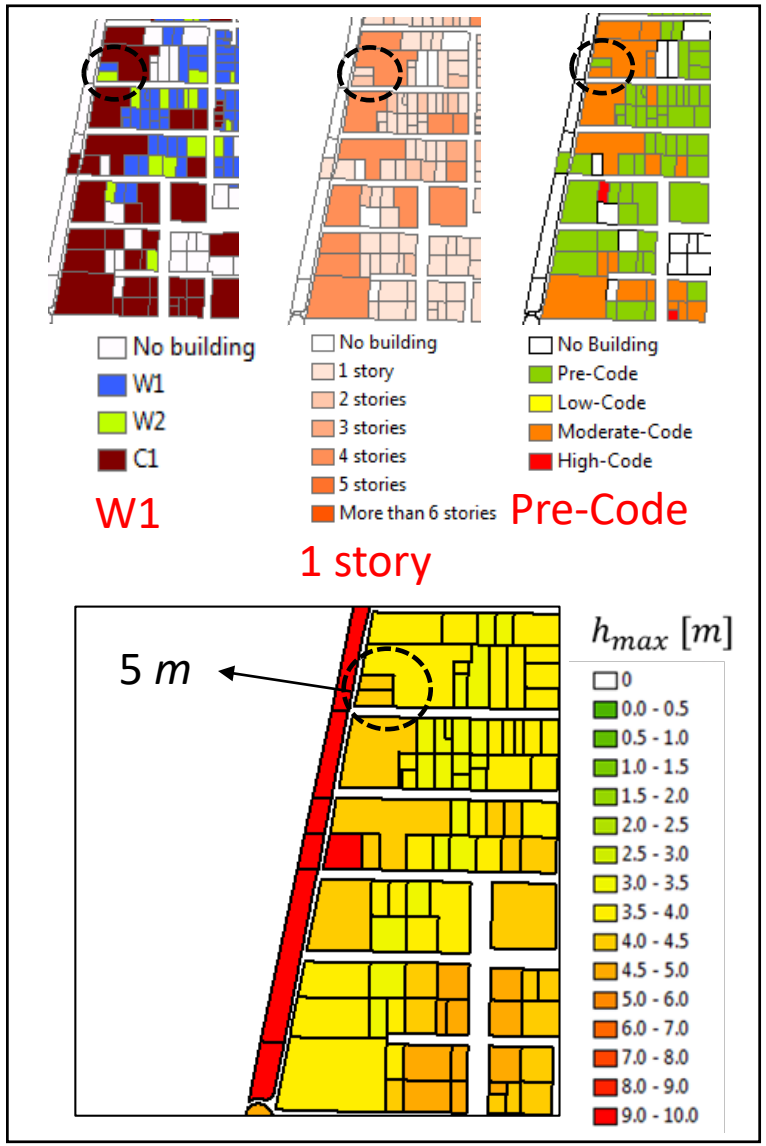
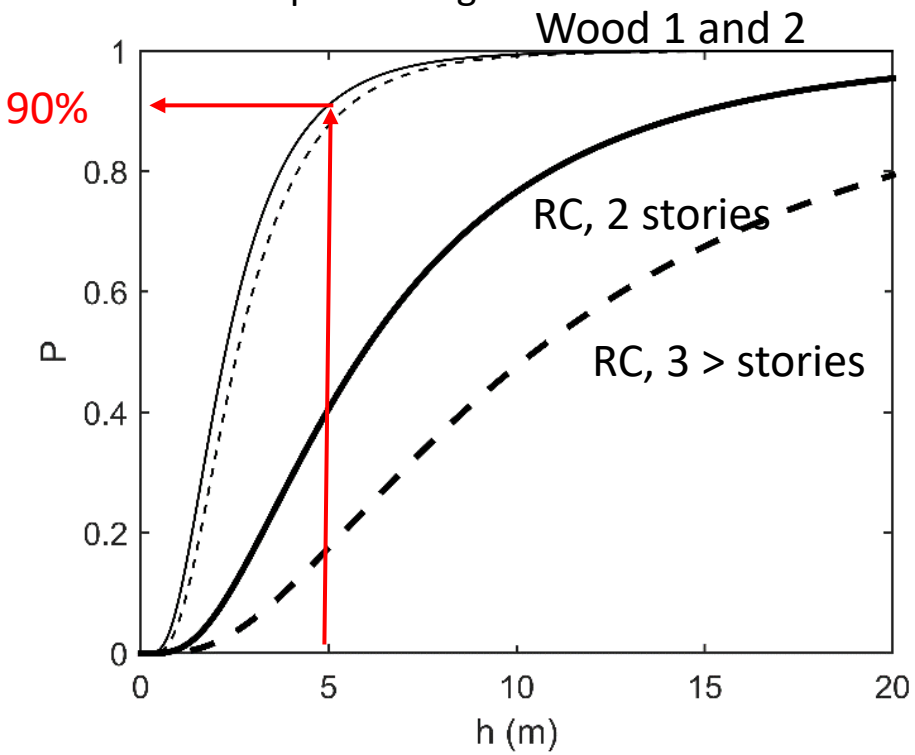


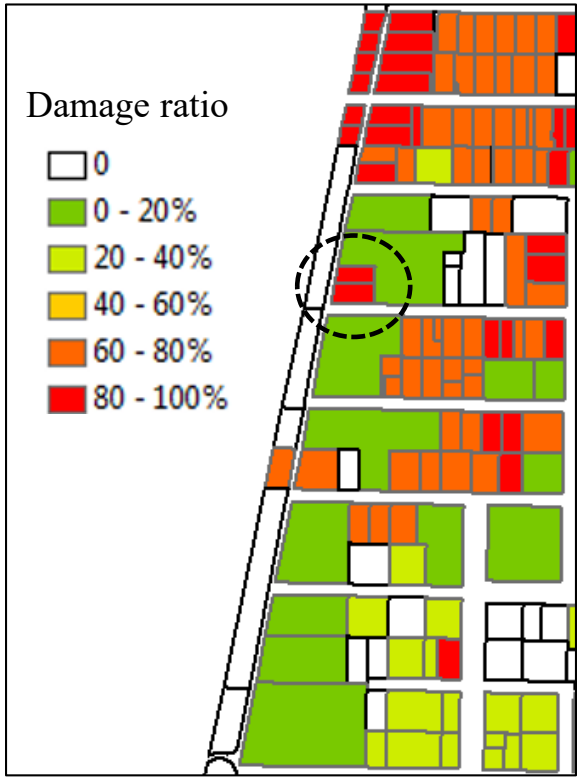
Photo taken by Hyoungsu Park, at Seaside Field trip (July, 14, 2015)

Example of Building Damage Assessment (at AEP = 0.001)

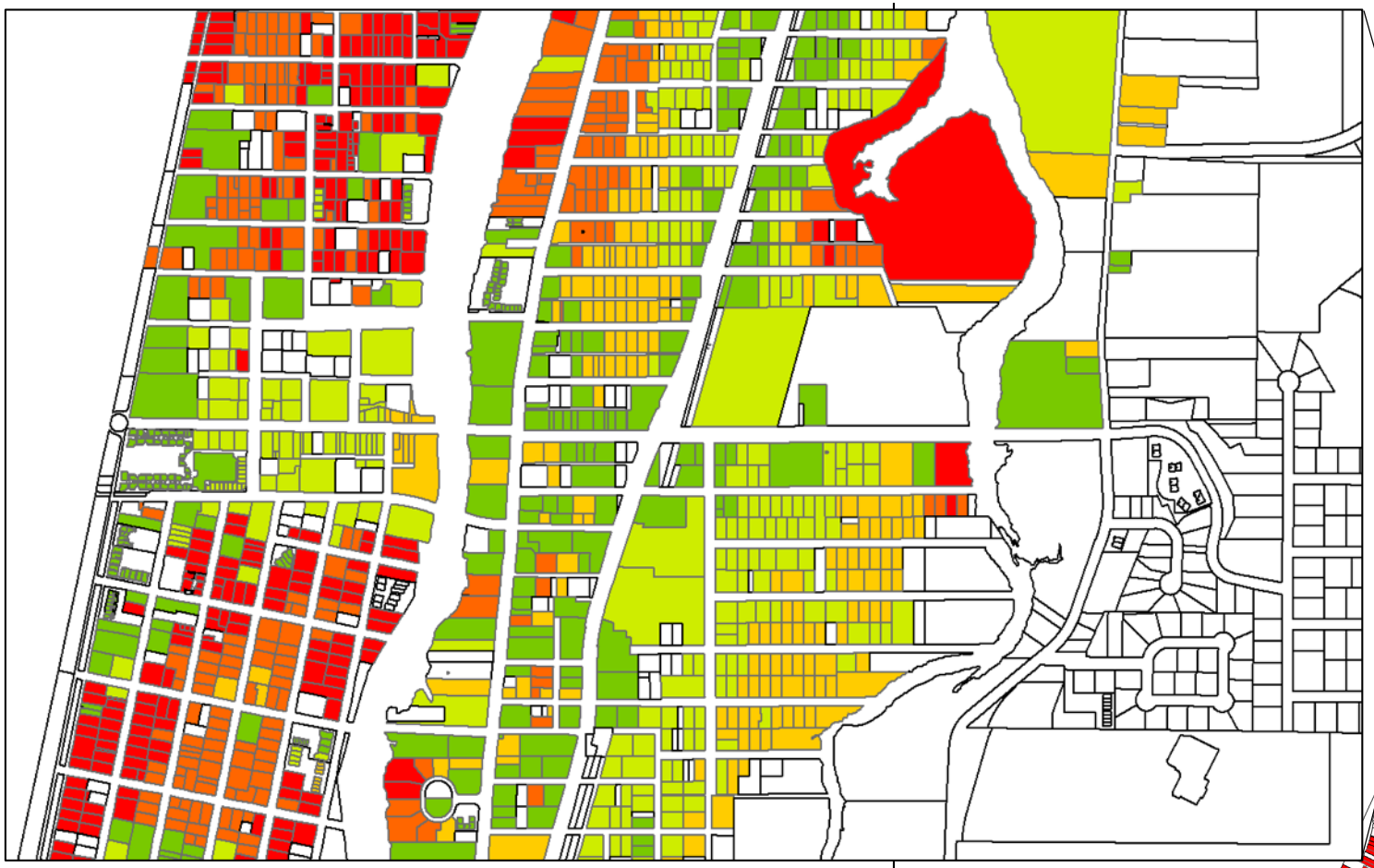


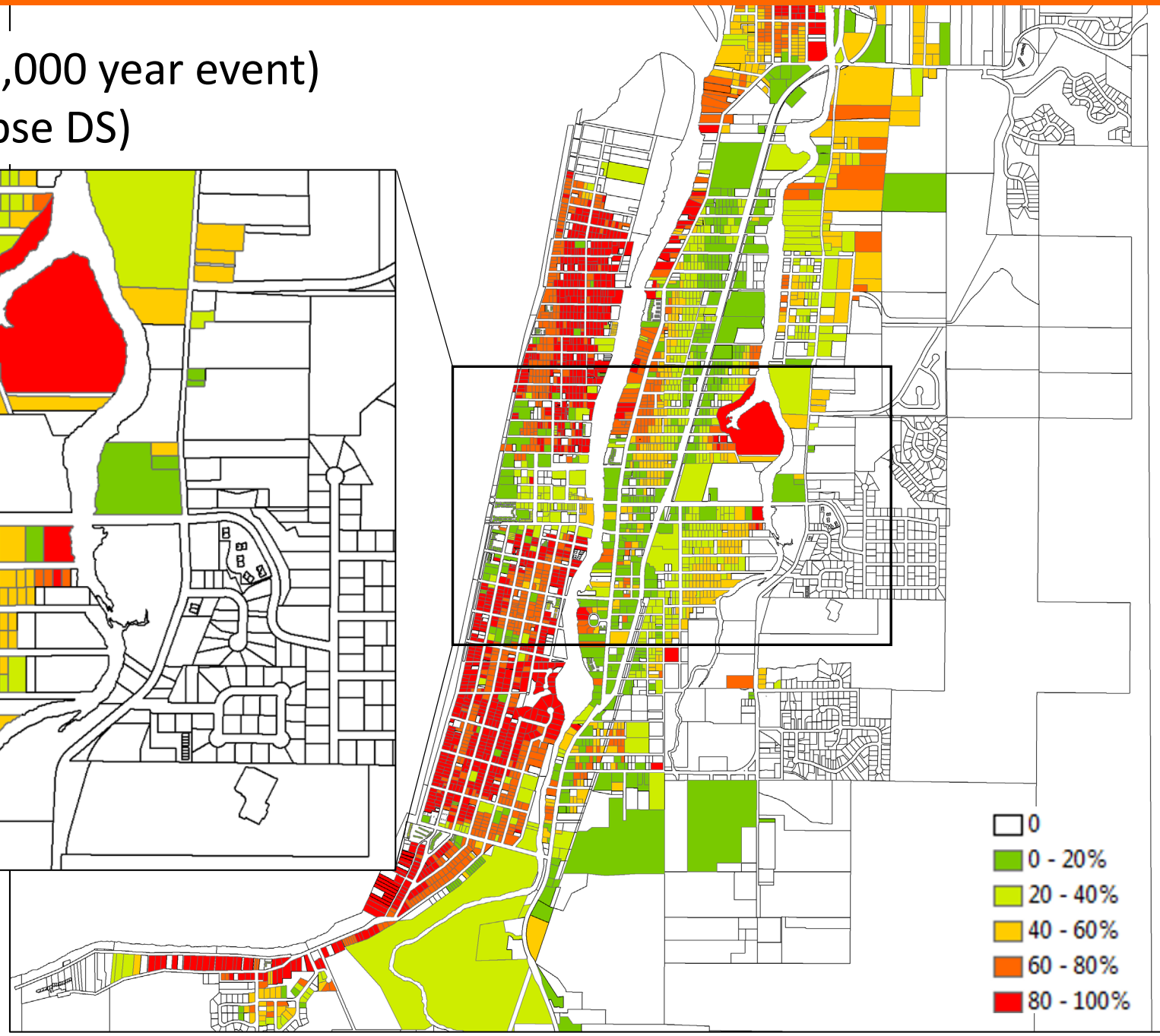
Fragility curves (Suppasri et al., 2013)
for Collapse damage





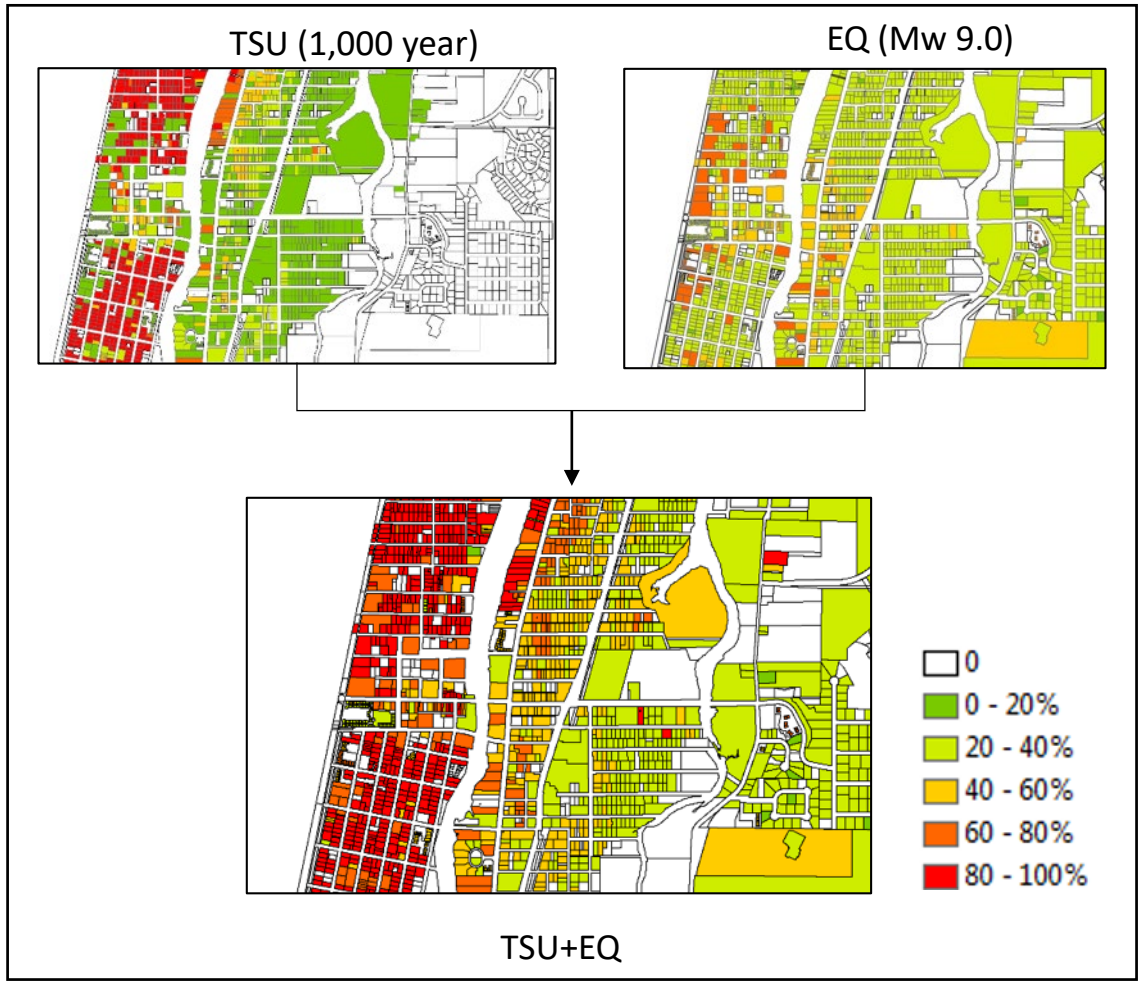
Probability damage at AEP = 0.001 (~1,000 year event) at CSZ with S2013 model (h_{max} , Collapse DS)

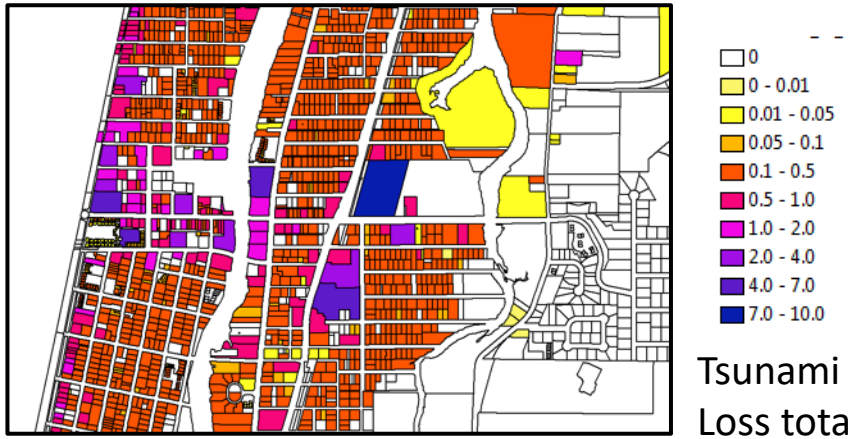




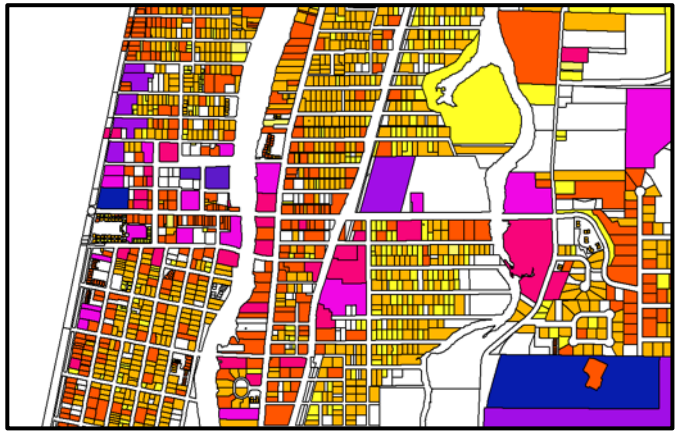
Estimate of Direct Losses

Dollar Loss = Dollar value of building × Damage ratio

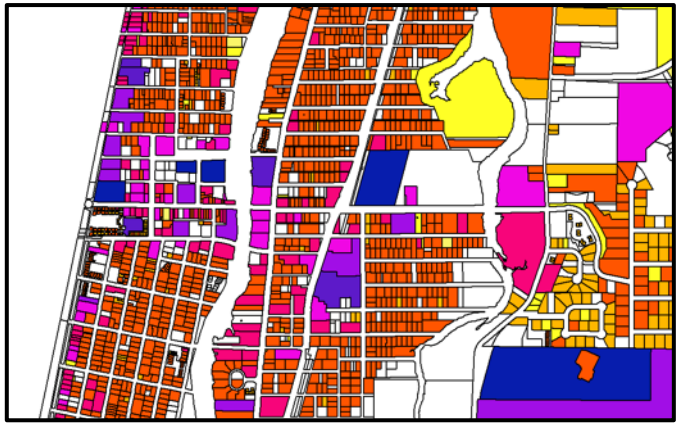




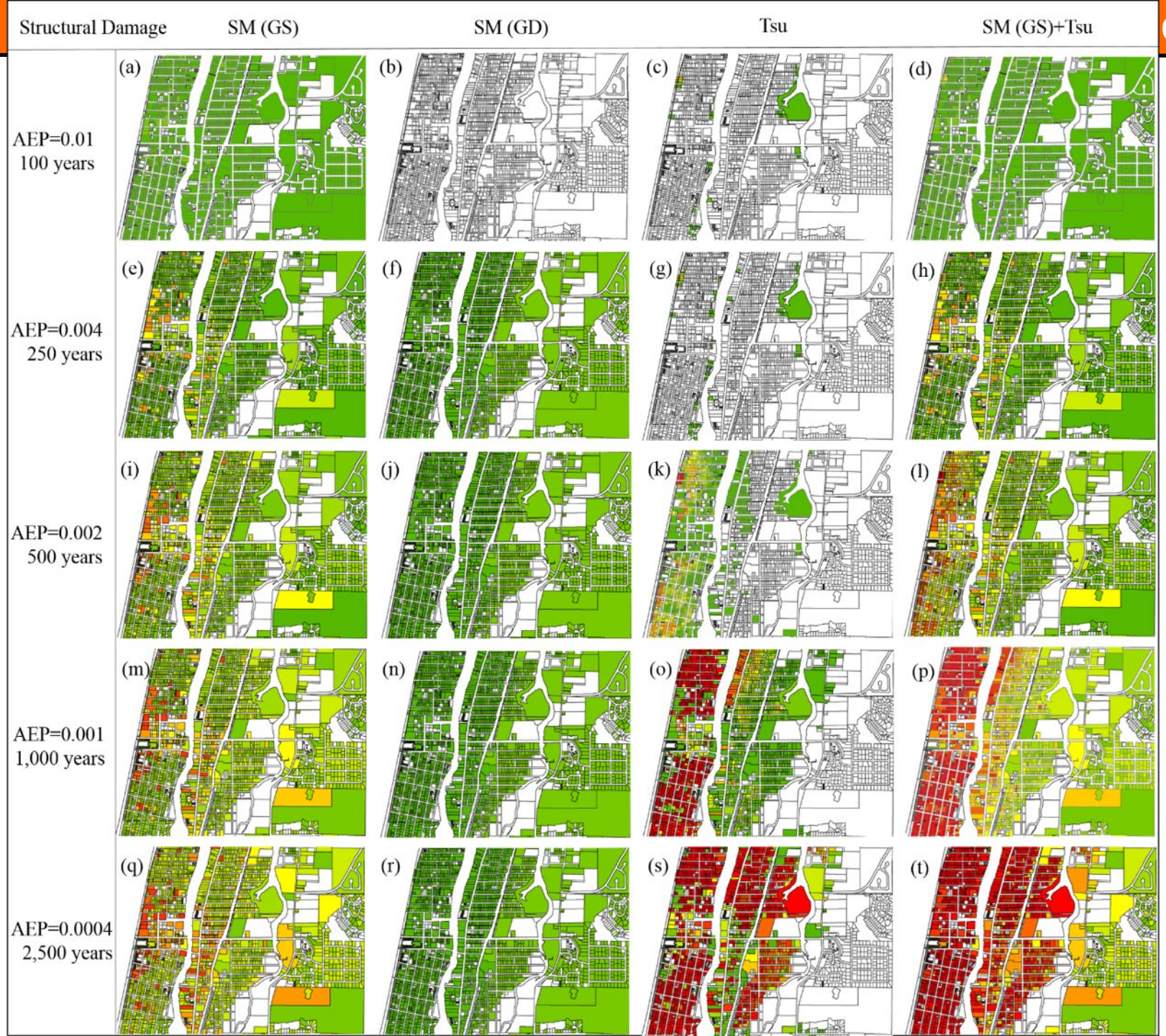
Tsunami
Loss total: 1,038 M



Earthquake
Loss total: 538 M



TSU + EQ
Loss total: 1,230 M

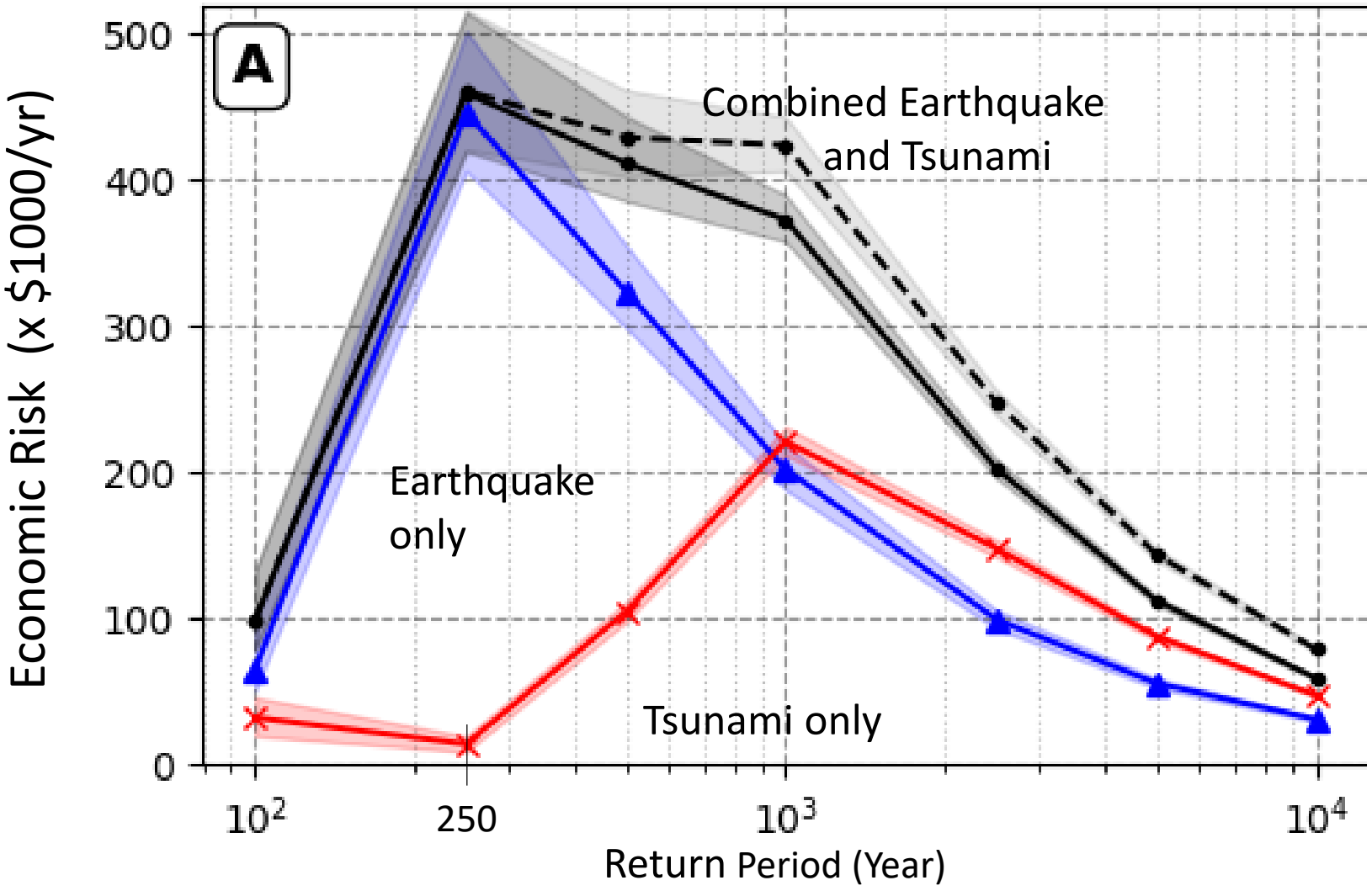


Higher probability
Lower consequences

Highest
Risk

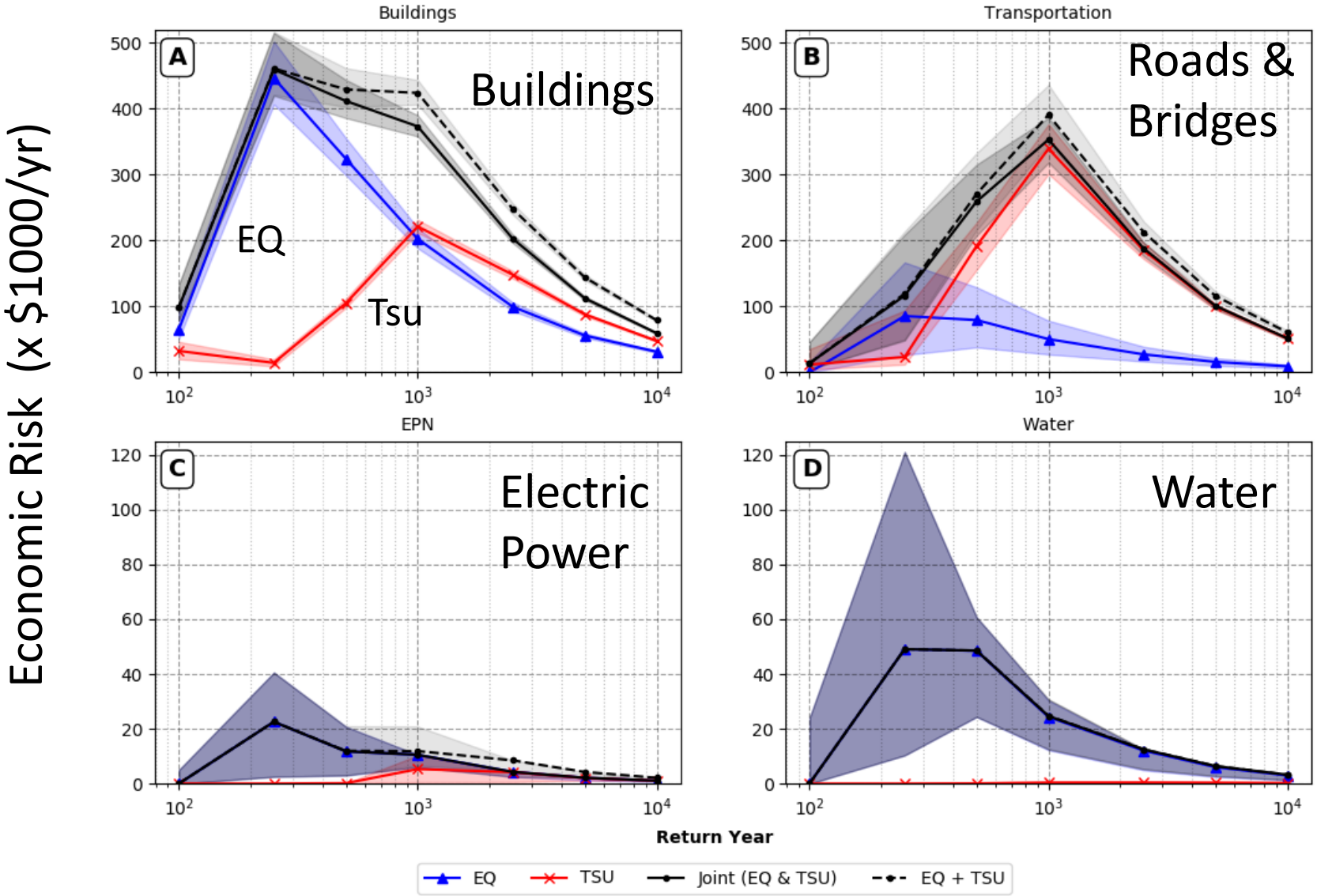
Lower probability
Higher consequences

Economic Risk for Building Damages in Seaside



Sanderson, D, S Kameshwar, N Rosenheim, DT Cox "Deaggregation of multi-hazard damages, losses, risks, and connectivity: An application to the joint seismic-tsunami hazard at Seaside, Oregon," *Natural Hazards,* (submitted, 8/2020).

Economic Risk for Different Infrastructure Networks in Seaside



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Open Source Platform for Community Resilience Modeling

https://incore.ncsa.illinois.edu/

NIST-funded CoE
HQ at Colorado State

Seaside Jupyter Notebooks

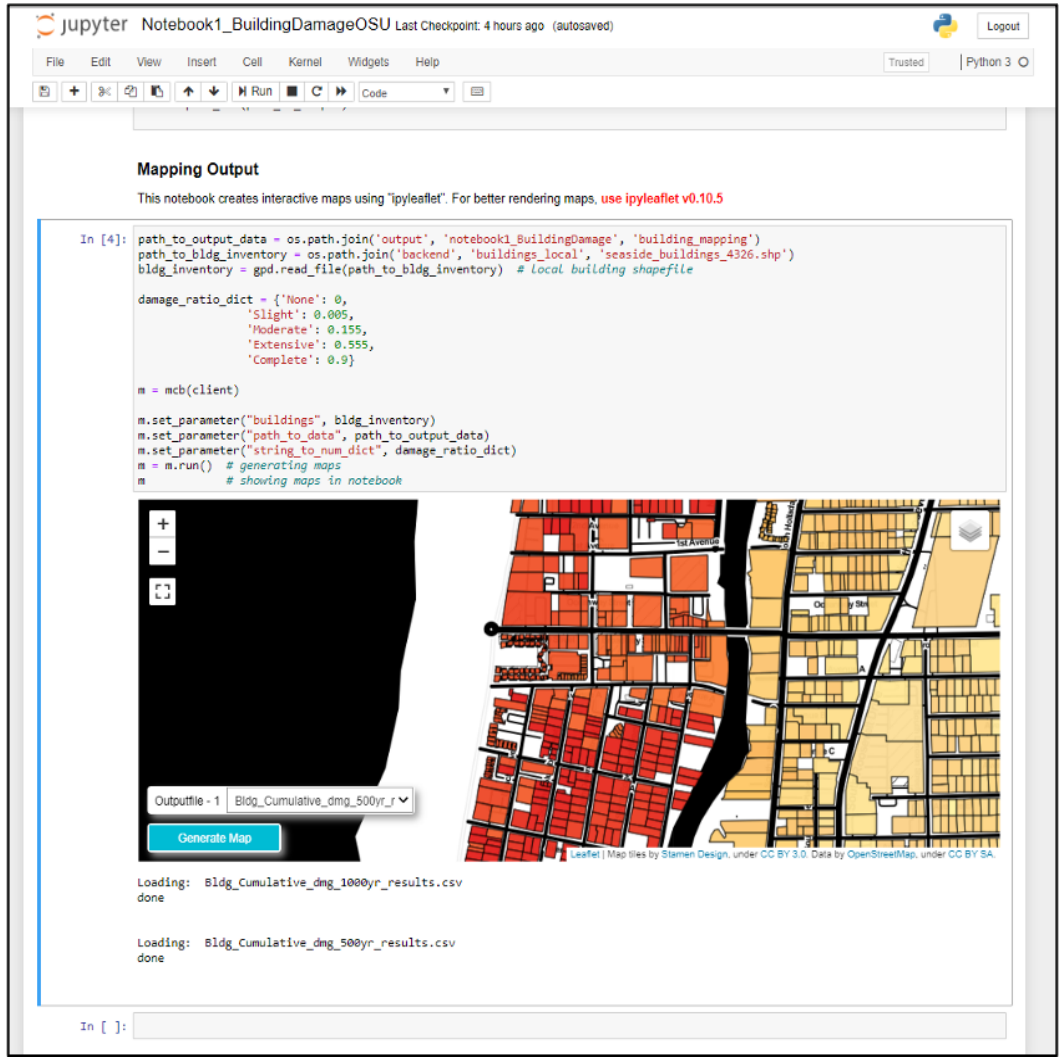
Finalized notebooks

- Seaside Example Notebook 1: Multi-Hazard Building Damage
  - Authors: Dylan Sanderson and Gowtham Naraharisetty
  - Date: Dec., 2019
  - Description: Demonstrates pyIncore's multi-hazard building damage analysis module

- Spatial Bayesian Network:
  - Authors: Dylan Sanderson, Dan Cox, and Gowtham Naraharisetty
  - Date: Jul., 2020
  - Description: Used to access and run a spatially-explicit Bayesian network that was populated using pyIncore

In progress notebooks

- Seaside Building Optimization
  - Authors: Tarun Adluri and Dylan Sanderson
  - Description: Multi-objective optimization of building mitigation strategies for Seaside.

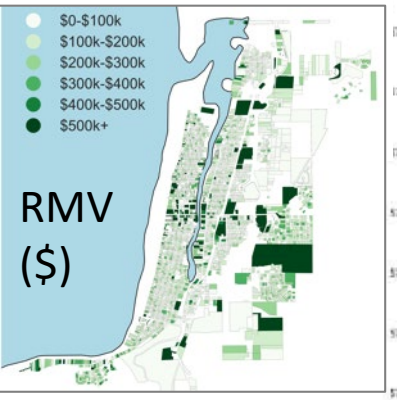


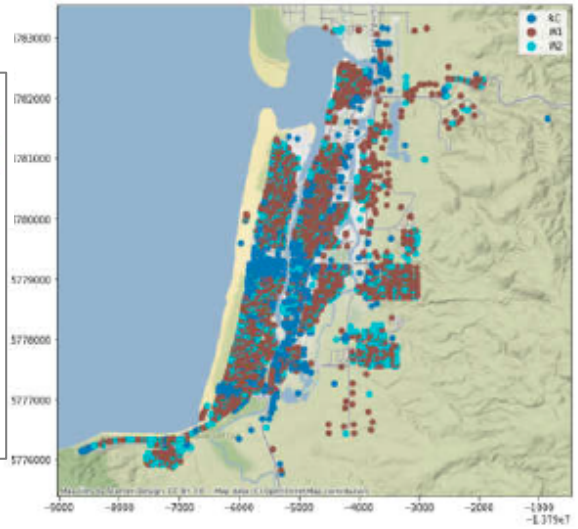
Combining Infrastructure Damage and Loss to Social Vulnerability

Seaside, OR: Race, Ethnicity, Tenure, Vacancy

Clatsop County, OR Population

Race, Ethnicity	Owner	Renter	Total
White NH	21,017	11,027	32,044
Black NH	55	48	103
Other NH	765	786	1,551
Hispanic	595	1,645	2,240
GQ			956
Total	22,432	13,506	36,894

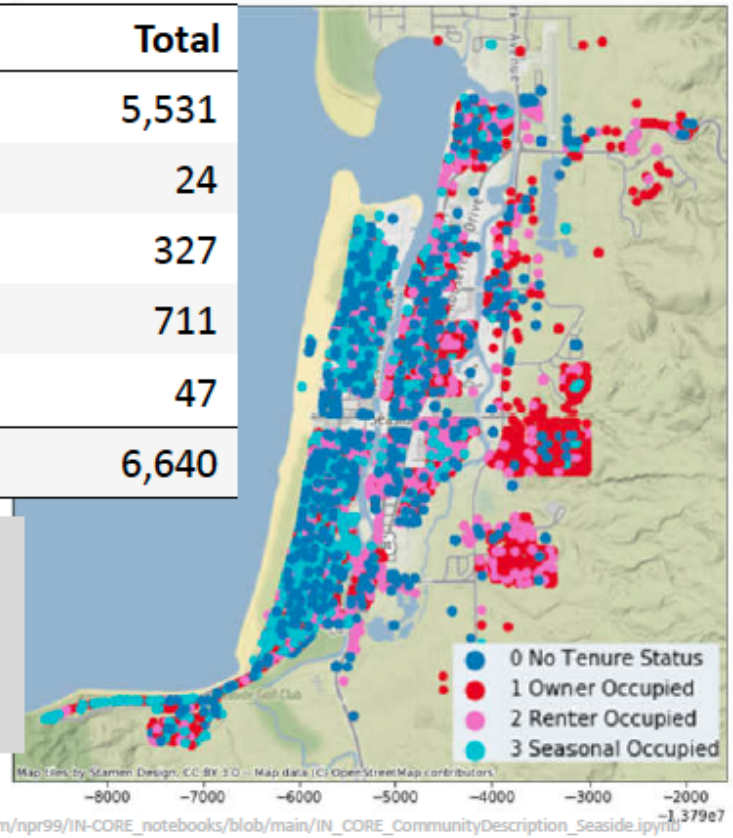




Housing Unit Inventory + Building Inventory

Race, Ethnicity	Owner	Renter	Total
White NH	2,631	2,900	5,531
Black NH	7	17	24
Other NH	136	191	327
Hispanic	187	524	711
GQ	nan	nan	47
Total	2,961	3,632	6,640

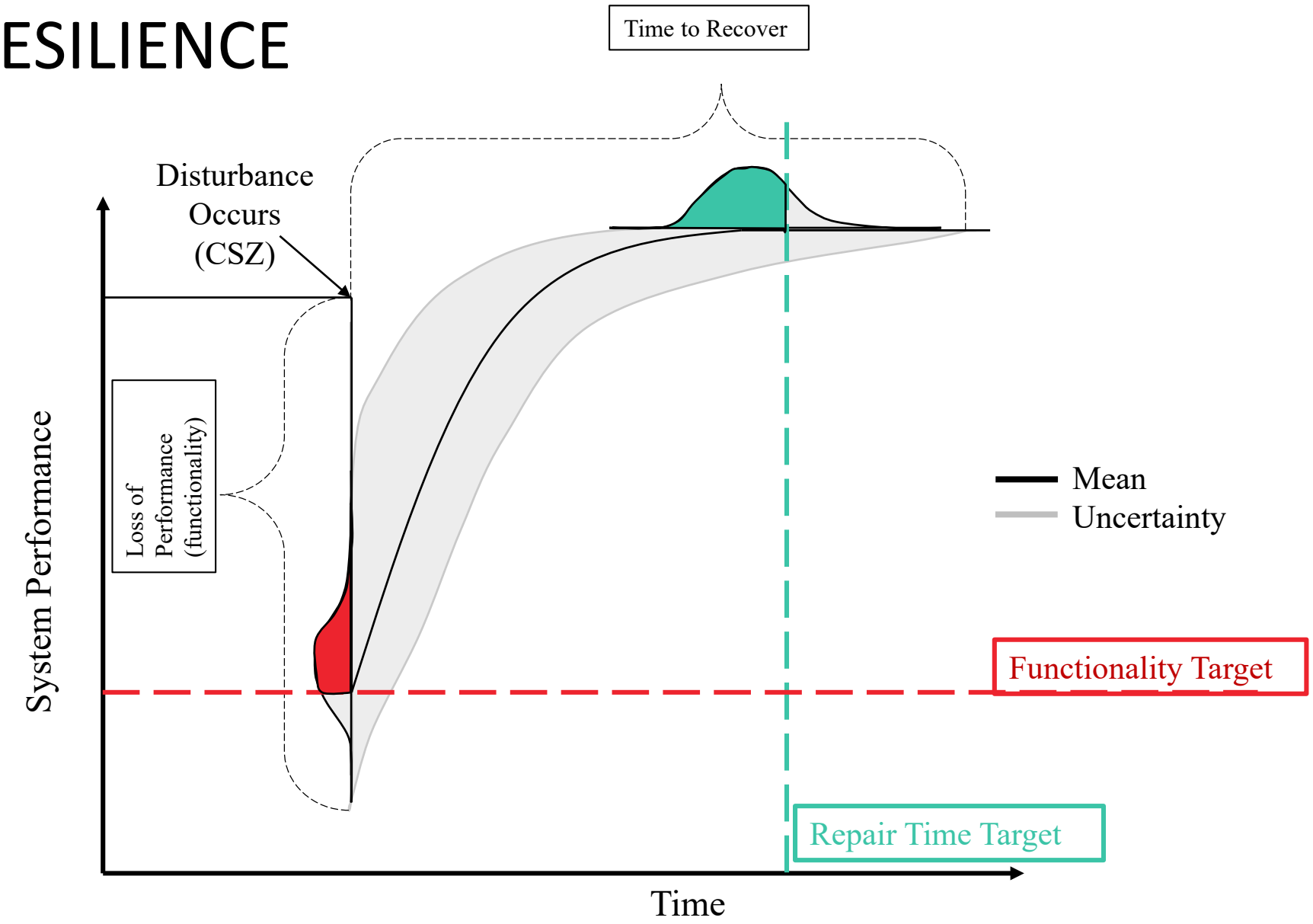
Seasonal and Vacant Housing Near the Coast



Provenance: https://github.com/npr99/IN-CORE_notebooks/blob/main/IN_CORE_CommunityDescription_Seaside.ipynb

Rosenheim, N., Guidotti, R., Gardoni, P., & Peacock, W. G. (2019). Integration of detailed household and housing unit characteristic data with critical infrastructure for post-hazard resilience modeling. *Sustainable and Resilient Infrastructure*, 1-17. https://doi.org/10.1080/23789689.2019.1681821
Guidotti, R., Gardoni, P., & Rosenheim, N. (2019). Integration of physical infrastructure and social systems in communities' reliability and resilience analysis. *Reliability Engineering & System Safety*, *185*, 476-492. https://doi.org/10.1016/j.ress.2019.01.008

RISK → RESILIENCE



1. Deaggregation of multi-hazard damages, losses, risks, and connectivity: An application to the joint seismic-tsunami hazards at Seaside, Oregon
2. A spatially explicit decision support framework for parcel- and community-level risk and resilience assessment using Bayesian networks

Establishing community resilience objectives

Oregon Resilience Plan (2013)

R	= difficult target
Y	= moderate target
G	= easier target

Comparison of Target States and Estimated Time for Recovery

Infrastructure Facilities	*Event Occurs*	*0 – 24 hours*	*1 – 3 days*	*3 – 7 days*	*1 – 4 weeks*	*1 – 3 months*	*3 – 6 months*	*6 – 12 months*	*1 – 3 years*	*3+ years*
Central Oregon Zone										
▶ OREGON STATE HIGHWAY SYSTEM										
State Highway System - Tier 1 SLR [1]			R	Y	G			S	X	
Roadways			R	Y	G/S		X			
Bridges			R	Y	G		S	X		
Landslides			R	Y	G			S	X	
State Highway System - Tier 2 SLR			R		Y	G			S	X
Roadways			R		Y	G/S		X		
Bridges			R		Y	G		S	X	
Landslides			R		Y	G			S	X
State Highway System - Tier 3 SLR				R		Y	G		S	X
Roadways				R		Y	G/S		X	
Bridges				R		Y	G		S	X
Landslides				R		Y	G		S	X
State Highway System - Other Routes					R		Y	G	S	X
Roadways					R		Y	G	X	
Bridges					R		Y	G	S	X
Landslides					R		Y	G	S	X
▶ AIRPORTS & AIR TRANSPORTATION										
Tier I - Oregon Airports System										
Redmond Municipal Roberts Field Airport - FEMA		R	S		Y	G	X			
Klamath Falls Airport		R	S		Y	G	X			
FAA Facility			R	Y	G					
▶ OREGON RAIL TRANSPORTATION										
UPRR										
CA/OR State Line to Bieber Line Jct. (Klamath Falls)			Y	G	S	X				

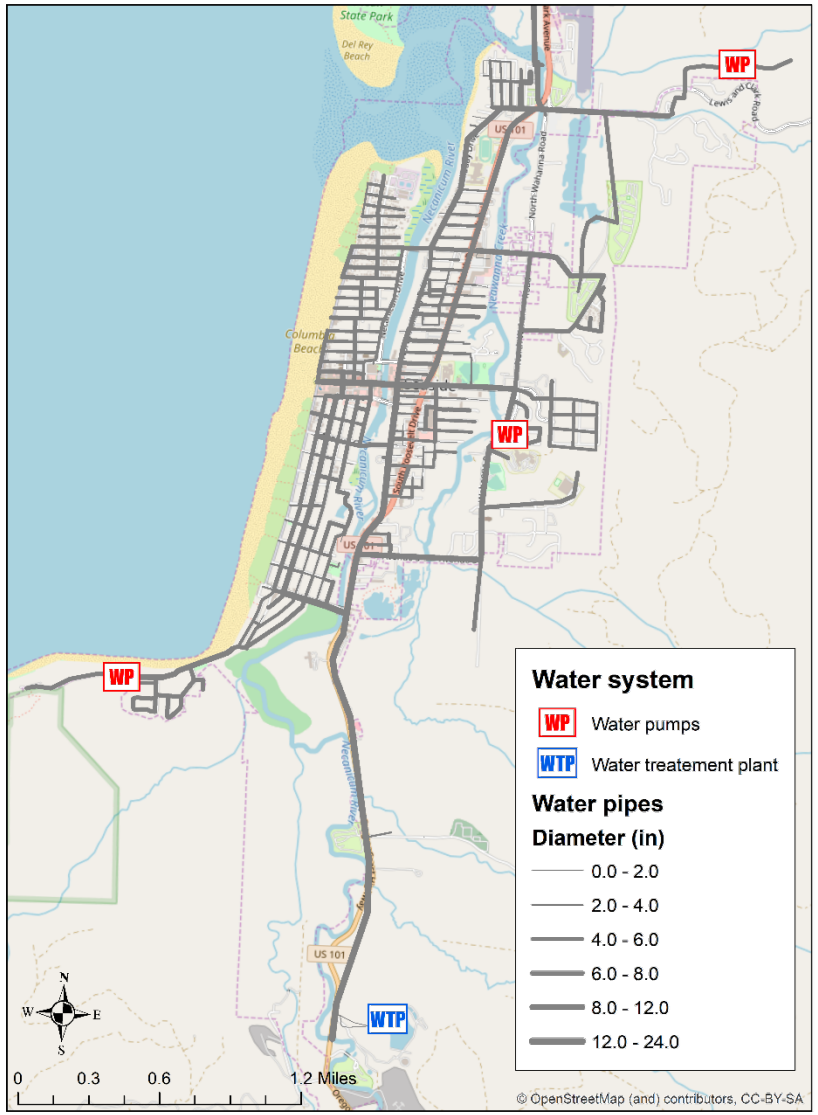
Decision Support Framework

- Community-specified targets
- Targets are MRI-specific
- Targets are Infrastructure-specific

Easy targets | Moderate targets | Difficult targets

Infrastructure	Return period (years)	Restoration time (in days)								
		0-3	3-7	7-15	15-30	30-90	90-180	180-360	360-720	720-1080
Buildings	100									
Buildings	250									
Buildings	500									
Buildings	1000									
Buildings	2500									
Buildings	5000									
Buildings	10000									
Transportation	100									
Transportation	250									
Transportation	500									
Transportation	1000									
Transportation	2500									
Transportation	5000									
Transportation	10000									
Water	100									
Water	250									
Water	500									
Water	1000									
Water	2500									
Water	5000									
Water	10000									
EPN	100									
EPN	250									
EPN	500									
EPN	1000									
EPN	2500									
EPN	5000									
EPN	10000									

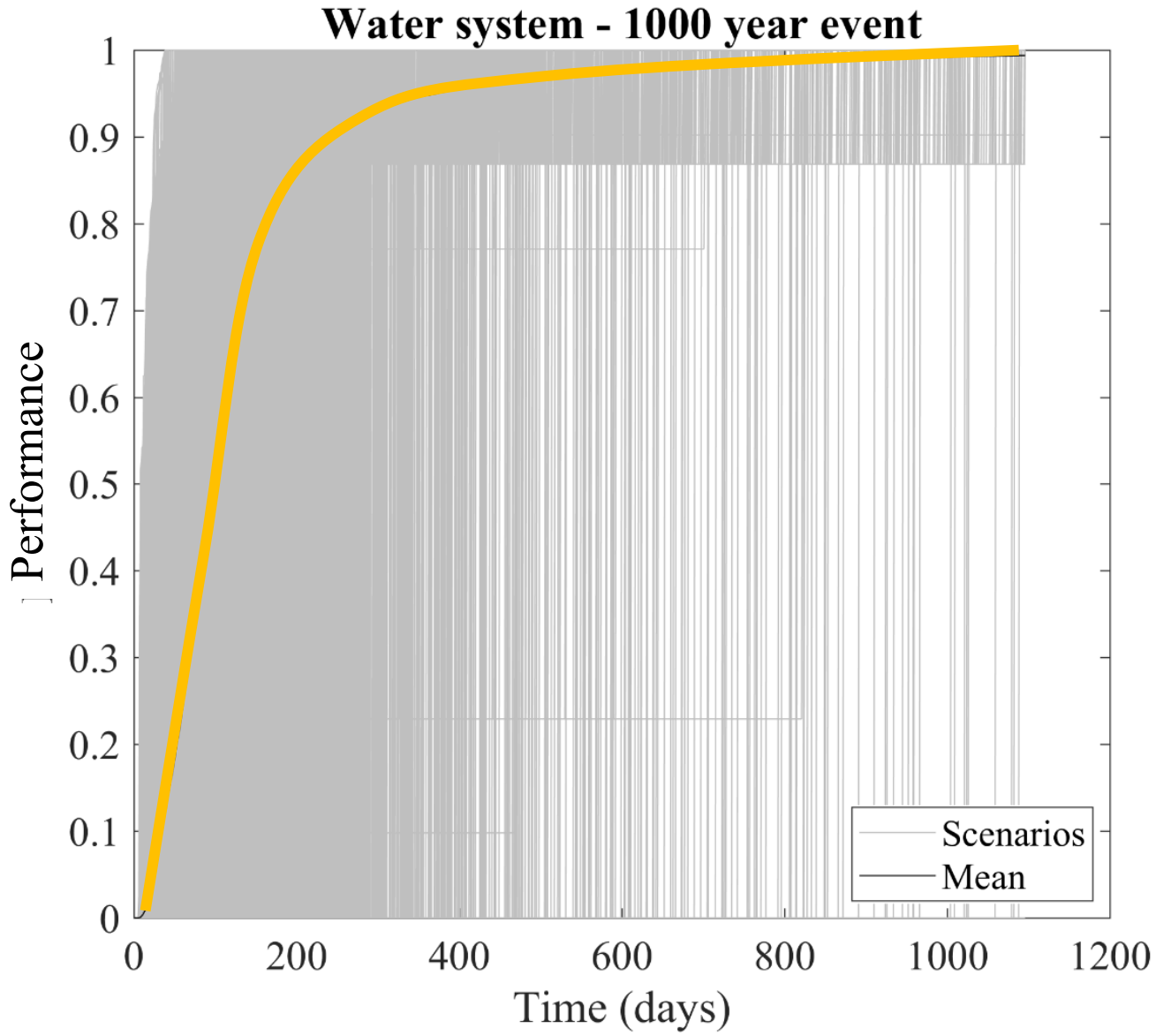
Example: Performance assessment of water system



- Return period events: 100, 250, 500, 1000, 2500, 5000, 10000 years
- EQ and tsunami, and combined damage estimation
  - Hazus fragility estimates for treatment plant, pumping station, and water pipes
  - Economic loss
  - Restoration time
- Performance: number of buildings connected to treatment plant and nearest pumping station – network analysis
- Monte Carlo Simulations – propagate uncertainties in component capacities and restoration time

Restoration Performance of Water System (Hazus restoration functions)

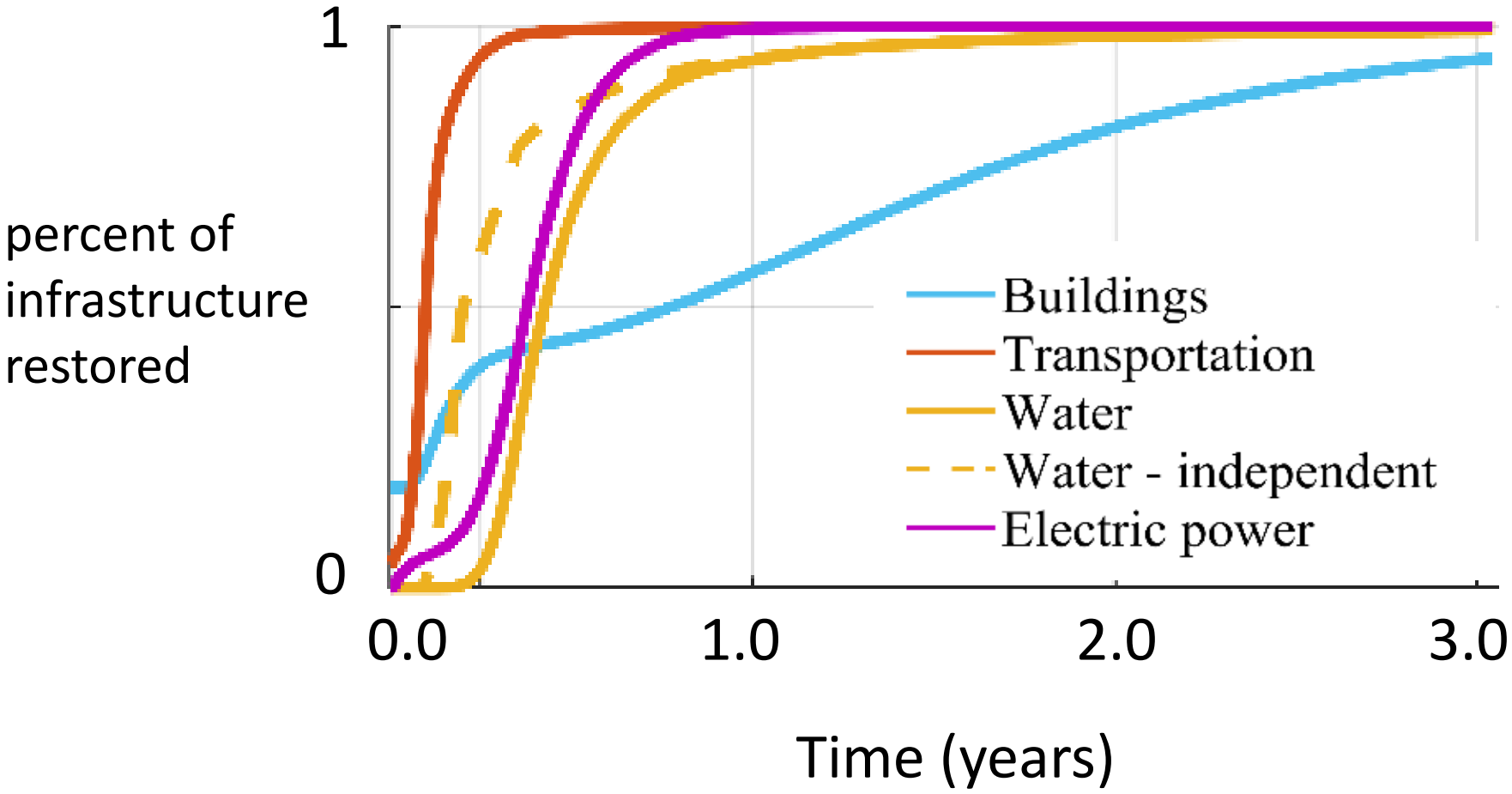
percent of buildings connected to water system



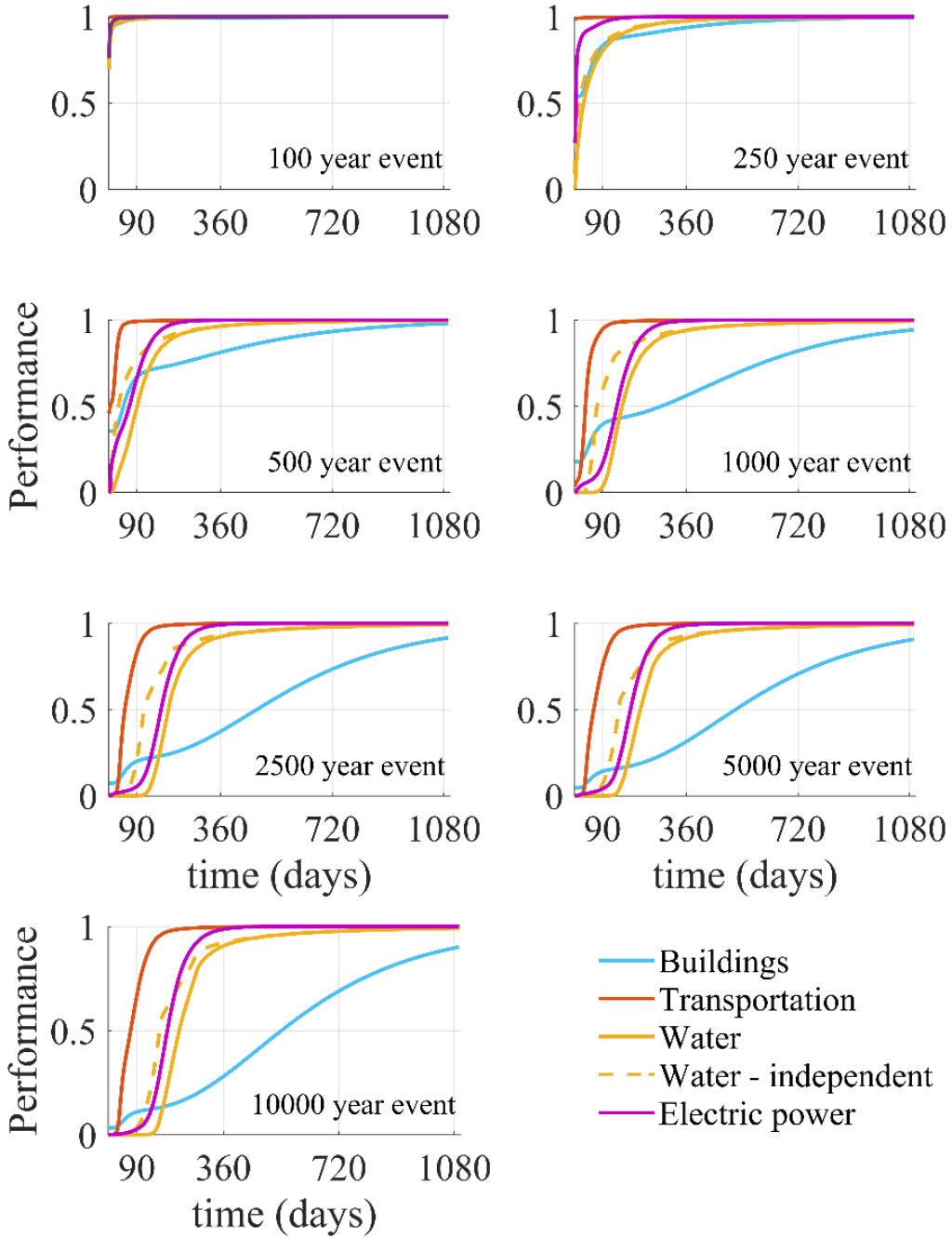
- connectivity only
- no water quality
- no water pressure
- no consideration of regional scale disaster

Restoration of infrastructure systems

(1,000-year event, seismic + tsunami)



Restoration of all systems as a function of recurrence interval



Bayesian network to assess community resilience

- Considered four infrastructure types:
  - Buildings
  - Electric Power Network
  - Transportation Network
  - Water Supply Network
- Connectivity among infrastructure
- Joint probability of meeting community targets for robustness and rapidity
- Can explore mitigation options

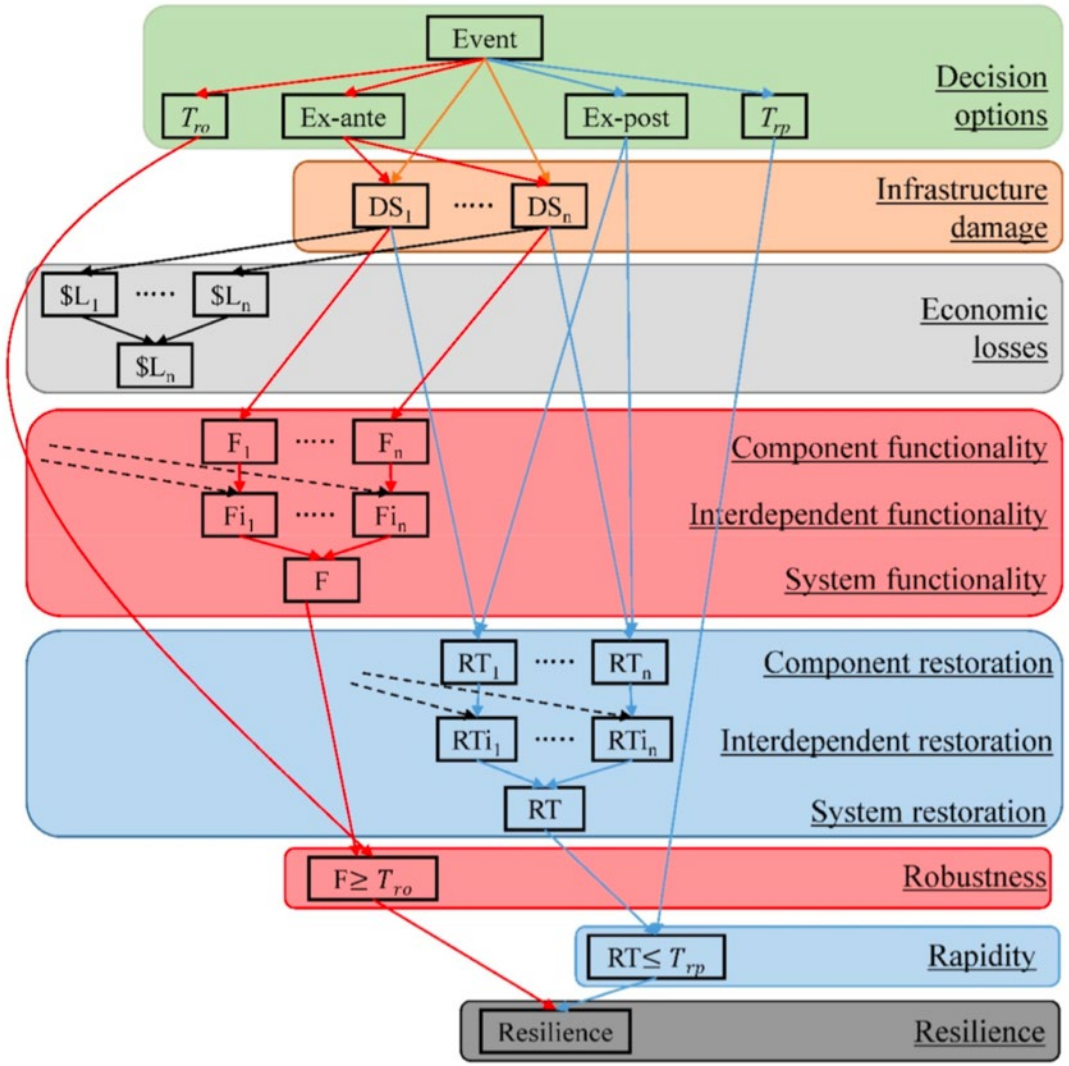


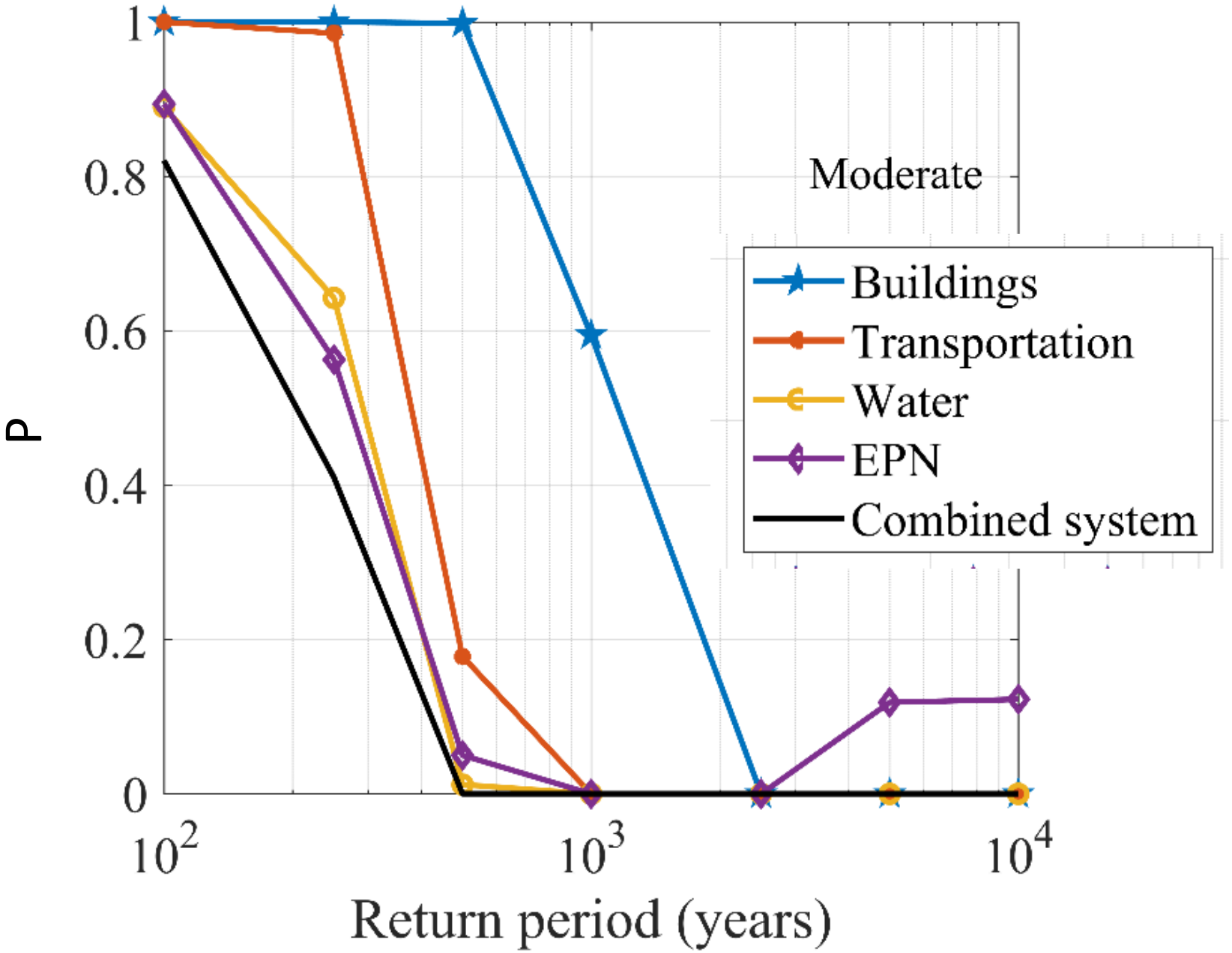
Fig. 11. Schematic representation of a BN for an infrastructure system.

Kameshwar, S., Cox, D., Barbosa, A., Farokhnia, K., Park, H., Alam, M., and van de Lindt, J. (2019). Probabilistic decision-support framework for community resilience: Incorporating multi-hazards, infrastructure interdependencies, and resilience goals in a Bayesian network. *Reliability Engineering and System Safety*, 191. https://doi.org/10.1016/j.ress.2019.106568

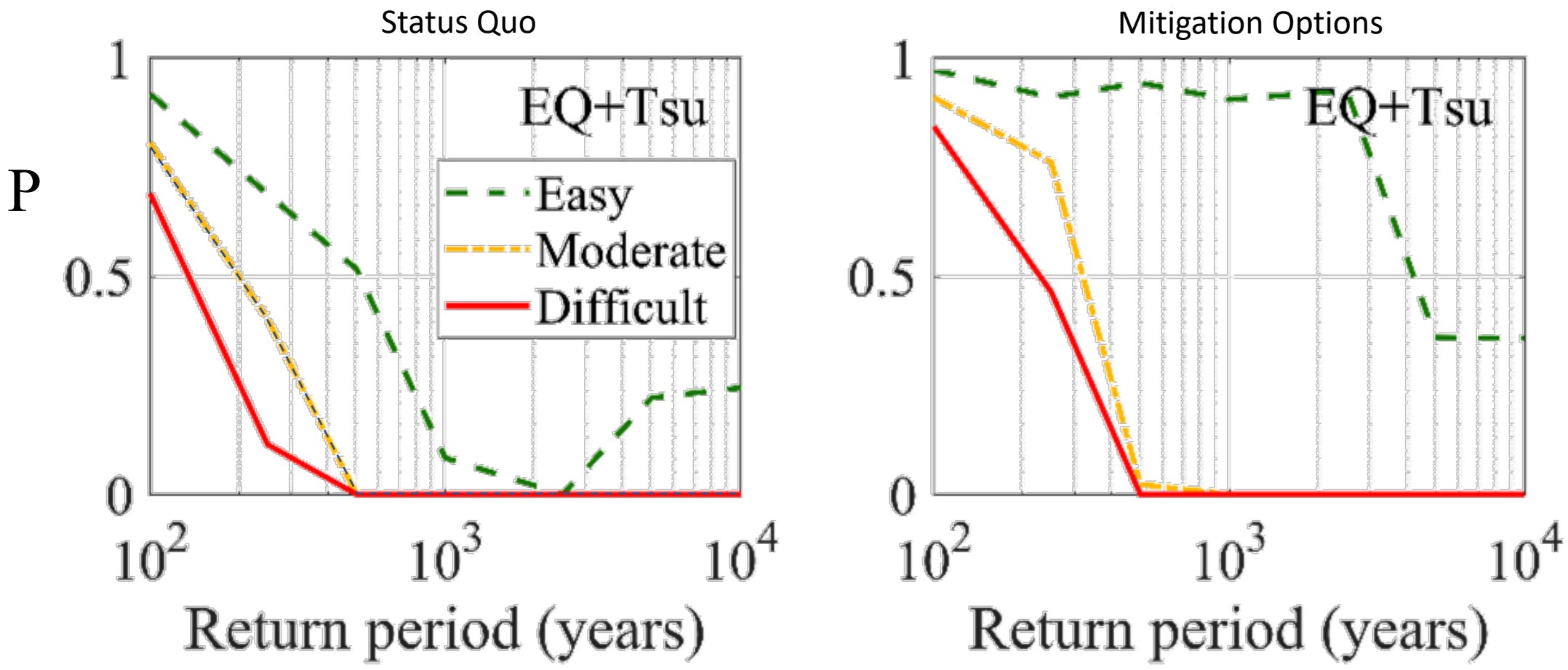
Model output:

Probability of achieving community resilience goals

- Combined EQ+Tsu
- Moderate targets
- “Resilience” depends on recurrence interval, goals



How to increase resilience? Expected benefits of mitigation measures to improve community resilience can depend on community targets.



Kameshwar, S., Cox, D., Barbosa, A., Farokhnia, K., Park, H., Alam, M., and van de Lindt, J. (2019). Probabilistic decision-support framework for community resilience: Incorporating multi-hazards, infrastructure interdependencies, and resilience goals in a Bayesian network. *Reliability Engineering and System Safety*, 191. https://doi.org/10.1016/j.ress.2019.106568

Tsunami Debris

"Over the past 5 years, debris removal accounted for approximately 27% of disaster recovery costs" -- FEMA 325 (2007)

Debris Forecasting

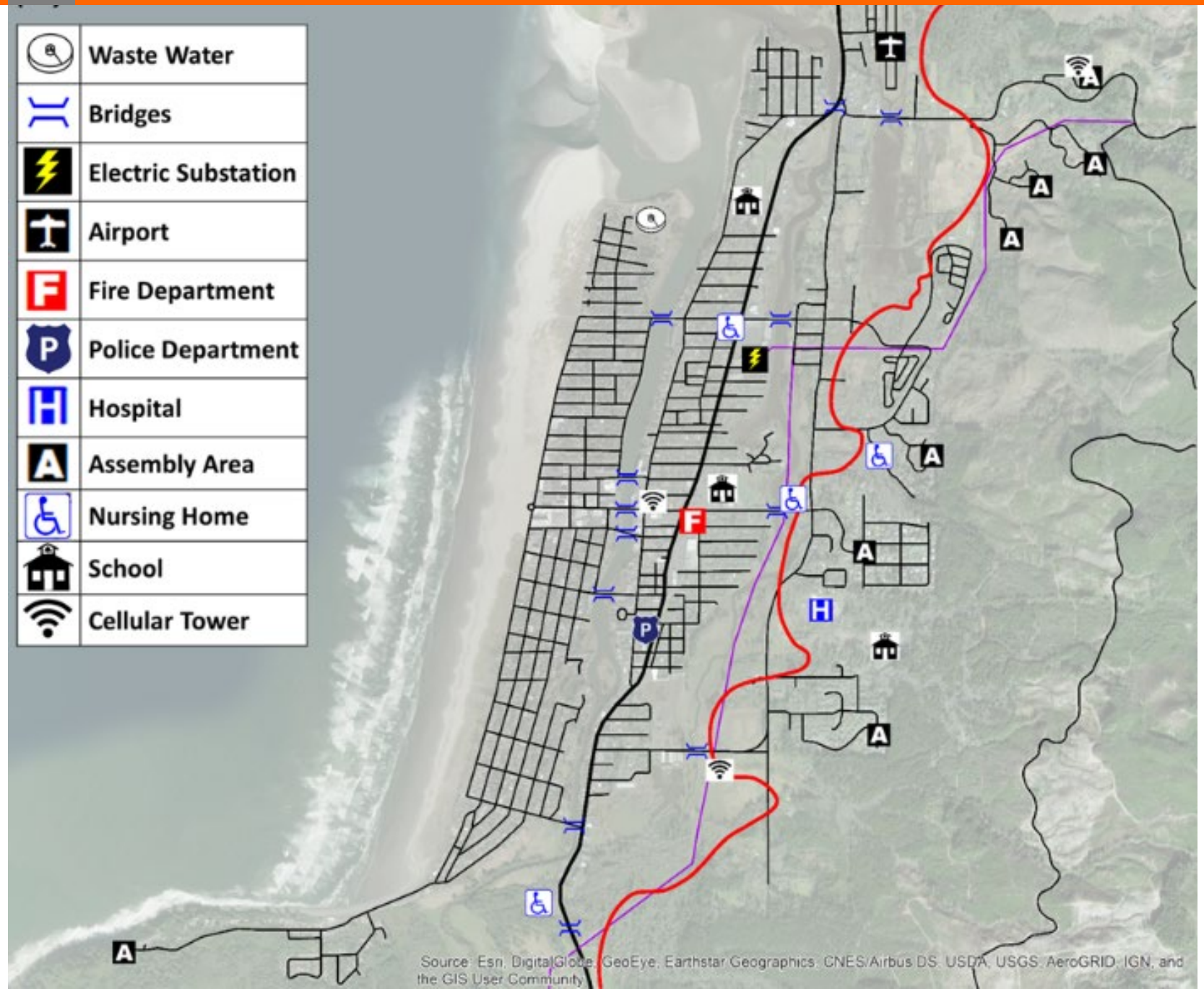
1. What is it?
2. How much is it?
3. Where is it?

Hazards and Disaster Debris types

	Natural			Anthropogenic					
	Vegetative	Soil, Sand, Mud	Putrescence	Construction & Demolition	Household Hazardous Waste (HHW)	White Goods	Personal Property	Vehicles + Vessels	Hazardous Waste
Hurricane	x	x	x	x	x	x	x	x	x
Tsunami	x	x	x	x	x	x	x	x	x
Flood	x	x	x	x	x	x	x	x	x
Tornadoes	x		x	x	x	x	x	x	x
Earthquake		x		x	x	x	x		
WUI Fire	x	x			x	x	x		
Ice Storm	x				x				

From FEMA 325, Figure 6.2 – Typical Debris Streams for Different Types of Disasters

Focus on critical facilities and lifelines



Debris Forecast Model: Quantification of debris at a single building

Based on Hazus-MH 2.1 (Earthquake)

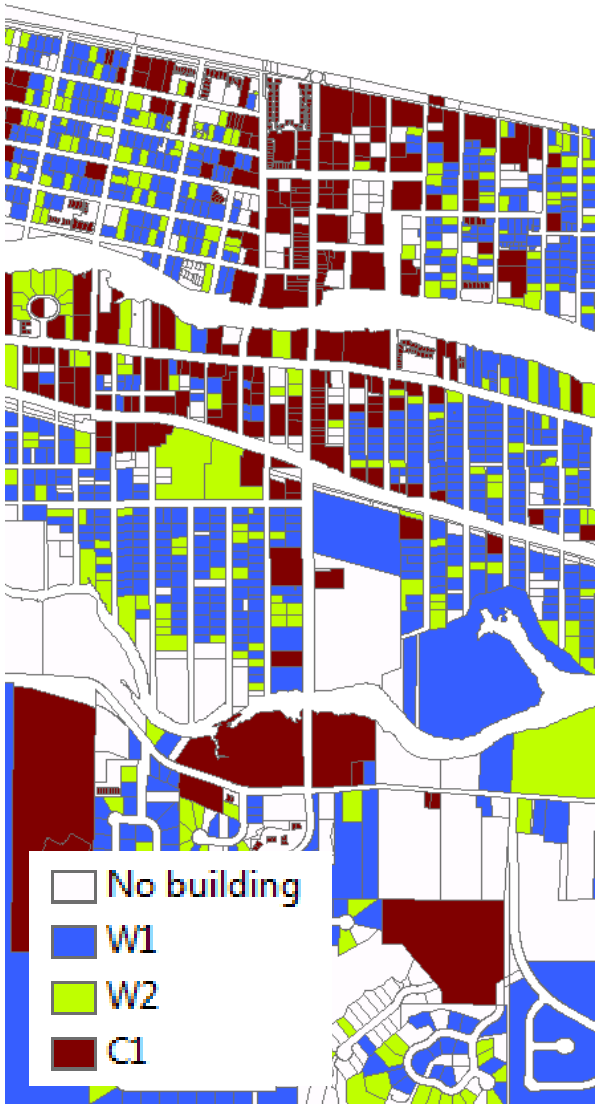
EDF for structural damage

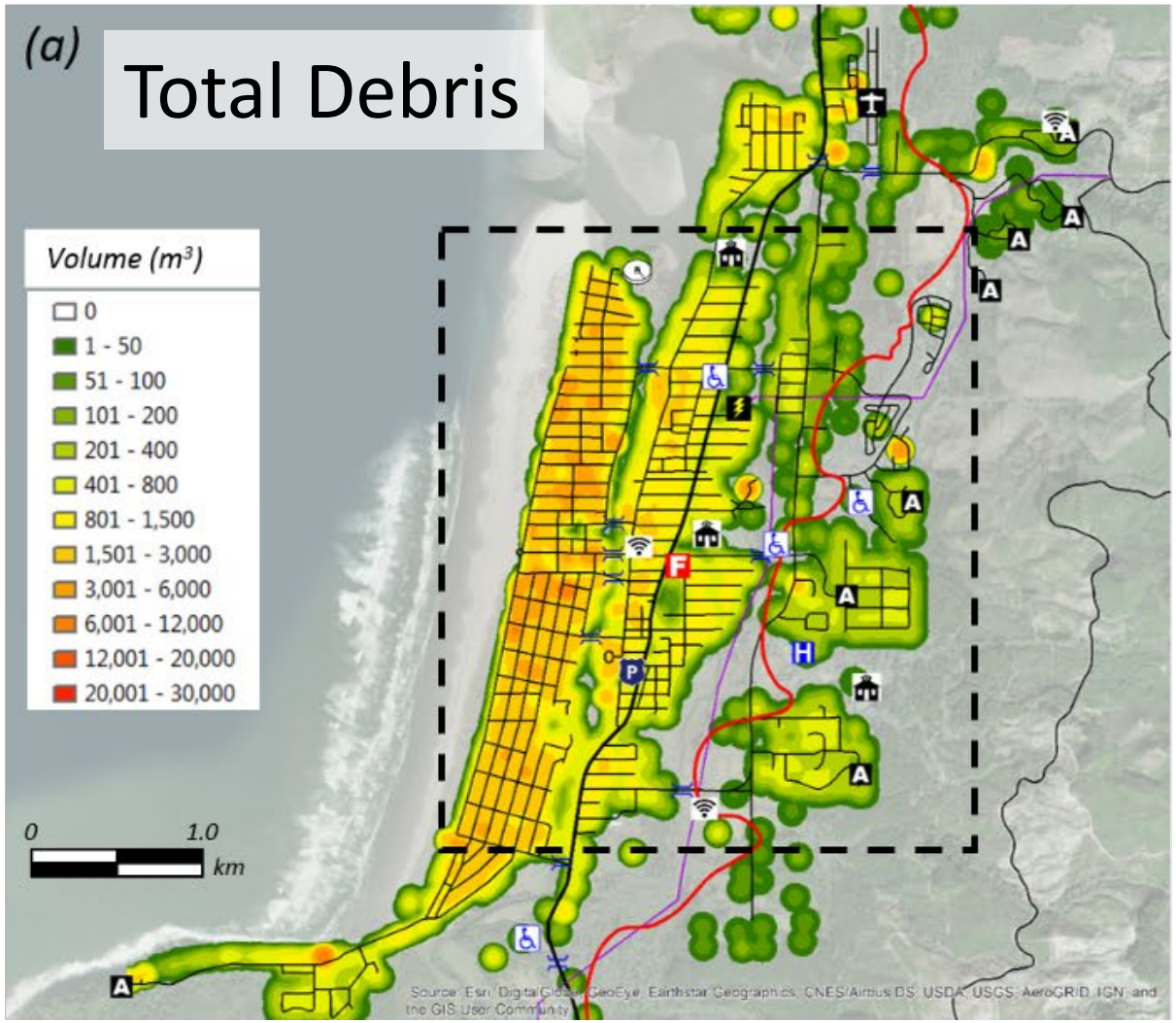
$$EDF_S = \int \left(\sum_i^4 P_S(i) \cdot DF_S(i) \right) f_S(r) dr$$

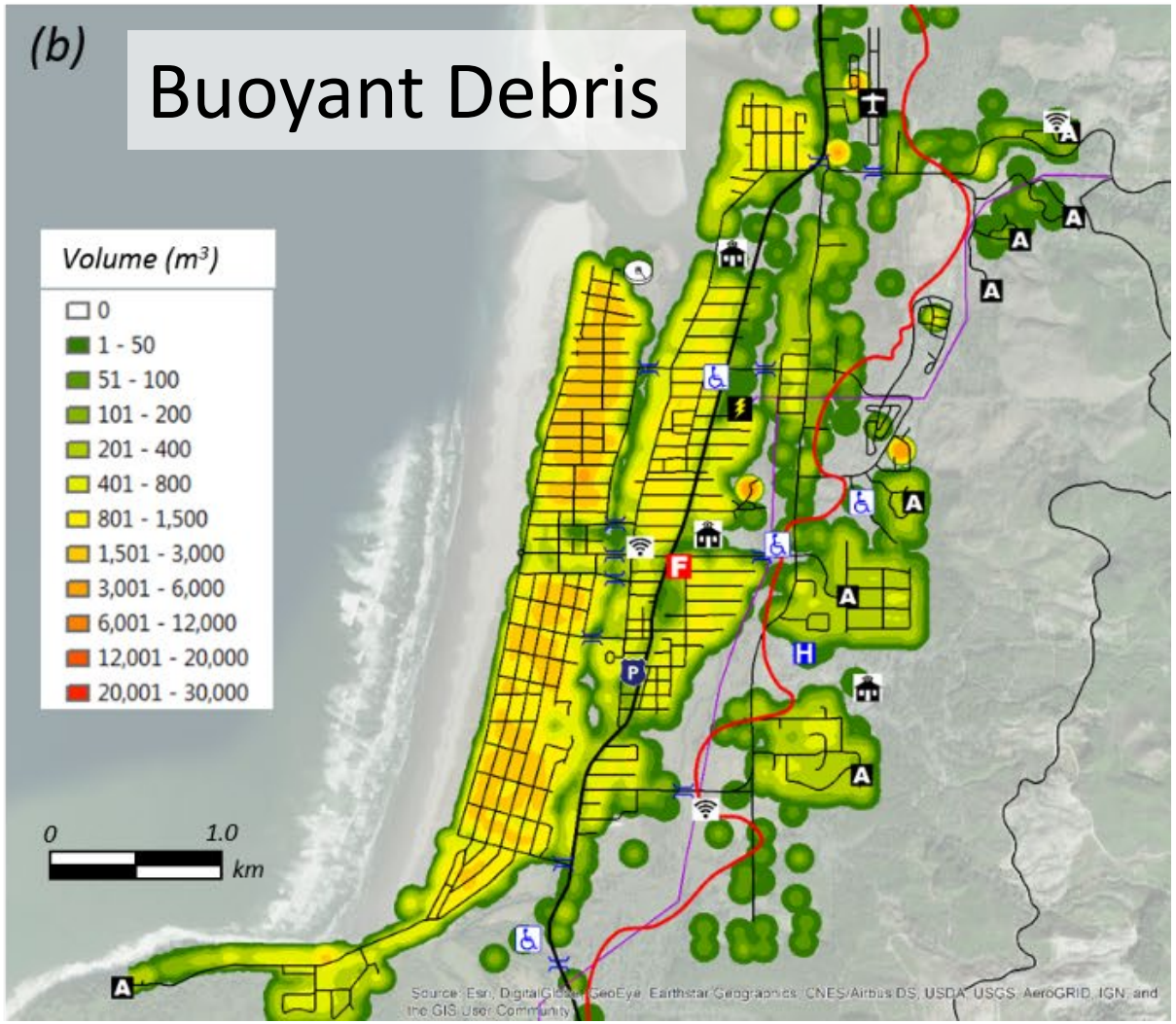
EDF for non-structural damage

$$EDF_{NS} = \int \left(\sum_i^4 P_{NS}(i) \cdot DF_{NS}(i) \right) f_{NS}(r) dr$$

EDF_S	Expected debris fraction from structural damage
i	Four damage states (slight, moderate, extensive and complete)
$P_S(i)$	Probability of structural damage at the 'i' damage state.
$DF_S(i)$	Structural debris fraction (percent) of unit weight at the 'i' damage states.
$f_{,S}(r)$	Structural debris fraction (percent) of unit weight at the 'i' damage states.
NS	Subscription for non-structural damage variables.



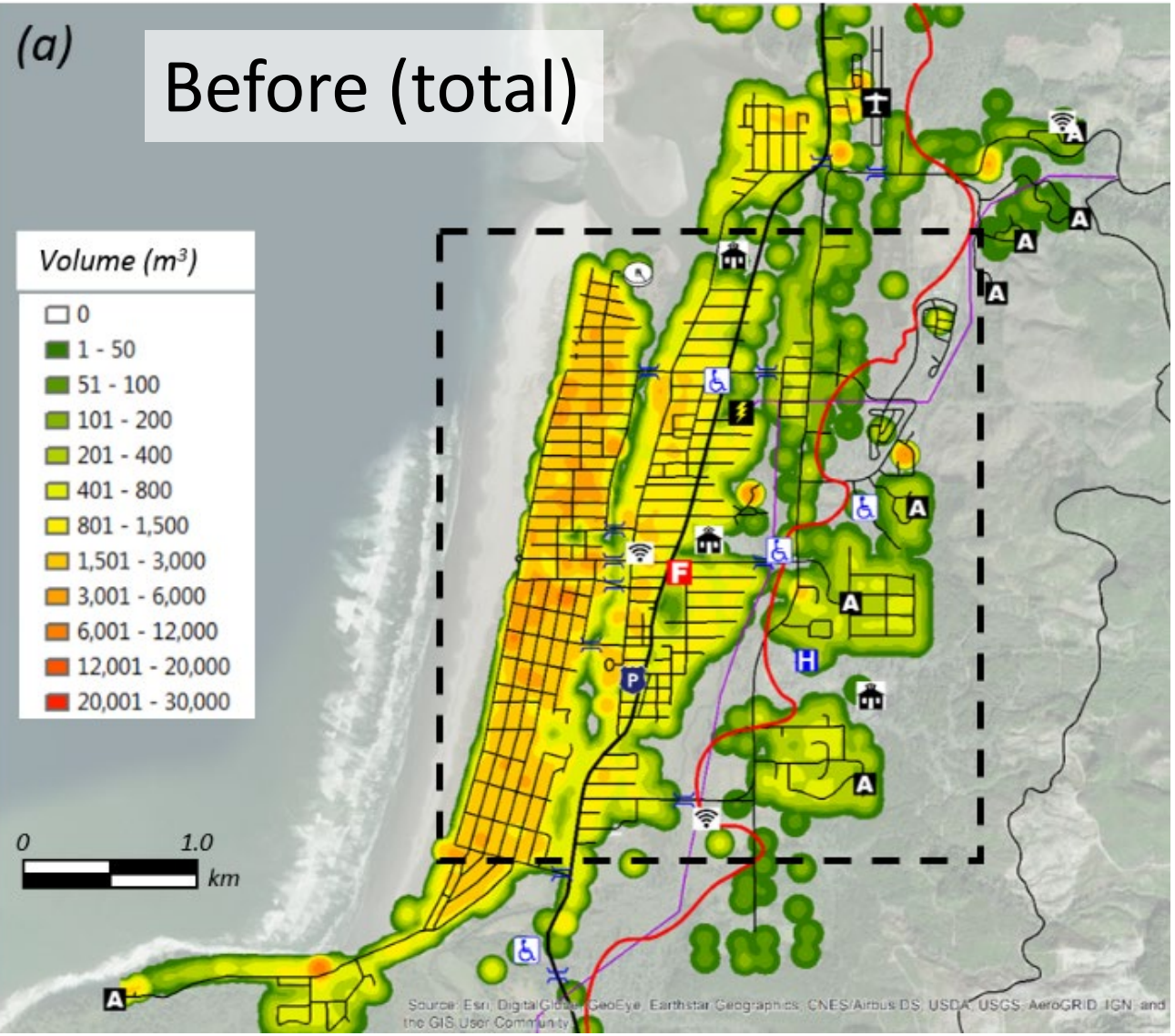


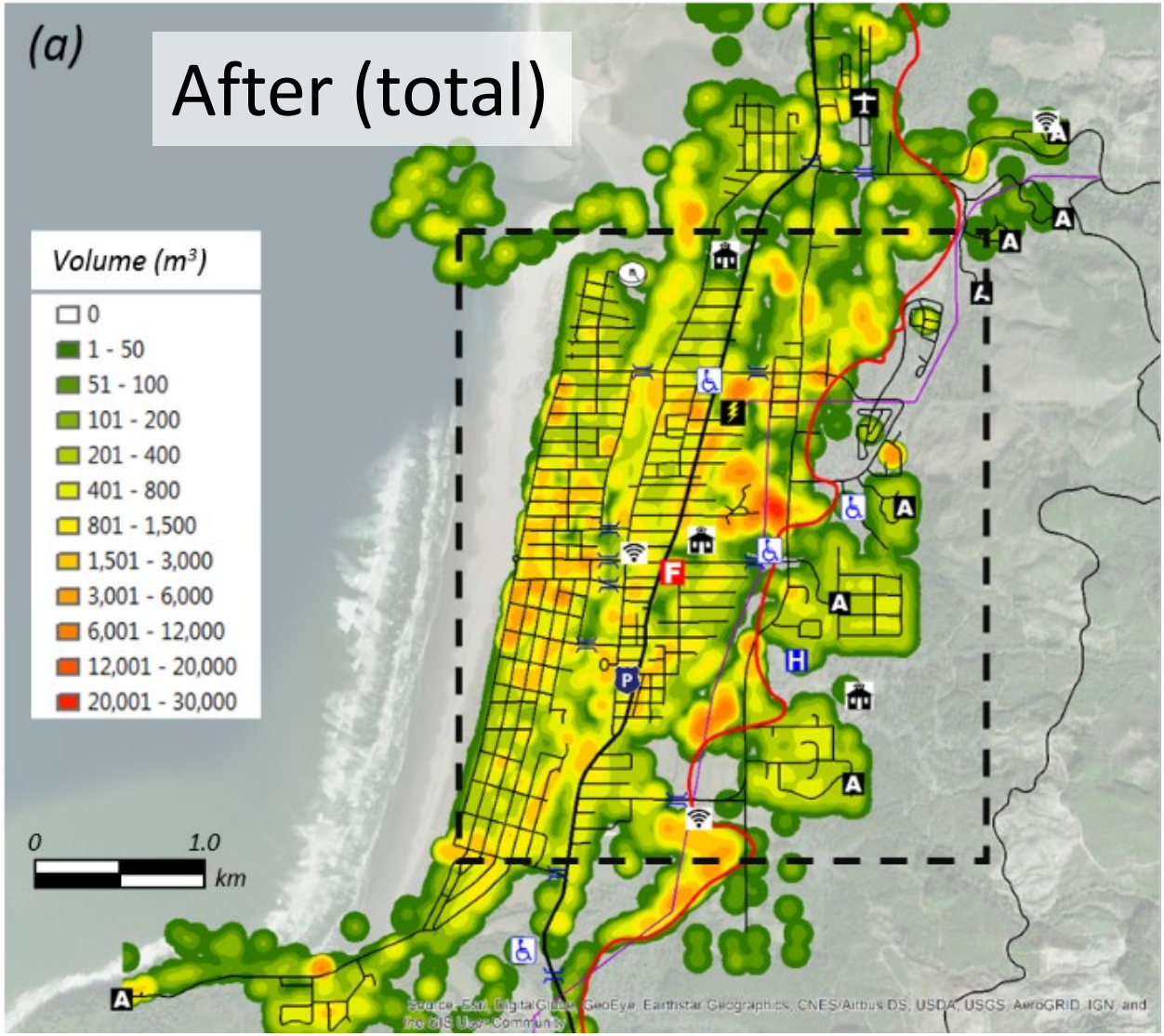


Distribution of expected debris volume (m^3) per unit area (hectare) for 1000-year event without advection. (a) Volume of total debris from EQ+TSU, (b) Volume of buoyant debris only from EQ+TSU.

Advection of buoyant debris from PSTDA

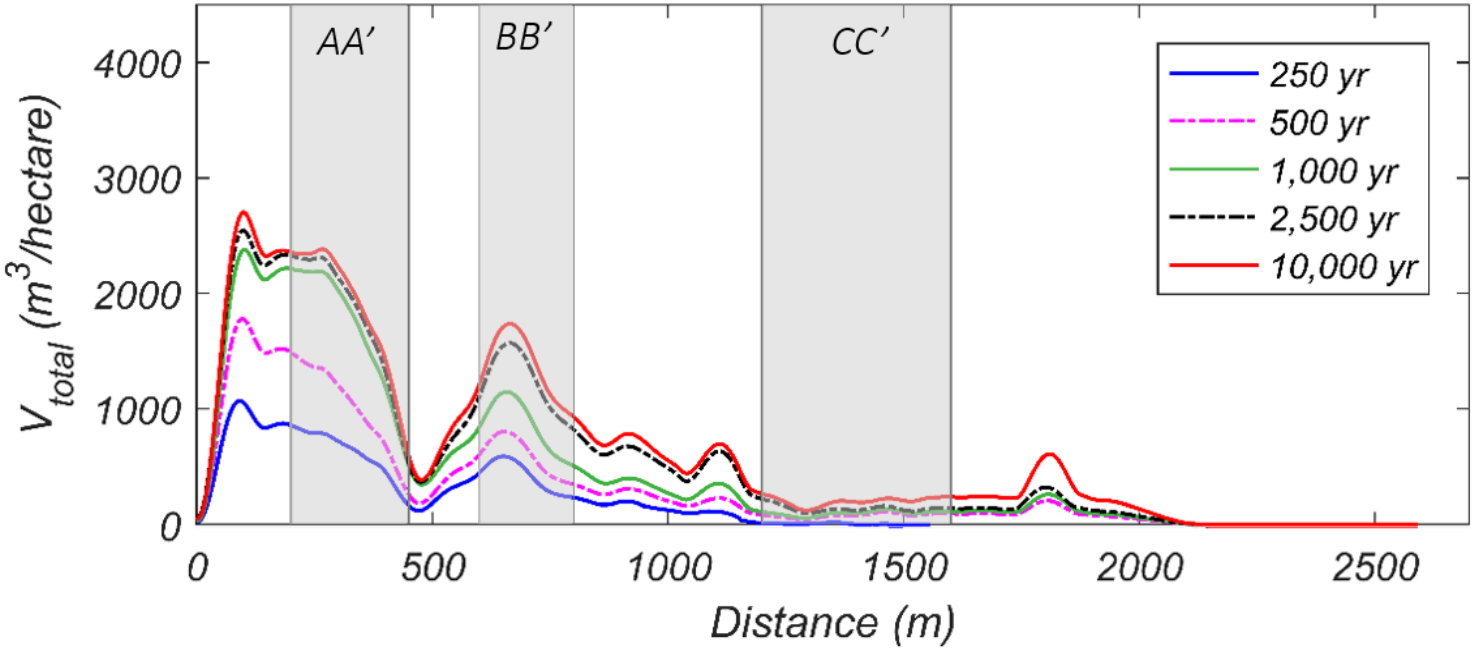
Thresholds: 3 m, 0.5 m/s | 1 m, 0.3 m/s | 0.5 m, 0.2 m/s





Park H, DT Cox (2019) "Effects of advection on forecasting construction debris for vulnerability assessment under multi-hazard earthquake and tsunami," *Coastal Engineering* 153, 103541, doi.org/10.1016/j.coastaleng.2019.103541

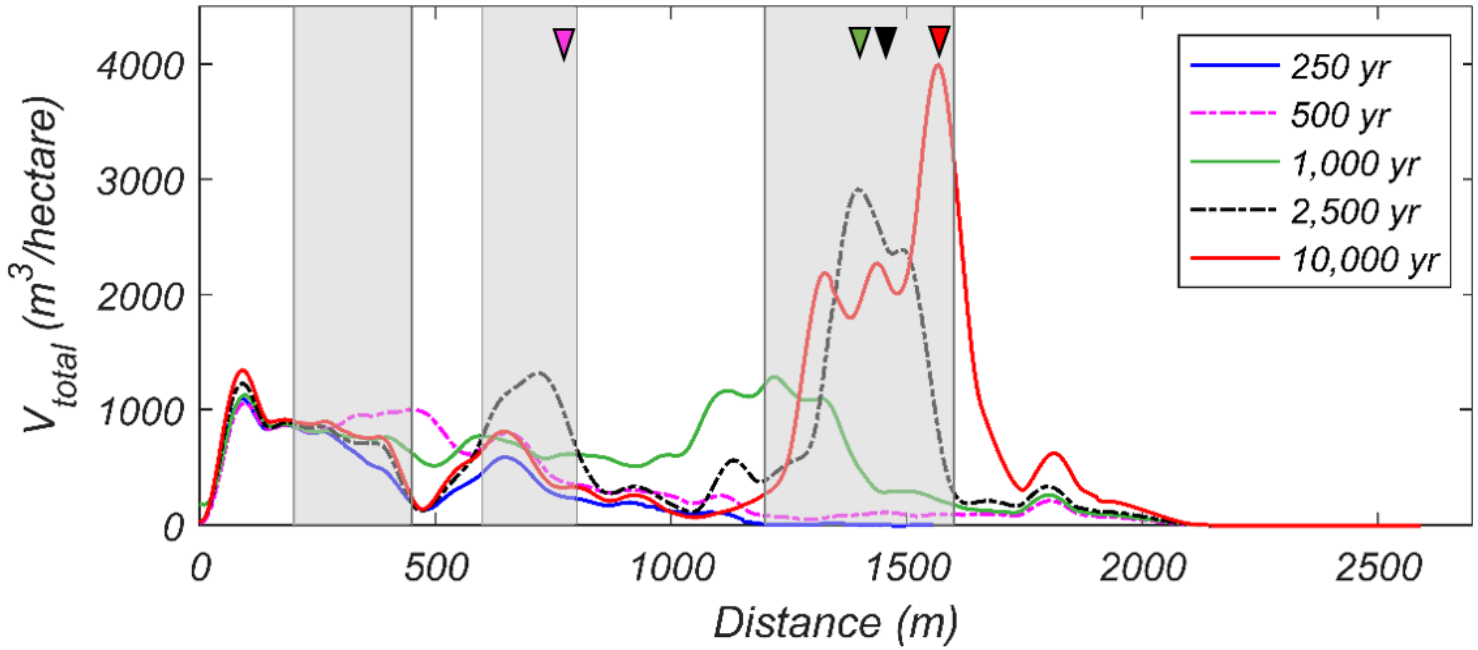
Volume of Building Debris in Seaside Generated by CSZ Earthquake and Tsunami



Shoreline

Inland

Volume of Building Debris Generated in Seaside by CSZ Earthquake and Tsunami with Transport



Shoreline

Inland

Post-event Community Connectivity and Access to Critical Facilities

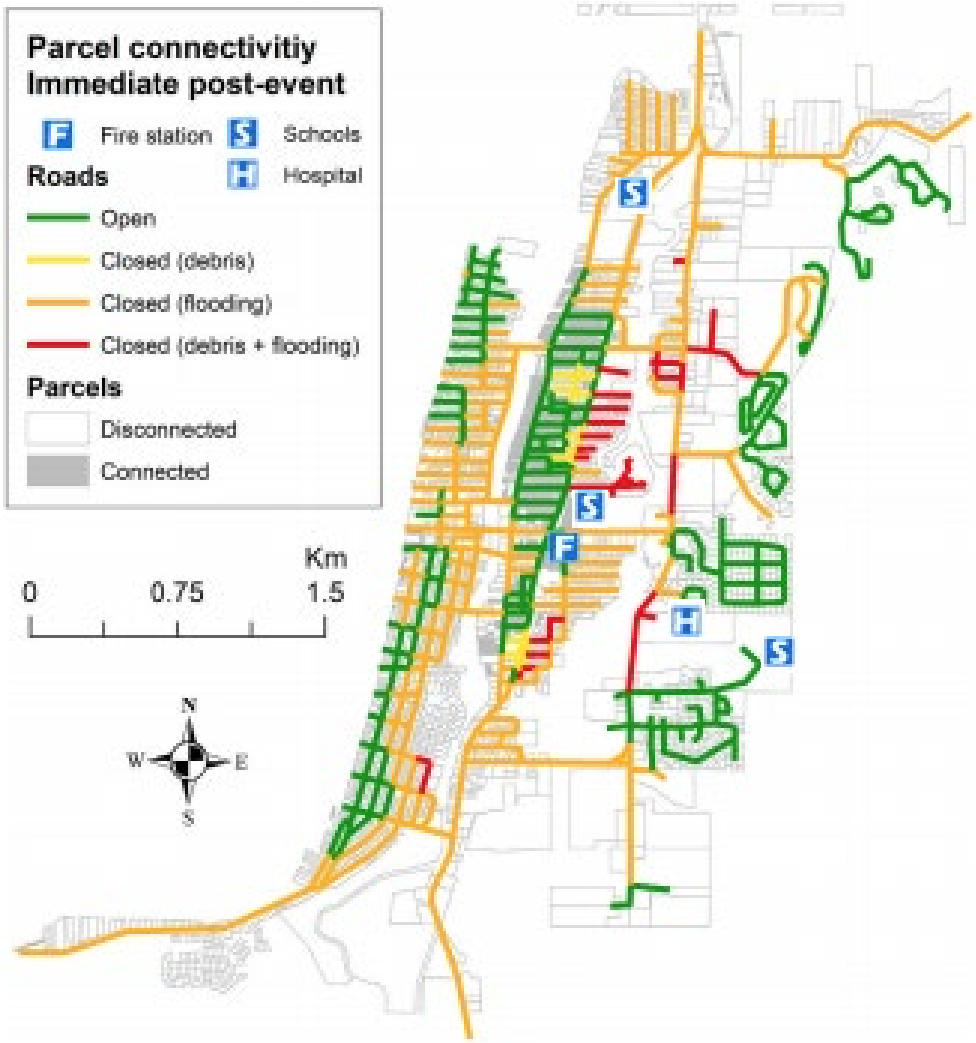
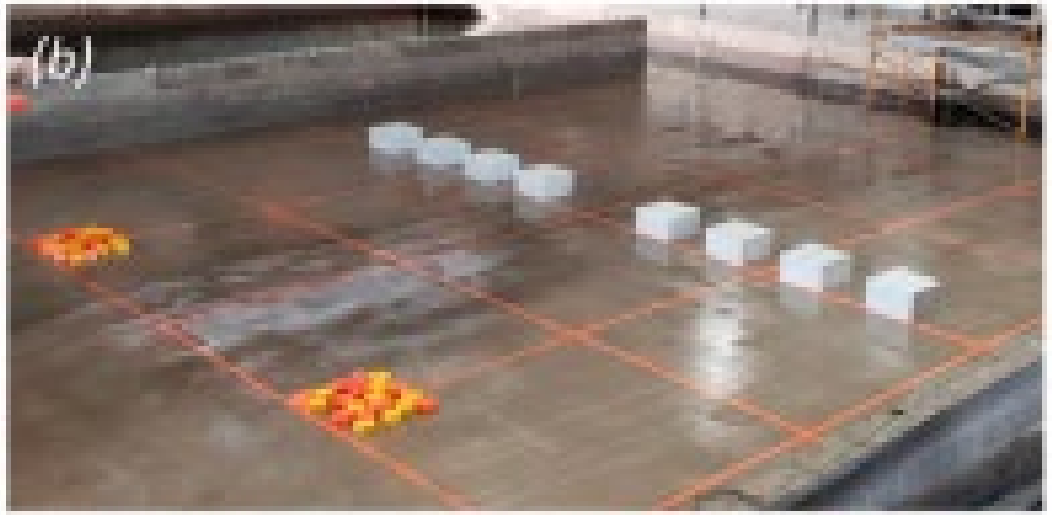


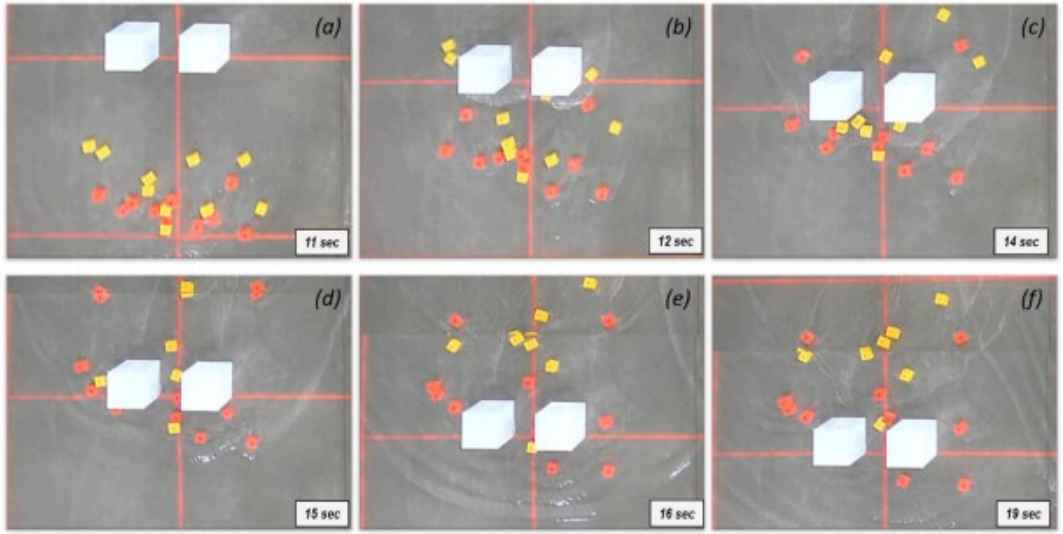
Table 1
Likelihood of accessing hospitals and the high school immediately after tsunami events.

(a) Connectivity to hospital					
Return period	AA #2	AA #5	AA #6	AA #7	AA #8
250	0.84	1.00	1.00	1.00	0.99
500	0.67	1.00	1.00	1.00	0.82
1000	0.00	0.00	0.00	0.00	0.00
2500	0.00	0.00	1.00	0.00	0.00
5000	0.00	0.00	0.00	0.00	0.00
10000	0.00	0.00	0.00	0.00	0.00

(b) Connectivity to high school					
Return period	AA #2	AA #5	AA #6	AA #7	AA #8
250	0.83	0.99	0.99	0.99	1.00
500	0.63	0.95	0.95	0.95	0.86
1000	0.10	0.00	0.34	0.02	0.32
2500	0.01	0.00	0.05	0.00	0.04
5000	0.00	0.00	0.00	0.00	0.04
10000	0.00	0.00	0.00	0.00	0.02

Kameshwar S, H Park, DT Cox, AR Barbosa (2021) "Effect of disaster debris, flood duration, and bridge damage on immediate post-tsunami connectivity," *Int. J. Disaster Risk Reduction*, https://doi.org/10.1016/j.ijdrr.2021.102119.

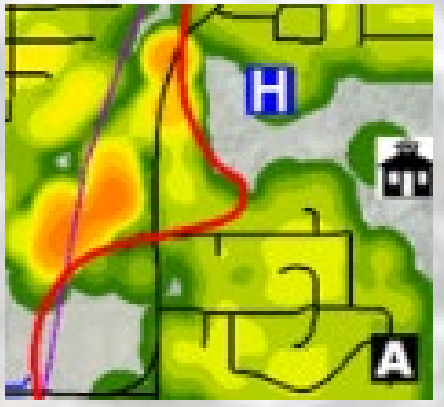


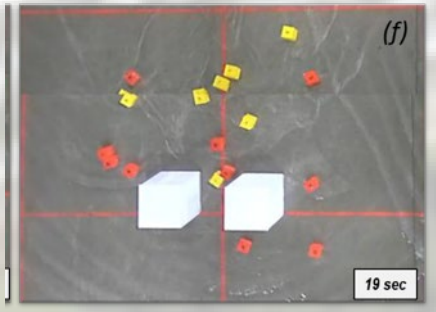


Park HS, MJ Koh, DT Cox, MS Alam, S Shin, (2021) “Experimental study of debris transport driven by a tsunami-like wave: Application for non-uniform density groups and obstacles,” *Coastal Engineering*, 166, doi.org/10.1016/j.coastaleng.2021.103867

Future Work for Debris

- Debris and subsequent damage
- Other Debris Sources – vegetation; vehicles
- Non-buoyant debris – buildings; sand, rock
- How to generalize the results?
  - Local topography and land use to screen for ‘hot spots’?
- Debris clearance/removal
- Seismic debris and tsunami evacuation
- Verification and validation





Thank you!

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Center for Risk-Based Community Resilience Planning
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