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*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

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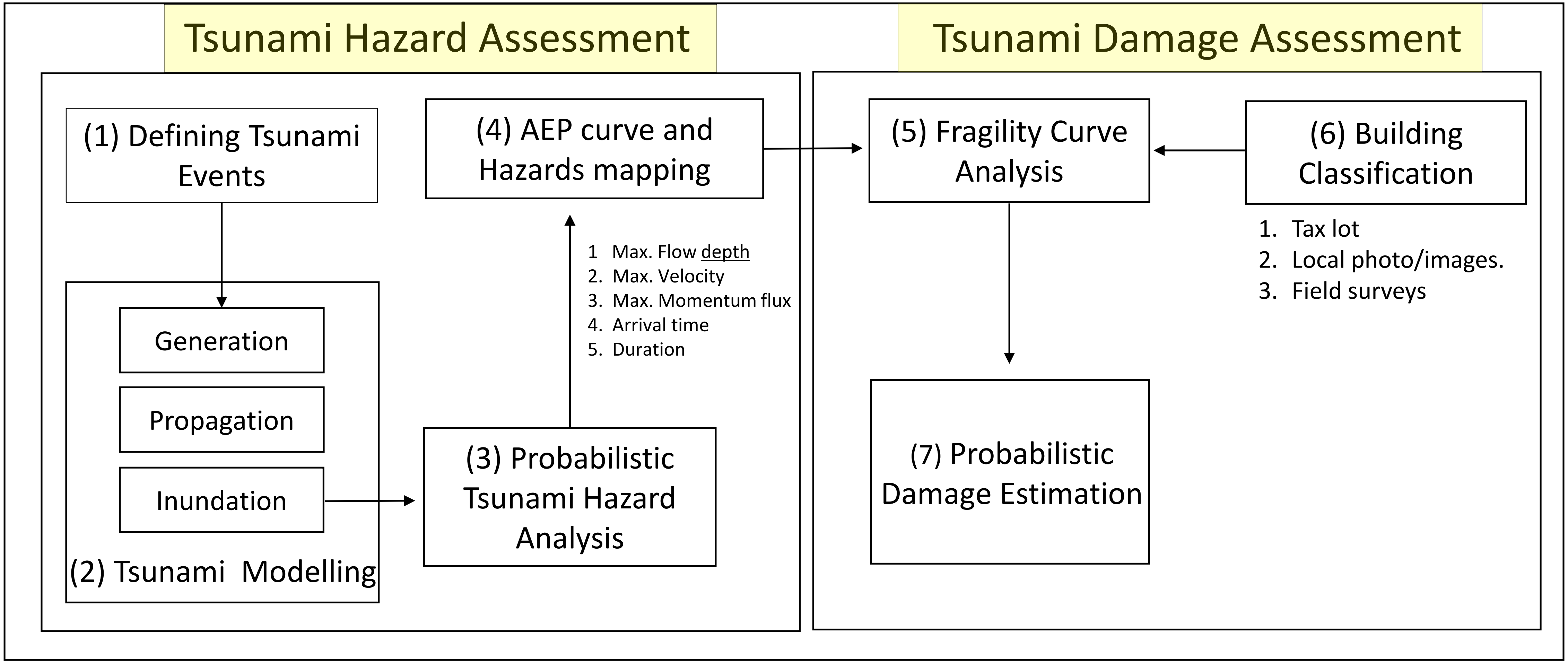
Center for Risk-Based Community Resilience Planning
*A NIST-funded Center of Excellence*

Risk = Hazard Probability X Negative Consequence

| | | | | | |
|---|---|---|---|---|---|
| 1970's | PS*HA* | Probabilistic **Seismic** *Hazard* Analysis | → | PS*DA* | Probabilistic **Seismic** *Damage* Analysis |
| 2000's | PT*HA* | Probabilistic **Tsunami** *Hazard* Analysis | → | PT*DA* | Probabilistic **Tsunami** *Damage* Analysis |
| 2010's | PST*HA* | Probabilistic **Seismic** and **Tsunami** *Hazard* Analysis | → | PST*DA* | Probabilistic **Seismic** and **Tsunami** *Damage* Analysis |

# Methodology of PTHA, PTDA



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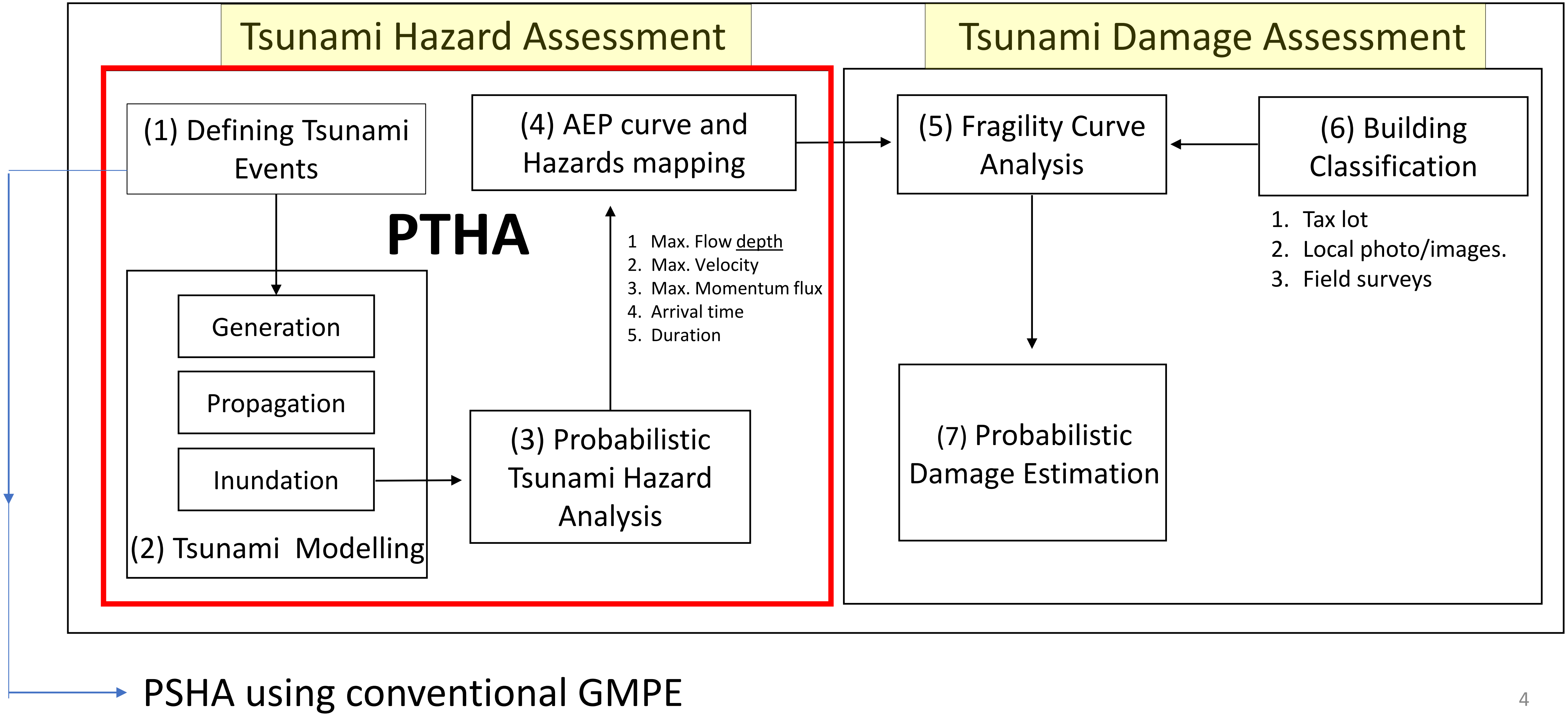
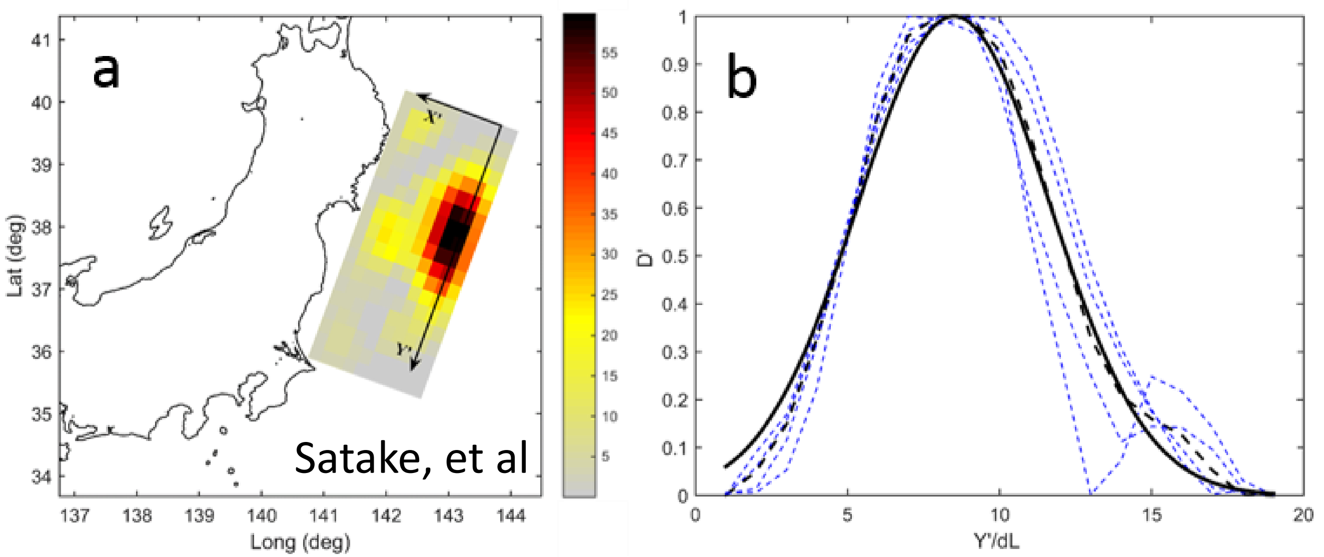
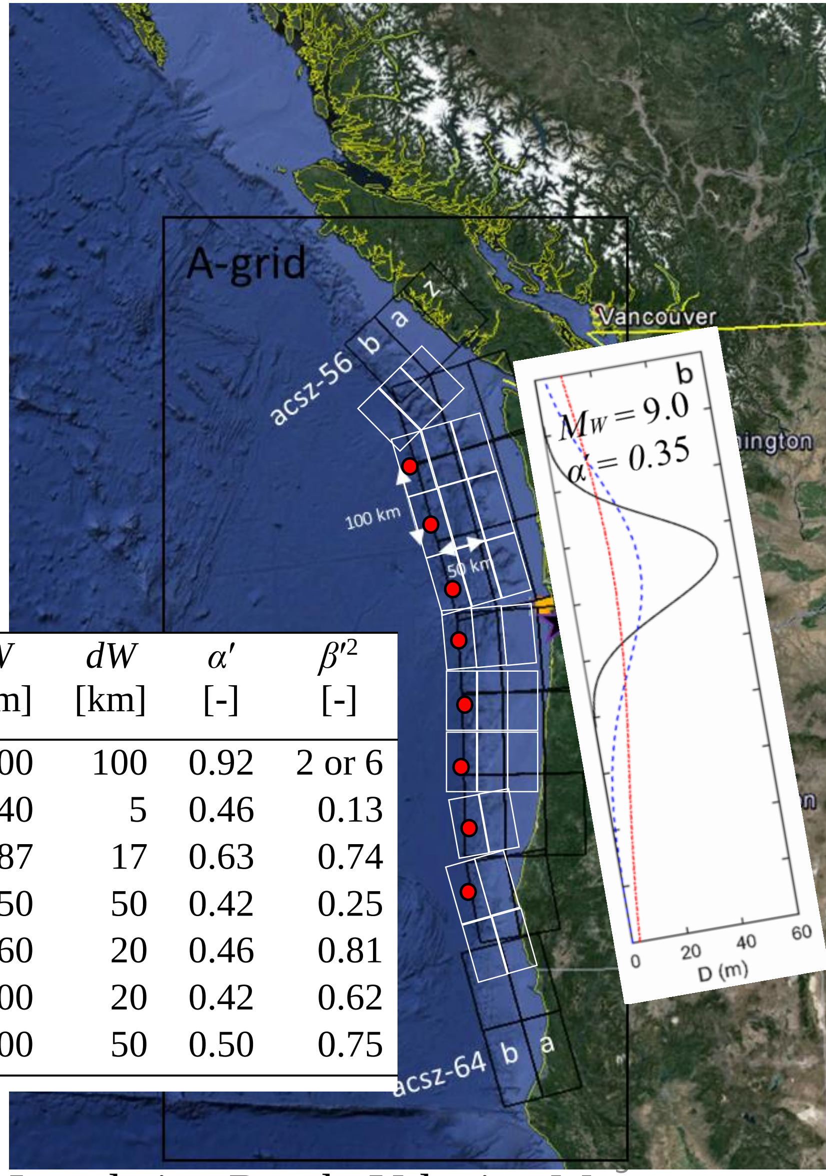


## 1) Inversion model results




## 4) Applying as input sub-faults in model




## 2) New tsunami slip model using a Gaussian distribution

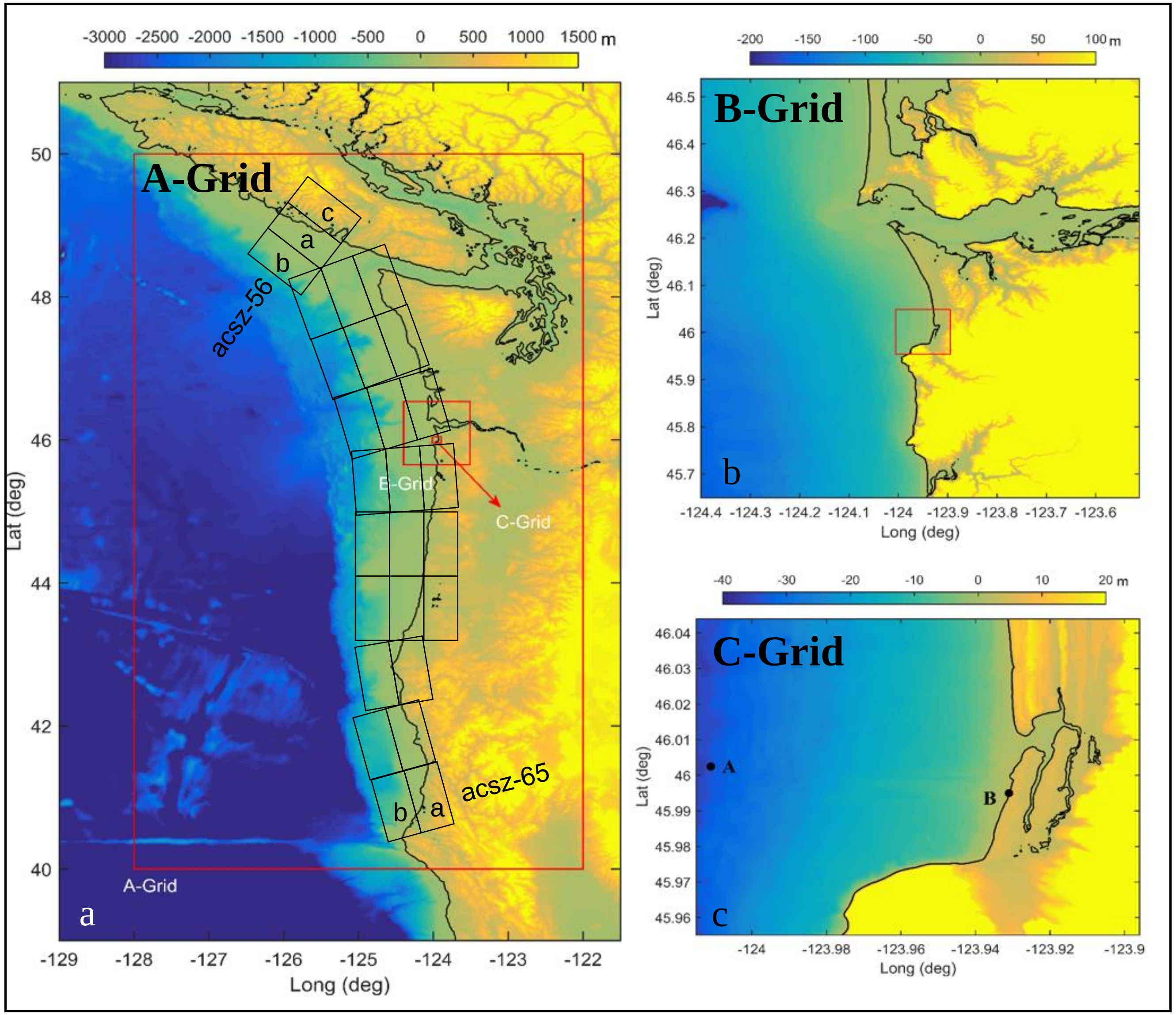
$$D' = f\left(Y'/dL \mid \alpha, \beta\right) = \frac{1}{\beta\sqrt{2\pi}} \exp\left(\frac{-\left(Y'/dL - \alpha\right)^2}{2\beta^2}\right)$$

$\alpha$ (Epicenter) , $\beta$ (Slip shape)

| Name | $M_W$ [-] | $D_P$ [m] | $L$ [km] | $dL$ [km] | $W$ [km] | $dW$ [km] | $\alpha'$ [-] | $\beta'^2$ [-] |
|---|---|---|---|---|---|---|---|---|
| 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 |

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

# Bathymetry of two numerical models

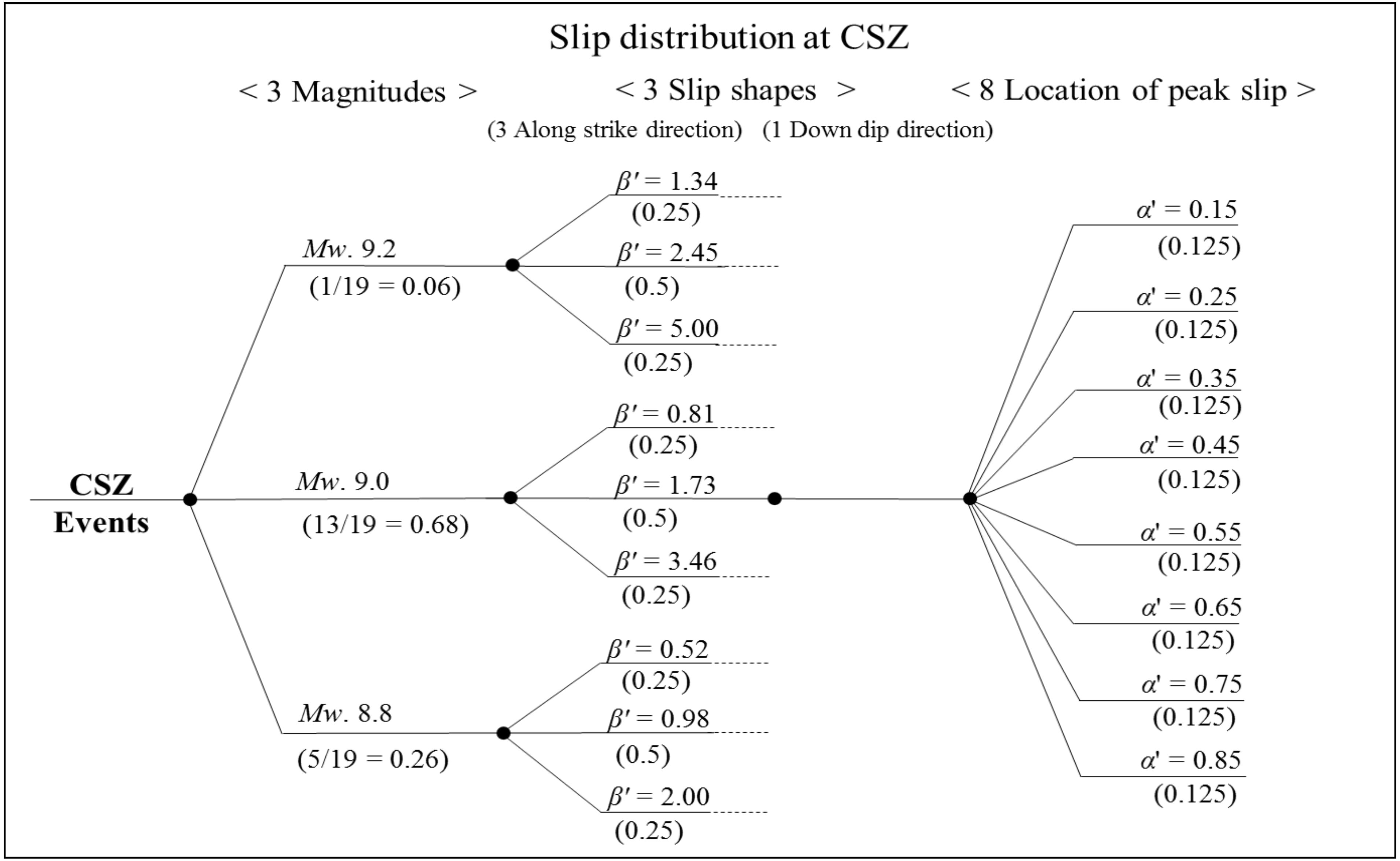



- ComMIT/MOST(NOAA) } A & B-Grid
- COULWAVE } Only C-Grid

| 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

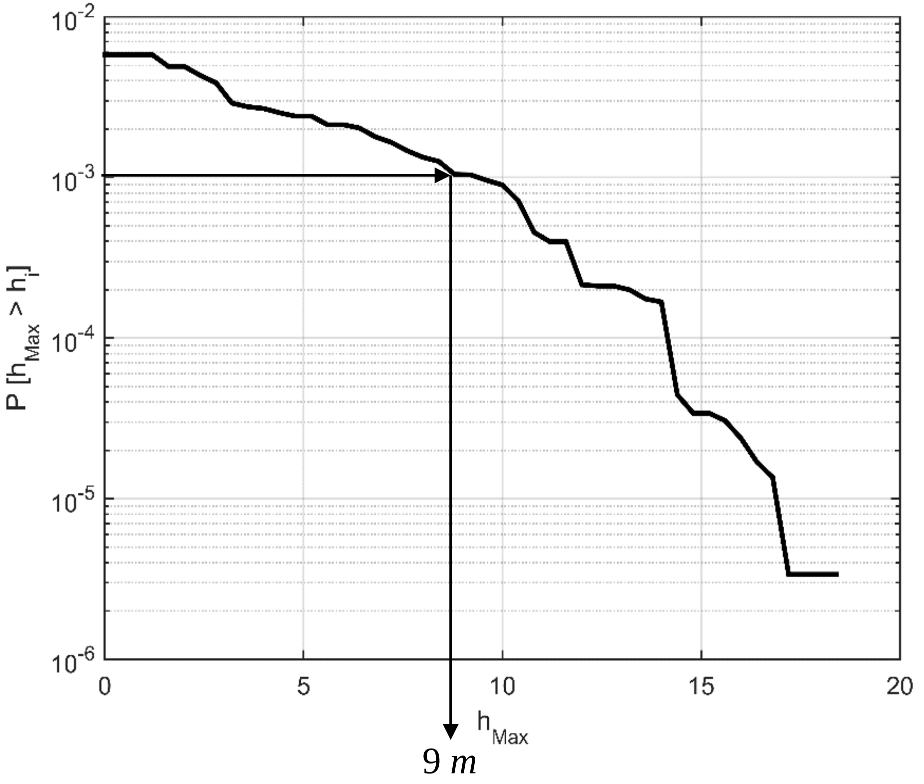


# Calculating annual exceedance probability (AEP) of IMs

AEP = 0.001 ~ 1,000 yr

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

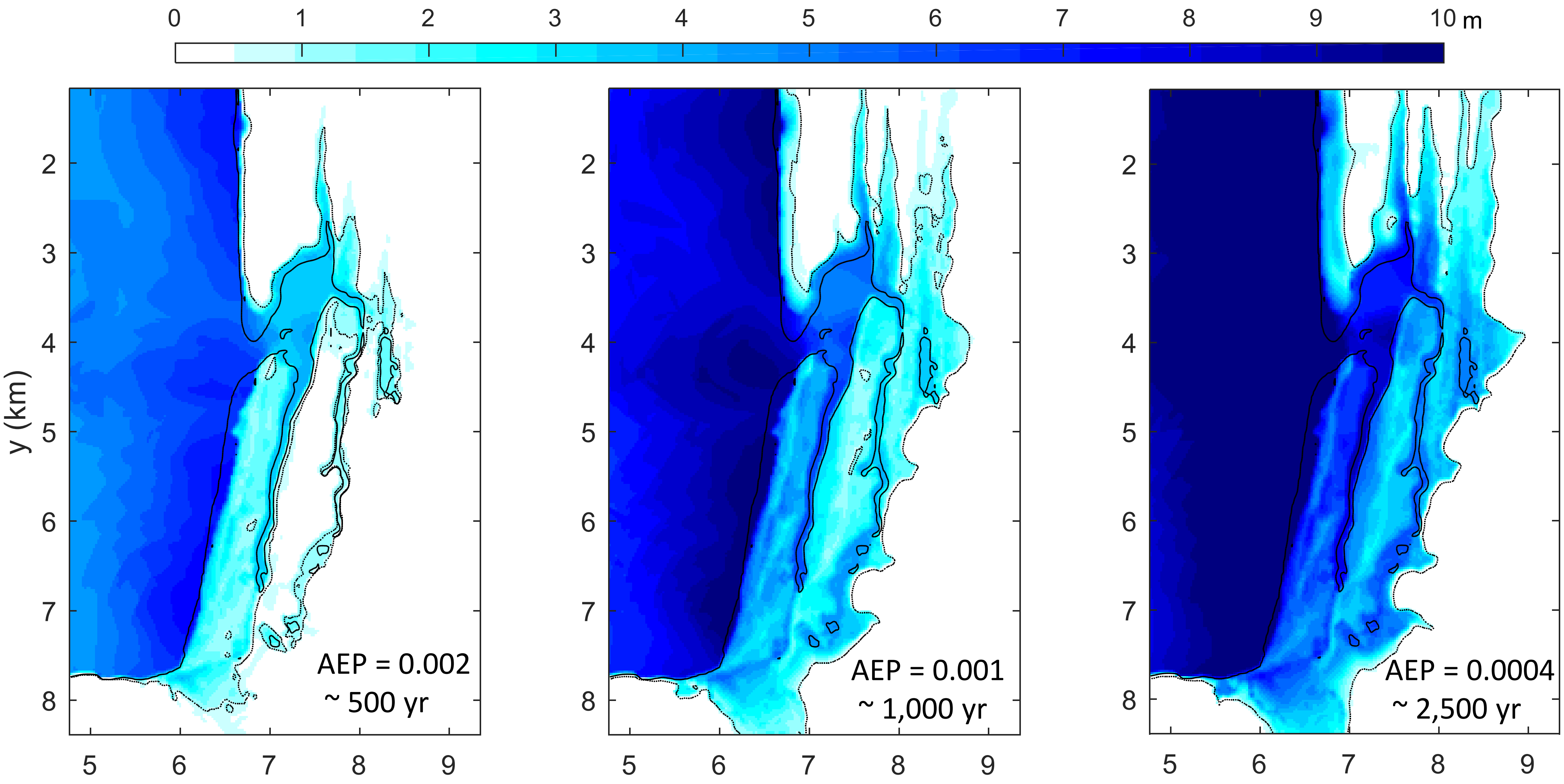
$$P\,[h_{Max} > h_i] = 1 - e^{-vt}$$




(4) Hazards map

# Hazards map at Seaside, OR

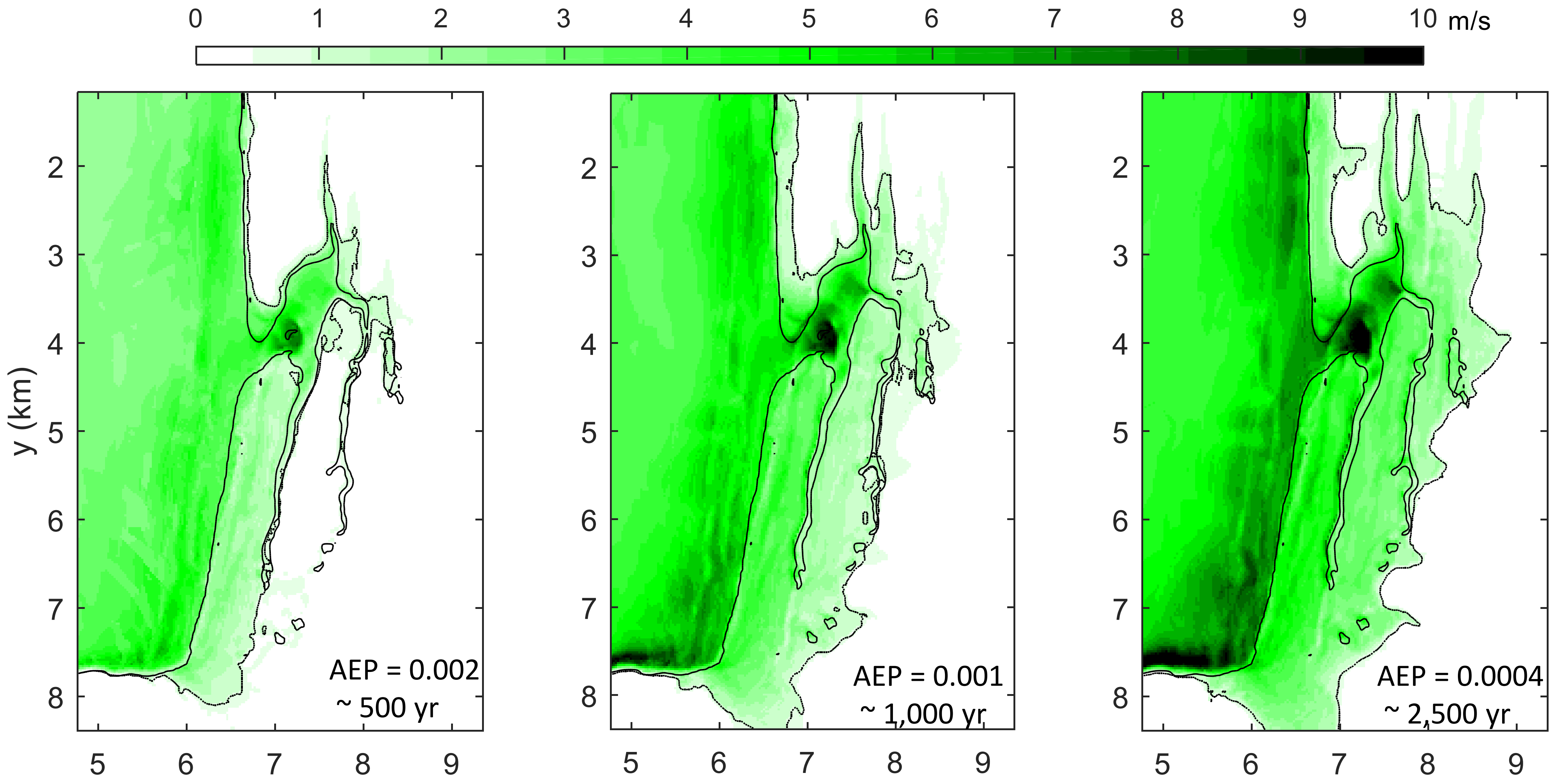
Example: Max. Flow depth ($h_{max}$)



(4) Hazards map

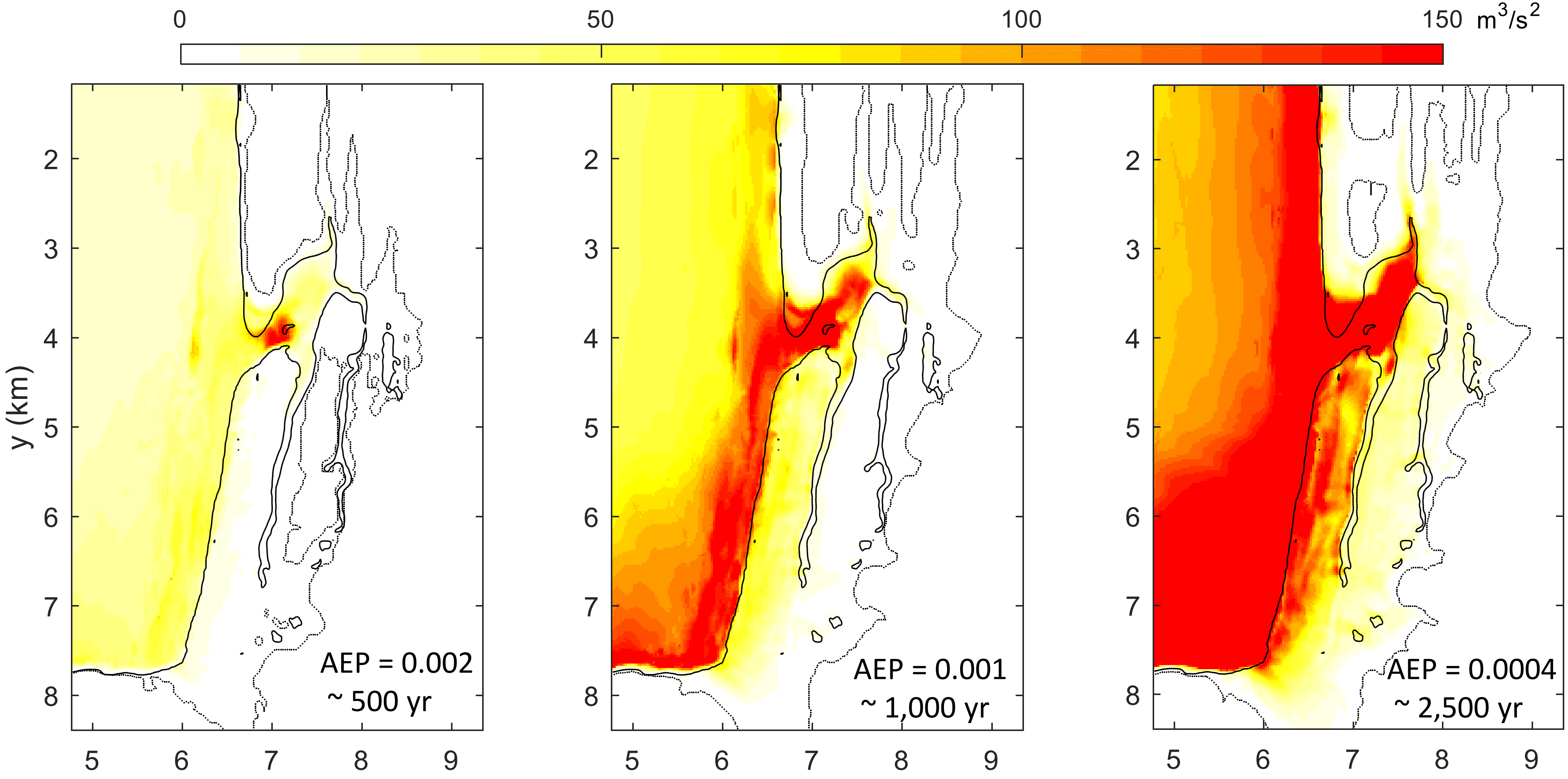
# Hazards map at Seaside, OR

Example: Max. Velocity ($V_{max}$)



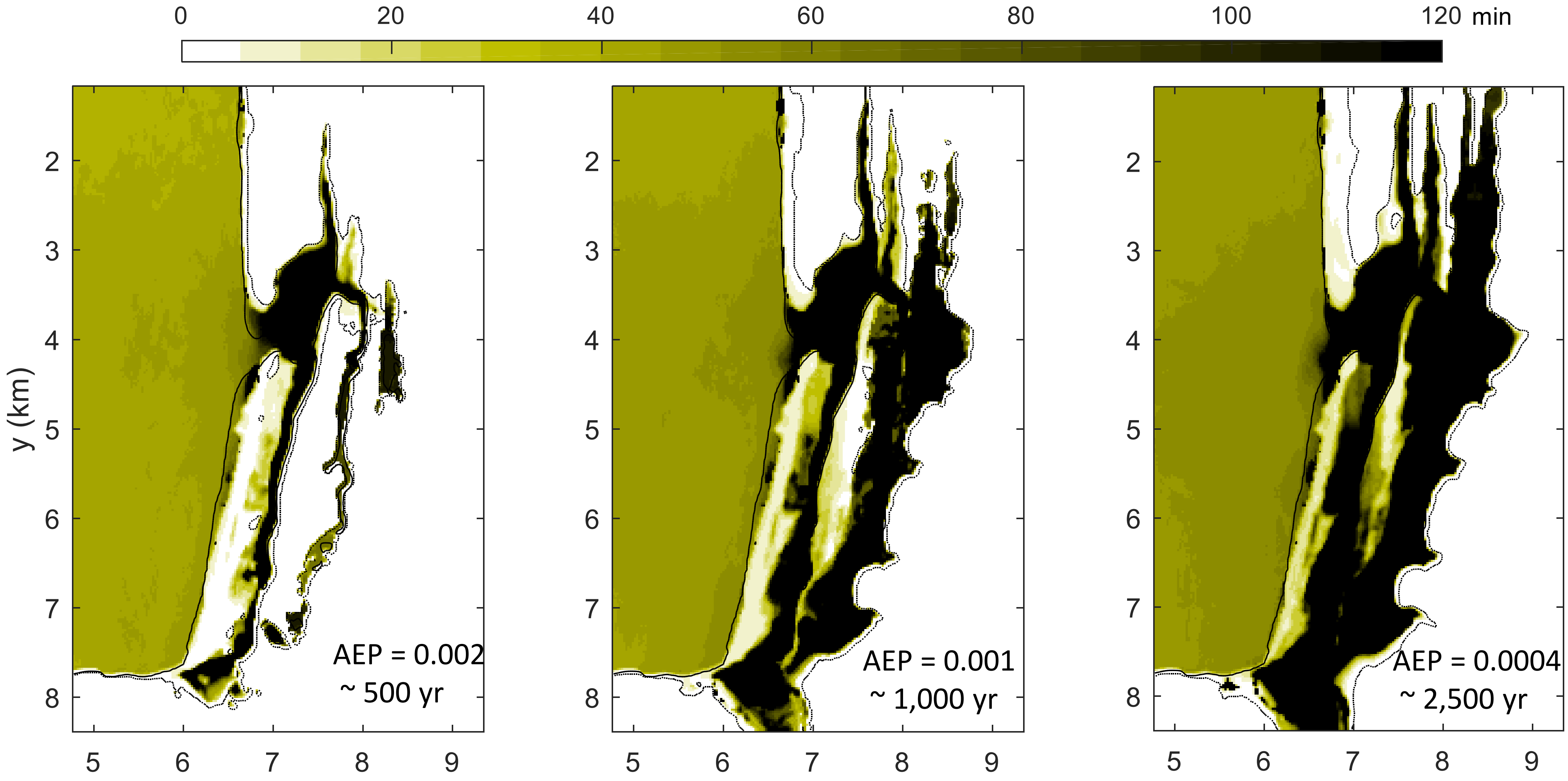
# Hazards map at Seaside, OR

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”

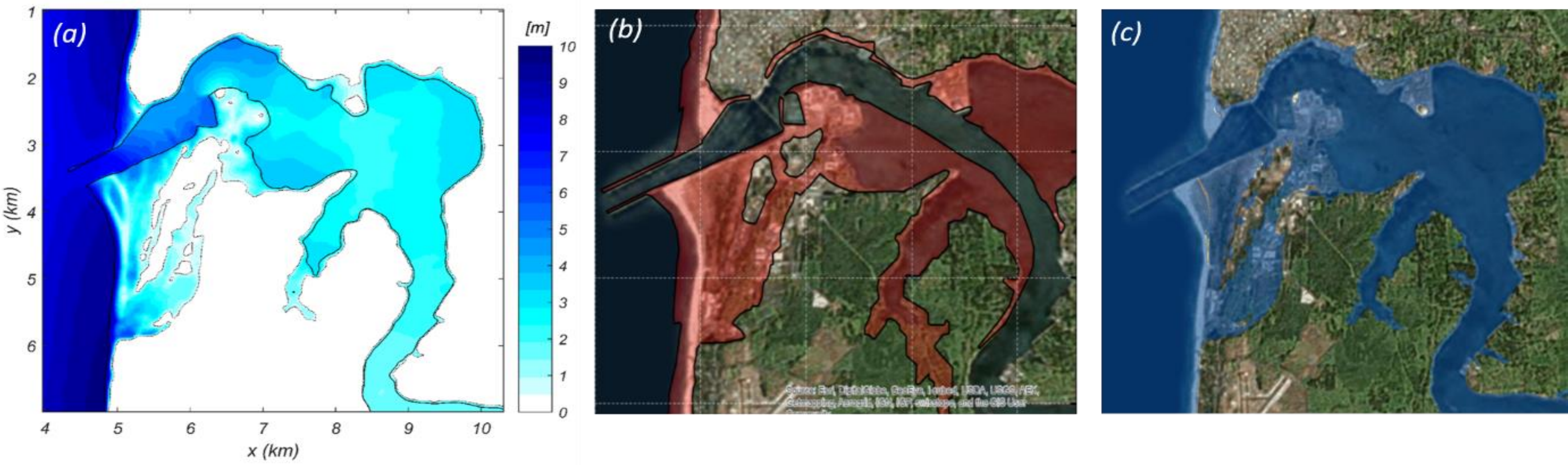
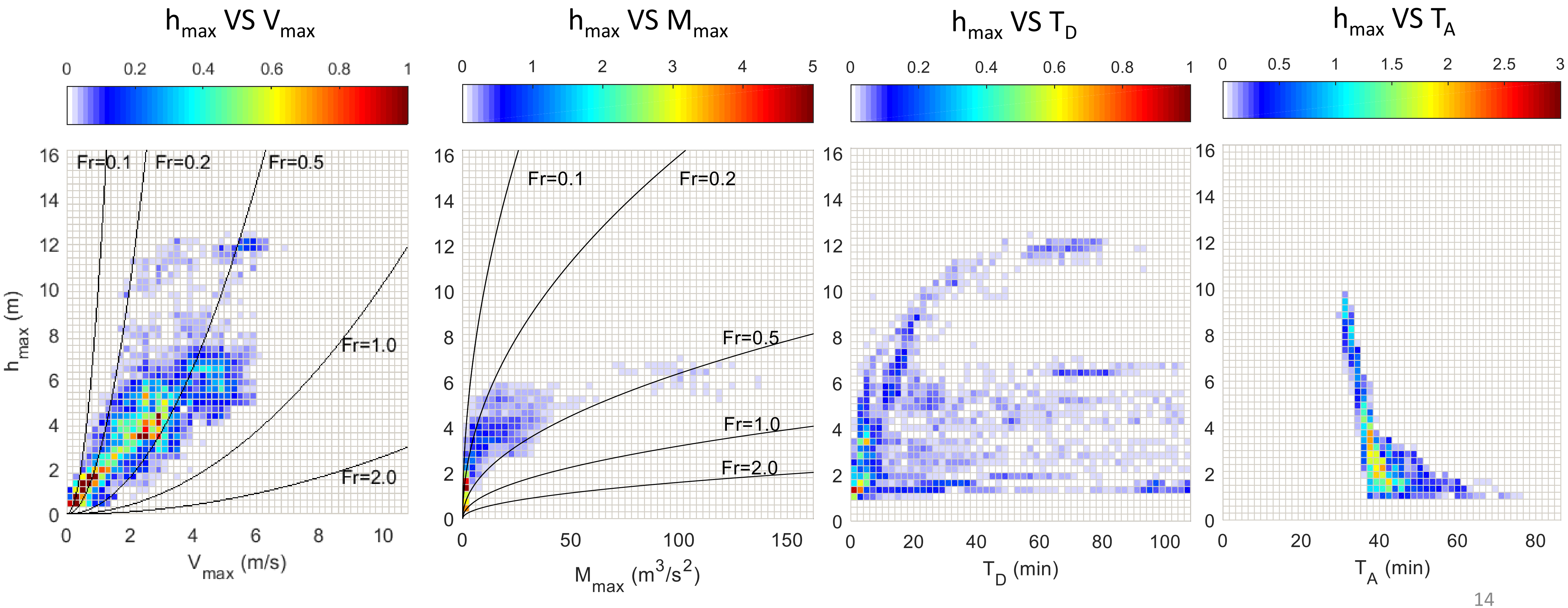


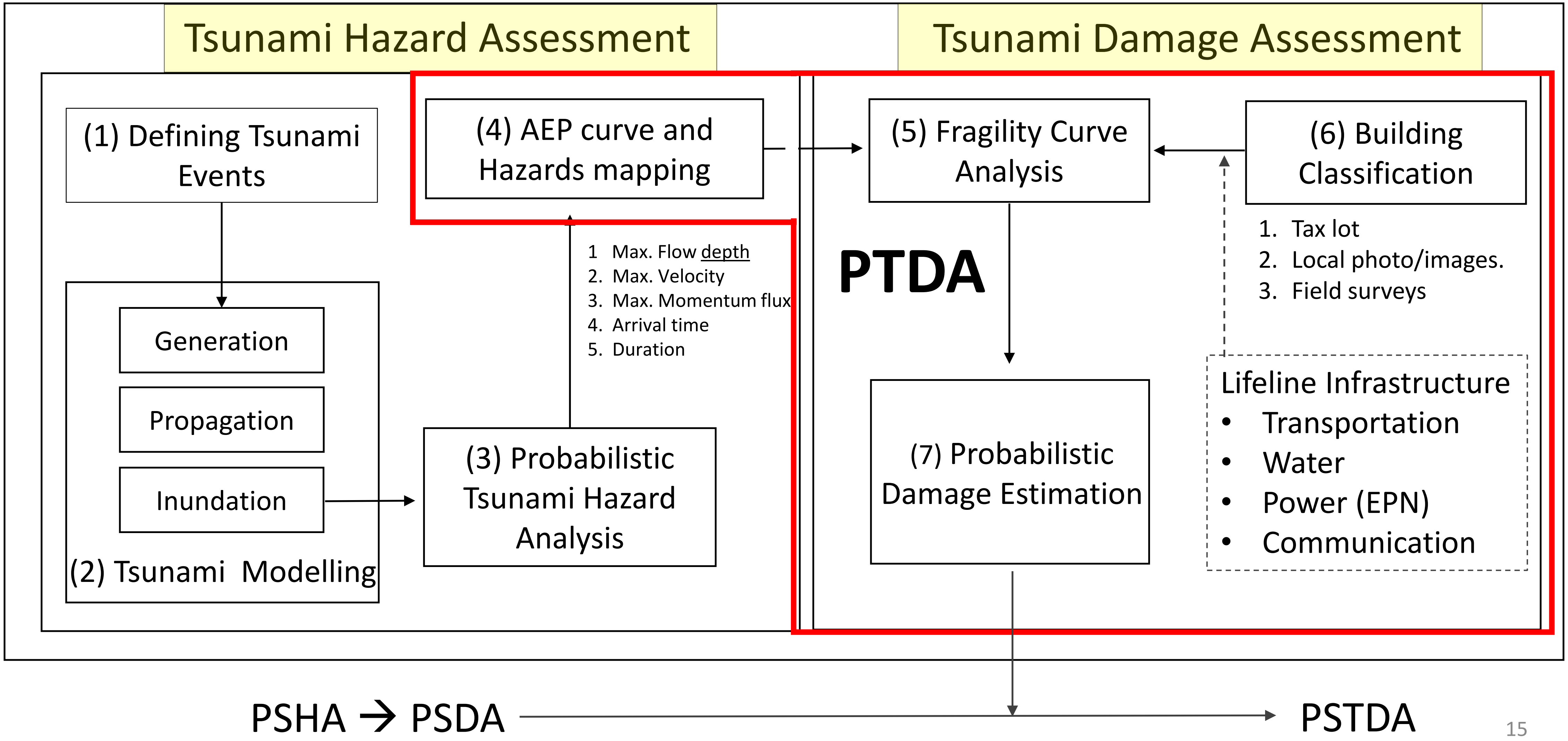

Figure 7: Comparison of maximum extent of tsunami inundation in Newport, Oregon, for (a) present study with AEP = 0.0004, (b) ASCE Tsunami Design Geodatabase (TDG) for AEP = 0.0004, and (c) DOGAMI TIM, ‘M’ scenario (b and c are courtesy of ASCE TDG and Oregon Department of Geology and Mineral Industries).

# 2. Joint Distributions of IMs

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



# Methodology of PTHA, PTDA




Tsunami Hazard Assessment
Tsunami Damage Assessment
(1) Defining Tsunami Events
Generation
Propagation
Inundation
(2) Tsunami Modelling
(3) Probabilistic Tsunami Hazard Analysis
1 Max. Flow depth
2. Max. Velocity
3. Max. Momentum flux
4. Arrival time
5. Duration
(4) AEP curve and Hazards mapping
(5) Fragility Curve Analysis
(6) Building Classification
1. Tax lot
2. Local photo/images.
3. Field surveys
(7) Probabilistic Damage Estimation

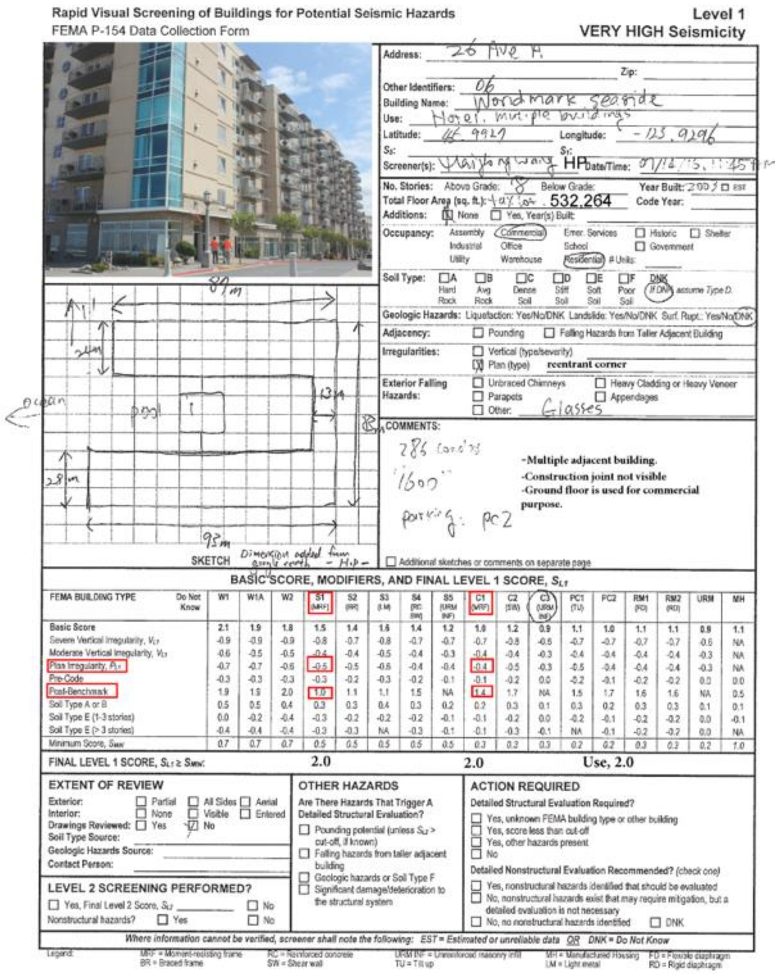
(6) Building classification

# Three tools for building information at study area

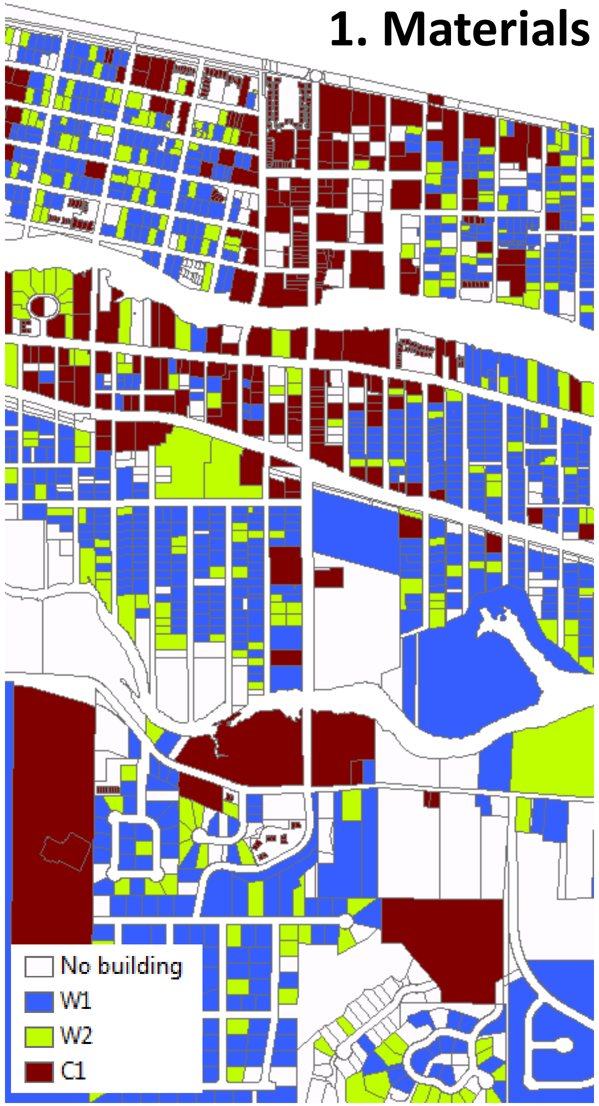
## 1. Tax lot (Stat_Class, Year)

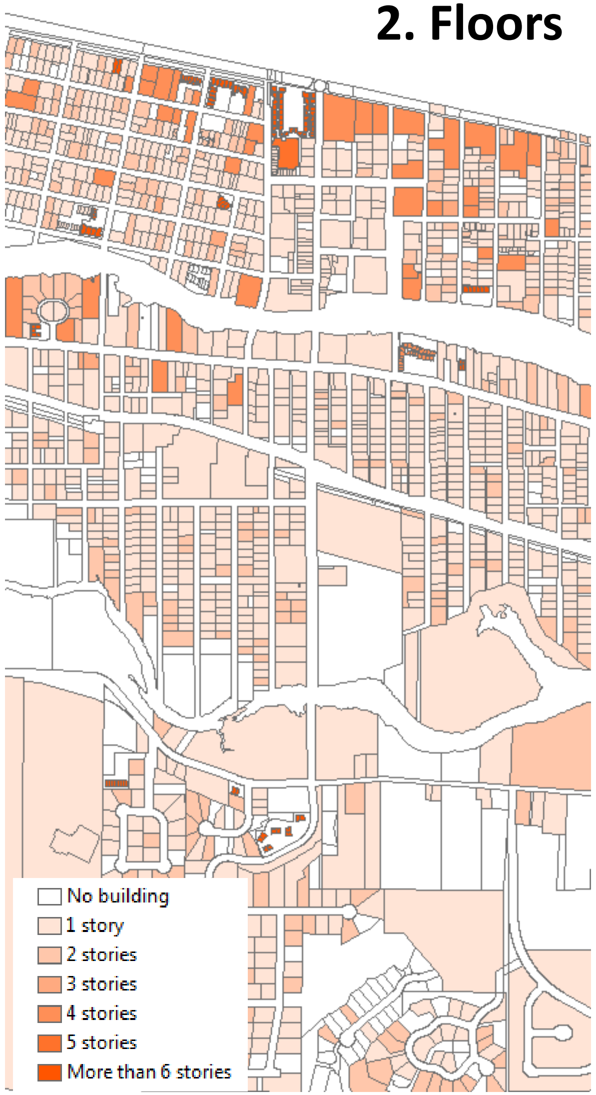
## 2. Pictures from Google map street view

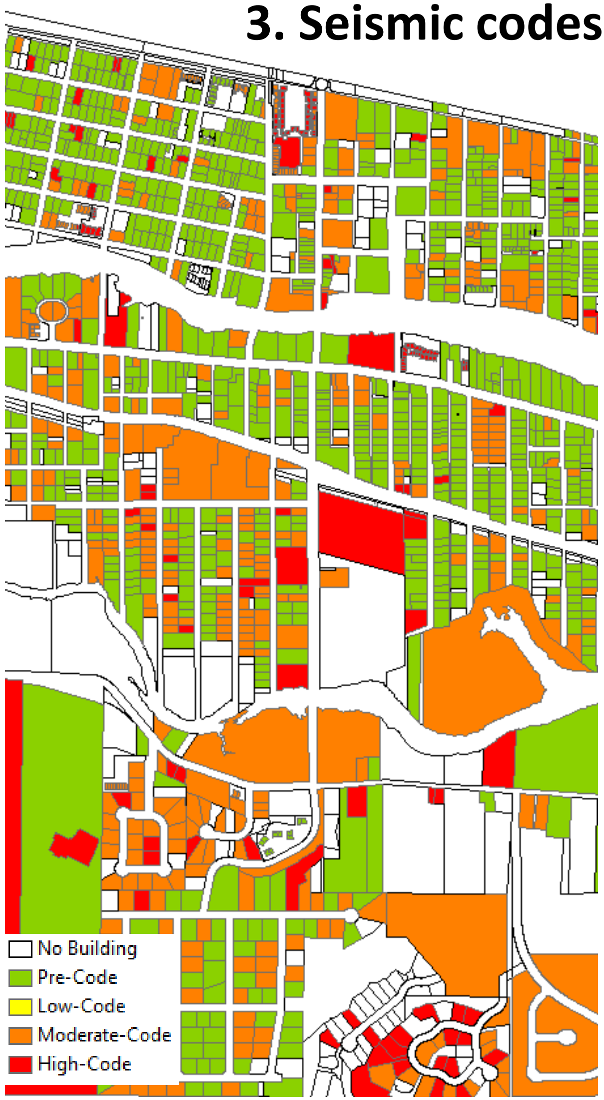

## 3. Fields survey Rapid Visual Screening (RVS)



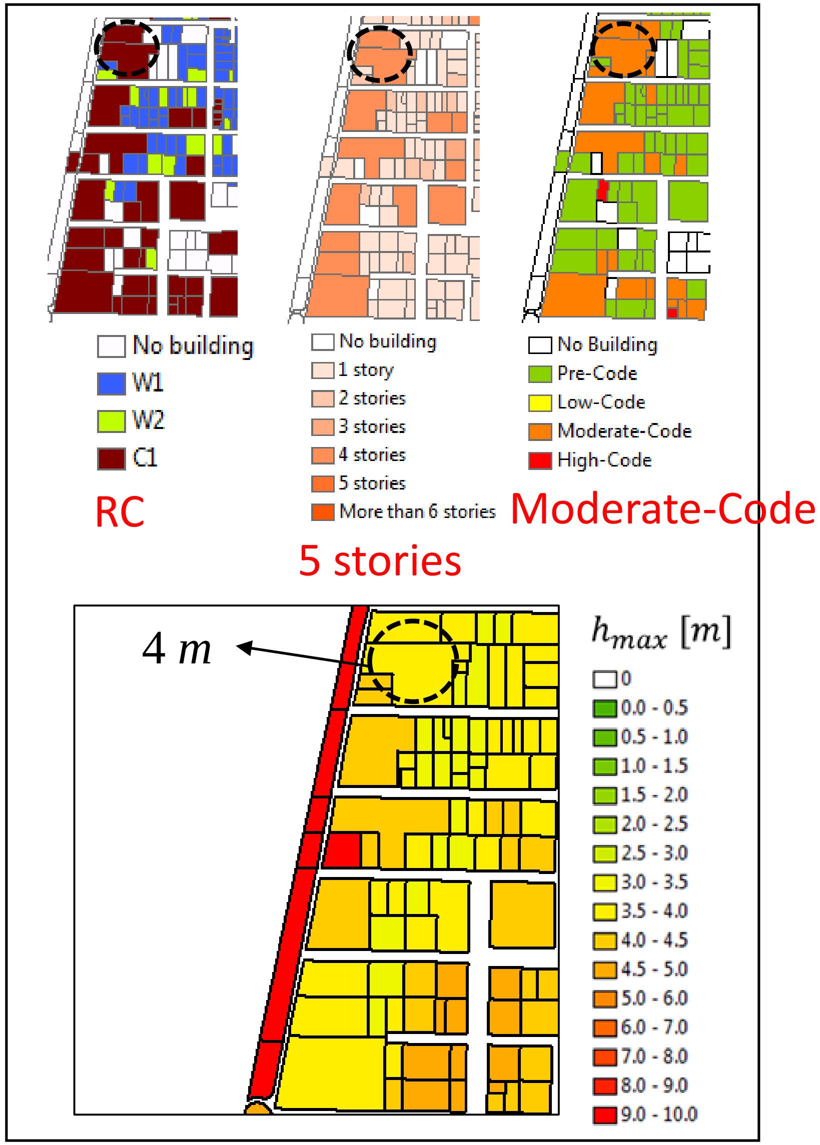
# Building Classification



# Example of building damage assessment (at AEP = 0.001)

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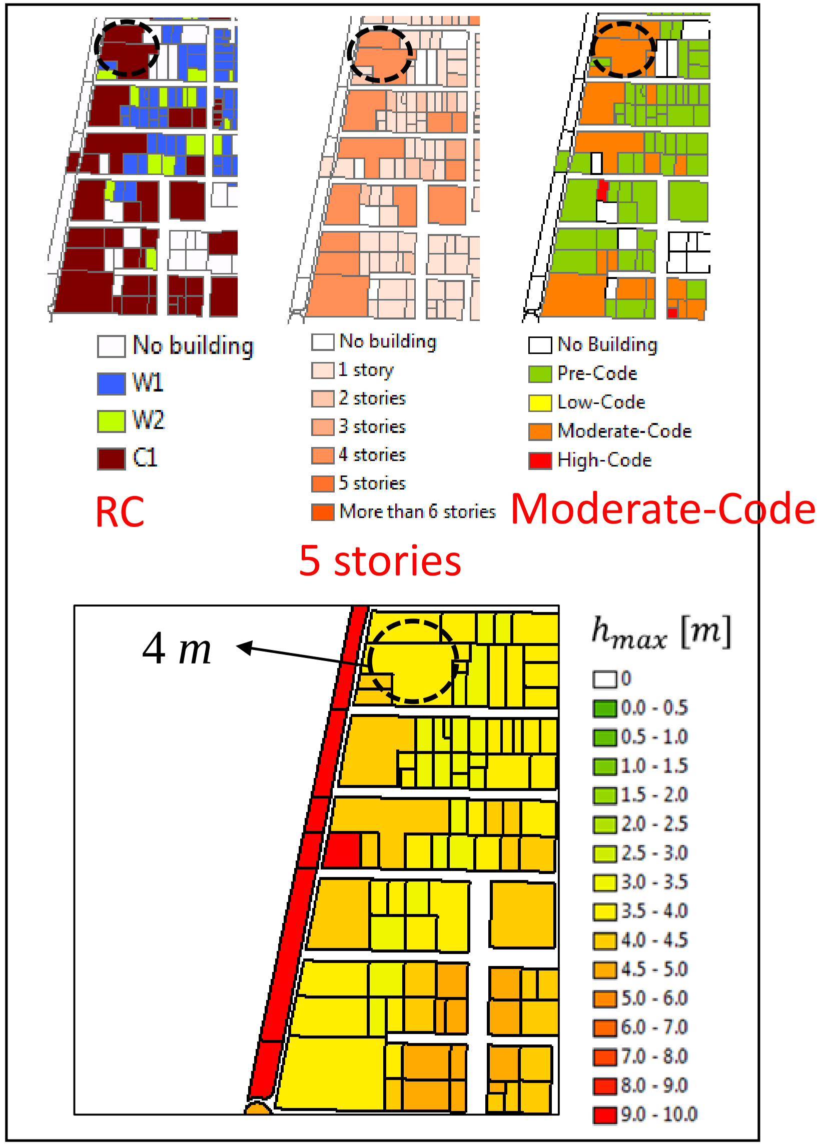
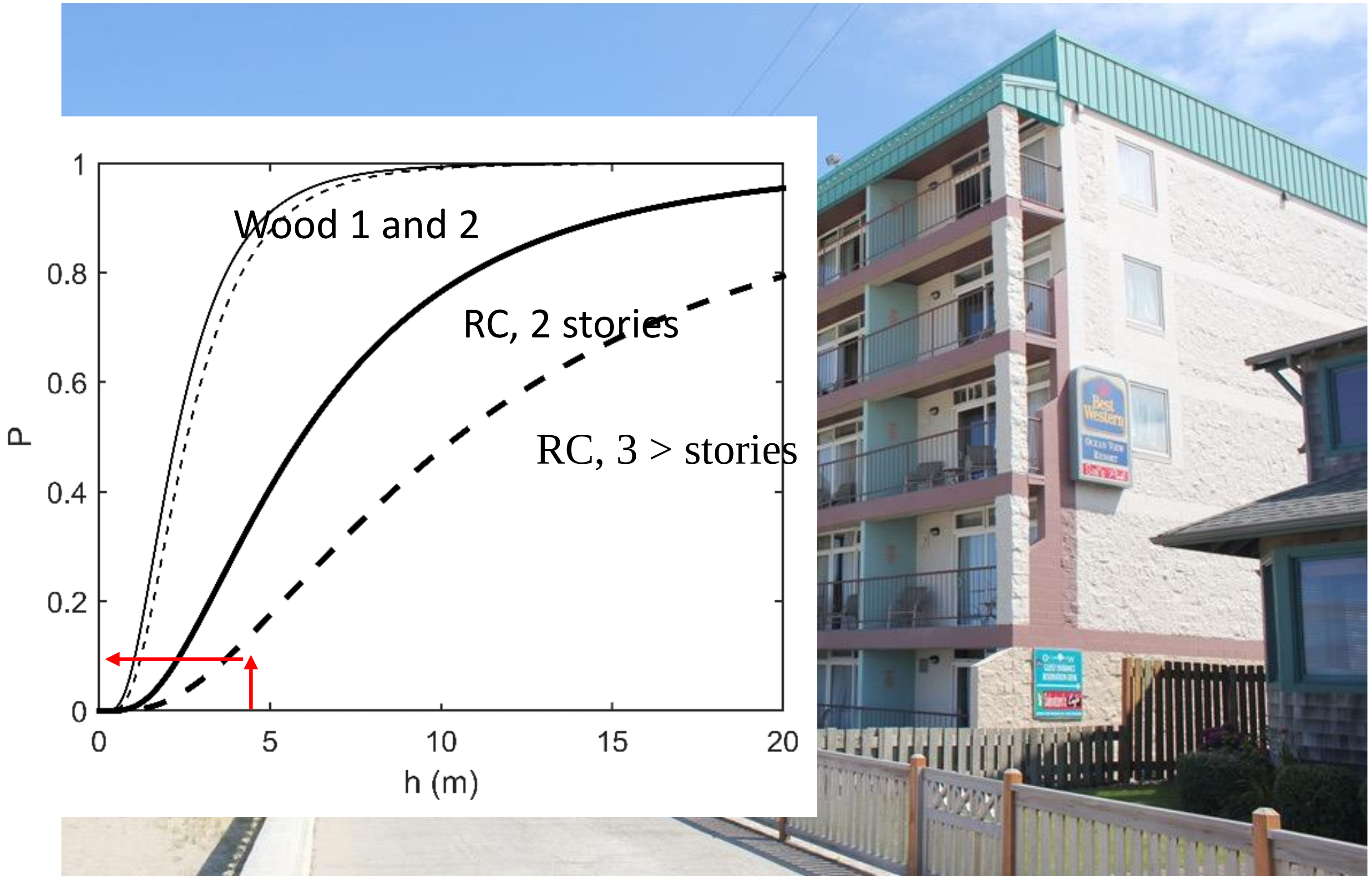
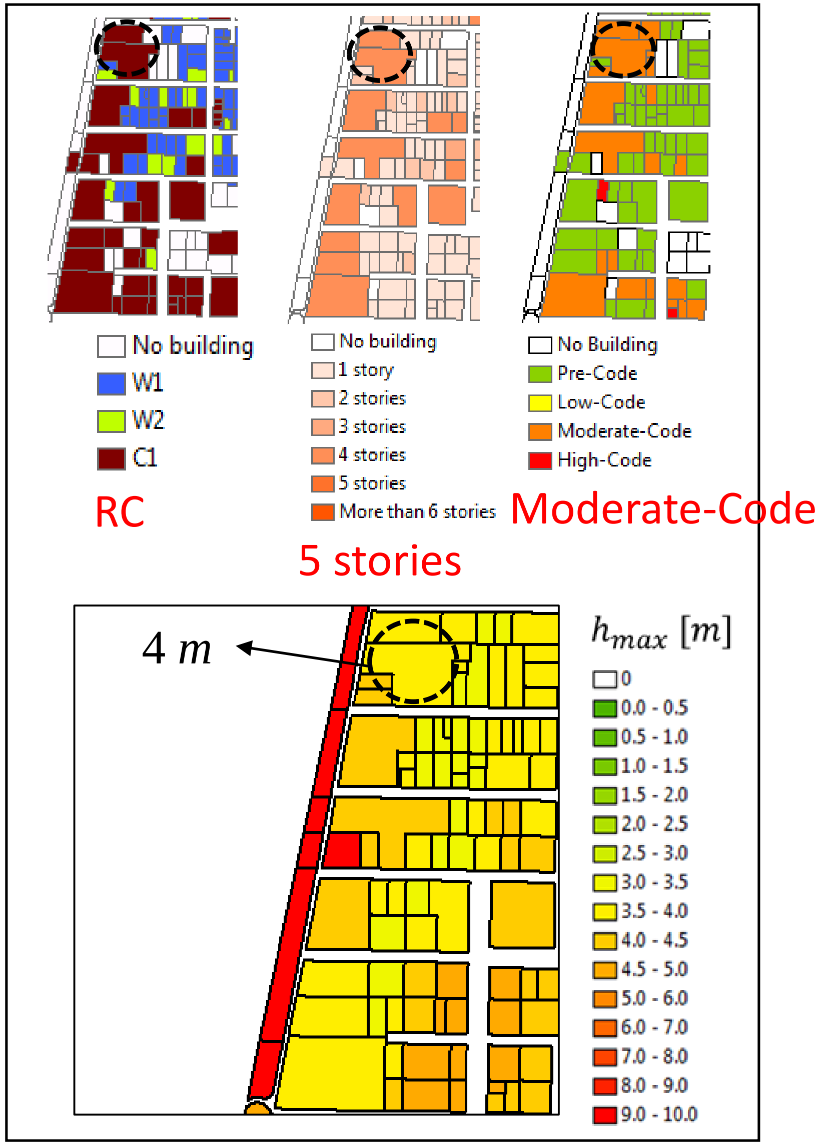
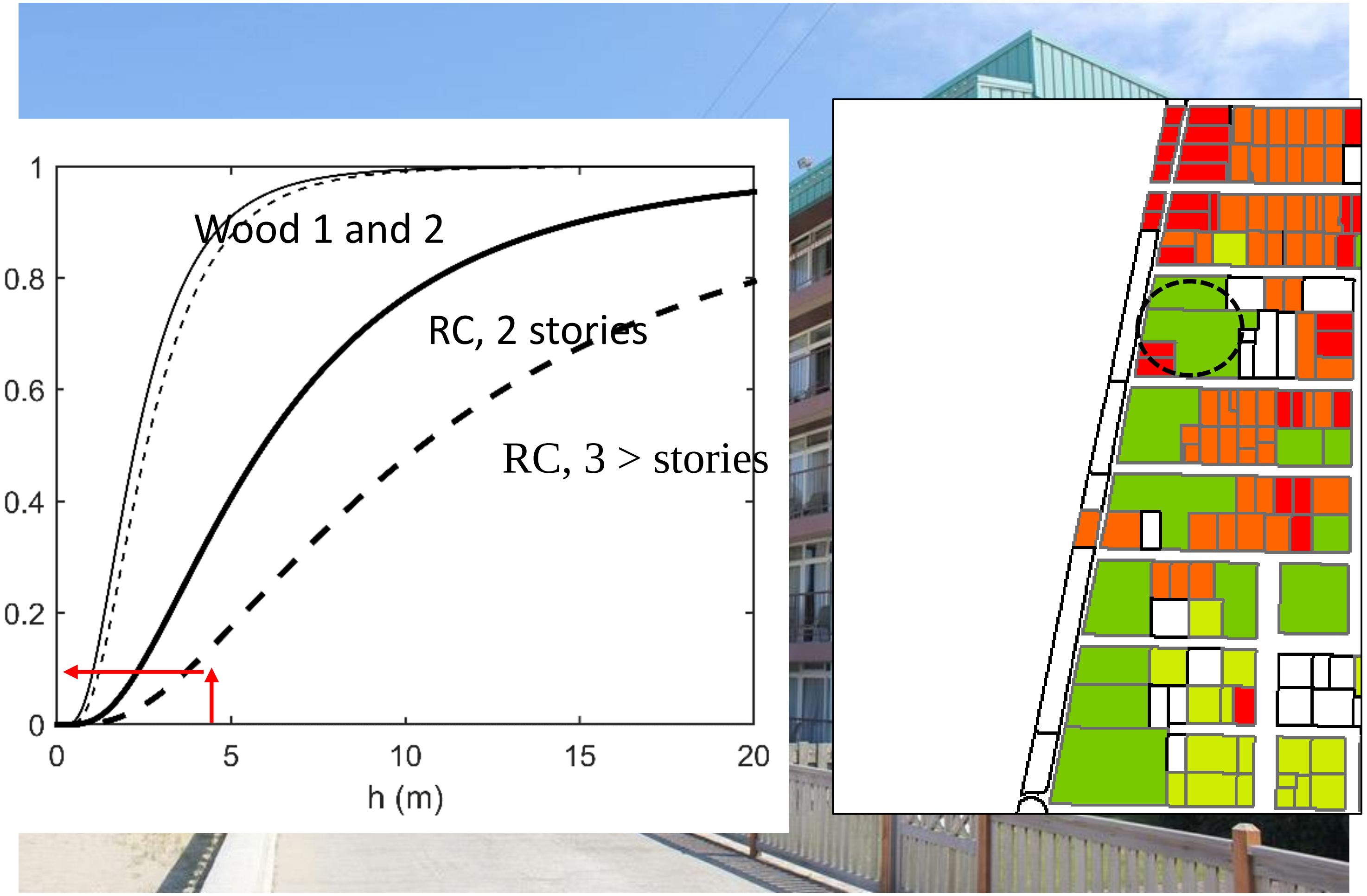



Fragility curves (Suppasri et al., 2013) for collapse damage

# 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)

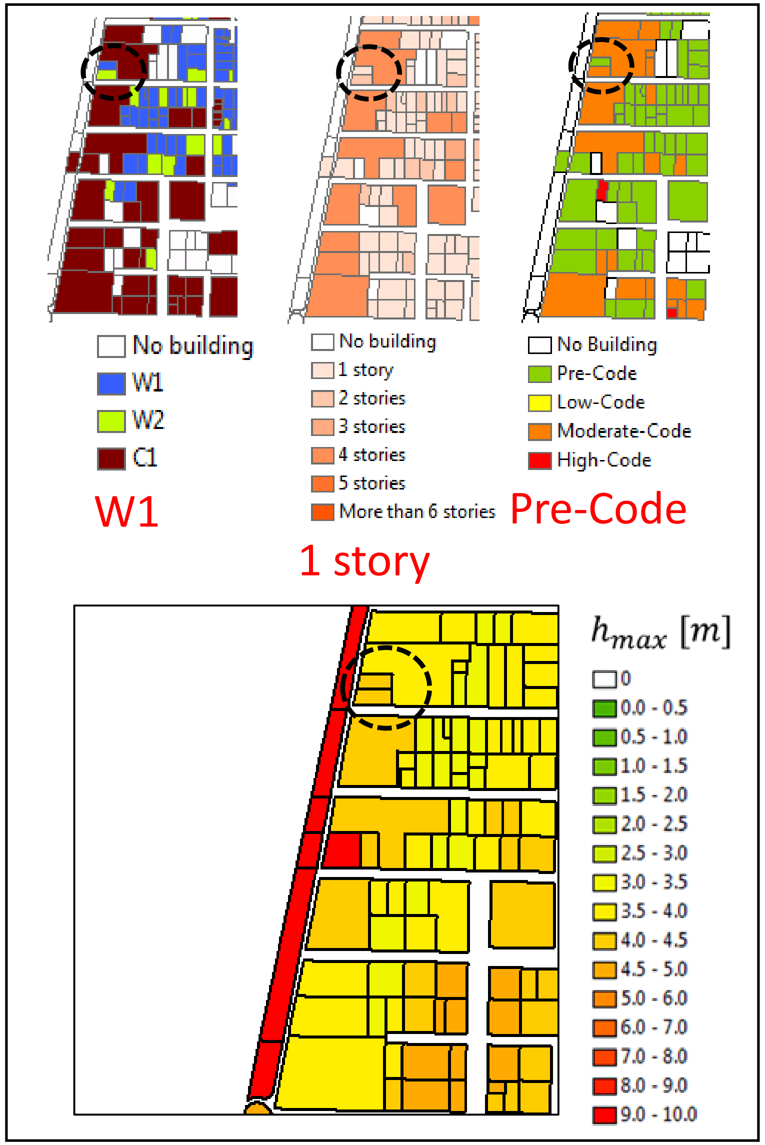
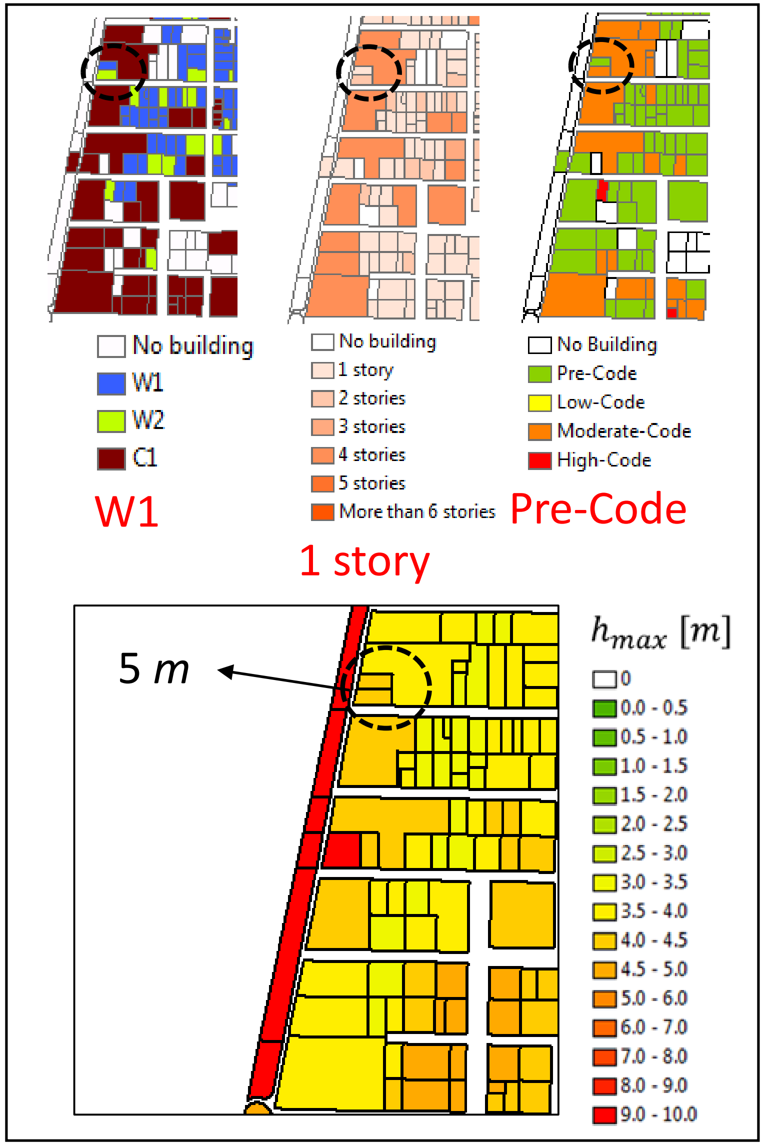
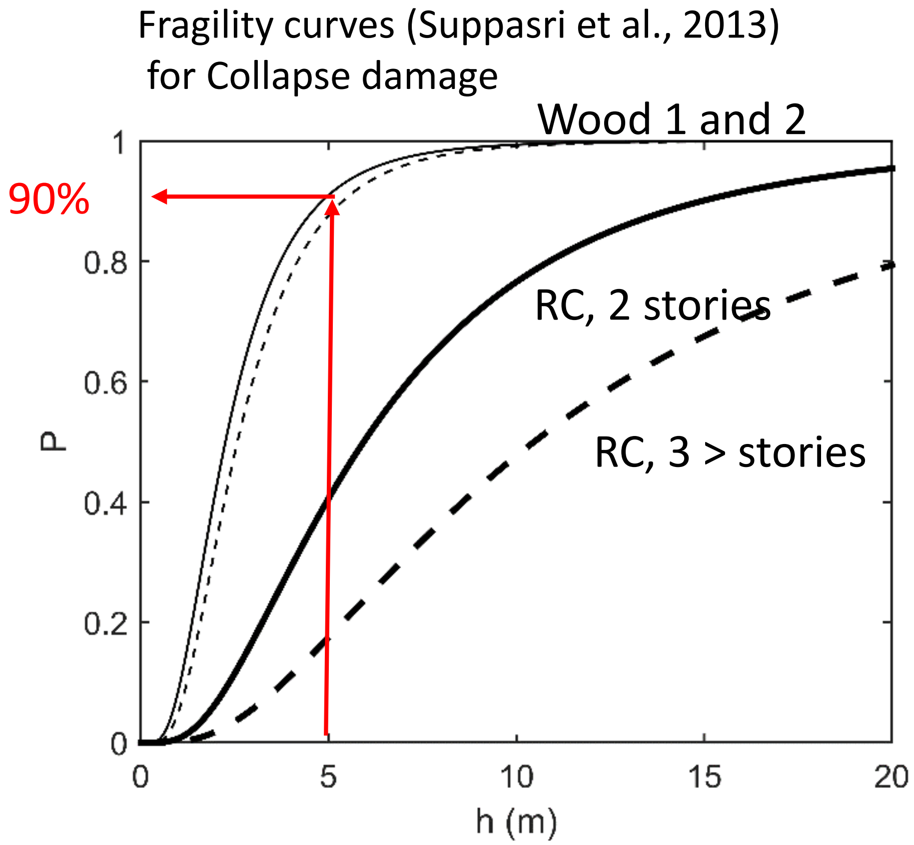
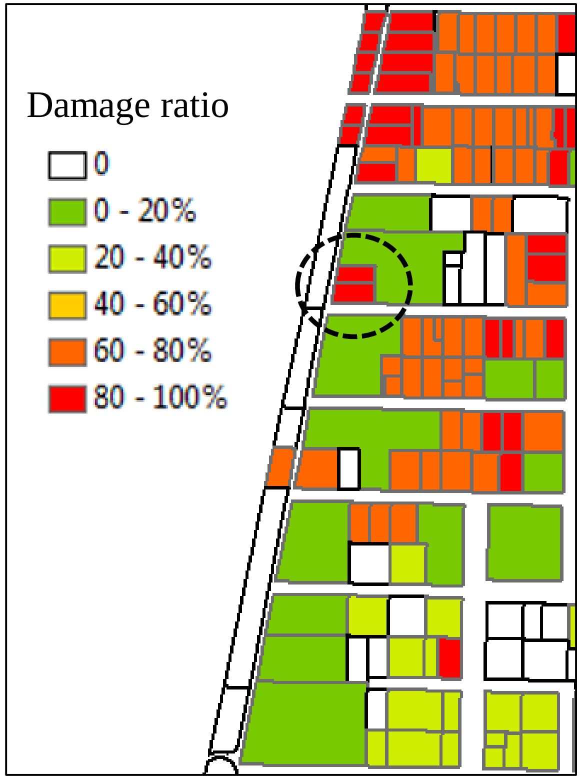



Photo taken by Hyoungsu Park, at Seaside Field trip (July, 14, 2015)

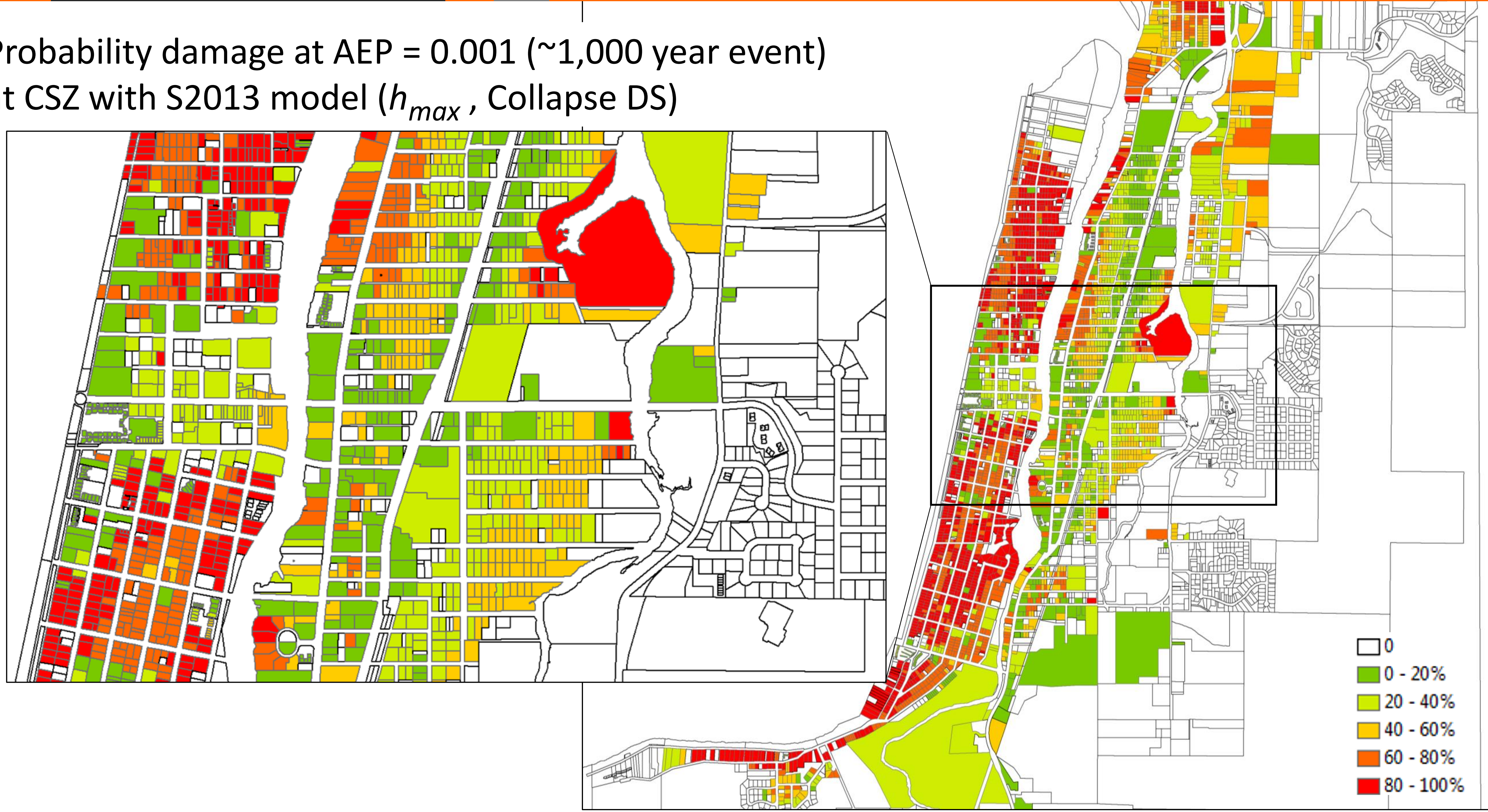
# Example of building damage assessment (at AEP = 0.001)



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



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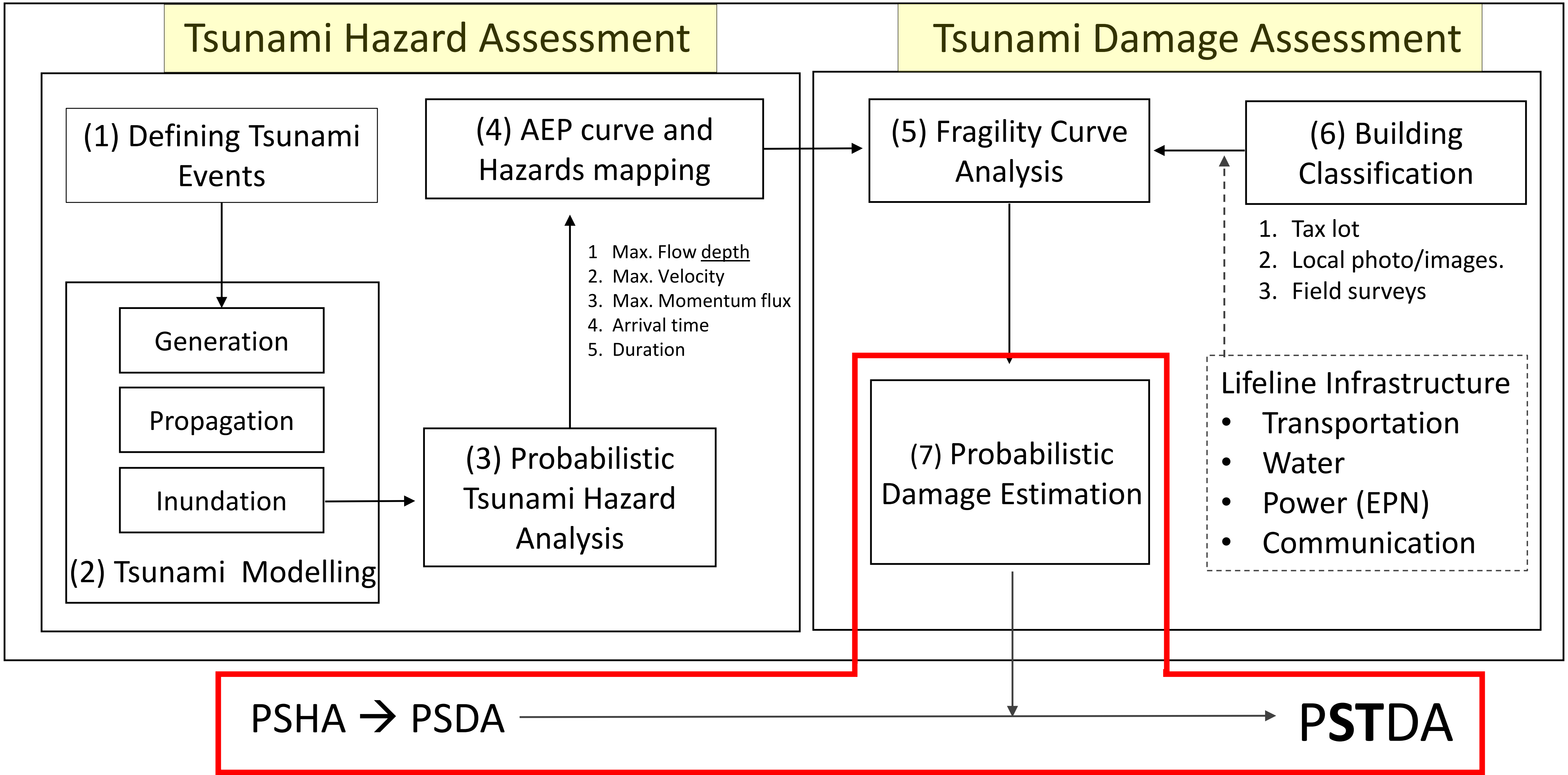


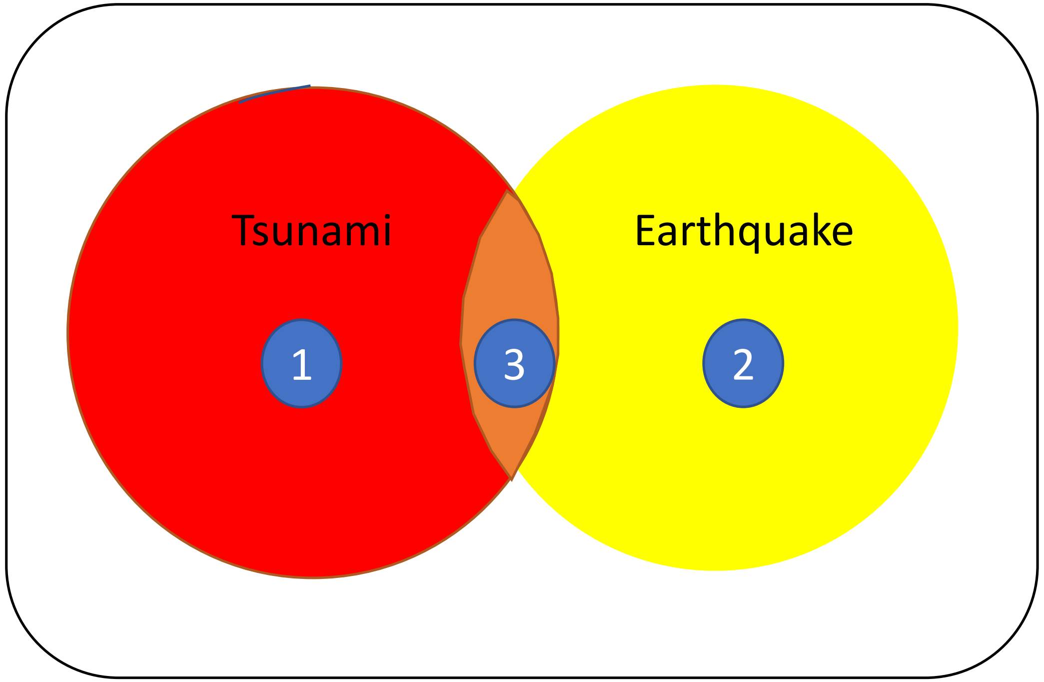
# Merging Tsunami and Earthquake damage assessment

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

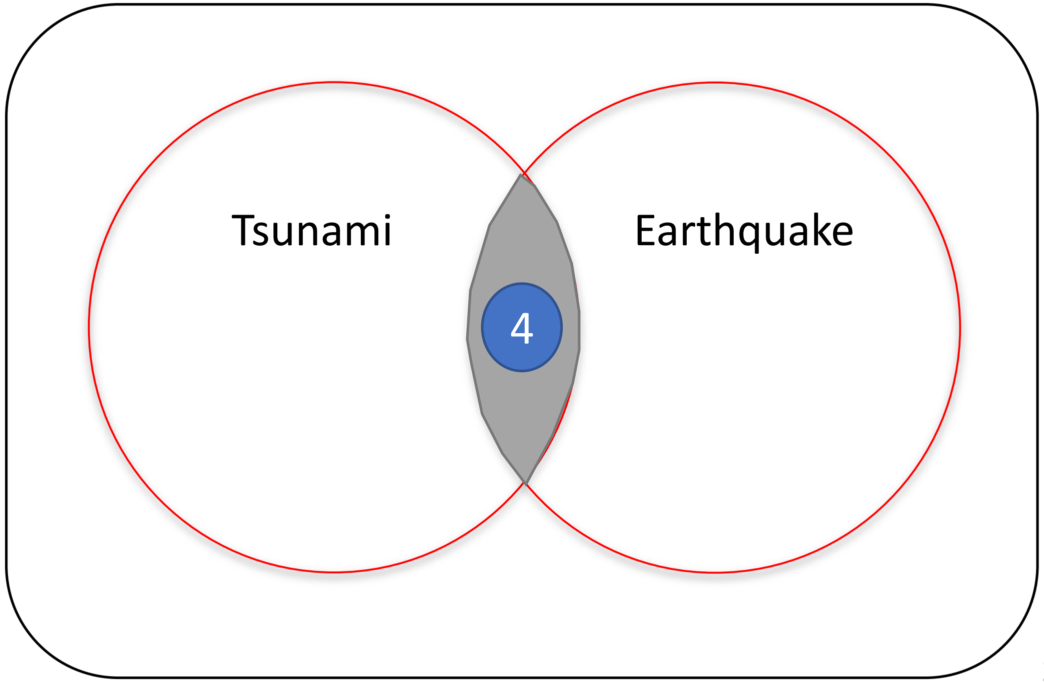
$$P[C_{STR}|EQ+TS] = \overset{1}{P[C_{STR}|EQ]} + \overset{2}{P[C_{STR}|TS]} - \overset{3}{P[C_{STR}|EQ]\,P[C_{STR}|TS]} + \underline{(P[\geq E_{STR}|EQ] - P[C_{STR}|EQ])\,(P[\geq E_{STR}|TS] - P[C_{STR}|TS])}\ \textcircled{4}$$

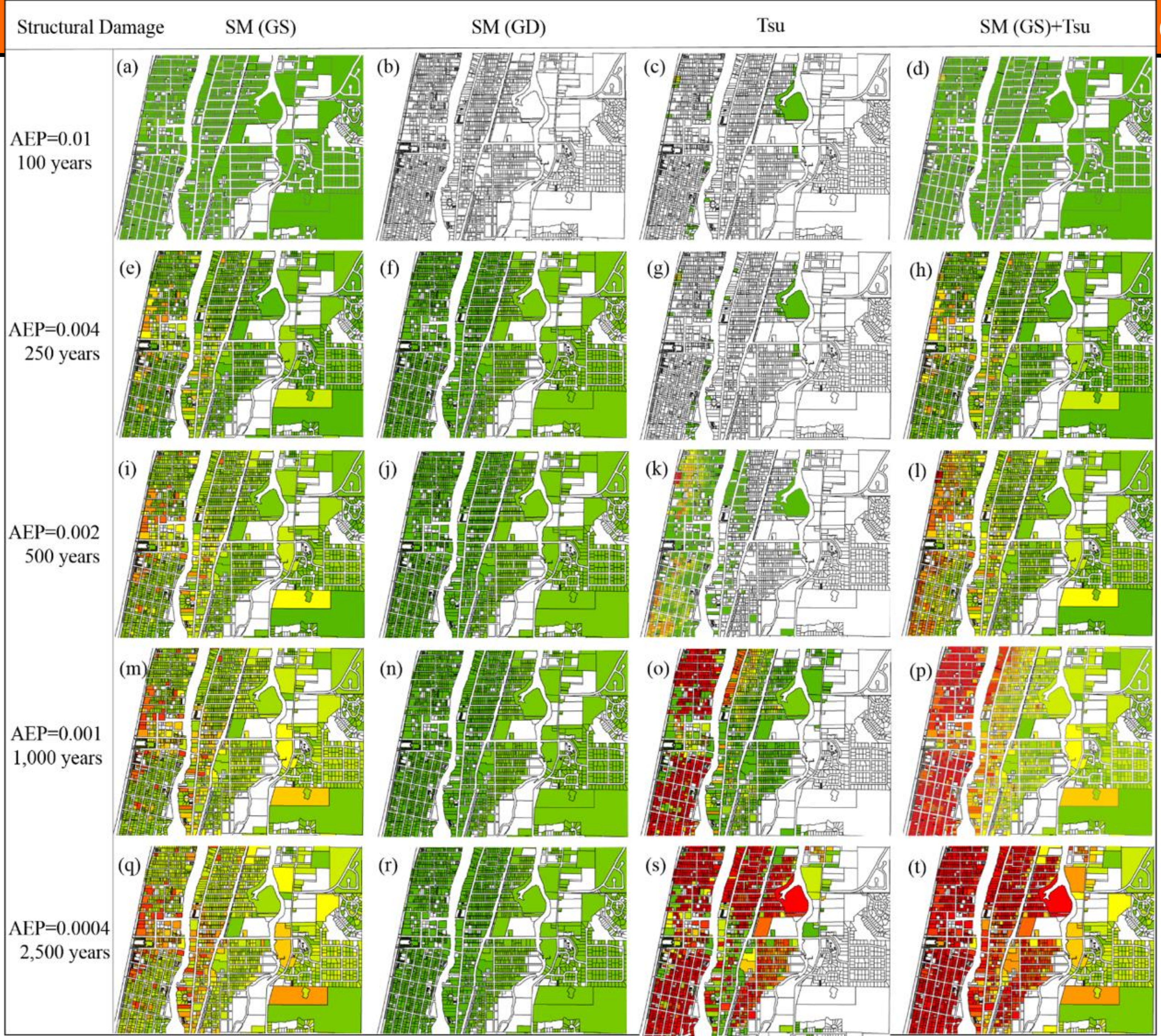
FEMA, 2013

From 'Complete' damage states




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





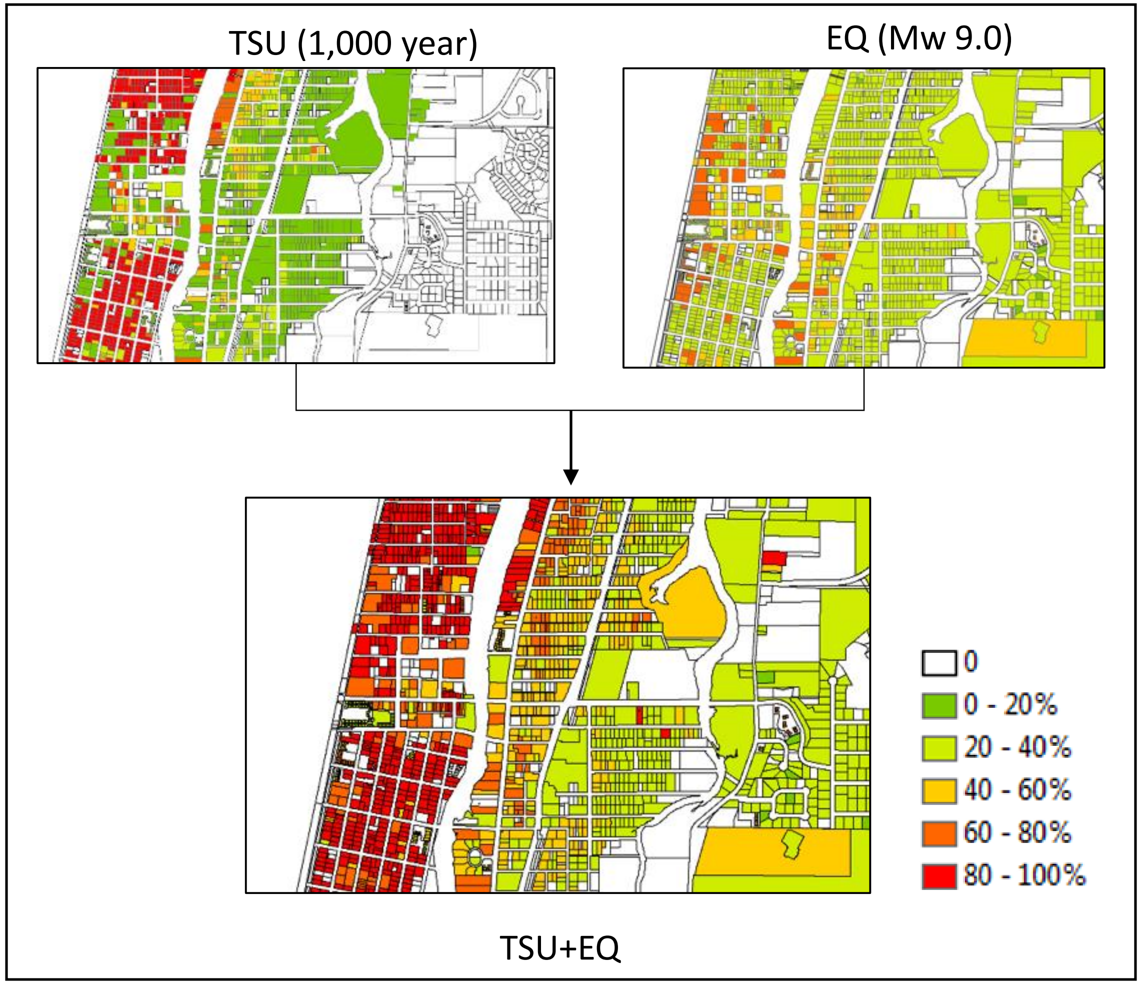

Higher probability
Lower consequences

Highest Risk

Lower probability
Higher consequences

## Direct loss Estimation

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


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

FEMA 325 (2007)

# Debris Forecasting

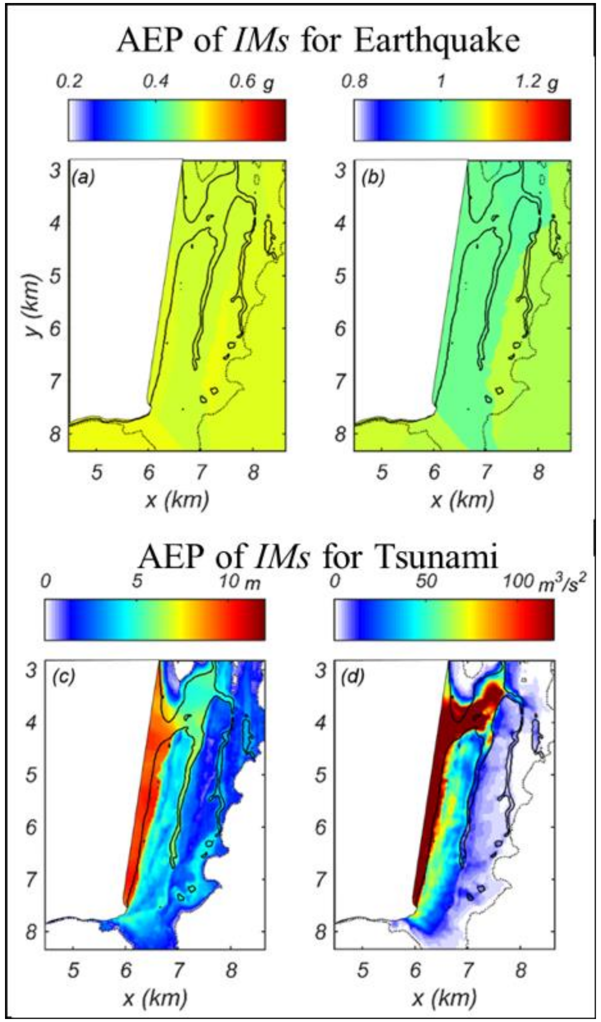
1. What is it?
2. How much is it?
3. Where is it?

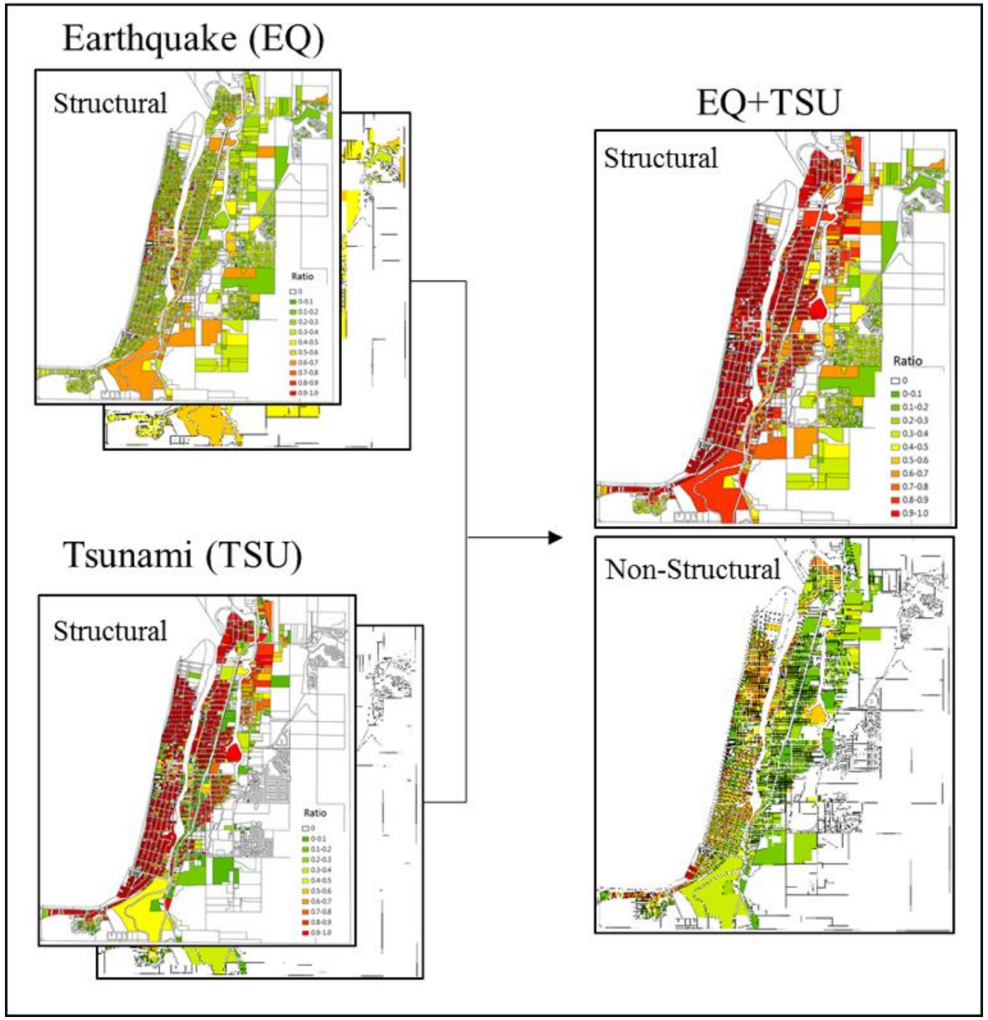
Hazards and Disaster Debris types

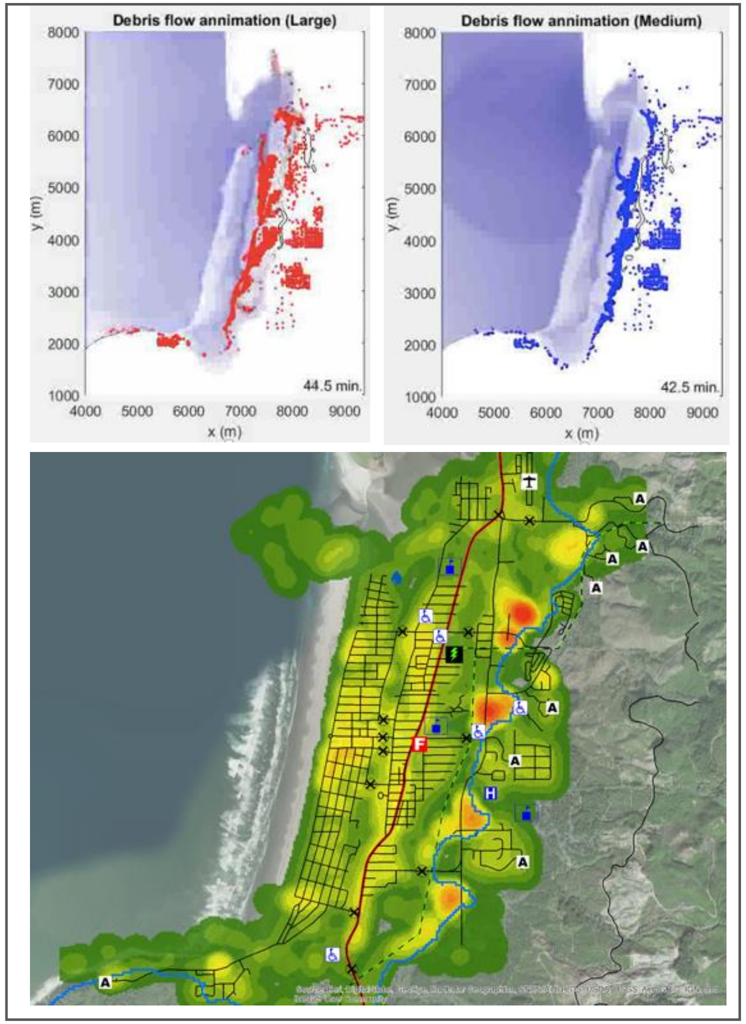
| | Natural | | | Anthropogenic | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Vegetative | Soil, Sand, Mud | Putrescence | Construction & Demolition | Household Hazardous Waste (HHW) | White Goods | Personal Property | Vehicles + Vessels | Hazardous Waste |
| Hurricane | x | x | x | x | x | 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

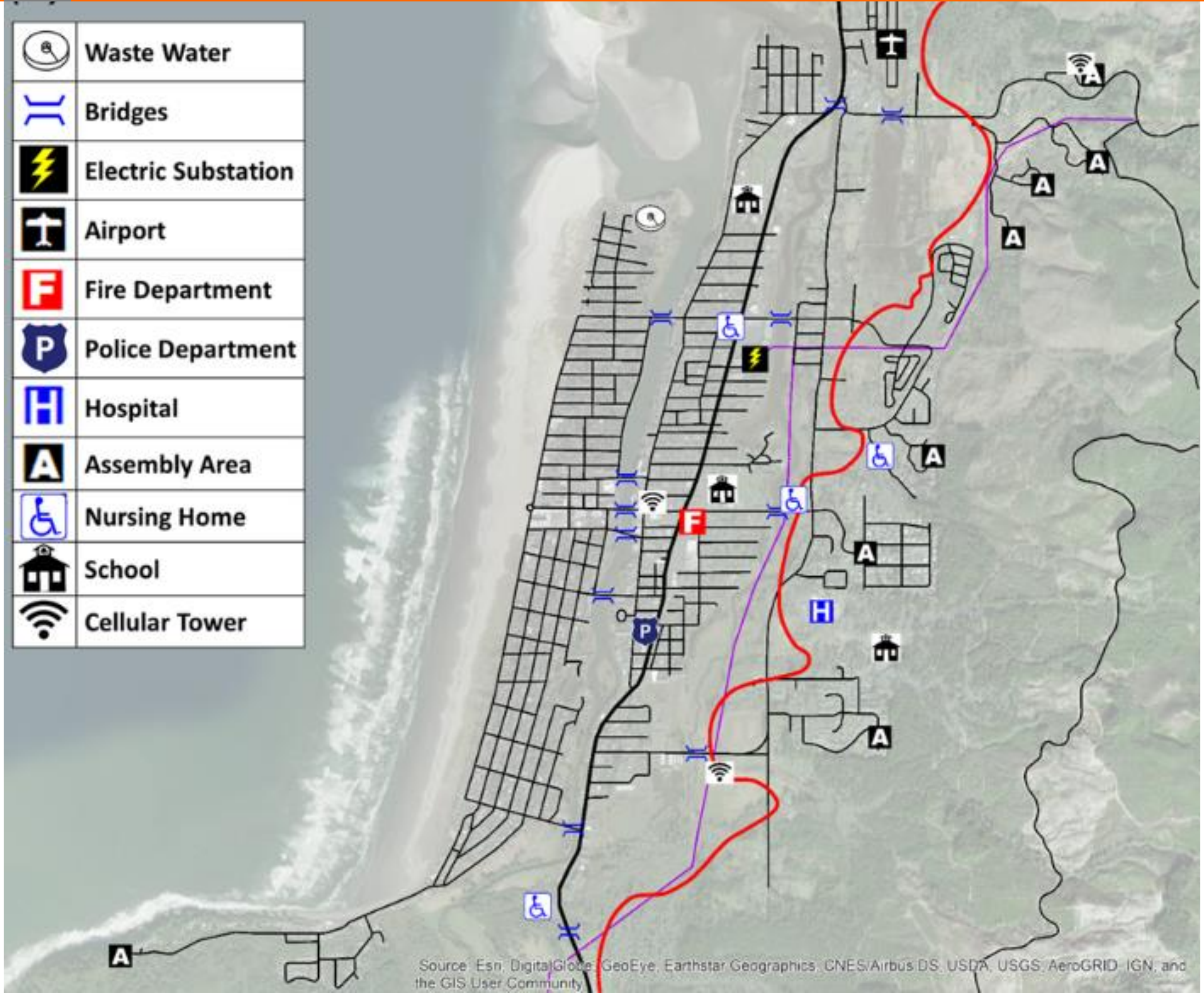
## Multi-hazard (PSTHA) → MH Damage and Loss (PSTDA) → Debris Forecast Generation & Advection



# Focus on critical facilities and lifelines



# Methodology of Debris Quantification

Based on Hazus-MH 2.1 (Earthquake)


Single house

For structural debris

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

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

For non-structural debris

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

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

# 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

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

Debris weight from non-structural damage

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

Total Weight of Debris

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

| | |
|---|---|
| $DW_S$ | Weight of debris from structural damage |
| $W_S$ | Weights of debris per 1000 ft$^2$ 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 |

Disaggregation to floating or non-floating debris

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

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

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)

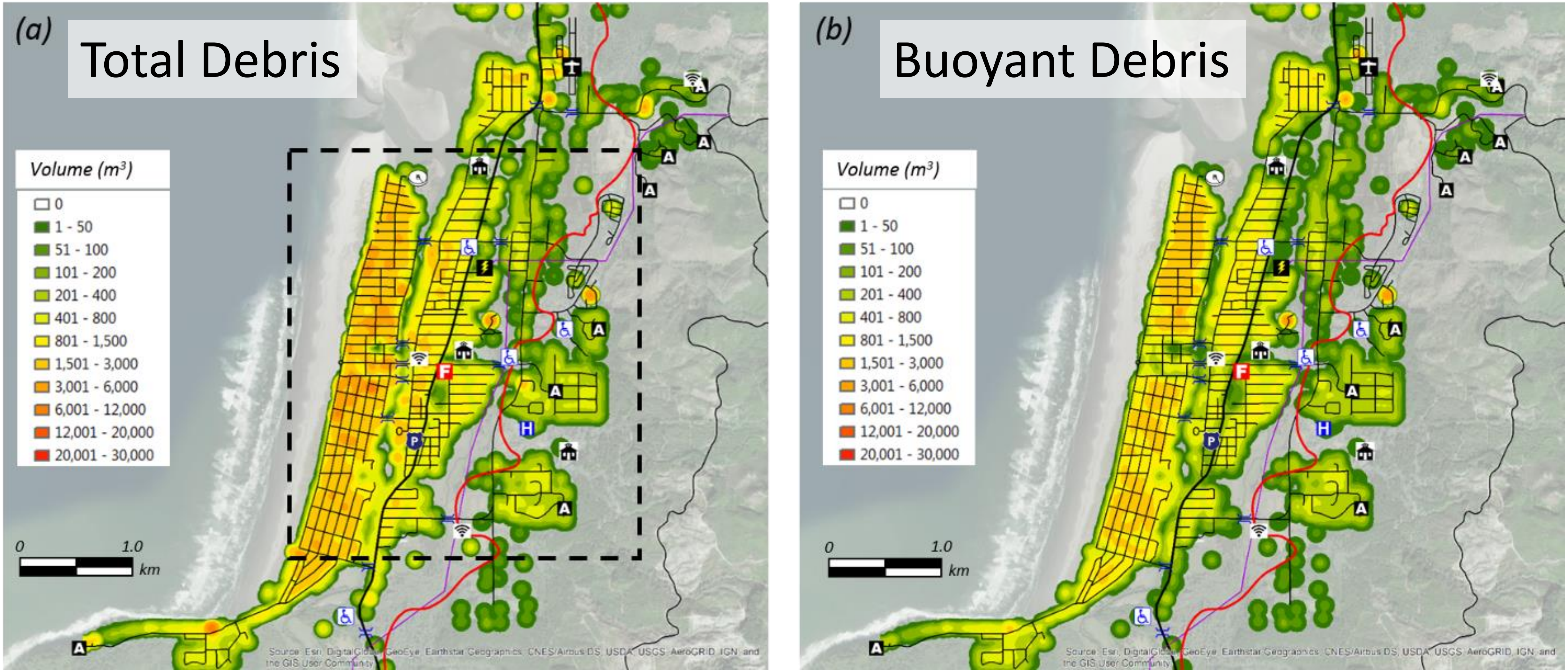
| Building Type | $DF_{S,F}$ (%) | | | | $DF_{NS,F}$ (%) | | | |
|---|---|---|---|---|---|---|---|---|
| | Slight ( i=1) | Moderate (i=2) | Extensive (i=3) | Complete (i=4) | Slight (i=1) | Moderate (i=2) | Extensive (i=3) | Complete (i=4) |
| W1 | 0.0 | 5.0 | 34.0 | 100.0 | 2.0 | 8.0 | 35.0 | 100.0 |
| 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 |

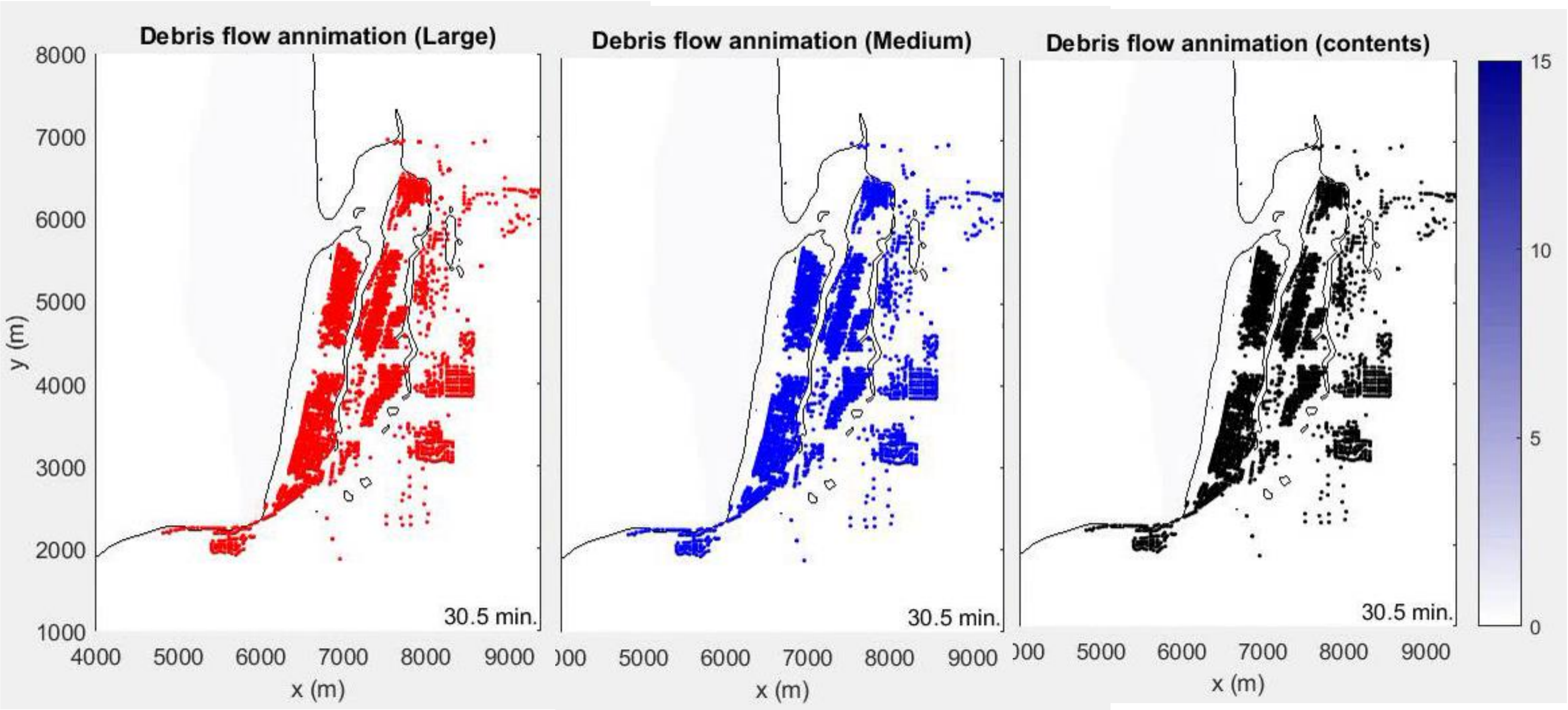
Table 3. Unit weight (tons per 1000 $ft^2$) for structural and non-structural elements for building types

| Building Type | Floatable (Wood, Brick, and others) | | Non-Floatable (RC and Steel) | | SQ (Footage of building/1000$ft^2$) |
|---|---|---|---|---|---|
| | 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 |

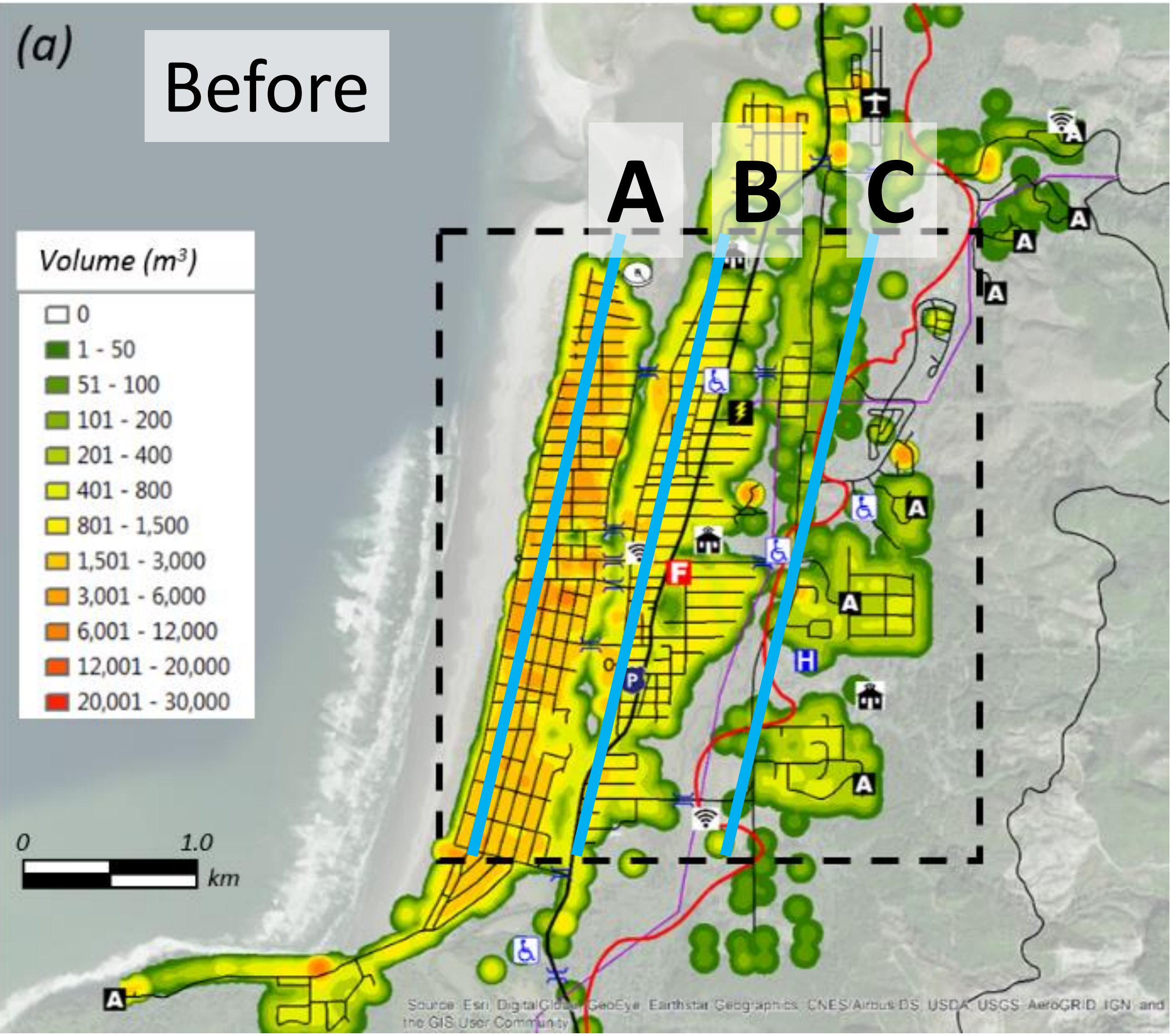


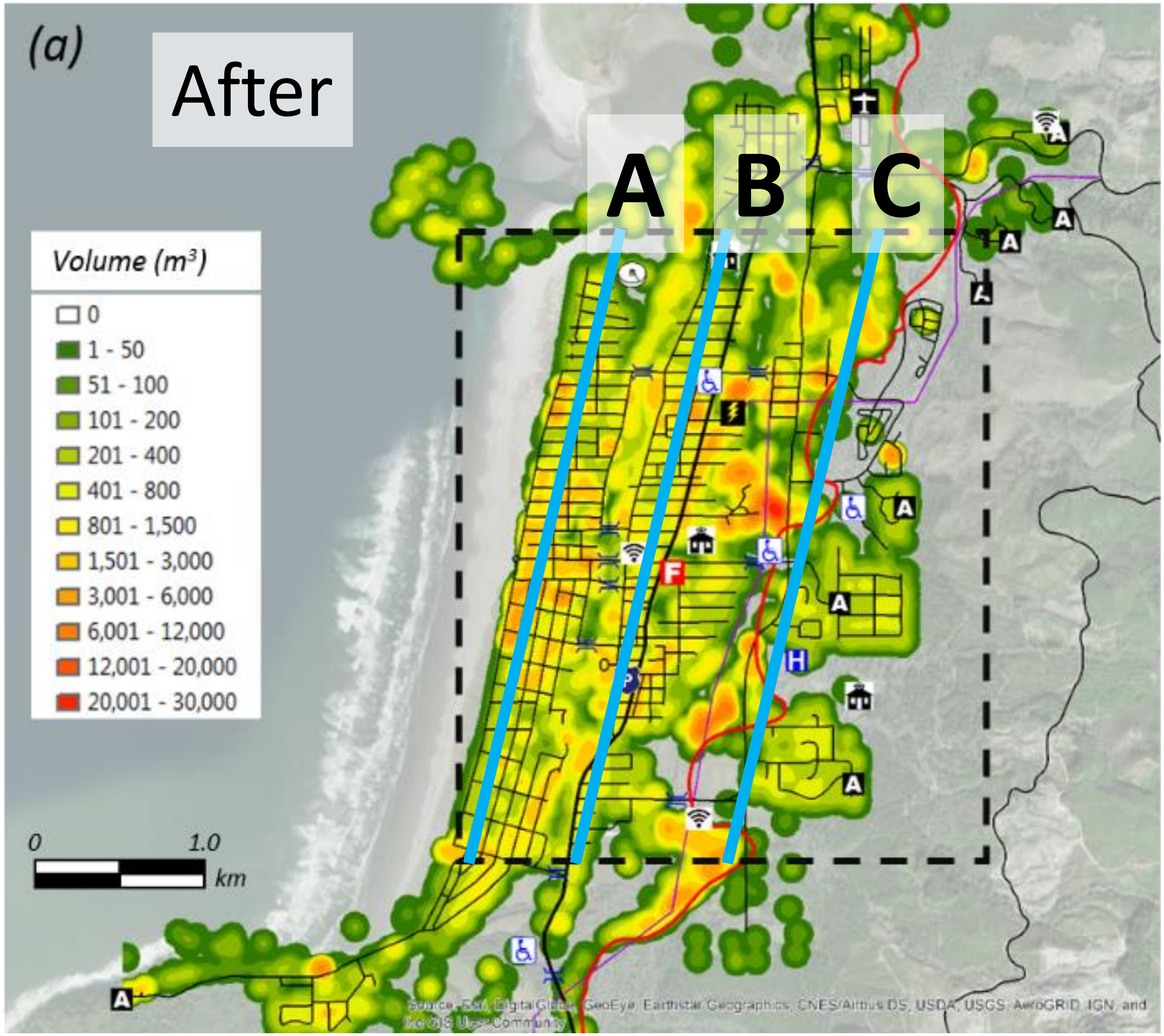

Distribution of expected debris volume (m³) per unit area (hectare) for 1000 year event without advection. (a) Volume of total debris from EQ+TSU, (b) Volume of buoyant debris only from EQ+TSU.

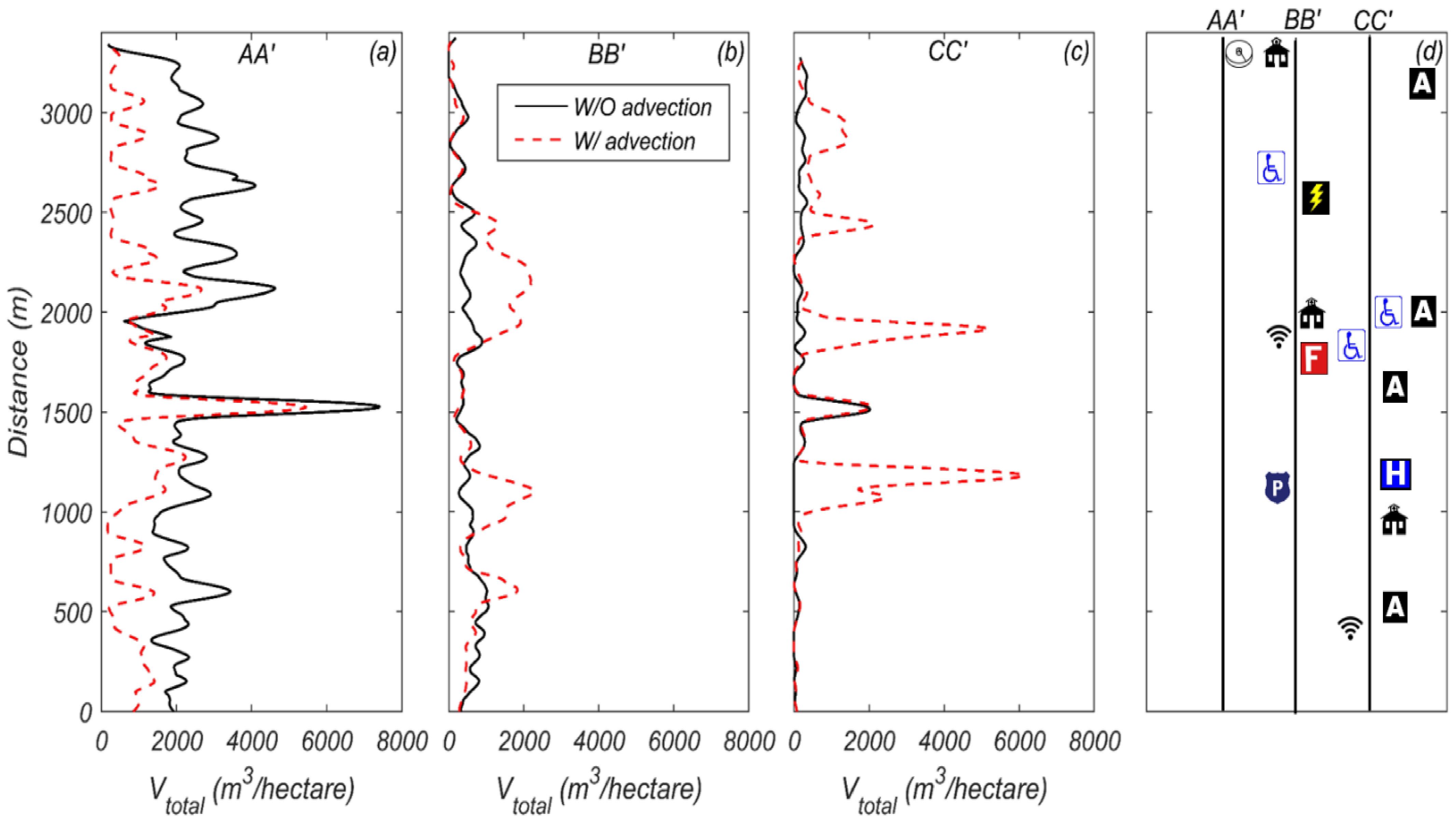
# Advection of buoyant debris from PSTDA at AEP = 0.0004 (2,500 yr)




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


(a)
Before
A
B
C
Volume (m³)
0
1 - 50
51 - 100
101 - 200
201 - 400
401 - 800
801 - 1,500
1,501 - 3,000
3,001 - 6,000
6,001 - 12,000
12,001 - 20,000
20,001 - 30,000
0
1.0
km

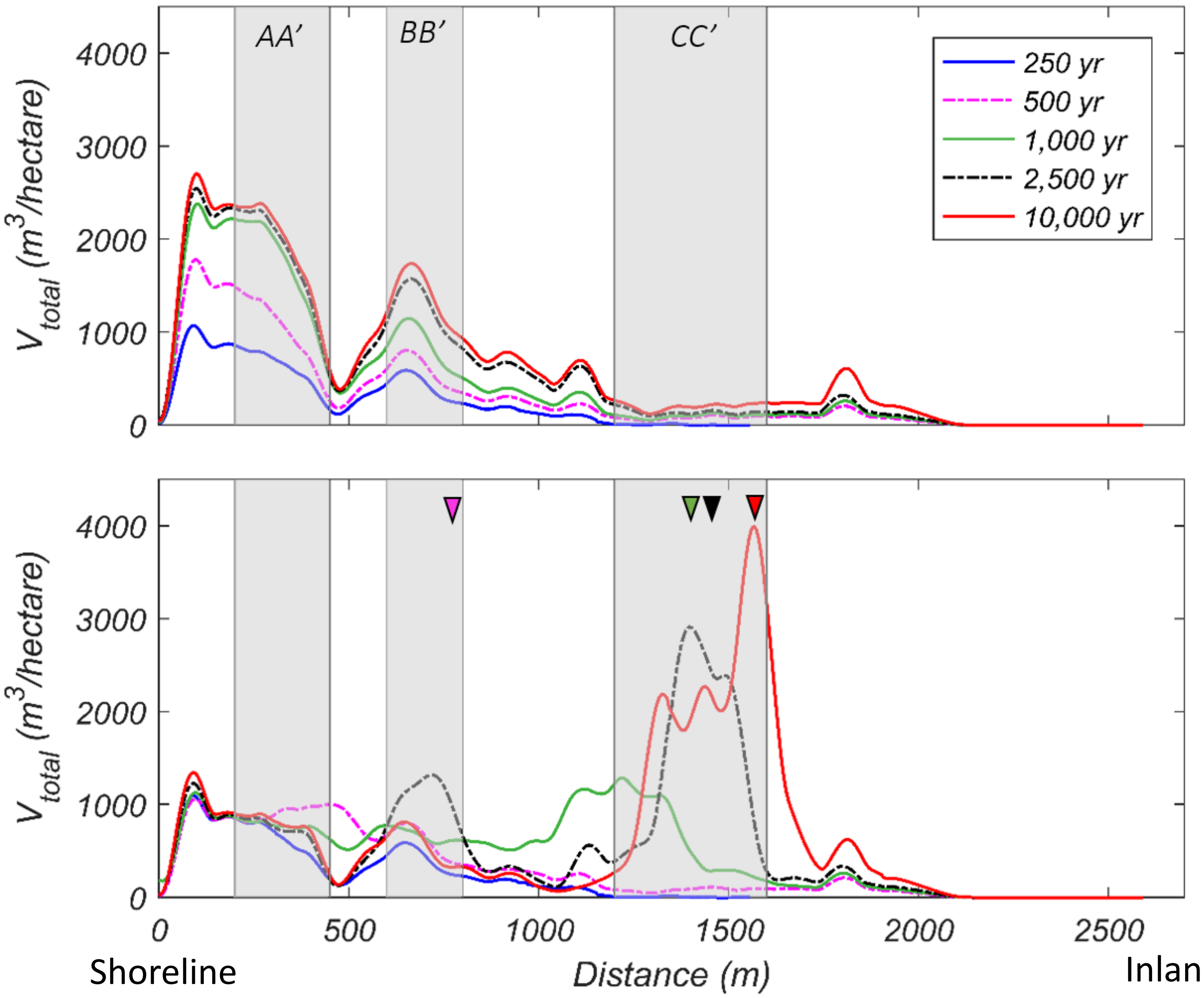

(a)
After
A
B
C
Volume (m³)
0
1 - 50
51 - 100
101 - 200
201 - 400
401 - 800
801 - 1,500
1,501 - 3,000
3,001 - 6,000
6,001 - 12,000
12,001 - 20,000
20,001 - 30,000
0
1.0
km




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

No advection

With advection




Shoreline

Inland

# 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!**