



36TH INTERNATIONAL CONFERENCE ON COASTAL ENGINEERING 2018

Baltimore, Maryland | July 30 – August 3, 2018

The State of the Art and Science of Coastal Engineering

Probabilistic Tsunami Hazard Assessment (PTHA) And Damage Assessment (PTDA) of the Built Environment: Application to the Cascadia Subduction Zone and Seaside, Oregon

Dan Cox¹, Hyoungsu Park¹, Mohamad Shafiquel Alam², Andre Barbosa²

¹Coastal and Ocean Engineering Program ²Structural Engineering Program
School of Civil and Construction Engineering, Oregon State University



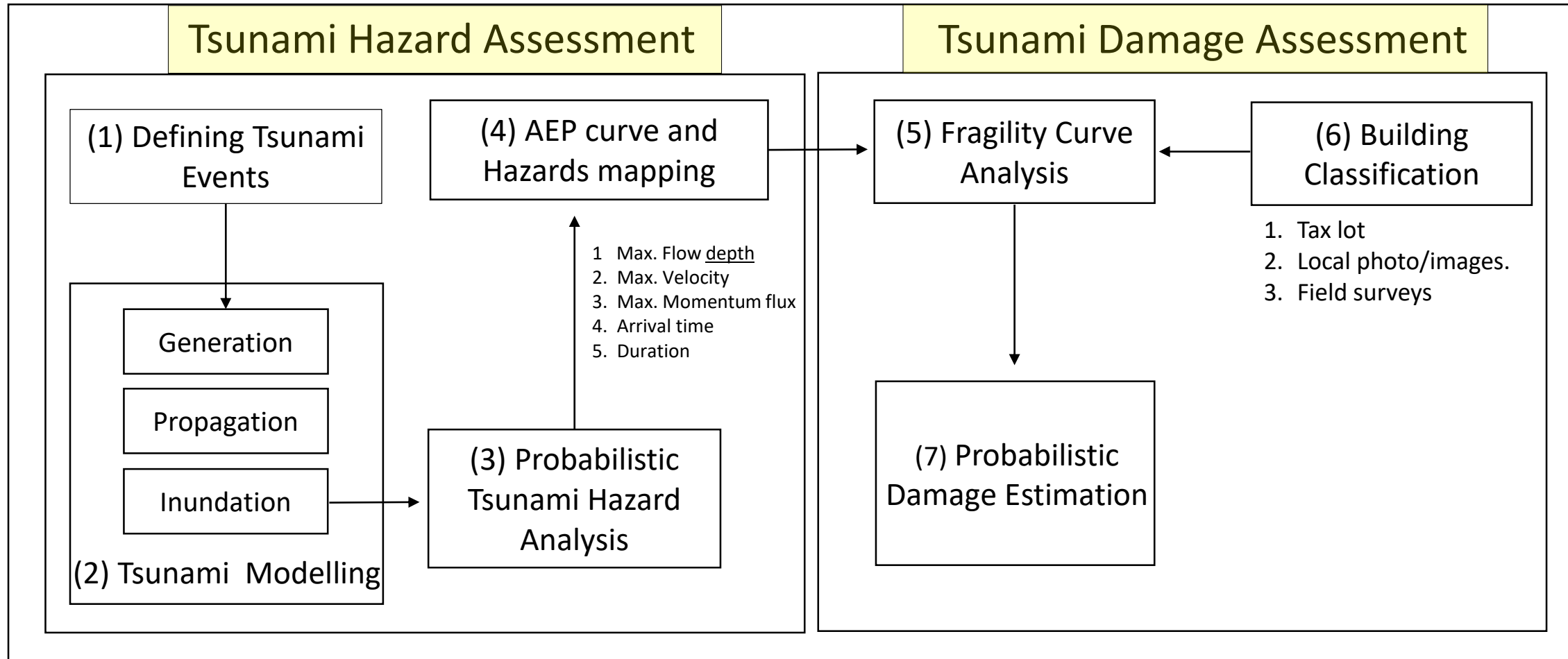
Center for Risk-Based Community Resilience Planning
A NIST-funded Center of Excellence



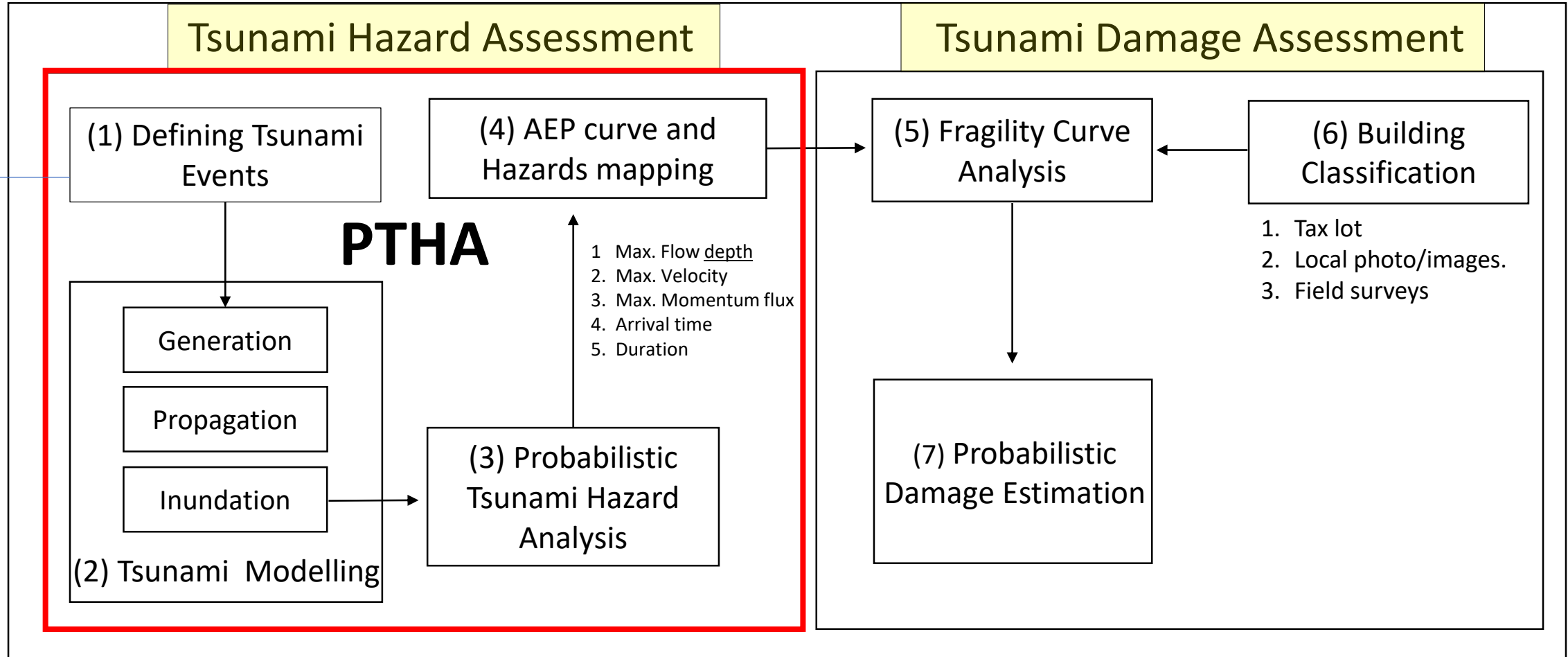
$$\text{Risk} = \text{Hazard Probability} \times \text{Negative Consequence}$$

1970's	PSHA	Probabilistic Seismic <i>Hazard</i> Analysis	→	PSDA	Probabilistic Seismic <i>Damage</i> Analysis
2000's	PTHA	Probabilistic Tsunami <i>Hazard</i> Analysis	→	PTDA	Probabilistic Tsunami <i>Damage</i> Analysis
2010's	PSTHA	Probabilistic Seismic and Tsunami <i>Hazard</i> Analysis	→	PSTDA	Probabilistic Seismic and Tsunami <i>Damage</i> Analysis

Methodology of PTHA, PTDA

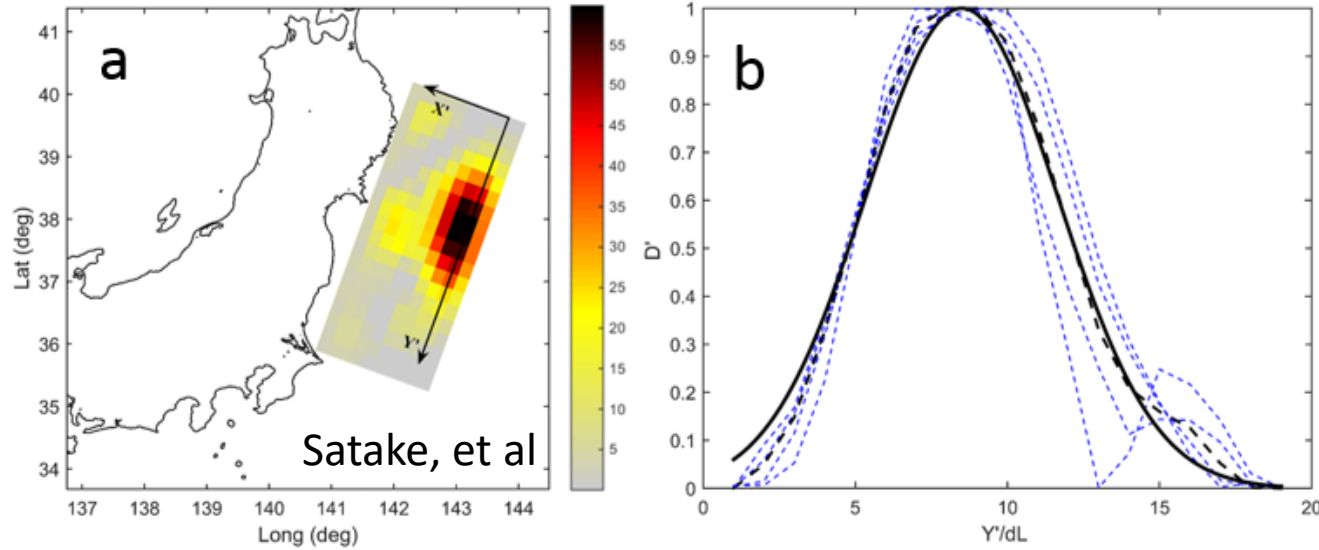


Methodology of PTHA, PTDA

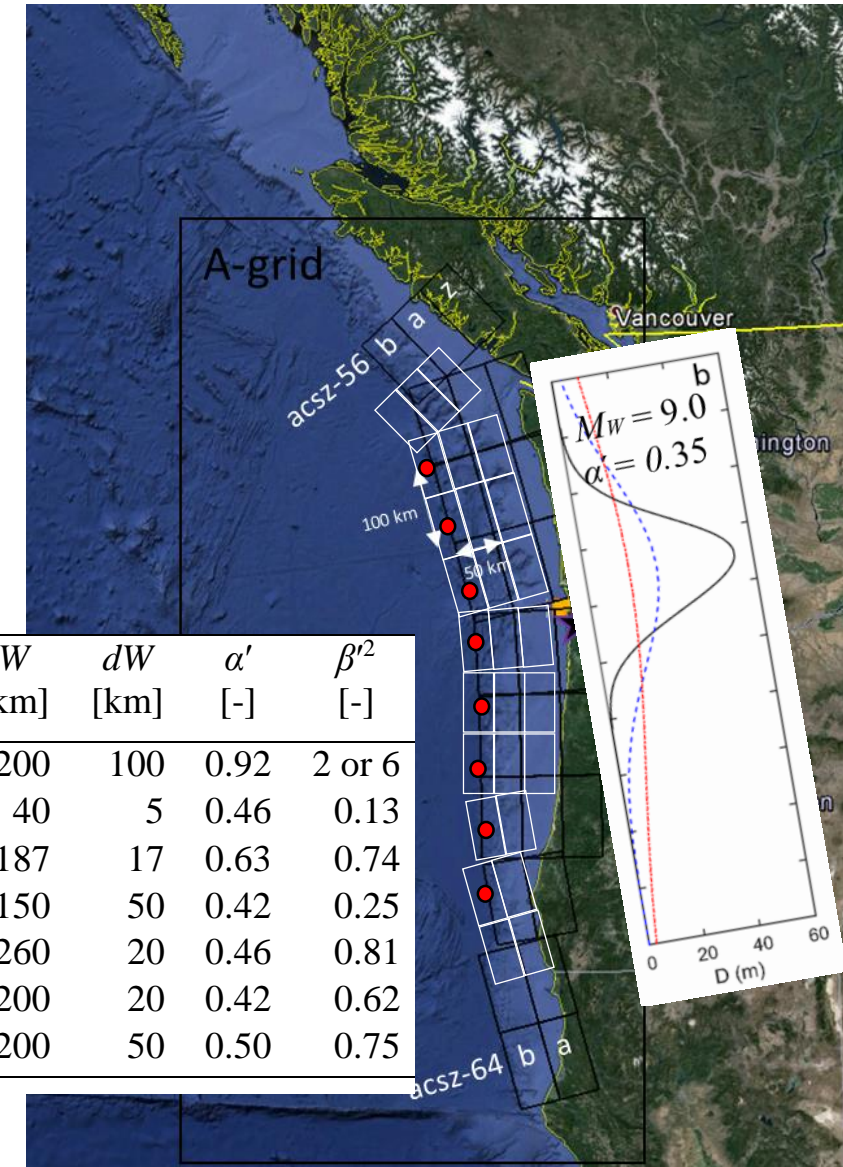


PSHA using conventional GMPE

1) Inversion model results



4) Applying as input sub-faults in model



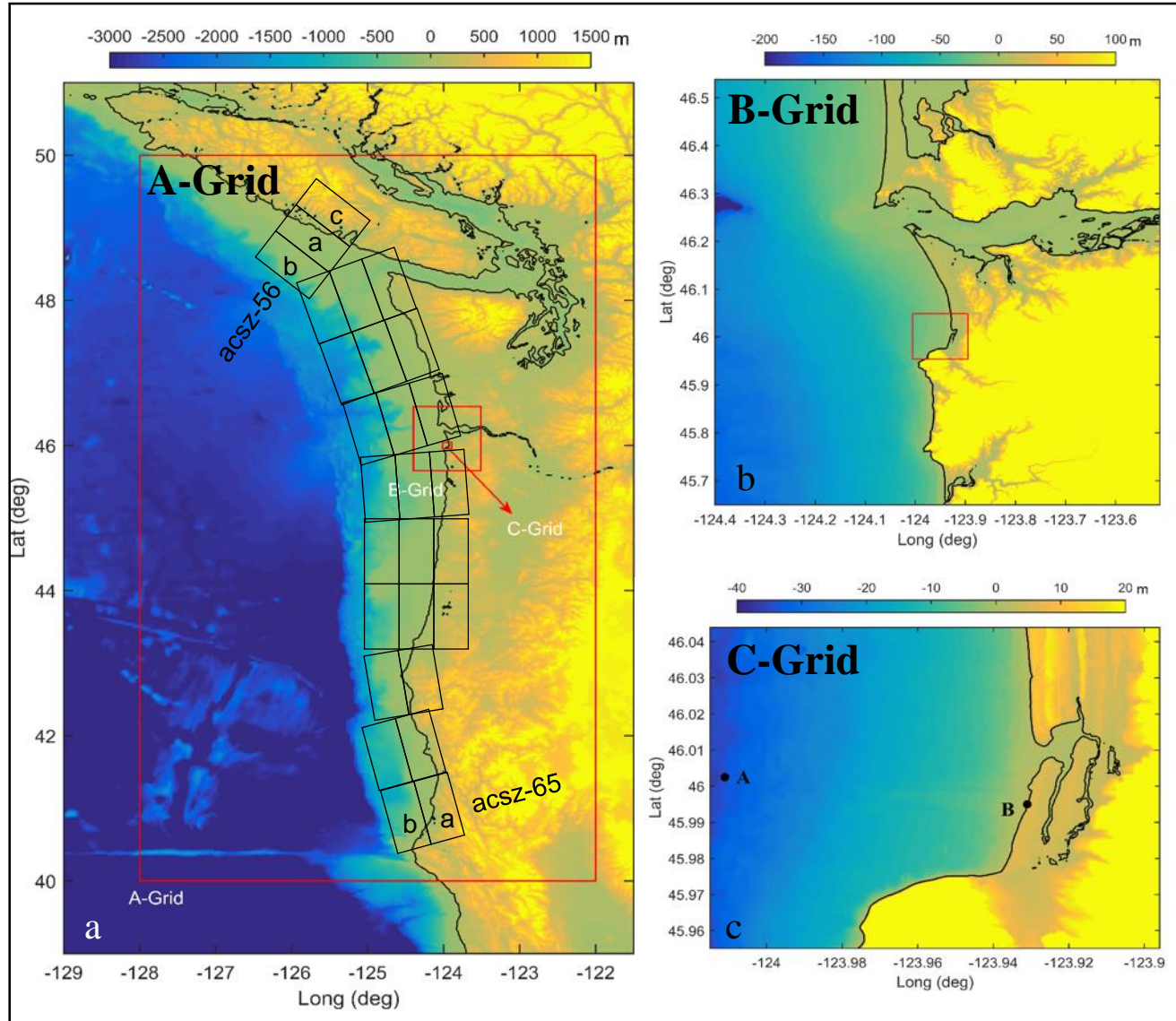
2) New tsunami slip model using a Gaussian distribution

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

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

Bathymetry of two numerical models

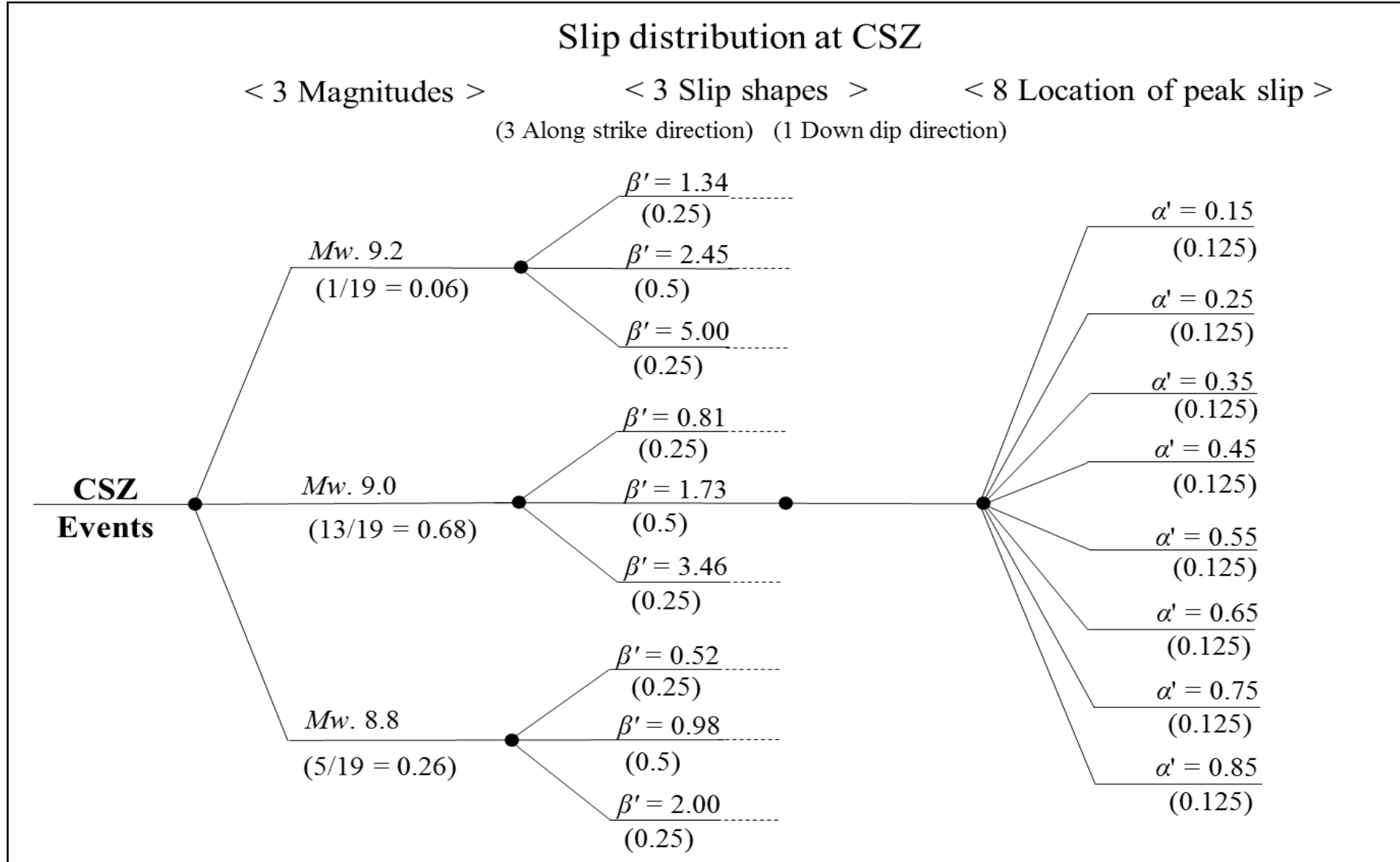


- ComMIT/MOST(NOAA) } A & B-Grid
- COULWAVE } Only C-Grid

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

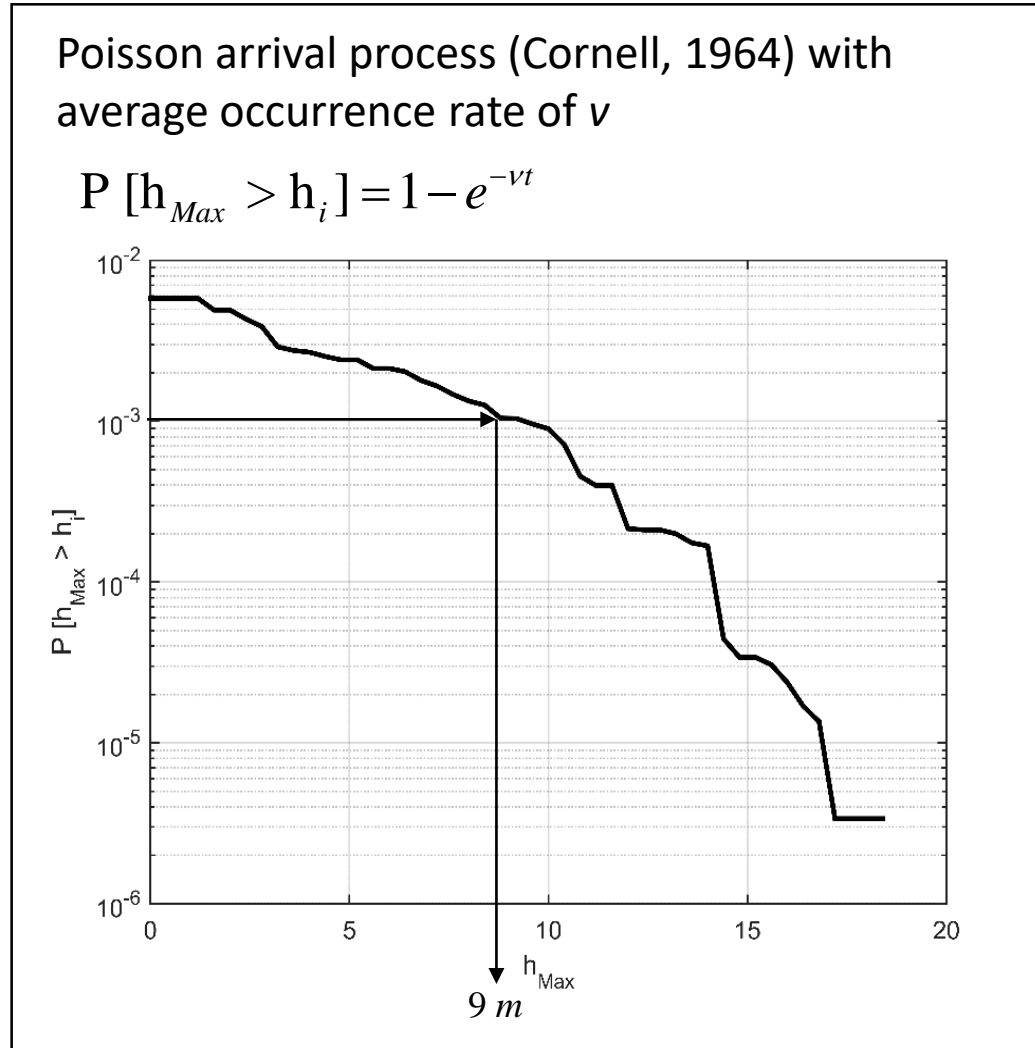
- Following default setup for each models
- Default friction, $n = 0.03$.

Logic tree model



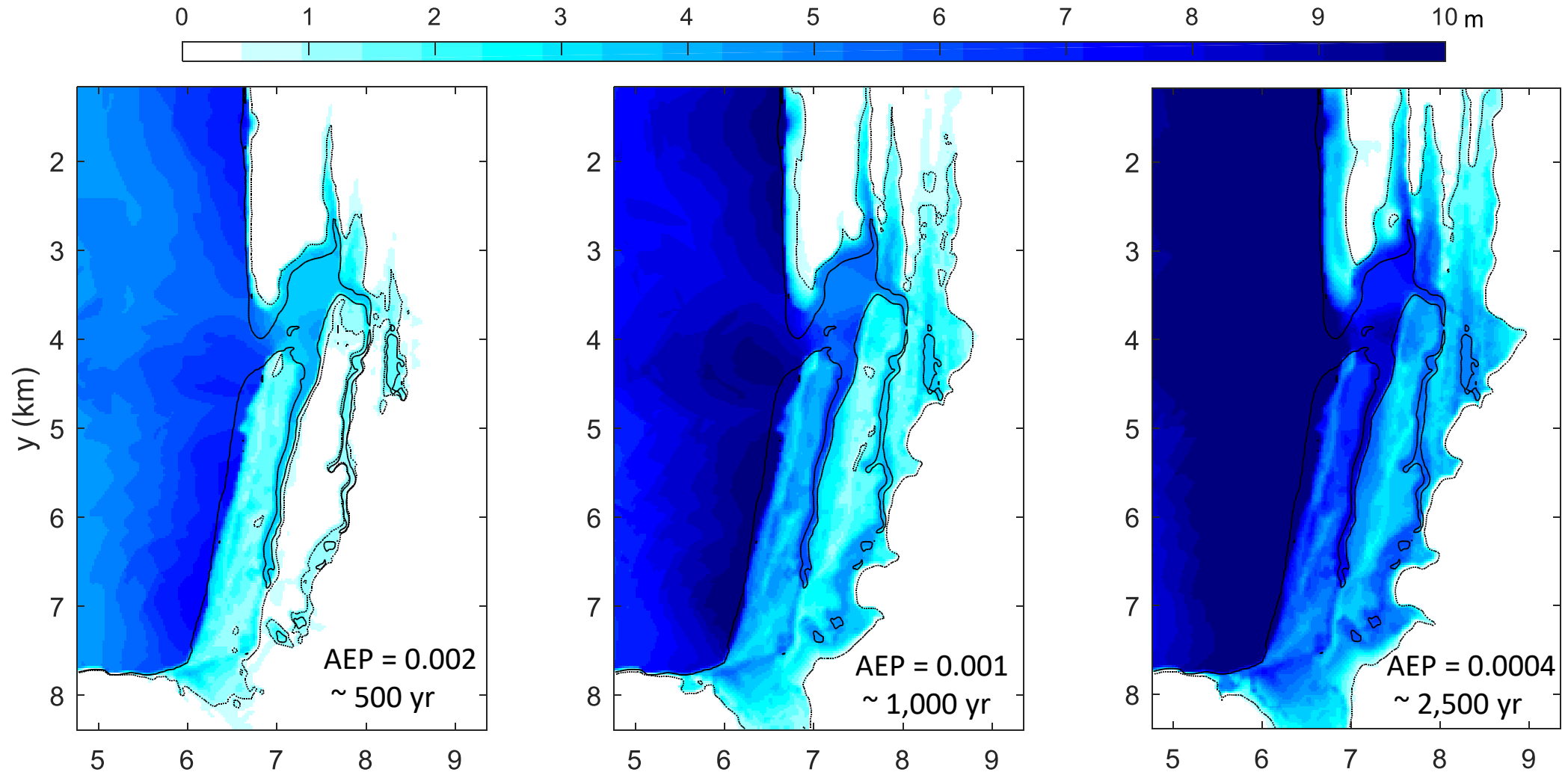
Calculating annual exceedance probability (AEP) of IMs

AEP = 0.001 ~ 1,000 yr



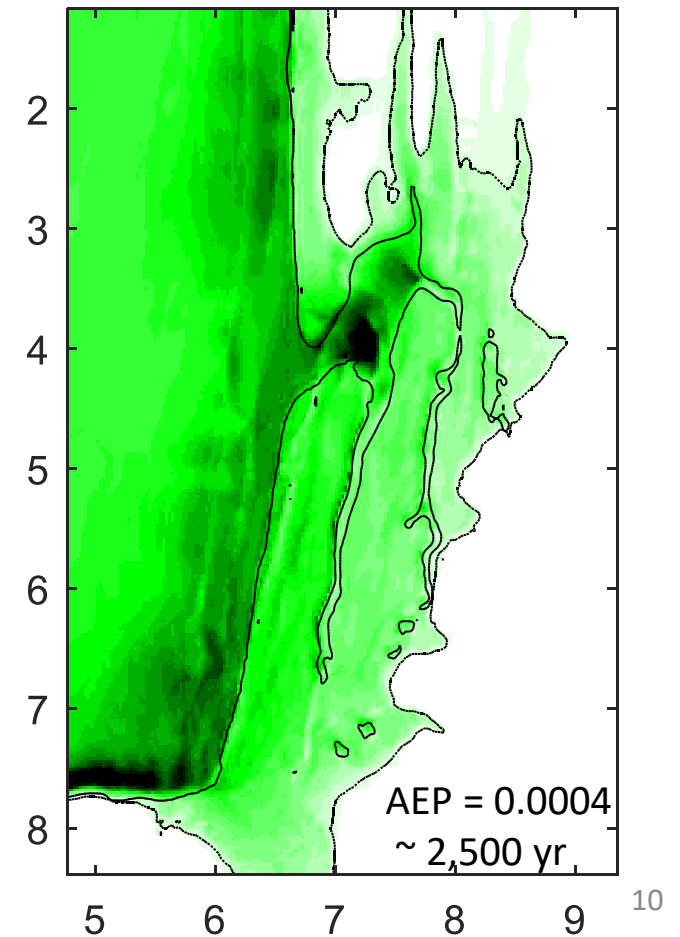
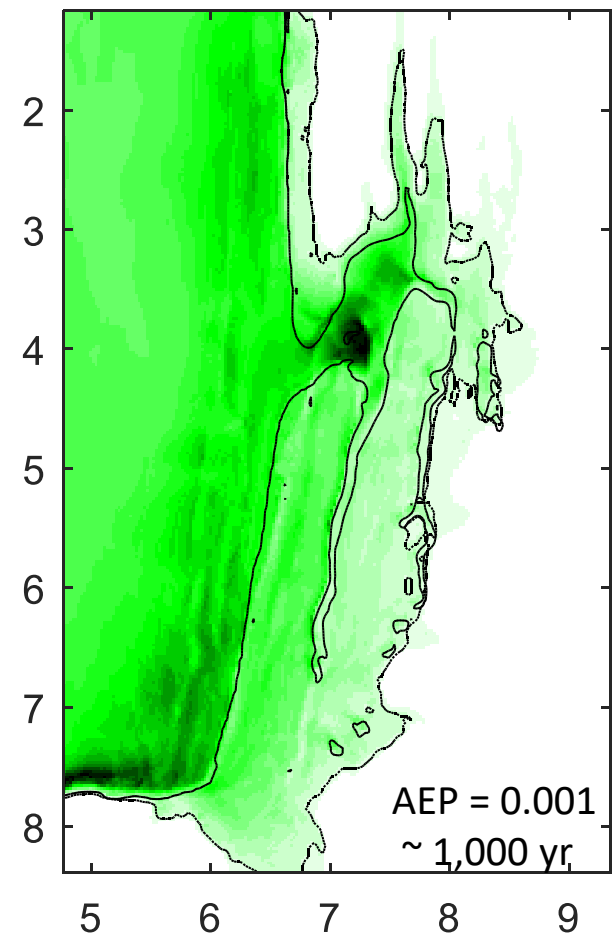
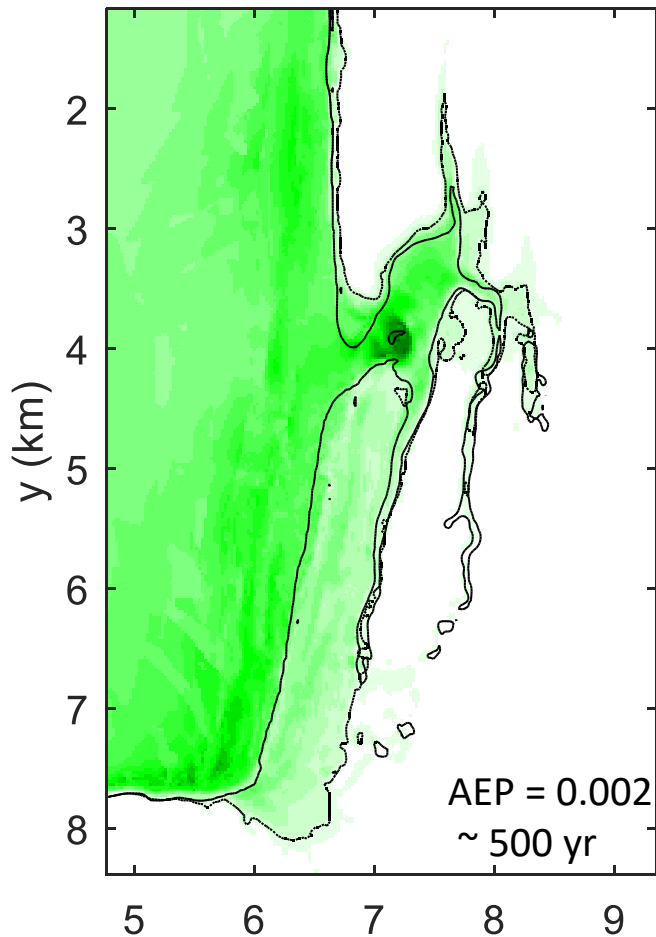
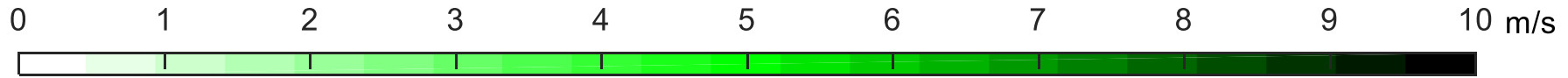
Hazards map at Seaside, OR

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



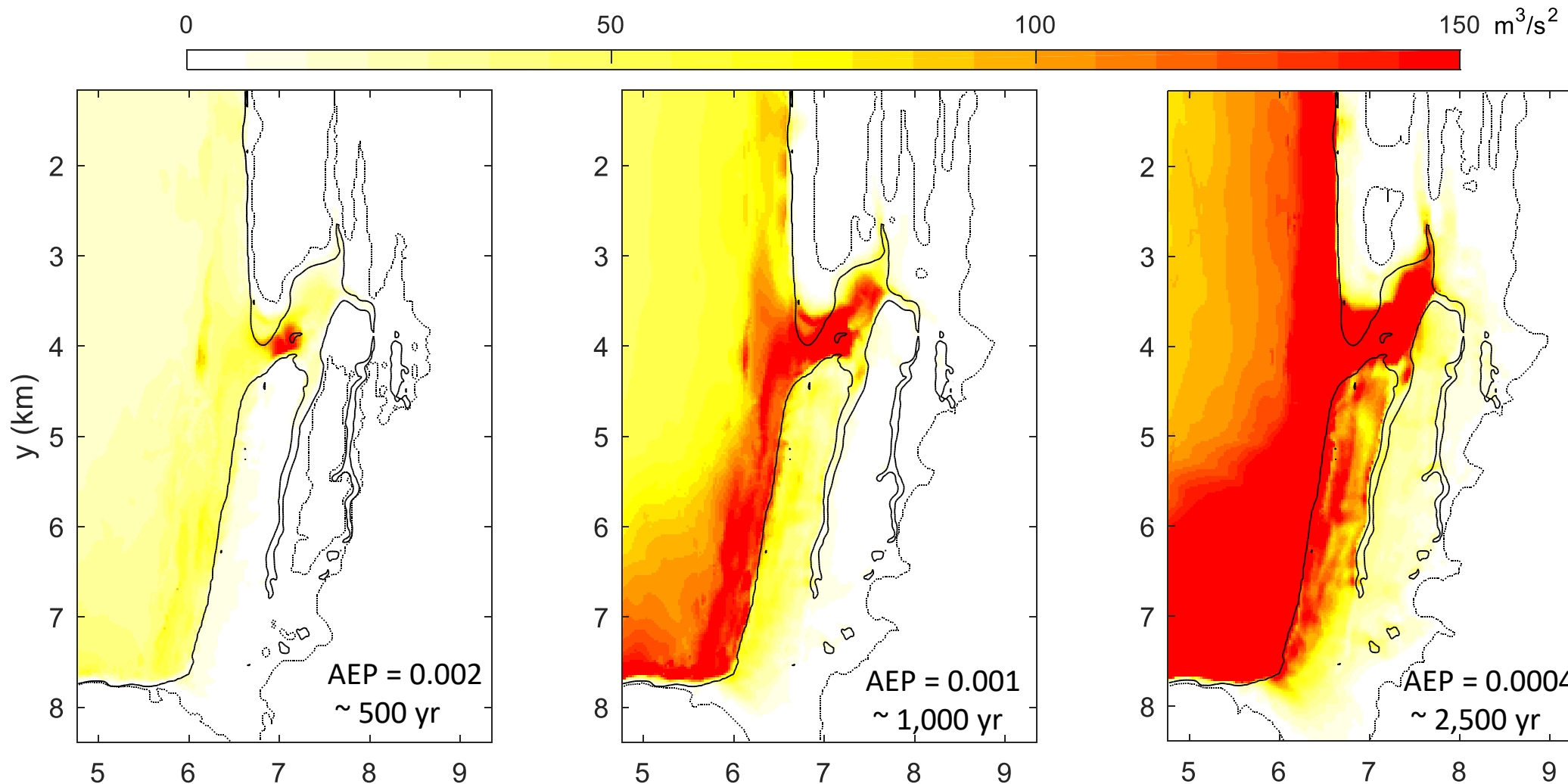
Hazards map at Seaside, OR

Example: Max. Velocity (V_{max})



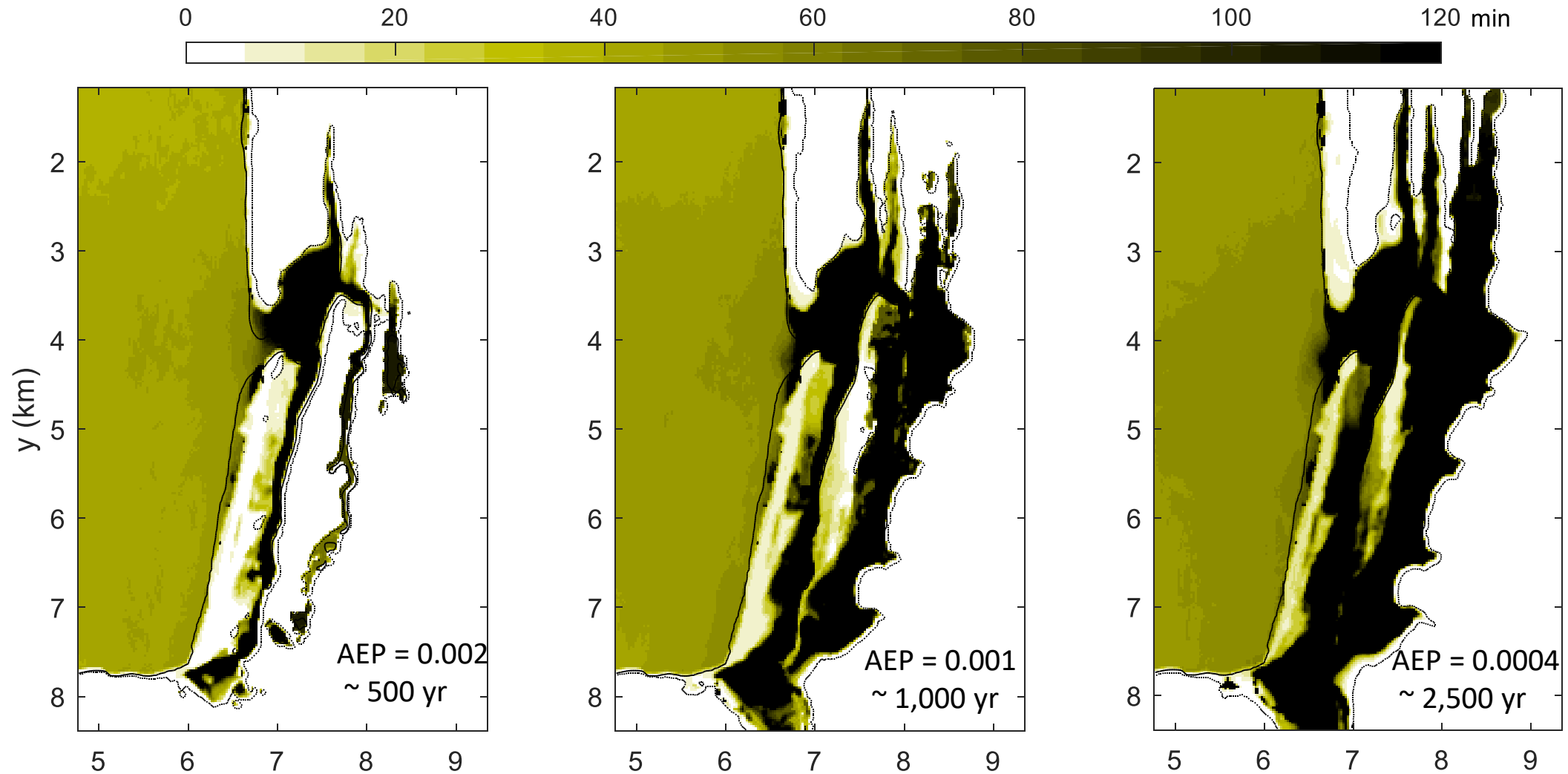
Hazards map at Seaside, OR

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



Hazards map at Seaside, OR

Example: Duration time (T_D)



PTHA Comparison for Newport, Oregon

Park and Cox, 2017

ASCE 7-16

DOGAMI "M"

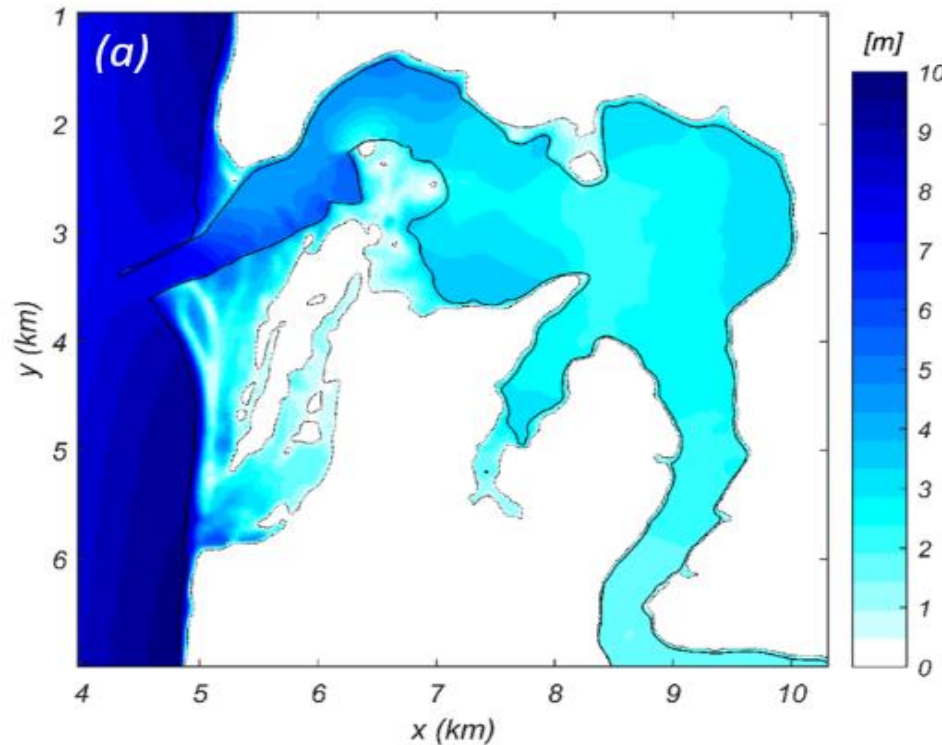
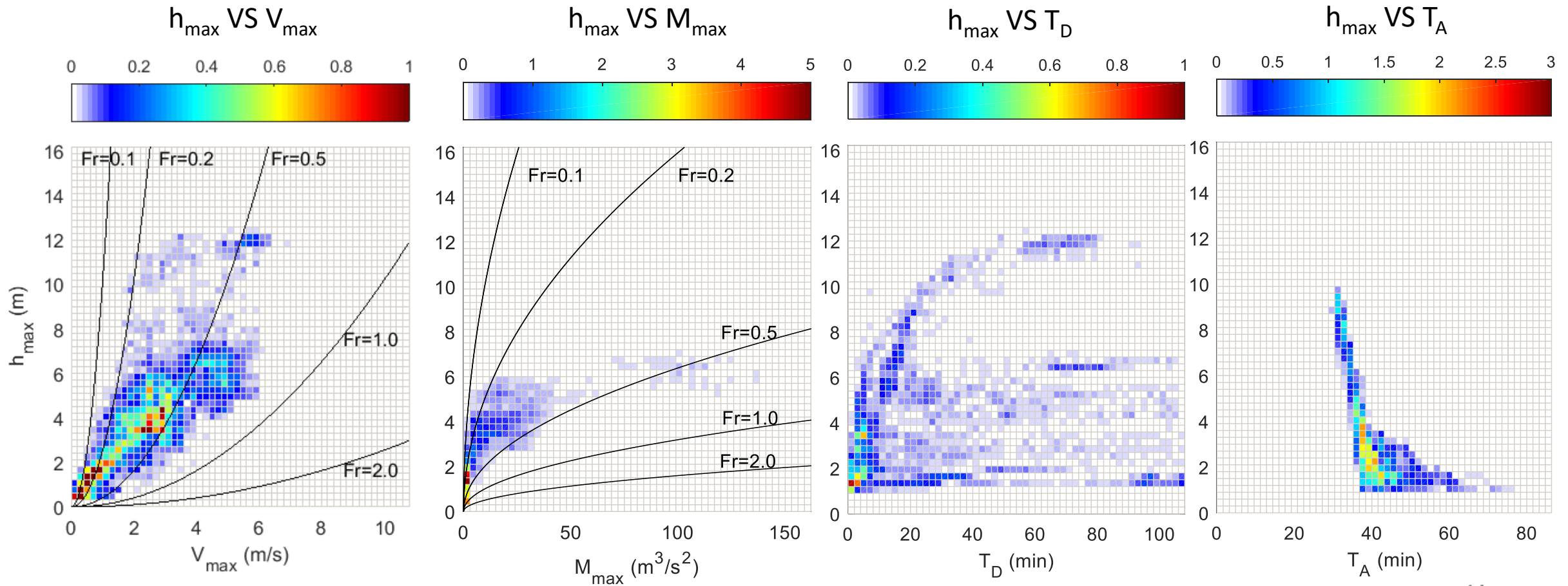


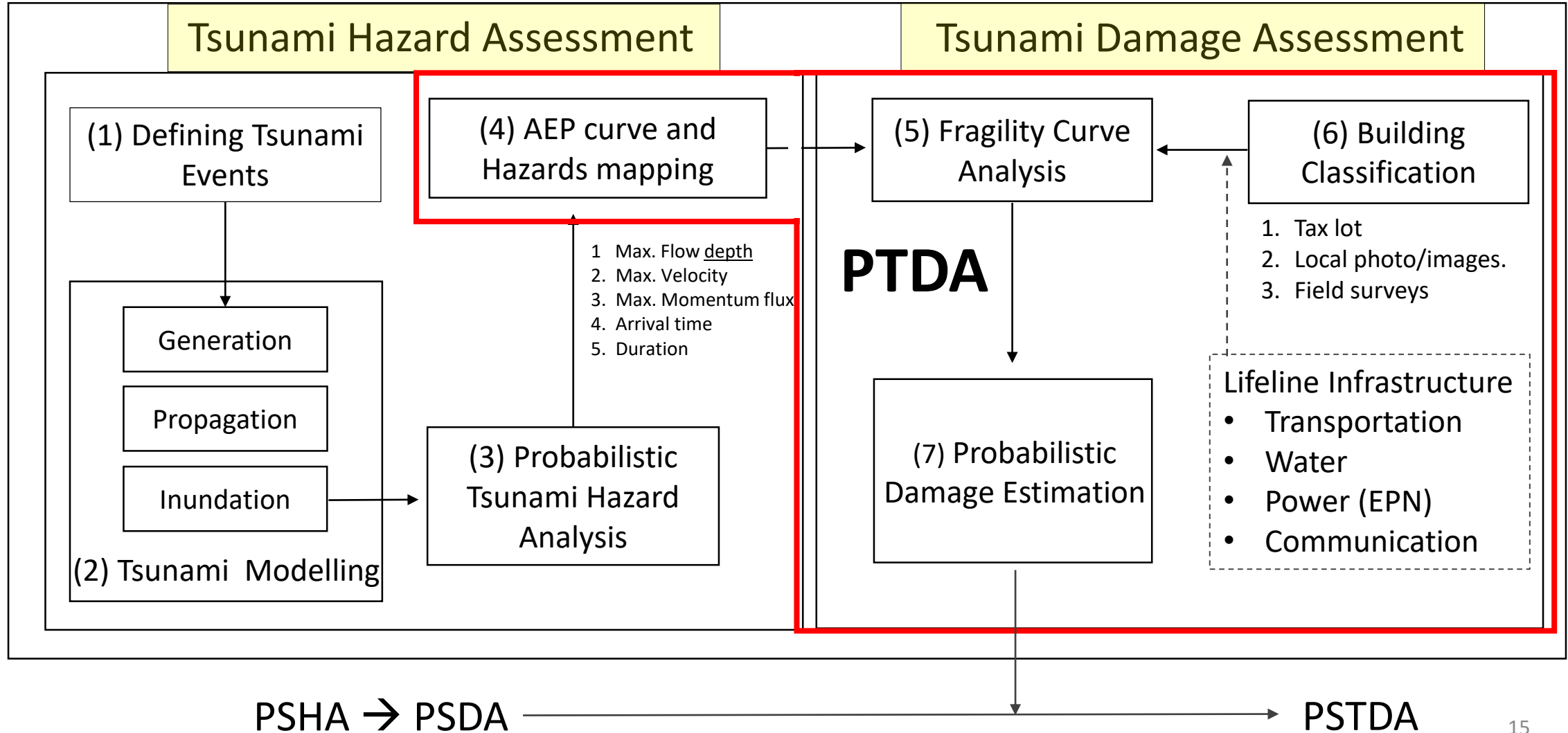
Figure 7: Comparison of maximum extent of tsunami inundation in Newport, Oregon, for (a) present study with AEP = 0.0004, (b) ASCE Tsunami Design Geodatabase (TDG) for AEP = 0.0004, and (c) DOGAMI TIM, 'M' scenario (b and c are courtesy of ASCE TDG and Oregon Department of Geology and Mineral Industries).

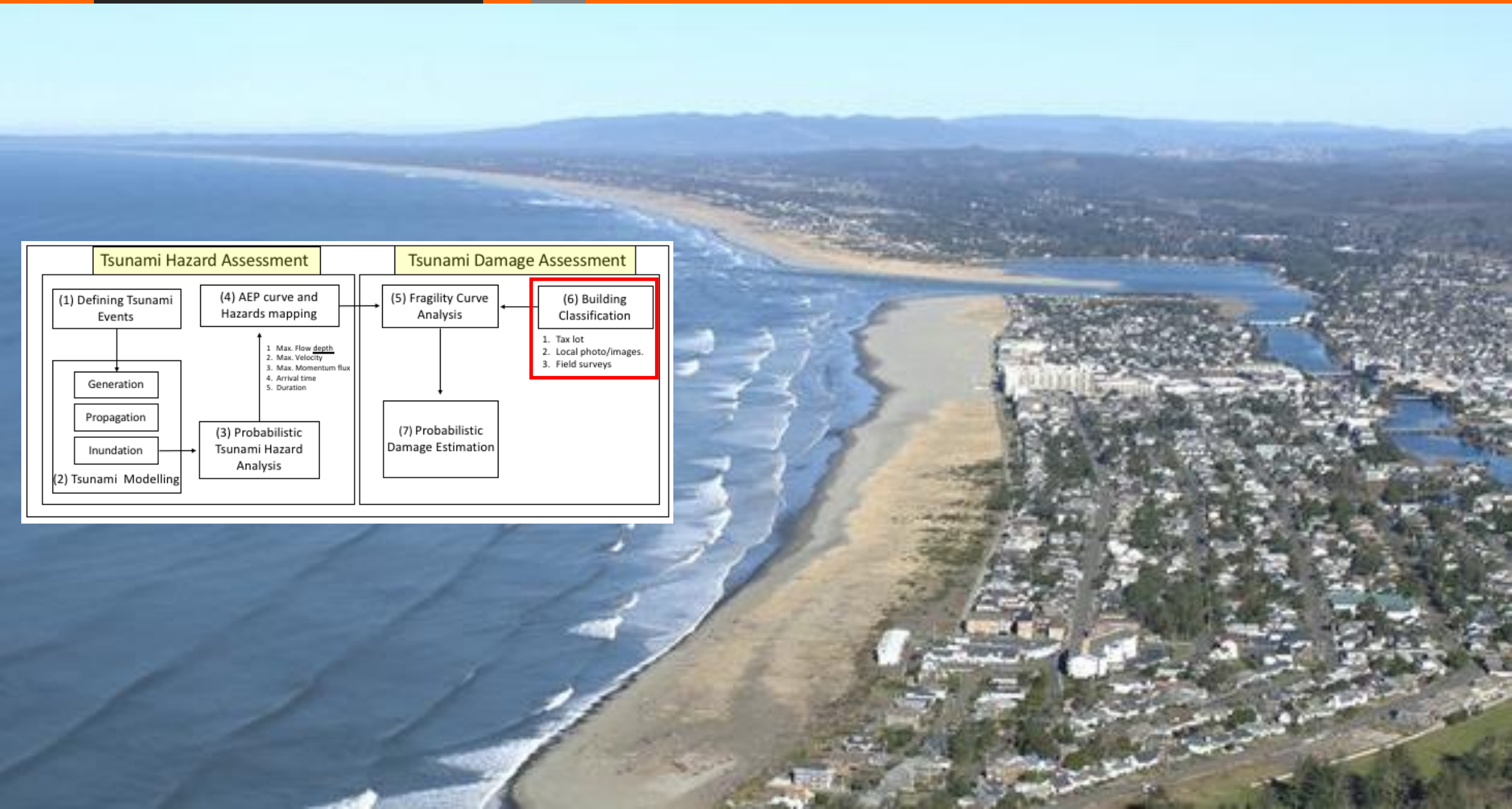
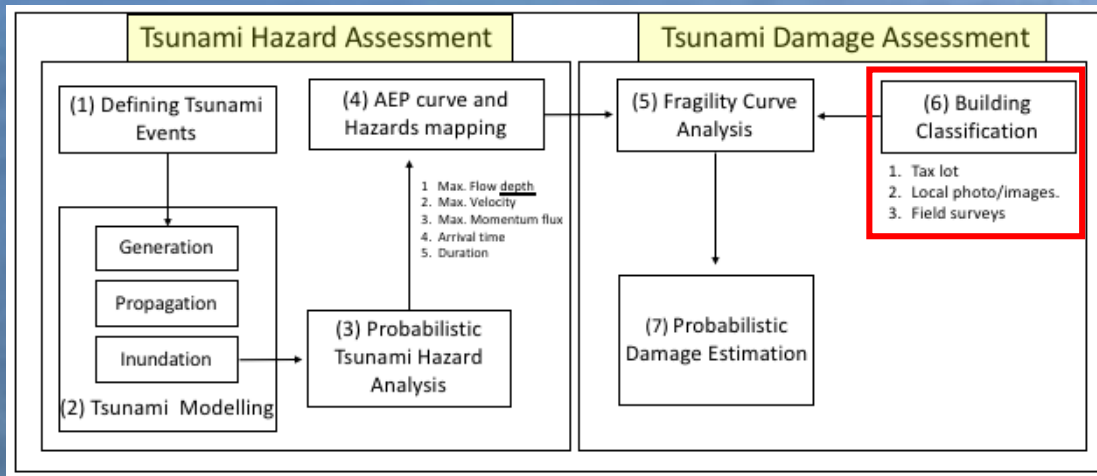
2. Joint Distributions of IMs

- Correlation or relationship among h_{max} and other IMs



Methodology of PTHA, PTDA







(6) Building classification

Three tools for building information at study area

1. Tax lot (Stat_Class, Year)

2. Pictures from Google map street view

3. Fields survey
Rapid Visual Screening (RVS)



Rapid Visual Screening of Buildings for Potential Seismic Hazards
FEMA P-154 Data Collection Form

Level 1
VERY HIGH Seismicity

Address: 26 Ave H, Zip: _____
 Other Identifiers: 06
 Building Name: Wordmark seaside
 Use: Hotel, multiple buildings
 Latitude: 46.9929 Longitude: -123.9296
 S: _____ HPData/Time: 07/18/15, 11:45 AM
 No. Stories: Above Grade: 8 Below Grade: _____ Year Built: 2007
 Total Floor Area (sq. ft.): 532,264 Code Year: _____
 Occupancy: Assembly Commercial Emer. Services Historic Shelter
 Industrial Office School Government
 Warehouse Utility Residential # Units: _____
 Soil Type: A B C D E F G H I J K L M N O P Q R S T U V W X Y Z Other (specify) _____
 Geologic Hazards: Liquefaction: Yes/No/DNK Landslide: Yes/No/DNK Surf. Rupt.: Yes/No/DNK
 Adjacency: Founding Falling Hazards from Taller Adjacent Building
 Irregularities: Vertical (top/sloveness) Plan (type) reentrant corner
 Exterior Falling Hazards: Unbraced Chimneys Heavy Chidding or Heavy Veneer Appendages Parapets Other: Glasses
 COMMENTS: 288 condors, 1600 parking, PC2
 -Multiple adjacent building.
 -Construction joint not visible
 -Ground floor is used for commercial purpose.
 Additional sketches or comments on separate page

FEMA BUILDING TYPE	Do Not Know	W1	W1A	W2	S1 (W1)	S2 (W1)	S3 (W1)	S4 (W1)	S5 (W1)	C1 (W1)	C2 (W1)	C3 (W1)	PC1 (W1)	PC2 (W1)	RM1 (W1)	RM2 (W1)	URM	MH
Basic Score		2.1	1.9	1.8	1.5	1.4	1.6	1.4	1.2	1.8	1.2	0.9	1.1	1.0	1.1	1.1	0.8	1.1
Severe Vertical Impairity, V _v		-0.9	-0.9	-0.8	-0.7	-0.8	-0.7	-0.7	-0.7	-0.8	-0.8	-0.7	-0.7	-0.7	-0.7	-0.7	-0.6	NA
Moderate Vertical Impairity, V _m		0.6	0.5	0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.3	NA
Plus Impairity, P ₊		-0.7	-0.7	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	NA
Pre-Code		-0.3	-0.3	-0.3	-0.2	-0.2	-0.2	-0.2	-0.1	-0.1	-0.2	-0.2	-0.1	-0.2	-0.2	-0.2	0.0	0.0
Plus-Benchmark		1.9	1.8	2.0	1.7	1.1	1.1	1.5	NA	1.4	1.7	NA	1.5	1.7	1.6	1.6	NA	2.0
Soil Type A or B		0.5	0.5	0.4	0.3	0.3	0.4	0.3	0.2	0.3	0.1	0.3	0.2	0.3	0.3	0.3	0.1	0.1
Soil Type E (1-3 stories)		0.0	-0.2	-0.4	-0.3	-0.2	-0.2	-0.2	-0.1	-0.1	-0.2	0.0	-0.2	-0.1	-0.2	-0.1	-0.2	0.0
Soil Type E (-3 stories)		-0.4	-0.4	-0.4	-0.3	-0.3	NA	-0.3	-0.1	-0.1	-0.3	-0.1	NA	-0.1	-0.2	-0.2	0.0	NA
Minimum Score, S _{min}		0.7	0.7	0.7	0.5	0.5	0.5	0.5	0.3	0.2	0.3	0.2	0.2	0.3	0.2	0.2	0.2	0.0

FINAL LEVEL 1 SCORE, S_{L1} = S_{min} 2.0 2.0 Use, 2.0

EXTENT OF REVIEW
 Exterior: Partial All Sides Aerial
 Interior: None Visible Entered
 Drawings Reviewed: Yes No
 Soil Type Source: _____
 Geologic Hazards Source: _____
 Contact Person: _____

OTHER HAZARDS
 Are There Hazards That Trigger A Detailed Structural Evaluation?
 Yes, score less than cut-off
 Yes, other hazards present
 No
 Falling hazards from taller adjacent building
 Geologic hazards or Soil Type F
 Significant damage/deterioration to the structural system

ACTION REQUIRED
 Detailed Structural Evaluation Required?
 Yes, unknown FEMA building type or other building
 Yes, score less than cut-off
 Yes, other hazards present
 No
 Detailed Nonstructural Evaluation Recommended? (check one)
 Yes, nonstructural hazards identified that should be evaluated
 No, nonstructural hazards exist that may require mitigation, but a detailed evaluation is not necessary
 No, no nonstructural hazards identified DNK

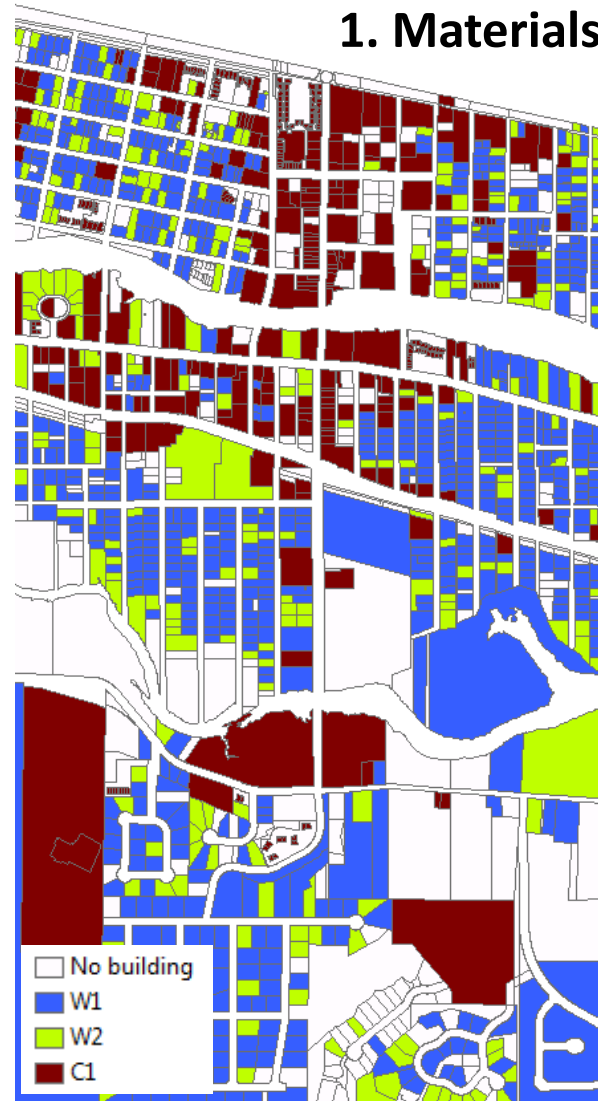
LEVEL 2 SCREENING PERFORMED?
 Yes, Final Level 2 Score, S_{L2} _____ No
 Nonstructural hazards? Yes No

Where information cannot be verified, screener shall note the following: EST = Estimated or unreliable data GR DNK = Do Not Know
 Legend: MB = Moment-resisting frame RC = Reinforced concrete URMB = Unreinforced masonry mbr BR = Braced frame SW = Shear wall TU = Tilt up OR = Unreinforced heavy mbr LM = Manufactured Housing PM = Precast diaphragm



Building Classification

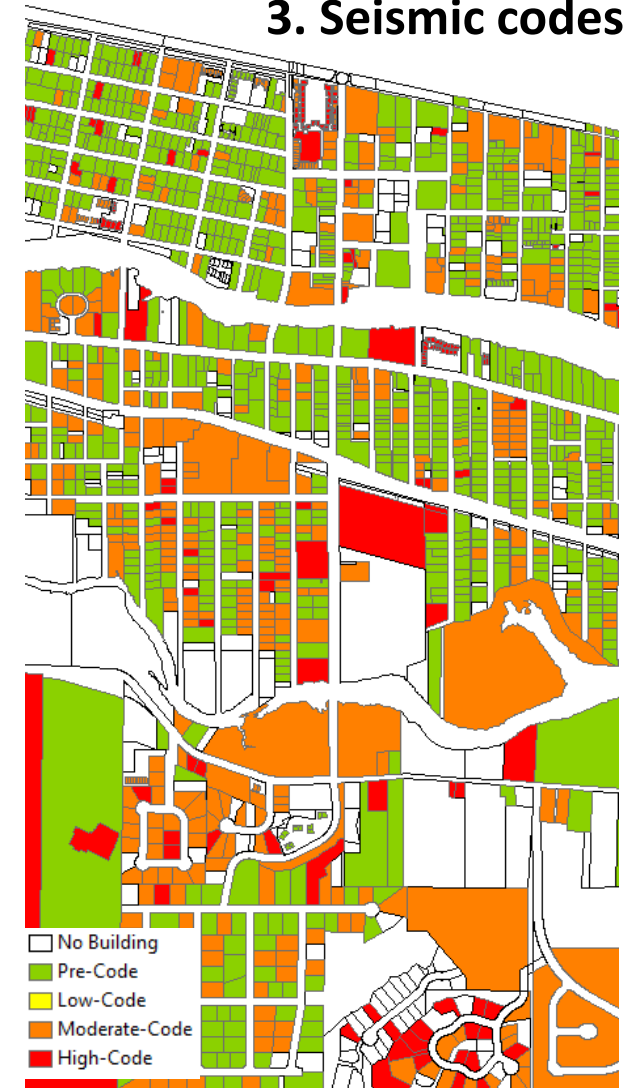
1. Materials



2. Floors

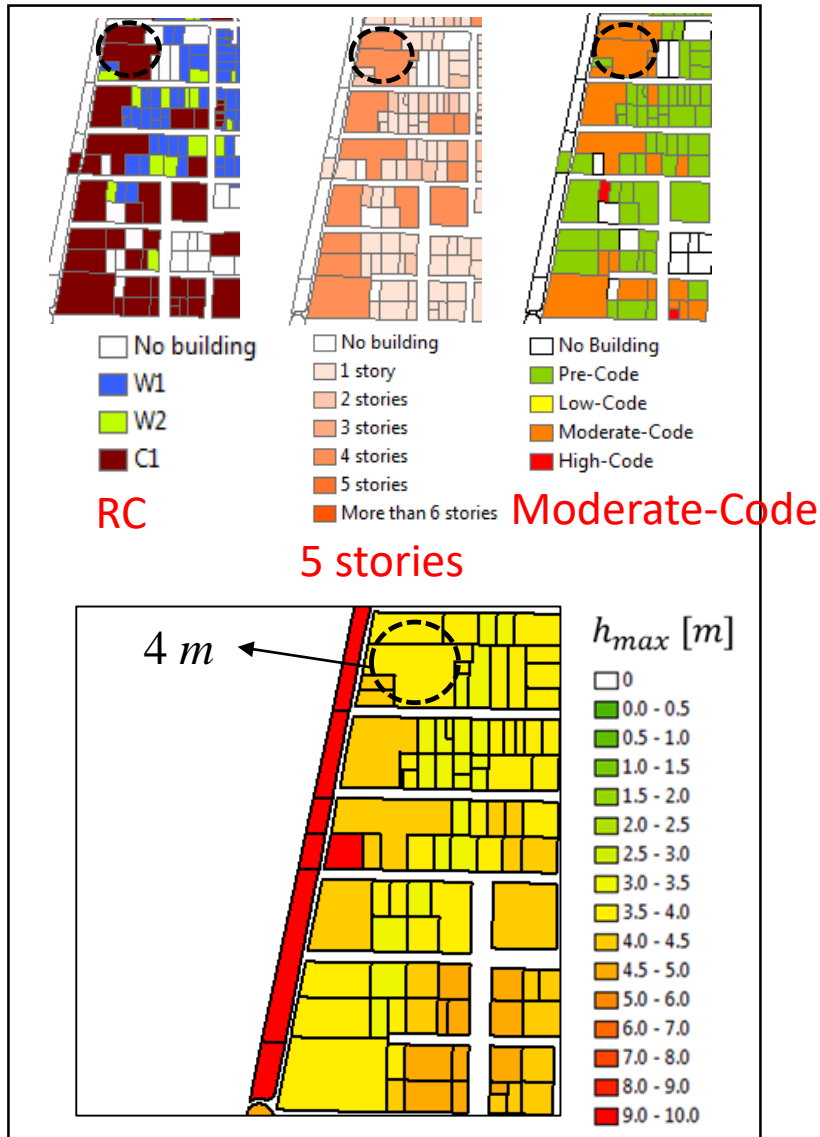


3. Seismic codes



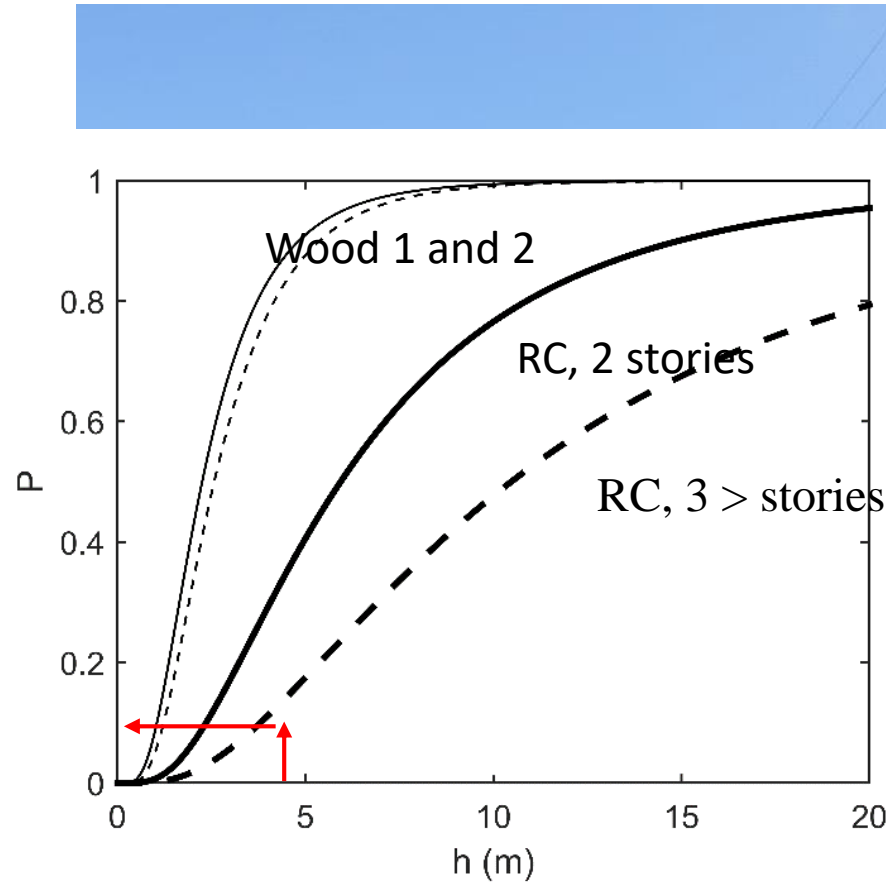
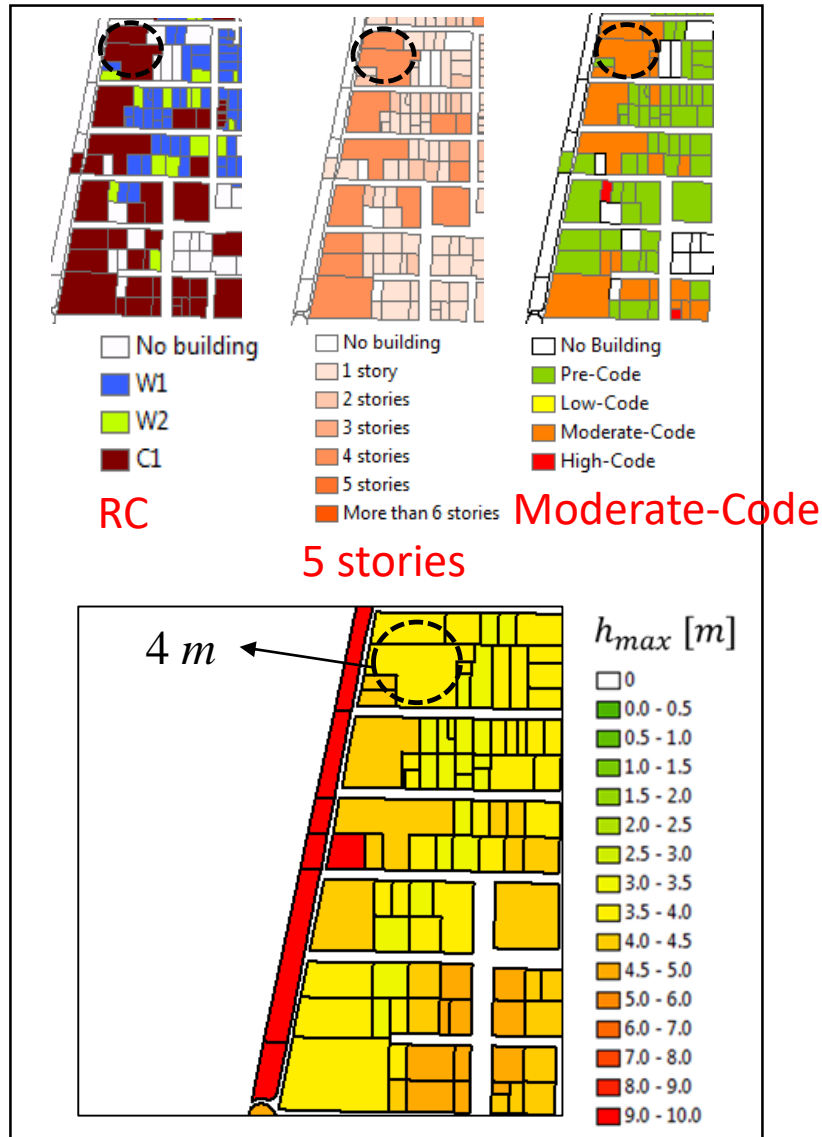
(7) Damage analysis

Example of building damage assessment (at AEP = 0.001)



(7) Damage analysis

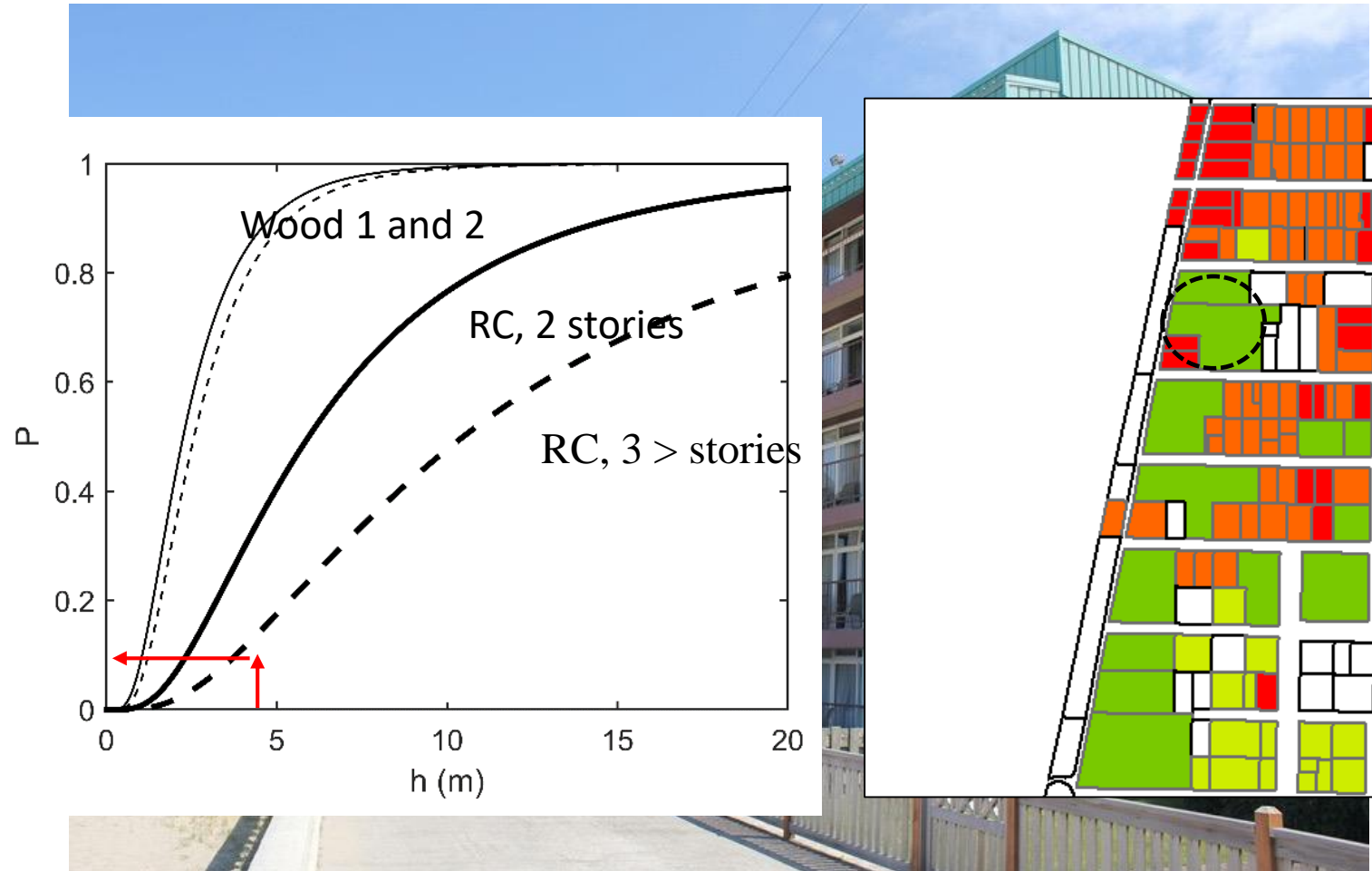
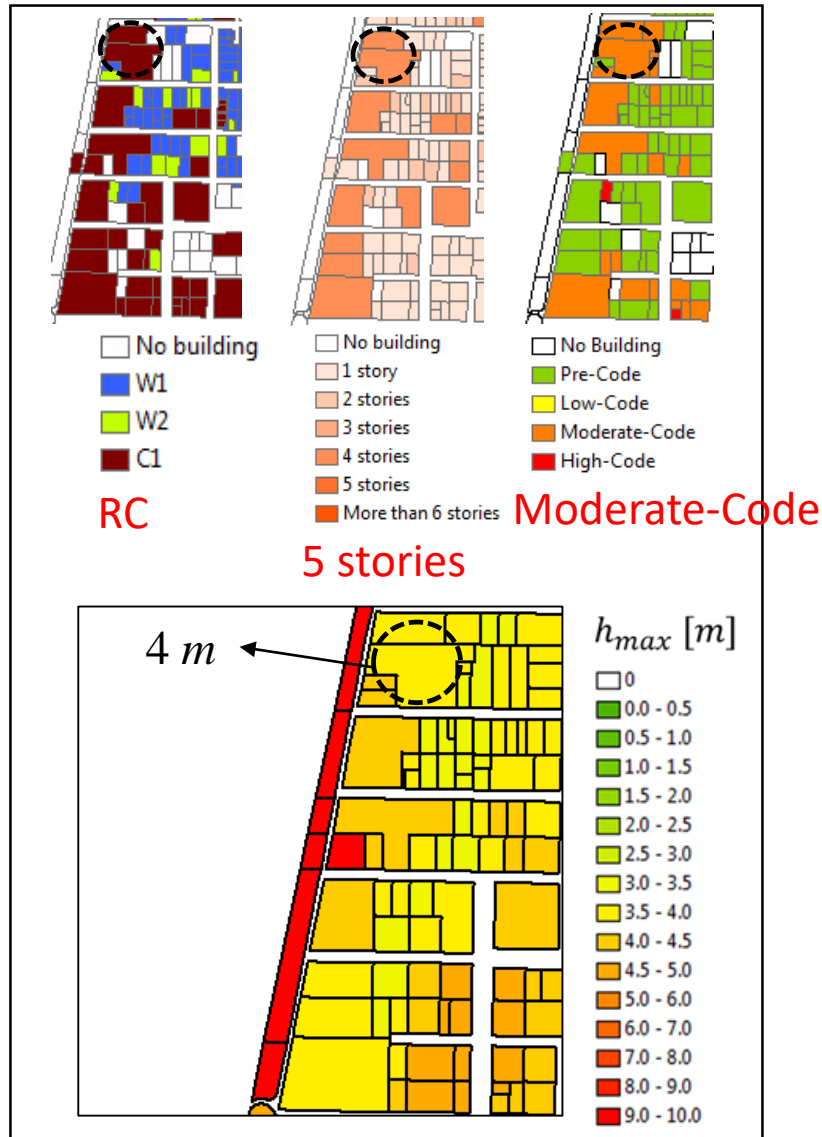
Example of building damage assessment (at AEP = 0.001)



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

(7) Damage analysis

Example of building damage assessment (at AEP = 0.001)



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

(7) Damage analysis

Example of building damage assessment (at AEP = 0.001)

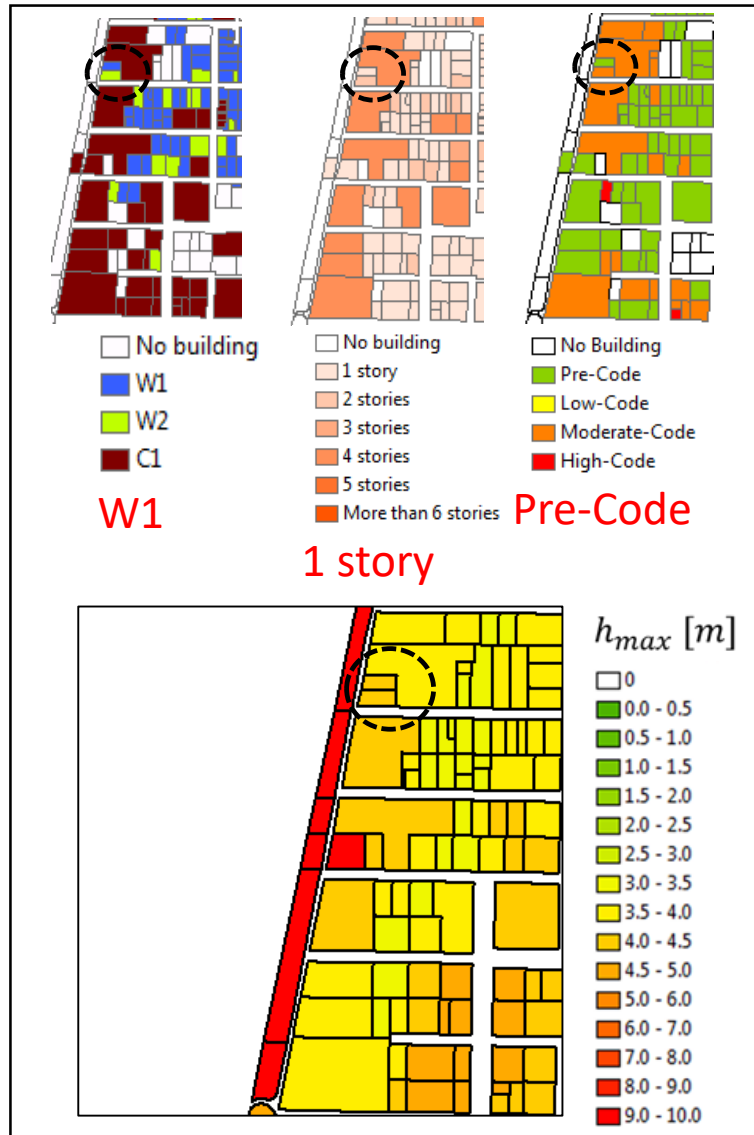
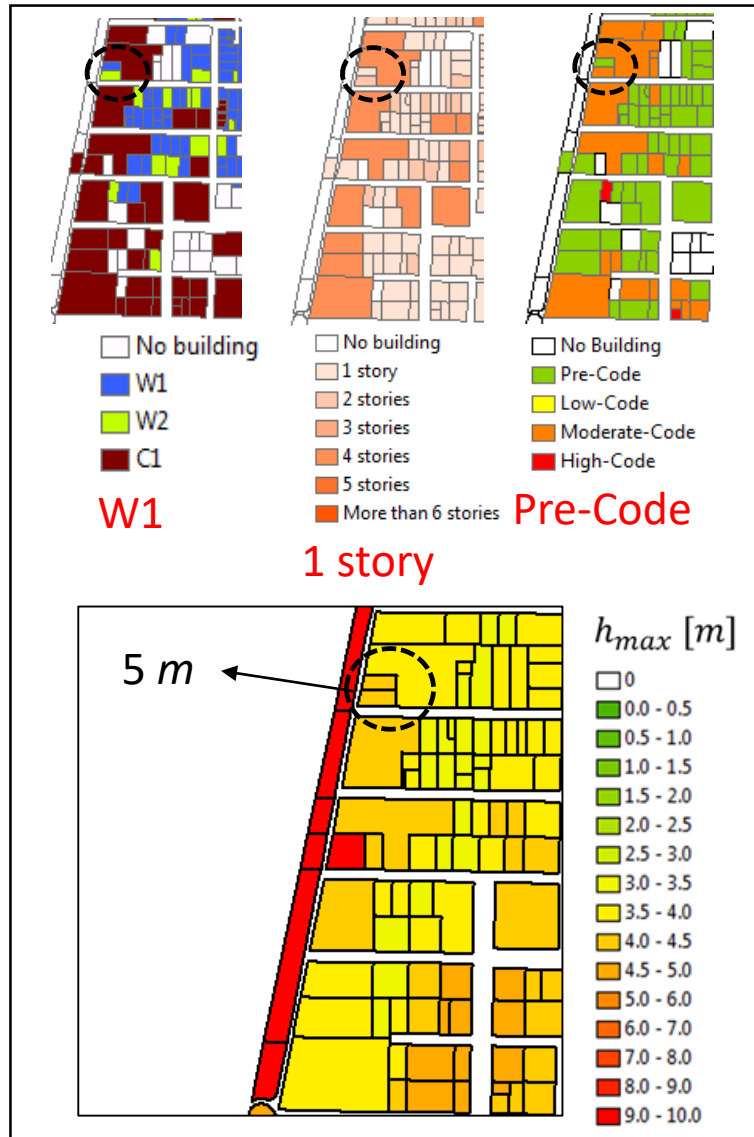


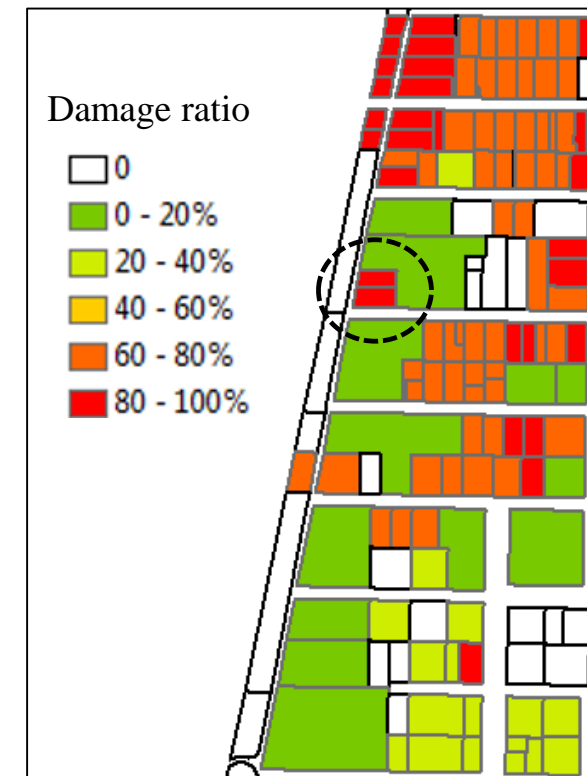
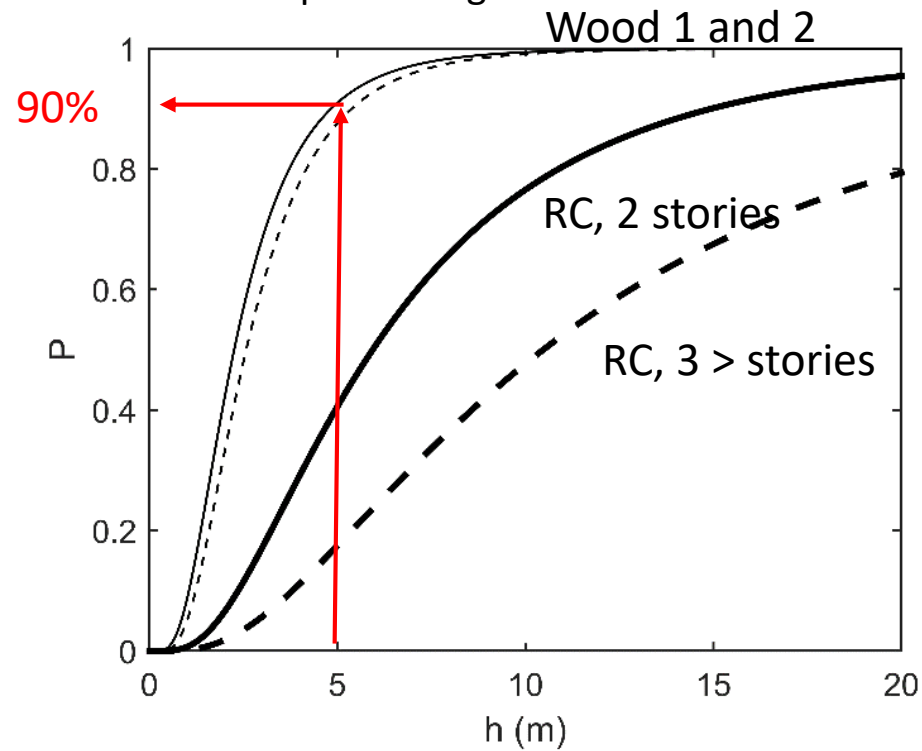
Photo taken by Hyongsu Park, at Seaside Field trip (July, 14, 2015)

(7) Damage analysis

Example of building damage assessment (at AEP = 0.001)



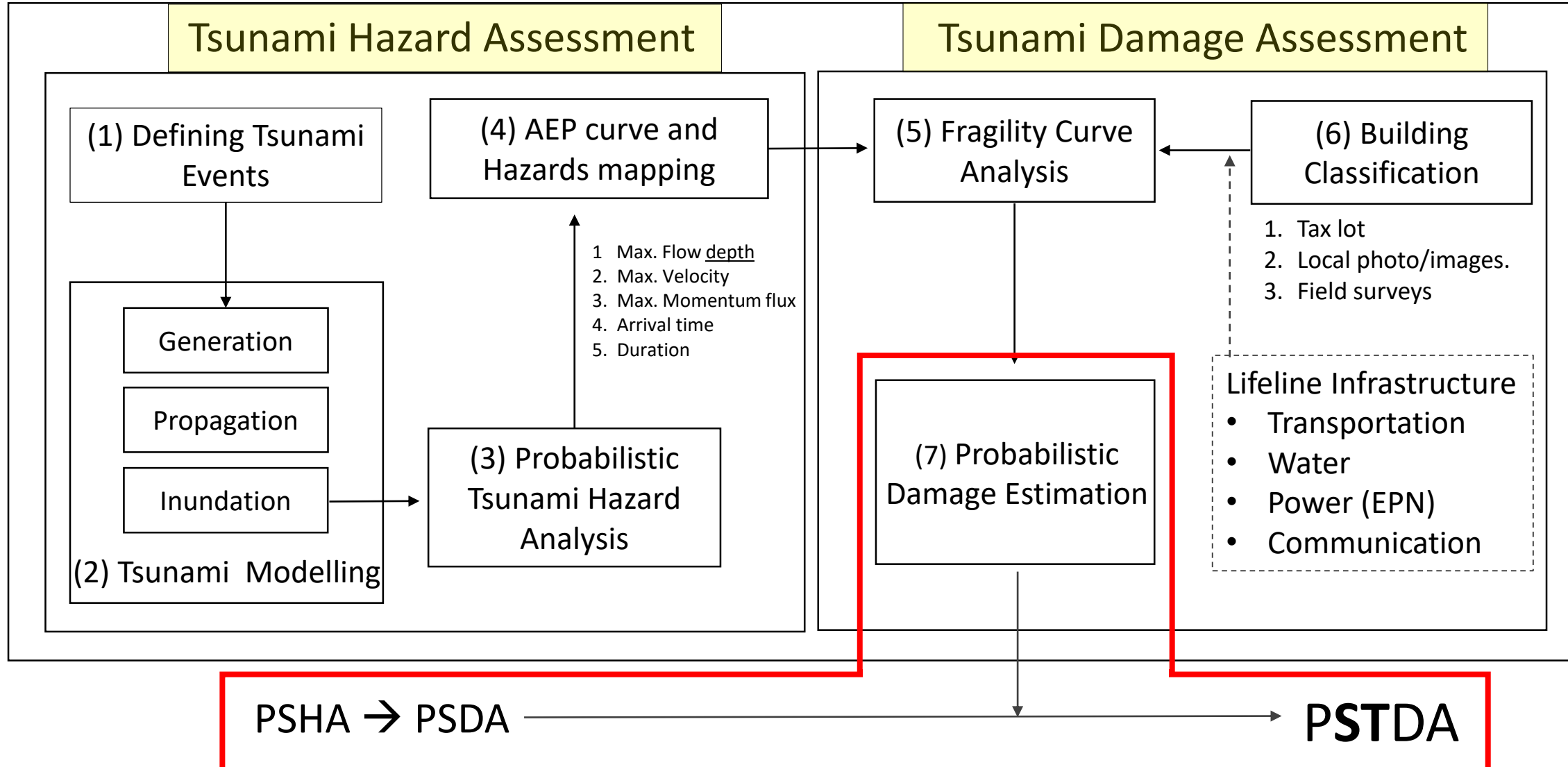
Fragility curves (Suppasri et al., 2013) for Collapse damage



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



Methodology of PTHA, PTDA



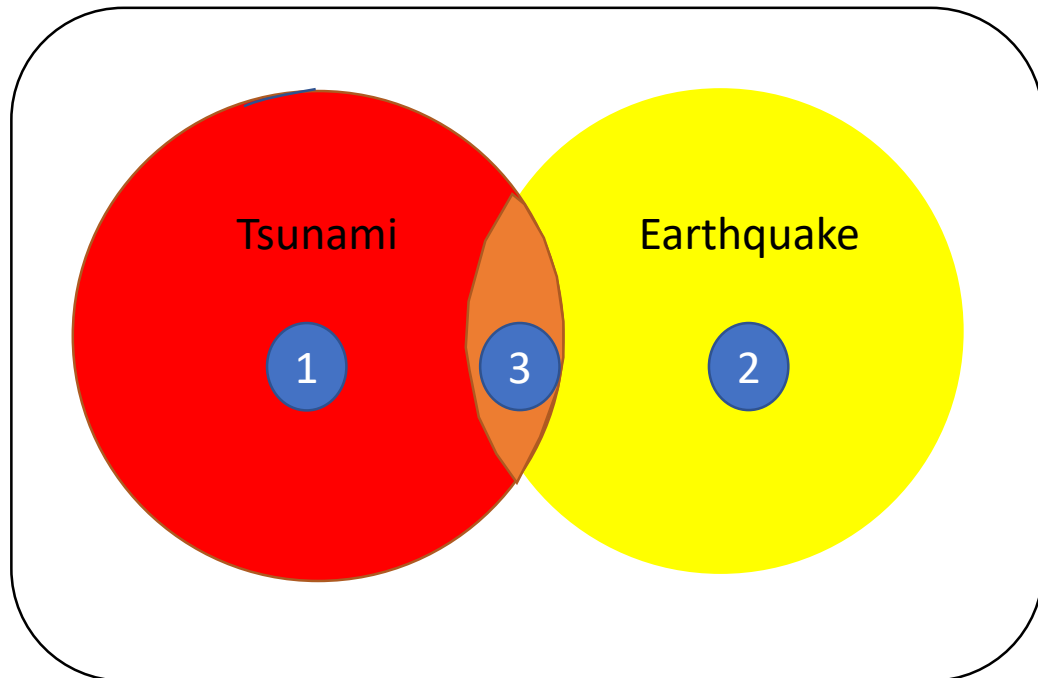
Merging Tsunami and Earthquake damage assessment

- Can utilize FEMA Hazus methodology to combine damage from multi-hazard events

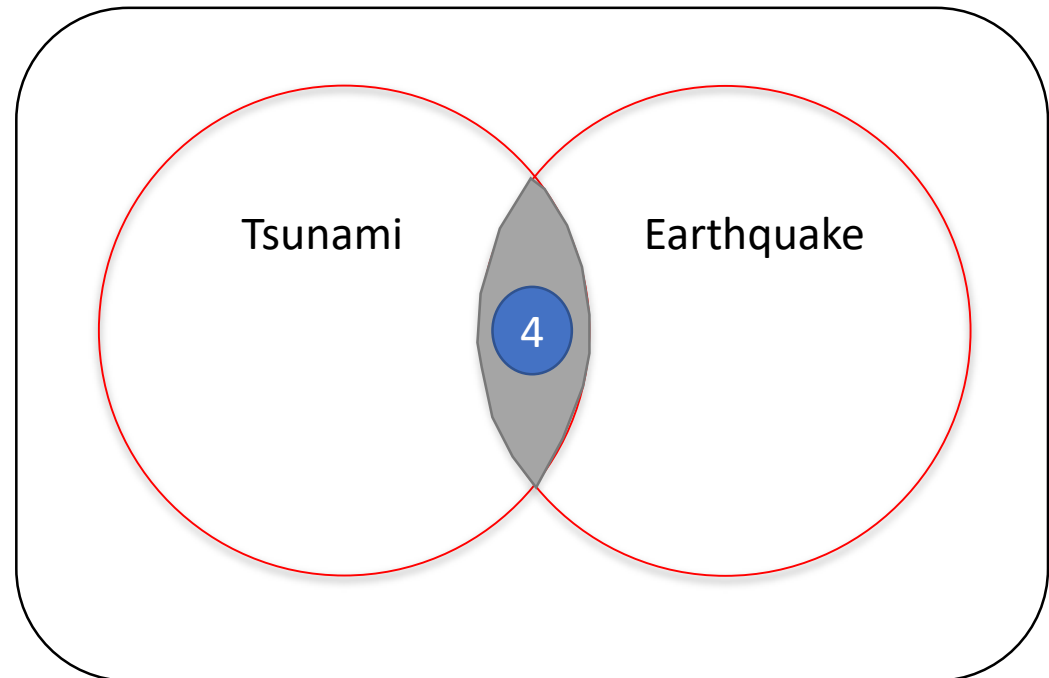
$$P[C_{STR} | EQ+TS] = P[C_{STR} | EQ] + P[C_{STR} | TS] - P[C_{STR} | EQ] P[C_{STR} | TS] + \frac{(P[\geq E_{STR} | EQ] - P[C_{STR} | EQ]) (P[\geq E_{STR} | TS] - P[C_{STR} | TS])}{P[C_{STR} | EQ+TS]}$$

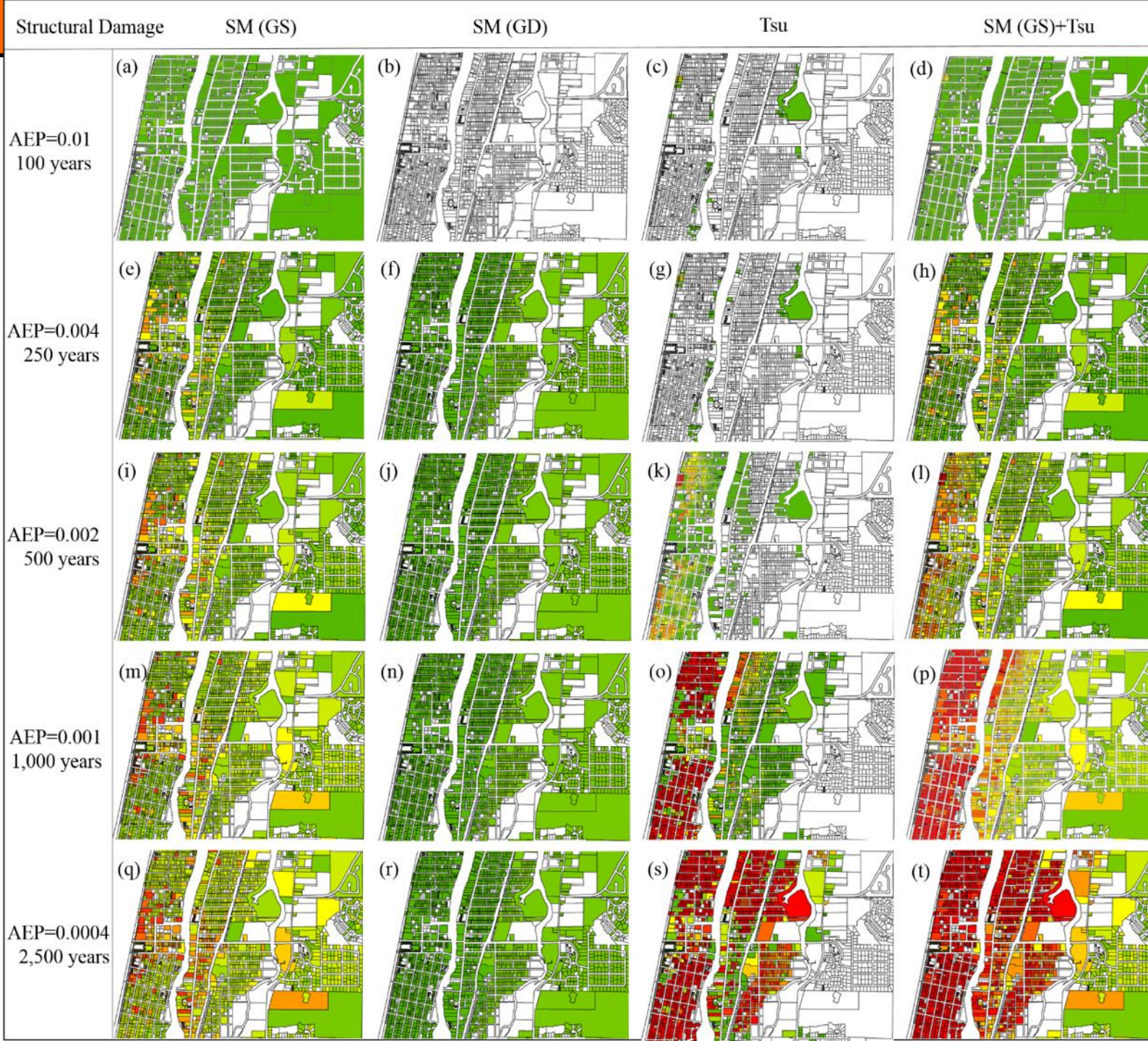
FEMA, 2013

From 'Complete' damage states



Portion of 'Complete' damage from 'Extensive' damage states





Higher probability
Lower consequences

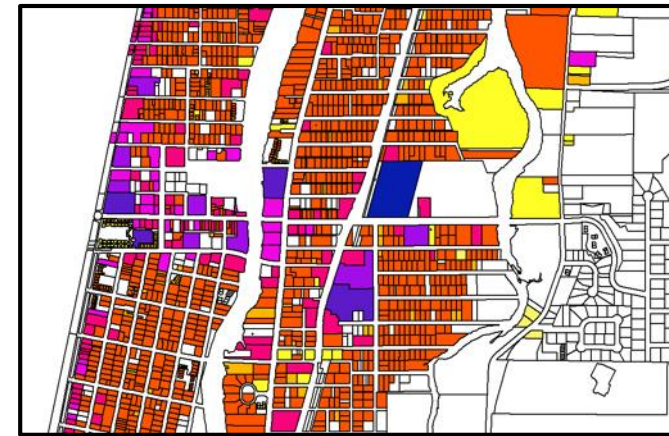
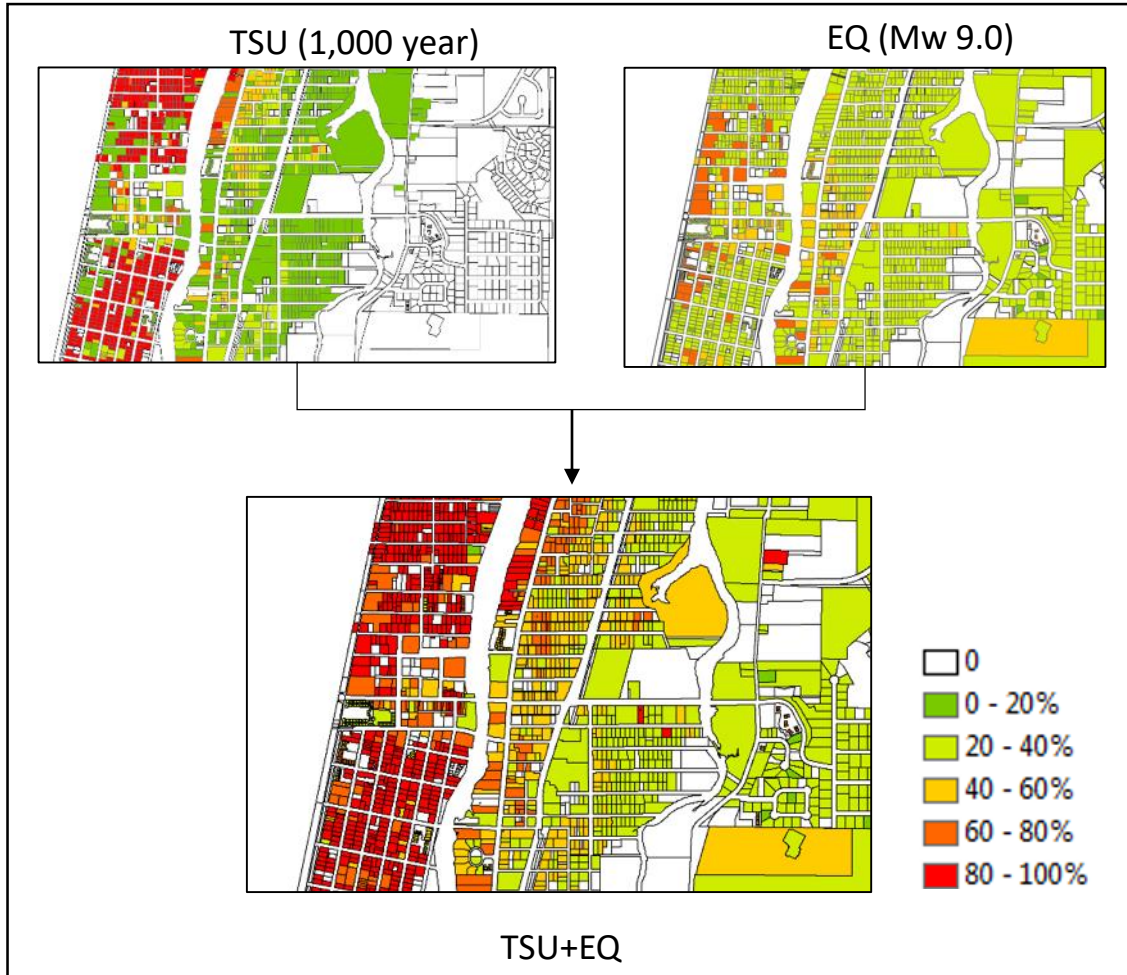


Highest
Risk

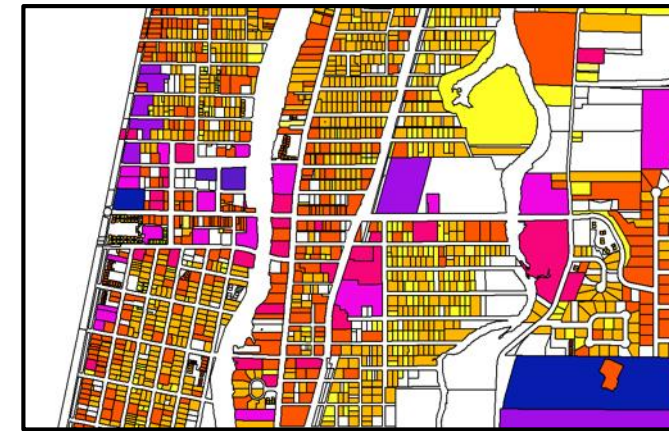
Lower probability
Higher consequences

Direct loss Estimation

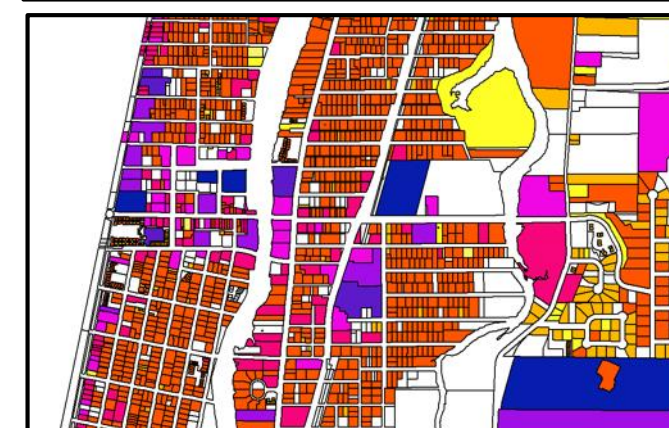
$$\text{Dollar Loss} = \text{Dollar value of building} \times \text{Damage ratio}$$



Tsunami
Loss total: 1,038 M



Earthquake
Loss total: 538 M



TSU + EQ
Loss total: 1,230 M



“Over the past 5 years, debris removal accounted for approximately 27% of disaster recovery costs”

Hazards and Disaster Debris types

Debris Forecasting

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

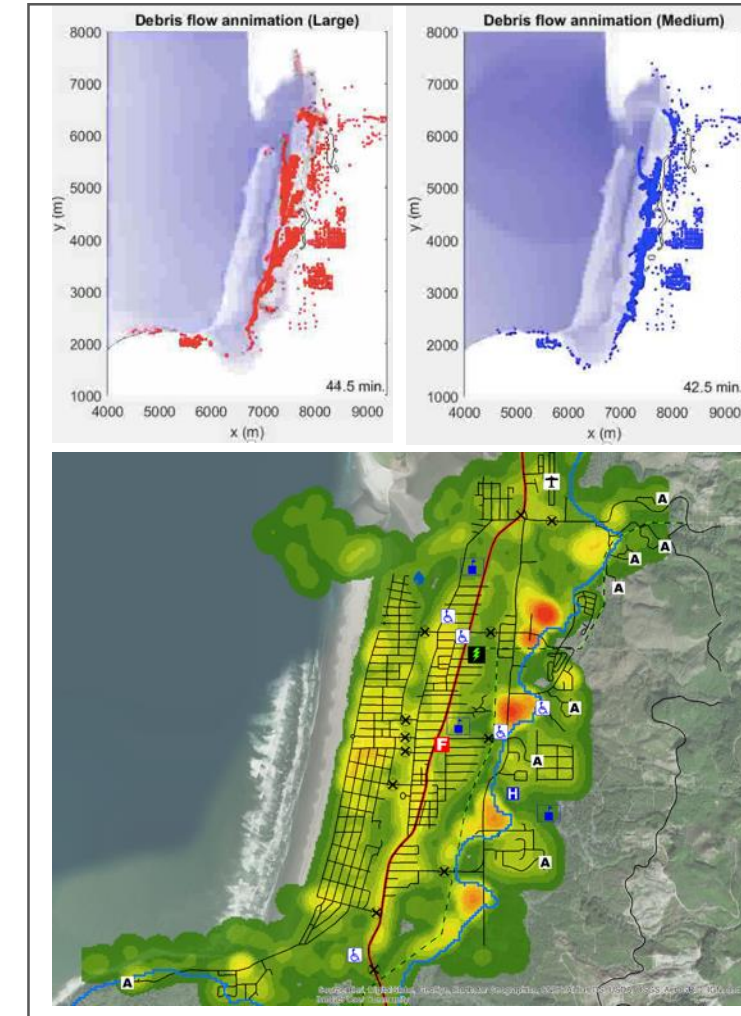
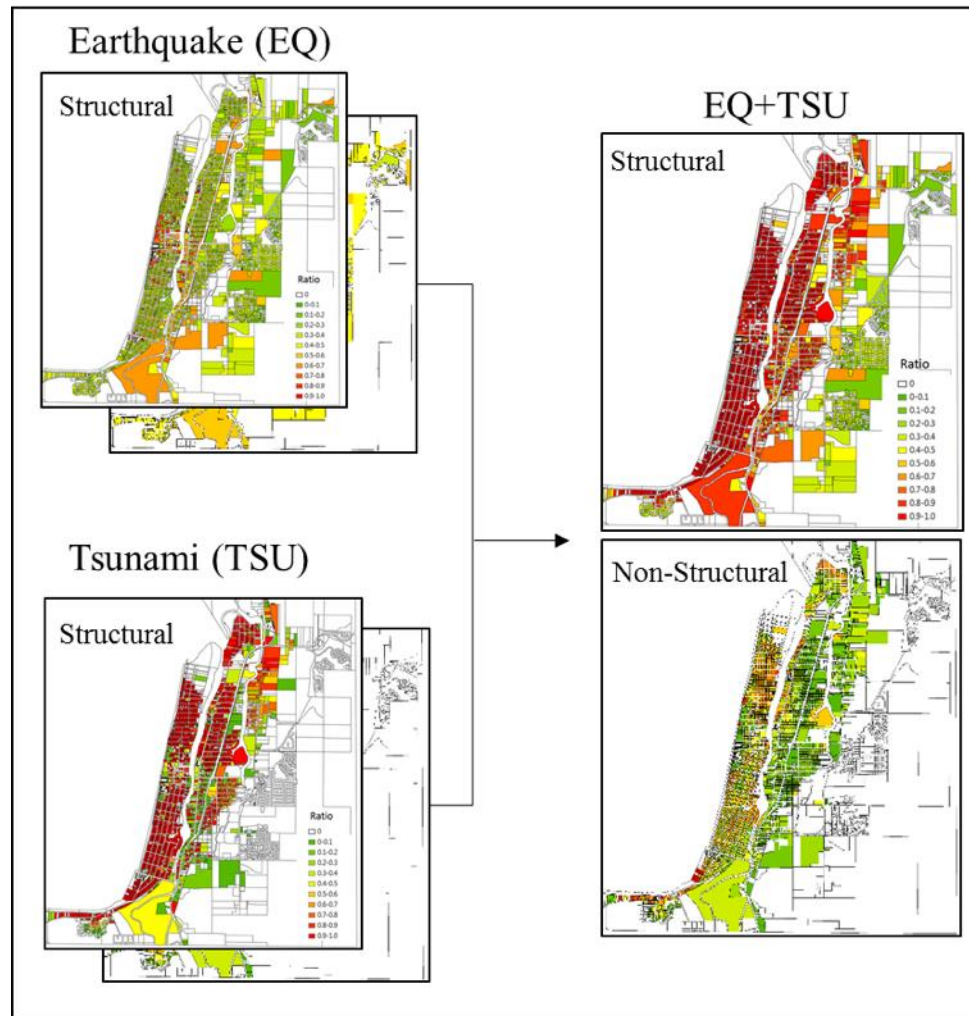
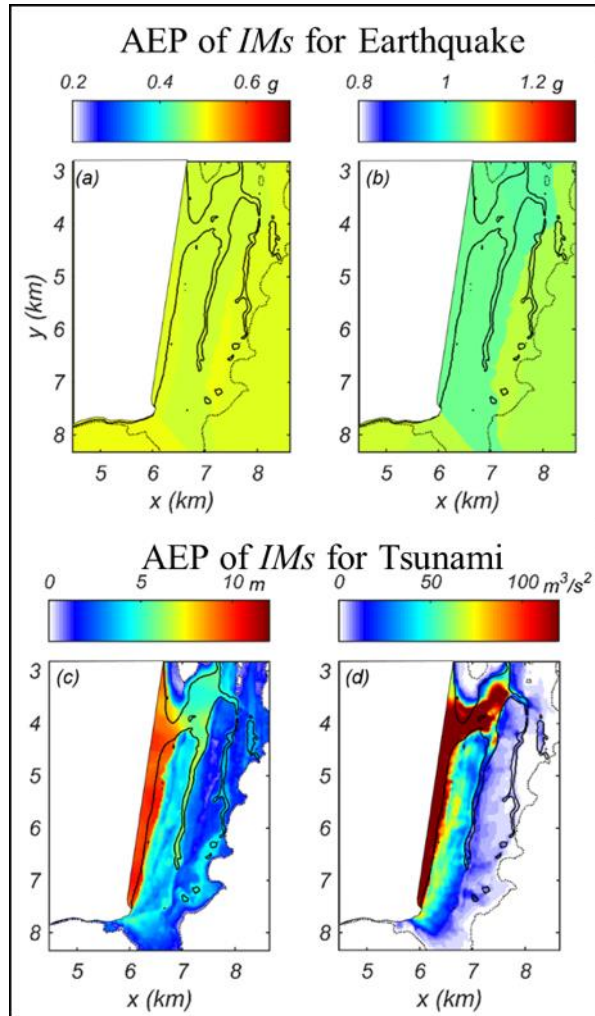
	Natural			Anthropogenic					
	Vegetative	Soil, Sand, Mud	Putrescence	Construction & Demolition	Household Hazardous Waste (HHW)	White Goods	Personal Property	Vehicles + Vessels	Hazardous Waste
Hurricane	X	X	X	X	X	X	X	X	X
Tsunami	X	X	X	X	X	X	X	X	X
Flood	X	X	X	X	X	X	X	X	X
Tornadoes	X		X	X	X	X	X	X	X
Earthquake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

Multi-hazard
(PSTHA)

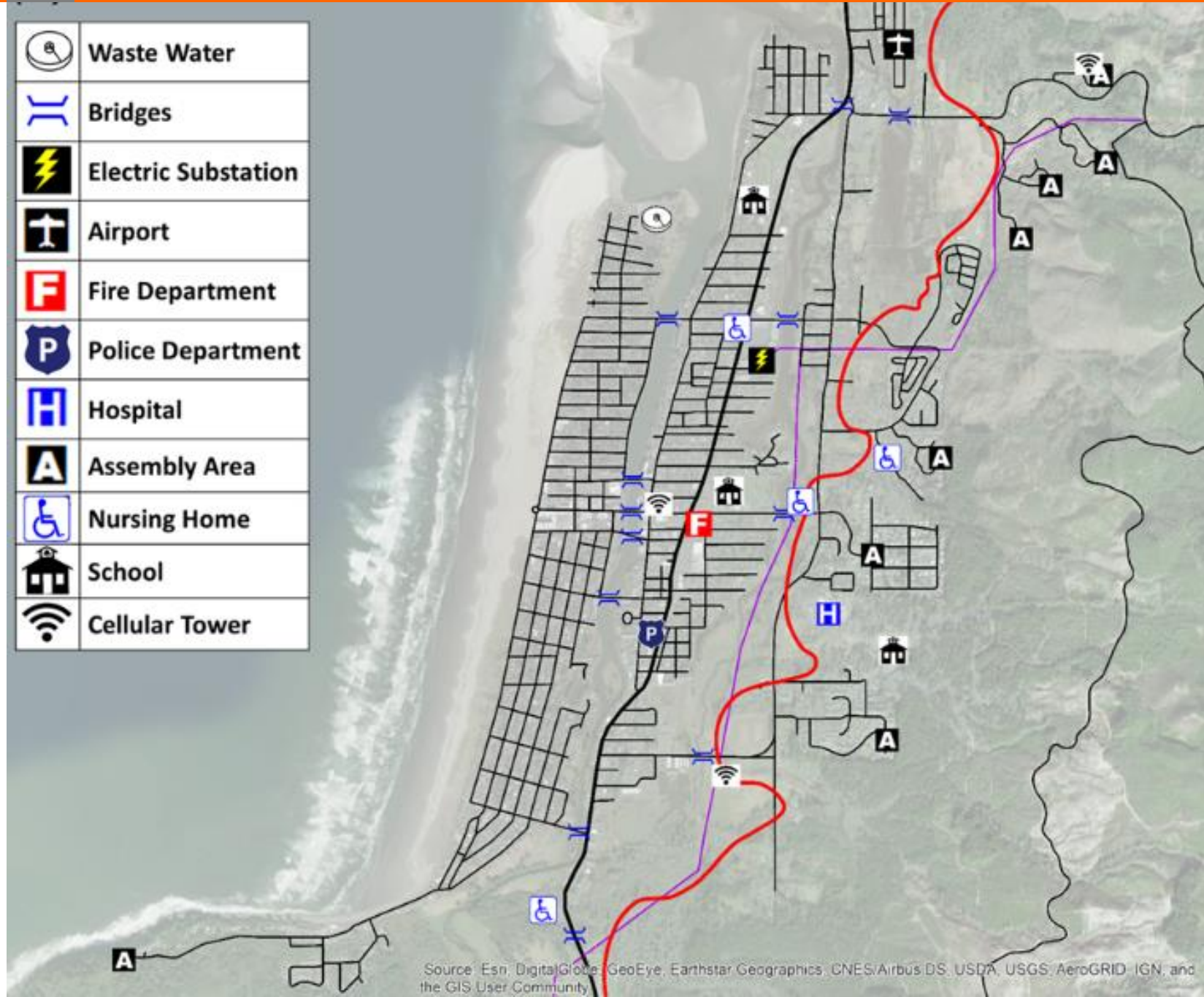
MH Damage and Loss
(PSTDA)

Debris Forecast
Generation & Advection



**Focus on
critical facilities
and lifelines**

	Waste Water
	Bridges
	Electric Substation
	Airport
	Fire Department
	Police Department
	Hospital
	Assembly Area
	Nursing Home
	School
	Cellular Tower



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Methodology of Debris Quantification

Based on Hazus-MH 2.1 (Earthquake)



Single house

For structural debris

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

$$DW_S = (EDF_{S,F} \cdot W_{S,F} + EDF_{S,NF} W_{S,NF}) \cdot (SQ \cdot FL)$$

For non-structural debris

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

$$DW_{NS} = (EDF_{NS,F} \cdot W_{NS,F} + EDF_{NS,NF} W_{NS,NF}) \cdot (SQ \cdot FL)$$

Debris Forecast Model: Quantification of debris at a single building

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.

Debris weight from structural damage

$$DW_S = (EDF_{S,F} \cdot W_{S,F} + EDF_{S,NF} W_{S,NF}) \cdot (SQ \cdot FL)$$

Debris weight from non-structural damage

$$DW_{NS} = (EDF_{NS,F} \cdot W_{NS,F} + EDF_{NS,NF} W_{NS,NF}) \cdot (SQ \cdot FL)$$

Total Weight of Debris

$$TDW = DW_S + DW_{NS}$$

Disaggregation to floating or non-floating debris

$$TDW_F = EDF_{S,F} \cdot SQ \cdot W_{S,F} + DF_{NS,F} \cdot SQ \cdot W_{NS,F}$$

$$TDW_{NF} = EDF_{S,NF} \cdot SQ \cdot W_{S,NF} + DF_{NS,NF} \cdot SQ \cdot W_{NS,NF}$$

DW_S Weight of debris from structural damage

W_S Weights of debris per 1000 ft² of floor area from structural damage

SQ Square footage of a building

FL Number of floor levels (stories)

F Subscript for floating debris

NF Subscript for non-floating debris

Total Volume of Debris

$$TDV = TDW_F \cdot \rho_F + TDW_{NF} \cdot \rho_{NF}$$

Table1. Floatable debris generated from structural and non-structural elements (in percent of weight)

Building Type	DF _{S,F} (%)				DF _{NS,F} (%)			
	Slight (i=1)	Moderate (i=2)	Extensive (i=3)	Complete (i=4)	Slight (i=1)	Moderate (i=2)	Extensive (i=3)	Complete (i=4)
W1	0.0	5.0	34.0	100.0	2.0	8.0	35.0	100.0
W2	0.0	6.0	33.0	100.0	2.0	10.0	40.0	100.0
C1	0.0	0.0	0.0	100.0	1.0	7.0	35.0	100.0

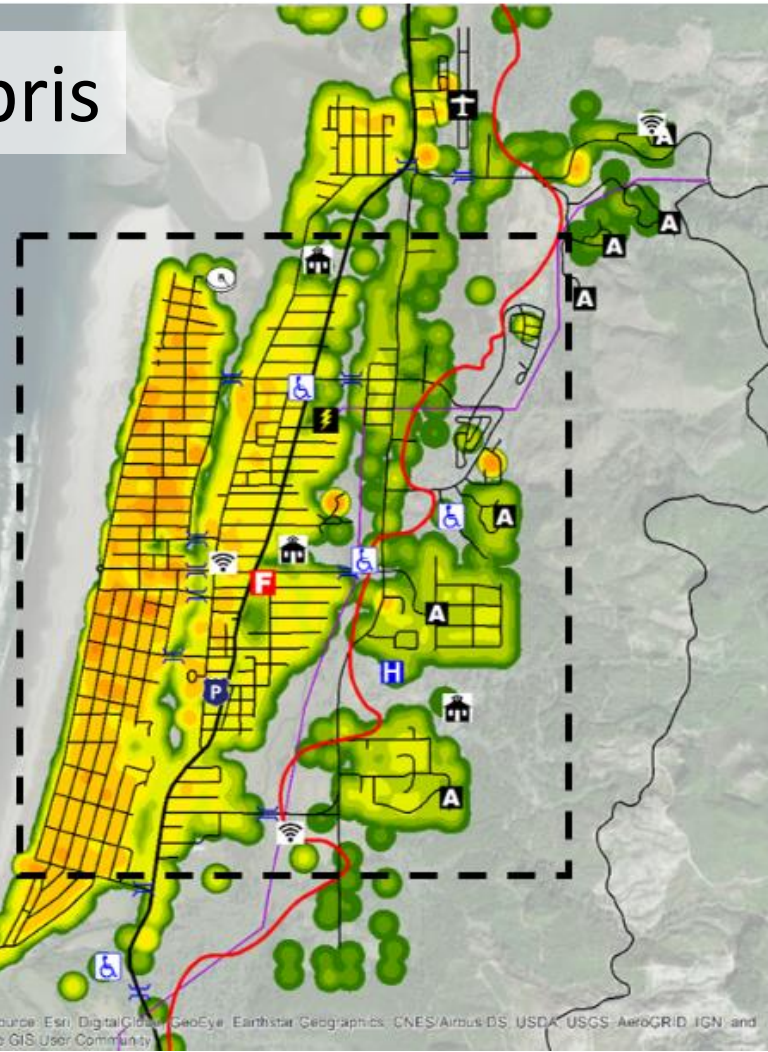
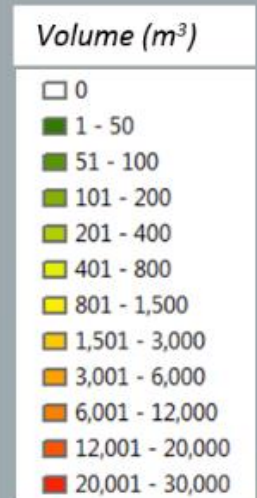
Table2. Non-Floatable debris generated from structural and non-structural elements (in percent of weight)

Building Type	DF _{S,NF} (%)				DF _{NS,NF} (%)			
	Slight (i=1)	Moderate (i=2)	Extensive (i=3)	Complete (i=4)	Slight (i=1)	Moderate (i=2)	Extensive (i=3)	Complete (i=4)
W1	0.0	3.0	27.0	100.0	0.0	0.0	0.0	100.0
W2	0.0	2.0	25.0	100.0	0.0	10.0	28.0	100.0
C1	0.0	5.0	33.0	100.0	0.1	8.0	28.0	100.0

Table 3. Unit weight (tons per 1000 ft²) for structural and non-structural elements for building types

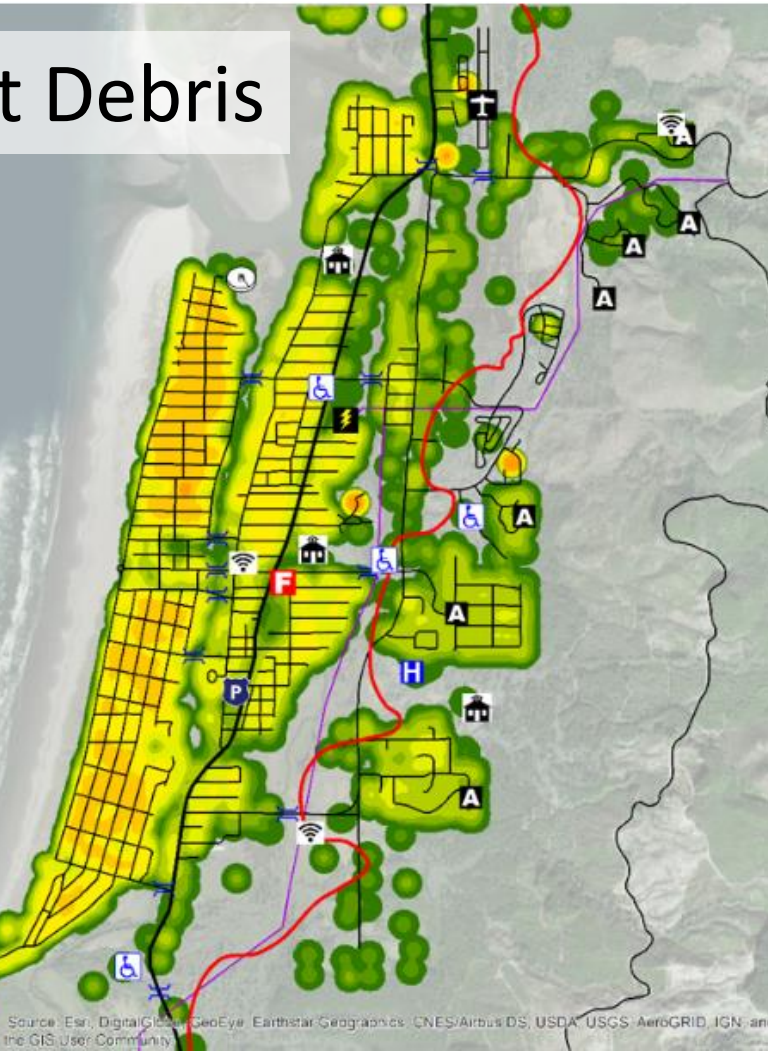
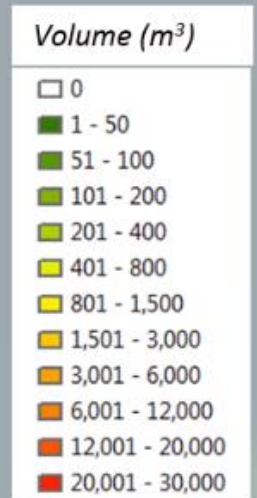
Building Type	Floatable (Wood, Brick, and others)		Non-Floatable (RC and Steel)		SQ (Footage of building/1000ft ²)
	Structural	Non-structural	Structural	Non-structural	
W1	6.5	12.1	15.0	0.0	1.5
W2	4.0	8.1	15.0	1.0	2.5
C1	0.0	5.3	98.0	4.0	3.0

(a) Total Debris



Source: Esri, DigitalGlobe, GeoEye, Earthstar/Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

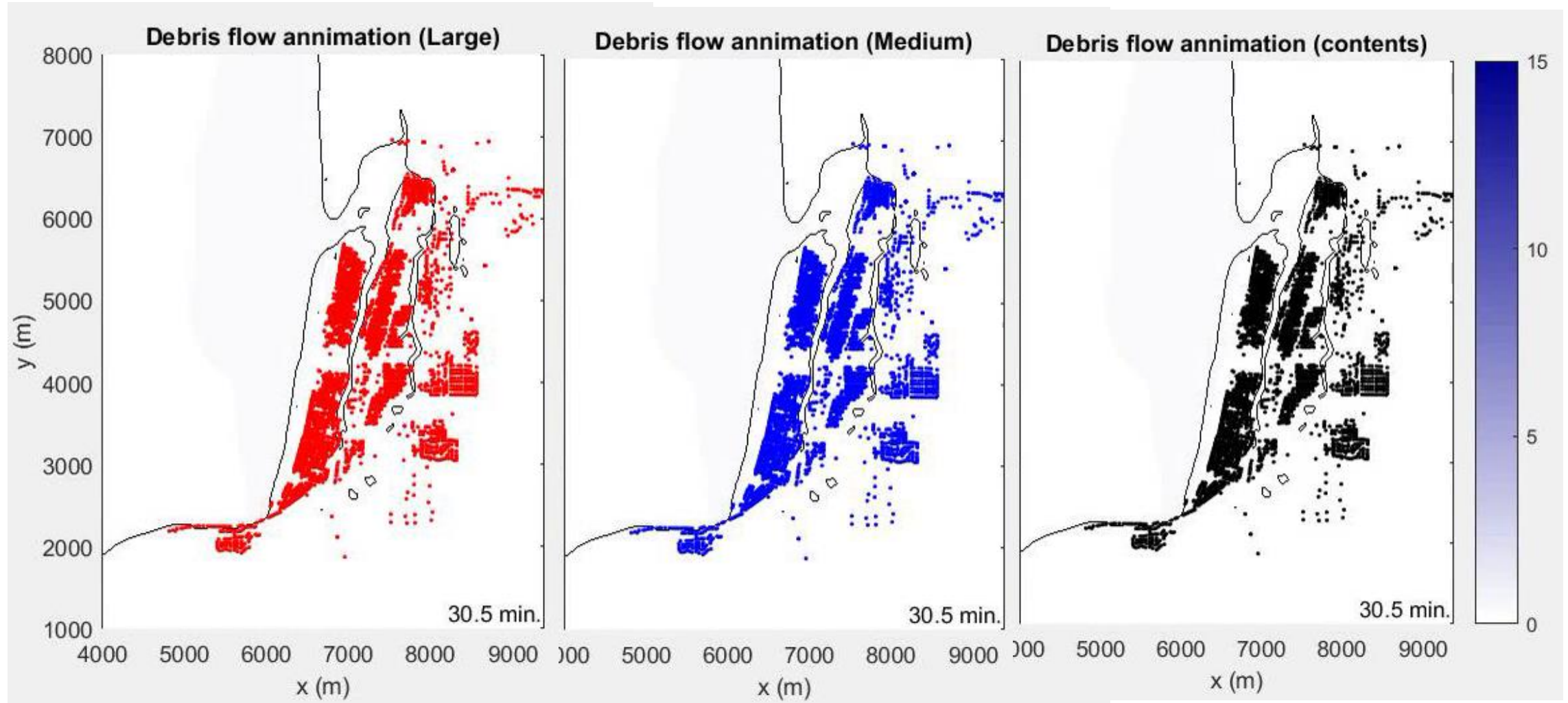
(b) Buoyant Debris



Source: Esri, DigitalGlobe, GeoEye, Earthstar/Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Distribution of expected debris volume (m³) 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.

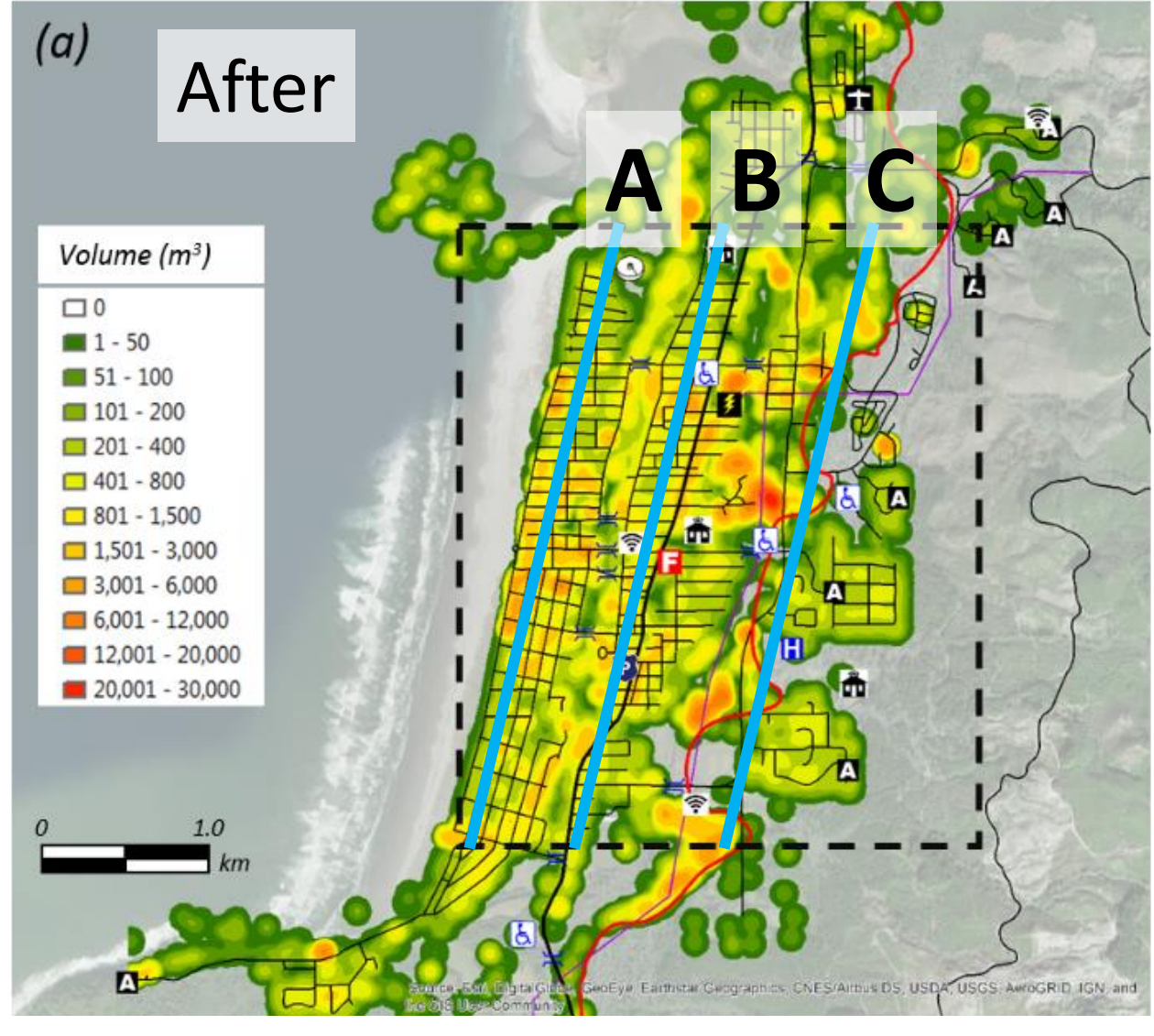
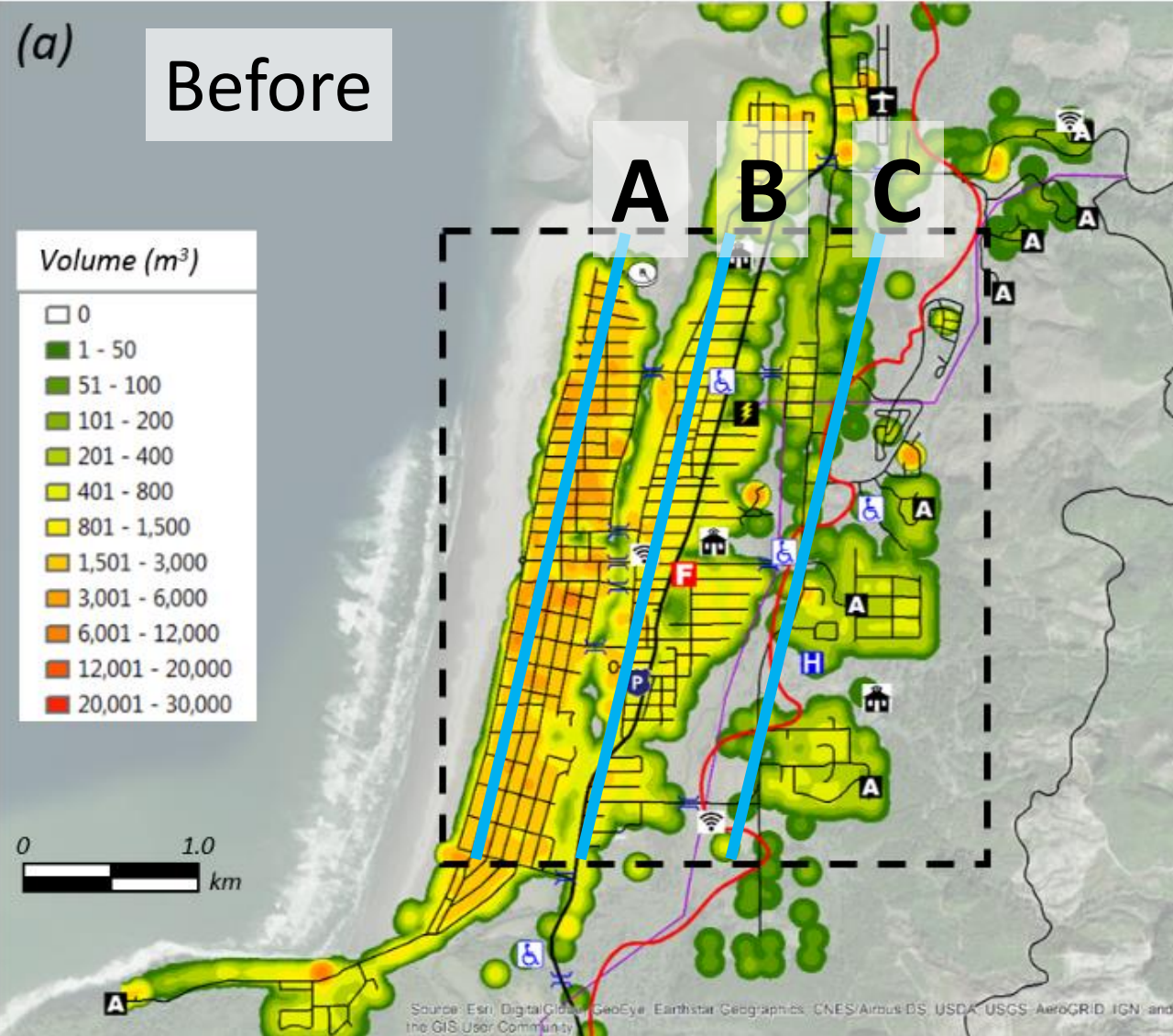
Advection of buoyant debris from PSTDA at AEP = 0.0004 (2,500 yr)

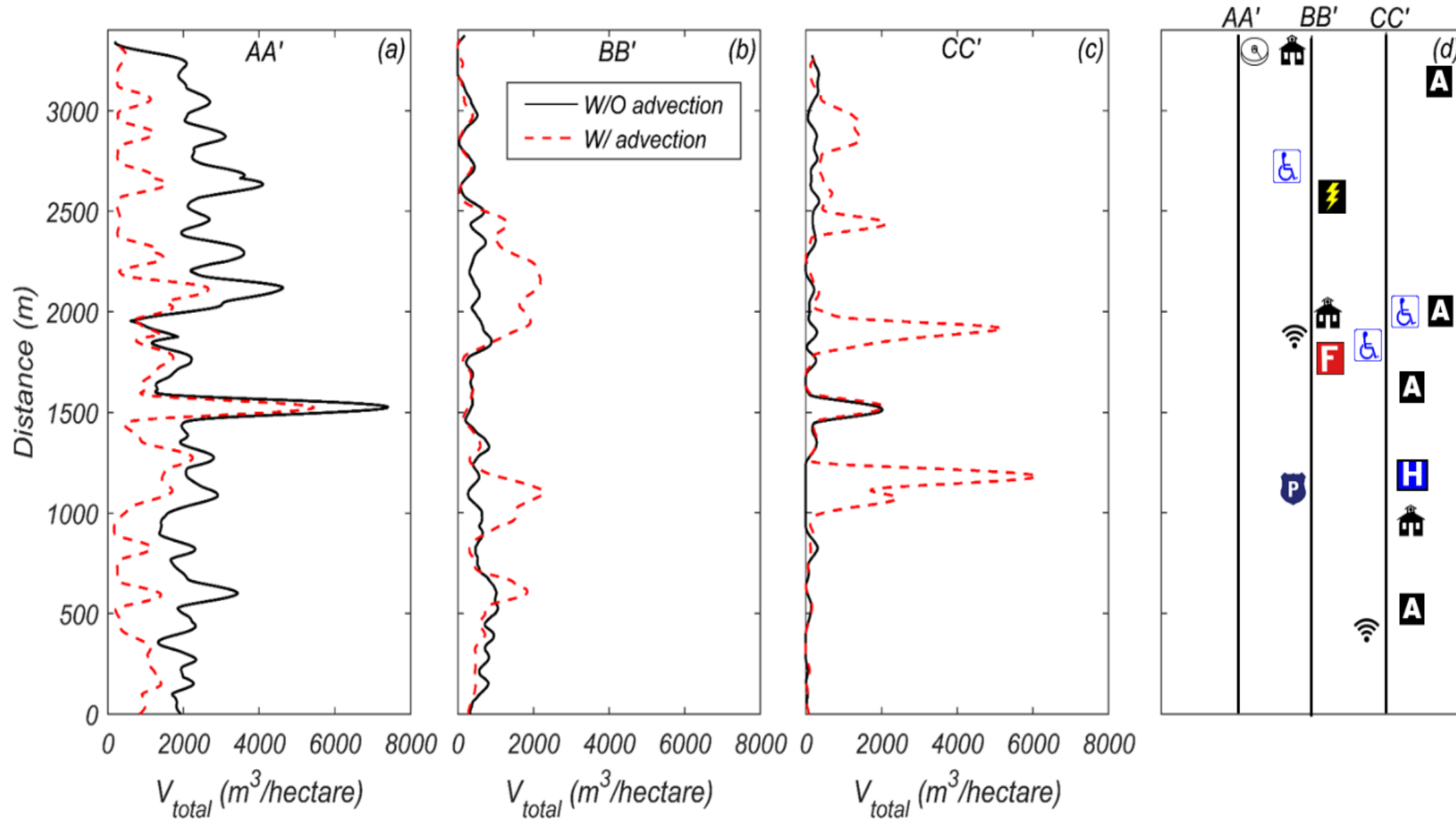


Thresholds: 3 m, 0.5 m/s

1 m, 0.3 m/s

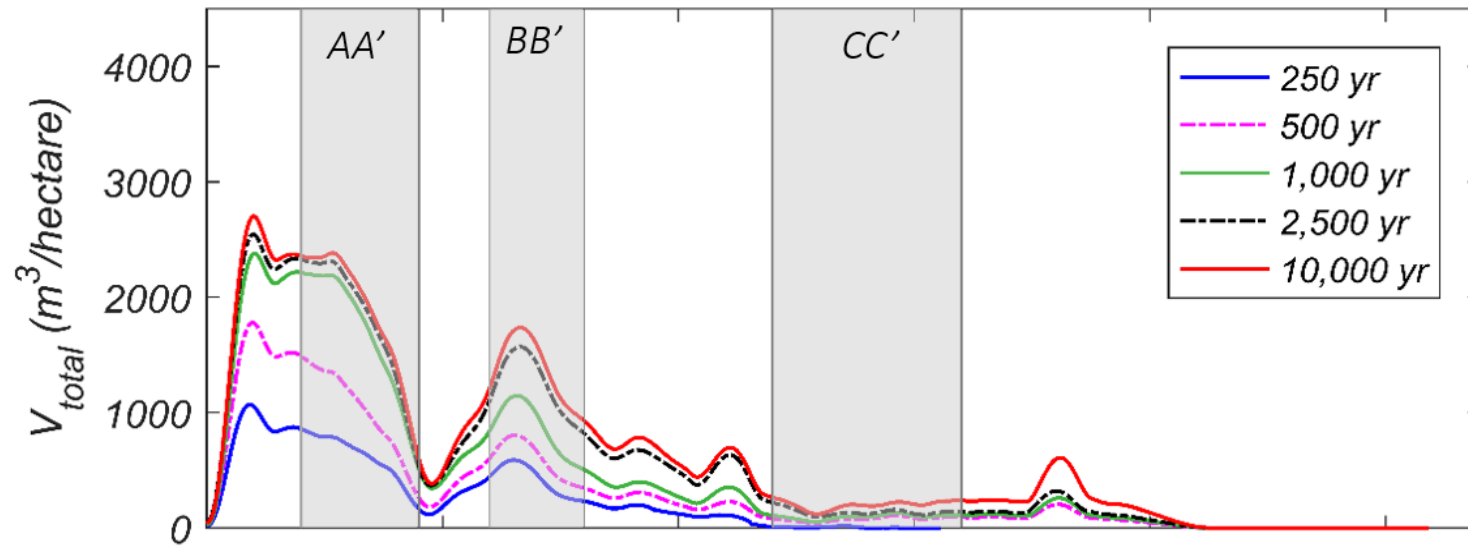
0.5 m, 0.2 m/s



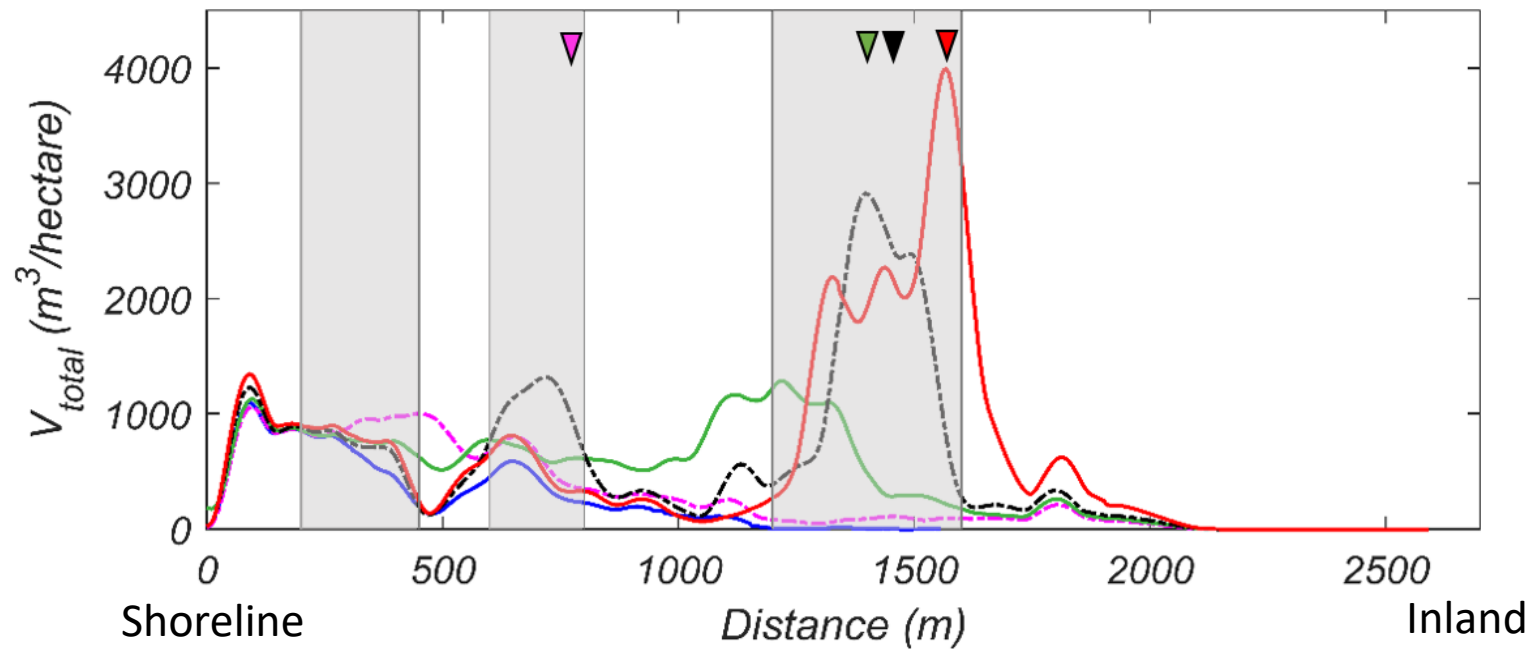


Cross-distribution of with and without advection debris at AA', BB', and CC'

No
advection



With
advection



Discussion/Future work

PSTHA

- Uncertainty in tsunami inundation due to built environment
- New PTHA for each mitigation measure? (eg. seawall)

PSTDA

- How accurate are tsunami fragilities?
- Methodology to combine seismic and tsunami damage?
- Extending from damage to economic loss and loss of functionality

Debris

- Debris impact on building damage (cascading effects)?
- Debris interaction with fluid?
- Including natural debris (vegetation, sand) and other (vehicles, boats, etc.)
- Need for debris collision for large vessels

Thank you!