NARSIS Workshop

Training on Probabilistic Safety Assessment for Nuclear Facilities

September 2-5, 2019, Warsaw, Poland

Introduction to External Hazard Events:

Background, Parameters, and Interactions

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2nd September 2019

Outline

- Background to event types which can hit NPPs
- What type of events can occur in Europe?
- How do we model hazards and their interactions?
- Extreme value statistics (station data) (Lecture 2)
- Flood example for an NPP (Lecture 2)

External Hazards:

Earthquake

Cyclone/Hurricane

Drought/ Cold/ Heatwave

Tsunami

Flood

Storm Surge

Volcano

Landslides

Storms, Tornado etc.

Biological

Meteorite / Debris / Aircraft

Bushfire

External Hazards Characterisation

Family

- Geophysical
- Hydrological
- Meteorological
- Climatological

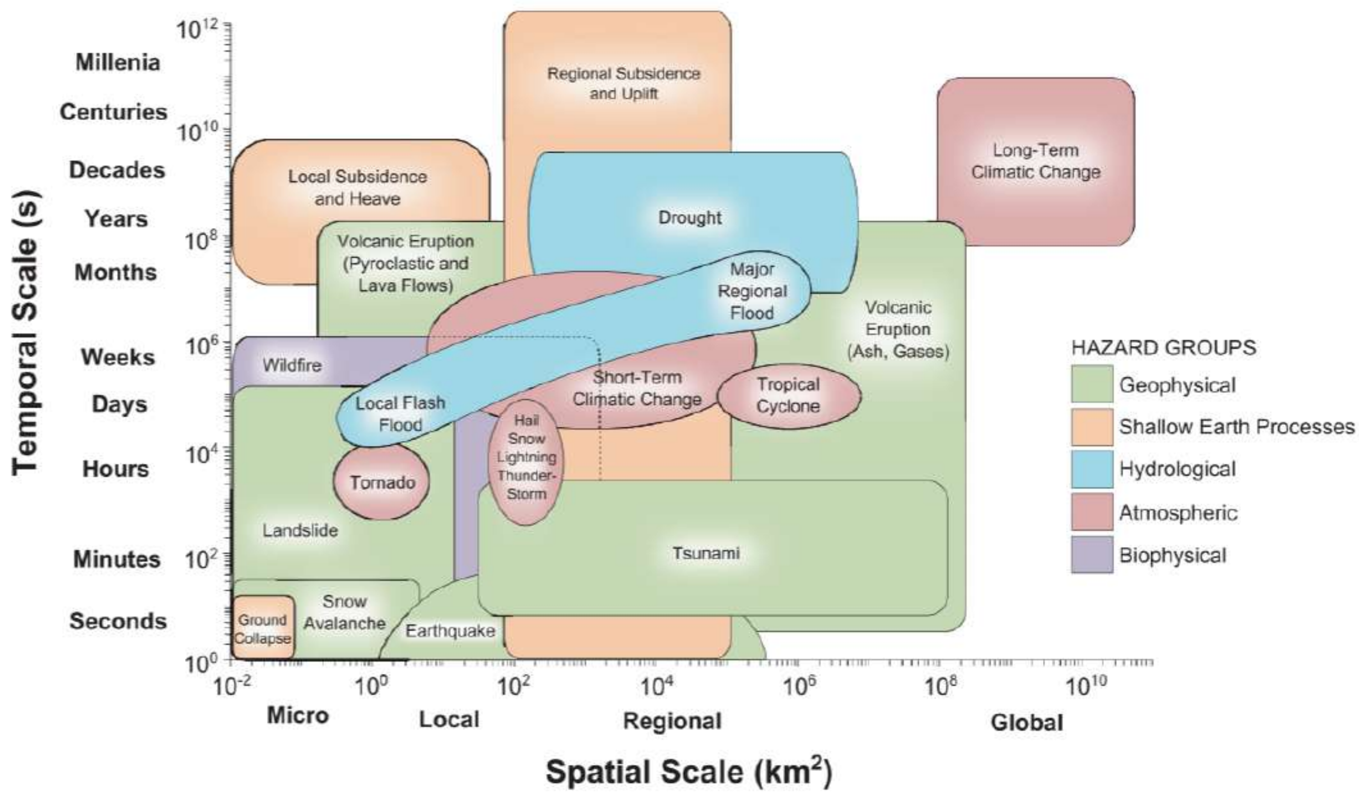
Main Event

- Geophysical: Earthquake, Mass Movement, Volcanic Activity
- Hydrological: Flood, Landslide, Wave Action
- Meteorological: Convective Storm, Extratropical Storm, Extreme Temperature, Fog, Tropical Cyclone
- Climatological: Drought, Glacial Lake Outburst, Wildfire

Peril

- Geophysical: Ash Fall, Fire following EQ, Ground Movement, Landslide following EQ, Lahar, Lava Flow, Liquefaction, Pyroclastic Flow, Tsunami
- Hydrological: Avalanche: Snow, Debris, Coastal Flood, Coastal Erosion, Debris/Mud Flow/Rockfall, Expansive Soil, Flash Flood, Ice Jam Flood, Riverine Flood, Rogue Wave, Seiche, Sinkhole
- Meteorological: Cold Wave, Derecho, Frost/Freeze, Hail, Heat Wave, Lightning, Rain, Sandstorm/Dust storm, Snow/Ice, Storm Surge, Tornado, Wind, Winter Storm/Blizzard
- Climatological: Forest Fire, Land fire: Brush, Bush, Pasture, Subsidence

External Hazards - Timescale



Interaction on a spatiotemporal scale of hazard types (Gill and Malamud, 2014)

Historical natural peril events

Great Kanto 1923, M7.9, $3.8-4.2bn (ca. $2 trn today), ~105000 deaths

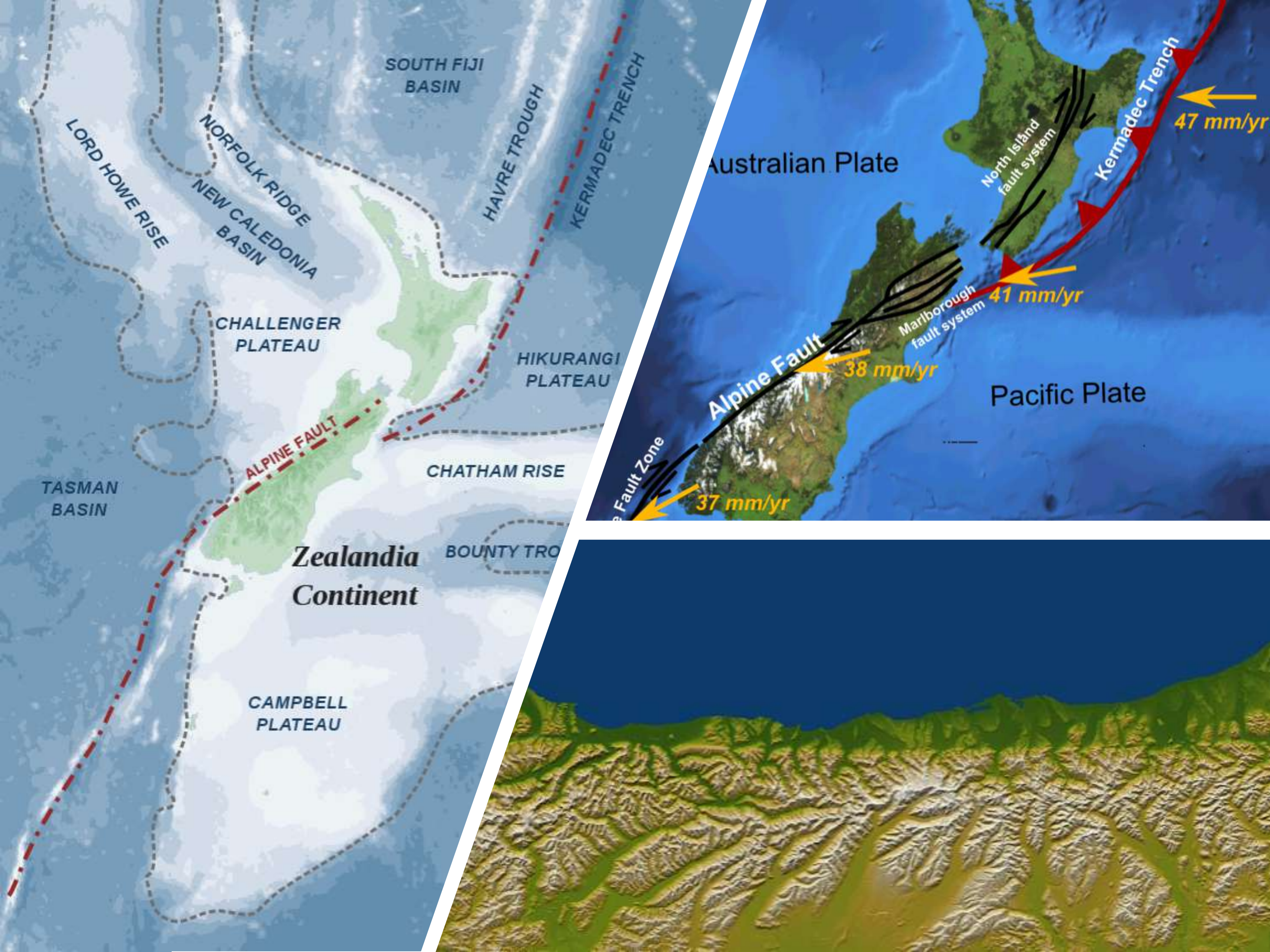
Tohoku 2011, M9.1, ~$350bn, ~22100 deaths

1902 Martinique Pelee Volcano

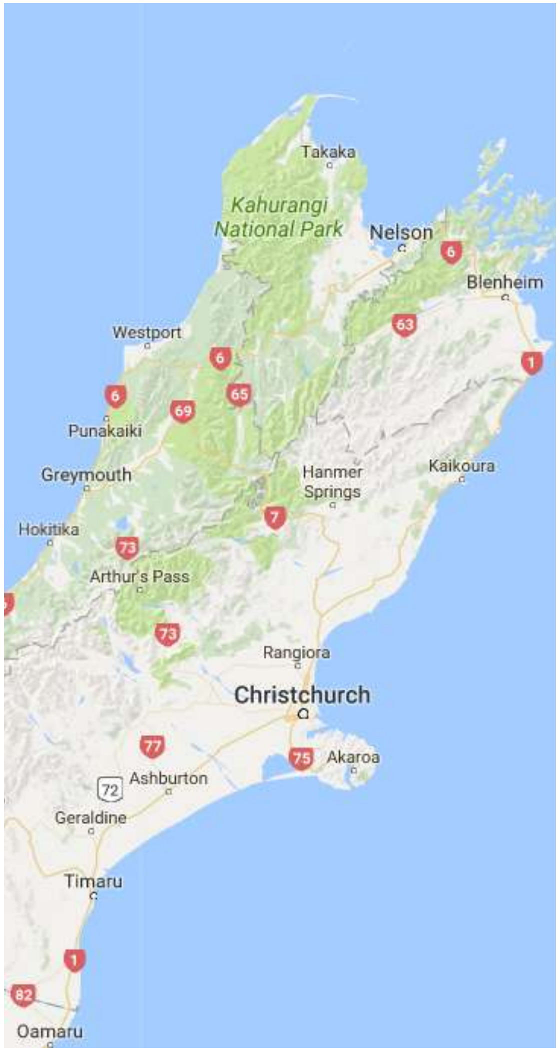
China 1931, Multiple Floods, ~$bn, ~2.5mn deaths*

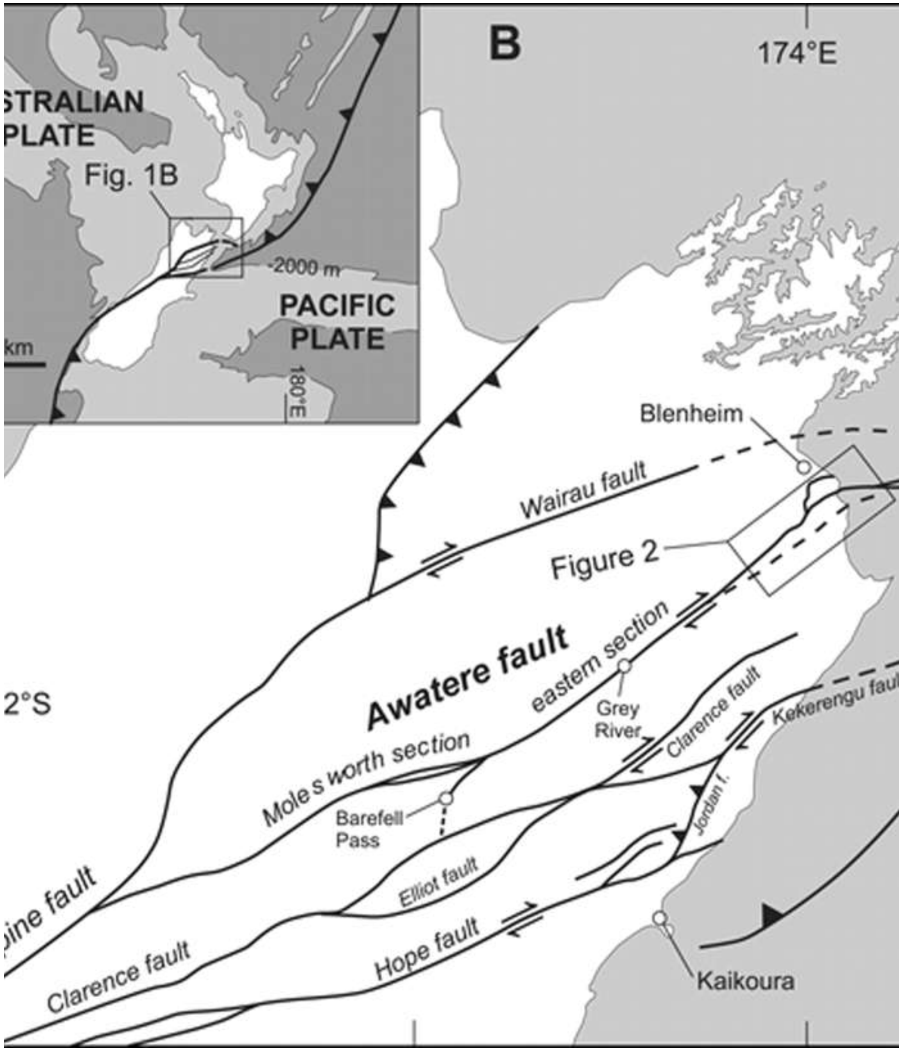
2013 Typhoon Haiyan

2010 Russian Heatwave/Fires – 55000+ deaths, $15bn

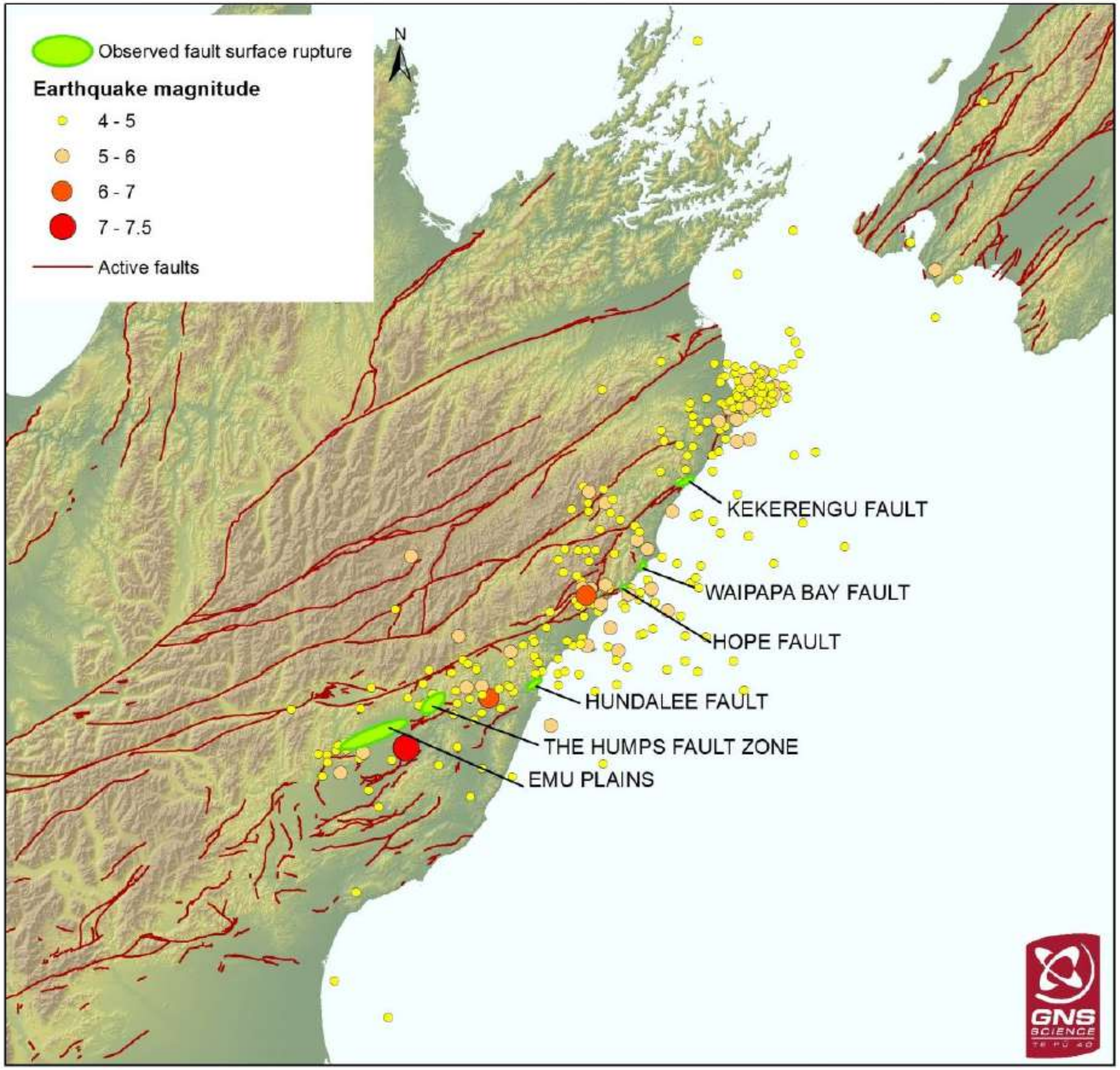

SOUTH FIJI BASIN
LORD HOWE RISE
NORFOLK RIDGE
NEW CALEDONIA BASIN
HAVRE TROUGH
KERMADEC TRENCH
CHALLENGER PLATEAU
HIKURANGI PLATEAU
ALPINE FAULT
CHATHAM RISE
TASMAN BASIN
BOUNTY TRO
Zealandia Continent
CAMPBELL PLATEAU
Australian Plate
Kermadec Trench
47 mm/yr
North Island fault system
41 mm/yr
Marlborough fault system
Alpine Fault
38 mm/yr
Pacific Plate
Fault Zone
37 mm/yr

Disasters can be complex…



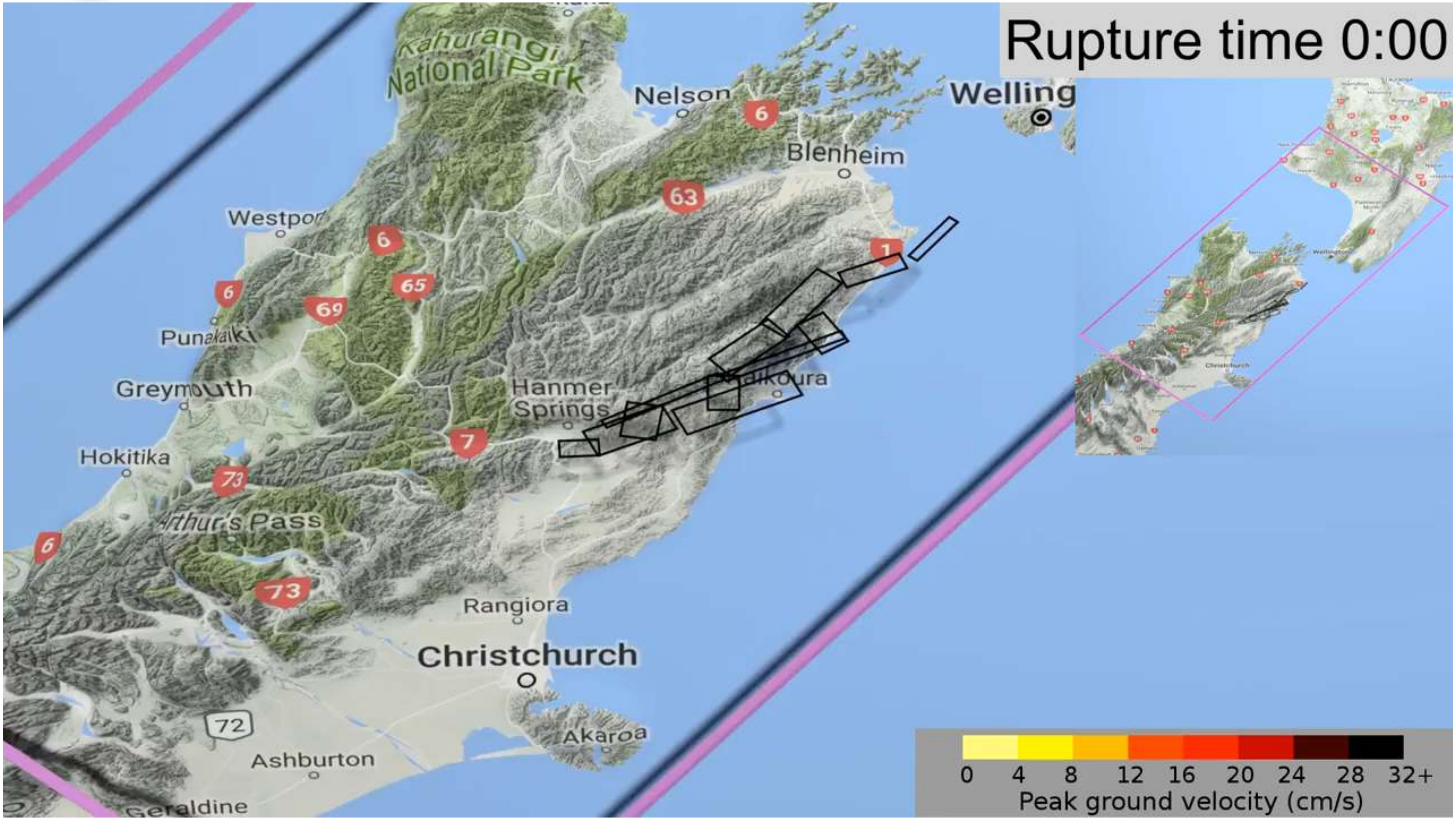


11 faults ruptured… in 3 mins



GNS

Mw7.8, 1.4g (Sa0.3=4g) Kaikoura



Center for eResearch, NZ

We were in Picton – multiple period shaking; landslides and mostly non-structural parapet, masonry, and infrastructure damage (Interislander terminal etc.)

Tsunami warnings with minor tsunami

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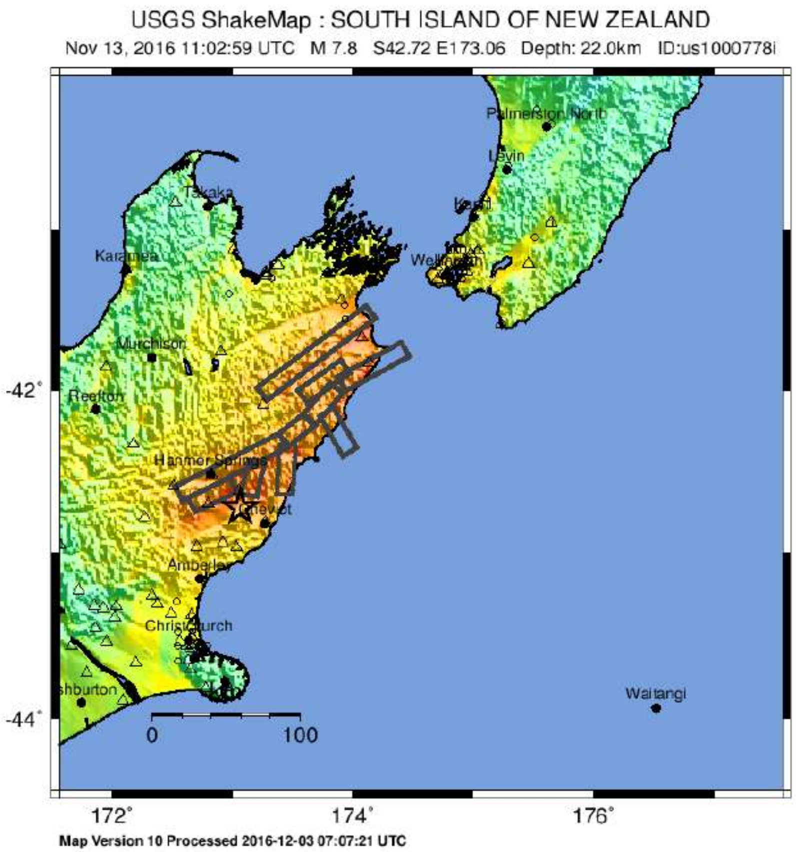
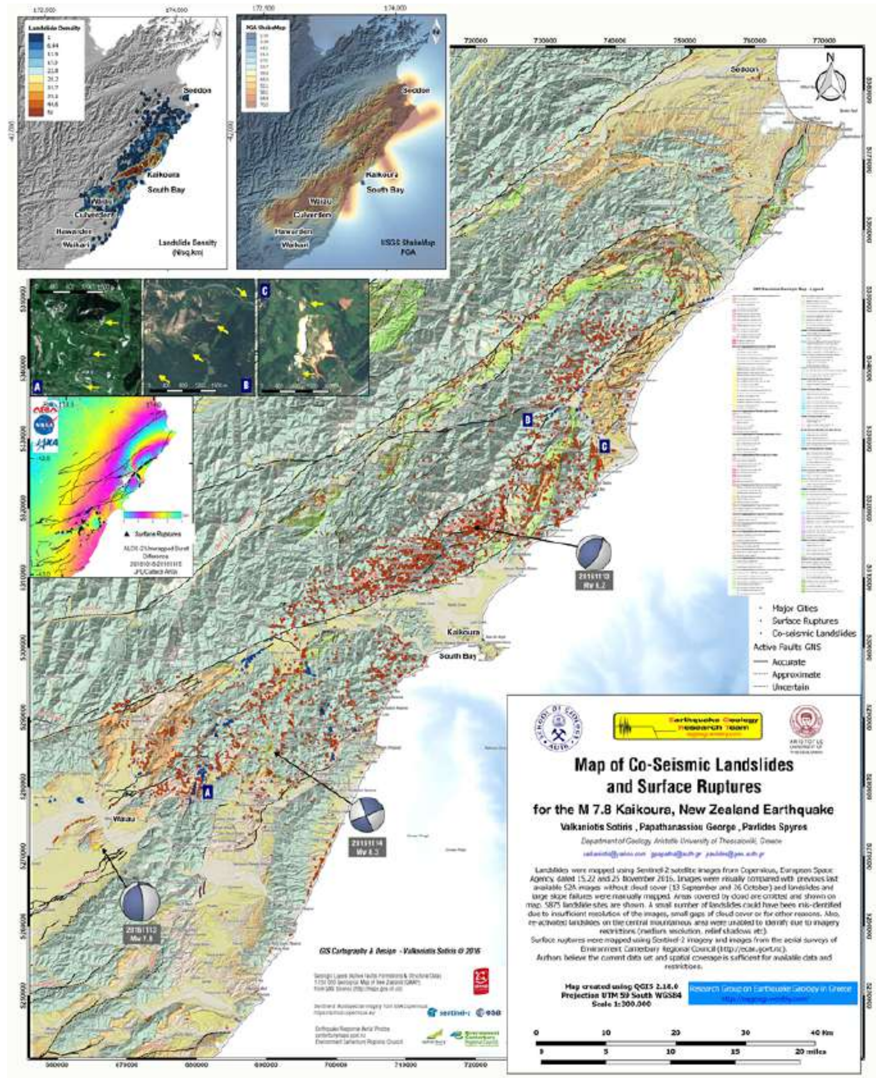
Combinations of earthquake shaking, landslide, tsunami

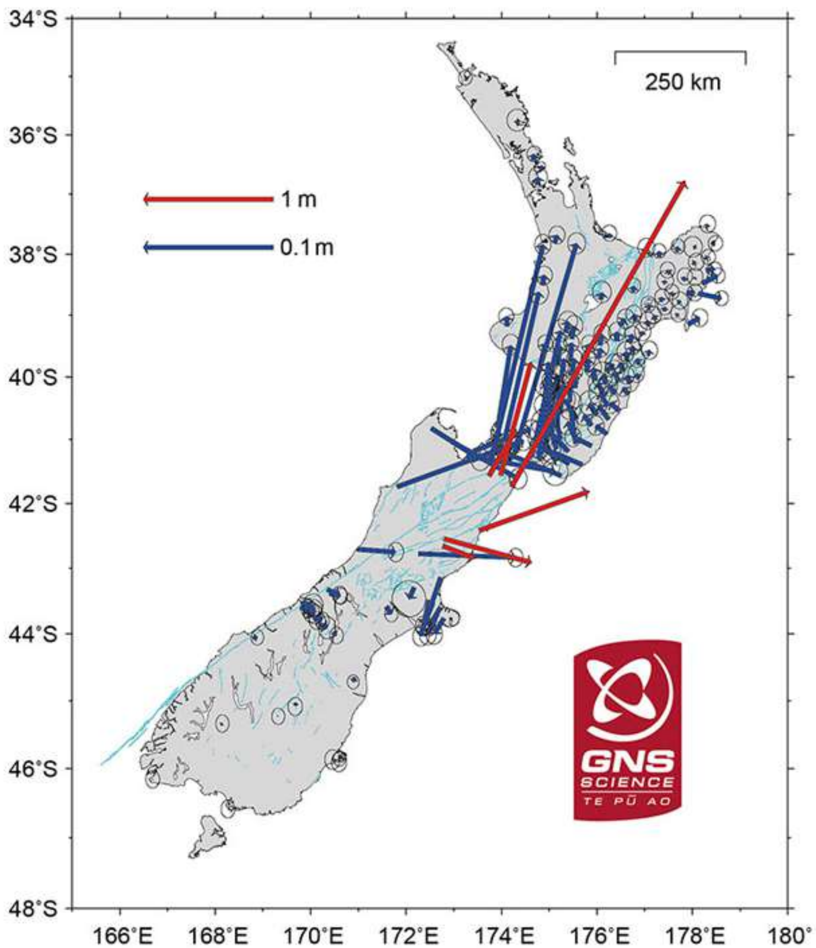


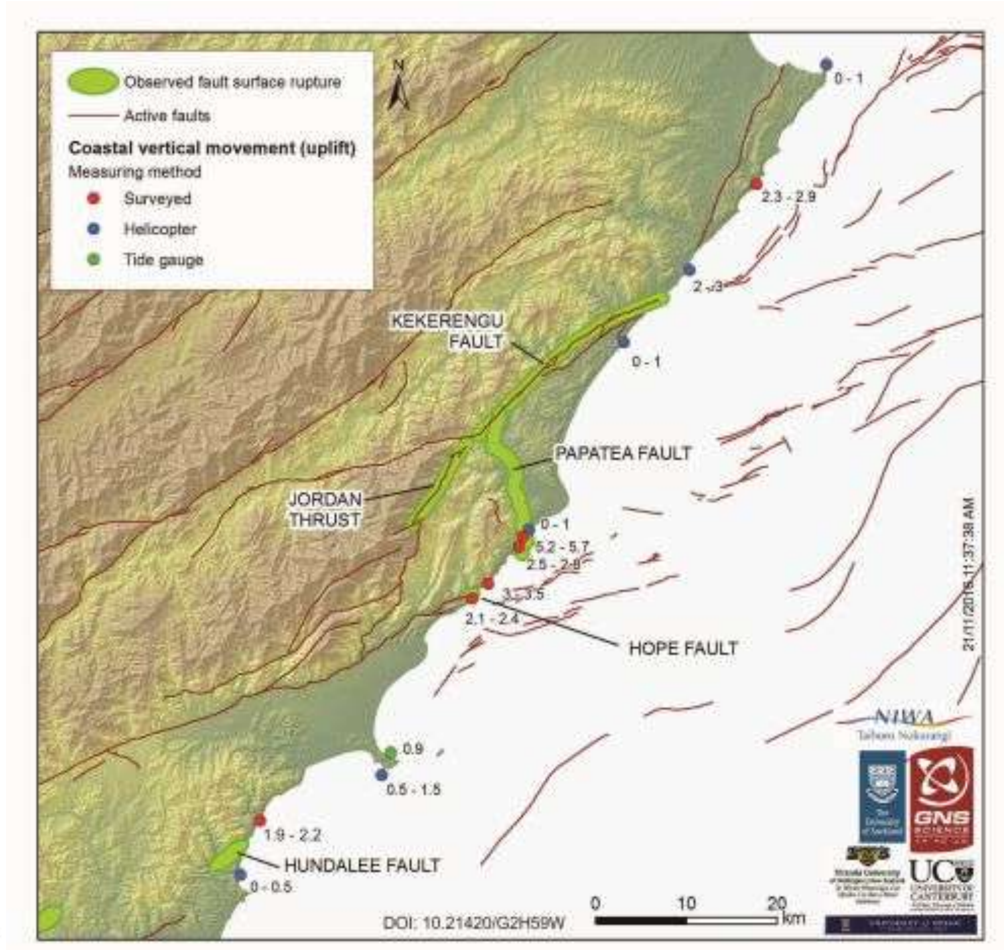
PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.05	0.3	2.8	6.2	12	22	40	75	>139
PEAK VEL.(cm/s)	<0.02	0.1	1.4	4.7	9.6	20	41	86	>178
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Worden et al. (2012)

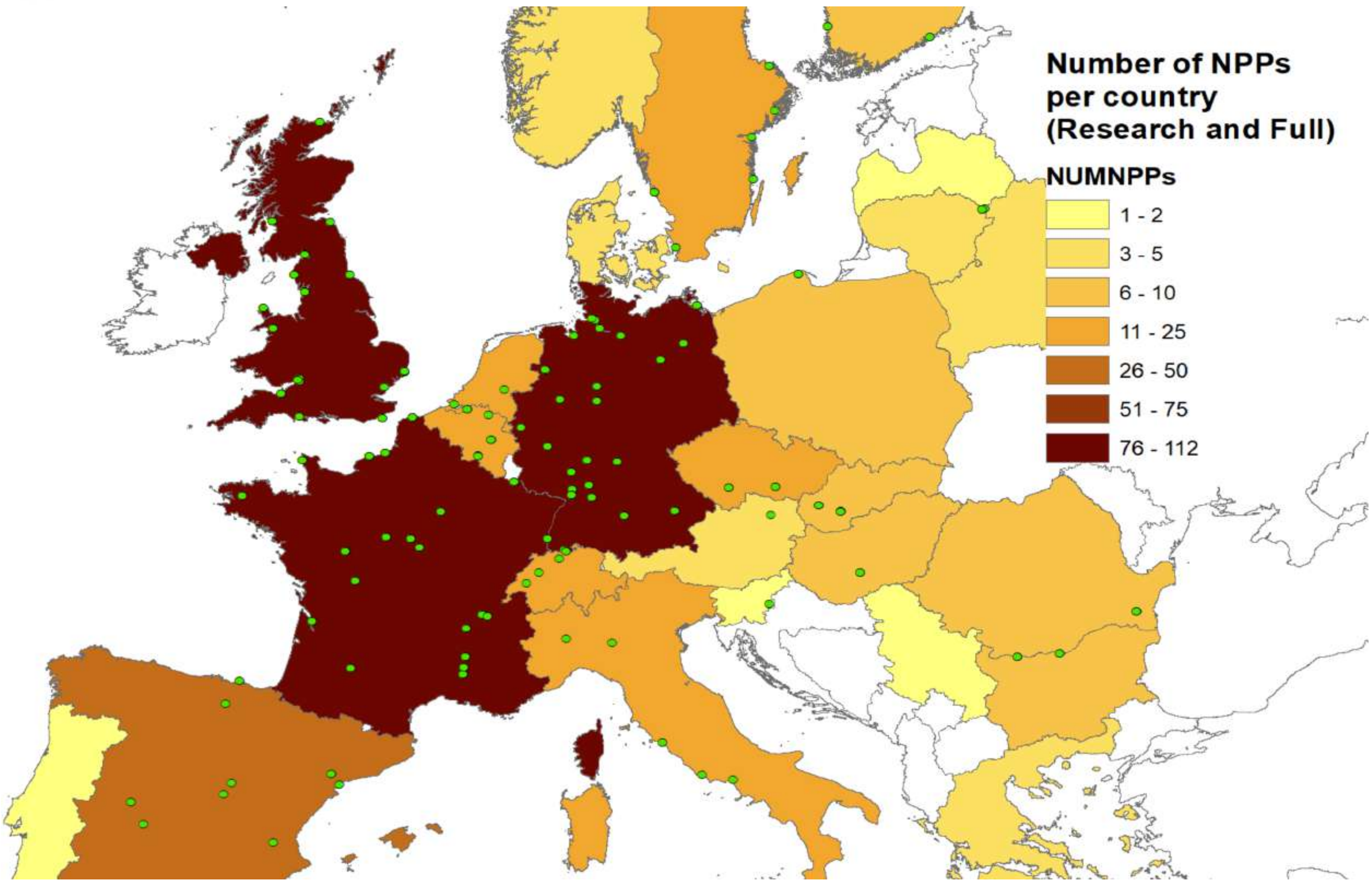


As well as ground movement





External Hazards: European Reactors



There have been a number of EU projects on disaster modelling

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Multi-Hazard

MATRIX armonia

Earthquake

SHARE SYNER-G

Flood

CORFU FP7 Collaborative research on flood resilience in urban areas

IMPRINTS

DROUGHT R&SPI

micore

SafeLand

Storms, Landslide

VUELCO

Volcano

ASAMPSA_E

Aims at examining in detail how far the PSA methodology is able to identify any major risk induced by the interaction between a NPP and its environment, and to derive some technical recommendations for PSA developers.

Key Concepts of NPP hazard modelling

- Important to examine external hazards on the plant from all possible scenarios and plausibility tests
- Components, infrastructure and connectivity into the plant with respect to nuclear plant – not just the plant itself

NPPs – historic events in EU

1999 Blayais Floods

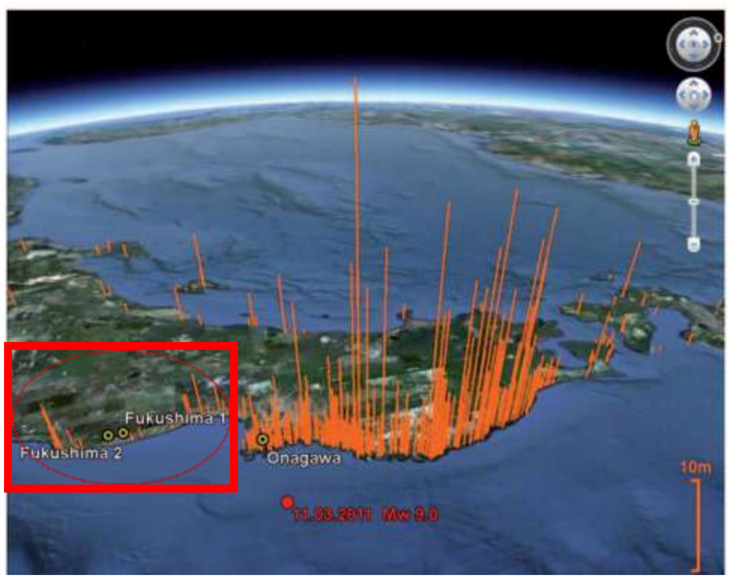
1980 Hinkley Point
Storm surge

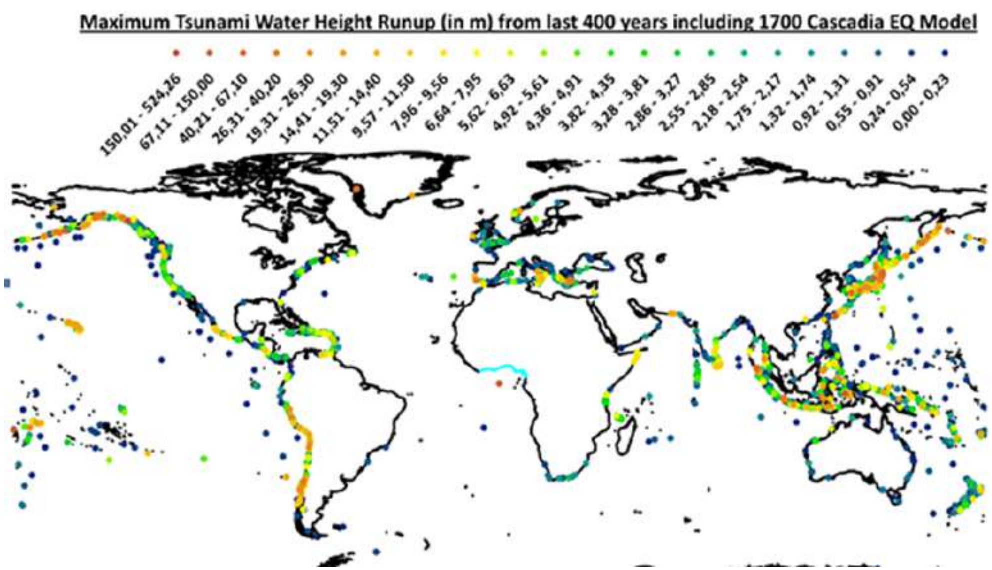
2019 Heatwaves

1984 Borssele, Low water

Major Natural Hazard-Nuclear Plant Interactions

- **1994 – heavy floods in India (inundation at Kakrapar, offsite power supply)**
- **2004 – tsunami in Madras (shutdown) and Kalpakkam (under construction)**
- **2011 – Tohoku earthquake at Fukushima, followed by tsunami (cut power supply, pump rooms flooded)**

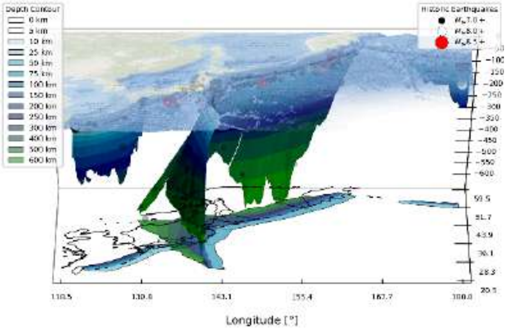


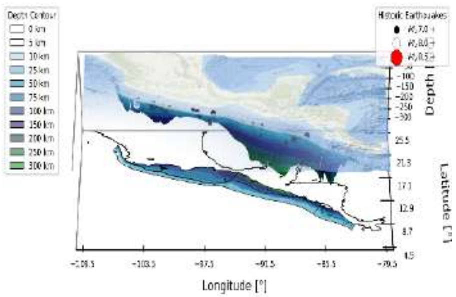


Nöggerath et al.

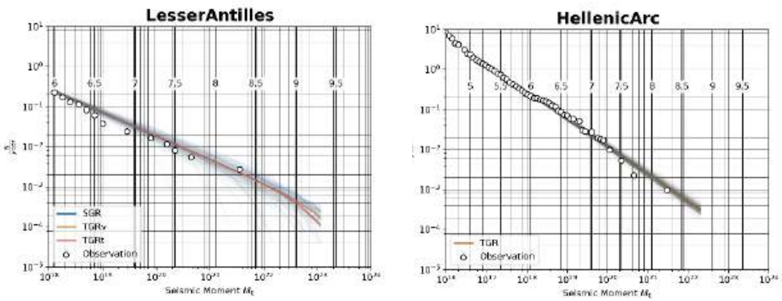
Earthquake induced tsunamis – Event Probability

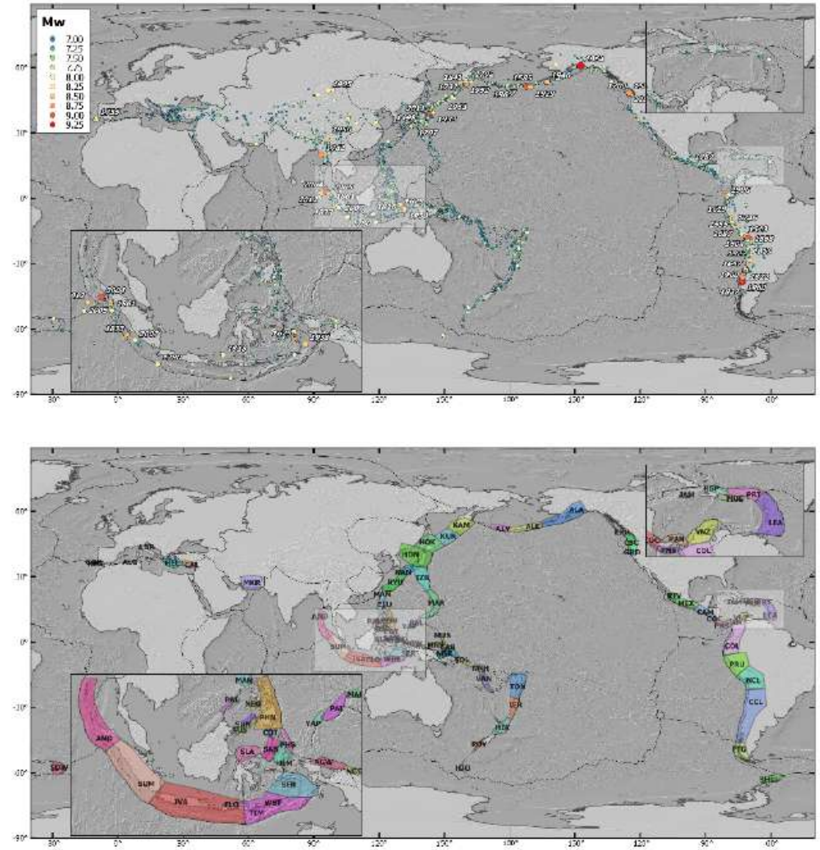
- (Re-)Assessment of paleo-tsunami & historic records
- 3D Geometry of rupture interface



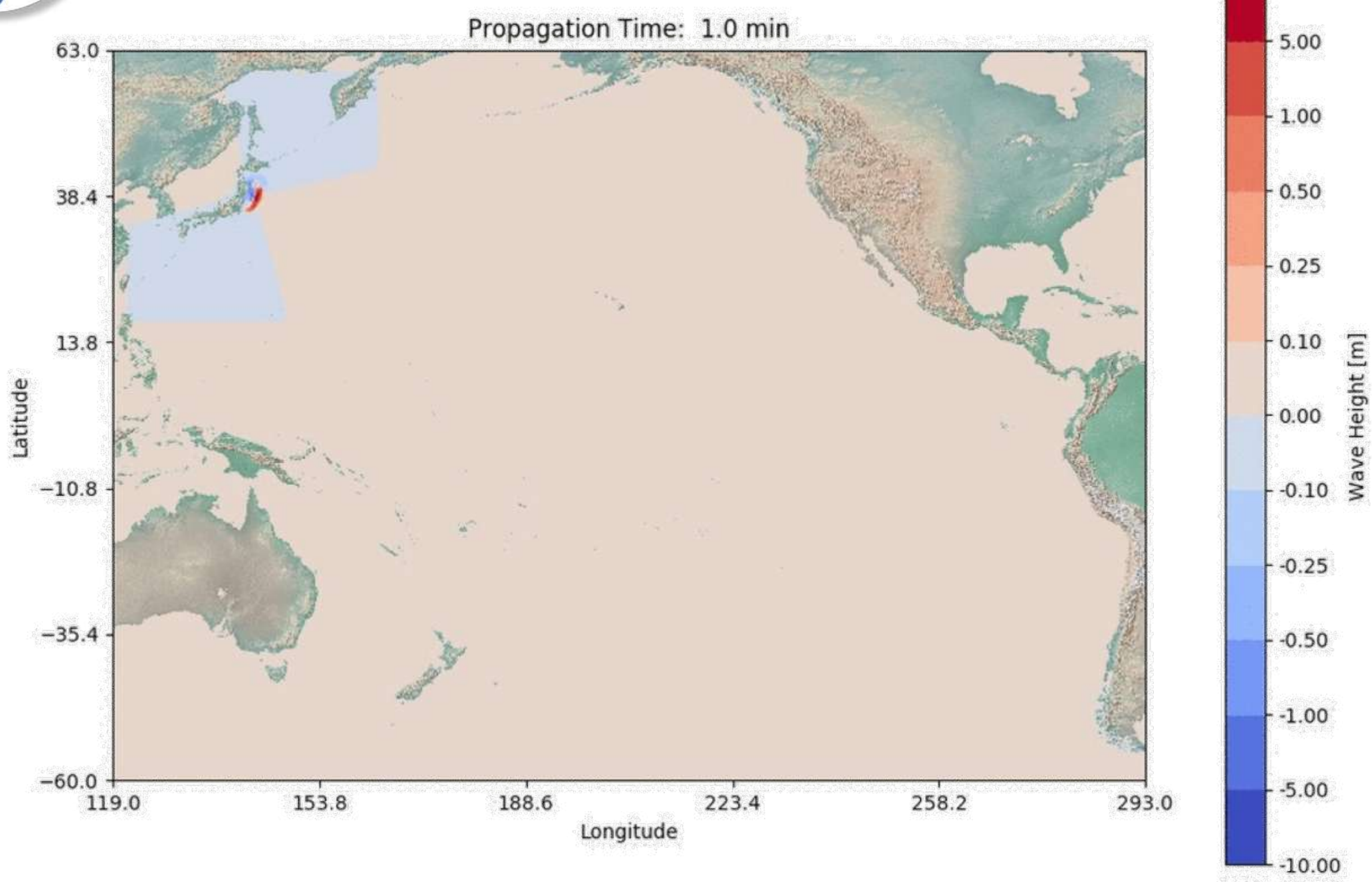


- Plate Motion Modelling



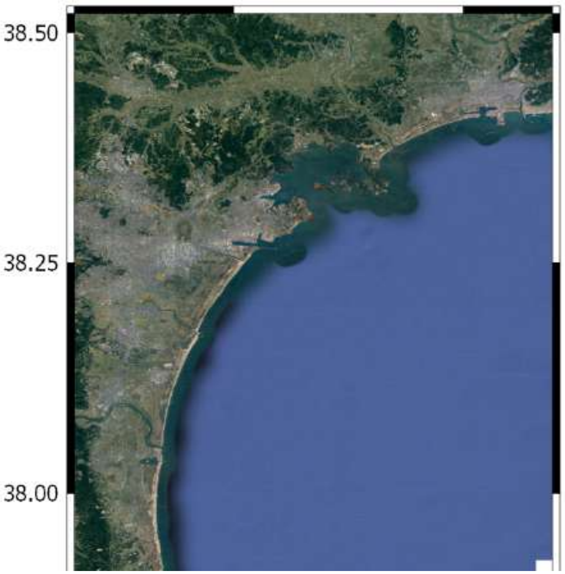


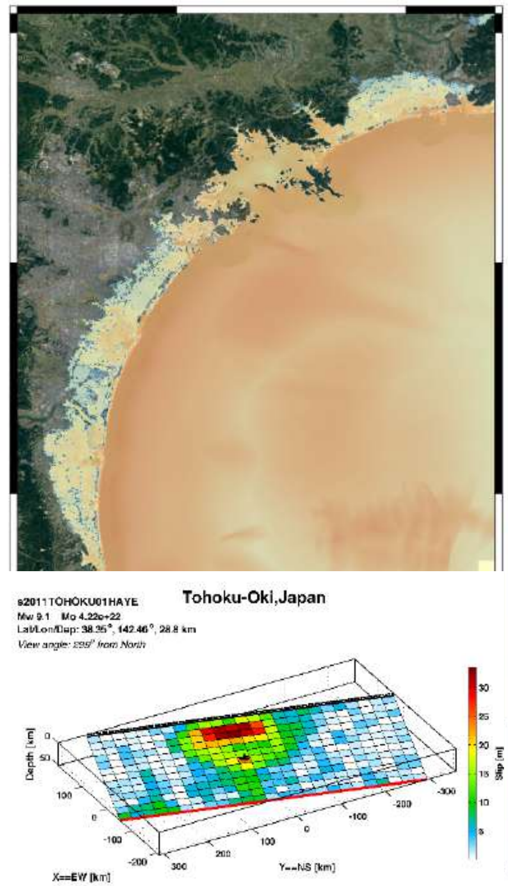
Tsunami - Propagation

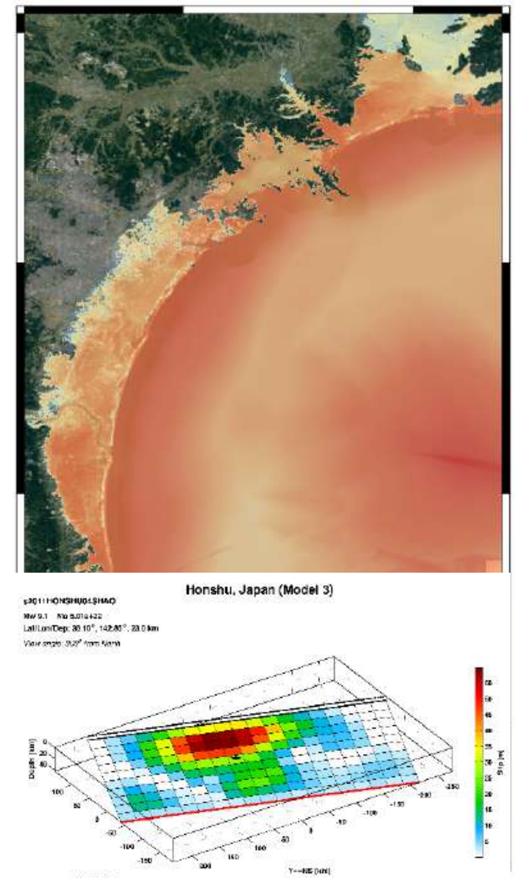


Tsunami – Water, debris, fire

Earthquake induced tsunamis – Event Quantification





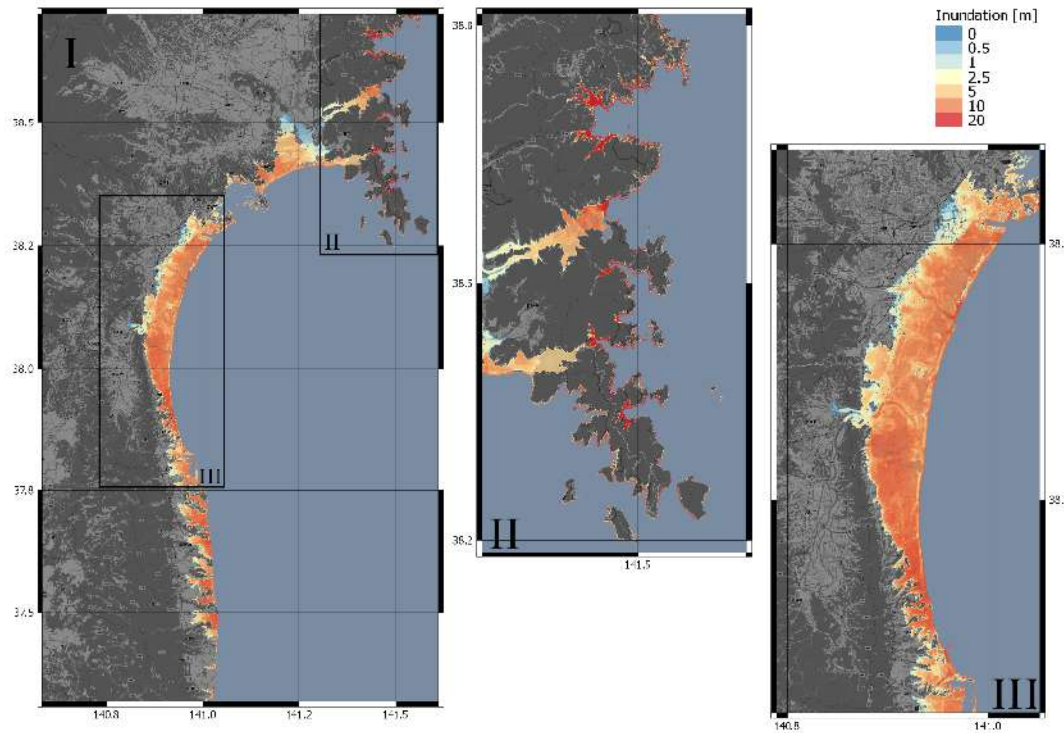


Beispiel
Japan, 2011
Magnitude 9.1
Inundation Variability due to rupture heterogeneity

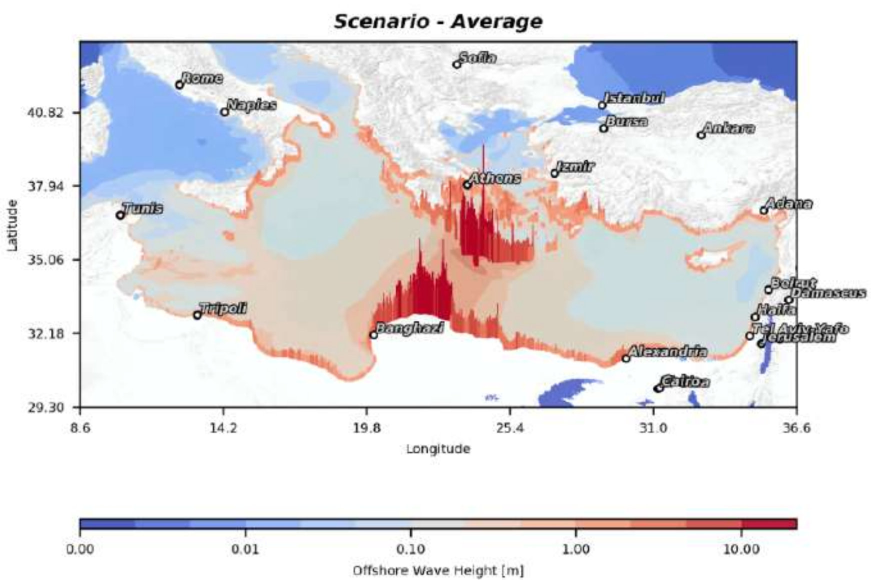
Schäfer & Wenzel, 2017

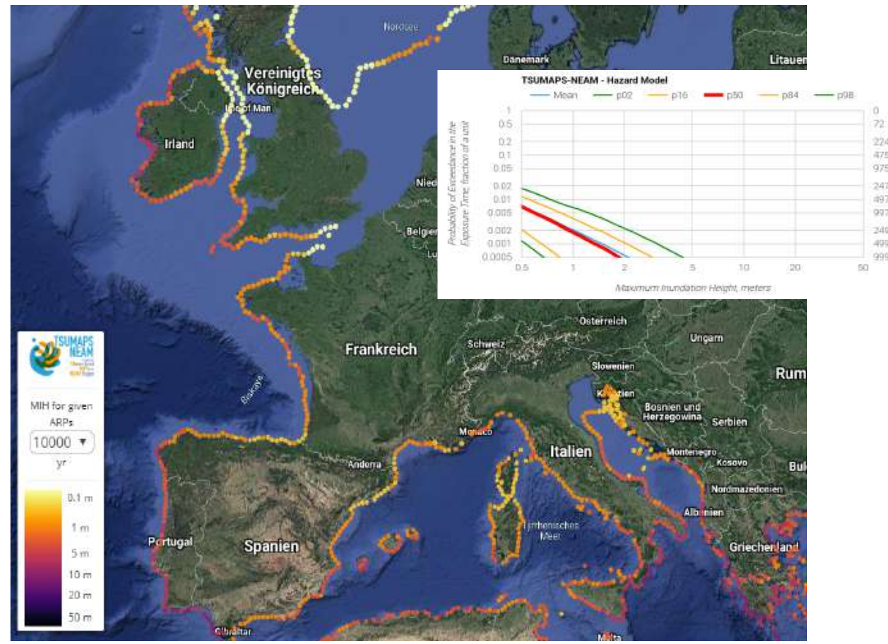
Inundation – High Resolution

- High resolution modelling: 10-50m
- Demand on digital elevation data
  - Topography (EU-DEM, 25m)
  - Bathymetry (EMOD, 250m)
  - Further enhancement at site: LIDAR
- Landuse/-cover data
  - Enhancement of hydraulic modelling (friction)



Deterministic vs. Probabilistic





- **Deterministic**
  - Single scenario modelling which allows for coping with uncertainties associated with adequacy of safety features
  - All conceivable hazard events examined
  - Many safety margins, classical
- **Probabilistic**
  - Hazard curves are produced using the properties of past hazards, earth dynamics, and various statistical relationships to characterise the temporal probability of an event occurring.
  - Combinations of events, residual risk and very rare events can be examined through fault trees.

Ways to calculate design basis events as a result of these external hazards

- Empirical modelling (using historical events as a basis for hazard)
- Expert Opinion (best hazard guess based on evidence)
- Analytical modelling (mathematical modelling of hazards)
- Combination approach

Learning from Stress Tests in EU for Earthquakes, Floods, Severe Accident Management

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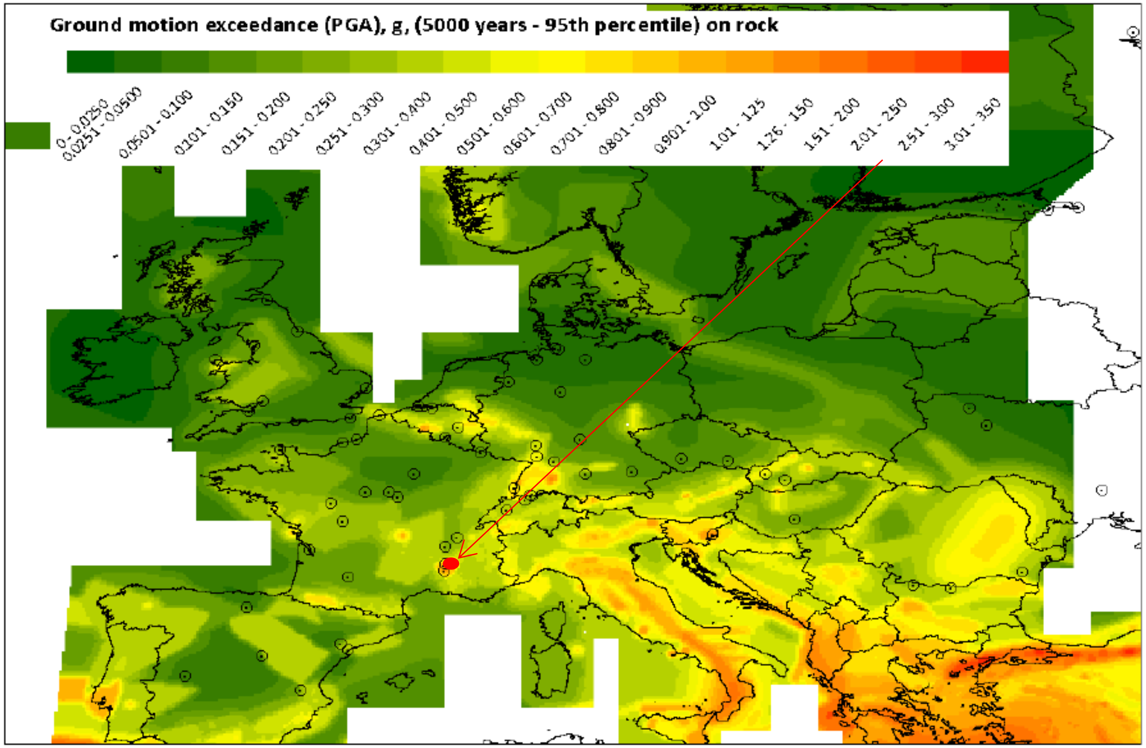
- Direct evaluation of existing nuclear power plants after Fukushima
- Design bases for flood and earthquake checked including methodology and provisions
- Scenarios such as loss of core cooling function or power examined
- Evaluation of maximum level that can be withstood by plant components

ENSREG
European Nuclear Safety Regulators Group

PSHA for Earthquakes in the EU

Probabilistic Hazard Maps for PGA around EU



Hazard Parameters for earthquakes – not that simple…

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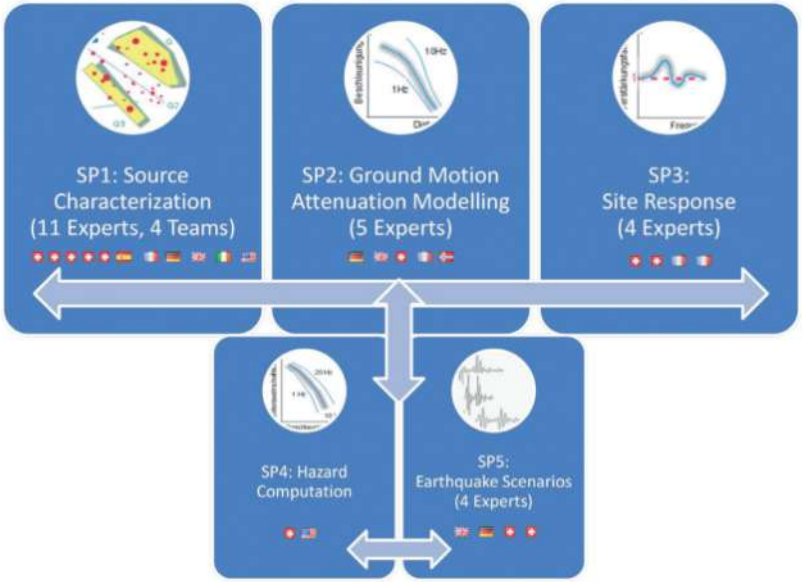
- **Why?**
  - Determination of Hazard metric depends on the component being examined and the location with which the analysis is being done.
  - Not many attenuation relationships have been produced beyond Spectral Ordinates (Sa, Sv, Sd)
  - Still need to work in the realms of manageable parameters (such as those where GMPEs are available)

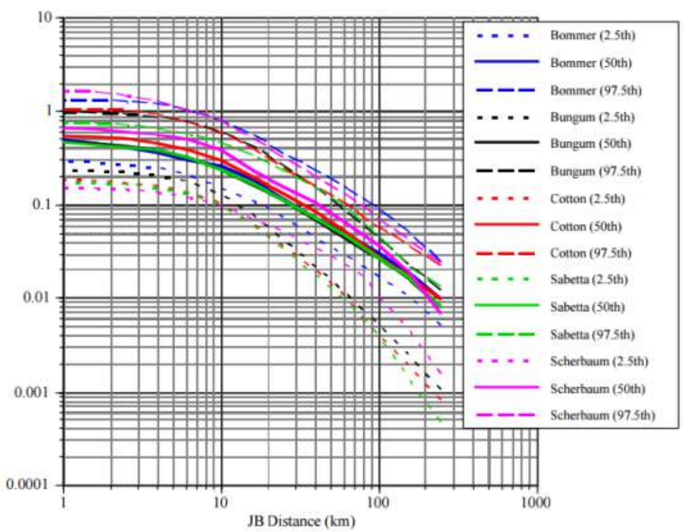
Rank	W1		W2		S1		C1		C2	
	IM	ρ	IM	ρ	IM	ρ	IM	ρ	IM	ρ
1	EPV	0.180	T_b	-0.456	EPV	0.788	EPA	0.663	T_b	-0.388
2	HI	0.174	T_d	-0.403	IDR_{max}	0.689	ASI	0.660	T_{90}	-0.290
3	AI	0.173	PGD	-0.352	δ_R	0.665	RMS_{90}	0.588	I_{MM}	0.211
4	PGV	0.168	EPV	-0.310	RMS	0.643	RMS_b	0.585	IDR_{max}	0.178
5	I_{MM}	0.167	HI	-0.294	PGV	0.636	AI	0.567	S_d	0.154
6	T_{90}	-0.165	PGV	-0.284	S_v	0.602	PGA	0.544	AI	-0.149
7	PGD	0.145	I_{MM}	-0.283	T_b	0.512	RMS	0.540	PGV	0.142
8	MMI	0.137	RMS_{90}	-0.258	I_{MM}	0.493	δ_R	0.522	S_a	-0.139
9	RMS_{90}	0.116	AI	-0.256	HI	0.487	EPV	0.517	HI	0.135
10	RMS_b	0.100	S_d	0.204	AI	0.430	HI	0.485	PGA	-0.115
11	RMS	0.079	PGA	-0.204	S_a	0.420	I_{MM}	0.475	ASI	-0.111
12	S_a	0.076	RMS_b	-0.197	RMS_{90}	0.388	PGV	0.473	δ_R	0.108
13	δ_R	0.073	MMI	-0.188	PGD	0.360	T_{90}	-0.424	EPA	-0.090
14	IDR_{max}	0.066	RMS	-0.176	T_d	-0.359	PGD	0.387	RMS	-0.090
15	ASI	0.066	S_v	0.174	RMS_b	0.290	IDR_{max}	0.377	PGD	0.086
16	EPA	0.060	EPA	-0.136	T_{90}	-0.241	MMI	0.251	S_v	0.063
17	$S_{a,DBSC}$	0.059	ASI	-0.135	MMI	0.231	T_b	0.247	RMS_{90}	-0.044
18	T_b	0.047	T_{90}	-0.114	$S_{a,DBSC}$	0.215	S_v	0.214	$S_{a,DBSC}$	-0.042
19	PGA	0.045	$S_{a,DBSC}$	-0.069	ASI	0.196	$S_{a,DBSC}$	-0.214	EPV	0.037
20	S_d	0.043	δ_R	0.050	EPA	0.170	T_d	0.195	MMI	-0.027
21	T_d	0.023	S_a	-0.046	PGA	0.133	S_a	-0.159	RMS_b	0.024
22	S_v	0.021	IDR_{max}	0.023	S_d	-0.082	S_d	0.025	T_d	0.012

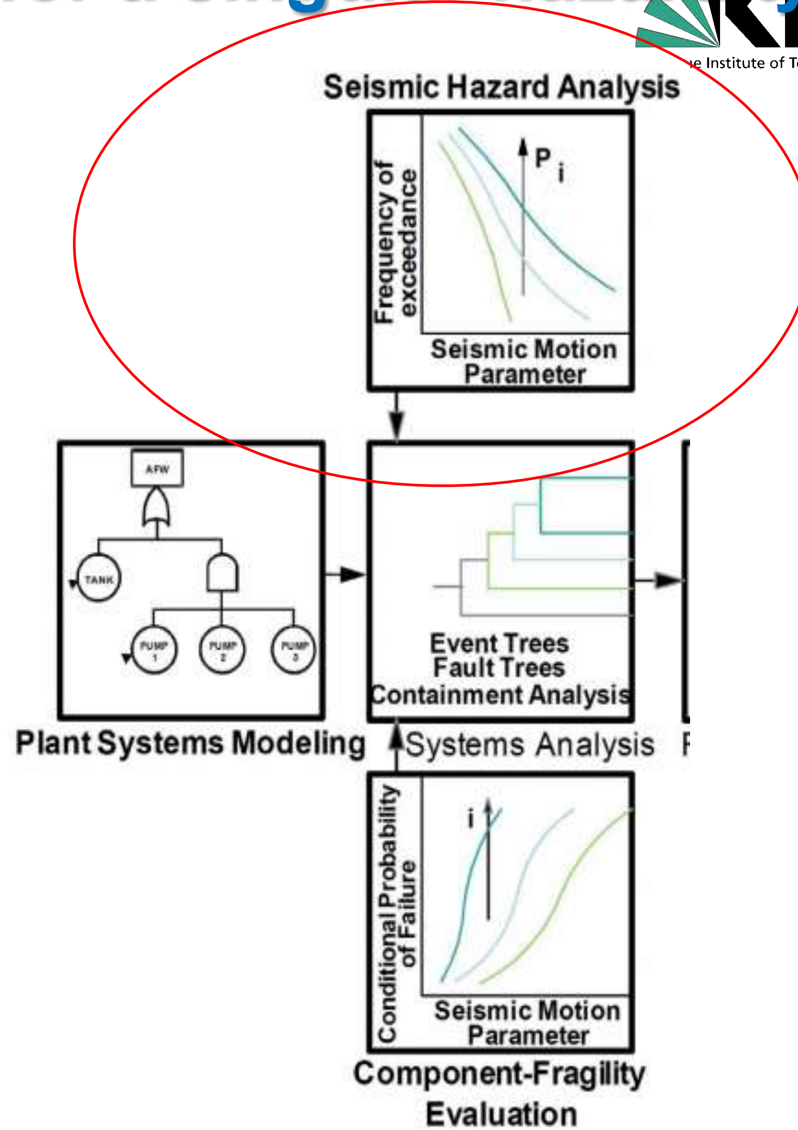
PGA – Peak Ground Acceleration, PGV – Peak Ground Velocity, PGD – Peak Ground Displacement, T_d – Total Record Duration, T_{90} – 90% Cumulative Duration, T_b – Bracketed Duration, RMS – Root Mean Acceleration for Total Duration, RMS_{90} – Root Mean Acceleration for 90% Duration, RMS_b – Root Mean Acceleration for Bracketed Duration, AI – Arias Intensity, ASI – Acceleration Spectral Intensity, EPA – Effective Peak Acceleration, HI – Response Spectrum or Housner Intensity, MMI – Modified Mercalli Intensity, I_{MM} – ShakeMap Instrumental Intensity, δ_R – Roof Drift Ratio, IDR_{max} – Maximum Interstory Drift Ratio, $S_{a,DBSC}$ – Spectral Acceleration Design Force Coefficient Ratio, S_d – Spectral Displacement at Predominant Period, S_v – Spectral Velocity at Predominant Period, S_a – Spectral Acceleration at Predominant Period

NERIES, 2007

Example: Process for a singular hazard type





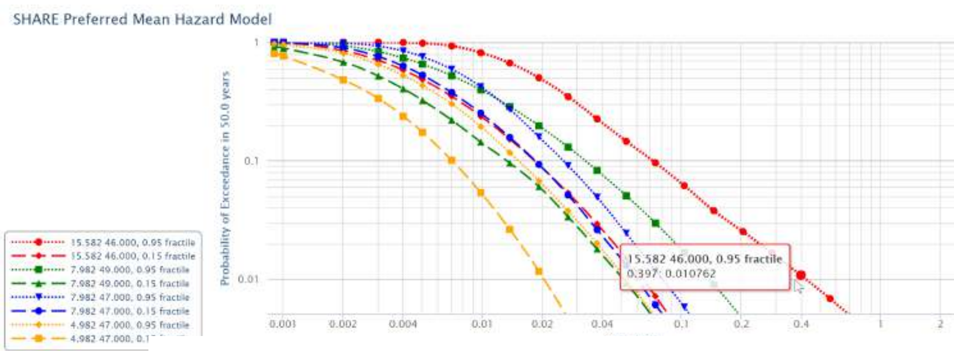


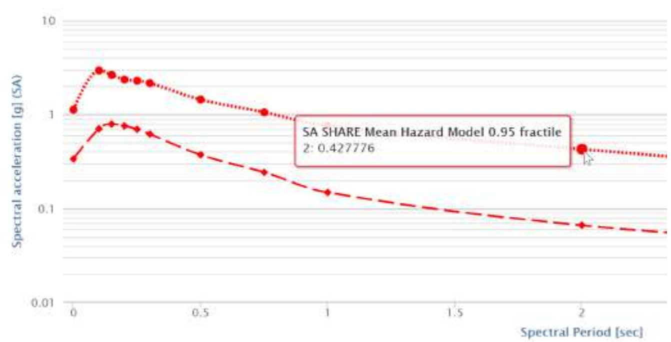
Renault et al., 2009

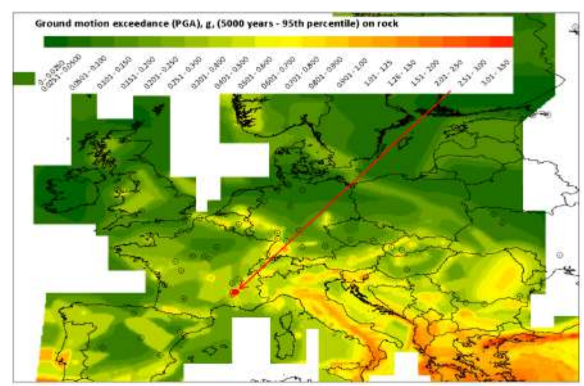
Comparison to hazard models

➢ Earthquake and Secondary Effects

- ❑ ESHM13, country datasets and ESHM18/20 as becomes available. Standard methodology.



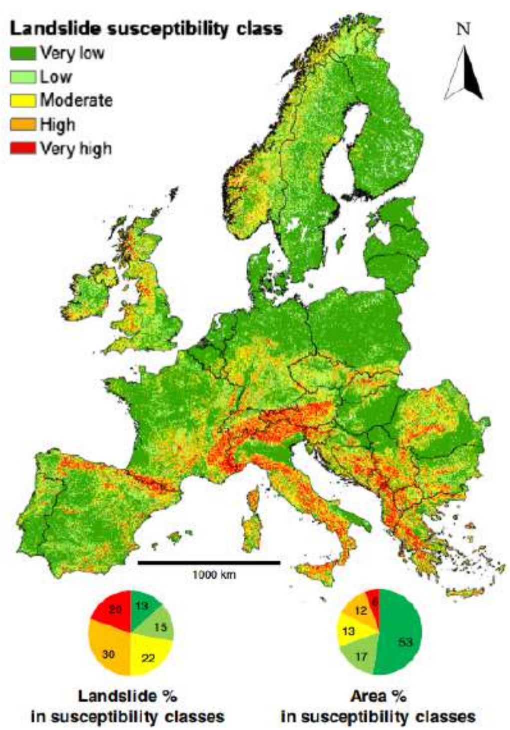


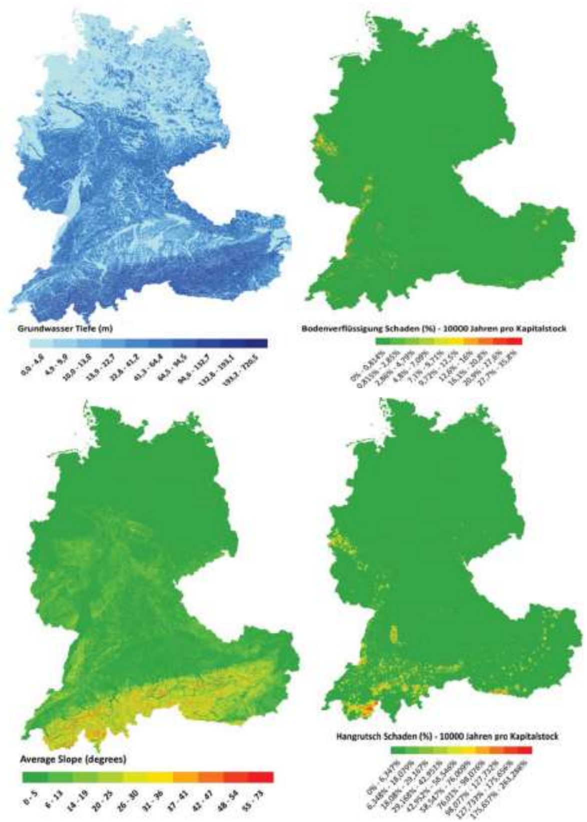


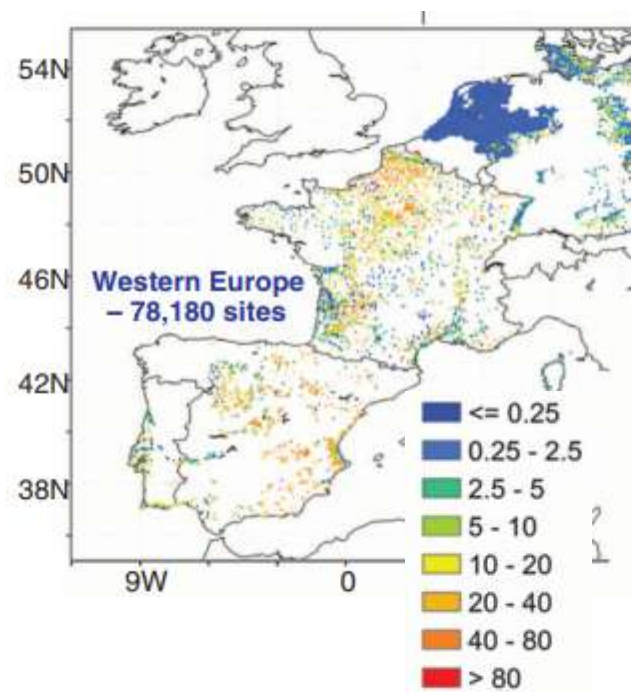
- ❑ Landslide (ELSUS)/Dam Break, Liquefaction, Tsunami

Secondary Hazards

➢ Cross-hazard datasets







Other External Hazards Characterisation

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Family

- Geophysical
- Hydrological
- Meteorological
- Climatological

Main Event

- Earthquake
- Mass Movement
- Volcanic Activity

- Flood
- Landslide
- Wave Action

- Convective Storm
- Extratropical Storm
- Extreme Temperature
- Fog
- Tropical Cyclone

- Drought
- Glacial Lake Outburst
- Wildfire

Peril

- Ash Fall
- Fire following EQ
- Ground Movement
- Landslide following EQ
- Lahar
- Lava Flow
- Liquefaction
- Pyroclastic Flow
- Tsunami

- Avalanche: Snow, Debris
- Coastal Flood
- Coastal Erosion
- Debris/Mud Flow/Rockfall
- Expansive Soil
- Flash Flood
- Ice Jam Flood
- Riverine Flood
- Rogue Wave
- Seiche
- Sinkhole

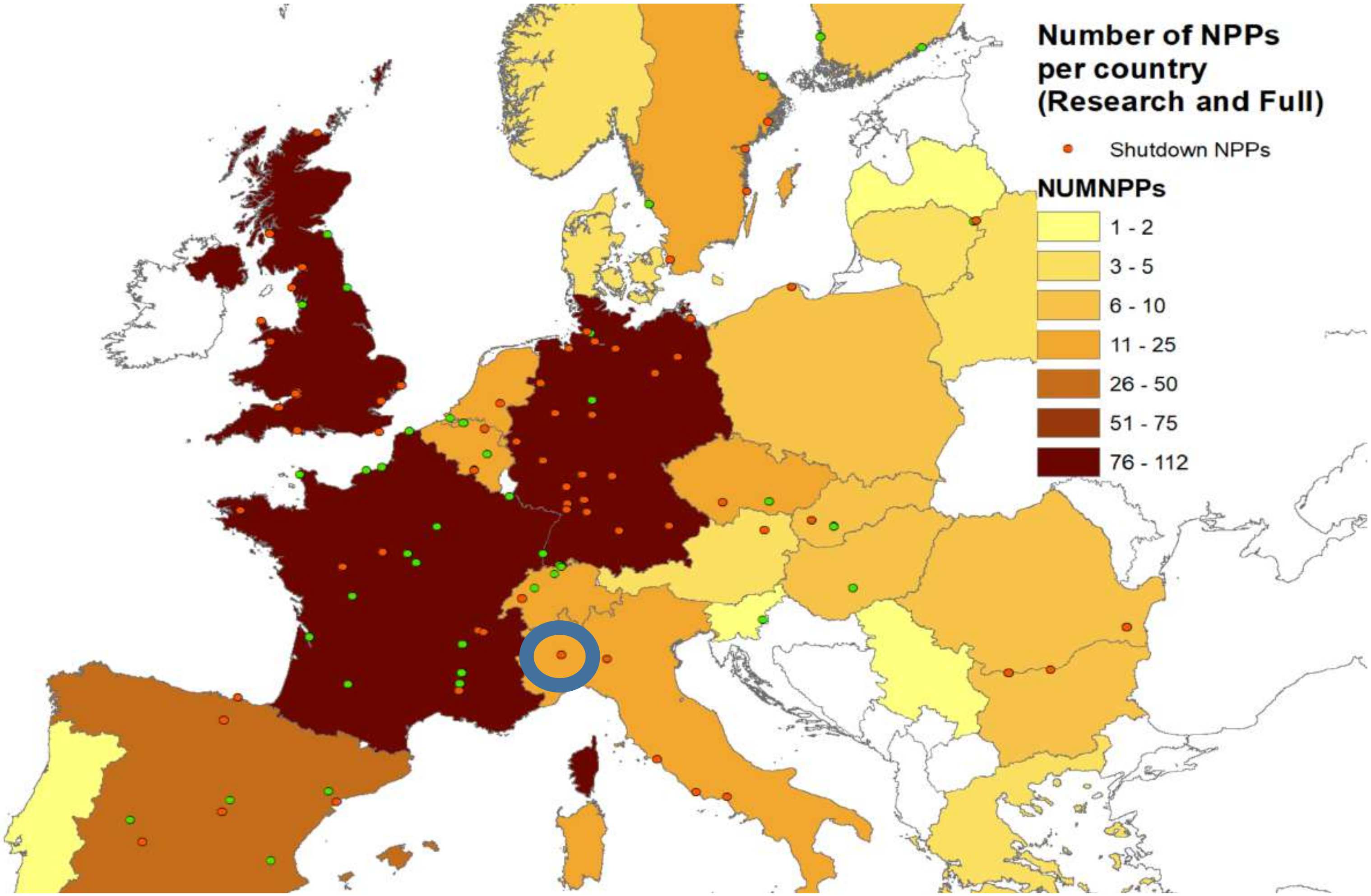
- Cold Wave
- Derecho
- Frost/Freeze
- Hail
- Heat Wave
- Lightning
- Rain
- Sandstorm/Dust storm
- Snow/Ice
- Storm Surge
- Tornado
- Wind
- Winter Storm/Blizzard

- Forest Fire
- Land fire: Brush, Bush, Pasture
- Subsidence

Parameters used for hazards

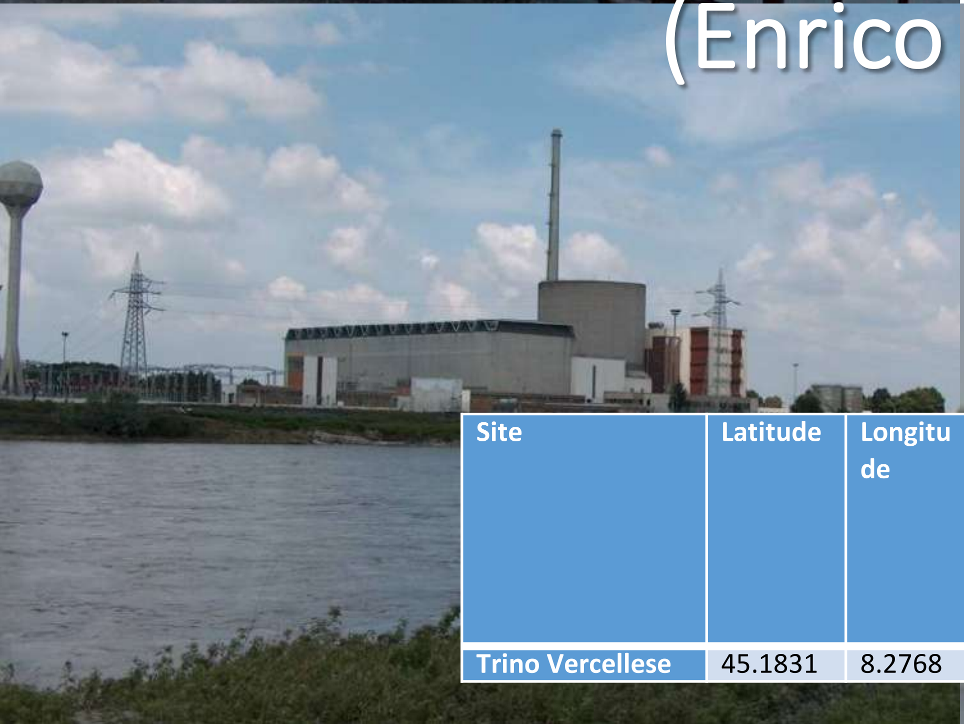
Disaster Type	Parameters
Storm Surge, Tsunami, Flood (Pluvial and Fluvial)	Water depth (m), velocity (m/s), and energy, flow, debris metrics, sediment transport, duration
Earthquake	Intensity, and shaking footprint; Ground motion (Sa, Sv, Sd + 100s of other parameters)
Landslide	Debris volume, displacement
Volcano	Tephra quantity (kPa), pyroclastic flow, lahar flow
Hail/Storm	Pressure, Hail track and hail size (mm), Reflectivity (dBz), Kinetic Energy, kA (current), duration
Wind, Tornado	Pressure, Wind speed (gust, sustained, height) Vorticity, Missile speeds
Rainfall	Intensity, frequency, duration curves
Extreme temperature, bushfire	Temperature, wind speed, heat output, energy

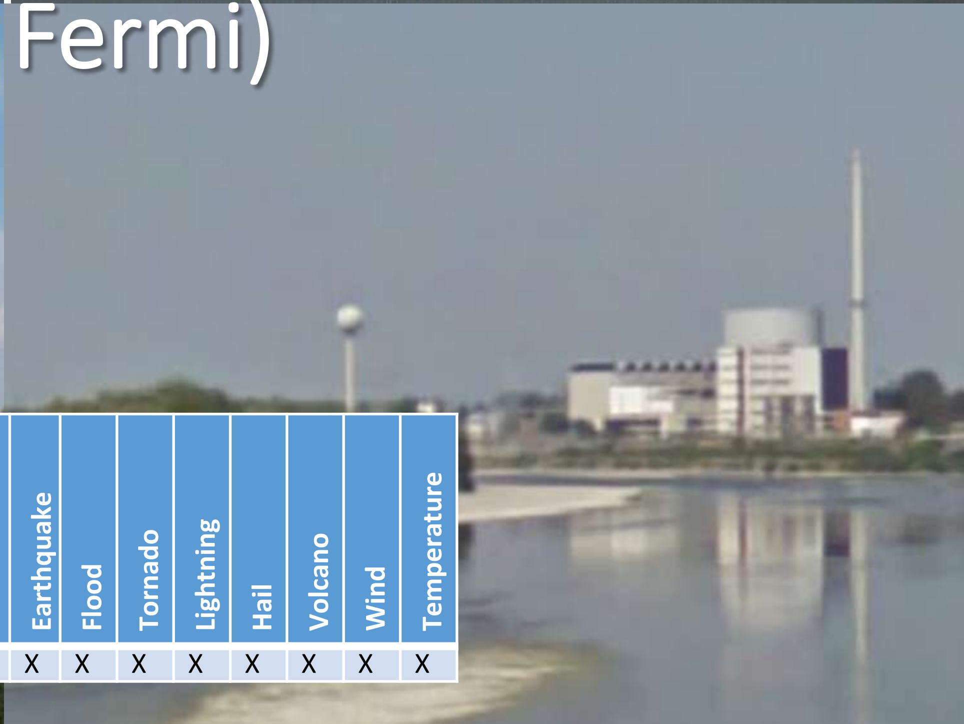
NPP sites



Number of NPPs
per country
(Research and Full)
Shutdown NPPs
NUMNPPs
1 - 2
3 - 5
6 - 10
11 - 25
26 - 50
51 - 75
76 - 112

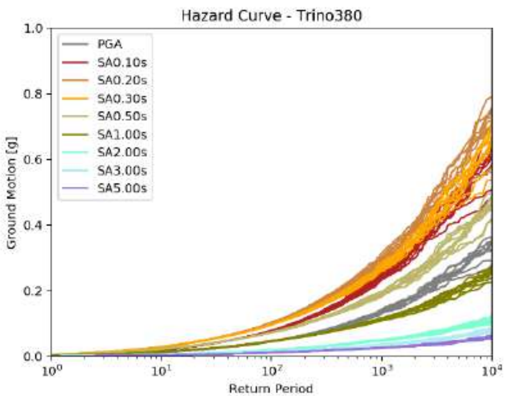
Trino Vercellese (Enrico Fermi)

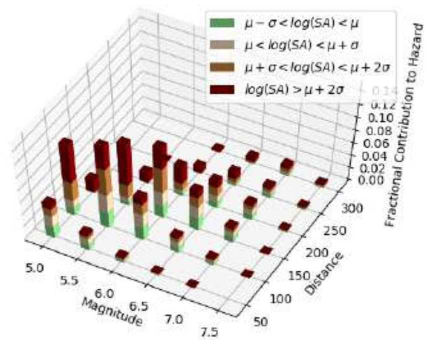


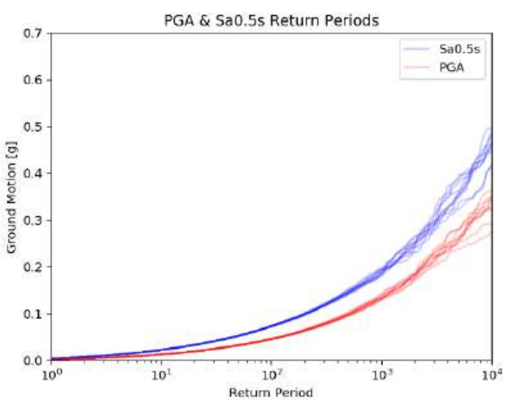


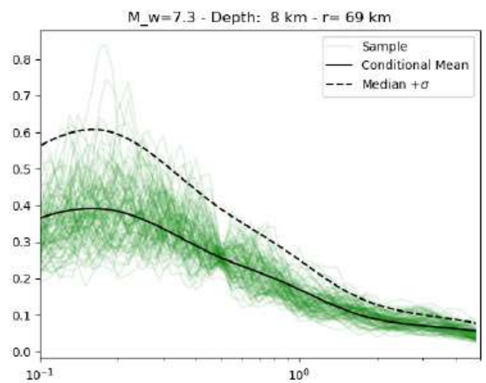
Site	Latitude	Longitude	Earthquake	Flood	Tornado	Lightning	Hail	Volcano	Wind	Temperature
Trino Vercellese	45.1831	8.2768	X	X	X	X	X	X	X	X

Earthquake Hazard curves





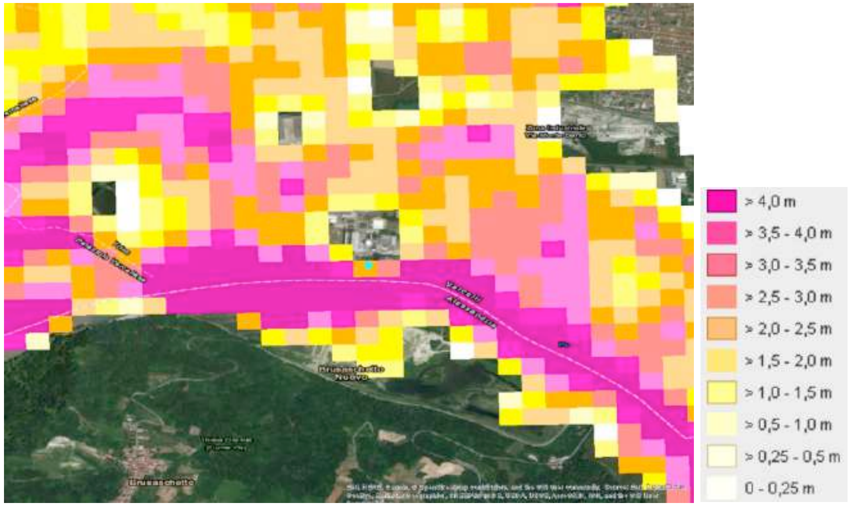


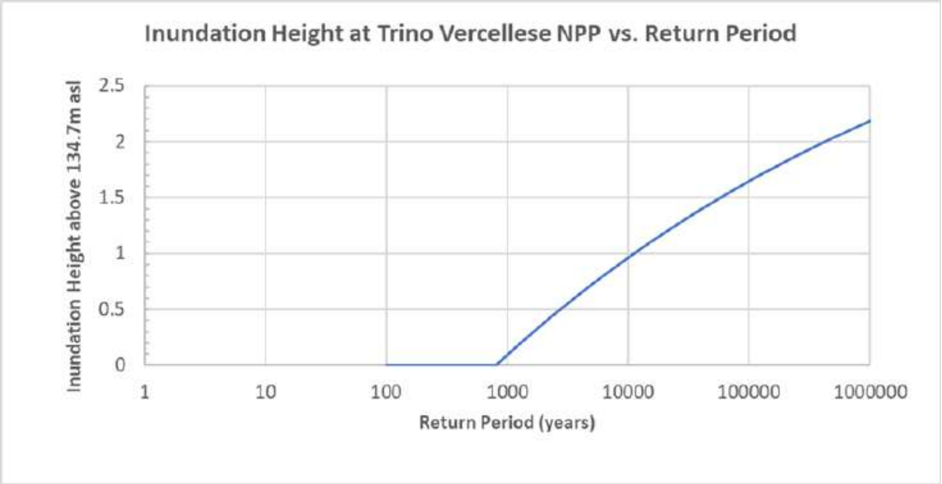


- **Parameters:**
  - Peak Ground Acceleration
  - Spectral Acc.
- **Additional hazards:**
  - Tsunami
  - Landslide
  - Liquefaction
  - Fault Rupture
  - Fire

Flood Hazard Curves

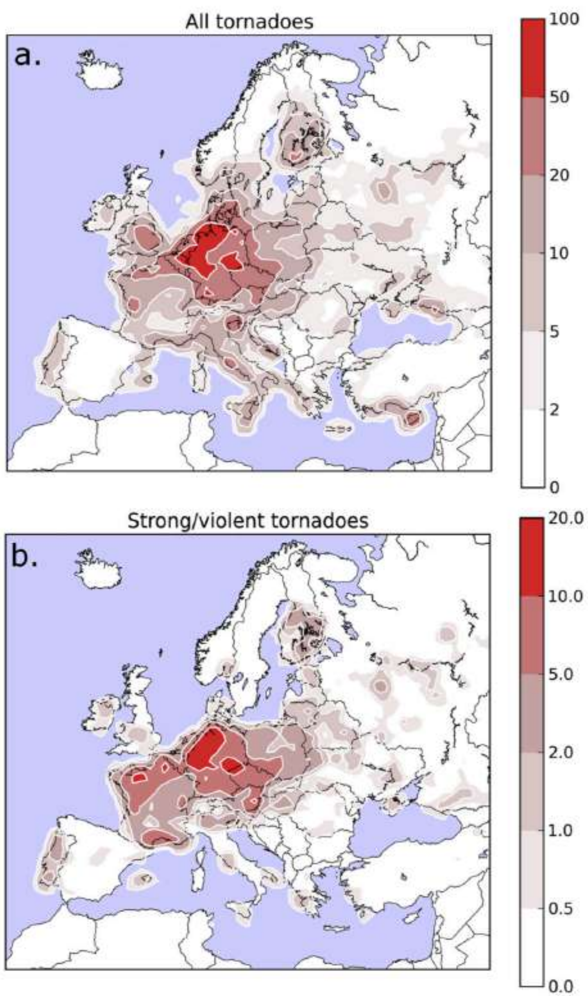
- **Long return periods often difficult to calculate**

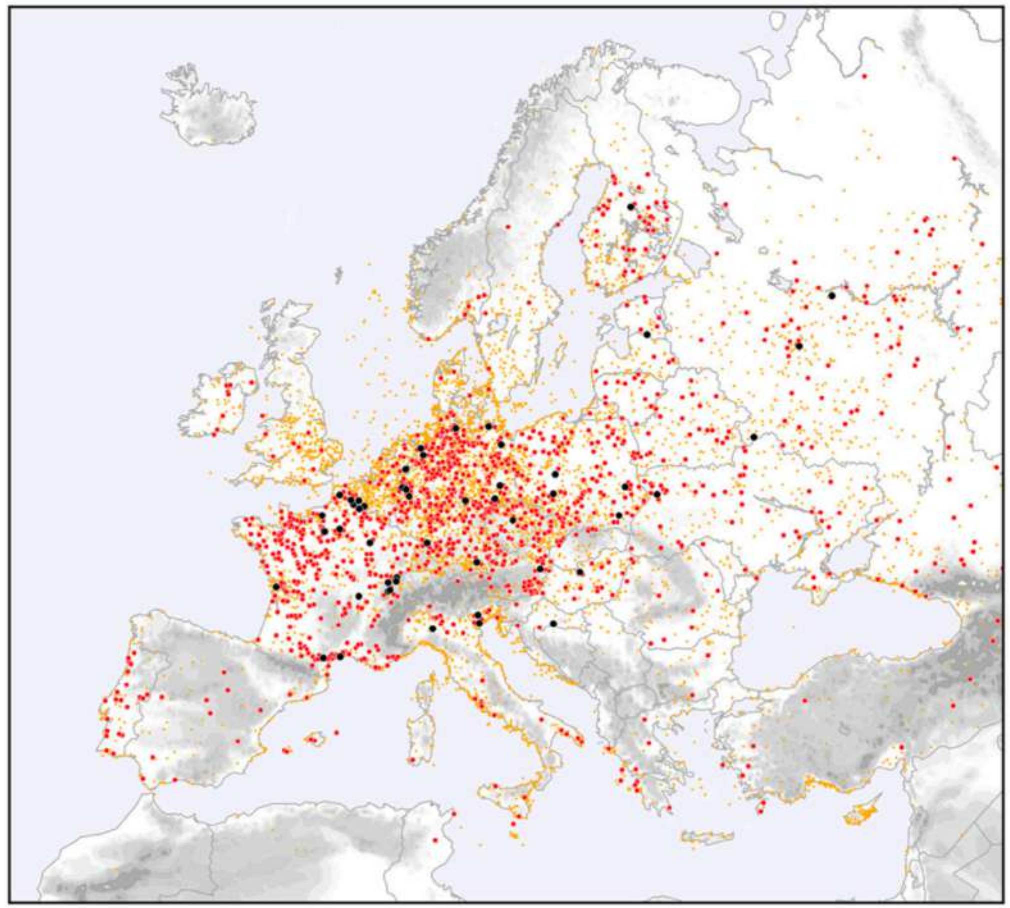




- **Gauge data, historic data, rainfall-runoff, hydraulic modelling, flood mitigation measures and extreme value statistics**

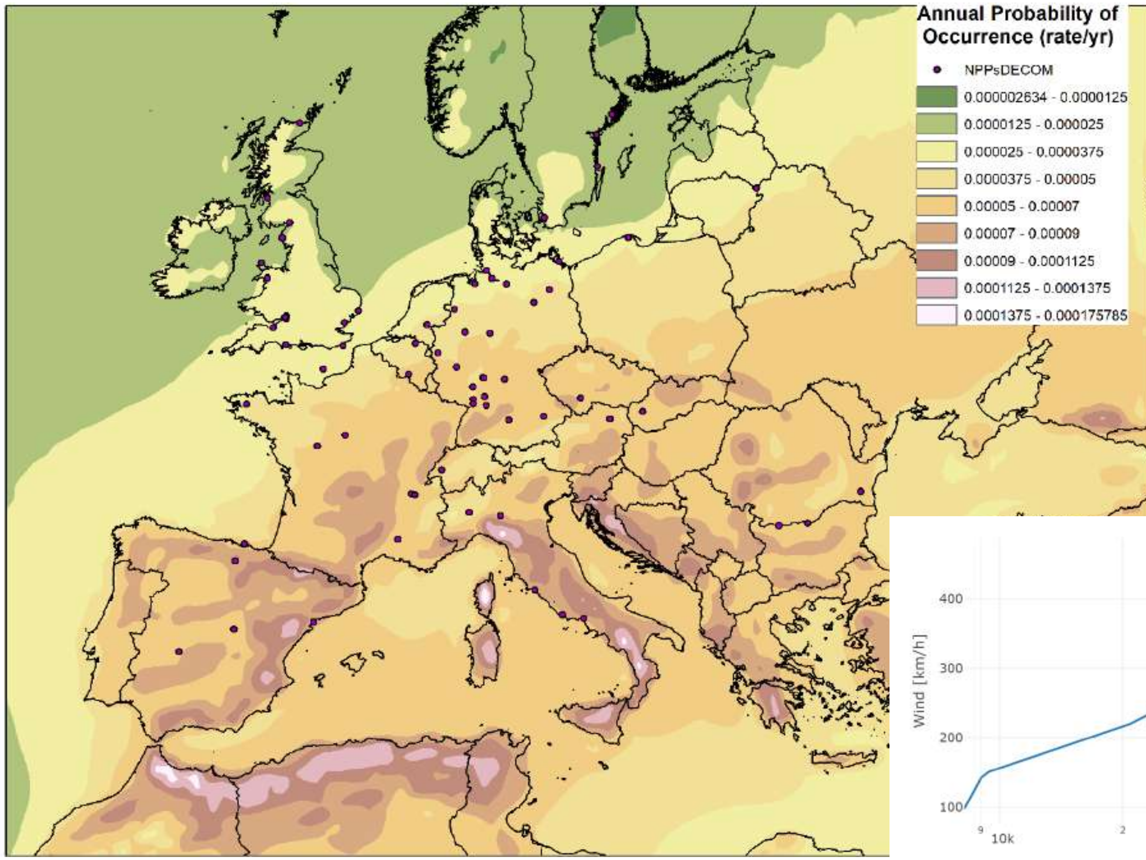
Historic Tornado Locations in Europe – lack of station data





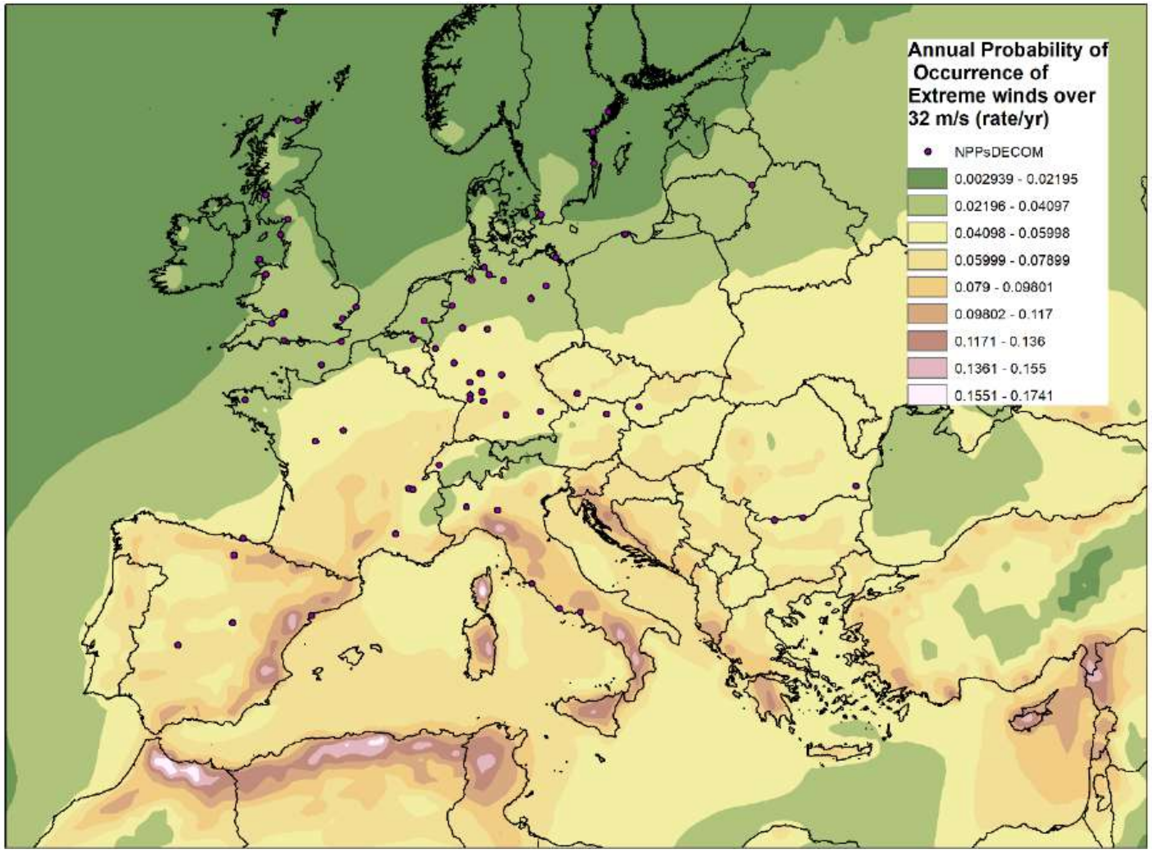
Gronemeijer and Kühne, 2014

Tornado – annual occurrence



- **Parameters:**
  - Wind speed
  - Enhanced Fujita
- **Additional hazards:**
  - Debris action
  - Flooding correlation etc.

Wind – annual occurrence



- **Parameters:**
  - Wind speed (3-sec gust, 1-min sustained, #)
- **Additional hazards:**
  - Debris action
  - Flooding correlation etc.

Hail

- **Parameters:**
  - Reflectivity (dBz)
  - Kinetic Energy, Hail size, #
- **Additional hazards:**
  - Associated storm activity

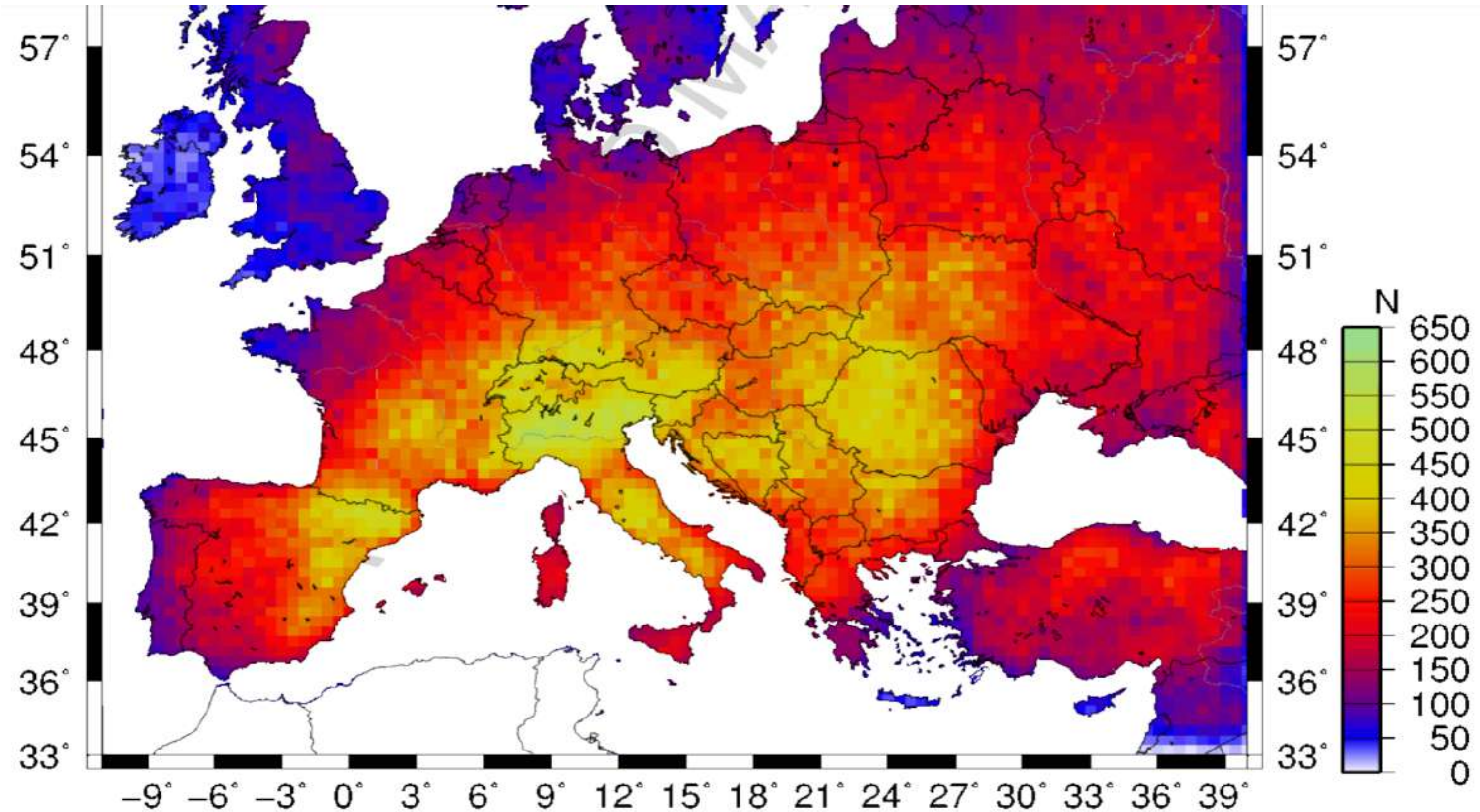
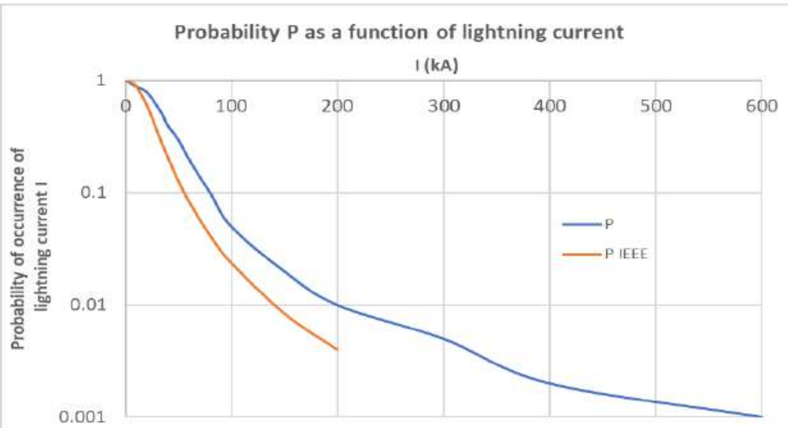
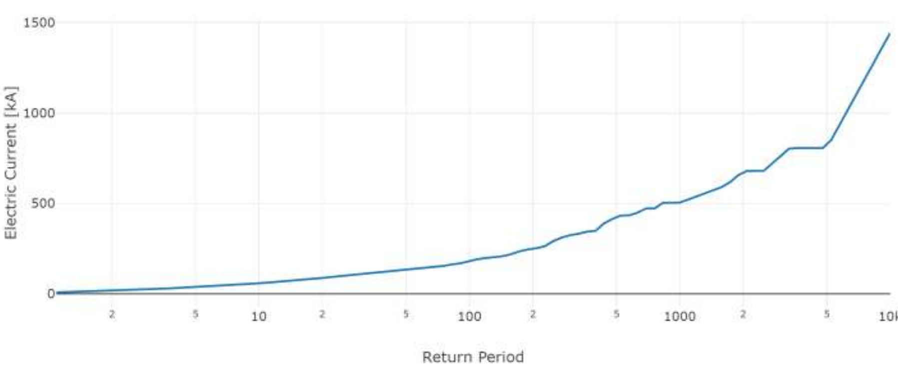


Figure 1: Hail event frequency as estimated by (Punge et al., 2014).

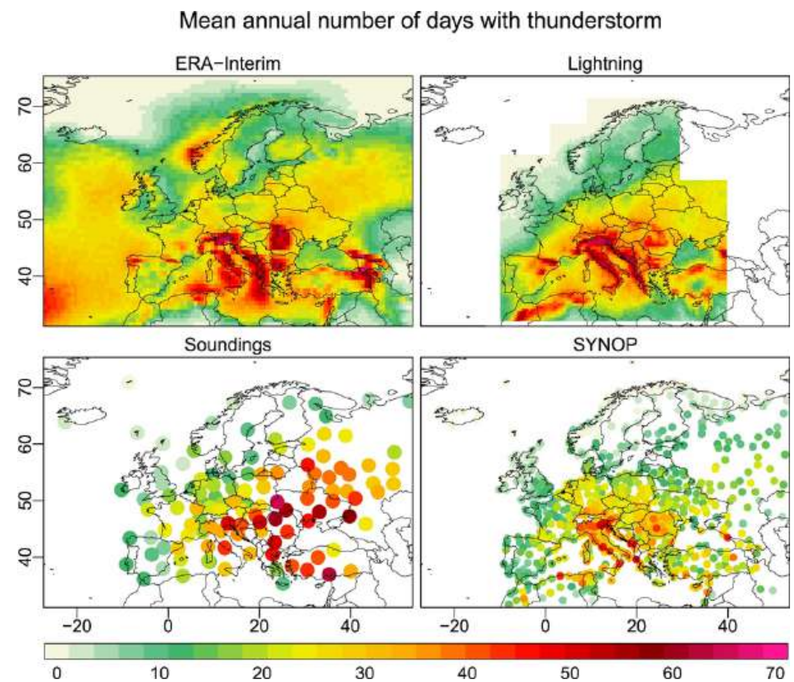
Lightning

- **Parameters:**
  - Current (kA)
  - Impulse, Time, Temperature
- **Additional hazards:**
  - Direct Energisation
  - Electromagnetic pulse
  - Ground potential rise



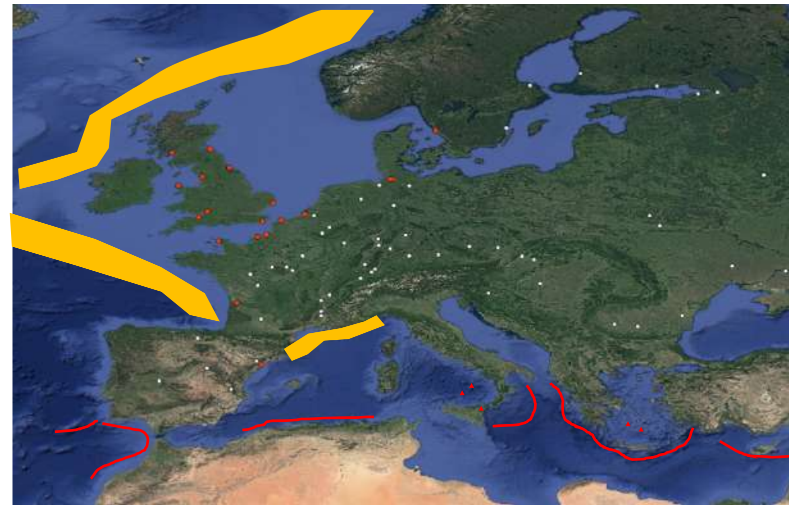


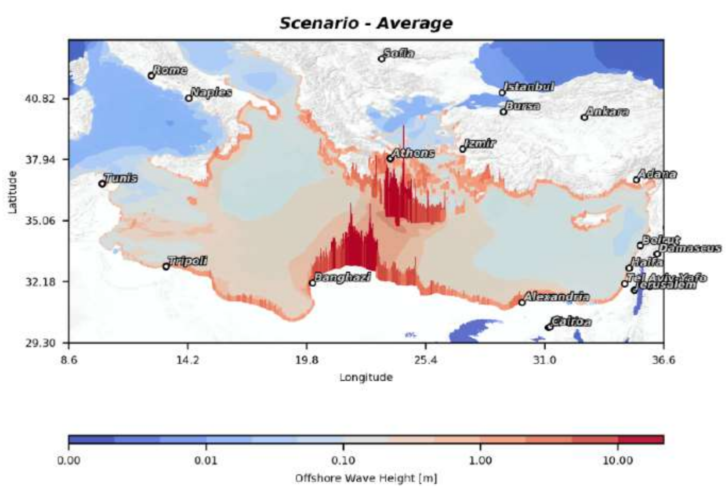
Lightning current (in kA) vs. return period for the Trino Vercellese plant



Tsunami Sources – NARSIS area

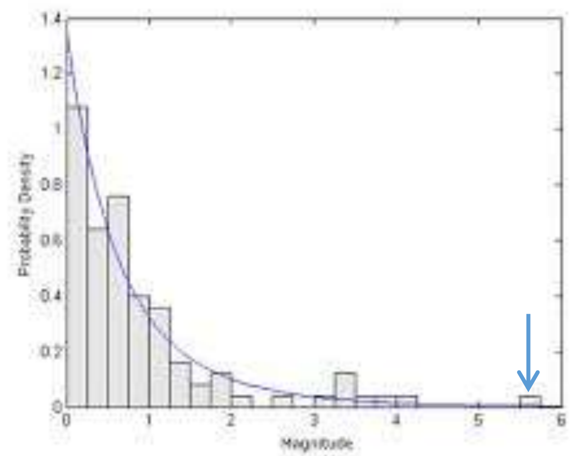
- **Tsunami Triggering:**
  - Earthquakes (rapid analysis)
  - Landslides
  - Volcanoes
- **Additional hazards:**
  - Ground Motion
  - Co-seismic uplift/subsidence
  - Debris transport





Problem: Limited historical data and the problems of probabilities

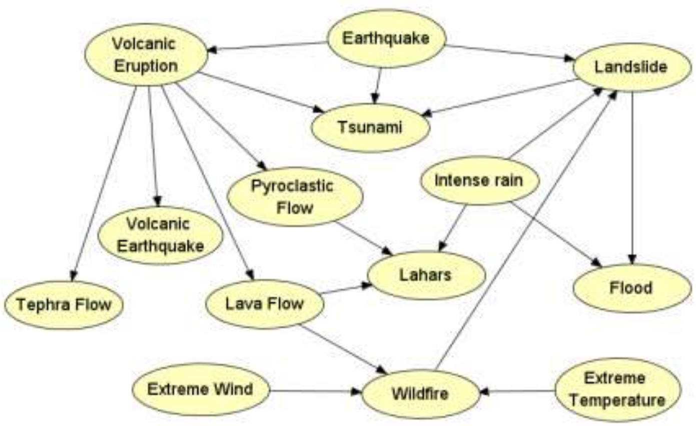
- We do not have over 1000 years of data in most cases for natural hazards (lack of knowledge)
- Extrapolation techniques of unlikely events based on limited data (underdesign)
- Function of desired design characteristics
- 100,000 to 1,000,000 year events or 2 + sigma at lower annual frequencies (design modelling)
- Characterisation of the randomness and variability – many unknowns!

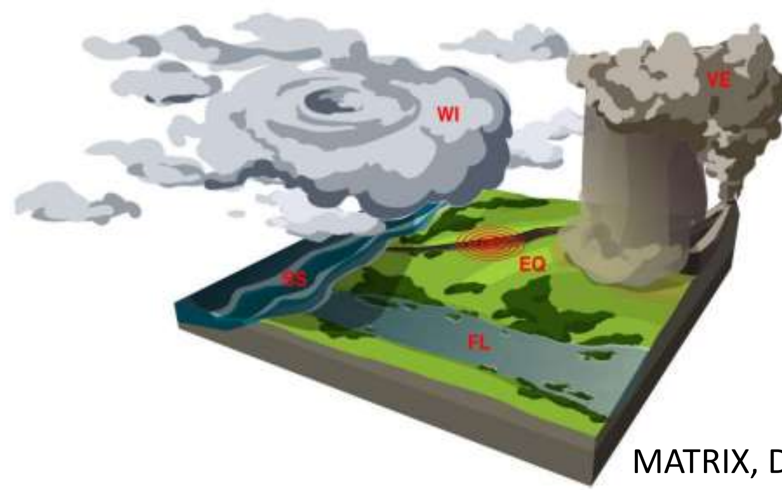


Over the next few days you will see how this is dealt with and what assumptions are made.

Natural Hazard Combinations

- Earthquake-Tsunami-Fire-Landslide
- Hurricane-Storm Surge-Flood
- Earthquake-Volcano-Tsunami-Mudslide
- Earthquake-Dam Break-Aftershocks (multi-hazard feedback loops)

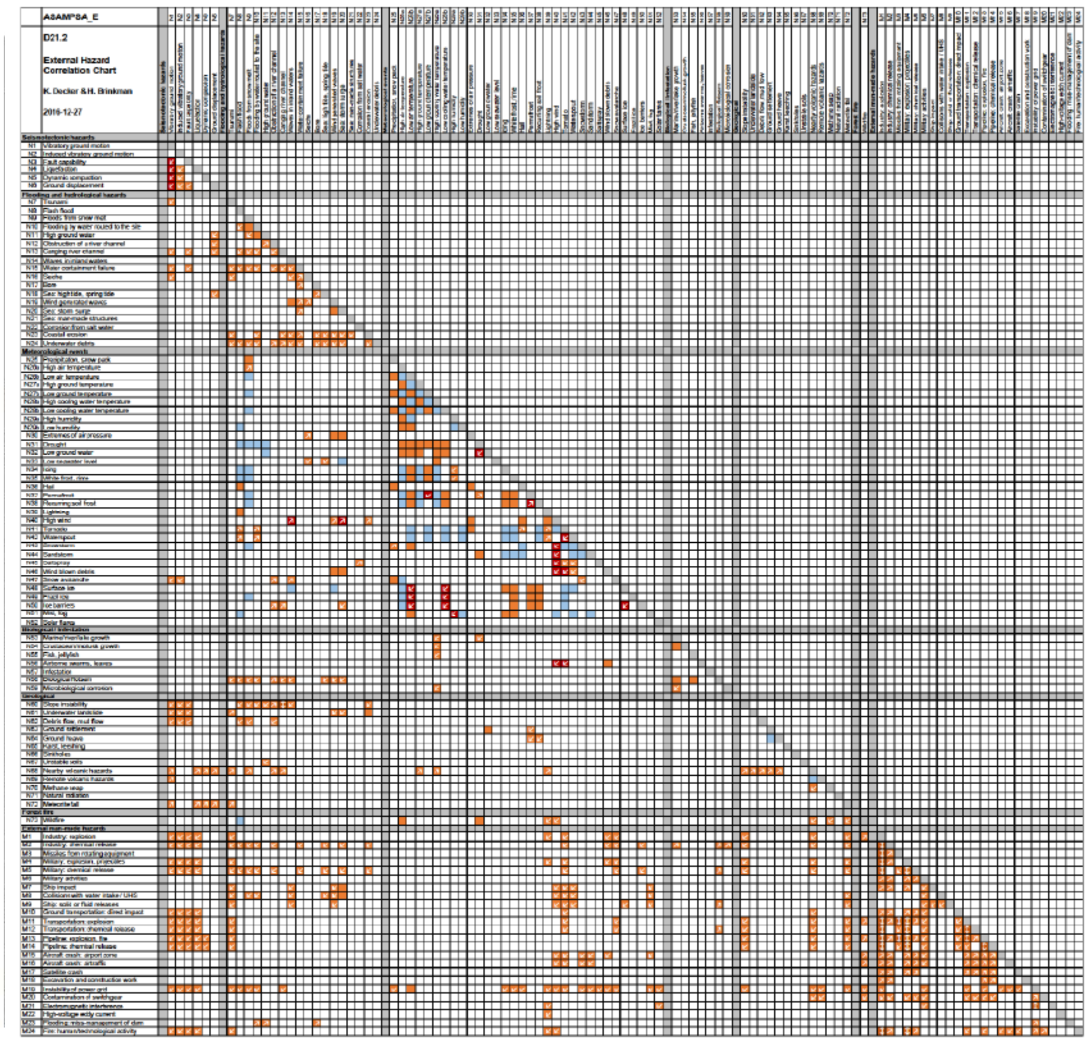




MATRIX, D5.5

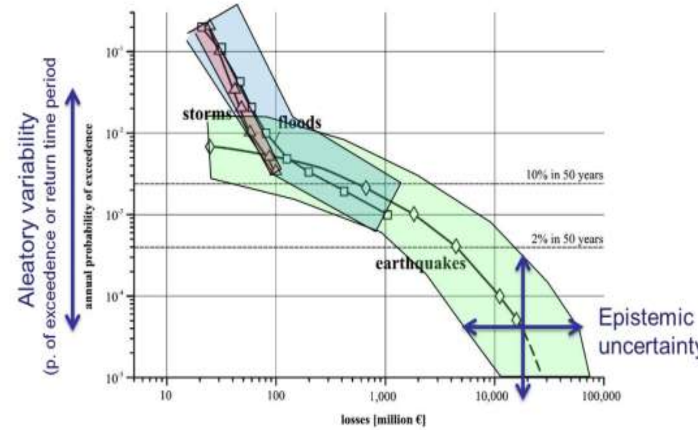
- Natural + Man-made disaster + Internal Hazard Interactions

ASAMPSA-E External Hazards Correlation (81 hazards)



Natural Hazard Combinations: Components

- Intensity vs. Duration vs. Frequency of original event (correlations)
- Spatial and temporal correlations within an event
- Historical occurrences of follow-on events
- Maximum Possible Events as per geology, wind formations
- Bayesian and Non-Bayesian approaches
- 10000 yr event with another 1000 yr event hazard and correlations etc.



	Windstorm	Earthquake	Bushfire	Volcano	Hail	Storm	Flood	Landslide
Windstorm	1	0.005	0.02	0.001	0.05	0.15	0.1	0.1
Earthquake	0.005	1	0.012	0.0073	0.001	0.003	0.008	0.13
Bushfire	0.02	0.012	1	0.004	0.01	0.1	0.12	0.05
Volcano	0.0001	0.001	0.0004	1	0.0005	0.0005	0.0008	0.001
Hail	0.05	0.001	0.01	0.0005	1	0.3	0.05	0.01
Storm	0.15	0.003	0.1	0.0005	0.3	1	0.3	0.4
Flood	0.1	0.008	0.12	0.0008	0.05	0.3	1	0.3
Landslide	0.1	0.13	0.05	0.001	0.01	0.4	0.3	1

Summary

- There are many methods for external hazards characterisation.
- Much data and work exists in the field including standards for each hazard type
- Uncertainties are found throughout every step of the hazard modelling chain
- Deterministic and probabilistic methods both have their place.
- Extreme value statistics and real-life examples are key to understanding NPP external hazard modelling.

Coming up next: Extreme Value Statistics and a French example for flood modelling for NPPs

Further Reference Documents

- ENSREG Stress Test documents
- ASAMPSA_E Documentation for various hazards
- See references in the NARSIS WP1 D1.1 report
- IAEA, 2003. Consideration of external events in the design of nuclear facilities other than nuclear power plants, with emphasis on earthquakes. Tecdoc 1347, 113pp.
- MATRIX project (EU)

An integrated hazard framework and software from hazards

KIT Karlsruhe Institute of Technology

RiskScape
InaSAFE
HAZUS MH EARTHQUAKE • WIND • FLOOD
CAPRA Probabilistic Risk Assessment Program
SELENA–RISe
MAEViz
EQRM Beta
DBELA
OPEN RISK
OPENQUAKE
"EXTREMUM"
SYNER-G
m-HARP
ERGO
RADIUS
RISKiitb
SEISMOCARE
less loss
SeisVARA-
OSIRE
QLARM
Deltares Enabling Delta Life
NEXT GENERATION HYDRO SOFTWARE
neries
ELER©
MIRISK
INLET
REDAS 2.8d
SES-2002
RORB Win
SOBEK
CREST
REDARS™
SAFER
台灣地震損失評估系統
Taiwan Earthquake Loss Estimation System
r.hazard.flood.py
EQSIM
CATS SAIC
EPEDAT
USGS PAGER
USGS WATER
nofdp IDSS
Kalypso
SIGE/QUATER
STRUCLOSS 1.4
SWWRP
Hydrognomon (Ύδρογνώμων)
EPA SWMM 5
Tc tcrm Tropical Cyclone Risk Model
Australian Government Geoscience Australia
open TELEMAC
GSFLOW
WaSiM-ETH
Hydrologic Engineering Center
Delft3D
PIHMv2.2
QUICK-2 v.2.0
SLOSH
SWAN Simulating WAves Nearshore
TOMAWAC
Centre for Ecology & Hydrology
Flood Estimation Handbook
HydroFOSS
dr3m
BASEMENT
ATHYS
ComMIT
MITgcm
r.tsunami
WAVEWATCH III
P-Surge 2.0
TsuDAT
CHAMP Coastal Hazard Analysis Modeling Program
RUNUP 2.0
ANUGA
ADCIRC

NARSIS Workshop

Training on Probabilistic Safety Assessment for Nuclear Facilities

September 2-5, 2019, Warsaw, Poland

Introduction to External Hazard Events:

Background, Parameters, and Interactions

Dr. James Daniell