UWI-NGI project 2006-2008

Tsunamis in the Caribbean - Regional Exposure and Local Risk Assessment

NOTE: The following contains example calculations simply meant to DEMONSTRATE a methodology, and should not be considered as final results meant for further use in planning, hazard or risk assessment.

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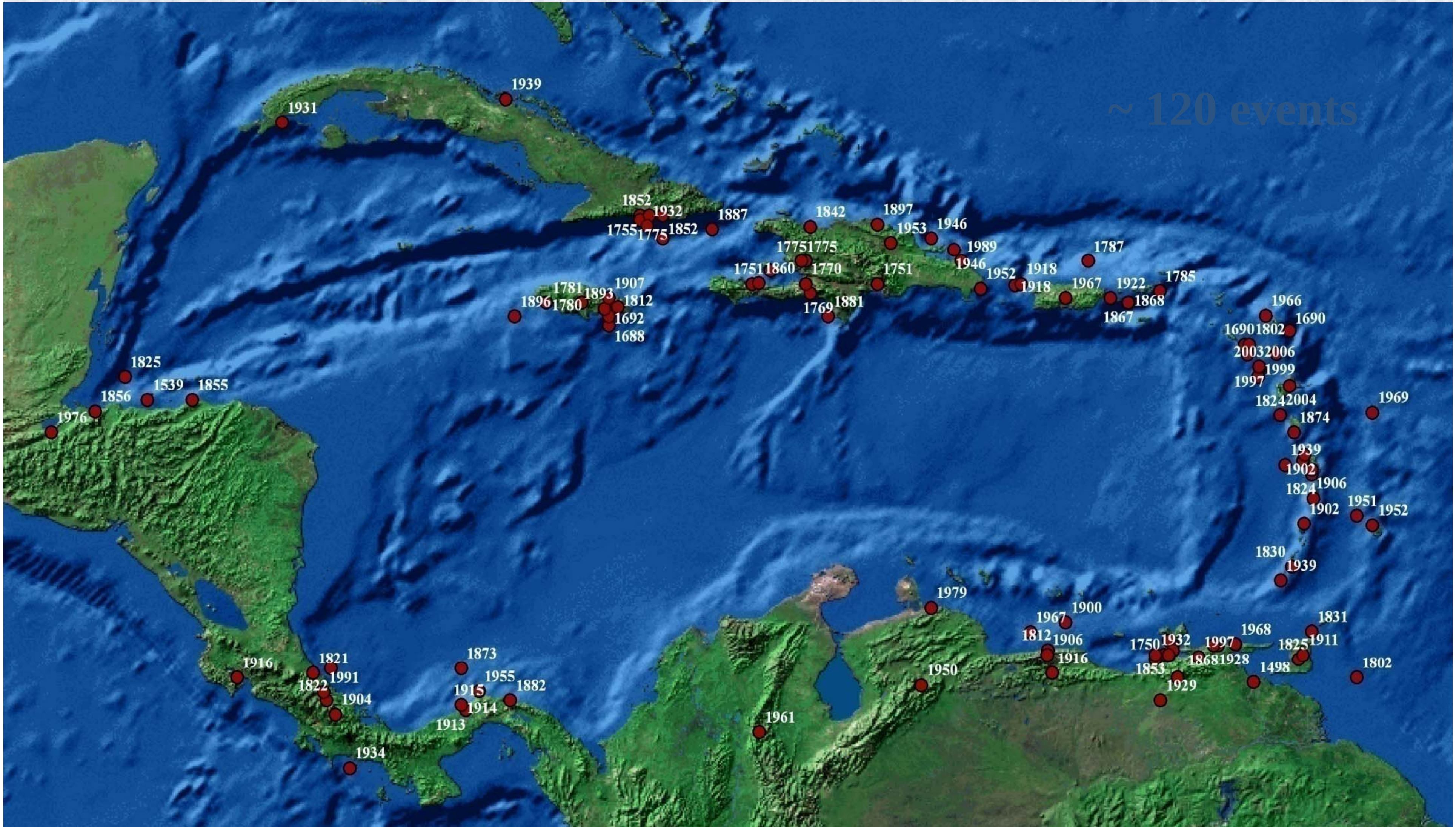
ICG/CARIBE EWS WG2 meeting, Pointe-a-Pitre, Guadeloupe, December 7th 2008

Caribbean Tsunami Database - Compilation of recorded events

- Critical assessment of two tsunami catalogues and one earthquake catalogue
  - National Geophysical Data Centre (NGDC)
  - Tsunami Laboratory Novosibirsk (TLN)
  - R. Engdahl

Source location for all recorded tsunamis in the databases – first data from year 1498

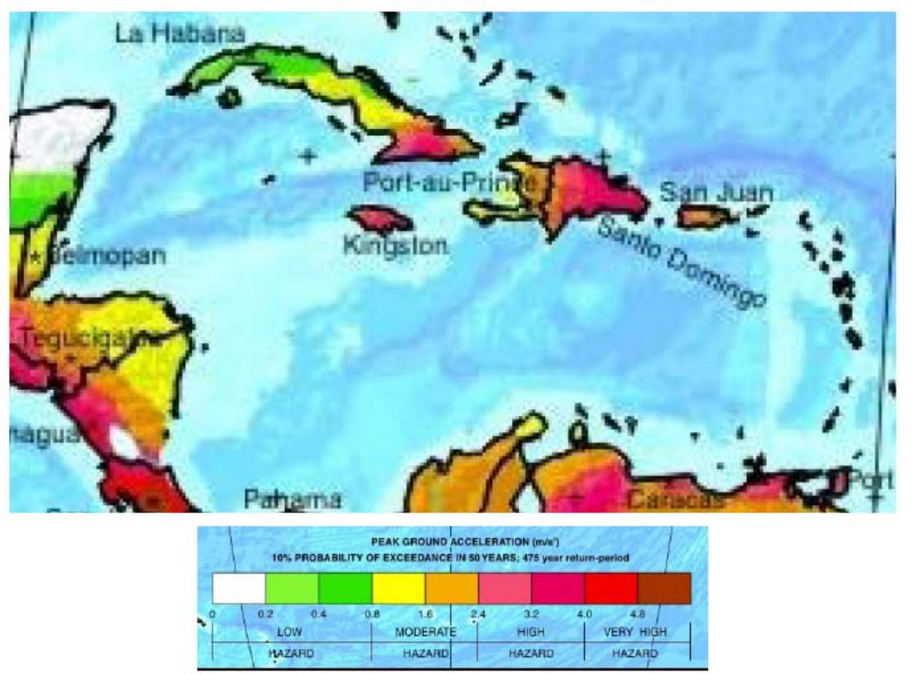


Tsunamis in the Caribbean Sea - example scenario criteria

- Sound choices based on the historical records
- Examples of various kinds of sources
- Regional distribution to serve as an example of regional exposure assessment
- Avoid reproduction of previous studies
- Relevant for partners in this project
- Relevant as input for Bridgetown tsunami risk demonstration project
- We will present:
  - 2 earthquake tsunami scenarios
  - 2 subaerial volcano debris flow tsunami scenario
  - 1 submarine landslide tsunami scenario
  - 1 trans-oceanic tsunami

Regional seismic hazard

- NE Caribbean more exposed than Lesser Antilles



re 2.8. Seismic hazard results for the Caribbean region from the Global Seismic Hazard Assessment Project (GSHAP; Shedlock et al., 2000).

Tsunamis generated by earthquakes – suggested scenarios

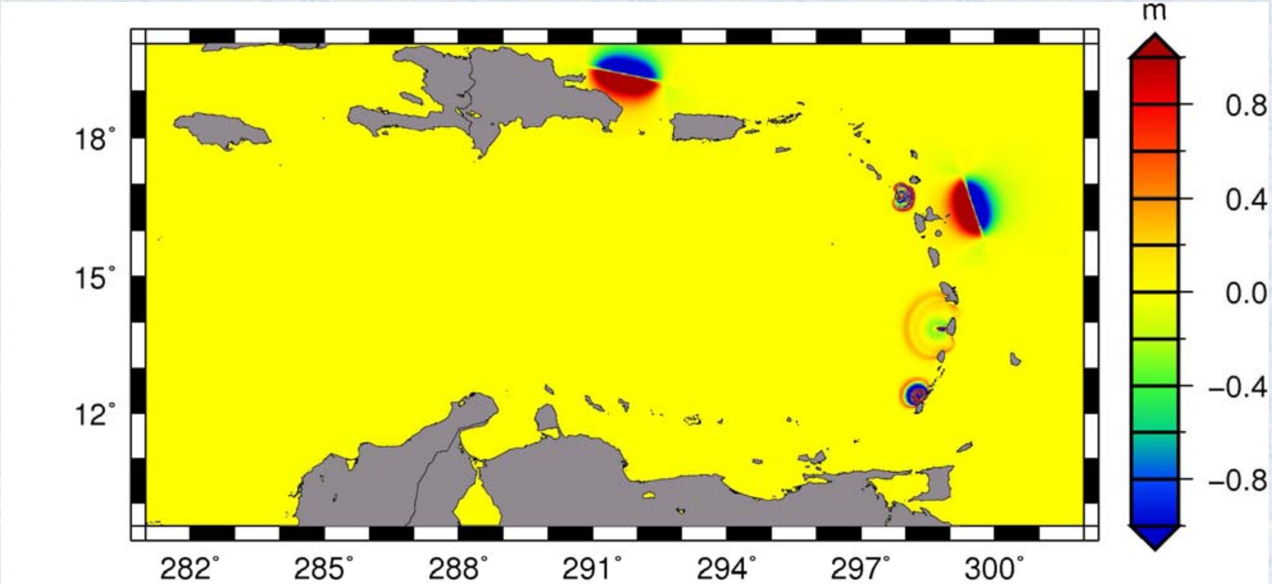
- Maximum magnitude:
  - Largest credible earthquake around M 8.0, no potential for tsunamis similar to 2004 Sumatra/Indian Ocean tsunami
- Locations:
  - Sources based on combination of
    - historical eq and tsunami occurrence
    - large scale tectonics

Tsunamis generated by volcanoes and landslides

- Information on volcanological sources provided by Dr. R. Robertson, SRC, and compiled by NGI
- 2 eruptive volcanoes:
  - Subaerial at Montserrat
  - Submarine Kick'em Jenny
- St. Lucia debris flow

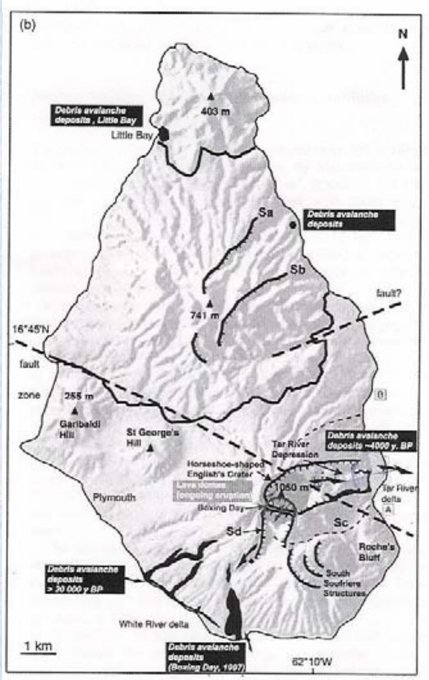
The scenarios

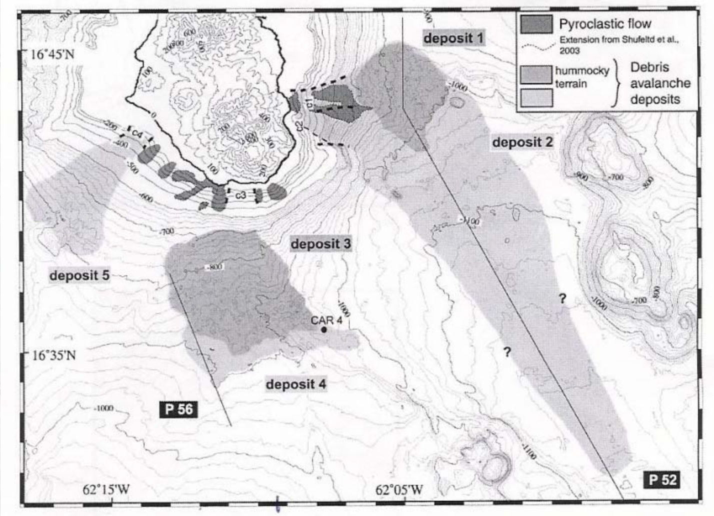
- Totally five scenarios
- Due to different return periods we divide our study into two groups, one for earthquakes and one for slides.
  - Earthquakes Mw 8.0 (Lesser Antilles and north of Hispaniola)
  - Slides (Monserrat, St. Lucia, and Grenada)



Example study III: Subaerial landslide from Soufrière Hills volcano, Montserrat

- Soufrière Hills: eruptive volcano, much focus
- 4000 BP event not modelled before (?), "worst case scenario" (?)
- English's Crater flank collapse
  - Deposit 1 formed by 1 event (Le Friant et al. 2004)
  - Volume: L x W x H = 1.6 x 1 x 0.1 km^3 = 1.6·10^8 m^3
  - Submerged run-out: 5.4 km (from deposits)
- Impact velocity: 30 m/s
- 1997: 2.5·10^7 m^3
- 2003: 2·10^8 m^3 (as smaller volumes, limited velocities)





Le Friant et al., 2004

Example study IV: Submarine landslide – close to Kick'em Jenny

- Most active volcanic centre in Lesser Antilles arc
- 8 km north of Grenada
- First observed in active eruption 1939, small tsunami
- Since then erupted at about 5-year intervals
- Summit of the volcano is now > 130 m below surface
- Multibeam surveys suggest flank collapse east of the active cone and debris flows running 15-30 km to the west with thickness of tens to hundreds of meters, smaller has a volume of 10 km^3 (Sigurdsson et al. 2006)

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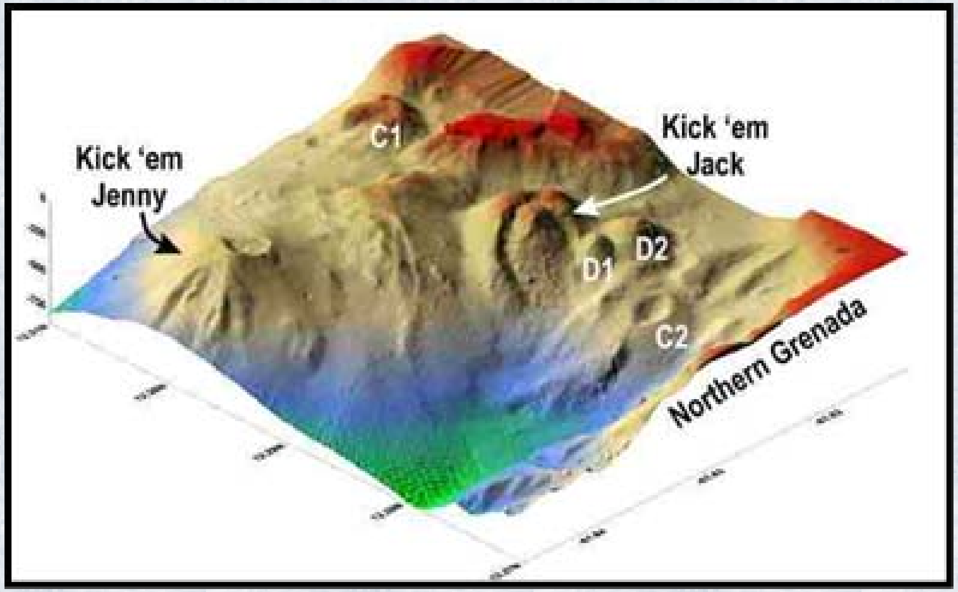
Kick'em Jenny and Kick'em Jack

- Not to the east
- Kick'em Jack not to be considered in terms of flank collapse



Source: http://www.uwiseismic.com/KeJ/kejhome.html

Gisler et al. 2006

- Depth of summit now 190 m,
  not significantly diminishing,
  water pressure confines the explosive effects
- SAGE hydrocode simulations:
  Coupling of explosive energy
  to wave energy is inefficient
  compared to slower mechanisms
  (only a few percent of source
  energy transferred)

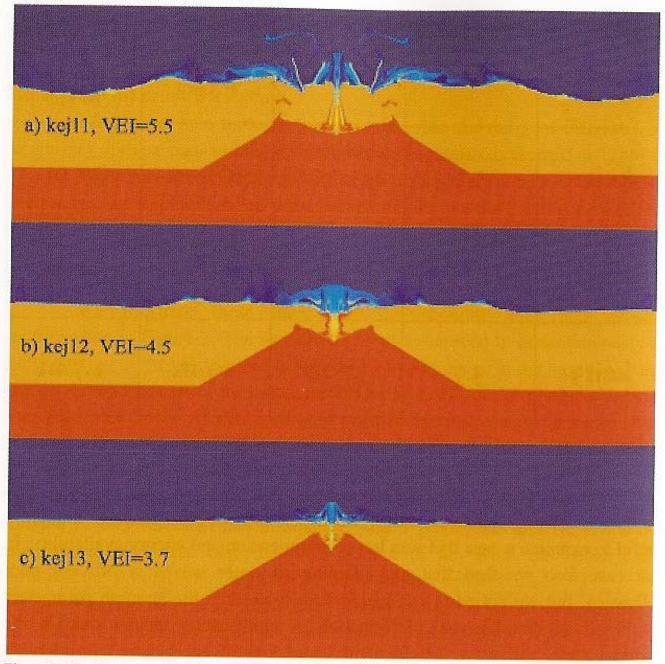


Figure 2. Final wave profiles for the three representative runs.

- Conclusion:
  - no danger
    (except for gases and missiles
    threatening shipping)
  - Efficient production of tsunami
    requires earthquakes or landslides
  - Tsunami danger from explosive eruptions less than from slope failure at that volcano (similar to that which caused the horse-shoe shaped cleft in which the volcano currently nestles)

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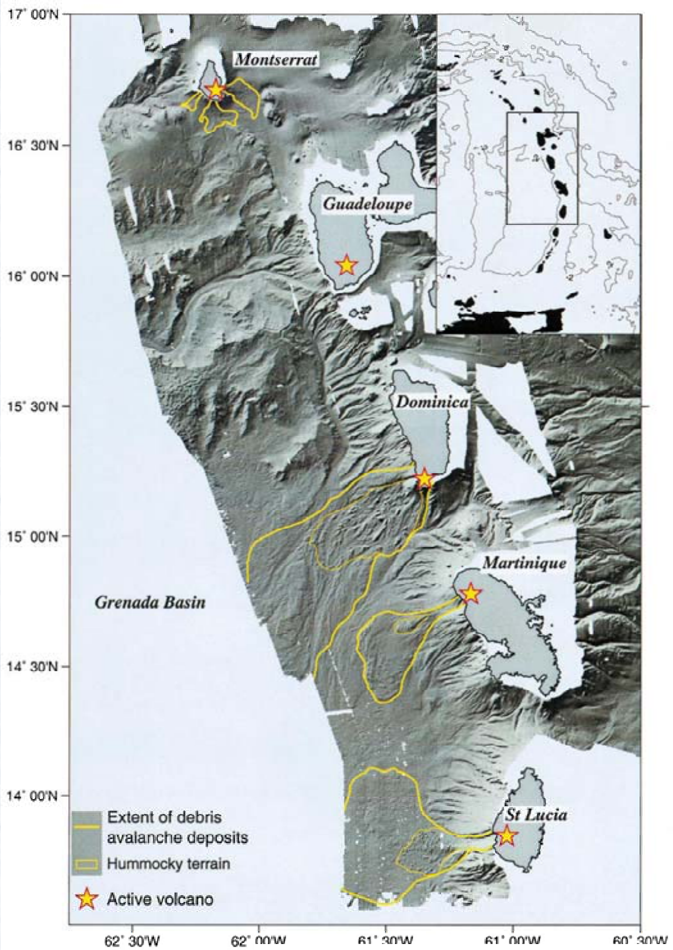
From these reasons...

- 0.6 km^3 western flank collapse on Kick'em Jenny
- Run-out 10 km to the west

  (from statistics, H/L = 1.5 km/ 10 km = 0.15)
- U_{max} = 45 m/s (from analytical calc)

Example study V: St. Lucia



Deplus et al. (2001)

- Run-out 18 km
- Max. vel. 40m/s
- W x H x L = 1.32x800x200x1200 = 250 Mm^3
- Lindsay et al. 2002:
  - Sulphur springs within Qualibou caldera is a susceptible area (but not the "worst case" large explosive magmatic eruption)
  - Lack of age data makes it impossible to develop an eruption frequency
  - Major activity 35-20 000 years BP
  - Deposits easily eroded, possible that more eruptions have occurred over the last 20 000 years and that products have not been preserved.

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Probability of earthquake scenarios

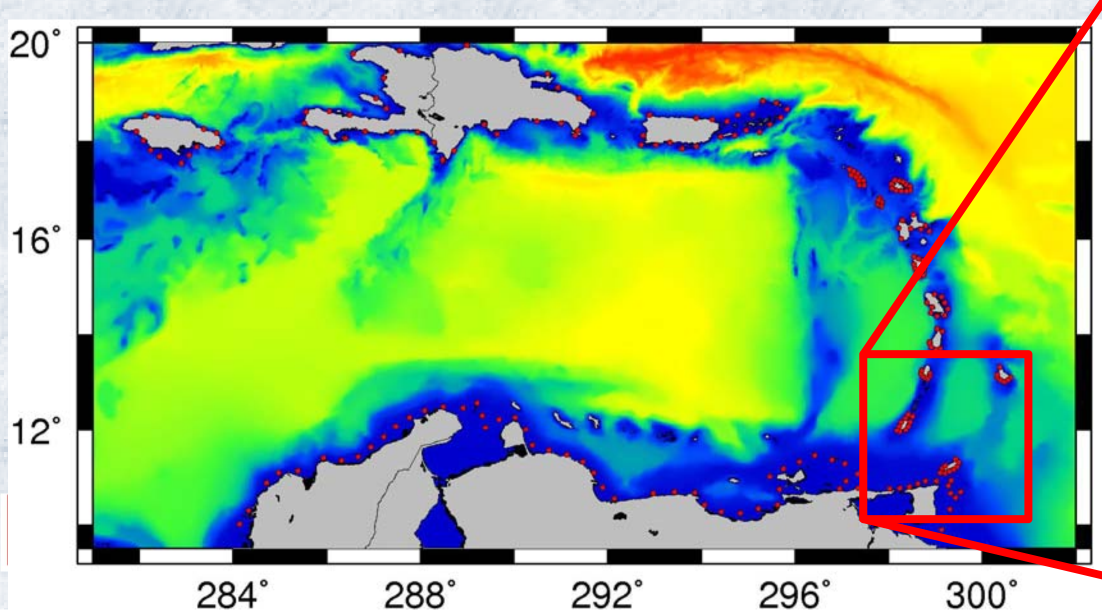
- From convergence rates, records, and literature
- Hence, the proposed M8 earthquake scenarios have a return period of approximately 500 years
  (i.e. a probability of 10 % of an event occurring in 50 years)
- Somewhat larger than Zahibo et al. (2007):
  - M8 earthquake return periods of ~200 years

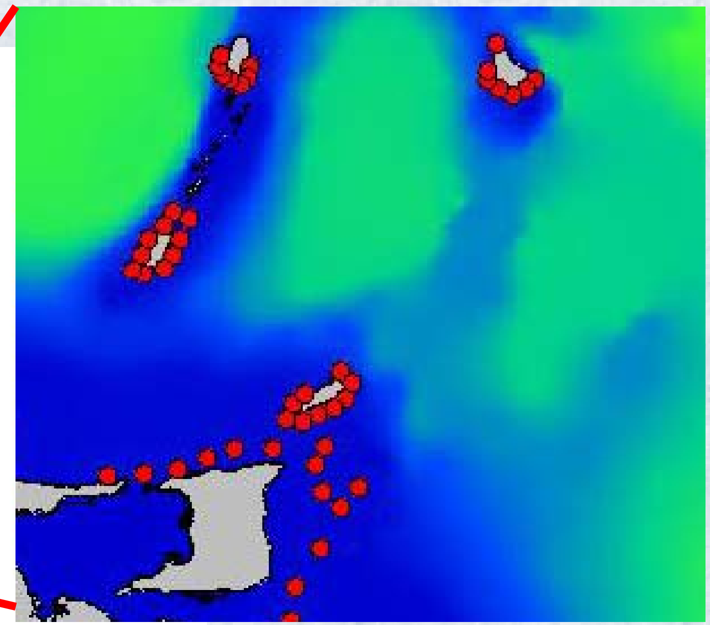
Probabilities – summing up

- Zahibo & Pelinovsky 2001:
  - Run-up exceeding 2-3 m:
    Return period 100 years
  - All events (cumulative), all kinds of tsunamis
- Earthquakes M8: return period 500 years
- Non-seismic :
  - Return period of smaller events in the northern part of the arc: order of 1000 years
  - Return period of larger events in the southern part of the arc: order of 10 000 years

Approach for the regional tsunami exposure assessment

- Defining a set of tsunami sources
- Simulate the tsunami propagation (GEBCO 1min grid)
- Extracting data at gauges at depths of 50 m
  - High number of gauges
- At each gauge we want to relate the surface elevation measured at the gauge to on-shore run-up





Considerations

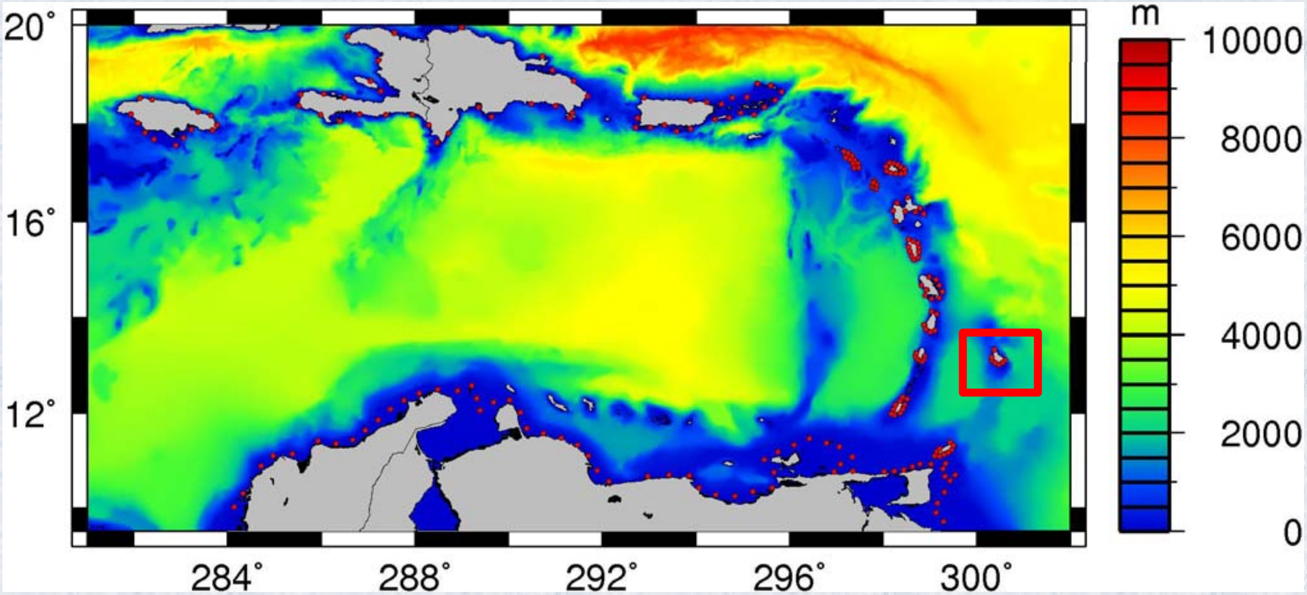
- Combined effects:
  - Sea level rise 0.2-0.5 m (In 2100, IPCC)
  - High tide, daily: 0.5-0.7 m

→ a waterdepth of 0.7 m is added

- Not taken into account (rare events):
  - Spring tide
  - Storm surges

Life of a tsunami

- Generation phase (earthq. or slide)
- Tsunami propagation
- Run-up on dry land



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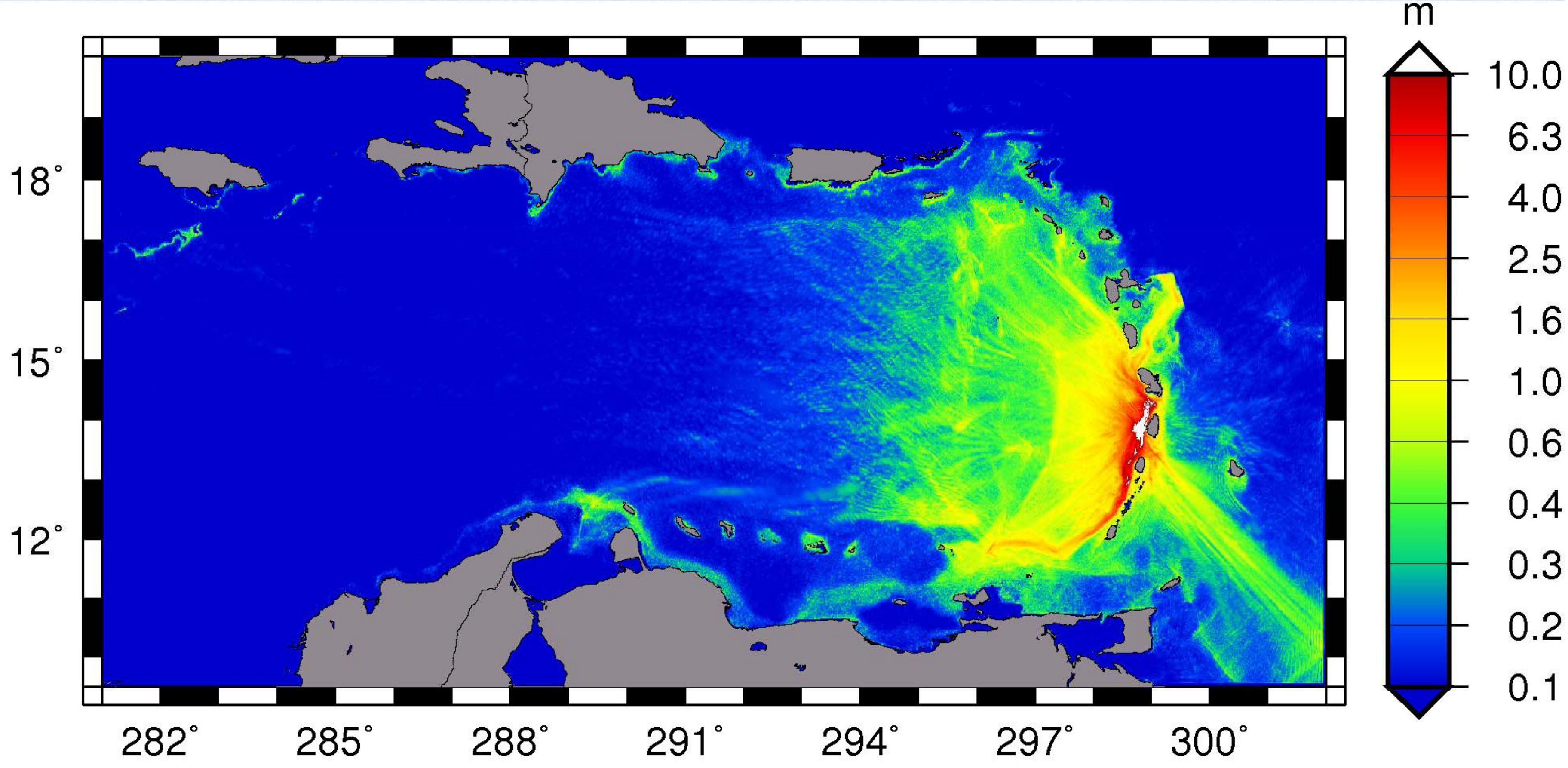
Tsunami modeling; generation

- Earthquake
  - prescribed initial condition using analytical formula of Okada (1992)
- Slide
  - runout length, velocity progression, slide dimensions
  - compute sink/source distribution (time dependent bottom deformations)

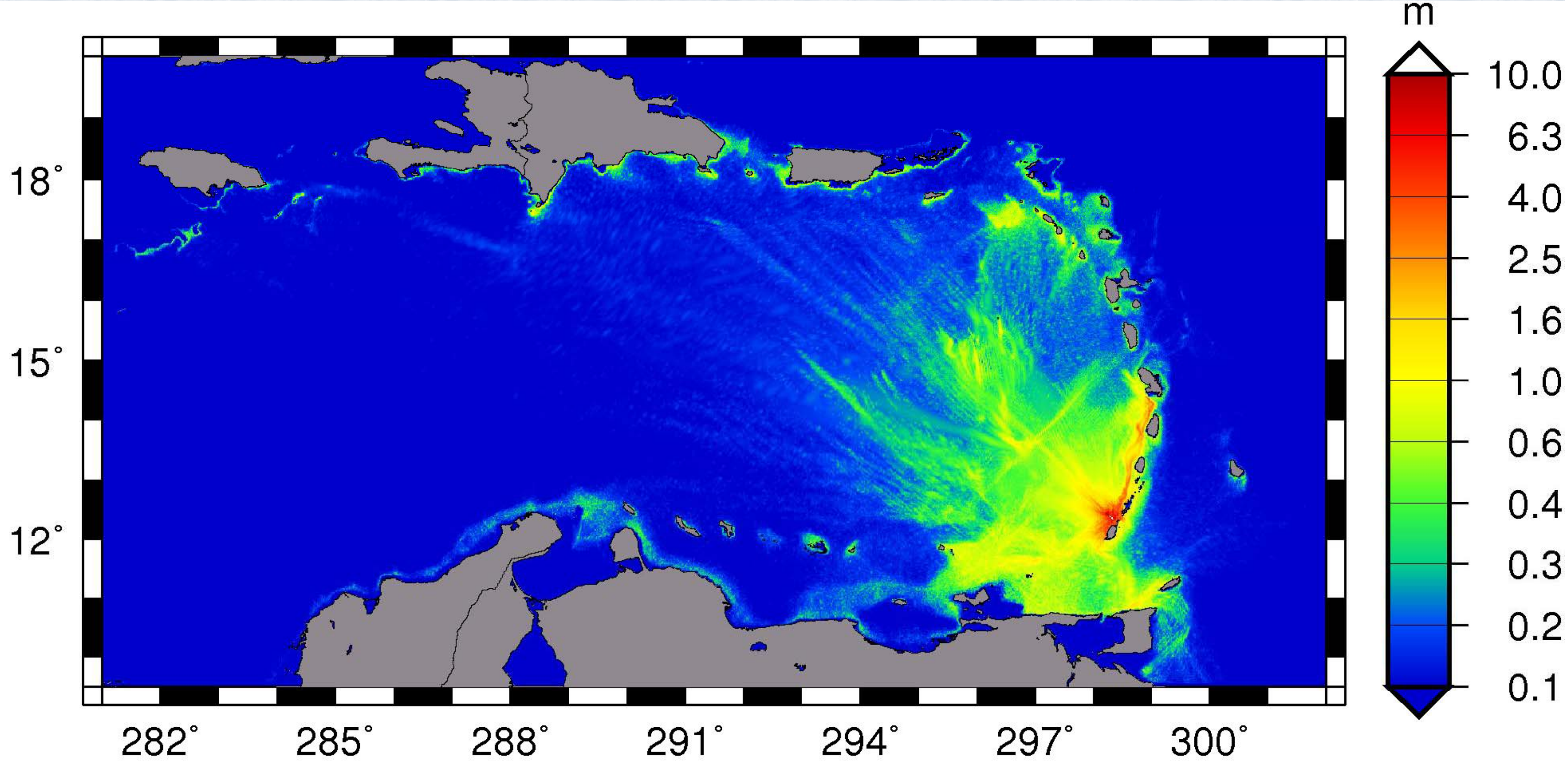
Tsunami modeling; propagation

- “Globouss” – depth averaged Boussinesq model developed at ICG/UiO/NGI
  - Improved model compared to previous models applied in this project
  - Dispersive effects (may be important for tsunamis propagating over long distances in deep water)
  - Non-linear effects (most important nearshore)
  - Cartesian or geographical coordinates
  - Coriolis forces and open boundaries
  - No possibility for calculating run-up
    - Noflux condition at shoreline, doubling of the surface elevation

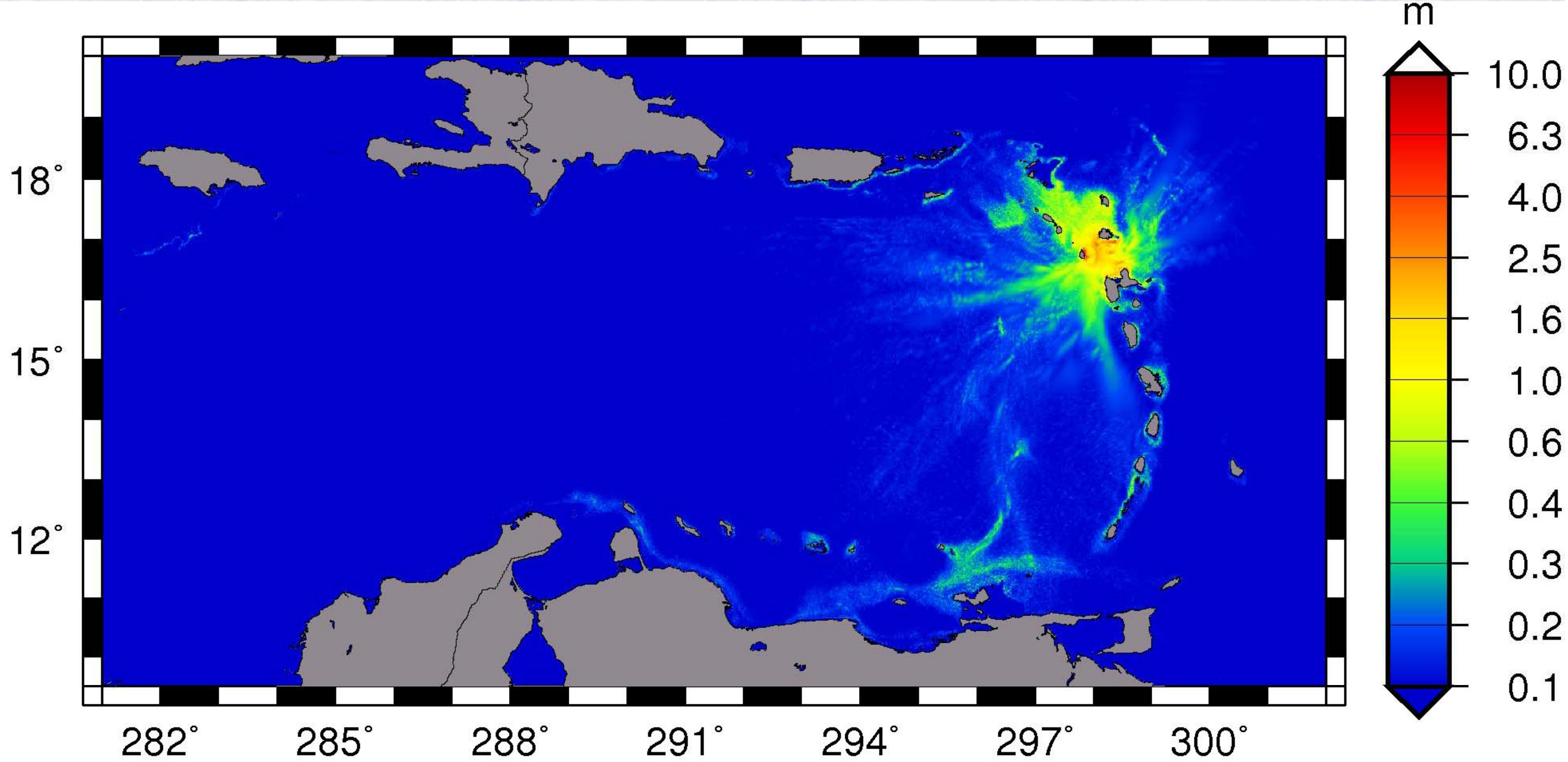
Tsunami simulation; St. Lucia slide



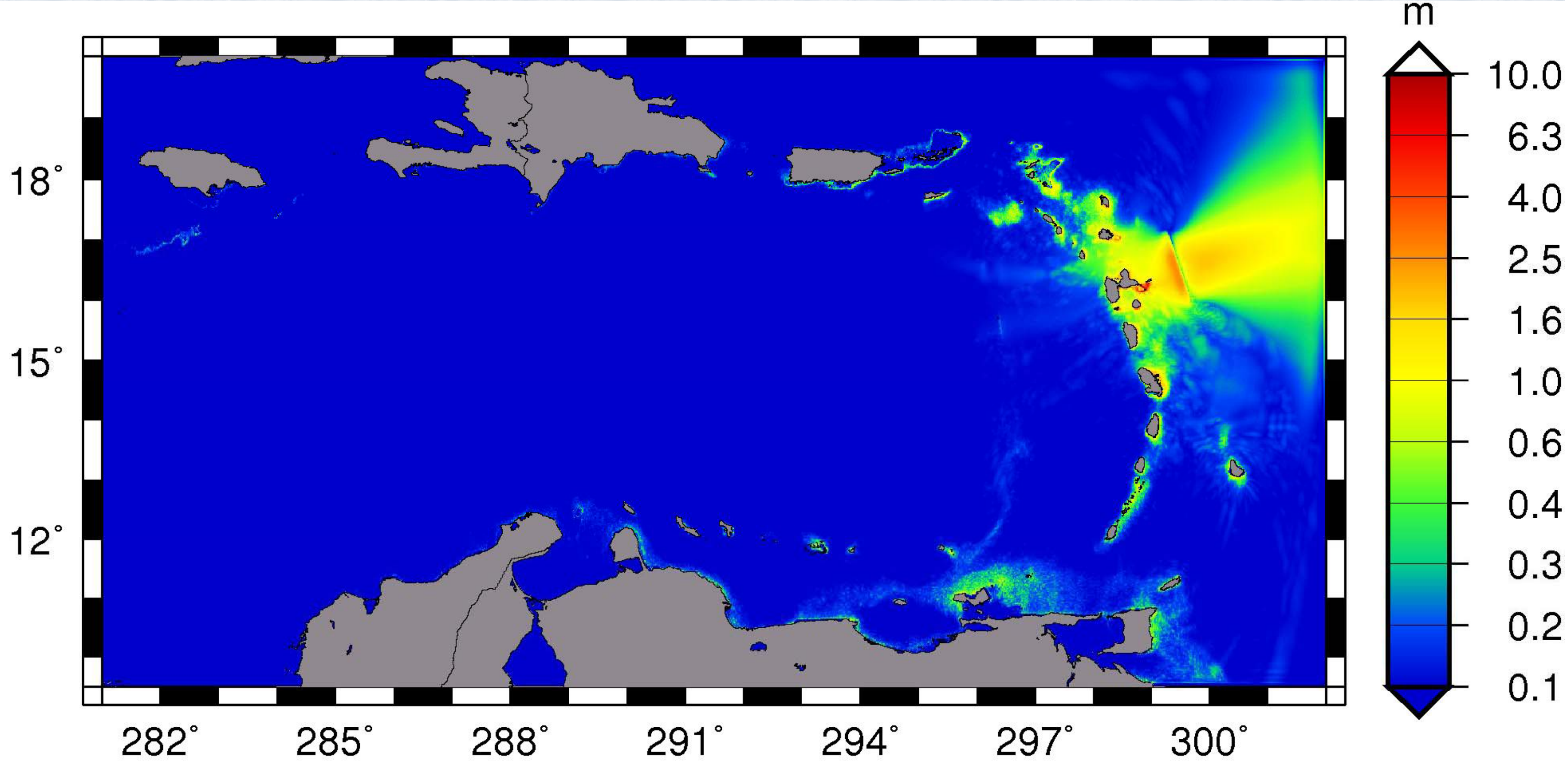
Tsunami simulation; Grenada slide



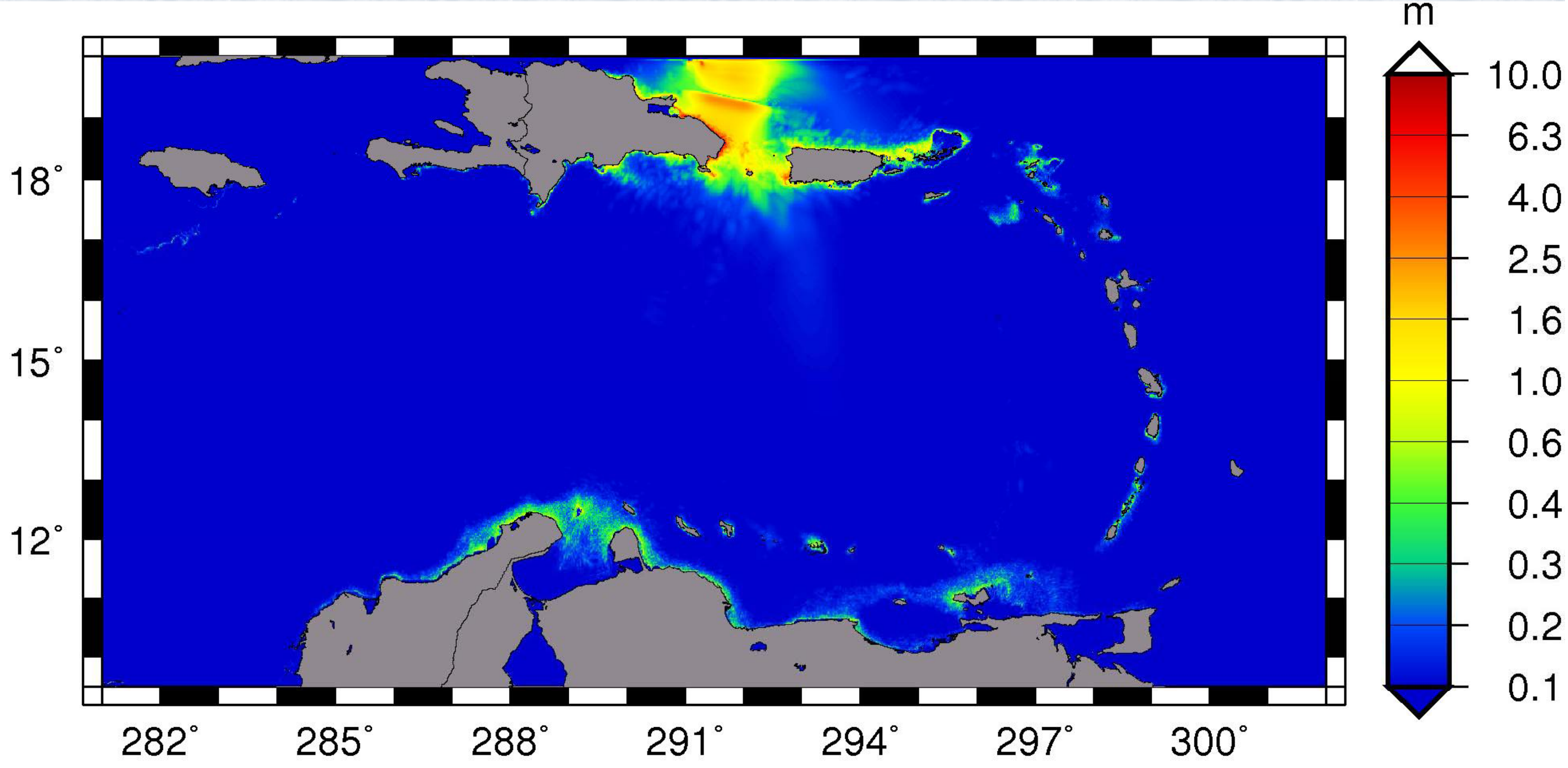
Tsunami simulation; Montserrat slide



Tsunami simulation; Lesser eq.



Tsunami simulation; Hispaniola eq.



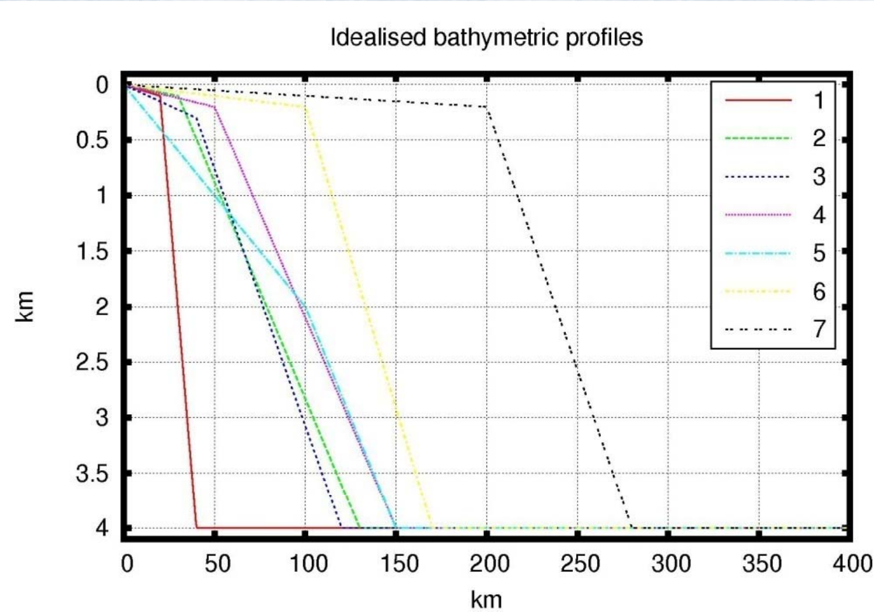
Method for run-up estimation

- We want to evaluate the surface elevation at several hundred locations
- Too time-consuming to do refined study with run-up models at each location
- Instead we apply *amplification factors* on the off-shore measured elevation to find the apporximate on-shore run-up

Amplification factors

Simulations along 1D profiles:

- Different idealized bathymetric profiles (see figure)
- Linear hydrostatic wave model (runup measured at shoreline)
- N-wave (sinus shaped)
    - Leading depression or leading elevation
- Different wave periodes
- Establish a set of amplification factors for different combinations of terrain and wave parameters



Run-up estimation

- At each gauge we determine
  - The scenario with highest maximum elevation
  - The period of incident wave (set manually)
  - The shape of the incident wave: Leading elevation or leading depression
  - Find the amplification factor based on the period, shape and the bathymetric profile

→ RUN-UP = max. elevation x amp. factor

Summary regional tsunami modeling

- A method for regional tsunami hazard assessment is presented
- Off-shore surface elevation is transformed into on-shore run-up by applying amplification factors
- Amplification factors
  - Based on bathymetric slope
  - Wave characteristics (shape and period)
- Method to be further improved and refined
- Run-up heights are successfully compared to refined numerical run-up modeling

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Regional tsunami exposure

- ”Risk = hazard x exposure x vulnerability”
- Separate evaluations for seismic and non-seismic sources due to different orders of return period magnitudes
- Trans-oceanic tsunamis not included
  - Extreme events have even longer return period
  - Longer warning time
- Adding 0.7 m for mean high tide
  - (and a little climatic sea level rise)

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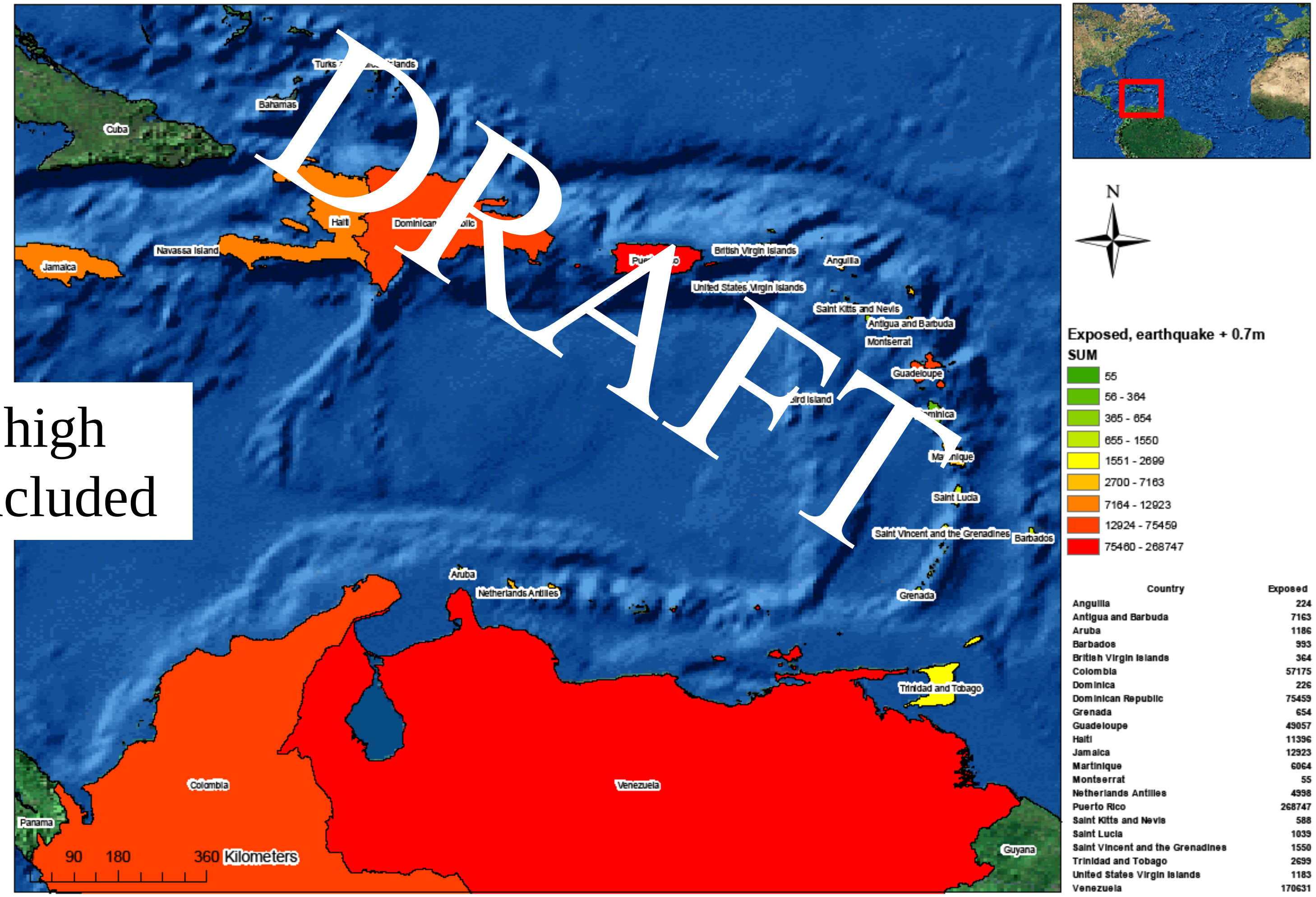
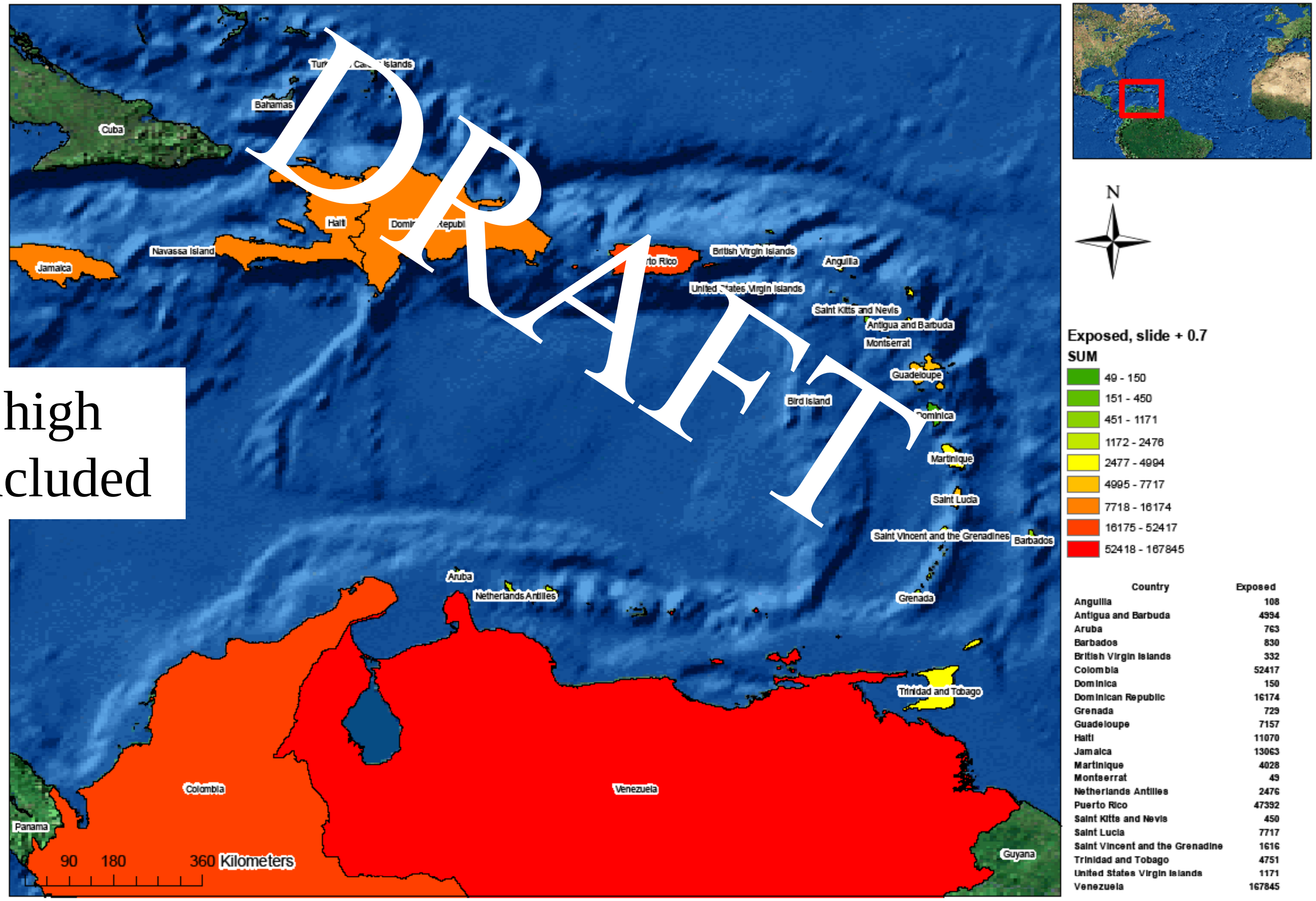
Regional exposure to seismic tsunamis



Country	Exposed
Anguilla	224
Antigua and Barbuda	7163
Aruba	1186
Barbados	993
British Virgin Islands	364
Colombia	57175
Dominica	226
Dominican Republic	75459
Grenada	654
Guadeloupe	49057
Haiti	11396
Jamaica	12923
Martinique	6064
Montserrat	55
Netherlands Antilles	4998
Puerto Rico	268747
Saint Kitts and Nevis	588
Saint Lucia	1039
Saint Vincent and the Grenadines	1550
Trinidad and Tobago	2699
United States Virgin Islands	1183
Venezuela	170631

Mean high tide included

Regional exposure to non-seismic tsunamis



Country	Exposed
Anguilla	108
Antigua and Barbuda	4994
Aruba	763
Barbados	830
British Virgin Islands	332
Colombia	52417
Dominica	150
Dominican Republic	16174
Grenada	729
Guadeloupe	7157
Haiti	11070
Jamaica	13063
Martinique	4028
Montserrat	49
Netherlands Antilles	2476
Puerto Rico	47392
Saint Kitts and Nevis	450
Saint Lucia	7717
Saint Vincent and the Grenadine	1616
Trinidad and Tobago	4751
United States Virgin Islands	1171
Venezuela	167845

Mean high tide included

Regional exposure to tsunamis, example seismic sources – Puerto Rico

Regional exposure to tsunamis, example non-seismic sources - St. Lucia

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Local tsunami run-up modelling; ComMIT/MOST

- NLSW equations
- Geographical coordinates
- Most common model for inundation/run-up modeling
- Require high-resolution grid
  - Nesting og grids, three levels
  - Run-up calculated on the finest grid

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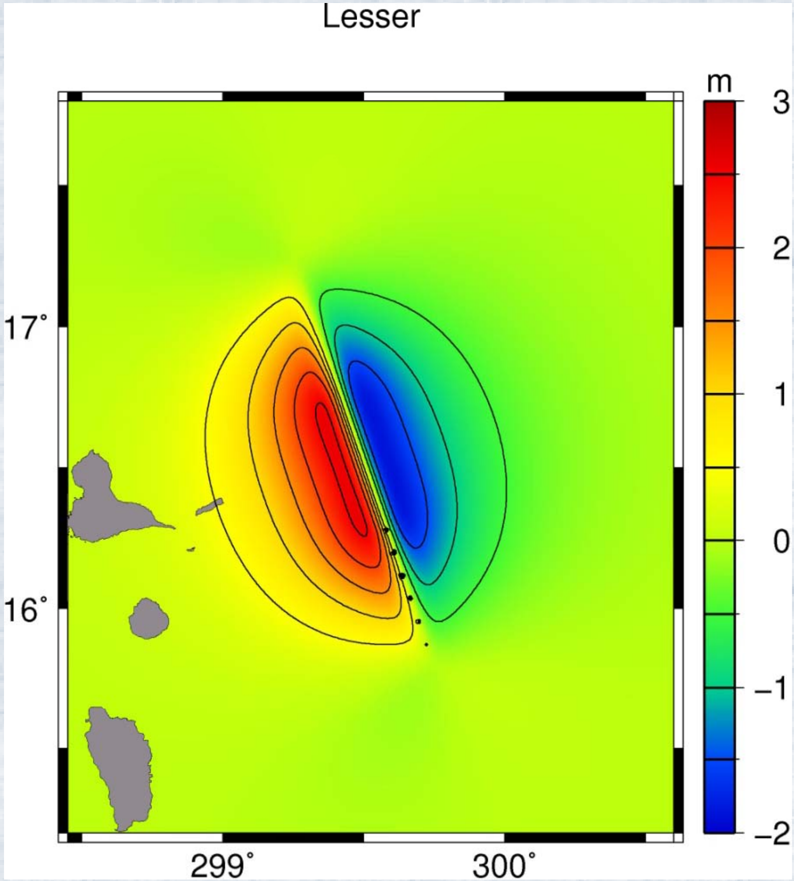
Coupling of models

- Own software established for producing inputfiles for ComMIT from tsunami propagation models
  - Propagation matrices for surface elevations and velocity
  - Whole fields stored at each timelevels (can be coarser both in time and space)
  - May now couple any tsunami model at NGI with ComMIT/MOST

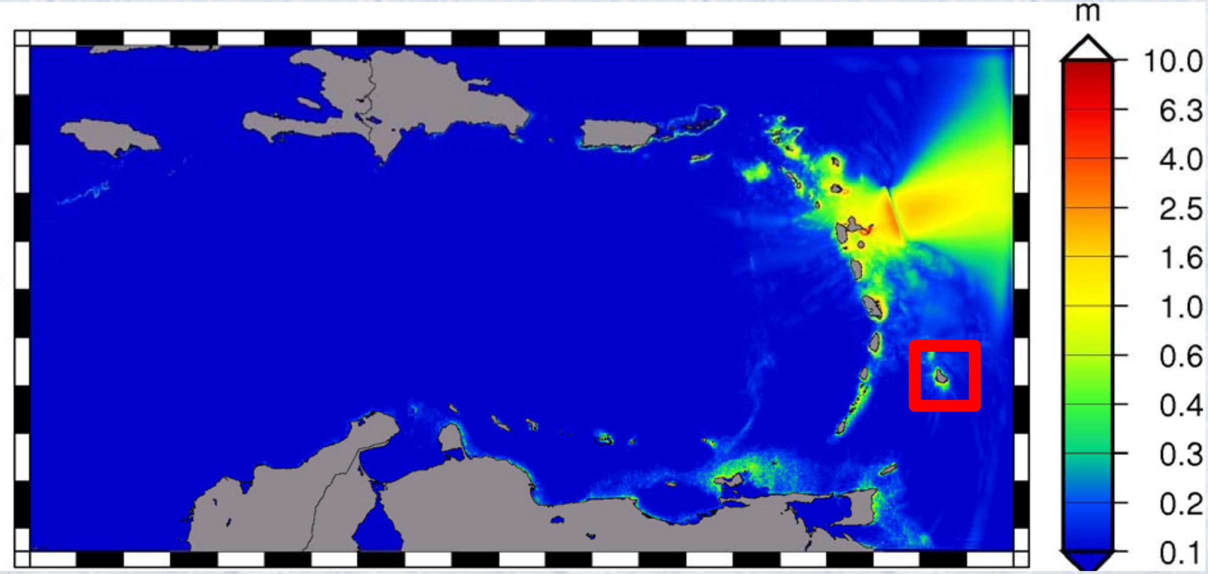
Run-up at Bridgetown; the tsunami scenario

- Mw 8.0 at Lesser Antilles (highest run-up at Bridgetown of the five scenarios)
- 3 segments, L=65 km, W=55 km,
  Slip = 6 m for central, 0-6 m for end segments
- Analytical Okada model (1992) applied to convert slip motions to seabed displacements



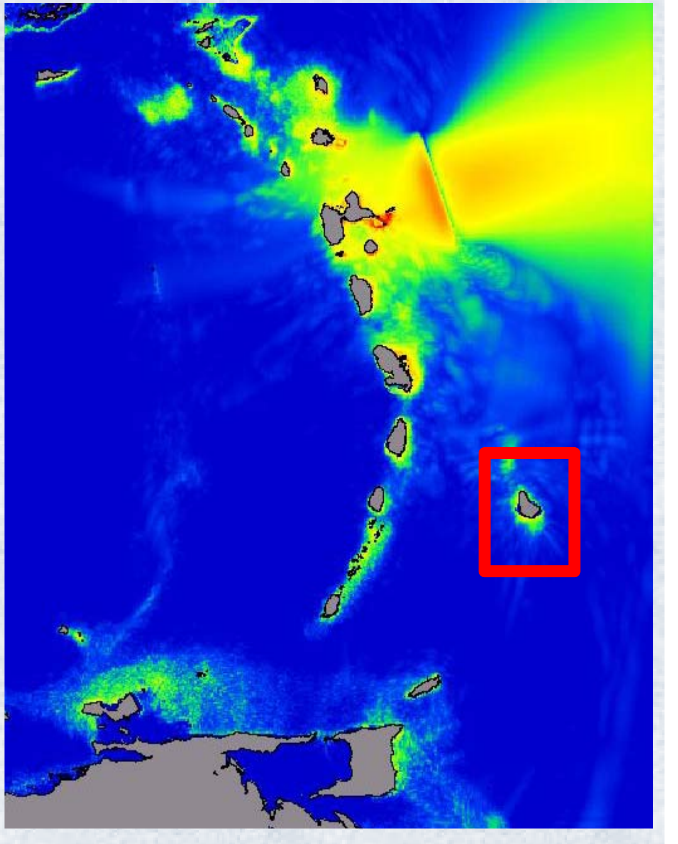
Tsunami simulation; Lesser earthquake

- Computational domain for the tsunami propagation phase
- Amplification of waves nearshore
- Minor effect of disperion



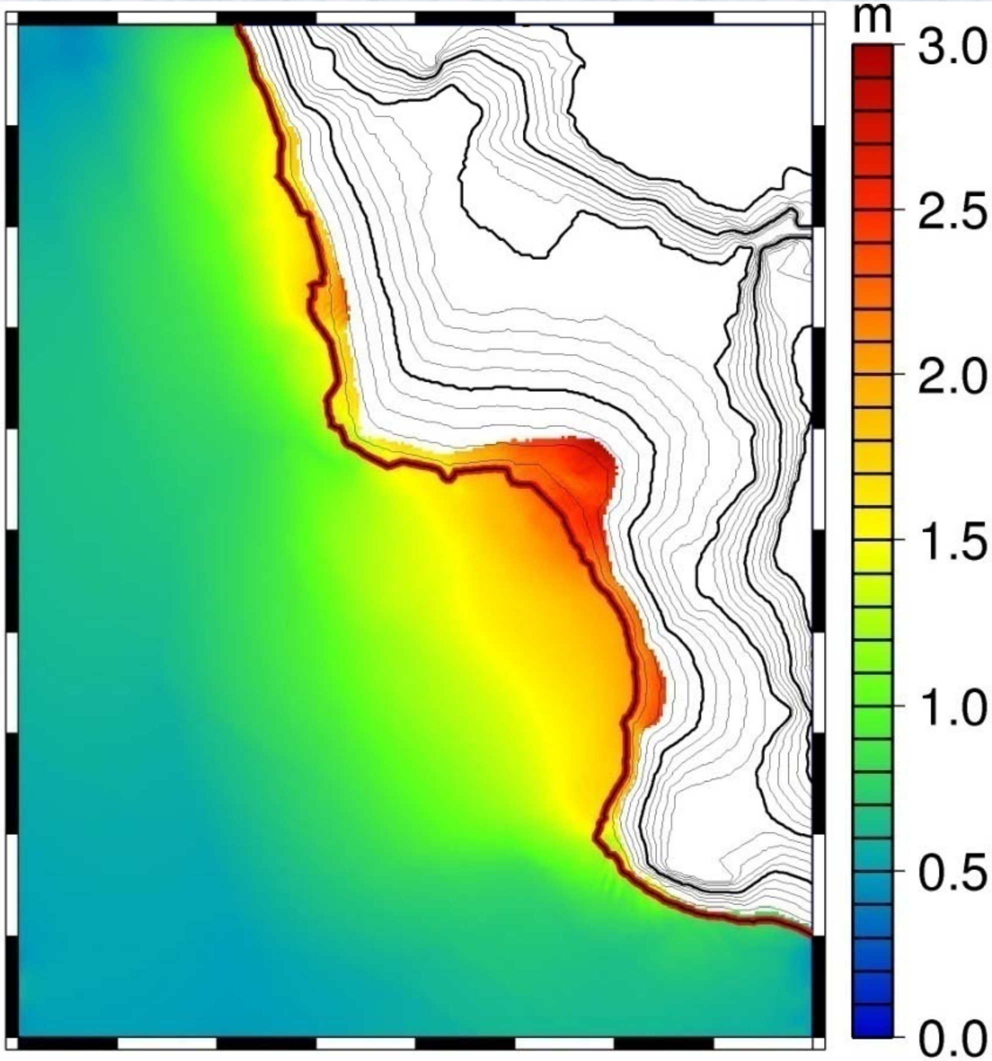
Input to ComMIT/MOST

- Values for surface elevation and velocities extracted from the tsunami propagation model
- Stored in netcdf-format
- High-resolution grid of Bridgetown



Maximum surface elevation

- Run-up 2-3 m
- Heighest run-up about 3 m
- Large local variations
- At the shoreline, maximum elevation 1.5 to 2.5 m



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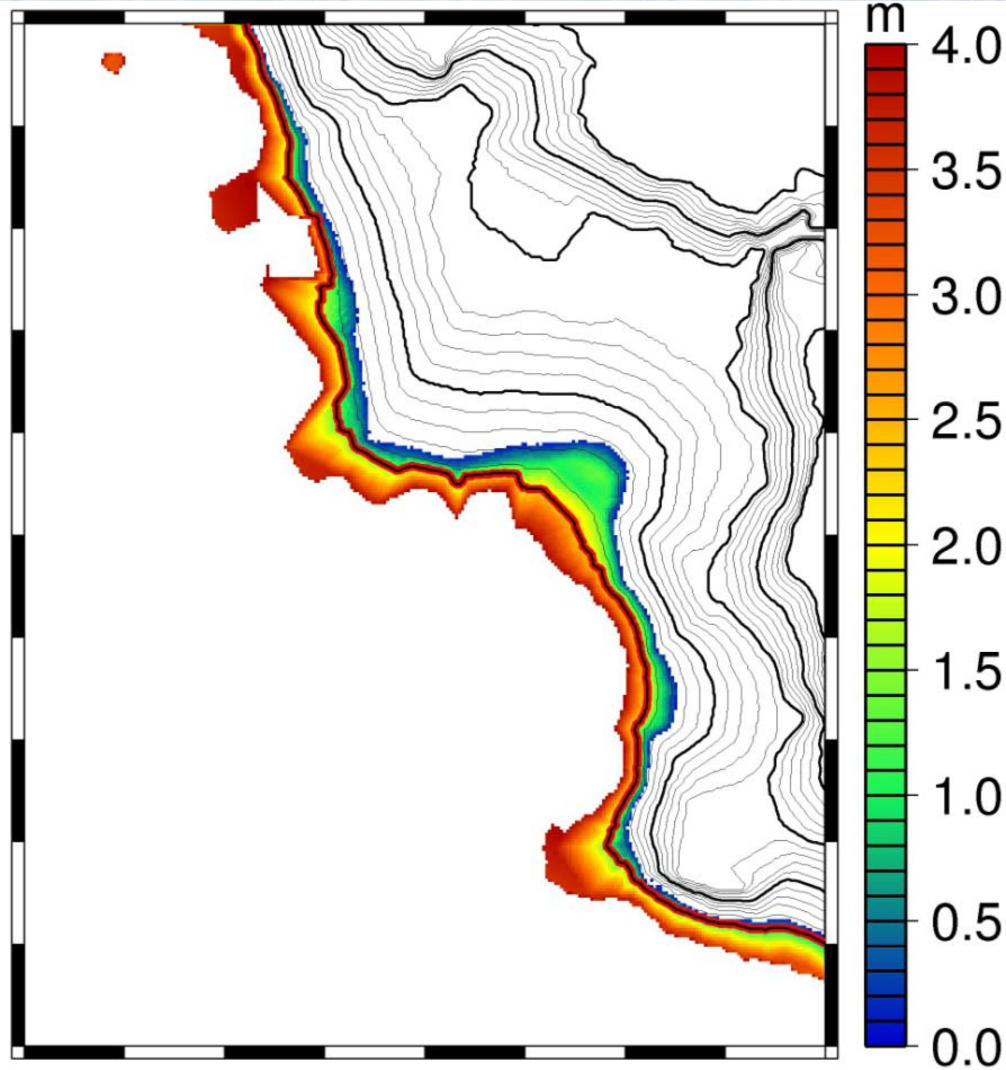
Maximum flowdepth

- Height of water above ground
- 2-2.5 m maximum flowdepth on shoreline



Summary; local run-up calculations

- The tsunami run-up from the Lesser earthquake scenario is evaluated
- Max run-up was calculated to approx. 3 m (high tide and sea-level rise; totally 0.7m above “Mean Lower Low Water” - MLLW)
- Large local variations

Local tsunami risk demonstration project for Bridgetown, Barbados

Tsunami hazard and risk maps

- For warning:
  - Inundation height
  - Highly populated / vulnerable areas
  - Critical facilities
  - Areas to be evacuated
  - Escape routes
  - Elevated / safe areas
  - Personnel to be warned
- For coping capacity (short term / long term)
  - Inundation height
  - Critical facilities
- For area planning:
  - Inundation height or momentum flux (loads – for design)
  - Previous events
  - Highly populated / vulnerable areas
- For risk comparison and preferences
  - Detailed
  - Quantitative
  - Preferably also economic losses

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- Risk = Hazard * Consequence
  - Hazard = maximum tsunami flow height related to a certain probability of occurrence
  - Consequence described by vulnerability and by density of population (exposure)
    - Vulnerability = 4 factors describing the buildings:
    - Height – material – barrier - use

Input data to produce consequence map

Dataset	**Datatype**	**Description**	**Origin**
Buildings	Polygon	Outline of all buildings	Official
BuildPoint	Point	Building centerpoins, derived from ”Buildings”	Derived
EnumDist	Polygon	Statistics for each enumeration district	Official
Study_Area	Polygon	Outline of the defined study area, below 10 meter a.s.l.	Digitized
BuildVul	Point	Vulnerability information of 1211 buildings within study area	Field work
Score	Table	Mapping table, giving the vulnerability score (1-4) for each of the four building factors: height, barrier, material, use	Nadia

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Mapping tables with vulnerability scores

HeightCode	HeightVulnerabilityScore	Description
1	4	Only one floor
2	2	2 floors
3	1	3 or more floors

BarrierCode	BarrierVulnerabilityScore	Description
1	4	No barrier
2	3	Low/narrow earth embankment
3	2	Low concrete wall
4	1	High concrete wall
5	2	Low stone wall
6	1	High stone wall

MaterialCode	MaterialVulnerabilityScore	Description
1	2	Stone
2	4	Wood or timber
3	3	Wood + concrete
4	1	Concrete
5	2	Metal
6	3	stone and wo
7	2	concrete/meta
8	3	concrete/ston

UseCode	UseVulnerabilityScore	Description
1	1	Residential/community service
2	3	Business/Commercial
3	4	Tourism
4	10	Government Services (Health, Education, Fisheries, transport
5	10	Emergency Services (Police, Fire,Coast Guard, EMS, medica
6	5	Community facilities (e.g. churches, community centers, recre
7	10	Utilities (water, electricity, sewage, telecommunications,fuel,
8	2	Heritage Sites
9	5	Banking and finance
10	0	Abandoned

Mapping ”subtables” for building use ’utilities’

UtilMatCode	UtilMatVulnerabilityScore	Description
2	3	Wood or timber
5	2	Metal
7	2	Concrete and Metal
4	1	Concrete

Mapping table for building material for utilities

UtilLocCode	UtilLocVulnerabilityScore	Description
1	3	Above ground
2	2	Both above ground and below
3	1	Underground

Mapping table for building location for utilities

UtilBarCode	UtilBarVulnerabilityScore	Description
1	4	No barrier
2	3	Low/narrow earth embankment
3	2	Low concrete wall
4	1	High concrete wall
5	2	Low stone wall
6	1	High stone wall

Mapping table for building barrier for utilities

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Problems encountered

- Buildings neither randomly selected nor randomly distributed
  - distribution of buildings not ”statistically correct”
  - Need to “extrapolate” information
- No link between surveyed buildings (GPS positioned) and ”official building outlines”

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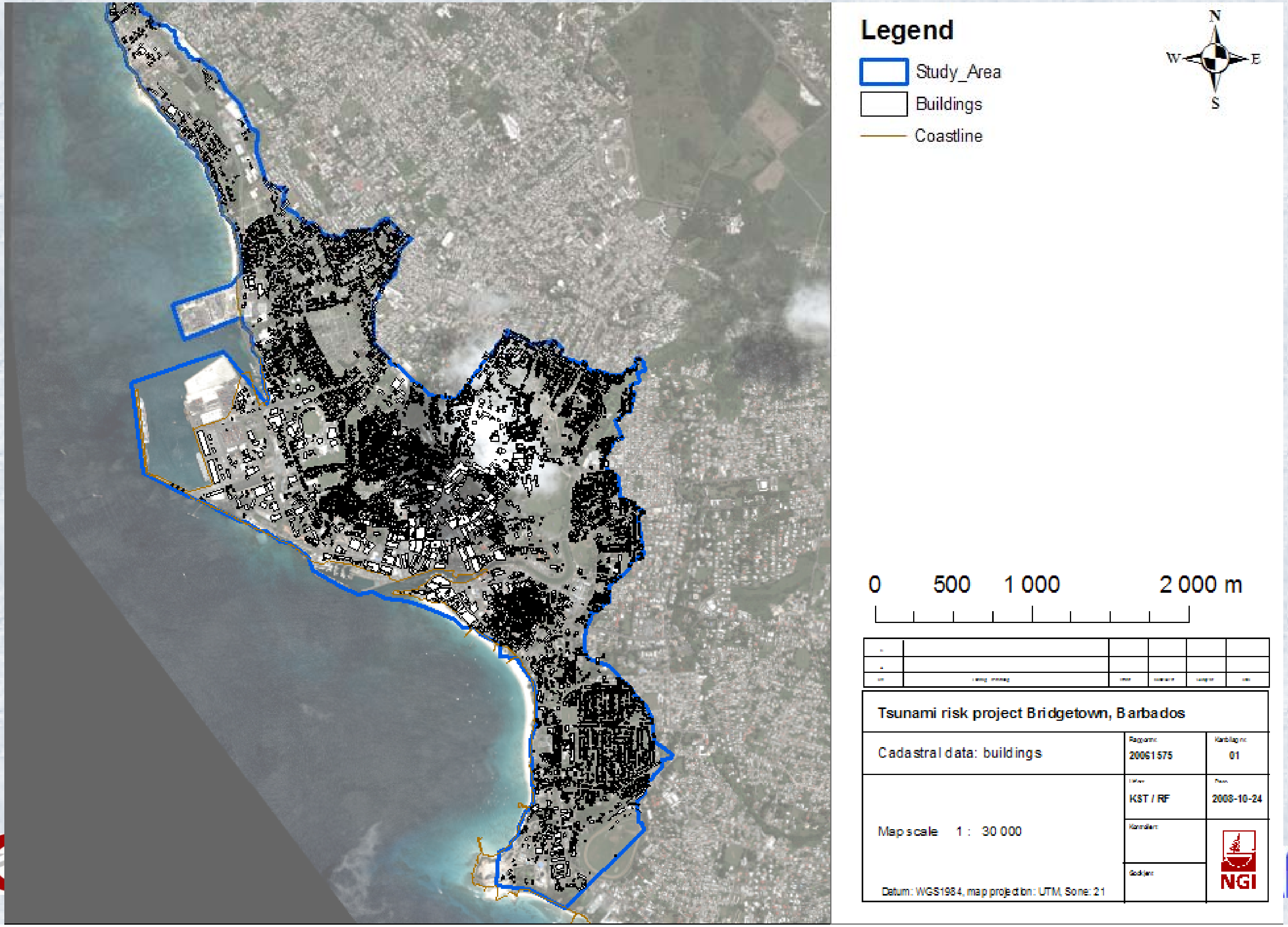
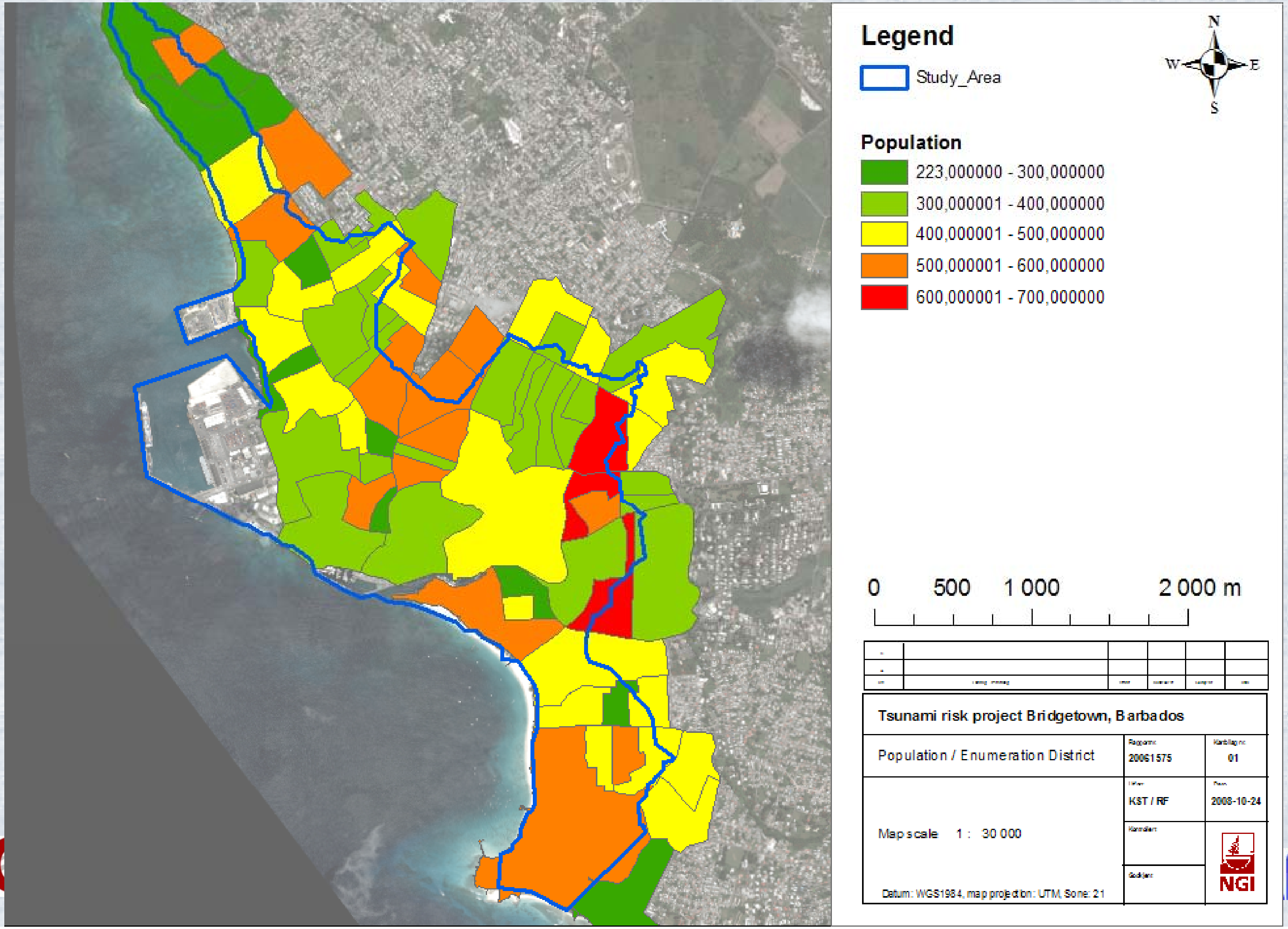
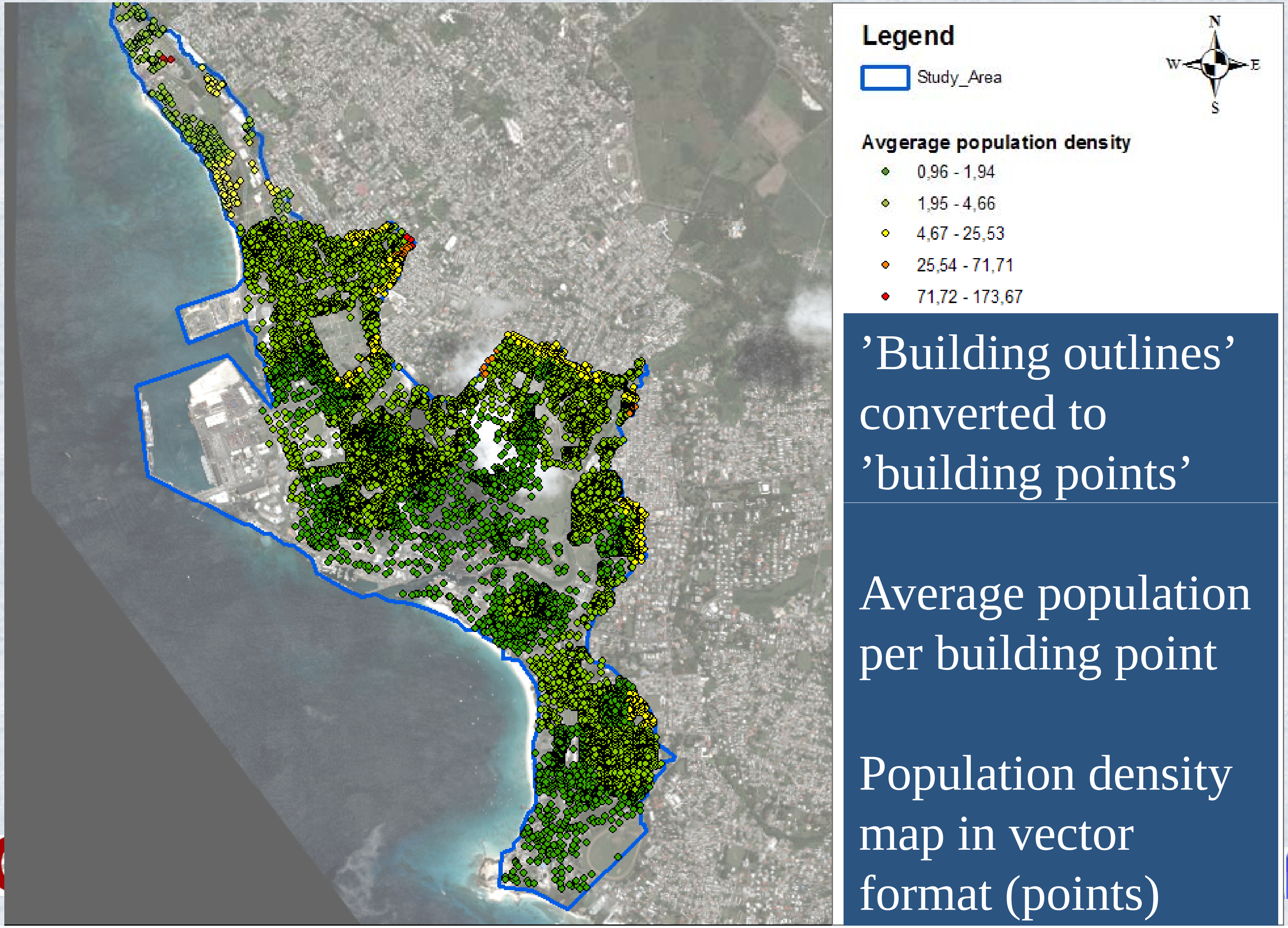
Generation of population density map



Generation of population density map



Generation of population density map

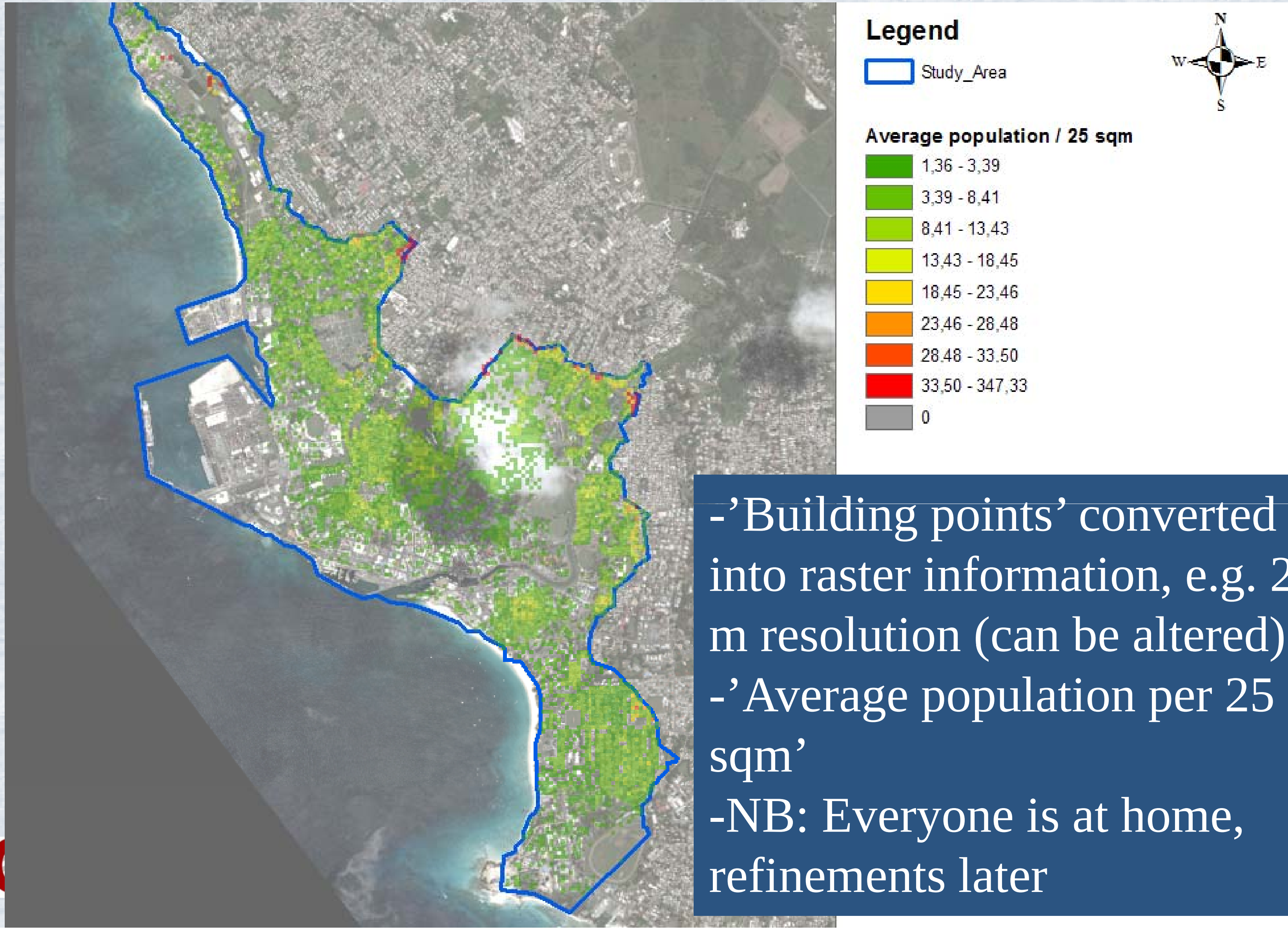


’Building outlines’ converted to ’building points’

Average population per building point

Population density map in vector format (points)

Final product: population density map



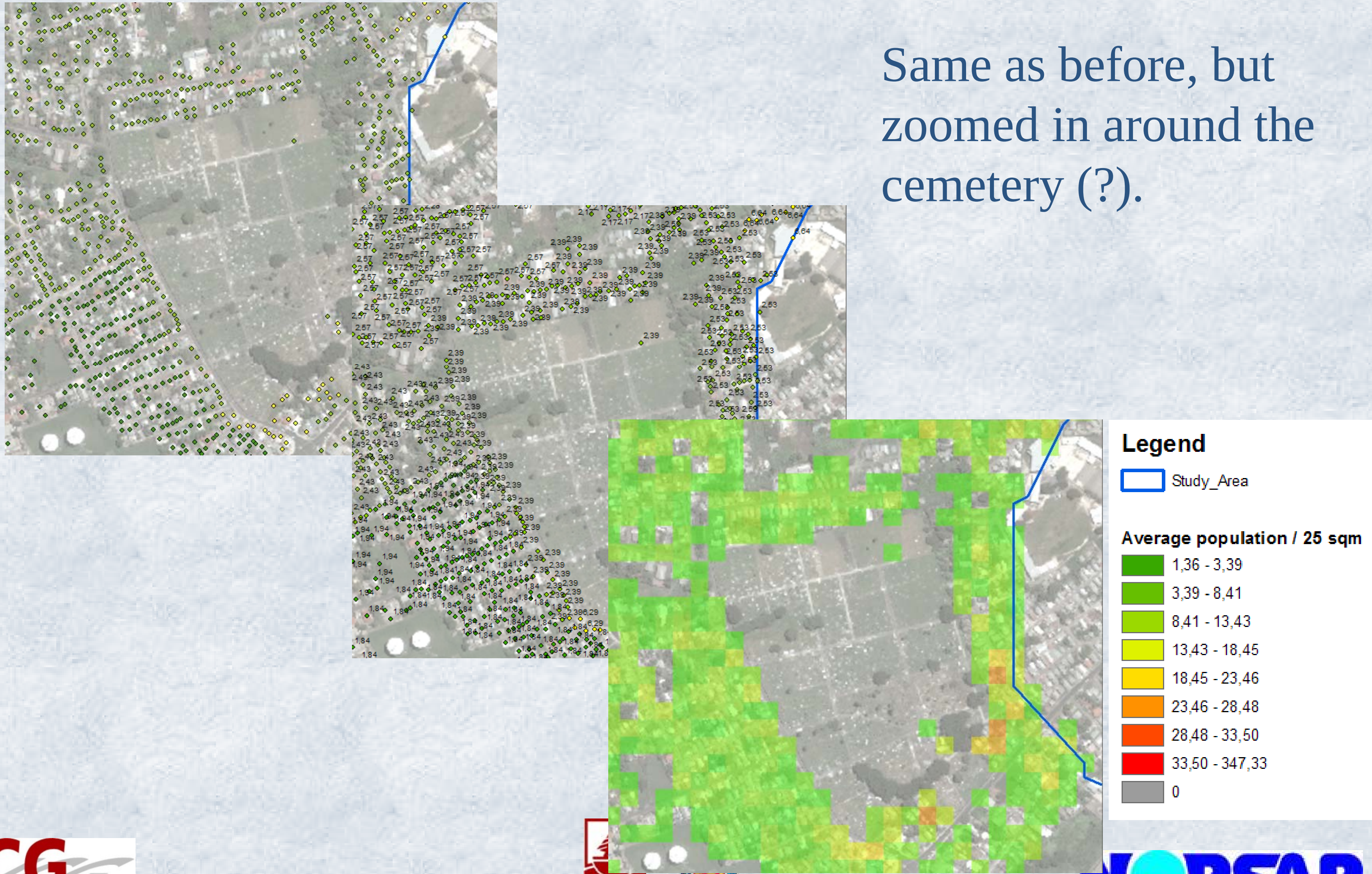
-’Building points’ converted into raster information, e.g. 25 m resolution (can be altered)

-’Average population per 25 sqm’

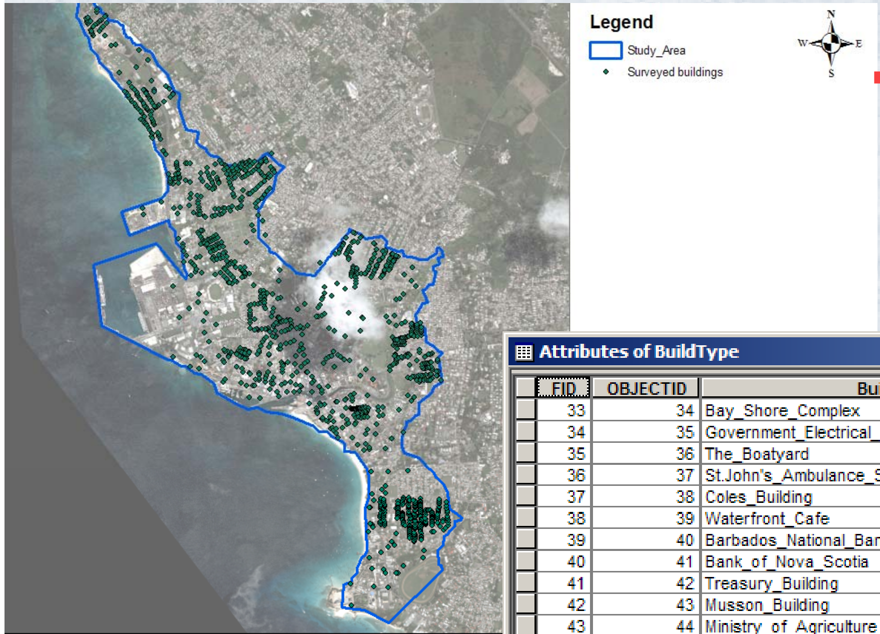
-NB: Everyone is at home, refinements later

Population density map (zoom-in)

Same as before, but zoomed in around the cemetery (?).



Generation of coping capacity map



Building use	Code
Residential/community service	1
Business/Commercial	2
Tourism	3
Government Services (Health, Education, Fisheries, Transportation, etc.)[1]	4
Emergency Services (Police, Fire,Coast Guard, EMS, medical etc.)	5
Community facilities (e.g. churches, community centers, recreational areas)[2]	6
Utilities (water, electricity, sewage, telecommunications, fuel, gas stations)[7]	7
Heritage Sites[3]	8
Banking and finance	9
Abandoned[4]	1[illegible]

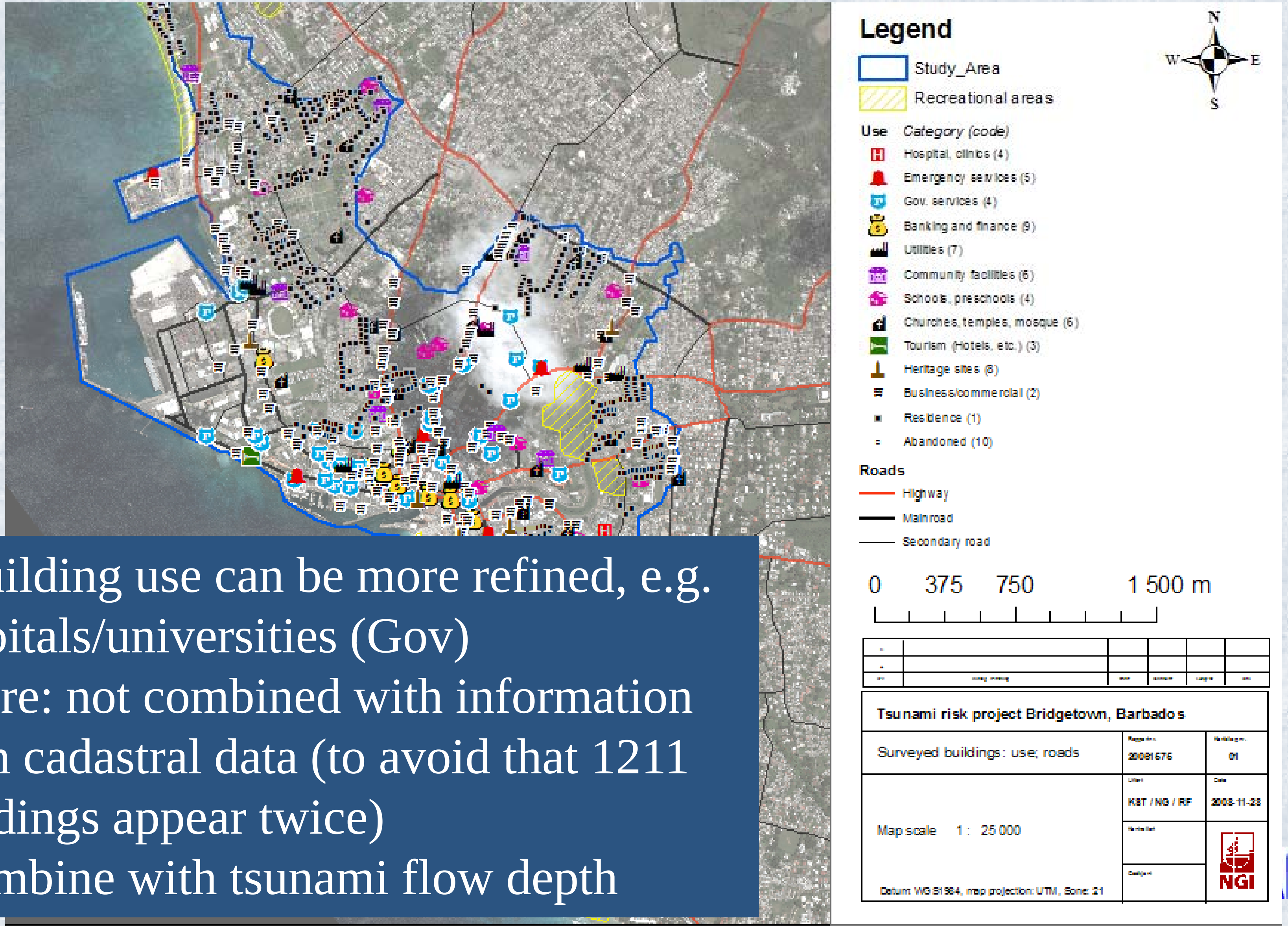
Attributes of BuildType

FID	OBJECTID	Building_N	N	E	Use	Comments
33	34	Bay_Shore_Complex	216705	1448933	2	
34	35	Government_Electrical_Engineering_Department	216722	1448945	4	
35	36	The_Boatyard	216735	1448919	2	
36	37	St.John's_Ambulance_Services	216755	1448937	5	
37	38	Coles_Building	216665	1449009	4	School_meals_dept/Barbados_Light_and_Po
38	39	Waterfront_Cafe	216505	1449171	2	
39	40	Barbados_National_Bank	216650	1449167	9	
40	41	Bank_of_Nova_Scotia	216650	1449167	9	
41	42	Treasury_Building	216622	1449272	4	Government_Departments
42	43	Musson_Building	215976	1449344	4	Ministry_of_Finance_and_Economic_Affairs
43	44	Ministry_of_Agriculture_Fisheries_Division	215917	1449344	4	
44	45	Barbados_Agricultural_Development_and_Marketing	215863	1449369	4	
45	46	Bridgetown_Fish_Complex	215695	1449375	4	
46	47	Pelican_Village	215468	1449497	3	
47	48	Port_of_Barbados	215228	1449612	4	
48	49	Bico_Ice_Cream_factory	215289	1449976	2	
49	50	Port_Authority_Headquarters	215226	1450269	4	
50	51	Atlantis_Submarines	215330	1450497	2	
51	52	Central_Purchasing_Department	215399	1450377	4	
52	53	Barbados_Coast_Guard_services	214941	1451002	5	
65	66	Berger_Paints_Limited	215299	1451016	2	

Record: 0 Show: All Selected Records (0 out of 1211 Selected) Options

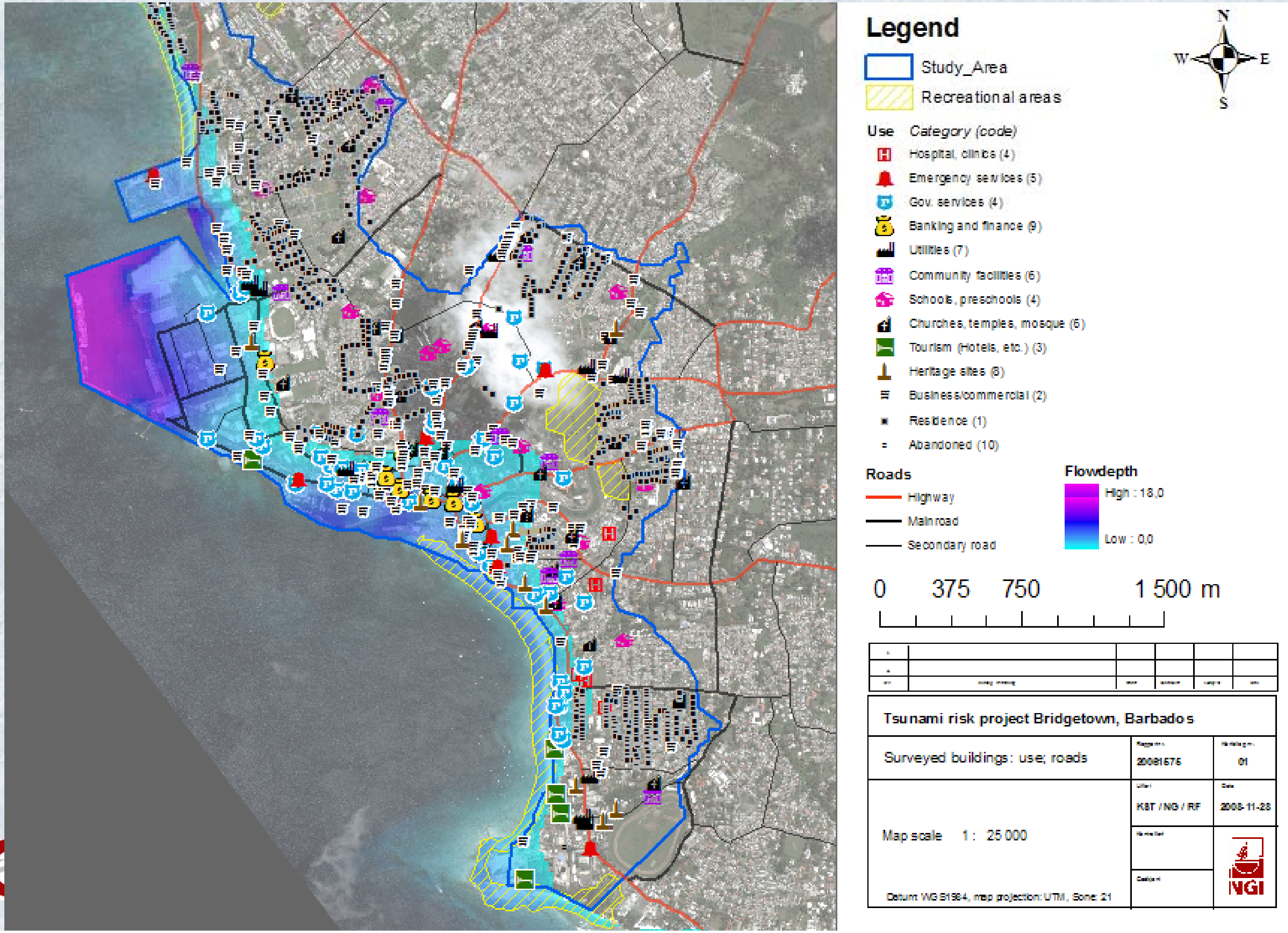
-1211 buildings surveyed by Nadia Gour, among others: ’use’
-10 ’ use categories’
- and recreational areas (beaches, parks) are category 11

Side-product: critical facility map (for 1211 surveyed buildings)

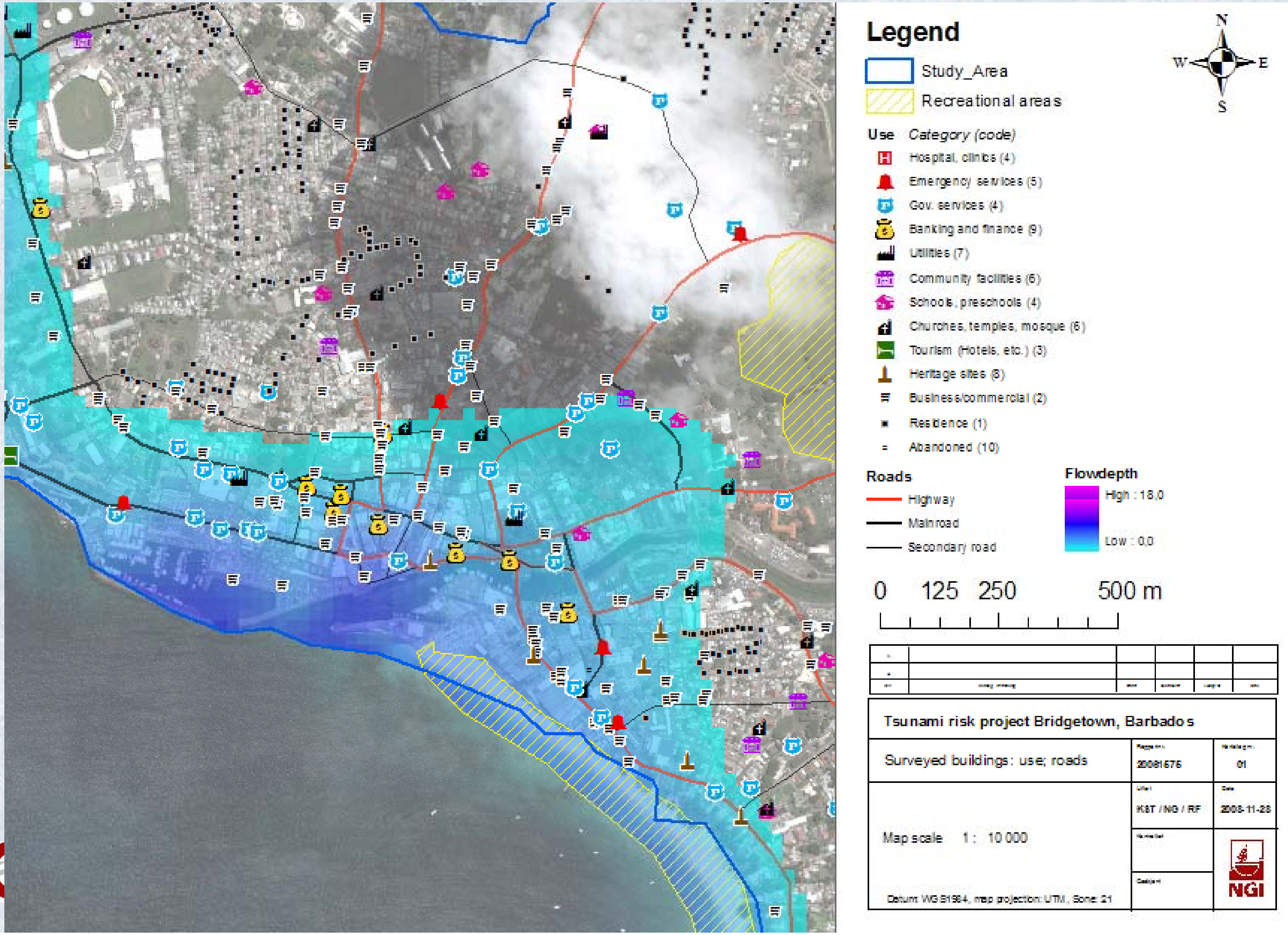


-'Building use can be more refined, e.g. hospitals/universities (Gov)
- Here: not combined with information from cadastral data (to avoid that 1211 buildings appear twice)
- combine with tsunami flow depth

“Final side product”: coping capacity map



“Final side product”: coping capacity map (zoom-in)



“Final side product”: coping capacity map

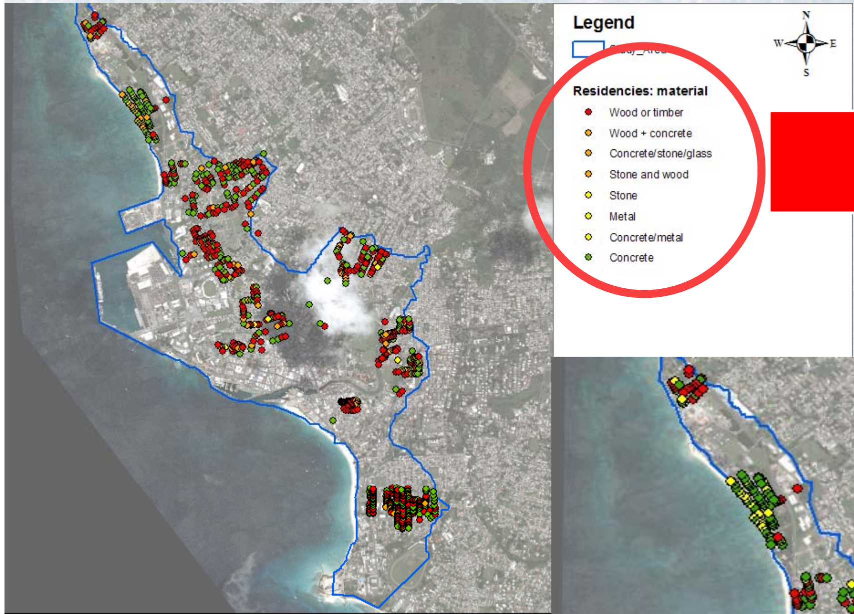
- Result for scenario “High-water plus Tsunami wave”:
  - Banking & finance sector would be considerably affected
    (8 out of 8 surveyed banking & finance buildings would be affected)
  - Emergency services would be considerably affected
    (4 out of 7 surveyed emergency services would be affected)
  - This does, however, not include hospital and clinics, as they are treated as an own subclass in this example
  - Commercial sector in city centre (around river mouth) would be considerably affected
  - Coastal road would be unserviceable within almost entire study area
  - Tourism would be considerably affected, because harbour, beaches, and many heritage sites would be affected

Coping capacity map: possible refinements

		Critical Facility Maps[12]	
Building use	Code	Short term/acute	Long term[14]
Residential/community service	1	1,00	1,00
Business/Commercial	2	1,00	1,00
Tourism	3	1,00	1,50
Government Services (Health, Education, Fisheries, Transportation, etc.)[1]	4	1,50	1,50 [11]
Emergency Services (Police, Fire,Coast Guard, EMS, medical etc.)	5	1,50	1,00
Community facilities (e.g. churches, community centers, recreational areas)[2]	6	1,5 [2]	1,00
Utilities (water, electricity, sewage, telecommunications, fuel, gas stations)[7]	7	1,50	1,00
Heritage Sites[3]	8	1,00	1,00
Banking and finance	9	1,00	1,50
Abandoned[4]	10	1,00	1,00
Open/public areas, streets, beaches[5,6]	11	1 or 1,5 [13]	1,00
Total			

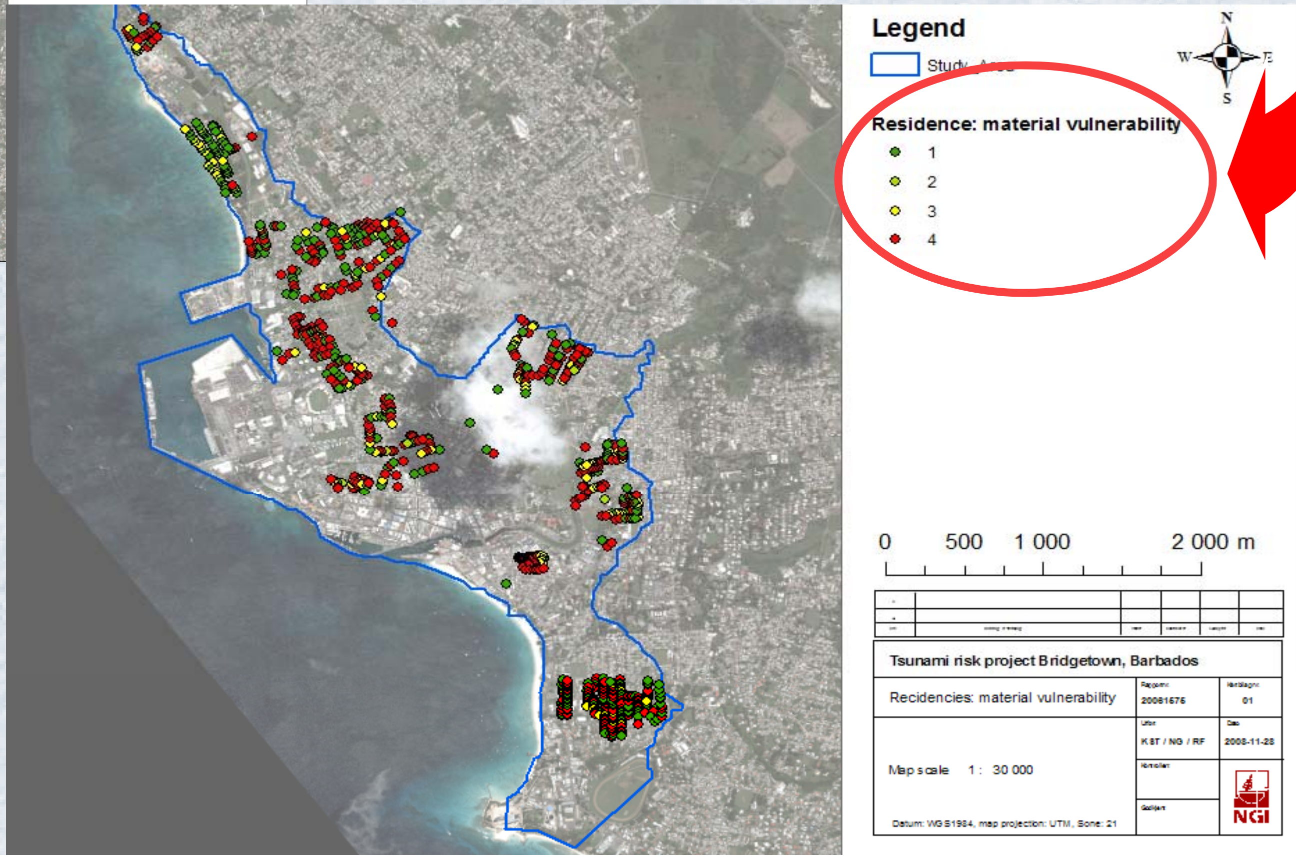
ICG NGI NORSAR

Generation of vulnerability map

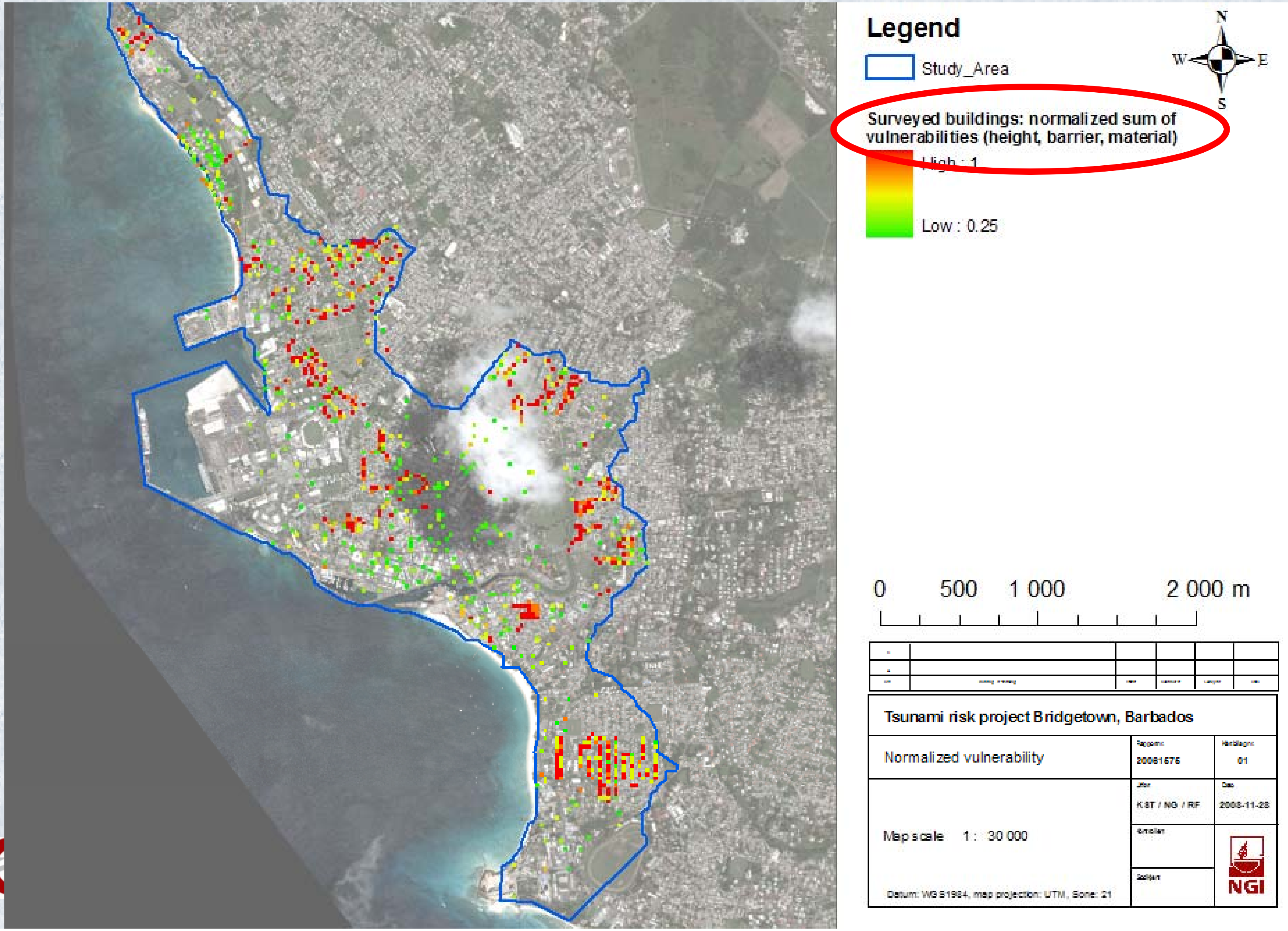


MaterialCode	MaterialVulnerabilityScore	Description
1	2	Stone
2	4	Wood or timber
3	3	Wood + concrete
4	1	Concrete
5	2	Metal
6	3	stone and wood
7	2	concrete/metal
8	3	concrete/stone/glass

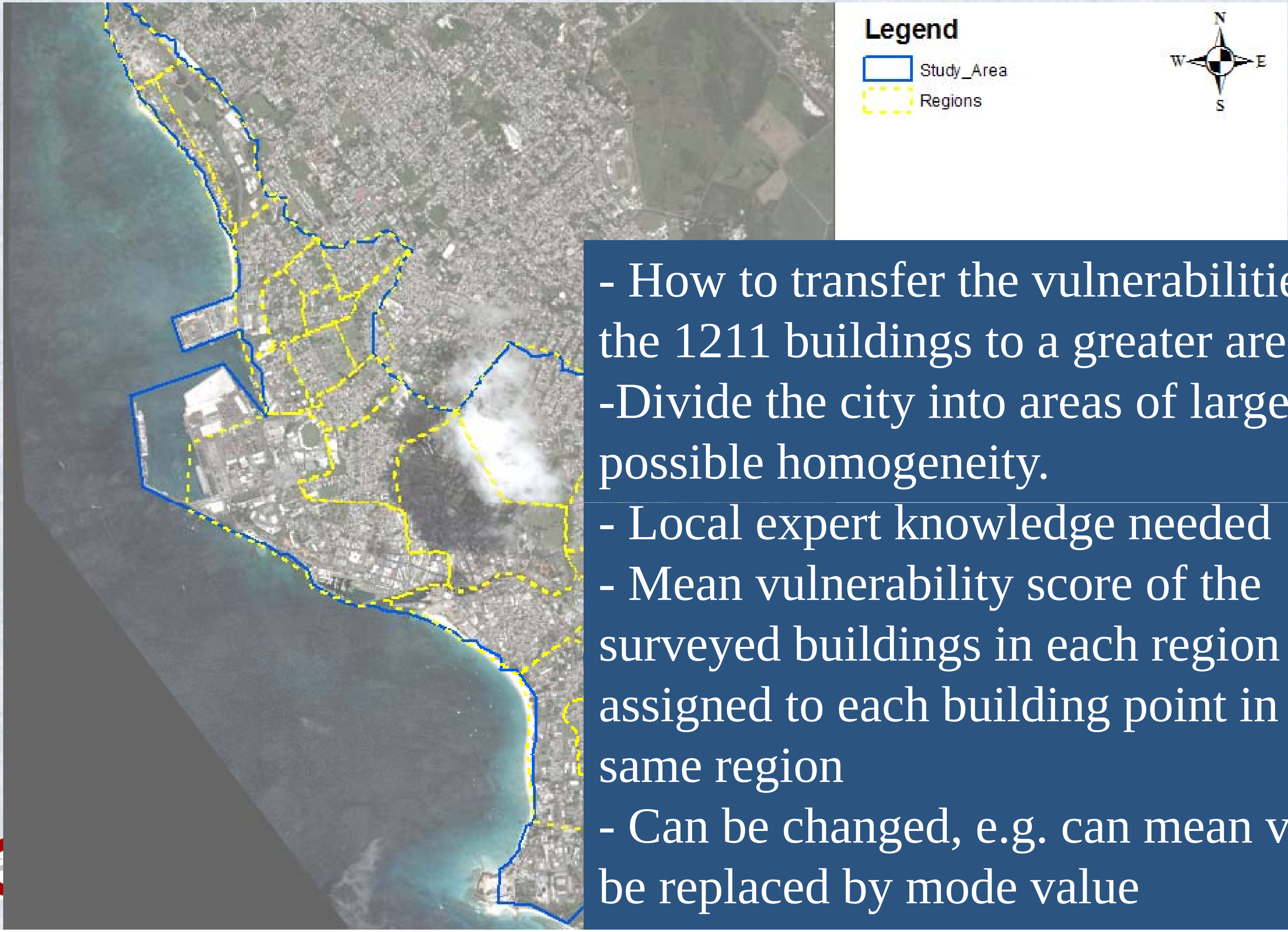
Mapping table for building material



Generation of vulnerability map

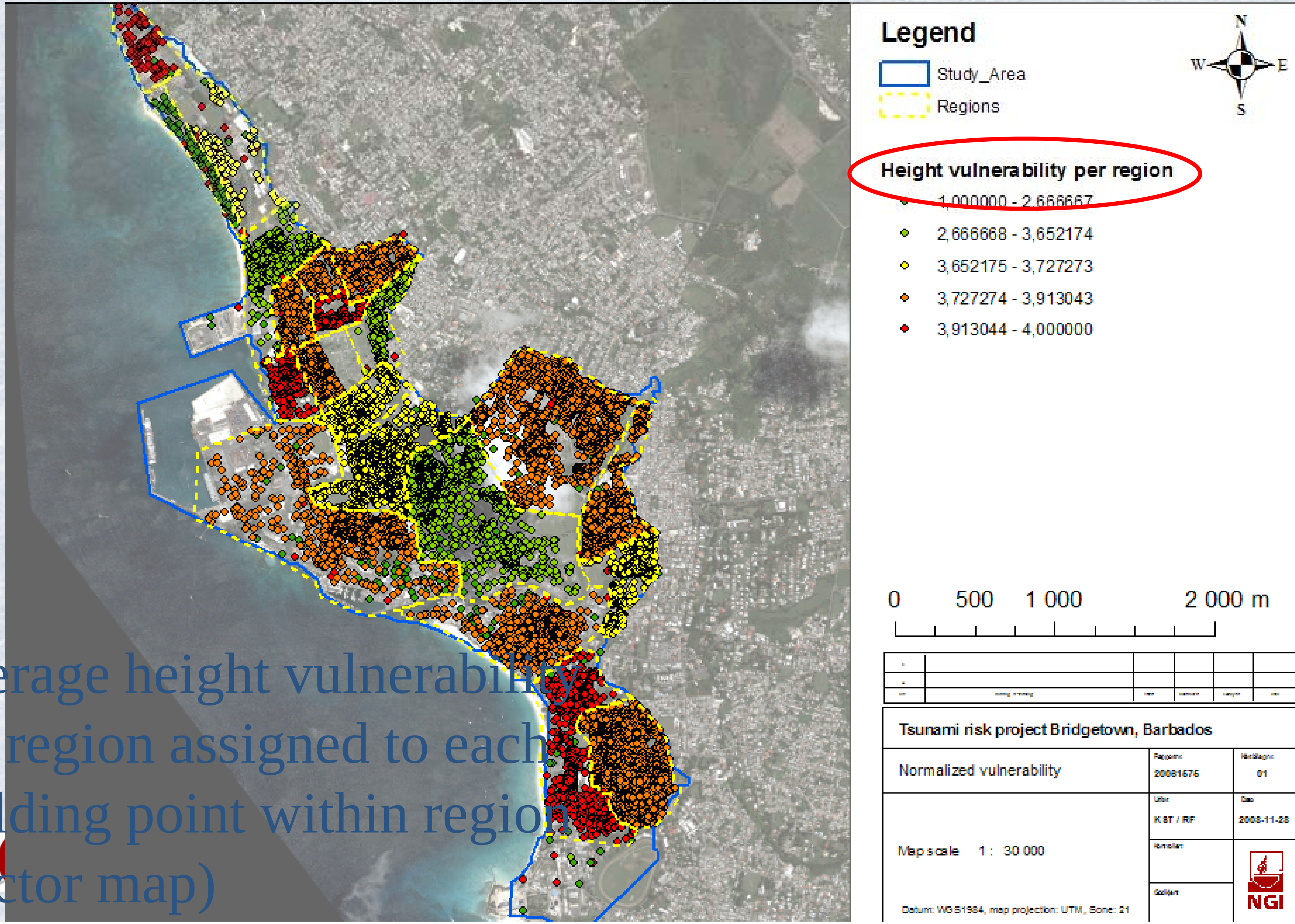


Generation of vulnerability map



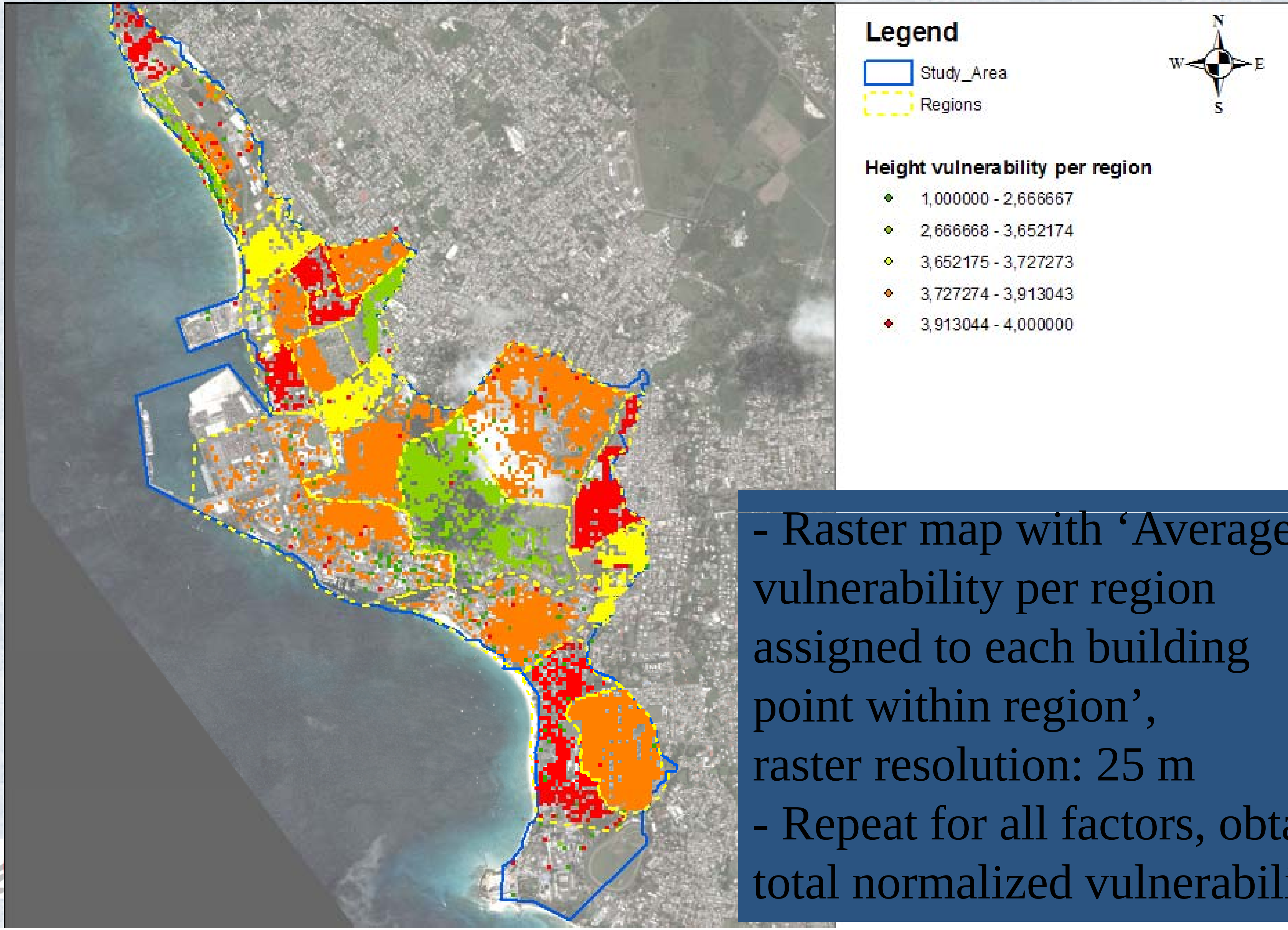
- How to transfer the vulnerabilities of the 1211 buildings to a greater area?
-Divide the city into areas of largest possible homogeneity.
- Local expert knowledge needed
- Mean vulnerability score of the surveyed buildings in each region is assigned to each building point in the same region
- Can be changed, e.g. can mean value be replaced by mode value

Generation of vulnerability map



Average height vulnerability per region assigned to each building point within region (vector map)

Generation of vulnerability map



- Raster map with ‘Average vulnerability per region assigned to each building point within region’, raster resolution: 25 m
- Repeat for all factors, obtain total normalized vulnerability

Last worksteps

- Combination of mortality with vulnerability
- Inclusion of day/night exposure
- Consideration of recreational areas

Other considerations:

- **Need to normalise vulnerabilities?**
- **We may lose higher risk scenarios**
  - Smaller, but more frequent
- **Vulnerability also depends on:**
  - Education, knowledge, awareness
  - TEWS
  - Other mitigation measures
    - evacuation plans and routes
    - safe elevated areas
    - barriers, ...
  - Age of population
  - Differences in night and day use of buildings, etc**.**
  - **....**
- **Other risk than mortality not considered**
  - Economic loss
  - Ecological
  - Reputation
- **Perceived risk**
- ....

Lessons learned

- Use 'building ID' rather than GPS position
  - Avoid all complicated transfer of information from surveyed buildings to mapped buildings
- Nothing impossible!
  - Local institutions / contacts (Cave Hill, CZMU, SRU)
  - A skilled student (or 10)
  - External (?) tsunami and GIS expertise