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Handbook of Tsunami Hazard and Damage Scenarios

SCHEMA (Scenarios for Hazard-induced Emergencies Management), Project n° 030963, Specific Targeted Research Project, Space Priority

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Executive Summary

The handbook on tsunami scenarios is the result of an intense work performed under the European FP6 co-funded project SCHEMA in a 39 month period from 2007 to 2010 by a Consortium of 11 partners led by Geosciences Consultants (Paris).

The handbook is one of the products of the project and has been conceived to illustrate the basic concepts and methods elaborated and applied in the project to produce tsunami scenarios in view of providing tools to assess tsunami hazard and potential damage. One of the main objectives was the elaboration of a general methodology that can be used in all possible cases and that can be easily adapted to the needs of the end users, i.e. chiefly the public administrators responsible for planning of the coastal zone development and protection strategies as well as people and organisations involved in disasters management and mitigation policies. For these reasons, the SCHEMA methodology has been applied to five test sites (Rabat, Morocco; Setúbal, Portugal; Mandelieu, France; Catania, Italy; Balchik, Bulgaria) differing very much from one another, and it has been tested with the active involvement of the end users, so ensuring that it will provide practical and useful tools and it is flexible enough to cover local needs.

The handbook first defines what is meant by tsunami hazard scenario and by tsunami damage scenario, as well as the concept of the worst-case credible scenario. This latter is a key-point in the handbook because the choice of the SCHEMA consortium was to adopt the approach of the worst-case credible scenario rather than of scenarios deriving from probabilistic analyses, since it is believed that there are no sufficient knowledge and data at present to assess return time probabilities of tsunamis and consequently to build on it the corresponding probabilistic scenarios.

The methodology, briefly outlined in chapter 3, consists of three main phases, in turn embracing more sub-phases or steps: namely 1) elaboration of a set of tsunami hazard scenarios for each test site (also referred to as target area), scenarios that are combined together in a single aggregated scenario; 2) vulnerability analysis of exposed elements based on earth observation data (collected through field survey and interpretation of satellite images); 3) development of tsunami damage scenarios. Phase 1 is described in detail in chapter 4, while phases 2 and 3 are illustrated in chapter 5.

This handbook has the purpose to highlight the SCHEMA approach to the tsunami scenarios and is deliberately short and synthetic. All the details on the methods and on their application can be found in the very many and lengthy documents (deliverables) produced by the consortium during the lifetime of the project. Here only the main concepts are given and are illustrated by a number of examples taken from the work performed by the partners of the consortium.

The final chapter of the handbook looks at the future, mainly emphasising the future challenges and how the methodology can be improved to tackle them. In this context the main subject is the multi-hazard, or in other words, how scenarios can be built to cover not only tsunamis, but also other dangerous phenomena. The challenge is open in the sense i) that there is already a vast acknowledgment that this is a serious and mature problem and ii) that at the same time no general way has been yet established to handle it. We expect that important developments will be made in the next years. .

1 Introduction

This handbook is one of the products of the project SCHEMA (see objectives and partners in annexes A and B; see also Annex C). It describes the methodology that was devised by the project partners to build scenarios of tsunami hazard and of tsunami damage and further helps define terms and concepts in a field that lacks of standards and of agreed terminology. The handbook is mainly addressed to the local administrators, responsible for public safety and for land management and planning, who need to assess tsunami hazard and risk and to use tools such as tsunami inundation and damage maps. It is believed that they will take advantage from knowing the methods and criteria on which the maps are built and from a clear definition of the involved terms and concepts, since this will allow them to fully exploit products and tools concerning tsunami impact. The handbook, though covering issues with a specific and technical content, is written as much as possible in a plane language, avoiding mathematical and numerical details and sophistications that could make reading difficult and hard. Such details are fully given in the technical reports produced by the project. Indeed, the handbook privileges the exposition of concepts and ideas and is rich of examples that are taken from the work and results that have been achieved by the partners of SCHEMA.

The handbook structure contemplates a chapter introducing the basic concepts of the tsunami hazard and damage scenarios, where among others, it is explained why the SCHEMA consortium has substantially preferred the approach based on deterministic credible worst-case scenarios on other possible approaches based on probability theory computations. In the following two chapters the various steps involved in computing scenarios for tsunami hazard and scenarios for tsunami damage are described in detail, by making recourse to examples taken from the studies performed by the partners of the project. In this context, the assessment of tsunami vulnerability is also dealt with as a necessary step along the road to producing damage scenarios. A final chapter is devoted to discussing the methodology, but especially to highlight the perspectives 1) for the application of our approach to areas different from the very few and limited ones that was possible to study within SCHEMA, 2) for possible improvements or even alternatives depending on availability of suitable sets of data, and 3) for addressing challenges as the development of multi-hazard scenarios.

2 Tsunami scenarios: concepts and methodology

2.1 Concepts and definitions

In the world of natural hazard studies, the "hazard" is the description of the physical phenomenon that is of an earthquake, a fire, a hurricane, a tsunami, etc. A scenario refers more to the hypothesis of a hazard occurrence in a given area and with a given level of intensity. According to documents provided by the Intergovernmental Coordination Group for the Indian Ocean Tsunami Warning and Mitigation System (ICG/IOTWS, 2007), a tsunami hazard scenario is built up by specifying the various characteristics of a tsunamigenic source. In other words, it essentially consists of the set of elements characterising the tsunamigenic earthquake or the submarine landslide in the source zone. Observe that this definition does not include the local effects on distant locations affected by the tsunami waves, and that it is not shared by many studies on tsunami hazard scenarios where the main focus is viceversa on the tsunami behaviour in the coastal zone. The hazard scenario definition that has been adopted in SCHEMA is the description of the tsunami that follows from a selected source, ranging from the oceanic propagation down to its local effects of inundation, run-up, drawdown, extension of the flooded and receding areas at the coast, including information on tsunami distribution in space and time. This is for the natural phenomenon or natural process. In addition to this, the tsunami scenario in SCHEMA embraces also the description of the tsunami impact on persons and goods in the coastal zone, in accordance with the needs of the end users. Therefore the notion of tsunami scenario can take two dimensions:

- the **tsunami hazard scenario** describing the natural phenomenon from its origin source and its oceanic development down to the coast hit by the waves and depicting the hazard level on the exposed area (the target) for the specific event considered;

- the **tsunami damage scenario** describing the possible damaging consequences of the tsunami on exposed elements (persons, objects) specified by end users.

Scenario maps should present the exposed elements of the area affected by waves and the effects of the sea inundation or recess, together with the respective damage intensity or level, either qualitatively estimated or quantitatively calculated.

The notion of a tsunami hazard scenario is generally associated with the characteristics of a single tsunami source and to the tsunami that this source may generate. Indeed for several purposes it can be advantageous to study the tsunami hazard resulting from a number of sources, typically for all the tsunamigenic sources that can affect a given target area. In this case, it is reasonable to study each individual tsunami scenario and its impact on the coastal zone, and then to combine the effects of all the sources in a suitable way in order to obtain the whole tsunami hazard threatening the target coast. What is obtained is named an **aggregated tsunami hazard scenario**, since it results from the combination or aggregation of the individual pictures. Often the source that is taken into account to build a single scenario is the most powerful source that is reasonable to expect (i.e. credible) in a given region according to the current knowledge of the natural ongoing processes, and hence the corresponding scenario is called the worst-case credible scenario.

Sometimes there are elements allowing one to associate a given hazard scenario with the estimate of the return time. If this can be done extensively for a series of scenarios, a probabilistic approach can be adopted and each computed scenario associated to an estimated occurrence probability. Implementing a probabilistic approach is, however, not always possible or convenient. For instance, assessing occurrence probabilities for earthquakes in a given source region is feasible if a sufficient data set of historical and instrumental events is available and a good quantitative knowledge has been gained of the local and regional tectonic processes (for example knowledge of the convergence rate of lithospheric plates in a subduction region), which often is the case only for regions of high seismicity or for regions with a very long records of earthquake events, favoured by a long civilisation tradition. On the other hand, assessing probabilities for tsunamigenic landslide occurrences is a quite difficult or even prohibitive task in most of the ocean slopes, due to the lack of data and uncertainties in the destabilising processes starting slope failure. Within SCHEMA the probabilistic approach was not pursued, because bounding a return period to a given scenario appeared to be quite risky and unfeasible for the Mediterranean region, the Atlantic and the Black sea, due to the very small number of major or recorded events. It appeared more realistic to consider the likely past or potential scenarios from various tsunamigenic sources, that is to consider a number of worst-case credible scenarios, and to compile them in an aggregated scenario to obtain the areas of maximum hazard.

2.2 Outlines of SCHEMA methodology

Building tsunami hazard and tsunami damage scenarios is a process that requires a number of steps. Within SCHEMA, a procedure or a methodology has been devised by the partners that is illustrated in Figure 1 and that has been applied as a common approach to the five test areas dealt with in the project (as already mentioned they are Setúbal, Rabat, Mandelieu, Catania and Balchik). Since one criterion of selection of the target areas was purposely that they should have been quite different from each other under several aspects (such as for instance in terms of tsunami data, tsunami sources, coastal and urban environment, social and cultural conditions), the application of the same methodology to all of them has constituted a good validation test for it.

From the sketch in Figure 1 it is clear that actions included in the blue box on the left refer to the building of tsunami hazard scenarios including regional as well as local level, while actions in the green box refer to the vulnerability and damage analyses that are carried out only at the local level in the target zones. Both sets of actions are necessary to provide input data for building tsunami damage scenarios at the local level.

The process to build a worst-case credible hazard scenario starts with the identification of the sources that are capable of producing the most significant tsunamis in the target area. For each of the selected sources, one computes the tsunami generation and the tsunami propagation up to the target area by means of numerical models. In the approach adopted in SCHEMA it has been seen as convenient to consider a regional frame, more focussed on the tsunami propagation aspects, and a local frame, more focussed on the inundation aspects in the target area. Correspondingly one can speak of regional scenarios and of local scenarios.

Figure 1 provides a scheme of the methodology embracing the production of regional and local scenarios for the separated cases and the combined scenario. The methodology goes beyond the hazard scenario and covers also the aspects of the impact and countermeasure, which mainly focuses on damage analysis on building and structures and on the identification of evacuation routes and the consequent evacuation strategies.

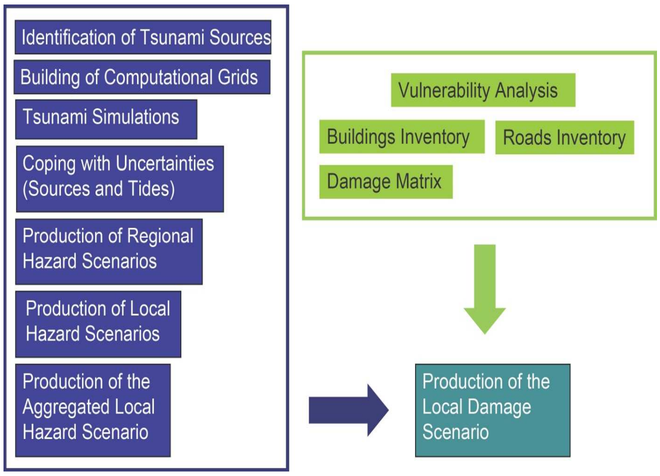

***Figure 1:** Sketch illustrating the developed methodology for producing tsunami hazard and tsunami damage scenarios*

This latter is the subject of a second handbook (Scheer et al., 2011), specifically devoted to tsunami evacuation planning and thus it will not be handled in this work. As for the impact, one relevant aspect is the evaluation of the damage produced by the tsunami to buildings, which implies at least three steps: knowledge of the characteristics of the buildings in the coastal zone (and according classification); definition of the relevant tsunami parameters affecting the building and correlation between parameters' magnitude and damage level (fragility curves, damage matrices); evaluation of the damage produced by the tsunami and consequent production of damage maps. In this section we only stress that damage analyses and maps can be produced for single scenarios and for aggregated scenarios. For example, if damage on a building is assumed to depend upon the thickness of the water flow (as is the case in the SCHEMA project), then the estimate of damage is actually performed by taking into account the flow thickness, that is one of the elements of the hazard scenarios and can be provided, according to end users' need for individual scenarios or for the aggregated scenarios or for both. In the aggregated case, in each point of the map the maximum flow depth may expectedly be associated with different tsunami cases.

This means that the overall damage picture estimated over the map does not derive from a single tsunami, but is the effect of a "virtual tsunami" that in each part of the map represents the worst possible case. The modification of the damage level due to other factors (either pertaining to the building itself, such as orientation with respect to the shoreline, number of storeys, type of ground-floor, etc., or pertaining to the surrounding environment, such as the presence of defence walls, the proximity to areas where floating objects can be raised and transported by the tsunami currents…) is quite difficult to estimate, and has been taken into account only grossly and in a qualitative way within the SCHEMA project.

Building a scenario means not only to specify steps and methods, but also to specify the type of results or products that are provided to the end users at the end of the procedure. In the project SCHEMA each scenario is described by means of a series of maps that are listed and characterised in Table 2.

Table 1: *List of the maps that characterise tsunami scenarios in the project SCHEMA*

Map name	**Description**
Regional tsunami hazard scenarios **(see section 3.6)**	They consist in a number of different-type maps showing the large scale tsunami propagation between the source zone and the target. They include tsunami sea-surface elevation fields taken at various times since the source initiation, as well as fields of tsunami travel times.
Local tsunami hazard scenarios **(see section 3.7)**	Local maps focus on smaller scales in the target area and depict fields of various parameters including the maximum sea-water elevation and speed, the line of maximum sea water ingression and regression. They are related to individual scenarios.
Aggregated scenarios (local maps) **(see section 3.8)**	Local maps for an aggregated scenario represent the synthesis of all the results calculated (or observed) for each potential tsunami scenarios concerning the same target location, with extraction of extreme intensities of all scenarios for various parameters (principally sea water elevation, water particle speed, flow depth, receding extension).
Tsunami damage scenarios **(see section 4)**	Based either on an individual scenario or on an aggregated scenario at the target area, these maps provide quantitative description of damage levels to buildings by using fragility functions and other major elements that increase damage intensity (secondary vulnerability criteria). Other elements useful to rescue operation can be included such as estimated submerged roads or likely obstructed streets.
Environmental damage scenarios	The recent experiences of the December 26, 2004 tsunami in the Indian Ocean showed that significant environmental changes (geomorphological, topo-graphic, bio-geochemical in soils) can occur on the submerged areas. These maps highlight the expected impact of the scenario tsunamis on industrial facilities and pipelines (e.g., soil and water contamination by dispersion of pollutants).
Evacuation maps	These maps should provide the shortest path to safe places from any point of the land area that is submerged by the tsunami. This is built starting from the aggregated scenario, which synthesises the effect of all possible worst-case credible tsunami waves, and results in the maximum extension of the inundated area. Information on evacuation paths, vertical shelters, safe places, and signals of warning and alerts have to be introduced in the evacuation maps. Evacuation maps and evacuation strategies are the subject of the SCHEMA handbook on the evacuation maps (Scheer et al., 2011) that complements the present publication, and will not be handled further here.

3 Tsunami hazard scenarios

As already stated in previous sections a tsunami hazard scenario refers usually to the tsunami produced by a single source (earthquake, landslide or volcanic eruption) of given size or intensity. For a given source there are a number of options that can be considered to build a scenario. If one restricts his attention to the hydrodynamic aspects of the tsunami field, which is what is technically meant by tsunami hazard scenario, the main elements that form the scenario can be listed as follows:

1. Map of the maximum sea surface elevation due to tsunami propagation
2. Maps with the instantaneous sea surface elevation at a specified propagation time
3. Map of arrival times of first waves
4. Synthetic tide gauge records in a number of selected nodes
5. Maximum inundation extent (floodable zone limit)
6. Maps of the maximum tsunami height and inundation depth (or thickness) in the flooded zone
7. Maximum receding level (minimum sea level off the shores)
8. Map of the maximum current speed (offshore and onshore).

The elements of the regional scenarios are the ones numbered from 1-4 in the above list. The map of the maximum sea surface elevation (point 1) shows the propagation path of the tsunami, that generally is characterised by a very strong anisotropy, as the double effect of the source geometry (usually with one dimension much longer than the other) and of the irregular sea bathymetry. The maps better representing the tsunami propagation are snapshots of the sea surface elevation taken at different times (point 2). From these one can see the tsunami front radiation from the source and possible reflections on the coasts. The tsunami travel time map (point 3) depicts the tsunami isochrones corresponding to different propagation times, each isochrones being defined as the line connecting all the points where the tsunami leading waves arrive at the same time. Records of tide-gauges computed offshore (point 4) give the time history of the tsunami in specified places and can serve to estimate the wave sequence, the typical tsunami period, the attenuation of the wave train with time and its significant duration.

Local scenarios include all the products and maps that are listed from 4 to 8 in the previous section. Observe that computing tide-gauge records is a task that can be included among the activities to build regional as well as local tsunami scenarios depending on the location of the virtual tide-gauge: if they are selected offshore along the tsunami propagation path, the computed records are elements of the regional scenario, while if they are selected within the target area (for example a tide-gauge in a local harbour or onshore), they are consequently elements pertaining to the local scenario. The maximum inundation extent (point 5) gives the largest area that is inundated by the tsunami, irrespective from the time of inundation: the tsunami can inundate the target area with a single wave or a series of waves arriving in different times with different amplitudes. The maximum inundation extent is the area that results from adding together all the areas flooded by the various tsunami waves. Accordingly, maps of the maximum tsunami elevation and maximum flow depth (point 6) provide information on the highest level reached by the sea surface in any given point and the maximum height of the water column. These two variables are obviously linked together on land, since the second derives from the first by simply subtracting the local altitude of the ground. The maximum receding level (point 7) gives the maximum area that remains dry offshore as the result of the tsunami arrival in the target area. Each tsunami trough causes the sea to withdraw from the usual position of the shoreline, leaving some areas uncovered by the sea water. The sum of the dry areas corresponding to the various troughs form the maximum receding level. The map of the maximum current speed (point 8) provides the maximum intensity of the horizontal water particle velocity computed in the target area, offshore and onshore. Though also the vertical velocity may have a role, tsunami simulation models usually neglect the vertical velocity. Indeed they use the average of the horizontal velocity on the water column that is from the sea floor up to the instantaneous sea surface level.

The only viable way to explore tsunami scenarios and to produce the above listed maps is to make recourse to numerical models and to perform numerical simulations where grids (regular or irregular) cover the domain of interest. Very important among the other maps are the fields of the maximum (minimum) sea water elevations in the target area: for any given case these show the maximum (minimum) level computed in any given node of the local grid and therefore are also useful to compute the inundation line and the run-down line. The first is the boundary line inland between the area not reached by the sea and the area which is flooded at least once by the series of tsunami waves. The second is the boundary line offshore that divides the area remaining always covered by the sea water and the area which remains dry at least once due to the retreating movement of the shoreline during the tsunami attack.

When the tide regime is strong and there is a relevant difference between high and low tide, which occurs more in the oceans than in closed basins and seas, tsunami hazard scenarios can be built distinctly for low tide and high tide conditions.

Typically a number of sources are needed to provide a complete picture of the many ways a tsunami can attack a given place. Producing a tsunami hazard worst-case credible scenario means indeed modelling worst-case credible tsunamis for a comprehensive set of sources affecting a given location and then combining them together in the aggregate scenario. The most reasonable way of aggregation is to build maps with the maximum extension of inundation and drawdown, and aggregated fields (such as sea inundation depth and current speed) with the maximum intensities. The resulting scenario should be referred to correctly as the tsunami hazard aggregated scenario, but it is often referred to simply as tsunami hazard scenario, under the assumption that the context clarifies what it really is. The aggregation synthesis regards only the local scenarios, and more specifically the products ranging from 5 to 8. A typical map of the aggregated hazard scenario, for example, is the map of the maximum extent of the inundation area, which is obtained by adding together all the inundated areas resulting from the various scenarios. This map carries information relevant for end users, since it distinguishes the coastal zone clearly into two classes, the area that is not inundated by any tsunami, and therefore is safe, and the area that can be affected by at least one of the tsunami cases.

3.1 Selection of the sources

The first step in order to build scenarios is represented by the choice of the sources that could have the highest tsunamigenic potential for the considered test site (see Figure 1). Seismotectonic studies of earthquake and tsunami catalogues are the main tools to be used to the purpose of compiling the worst-case tsunami scenarios. For the test sites treated in SCHEMA a careful examination of data and of the existing literature provided the motivation for the selection of sources as may be found in the scientific reports produced by the project partners. In this handbook we simply provide the list of such sources through Table 3 and of the main related references taken from the literature.

For the Rabat test site two of the three selected scenarios are based on historical earthquakes: one is a source hypothesis of the event following the strong earthquake occurred in 1755 (Baptista et al., 2003) and the second is the Mw=7.9 earthquake occurred in 1969 and located south of the Gorringe Bank, SW off Portugal. The third scenario is represented by a hypothetical tsunamigenic huge volume landslide that could follow from the eruption of the Cumbre Vieja volcano in the Canary island of La Palma (Ward and Day, 2001).

Table 2: *List of the sources selected in SCHEMA*

Test site	Partner	Sources
Rabat, Morocco	ACRI-ST	• Cumbre Vieja volcano potential slope collapse (Ward and Day., 2001) • 1755 Lisbon Earthquake (Baptista et al., 2003) • 1969 Gorringe Bank Earthquake (Gjevik et al., 1997; Guesmia et al., 1998)
Setúbal, Portugal	HIDROMOD	• 1755 Lisbon Earthquake (Baptista et al., 2003) • Marques de Pombal Fault (Zitellini et al., 1999 ; Omira et al., 2009) • Guadalquivir Bank Fault (Omira et al., 2009)
Mandelieu, France	GSC, UNIBOL	• 1887 Western Liguria Earthquake (UNIBOL after DISS, 2009) • 1979 Nice Landslide (Assier-Rzadkiewicz et al., 2000) • 2003 Boumerdes-Algiers Earthquake (UNIBOL after Delouis et al., 2003; Tinti et al. 2005)
Catania, Italy	UNIBOL	• 365 A.D. West Hellenic Arc Earthquake (Papazachos 1996; Tinti et al., 2005) • 1693 Eastern Sicily Earthquake (Argnani and Bonazzi, 2005) • 1693 Eastern Sicily Speculated Landslide (Armigliato et al., 2007) • 1908 Messina Strait Earthquake (Pino et al., 2009) • 1908 Messina Strait Earthquake plus Speculated Landslide) (UNIBOL)
Balchik, Bulgaria	SRI-BAS, NOA-GI	• VI Century A.D. Earthquake (fault with strike 40°) (after Ranguelov et al., 2008) • 6th Century A.D. Earthquake (fault with strike 90°) (after Ranguelov et al., 2008)

For the Setúbal test site three main offshore faults or fault systems have been examined. The first is the same selected for the Rabat test site and considered as the source of the 1755 Lisbon earthquake and tsunami (Baptista et al., 2003). Two more sources placed in the Gulf of Cadiz have been identified by considering the complex seismotectonic setting of the region that is governed by the convergence between the African and the Eurasian plates: they are the so called Marques de Pombal fault (Zitellini et al., 1999) and the Guadalquivir Bank fault (Omira et al., 2009). As an example, Figure 2 shows the sea water elevation produced by the scenario earthquake rupturing Marques de Pombal fault, with parameters taken from Omira et al. (2009).

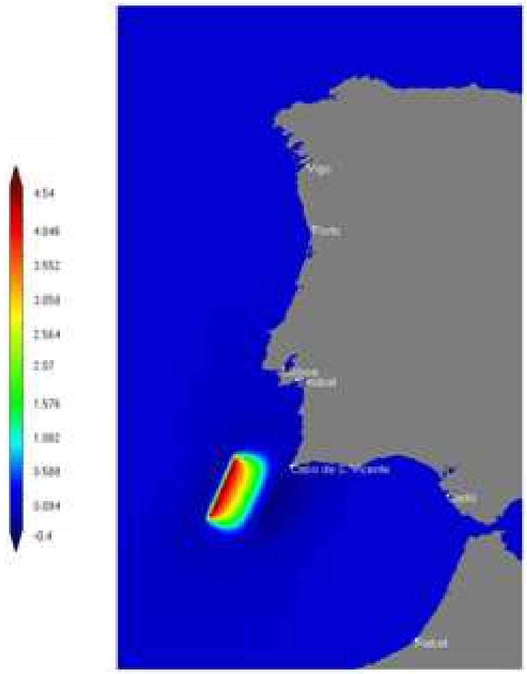

Figure 2: *The Marques de Pombal fault (Omira et al. 2009), SW off Lisbon, was selected by HIDROMOD to build one of the worst-case credible scenarios for the Setúbal test site. Here the computed initial sea surface elevation produced by the earthquake is portrayed.*

As regards the Mandelieu test site, in Côte d'Azur, France, three different scenarios have been built on the basis of three past tsunamigenic events: the 1887 Ligurian earthquake (Eva and Rabinovich, 1997), the 1979 Nice landslide (Assier-Rzadkiewicz et al., 2000) and the recent 2003 Algerian earthquake (Yelles et al., 2004). Two sources are local, placed at a small distance from the target, while one is quite remote on the other side of the western Mediterranean basin.

Five tsunamigenic sources have been selected for the Catania test site. One of them, a remote source, is located in the West Hellenic Arc and is based on the 365 A.D earthquake that hit western Crete (Papazachos, 1996) and that originated a tsunami affecting the central and eastern Mediterranean sea coasts (Tinti et al., 2005). The remaining four are based on the two catastrophic local events that occurred in the East of Sicily and in the Messina Straits in 1693 and 1908 respectively (see Tonini et al., 2011).

As far as Balchik, Bulgaria, is concerned, the source zone has been chosen by mainly considering the strong tsunamigenic earthquake that occurred in the 6th century A.D. off the town, but also the more recent 1901 earthquake, damaging Balchik, since such events are speculated to share the same source area. Due to the difficulty in the precise fault characterisation, two hypotheses have been explored differing for the strike angle of the fault, thus resulting in two different scenarios.

Some remarks can be made at this point. First, for all test sites more than a single source has been taken into account. This is quite expected, since most of the possible target areas worldwide may be affected by large tsunamis generated by different sources, but it is not a constraint of the method. In some special cases only one source could happen to be relevant for the analysis. Second, for some of the test sites not only earthquakes, but also landslides, either located in volcanic environment or in continental margin slopes, have been selected as possible sources. This is a factor providing a strong argument against the adoption of a probabilistic approach for scenario construction, since return times of landslides is very difficult to assess. Third, it is stressed that several sources have been selected on the base of historical occurrences. This however does not mean that the goal of the analysis is the reconstruction of the historical tsunami, but simply that the historical tsunami is used as a good hint for building the scenario. Usually, the worst case scenario makes use of a source that is more intense (e.g. of larger magnitude in case of an earthquake) than the one estimated for the historical case. Fourth, the choice of the tsunami sources is the result of careful scientific considerations, and has a certain degree of arbitrariness since it comes from subjective analysis. This is a common problem in many aspects related to hazards assessment and can be dealt with in different ways. In SCHEMA the problem of the unavoidable lack of objectiveness in the scenario sources and, which is the other side of the coin, of the parameters' uncertainties has been solved by assuming that in addition to the standard scenarios, also a parallel series of "augmented source" scenarios should have been developed. To be more specific we applied two different methods to obtain an "augmented source". Details on the uncertainties and how they have been introduced and calculated will be given in Section 4.3.

3.2 Numerical models

Following the selection of the sources for a given test site, numerical simulation of the tsunami are to be performed (see Figure 1). This has been carried out in the project SCHEMA for each test site by partners with expertise in tsunami numerical modelling. The tsunami code models used in SCHEMA are listed in table 4.

Table 3: *Tsunami numerical models used for the test sites of the project SCHEMA.*

Partner	Model name	Test site	Two-way Nesting	Solution
ACRI-ST	TIDAL	Rabat	No	Boussinesq
HIDROMOD	MOHID	Setúbal	Yes	Shallow water
GSC, UNIBOL	COMCOT UBO-TSUFD	Mandelieu	Yes	Shallow water
NOA-GI	FUNWAVE	Balchik	Yes	Boussinesq
UNIBOL	UBO-TSUFD	Catania	Yes	Shallow water

All models solve the Navier-Stokes equations for water waves propagation under the approximation that the vertical velocity of water particles is negligible and that the horizontal velocity components are uniform along the vertical column of the fluid.

TIDAL is a general-purpose software tool for solution of the fluid flow, heat and mass transfer problems in shallow water bodies. It can be used to simulate transient or steady state problems in a water body with irregular coastline, complex bathymetry, and islands. The water body may contain rivers, sources, inlets and outlets. It may have coastal plains or tidal flats which get inundated with or drained of water from time to time.

HIDROMOD performed tsunami propagation simulations using MOHID modelling system (see http://www.mohid.com). MOHID is an open source 3D water modelling system that was used in 2D approximation for tsunami calculations. It was developed by MARETEC (Marine and Environmental Technology Research Center) at Instituto Superior Técnico (IST) which belongs to Technical University of Lisbon. The MOHID modelling system allows the adoption of an integrated modelling philosophy, not only of processes (physical and biogeochemical), but also of different scales (allowing the use of nested models) and systems (estuaries and watersheds), due to the adoption of an object oriented programming philosophy. For tsunami application the code was applied in the long wave approximation version (see Vaz et al., 2007).

The numerical tool used by GSC is the ComMIT (Community Model Interface for Tsunami) package, based on the Method of Splitting Tsunami (MOST)l, and developed by the Pacific Marine Environmental Laboratory (PMEL) of the National Oceanic and Atmospheric Administration (NOAA) of the United States (http://nctr.pmel.noaa.gov/ComMIT; see also Titov and Synolakis, 1995).

NOA-GI simulated tsunami propagation and inundation with FUNWAVE, a Boussinesq water wave model, that was initially developed for modelling ocean wave transformation from deep water to the coast, including breaking and runup (http://chinacat.coastal.udel.edu/programs/funwave/ funwave.html; see also Kirby et al., 1998).

To perform numerical simulations for the Catania and Mandelieu test sites, UNIBOL has made use of the in-house developed tsunami propagation code UBO-TSUFD, which solves both linear and non-linear shallow water equations with a leap-frog algorithm over staggered structured grids with the finite difference technique.

A nested multi-grid system (see Figures 3 and 7) is implemented for all the codes to allow for different grid resolution in modelling regional wave propagation across deep ocean and local impact in the shallow nearshore zone: however TIDAL uses the output of the large coarser grid as input of the small finer grid (one way coupling), while other codes account for a full coupling between the coarser and the finer grid, though coupling techniques differ from one code to the other.

The set of the models used in SCHEMA and given in Table 4 does not cover all the possible models available for tsunami propagation. Several others have been developed especially in the last years, after the great increase of interest on tsunamis following the 2004 disaster in the Indian Ocean. It is stressed here that the SCHEMA methodology does not determine or recommend a specific tsunami simulation code. It is simply observed, however, that tsunami modelling plays a very fundamental role in the procedure since it is at the basis of the creation of the tsunami scenarios, and therefore the utilisation of any in-house or commercial software has to be made by paying attention to the advantages and limitations of the codes, with the warning that performing simulations in a black-box mode might lead to some unreliable artefacts. A further remark is that all the tsunami simulation codes used by the SCHEMA partners were validated on a common case, more precisely by computing the Indian Ocean 2004 tsunami propagation from the source up to the Seychelles archipelago and by comparing numerical results with observed run-up data in the Praslin Island and with the tide-gauge record in the port of Pointe La Rue, in the Mahé Island (see SCHEMA Deliverable 1.3, 2008).

3.3 Bathymetry and topography databases

Tsunami propagation is sensitive to sea bathymetry, and tsunami impact on the coast and flooding are sensitive to coast topography. Therefore, it is not surprising that all tsunami models are sensitive as well to bathymetry and topography data and that a very important step for tsunami simulation is the creation of an adequate topo-bathymetric set of computational grids. This task seems simple in principle, but in practice it is quite complex due to the lack of data with the proper resolution and/or due to the fact that such data may exist but are not easily and openly available. Indeed a big step forward has been done in recent years as the results of international projects that produced homogeneous worldwide gridded datasets of bathymetry and topography such as GEBCO (General Bathymetric Chart of the Oceans; http://www. gebco.net/) and SRTM (Shuttle Radar Topography Mission; http://srtm.usgs.gov/) with resolution of 30 arc-second and 90 m respectively. This resolution is sufficient for regional scales and for producing regional tsunami hazard scenarios (see Table 2), but it is not enough for the detailed local study required for the SCHEMA test sites. Hence, each partner has collected topo-bathymetric data from a variety of sources also in collaboration with local administrations, and then has compiled gridded datasets by means of suitable procedures of data merging and interpolation.

3.3.1 Combining land and sea datasets

A further complication derives from a need that is typical of tsunami studies pointing to computation of wave inundation and run-up. Usually, topographic data and bathymetric data are acquired by different agencies and institutions and processed independently, which has the consequence that they have no common reference frame or no common zero for the vertical coordinate. Indeed, it is tradition that land elevations are determined with reference to the mean sea surface level over a long period (preferably around 18 years), while sea depth in nautical charts is relative to the chart datum, which is defined to be a level below which tide rarely falls, let's say the minimum tidal level. It is quite frequent, therefore, that the coastline representations of these data sets are inconsistent. If one just limited to put these data together, a transect crossing the shoreline would result almost always into a discontinuous jump in passing from sea to land. So special care, with specific processing and data validation, is needed to create a coherent unique data set in the coastal zone, where the resolution requested in SCHEMA ranges for 1-40 m.

One example of compilation of various datasets for local tsunami scenarios is given in Figure 3 and in Figure 4 that refer to the test site of Mandelieu, France. It is seen from Figure 3 that the bathymetry results from the combination of GEBCO data and data acquired by IFREMER (Institut Français de Recherche pour l'Exploitation de la Mer, 1998 and 2004) and SHOM© (Service Hydrographique et Océanographique de la Marine) during a series of cruises carried out far offshore and nearshore.

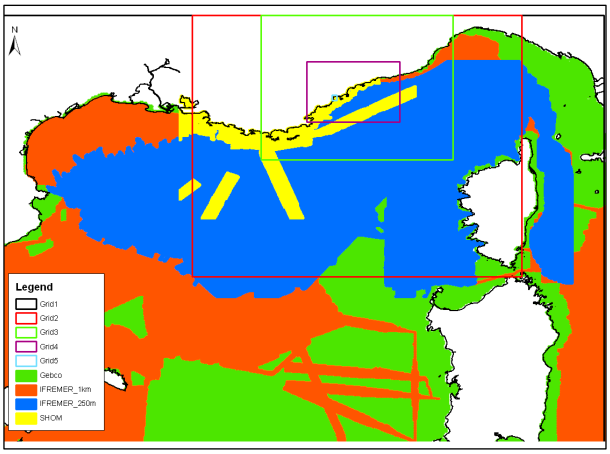

Figure 3: *Compilation of bathymetric data for the Mandelieu test site by GSC. Rectangles represent the boundaries of the computational grids of the multi-grid system created by UNIBOL for numerical simulations.*

A very accurate local digital elevation model (DEM) was used for the topography of Mandelieu. The position of the coastlines, which is the boundary between the DEM and ocean data, has been inferred from analysing Google Earth images and validated through in-field observations (Figure 4). In addition, the position of the coastline may be used as a constraint to harmonise sea and land data sets in the process of building a unique topo-bathymetric database.

Figure 4: *Example of detailed coastline in the area of the Mandelieu test site. The coastline position has been deduced by photo interpretation of Google Earth images.*

DEMs have been acquired by the SCHEMA partners for all the test sites. An example is given in Figure 5 that portrays the DEM of the Varna region in Bulgaria, utilised for the test site of Balchik.

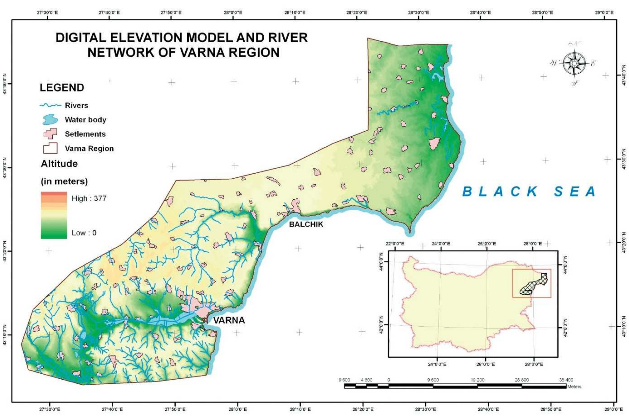

Figure 5: *Digital Elevation Model (DEM) of the Varna region, Bulgaria, including the town of Balchik that was selected as one of the SCHEMA test sites (made available to SCHEMA by SRI-BAS).*

3.3.2 The problem of tides

It is trivial to observe that coastline position changes constantly because of the water erosion, human activities and tides. In particular tides can change the shoreline position very rapidly during the day in some locations. As regards tsunami scenarios, tides can change significantly the level of inundation produced by a tsunami, and therefore the impact of the tsunami onshore and the consequent tsunami damage scenario. Within SCHEMA, the tide problem has been addressed by considering that for places where tides are strong it is convenient to elaborate two distinct local tsunami scenarios, one for the low-tide and one for the high-tide conditions. In the perspective of the worst-case credible scenario adopted in SCHEMA, however, the high-tide scenario is the one associated with the higher impact and expected higher level of damage. Therefore, if in the phase of computing tsunami hazard scenarios both tide regimes are taken into account, the next phase of tsunami damage scenarios is only elaborated for the high-tide conditions. Tides are quite weak in the Mediterranean and in the Black sea, and indeed they are not so relevant in the test sites of SCHEMA located in these basins, while they are strong in the Atlantic ocean. An example is given in Figure 6 for the peninsula of Troia in the test site of Setúbal, Portugal, where the inundation produced by a high tide of 3.8 m is shown.

Figure 6: *Difference between high and low tide coastlines in the Troia Peninsula in Setúbal test site as computed by HIDROMOD.*

As regards tsunami computations, tide is assumed as a static process in SCHEMA, that is able to change the reference value of the sea level, and therefore the value of the land elevations or of the seafloor depths. In other words, once one has built a local grid for the low tide condition, the grid for the high tide can be simply obtained by subtracting the same fixed amount to elevation values of all the nodes of the grid.

3.4 Handling different resolutions

Tsunami hazard scenarios can be distinguished in regional and local scenarios as explained in the previous chapter 3 that is scenarios covering the large-scale tsunami propagation over large distances and scenarios covering the impact of tsunamis against land structures that is typically a small-scale process. The space resolution needed to represent adequately the interaction of tsunami waves with local elements is governed by the geometrical scale of the obstacles we like to describe, while in the large scale it is dictated by the tsunami wavelength or the scale of the sea floor main features. Typically, if we like to describe how a breakwater interacts with a tsunami wave or how a tsunami attacks a building, we need grid spacing in the range of 1-10 m, while in the deep ocean grid spacing can be 500-5000 m to treat propagation of tsunamis generated by large earthquakes.

Numerical models handle different resolutions in two different ways, which is either by using a single unstructured grid with heterogeneous resolution or by means of a set of structured interconnected grids that have different node density. Typically the first category is the category of grids formed by polygons, such as triangles, of various size, that are used by codes based on the finite-element technique: smaller polygons are used to cover those areas of the domain where higher resolution is required. No such models have been used in the project SCHEMA. The second category covers the domain by a series of grids, nested one in the other, with the coarser including the finer one. This technique, which is adopted by the finite difference models, allows one to compute the propagation of waves with increasing resolution as the wave passes from a coarse grid to a fine grid. By combining a series of grids, one can get the desired level of resolution in the area of interest.

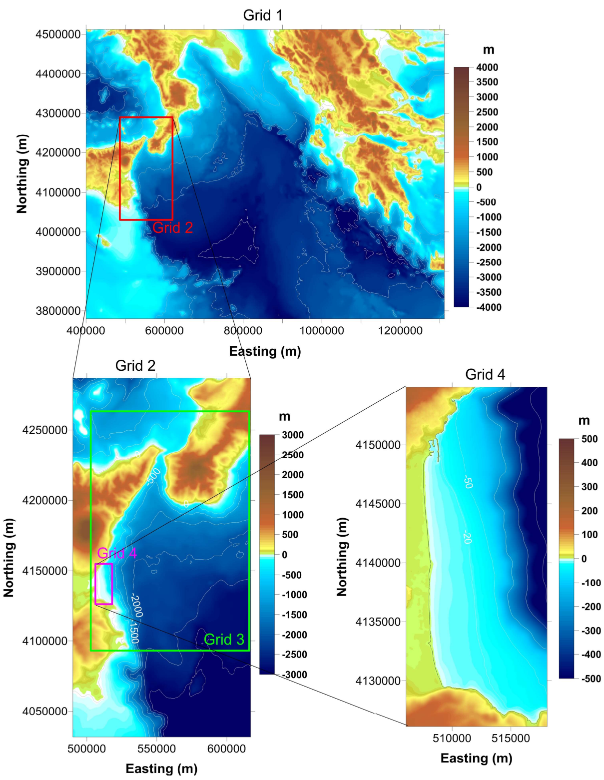

Figure 7: *System of four nested grids used by UNIBOL to cover the Central Mediterranean region from the West Hellenic Arc (that is between Peloponnesus and western Crete and is the source of the 365 A.D. earthquake and tsunami) to eastern Sicily, where the test site of Catania is located.*

As explained in section 4.2 all models used by the SCHEMA partners use a nested grid system to cover the computational domain. An example of such nesting was already provided by means of Figure 3 where it is seen that the Mediterranean Sea offshore Mandelieu is covered by a set of five grids, with the highest resolution provided by a spacing of 8 m in grid 5. A further example is given in Figure 7. Here the region between the source of the 365 A.D. tsunami and the town of Catania (see Table 3) is covered by a set of four meshes, with grid spacing passing from 3000 m for the coarser outer grid (grid 1) down to 40 m for the finer grid (grid 4) covering the town of Catania and the beach south of Catania called La Plaia, passing through the intermediate steps of 1000 m (grid 2) and of 200 m (grid 3) (see Tonini et al., 2011).

3.5 Coping with uncertainties

Uncertainties on the results of computations are unavoidable and depend on a very large number of factors. In the frame of tsunami hazard scenarios based on the worst credible cases uncertainties are mainly due to the selection of tsunami sources and to the computation of the tsunami propagation. The sources are selected on the basis of the personal judgement of experts, and therefore there is always a certain degree of subjectivity involved: one could select more sources, or other sources, or the same sources but with a different level of intensity (smaller or larger). The propagation depends on the assumed tsunami generation model, on the quality of the tsunami simulation model, and on the quality of the topo-bathymetric data set. More details about this latter point can be found in Gardi et al. (2010).

The simulation models used by the partners have been validated against classical benchmark tests and have been applied to very many long-wave simulation cases. They seem at the state-of-the-art level and seem reliable. Topo-bathymetry data sets have been assembled with great attention, but the average accuracy of the data is difficult to ascertain and even more difficult is to determine the amount of the largest possible error. Consider that a discrepancy of a few meters in the sea depth in the deep ocean has little influence on tsunami propagation, but it matters very much in the nearshore zone and on land, since it may affect significantly the extension of the inundation area.

A convenient way to cope with uncertainties is to perform a sensitivity analysis, which means to change some input parameters in the procedure, to perform computation with the new set of parameters and to see how different the final results turn out to be. Since the most relevant parameter is the source level, the analysis has been restricted only to this kind of change, to keep it simple and to keep it economical. Since the sources used for the SCHEMA test sites are essentially either earthquakes or landslides (see Table 3), two different strategies have been adopted.

When the tsunami is caused by an earthquake, it is known that the earthquake initially displaces the sea water up or down by almost the same amount by which it moves the sea floor. In the area where the earthquake determines a co-seismic subsidence (uplift) of the sea floor, the sea level goes down (up) and forms a trough (crest) at the sea surface. The sea surface pattern produced by the earthquake is known as the initial state (or condition) of the tsunami wave. Changing the size of the earthquake means to change the size of the vertical displacement of the sea floor, and hence of the amplitude of the initial tsunami wave, and viceversa. In order to perform the sensitivity analysis for earthquake-induced tsunamis, the SCHEMA partners have taken each earthquake source of Table 3 and increased the amplitude of the initial tsunami by 20%.

The generation mechanism of a landslide tsunami is more complex than for an earthquake. The concept of initial tsunami wave has no meaning anymore since the tsunami generation goes along with the process of landsliding. We may however notice that tsunami wave amplitude is strongly correlated to the thickness of the landslides and, within a certain extent, there can be seen a linear dependence. In analogy with the earthquake generation case, therefore, sensitivity analysis has been carried out by increasing the thickness of the landslide by the same factor of 20%.

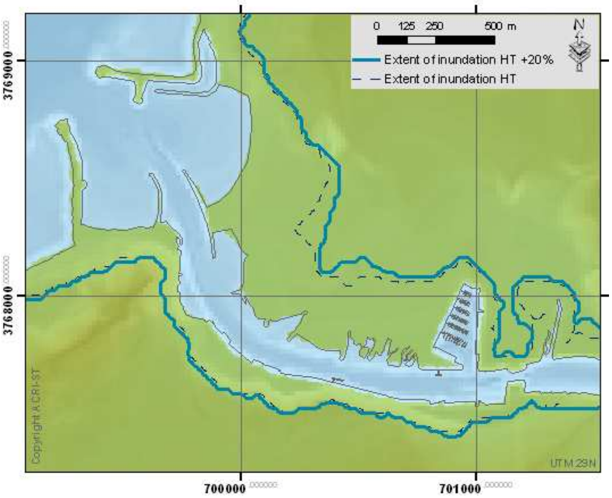

***Figure 8**: Comparison of the extent of inundation between a local scenario (dashed dark blue line) and the correspondent "augmented scenario" (light blue line). The example refers to the Rabat test site and the scenario is the one based on the historical 1755 Lisbon earthquake and is the result of collaboration between ACRI-ST and CRTS.*

The scenario elaborated with the more intense source is named here **augmented scenario** while the one with the reference size is called reference scenario or more often and more simply scenario. It is obvious that the tsunami effect on the coast for the augmented source will be more severe: the inundation line will move more landward, the run-down line will move more offshore, the maximum sea surface elevations and depressions will be higher, etc.

3.6 Regional tsunami hazard scenarios

Regional tsunami hazard scenarios are obtained by means of numerical simulations of tsunami and mainly focus on the propagation features of the tsunami waves from the sources up to the vicinity of the target area. What is meant for such a scenario is outlined in Table 2 and better specified at the beginning of this chapter. In this section we restrict ourselves to give some examples of the maps that contribute to composing the scenario, maps that are taken from the studies of the various partners.

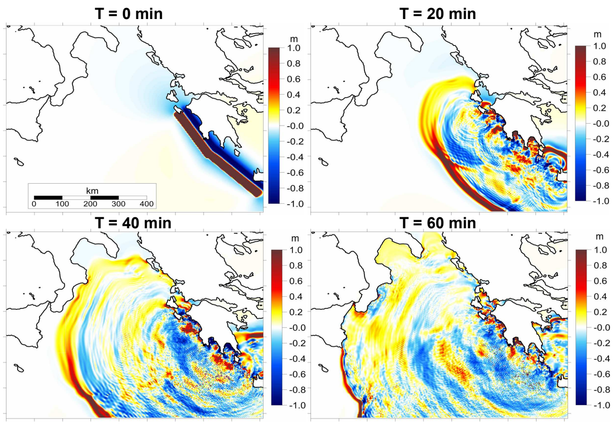

***Figure 9:** Tsunami propagation snapshots for one of the scenarios considered for the Catania test site, based on the 365 A.D. event occurred off western Crete, Greece, computed by UNIBOL.*

Snapshots of the computed tsunami wave fronts are depicted in Figure 9. They refer to the tsunami produced by a source in the subduction zone of the western Hellenic Arc. The initial sea surface displacement (left-top corner) shows that the parent fault system consists of two fault segments spanning an overall length exceeding 400 km and ranging from West Crete to West Peloponnesus. The main front travel toward SSW and it takes more than 40 min for it to reach eastern Sicily and the town of Catania (see Tonini et al., 2011).

Travel times maps are another component of the regional tsunami hazard scenario. Figure 10 gives an example of such a map displaying the Atlantic Ocean propagation of the tsunami produced by the assumed sector collapse of the volcano Cumbre Vieja in the Canary islands. Travel time maps give the minimum time needed by the tsunami front to reach a specified location. Among the sources taken into account (see Table 3) in the project SCHEMA, the ones that happened to be most remote in terms of propagation time are the landslide in La Palma for Rabat, the earthquake of Boumerdes-Algiers for Mandelieu and the earthquake on the western Hellenic Arc for Catania.

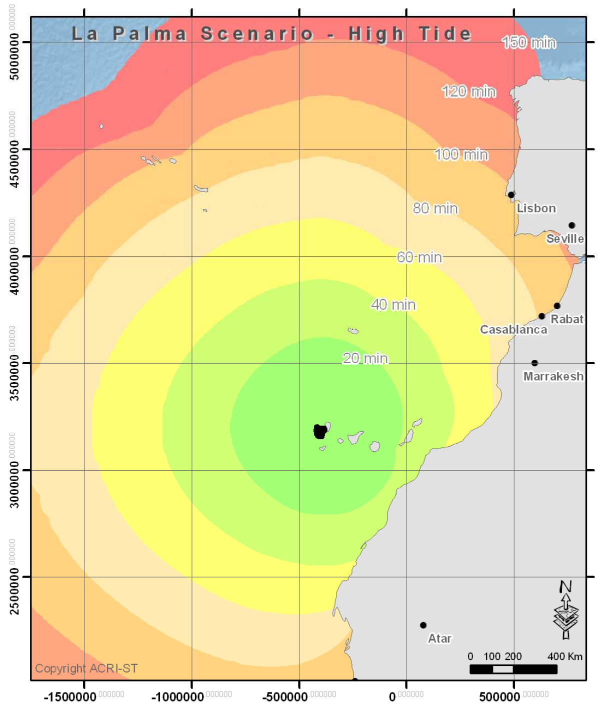

Figure 10: *Propagation time map of the scenario associated with the mega-collapse of the Cumbre Vieja in the La Palma island elaborated for the Rabat test site by ACRI-ST. It is seen that the first tsunami waves will reach Rabat in about 90 min.*

Maps with the snapshots of tsunami propagation need to be complemented by the maps of the maximum and minimum sea surface elevation induced by the tsunami. This is quite useful since it gives an immediate picture of the main pattern followed by the tsunami fronts and of the areas where they arrive with higher amplitude and therefore more energy. Figure 11 refers to the tsunami associated with the Marques de Pombal fault, that is one of the sources selected for the Setúbal test sites. It appears quite clearly that tsunami propagation is not isotropic. Most wave energy goes along beams perpendicular to the fault axis (that is approximately NNE-SSW). On radiating from the source, these beams are soon strongly bended towards the Cape Saint-Vincent as the effect of the bathymetry. The increase of the computed maxima close to the coast is the result of the well-known near-shore amplification experienced by tsunamis.

3.7 Local tsunami hazard scenarios

Local hazard scenarios are the final step of the tsunami hazard scenario phase and are centred on the local aspects of the tsunami interaction with the coast with focus on the extreme values of the hydrodynamic fields, such as the maximum sea water elevation, the maximum fluid speed, etc. that can serve to characterise the impact of the tsunami on the elements exposed.

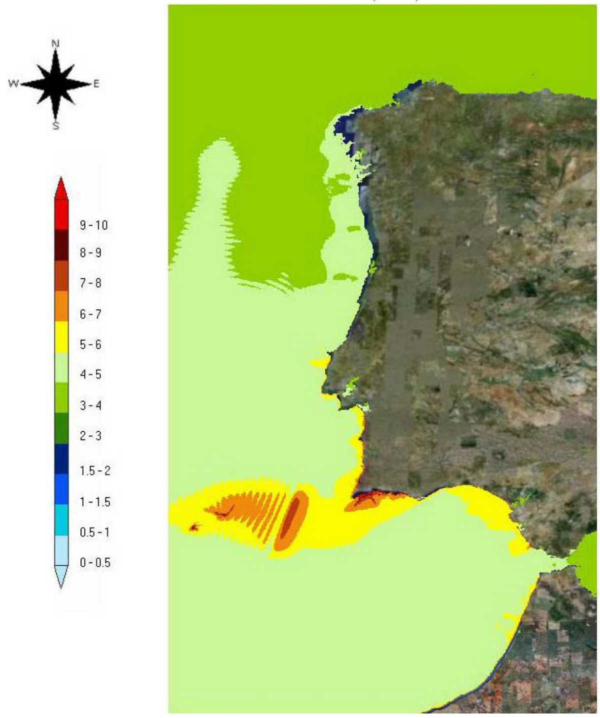

Figure 11: *Maximum sea surface elevation (in meters) for the Marques de Pombal fault tsunami analysed for the Setúbal test site on a regional scale. Computations were performed by HIDROMOD, with initial tsunami conditions provided by UNIBOL..*

The local maps are the most demanding in terms of accuracy of the topo-bathymetric data set and of the resolution of the computational grid, since results of the tsunami simulation depend strongly on the quality of the grids.

The set of Figures 12-14 display the fields of the maximum water elevation and the minimum water elevations as well as the maximum current speed in the test site of Rabat, computed for the scenario associated with the 1755 earthquake in condition of high tide (2.97 m above the minimum level).It is interesting to note that tsunami penetrates deep into the river Bouregreg separating the towns of Rabat (on the SW bank) and Salé (on the NE bank), even though the river mouth is protected by a complex system of breakwaters. Tsunami penetration along rivers is a common feature of the tsunami dynamics, so that often elements and people located on the river banks in the proximity of the river mouth are exposed to tsunami threat as much as the ones located on the sea coasts.

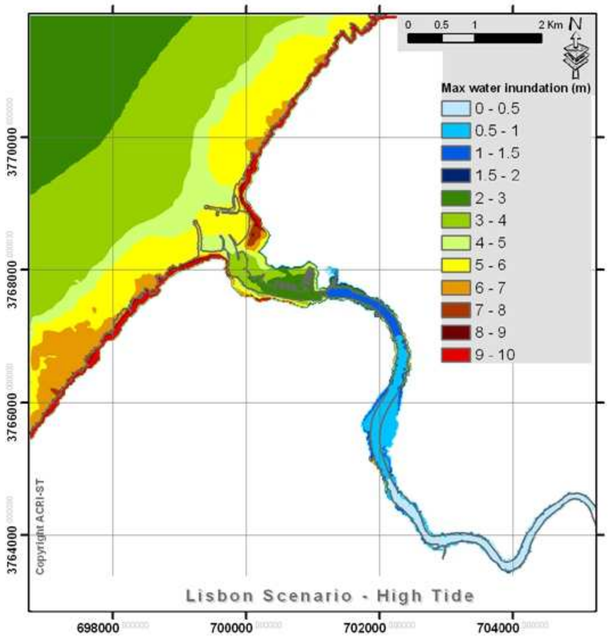

Figure 12: *Maximum water elevation, Rabat test site, 1755 Lisbon earthquake scenario, computed by ACRI-ST.*

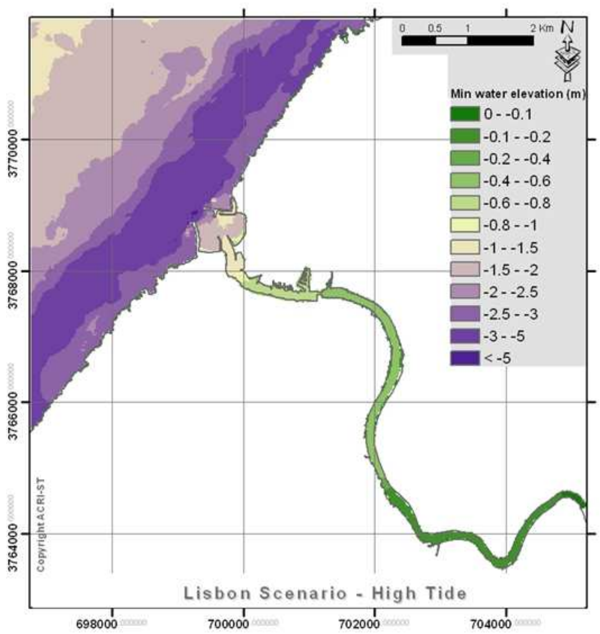

Figure 13: *Minimum water elevation, Rabat test site, 1755 Lisbon earthquake scenario, computed by ACRI-ST.*

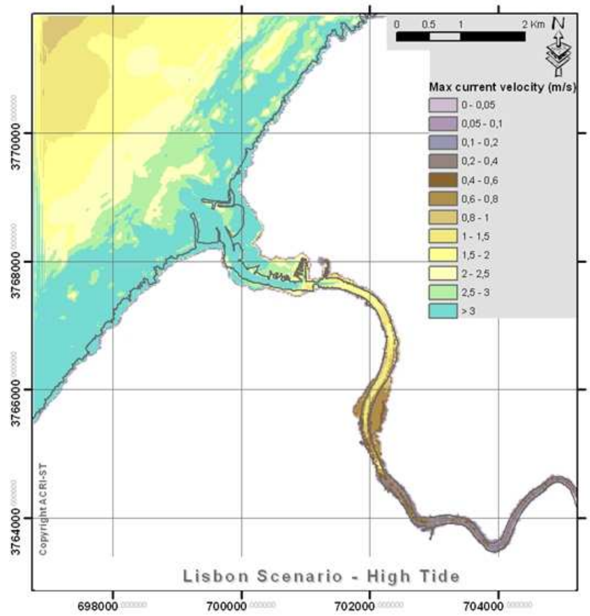

Figure 14: *Maximum current speed, Rabat test site, 1755 Lisbon earthquake scenario, computed by ACRI-ST.*

3.8 Aggregated scenarios

When applying the worst-case credible scenario approach to the tsunami hazard assessment, a fundamental step is the combination of the results obtained for the single tsunami sources. The result of the combination is the aggregated scenario, the process of aggregation consisting in selecting for each position of the map the extreme value (the highest or the lowest) computed for the individual cases, as explained in chapter 3.

An example of aggregation is given in Figure 15 referring to the test site of Catania and displaying the field obtained by combining the maximum sea elevation computed for the five scenarios examined for this site (see Table 3 and Tonini et al., 2011). The inundation line is the boundary of the maximum extent of flooding. Notice that often the aggregated map is dominated by one individual case, that in each point of the map attains the maximum (minimum) value. This happens for instance for the test site of Rabat where the scenario of the 1755 tsunami is by far the most severe with respect to the others considered. As a consequence Figures 12-14 can be taken also as further examples of aggregated scenario maps.

4 Tsunami damage scenarios

Tsunami damage scenarios describe at the local scale the possible damaging consequences of the tsunami as given in the tsunami hazard scenarios treated in the previous section. With reference to the basic outline of the methodology sketched in Figure 1, we see that this is the last phase of the analysis, and must be preceded by the vulnerability analysis.

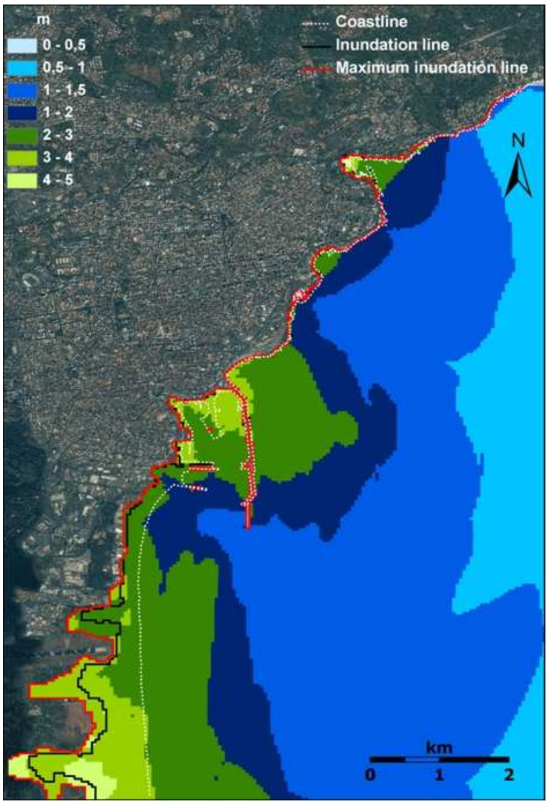

***Figure 15:** Aggregated map of the maximum sea elevation computed for the Catania test site by UNIBOL. The aggregated inundation line (black) and the inundation line (red) deriving from combining the augmented scenarios are drawn together for comparison.*

The first part of this chapter is devoted to highlight how vulnerability of elements exposed to tsunami can be assessed and how the level of damage can be formally related to the level of hazard, while the second part of the chapter is focussed on the way tsunami damage scenarios are built. In analogy with the definition of the tsunami hazard scenarios, even for a tsunami damage scenario we can state that it consists of a series of specific maps where exposed elements of the target area affected by waves and by inundation effects, are mapped with the indication of the respective damage level, either qualitatively estimated or quantitatively calculated. These maps can be produced on the basis of a single tsunami hazard scenario, or for the aggregated scenario, resulting from the combination of all the single cases. In this approach we attribute a more relevant meaning to the analysis moving from the aggregated scenario, and if no further specification is made, this is what we mean here for **tsunami damage scenario**.

A further step is to build evacuation maps that can only be compiled after the damage scenario analysis is completed. A specific handbook that is a companion publication of this one is entirely devoted to methods for building evacuation maps and for devising evacuation strategies capable to ensure the most appropriate response in case of tsunami attack (Scheer et al., 2010). Therefore the subject will only touched very briefly at the end of this chapter.

4.1 Assessment of vulnerability

Objects or elements exposed to tsunami attack are very many and belong to different categories. Most of the efforts in the project SCHEMA have been devoted to assess the vulnerability of buildings. Tsunamis can cause damage to buildings depending on several factors that can be synthesised as follows:

- the intrinsic resistance of the constructions due to their structural characteristics;
- the proximity of buildings to the shoreline;
- the wave height affecting the buildings;
- the environment around the building.

The direct mechanical actions which can affect building resistance and lead even to complete collapse are, according to Yeh et al. (2005):

- hydrostatic forces;
- buoyant forces (vertical forces);
- hydrodynamic forces;
- surge forces;
- impact of floating objects and debris and pressure of these objects;
- breaking waves forces.

To this basic physical description one can add:

- total number of waves and backwash events that hit the building;
- flood duration.

Very few of these factors can be easily found in the field and described at the scale of each building over the vast area that is subject to flooding under the action of a big tsunami. This provides the justification for a reductive approach that considers only a subset of such factors or even a single and measurable dimension of the tsunami. In most of the existing methods, the direct damage to a given building is defined only as a function of the flow depth, that is the height of the column of water arriving at the building, with the understanding that buildings should be differentiated according to their structural capacity to resist. In other words, damage level to buildings depends on building type and on inundation depth.

The first approach of this type was proposed by Shuto (1993) and has been reused by various authors more recently. More specifically, the application of the method needs a number of prerequisites such as:

- a standardized building typology;
- a standardized damage scale;
- a damage function for each building type relating damage to flow depth;
- an inventory of buildings

The first step consists in adopting a standardized building types description to qualify all or almost all constructions on the coasts exposed to tsunami hazard. After the tsunami of the December 26, 2004, various authors (Leone et al., 2006 and 2010; Garcin et al., 2007; Reese et al., 2007) have proposed typologies of buildings in order to elaborate vulnerability functions. The building typology proposed here is principally derived from Leone et al. (2006), but has been completed and enlarged in order to include the type of constructions that one can find in the five test sites of the project SCHEMA.

Four main classes of buildings (divided in sub-classes) have been defined on the basis of their structural characteristics of resistance, as is given in Table 5:

- I. Light constructions;
- II. Masonry constructions and not reinforced concrete constructions;
- III. Reinforced concrete constructions;
- IV. Other constructions.

Table 4: *Building typology depending on the resistance capacity of the constructions*

Class		**Building types**	**Height & storeys**
I. Light	A1	Beach or sea front light constructions of *wood, timber, clay*	0 to 1 level Rarely 2
	A2	Very light constructions without any design. Very rudimentary huts, built using *wood or clay, timber, slabs of zinc*	1 level only
II. Masonry, and not reinforced concrete	B1	*Brick not reinforced, cement, mortar wall, fieldstone, masonry*	1 to 2 levels
	B2	Light and very concentrated constructions: *wooden, timber and clay materials*	1 to 2 levels
	C1	Individual buildings, villas: *Brick with reinforced column & masonry filling*	1 to 2 levels
	C2	Masonry constructions made of *lava stones blocks*, usually squared-off, alternating with *clay bricks*	1 to 2 levels
	D	Large villas or collective buildings, residential or commercial buildings: *Concrete not reinforced*	1 to 3 levels
III. Reinforced concrete	E1	Residential or collective structures or offices, car parks, schools: *reinforced concrete, steel frame*	0 to 3 levels
	E2	Residential or collective structures or offices, car parks, schools, towers: *reinforced concrete, steel frame*	> 3 levels
IV. Other	F	Harbour and industrial buildings, hangars: *reinforced concrete, steel frames*	Undifferentiated
	G	Other, administrative, historical, religion buildings	Undifferentiated

The damage level on buildings may be classified through a discrete qualitative scale with increasing severity, from no damage to total collapse. A 6-degree scale was adopted by SCHEMA in agreement with the one proposed by Leone et al. (2010), Peiris (2007) and

Garcin et al. (2007), and is given in Table 6. Here also the possible utilisation of the building in the immediate post-disaster emergency period is suggested (see column 3) as well as how effective satellite observation techniques are expected to be in detecting and assessing the damage level (see the fourth column).

Table 5: *Scale for damage levels of buildings*

Damage Level	Damage on Structure	Use as shelter / post crisis use	Detection by Earth observation
D0 No damage	No significant damage	Shelter / immediate occupancy	No sign of damage visible on building and surrounding environment. The absence of damage cannot be proved only through space imagery.
D1 Light damage	No structural damage - minor damage, repairable: *chipping of plaster, minor visible cracking, damage to windows, doors.*	Shelter / immediate occupancy	Barely visible
D2 Important damage	Important damage, but no structural damage: *out-of-plane failure or collapse of parts of wall sections or panels without compromising structural integrity, leaving foundations partly exposed.*	Evacuation / Unsuitable for immediate occupancy, but suitable after repair	Damage on roof hardly visible. Other damage not visible.
D3 Heavy damage	Structural damage that could affect the building stability: *out-of-plane failure or collapse of masonry, partial collapse of floors, excessive scouring and collapse of sections of structure due to settlement.*	Evacuation / Demolition required since unsuitable for occupancy	Not or hardly visible if roofs have not been removed
D4 Partial failure	Heavy damages compromising structural integrity, partial collapse of the building	Evacuation / Complete demolition required	Visible
D5 Collapse	Complete collapse: *foundations and floor slabs visible and exposed.*	Evacuation	Very visible

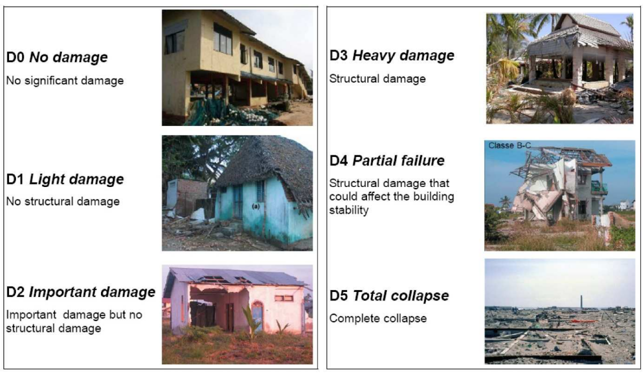

Figure 16: *Examples of structural damage to buildings according to the damage scale proposed in Table 6.*

Figure 16 illustrates the damage scale proposed in Table 6, which classifies the structural damage to buildings in the province of Banda Aceh (Sumatra) after the 2004 tsunami. The pictures assembled in Figure 16 refer to the effects of the disastrous 2004 tsunami in the Indian Ocean (sources: Leone et al. 2010, Peiris 2006 and Garcin et al. 2007).

4.2 *Damage functions and damage matrix*

An approach developed for the estimation of the building vulnerability consists in deriving empirical damage functions starting from field observations (Ruangrassamee et al., 2006; Leone et al., 2006; Peiris, 2006; Reese et al., 2007). The damage level should be linked to the only reliable and uniform dimension of the tsunami magnitude which can be observed or measured after all tsunami events: the maximum flow depth.

The damage functions proposed for buildings have been elaborated from a database compiled in the southwest area of Banda Aceh (Sumatra, Indonesia) that was hit by the 2004 Indian Ocean tsunami. They refer only to building classes A, B, C, D and E1 that could be checked in the studied area by field survey and by photo-interpretation. Unfortunately, the lack of samples concerning building classes E2, F and G in the database of Banda Aceh has not permitted to calculate empirical laws of average damages.

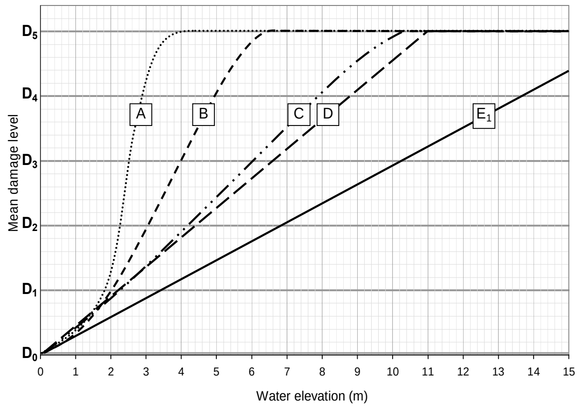

Figure 17: *Damage functions for building classes A, B, C, D, E1 derived from real field observations collected after the Indian Ocean tsunami occurred on December 26, 2004 developed during project SCHEMA by GSC.*

Damage functions were developed from real observations of the weighted mean damage level and the maximum observed flow depth in Banda Aceh area. The resulting function is an enveloping curve which provides the maximum level of damage (according to the damage scale in Table 6) that is expected in correspondence of a given value of the maximum flow depth induced by tsunami. For all curves, damage increases with flow depth. Saturation of the curves at the D5 level, meaning total collapse, occurs to class A (light constructions) with flow depth much smaller than for class E (reinforced concrete): about 4 m vs. more than 15 m. Figure 17 displays such curves plotted together for a better comparison. A detailed description of the method and updated damage functions may be found in Valencia et al. (2010).

Since the damage function given above put in relation a continuous variable (flow depth) with a discrete variable (damage level), it results naturally that each damage level is associated with an interval of flow depth values. In virtue of such consideration, the set of curves plotted in Figure 17 can be also given under the form of a matrix, that may be called **damage matrix** and that is shown in Table 6.

The thresholds have been fixed in order to take into account the worst-case scenarios. The damage level D0 corresponds only to the non-flooded areas, in other words to the areas where the water level is equal to zero. Above 0 m of water, there is a chance for the buildings to suffer at least from minor damages. From Table 6 it is seen that a tsunami that is so severe as to inundate with a flow depth larger than 12.5 m is expected to cause the complete collapse of all the constructions up to the category E1 that happen to be on its way.

Table 6: *Damage matrix adopted in the project SCHEMA. Values of the flow depth are given in meters.*

Damage level	**Lower and upper values of the flow depth (m) for each building typology**				
	A	**B**	**C**	**D**	**E1**
D0: *No damage*	0	0	0	0	0
D1: *Light damage*	0 1.8	0 2	0 2.5	0 2	0 3
D2: *Important damage*	1.8 2.2	2 3	2.5 4	2 4.5	3 6
D3: *Heavy damage*	2.2 2.6	3 4	4 6	4.5 6.5	6 9.5
D4: *Partial collapse*	2.6 3.8	4 5	6 8	6.5 9	9.5 12.5
D5 : *Total collapse*	> 3.8	> 5	> 8	> 9	> 12.5

4.3 Creating a building inventory for tsunami scenarios

A **standardised building typology** (Table 4), a **standardised damage scale** (Table 5) and a **standardised damage matrix** (Table 6) are three of the four prerequisites that were listed in the first section of this chapter and that are needed to build tsunami damage scenarios.

Creating a building inventory is a quite demanding task that can find great benefits from collaboration with local administration and consultation of public cadastral archives or public databases. Often such data bases are given in the form of thematic layers of GIS archives produced, maintained and distributed by public institutions or agencies with responsibility on the territorial information and on territorial mapping. However, data from public archives, if available, often are insufficient since several parameters needed for characterisation of buildings in regard to tsunami vulnerability may not be found there, and specific activities of data acquisition have to be undertaken.

In all test sites of the project SCHEMA a great care has been devoted to creating a suitable database of buildings with the aim to allocate a vulnerability class to each construction by photo-interpretation according to the buildings' typology adopted (see Table 4). The analysis is to be restricted to the coastal zone and in principle should be only carried out within the flooded area. However, since the maximum extent of inundation is only known at the end of the tsunami hazard scenario phase, one can perform his studies in a larger area that is expected to include the maximum area of inundation and that can be determined on the basis of rough overestimation of the local tsunami height. All possible data should be used to assemble the building inventory in the site of responsibility, complementing the available public databases with satellite images and with in-field surveys. Satellites imagery interpretation is a powerful tool for a massive classification of very many constructions, but needs validation against ground-based observations.

Figure 18 is an example taken for the test site of Mandelieu due to GSC: the same building attributed to class B is seen from the ground and identified in satellite image, which permits one to attribute the same class to other constructions in the surrounding having the same or similar aspect.

In the set of Figures from 19-21, maps of the distribution of the constructions types for the test sites of Rabat, of Mandelieu and of Balchik are shown to illustrate the results obtained at local level. Standardisation of the palette for the graphical symbols (coloured circles) identifying the building classes favours the comparison between the various test sites. It is stressed that, on creating the buildings inventory, the main goal is to classify each construction that is found in the exposed coastal zone. However, in case of very high house density, like in the centre of Rabat, analysis of individual buildings is a quite hard and not very useful task, and classification can be instead applied to blocks characterised by buildings of the same type. The buildings' density of the blocks depends on the urban architectural conditions.

Figure 18: *Classification of a building from a satellite Google Earth image (below) validated through a picture taken during a field survey (above) carried out by GSC in the Mandelieu test site.*

Figure 19: *Map of the buildings' typology on the coast and river bank of Rabat, after the work of CRTS. Copyright Quickbird image, 2008-09-28, res: 0.63m.*

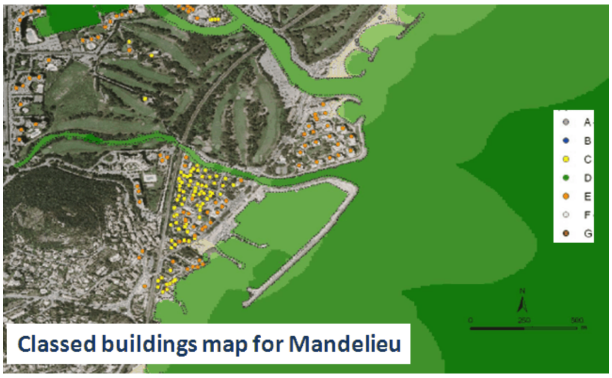

Figure 20: *Buildings' typology distribution of Mandelieu, mapped by GSC*

Figure 21: *Buildings' typology distribution for the harbour of Balchik, after SRI-BAS*

4.4 *Inventories of other relevant objects*

In addition to buildings and constructions, there are many other objects contributing to the damaging effects of a tsunami. Some of these are relevant since they can increase the consequences of a tsunami on buildings, but others are relevant as they are intrinsically vulnerable or because their total or partial unavailability due to the tsunami attack can have strong negative impact either on the short-term response capacity (rescue and relief) or on the long-term resilience of the affected population. In the first category, one can include all those objects that can be easily mobilised and carried by the tsunami currents in the form of floating debris, which is known to increase significantly the destructive power of tsunamis. The main elements of potential debris have been identified in vehicles on land (for instance motorcycles, cars and even trucks, trailers and buses), as well as heavy boats and vessels in the sea. The main source areas for these objects are heavy traffic roads, open parking places in the proximity of the sea and marinas. Since some of these objects may have high economic value per se, they can also be included in the second of the above mentioned categories. Objects in the third categories are typically lifelines (e.g. electric power, telecommunication, water and waste water, gas), civil protection emergency structures (fire brigade service centres, hospitals and emergency medical centres) and transportation networks including airports, ports, railway and bus stations as well as relevant infrastructural elements such as bridges.

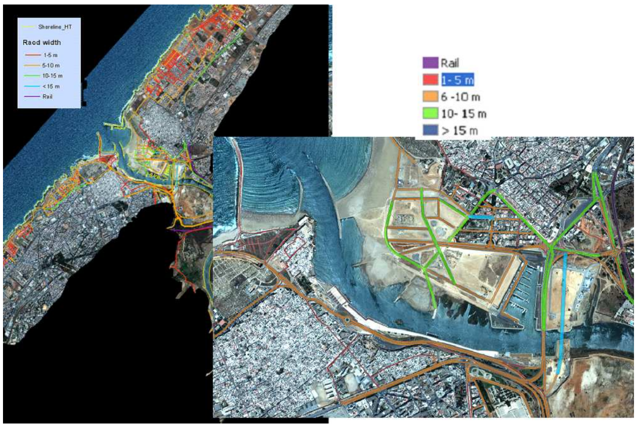

Figure 22: *Road classification based on the road width in the belt close to the shoreline and to the banks of the river Bouregreg in the Rabat test site (CRTS). Copyright Quickbird image, 2008-09-28, res: 0.63m.*

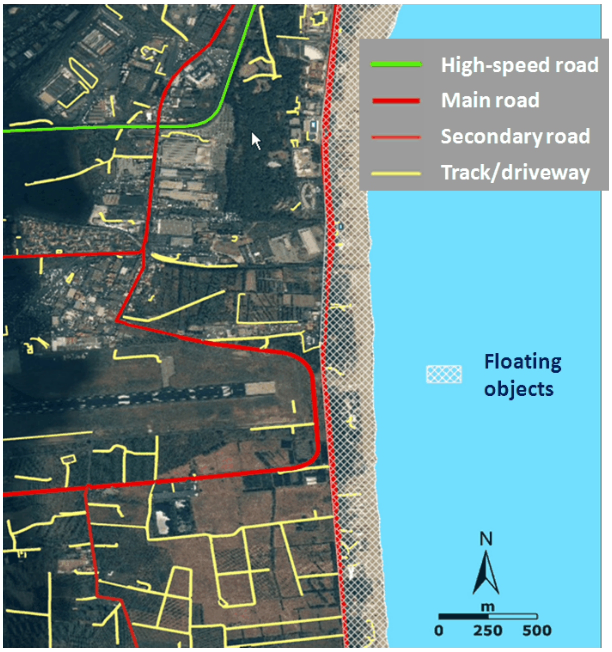

Figure 23: *Road classification based on road relevance in the coastal belt of La Plaia south of Catania test site. Also areas that are a potential source of floating objects, such as light wooden beach constructions are shown (UNIBOL).*

A quantitative assessment of tsunami damage to these additional elements is quite complex and has not been undertaken in the project SCHEMA. However, partners in connection with the end users have identified the most critical elements and have created suitable thematic maps to be added to the ones of the building classification. In all test sites, one element that was considered of great interest was the road network, with roads classified according to their width and their relevance (from unpaved dirt tracks up to high-speed roads and highways).

Examples of road classification in the proximity of the potentially flooded area are given in Figure 22 and in the next Figure 23 referring respectively to Rabat and Catania.

4.5 Tsunami damage maps

Damage maps are the basic elements of a damage scenario. They can be built only after the tsunami hazard scenario and the vulnerability analysis have been fully completed, since they provide the basic input according to the sketch represented in Figure 1. By combining the aggregated fields of flow depth resulting from the tsunami hazard scenarios with the distribution of buildings resulting from the building inventory and by making use of the damage matrix, it is possible to estimate the level of damage to each building that is produced by the worst-case credible aggregated scenario. This procedure was applied not only to the aggregated scenarios, but also to the augmented scenarios, i.e. the scenarios dealing with sources of increased size, in order to explore how results are sensitive to changes in the sources. Furthermore, such an analysis was also undertaken for the individual scenarios.

It is noticed here that from a logical point of view, scenarios can be seen as thematic layers of a GIS and the aggregated scenario is a new layer that results from selecting in each space point of the layer the worst (most severe) case. On the other hand, even maps resulting from the vulnerability analysis (classed buildings distribution, road network maps, etc.) may be fed into a GIS database in the form of specific layers. Crossing flow depth layers with buildings layers through the filter of the damage matrix in order to evaluate the damage to each building is an operation that can be automatically carried out in a GIS environment, if specific computational tools are developed. This operation has been performed in all test sites of SCHEMA. The following Figures display some of the results of the project. Figure 24 shows the damage scenario at the mouth of the Bouregreg river (Rabat). The aggregated scenario coincides with the scenario associated with the 1755 earthquake source (augmented and in high-tide conditions). Notice that many constructions in low land turn out to be severely damaged or destroyed.

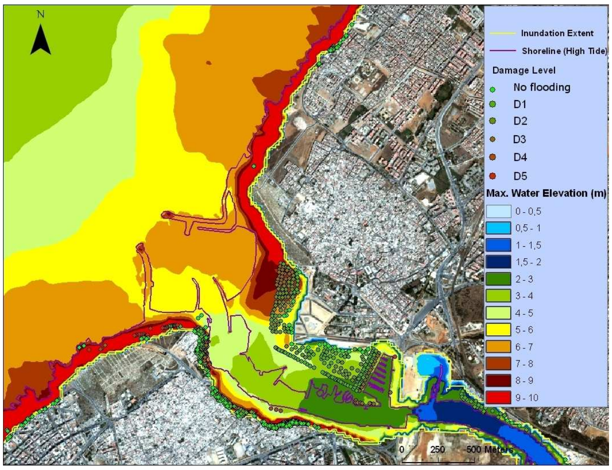

Figure 24: *Damage scenario zoomed on the mouth of the Bouregreg river resulting from the collaboration between ACRI-ST and CRTS. Copyright Quickbird image, 2008-09-28, res: 0.63m.*

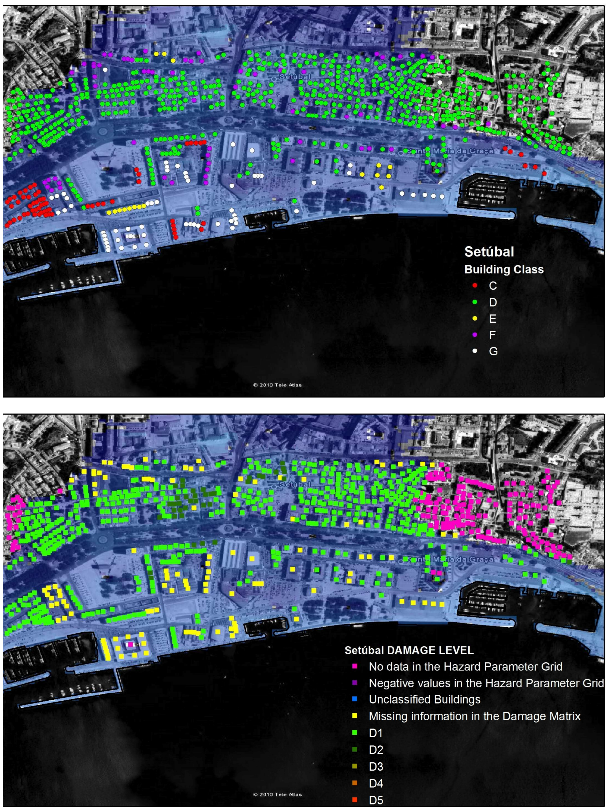

Figure 25: *Buildings typology distribution (upper panel) and damage scenario (lower panel) for the harbour town of Setúbal calculated by HIDROMOD. Notice that no evaluation of damages (yellow square) is possible for those classes (F and G) for which no entry in the SCHEMA damage matrix is available.*

Figure 25 shows the buildings distribution (upper panel) as well as the damage scenario (lower panel) for the town of Setúbal. Even for this test site the damage scenario is the one associated with the 1755 earthquake in condition of high tide. It is seen that the tsunami penetrates a long distance into the town with very substantial flow depth causing severe damage (D3-D4) to very many buildings. It is worth observing that there are constructions belonging to classes F and G for which no fragility curve has been elaborated in SCHEMA and hence no entry in the damage matrix is available. The consequence is that no evaluation of damage is possible for such buildings.

Figure 26 depicts the damage scenario calculated for the area located south of the town of Catania called La Plaia (which is a famous touristic attraction thanks to its beautiful sandy beach). According to studies by the UNIBOL team, the aggregated scenario is mainly dominated by the scenario based on the 365 A.D. earthquake in the western Hellenic Arc and by the scenario built on the 1908 earthquake combined with a landslide. Land is here quite flat and the scenario tsunami can penetrate a long distance from the shore.

Most of the constructions built on the beach, that are predominantly temporary facilities mainly for tourists, result to be damaged by the tsunami.

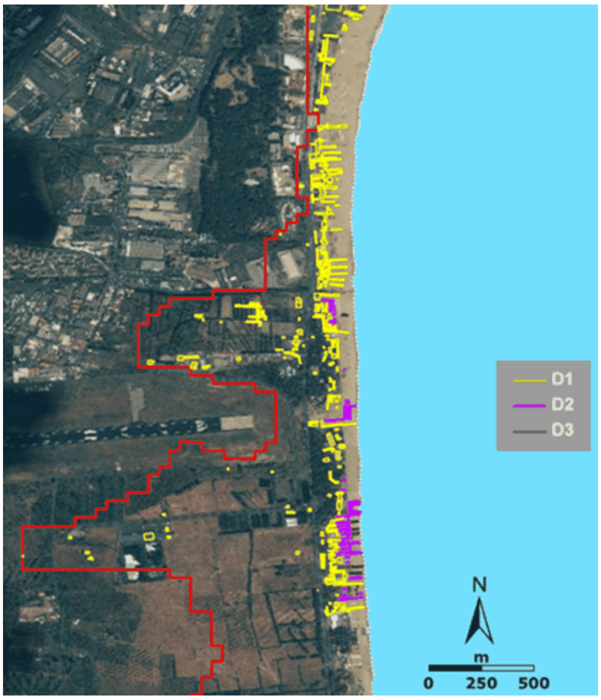

Figure 26: *Aggregated damage scenario computed in the area of La Plaia south of Catania by UNIBOL for the augmented sources. Most constructions on the beach result to be damaged, but flow depth is too low to cause them to collapse*

Figure 27 gives two distinct damage scenarios for the two earthquake sources selected for the Balchik test site. Since the characterisation of the local tectonic is poor, the two sources represent in practice two fault hypotheses for the same earthquake source, differing only in the strike angle: 40° strike vs. 90° strike. The corresponding scenarios are portrayed respectively in the upper and lower panel. Though the second tsunami results to be quite stronger than the first one, the damage scenarios do not differ very much from one another. Tsunami impact seems to be weak and only a few constructions on the sea front are lightly damaged.

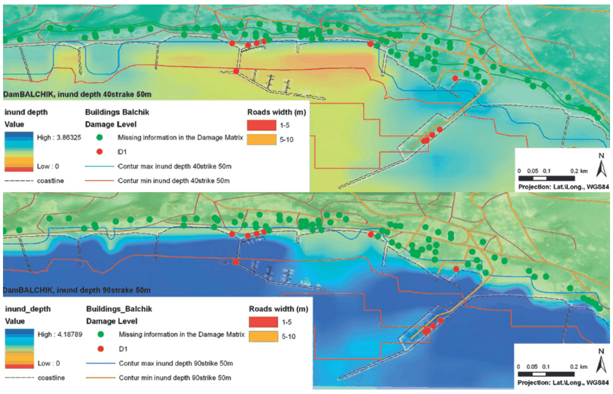

Figure 27: *Damage scenarios computed in Balchik test site by SRI-BAS and NOA-GI for a local earthquake fault striking 40° (upper panel) and striking 90° (lower panel).*

It is worth stressing that for the production of damage maps, a software package (DamASCHE) has been developed as a module for ArcGIS. Three types of input are required by this module: a raster layer representing the hazard parameter; a shapefile layer of points representing the buildings locations, with a file containing information on their vulnerability class (“A”, “B”, “C” or “D”); and the damage matrix. The DamASCHE tool overlays the different data layers and gives the estimated level of damage expected for each building as a function of its building class and flow depth foreseen in its location.

4.6 Mapping other damage factors

Buildings inventories and maps of expected damage to buildings are not the only elements that characterise damage scenarios, but other factors may concur. Indeed producing tsunami damage scenarios means combining data from tsunami hazard scenarios not only with the vulnerability criteria regarding buildings, but also with criteria regarding the exposed elements that have been introduced in section 4.4 and regarding the population that is found systematically (e.g. residents, people at work) or occasionally (e.g. tourists) in the coastal areas affected by tsunamis.

Several secondary factors that can affect buildings could increment the expected level of damage. One of such factors is the volume of floating debris, and main sources of debris have been identified in open parking places and marinas from which tsunami currents can raise cars and boats and then carry them violently against building walls and columns or even on the top of the roofs. Figure 28 shows the areas reserved for car parking and the marinas with moored boats that happen to lie within the area inundated by the tsunami associated with the 1755 scenario for the Setúbal test site. Only the information is provided, but no further elaboration is made, since there is no quantitative way to link the presence of debris sources to the damage level of buildings downstream. It can only be stated that damage will be increased, or in other words, that computations performed only with the damage matrix could lead to underestimate the damage in some cases.

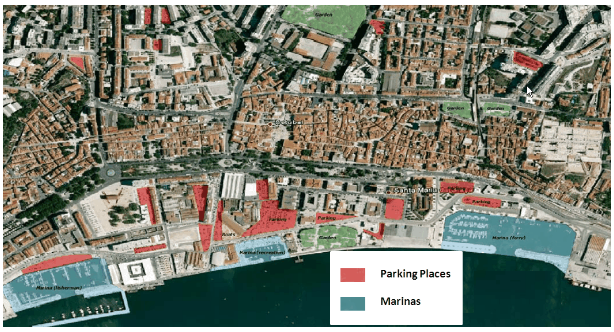

Figure 28: *Marinas and parking places identified in Setúbal that are found within the inundation area of the tsunami hazard scenario (HIDROMOD).*

Figure 29: *Map of obstacles and accessibility for Mandelieu test site (GSC). Beach stairs, pedestrian tunnels under railway and walls all along the beach can be obstacles or critical points in case of evacuation.*

Mapping road network and potential obstacles provides an immediate view of possible local interruptions and problems that could be encountered in case of evacuation or accessibility to the affected area. Figure 29 shows the map of obstacles and road system for the Mandelieu test site. Tsunami hazard scenario of the Boumerdes-Algiers earthquake in Mandelieu does not provoke substantial inundation, but, as proven by the tsunami scenario, in some places the littoral road can be flooded and potentially interrupted, which is an element of paramount importance in view of evacuation or rescue operations. The evacuation could become critical due to obstacles in the beach area as beach stairs, pedestrian tunnels, railway tracks and walls along the beach.

An example comes from the test site of Catania. The road network in proximity of the area of La Plaia (Catania) is severely affected by the tsunami aggregated scenario that penetrates more than 1 km inland. Though there is no quantitative analysis of the possible damage to roads, the extension of the affected area may give some reasonable hints that roads might be interrupted in several points. This would probably cause that the beach of La Plaia, populated by thousands of tourists in the summer peak season, remains isolated and not accessible from land by rescue teams.

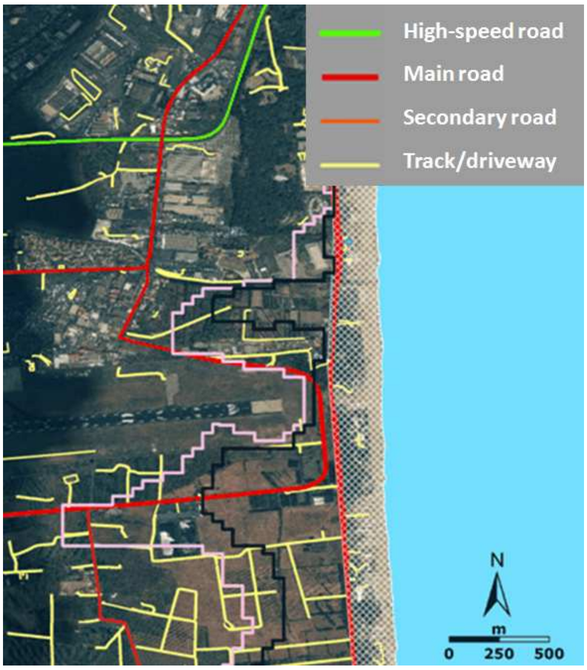

Figure 30: *Roads in the area of La Plaia, Catania, plotted together with the inundation line (pink) for the aggregated scenario (resulting from augmented sources). The entire main roads system is affected by the tsunami with the consequence that the beach of La Plaia might be isolated and hardly reachable from land by rescue teams in case of emergency (UNIBOL).*

5 Conclusions and perspectives

This handbook shortly illustrates the main concepts of a methodology for tsunami hazard assessment and for damage evaluation that is based on scenarios, and more precisely on individual worst-case credible scenarios to be aggregated in a final scenario.

We have given reasons why worst-case scenario approaches should be preferred to probabilistic scenarios when return periods of the tsunamigenic sources are far from being determined, which is almost always the case when tsunamigenic landslides are concerned. We have pointed out that concepts like credibility and worst-case are quite subjective and that, therefore, also subjective is the selection of tsunami sources, which is the starting point of the method.

A way to reduce subjectivity or to cope with subjectivity is to allow for a certain degree of flexibility in the source parameters. We have treated this possibility under a slightly different point of view in the handbook, since it was introduced under the name of sensitivity analysis.

One of the pillars of the method is the development of tsunami hazard scenarios: this is carried out by selecting the largest tsunami sources affecting a given target area, and then by running tsunami simulations in order to compute the tsunami impact. Tsunami modelling is therefore a basic tool, and this requires good models and good input data. As for the latter, it has been stressed that bathymetric and topographic data of good quality (accuracy and resolution) are needed especially in the coastal belt zone (offshore and onshore), which usually implies a lot of efforts for data collection and processing. The major interest resides in the computation of the tsunami behaviour at the coast, which includes interaction with small-scale features like harbour breakwaters and jetties, inundation of dry land, interaction with on-land structures, penetration along rivers. All these aspects are handled by the last-generation tsunami simulation models, but all such models imply approximations of the hydrodynamic equations especially in the proximity of the mobile shoreline and of field discontinuities or strong gradients that need to be managed with care to avoid that possible model artefacts be exchanged for real physical effects.

The tsunami hazard scenario has been defined by means of the set of products that the analysis gives as output, in the form of maps and graphs, by distinguishing between the propagation in the large scale (regional scenario) and in the small scale (local scenario), the latter being the most relevant for setting up scenarios of damage. Consequential to the possibility to define a multiplicity of tsunami sources and therefore of scenarios for a given target, is the concept of aggregation that combines all the scenarios in a single one. In the worst-case scenario approach, aggregation simply implies to select at each space position the most intense value among the ones computed for the various scenarios.

The second pillar of the method is the vulnerability analysis using earth observation imagery and field survey. This basically is requested to identify the elements exposed to tsunami hazard and to define some relationships between the intrinsic features of these elements and the physical parameters describing the tsunami hazard. Our method has put buildings at the centre of the scene, by defining a building classification, by introducing a qualitative damage scale, by determining damage functions for each building class (or equivalently a damage matrix) that relate the damage level to the tsunami flow depth, and by setting up inventories of the buildings' typology in coastal zones by photo-interpretation.

Finally, the collaboration with end users and local stakeholders allowed refining the developed vulnerability-assessment methodology according to their needs. The production of scenarios was compiled in an Atlas for each test site in order to support stakeholders (civil protection, local authorities) in crisis preparedness and management for tsunami hazard.

Challenges start just here. They mainly regard how to take into account other vulnerable elements in addition to buildings, and how to take into account other factors in addition to depth flow to better estimate damage to buildings.

In the handbook we have provided a first initial answer to this problem. For example, we have identified factors that can increase the damage level for buildings (aggravating factors such as sources of mobile, potentially floating, objects in the upstream side of buildings: open car parking places, marinas) and we have added them on the maps. We have also identified strategic vulnerable elements such as lifelines, emergency service centres, and road networks. Even in this case, our answer has been mapping and crossing them with the inundation line resulting from the tsunami hazard scenario in order to check if they happen to lie within or outside the flooded area.

The partners of SCHEMA have fully applied the methodology outlined here and have computed all the scenarios described here for the five test sites selected in the project. Very detailed accounts of the various steps can be found in the documentation of the project (www.scemaproject.org). As mentioned before, for each test site an Atlas in original national language has been produced containing all the maps covering the tsunami hazard scenarios up to the tsunami damage scenarios. Figure 31 displays one page of the Atlas produced by CRTS and by ACRI-ST for the test site of Rabat.

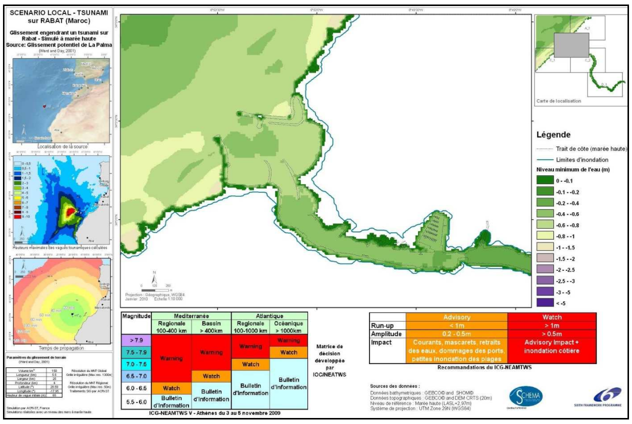

Figure 31: *Example of a detailed local scenario selected from the Atlas focussed on the Rabat test site. The maximum water withdrawal is shown in the main picture together with the maximum inundation line for the La Palma potential scenario. General information on the specific scenario is given by the surrounding images at regional scales together with tables containing information useful for warning strategies.*

In the future, more complete answers are to be elaborated and a more quantitative approach has to be devised for all categories of vulnerable objects and not only for buildings. This is quite complex because a physical model describing the interaction of tsunami with such objects is needed and because such objects may also interact with each other and not only with the water flow.

Separate considerations are to be made as regards human beings and human losses. The individual and societal aspects of a disaster in general and of a tsunami disaster in particular have been the subject of numerous studies especially after the 2004 Indian Ocean event. It was then recognised that local communities have their own proper dimension and that many actions (rehabilitation, resilience) and countermeasures (tsunami warning systems and evacuation plan implementation) cannot be solved without the direct involvement of local people. Such studies, so far, have not produced viable methods for defining vulnerability of persons and of coastal societies as a whole and not even for defining some damage multidimensional matrices on the basis of quantitative analyses.

A final remark on possible future extension of the method regards the multi-hazard approach. A tsunami scenario often has little value if it is examined alone. Indeed often a tsunami is caused by a local earthquake, so that the target area is affected both by seismic shaking and by tsunami waves. Hence, vulnerable objects such as buildings are to be resistant to both kinds of soliciting forces. The tsunami can affect a building after it has been weakened by the earthquake, and an aftershock in turn can affect a building after it has been attacked by a tsunami. Multi-hazard needs therefore that a more complicated physical model is used and also that different scientific communities talk each other and cooperate in a multidisciplinary approach.

These are the challenges for the future. These are the problems that end users and coastal population under risk ask us to solve. These are the problems we like to solve.

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Annex A – The project SCHEMA

SCHEMA is a research effort that has been carried out by a consortium including initially eleven organizations based not only in the European Union, but also in Turkey and in Morocco (see Annex B). The partnership aimed at using Earth observation data in order to develop a general methodology suitable for helping experts to build up hazard, vulnerability and impact damage maps related with the occurrence of tsunamis. The project has been coordinated by Geosciences Consultants (GSC), a French private enterprise based in Paris. It has been launched in August 2007 with duration up to the end of October 2010 and financed by the European Commission within the 6th Framework Programme.

The key features of the research and development work under SCHEMA can be summarised in the following bullet points:

- the clarification of concepts such as vulnerability, hazards, scenarios, in order to produce documents and maps accessible and understood by end-users (civil protection, rescue planners);
- an analysis of mathematical modelling limitation to reproduce reality in order to assess the degree of uncertainty when risk is estimated on models and not on real past events;
- the development of a general methodology, validated by end users, to produce scenarios for tsunami and for related phenomena hazardous impact;
- the extraction of vulnerability and hazard level indicators, as used in the general methodology, from Earth observation data;
- a first validation of the methodology on real life cases as observed during the recent tsunami in Asia;
- a thorough validation of the resulting prototype methodology on 5 test sites typical of different environments (Setúbal in Portugal, Rabat in Morocco, Mandelieu in south France, Catania in Italy and Balchik in Bulgaria).

SCHEMA partners have worked keeping end users in mind and the advantages to them deriving from SCHEMA research and products. These benefits can be synthesized in the list below:

1. for civil security organisations: a comprehensive and homogeneous technique to assess tsunami and related phenomena risk levels based on intrinsic vulnerability variables (building heights, building types, inhabitant description) and environment variables (density of buildings per unit area, road width,…) and, thus, a technique capable of helping them to develop general preventive emergency measures;
2. for rescue planners: a clear-cut description of accessible areas under multi-disaster occurrence, to help rescue planners design effective rescue operations providing them the tools to evaluate vulnerability variables under crisis organisation modes;
3. for public safety policy makers: a set of policy recommendations to standardise data collection and preparation for vulnerability studies, based on tsunami and related phenomena simulation scenarios that concentrate prevention and education efforts within the most exposed areas;
4. for insurance companies: useful spatial data related to potential maximum claims for building damages within potentially flooded zones, thus allowing them to answer questions such as: what level of premiums should be set for buildings, content loss and business interruption loss insurance in risky areas? What is the potential level of claims for a particular portfolio of insured assets in a given location?
5. for land management and planners: the approach that combines models, field surveys and vulnerability assessments should be used as an input in the planning of coastal management and taken into consideration when building or modifying a coastal zone exposed to a tsunami hazard.

In view of achieving the project goals, the SCHEMA partners have identified six specific Objectives (Obj) and have structured the work in as many Work-Packages (WP), that are given side by side in Table A1. A seventh WP covers the project coordination and management.

Table A1: *Work Packages (WP) and Objectives of the SCHEMA project.*

WP	**Description**	**Objectives**
1	Lessons learnt from on going research and Indian Ocean tsunami	*To draw, from post-disaster studies of the 2004 Indian Ocean tsunami, input and output data required for hazard modelling, vulnerability/damage assessment and emergency management involving tsunami threats.*
2	Definition of requirements for consensual description of tsunami hazard intensity, damages, vulnerability and evacuation	*To specify consensual rules that provide hazard, vulnerability and damage scenario descriptions to be used by security/relief managers, rescue planners and policy makers.*
3	Development of a methodology for vulnerability mapping and design of an approach for crisis scenarios elaboration involving tsunami	*To design and develop a scenario elaboration methodology, in coordination with rescue and relief operators.*
4	Building prototype scenarios of events and evacuation plans on five test sites	*To propose tsunami-based disaster scenarios in five selected test sites, involving earthquakes with or without early warning systems, and providing relevant evacuation schemes, with appropriate rescue and relief processes in line with cascading events (earthquake or landslides followed by a tsunami).*
5	Prototype scenario validation by local authorities and feedback to the scenario design methodology	*To validate the general scenario development methodology based on reviewing results in the test sites with policy makers, field relief and rescue operators, city planners and civil security organisations.*
6	Methodology transfer and dissemination with harmonization of recommendations	*To disseminate the resulting methodology through relevant workshops and by using web portals.*
7	Coordination and strategic management	

Annex B - Partners of the SCHEMA consortium

Logo	Short name	Country	Expertise	Role in SCHEMA project
	GSC	France	All natural hazards, vulnerability assessment, damages assessment, Earth observation. Mitigation measures and vulnerability reduction	**Coordinator** Methodology to build up GIS mapping of natural hazard and damages. Work on the French test site
	ALGOSYSTEMS	Greece	GIS, management of natural hazards, multirisk assessment	Dissemination and user feed back. Work on evacuation simulation
	HIDROMOD	Portugal	Wave propagation modelling, emergency response planning	Tsunami modelling, work on the Portuguese test site
	UNIBOL	Italy	Tsunami observations, generation mechanism, modelling, hazard and risk assessment	Methodology build up, tsunami modelling, work on the French and Italian test sites
	UNICOV*	United Kingdom	Risk/vulnerability/ capability assessment, scenario development	Tsunami vulnerability assessment, crisis management, users feed back
	NOA-GI	Greece	Earthquake monitoring, seismic and tsunami hazard assessment, studies on seismic and tsunami sources, tsunami modelling and risk mapping	Methodology build up, tsunami modelling, work on the Bulgarian test site
	CRTS	Morocco	Morocco Earth observation in charge of hazard mapping for Morocco, vulnerability assessment	Vulnerability assessment, work on the Moroccan test site
	ACRI-ST	France	Fluid dynamics, geophysics, ocean modelling, surveillance and forecast of the Earth environment, integrated on-line Earth observation systems	Methodology build up, tsunami modelling, work on the Moroccan test site, contributing to work on the French test site
	SRI-BAS	Bulgaria	Earth remote sensing, onboard systems, geoinformatics	Vulnerability assessment, work on the Bulgarian test site
	JRC-IPSC	European Commission	Hazard assessment and prevention, vulnerability assessment, users needs assessment	Dissemination and feedback from user panel. Work on evacuation plans.
	TUBITAK – MRC-EMSI	Turkey	Earthquake and tsunami hazard mapping and assessment, geophysical monitoring, natural processes modelling	Exchange of experience on on-going work related to earthquake and tsunami in Turkey. Feedback from local users

* Partner withdrawn in the course of the project

Annex C – SCHEMA website

The project SCHEMA website can be found at http://www.schemaproject.org. The web site provides all the essential information about the project and thanks to the horizontal navigation menu one can easily have a synthetic view of it ("Project description") and of its main "Objectives". Furthermore some details can be found on the work flow ("Work packages"), on the "Test sites" and on the partners involved ("Partnership").

An additional vertical navigation menu is available providing information related to the work done during the project: namely, the list of the final deliverables describing the different phases of the project ("Publications"), the list of the meetings organized to allow exchange of results and data among partners ("Meetings"), the list of the works presented at international meetings and papers published in international journals resulting from the efforts of the partners in the frame of SCHEMA ("Dissemination"). A further button, "News" gives the last updated information to partners. Finally, clicking on the "Links" section, one gets a list of links to related projects or to websites containing information on related topics.

The restricted area ("Consortium area") allows partners to log in and share material, data and opinions in a confidential way.

Figure 32: *Homepage of the SCHEMA project website.*

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European Commission

EUR 24691 EN– Joint Research Centre – Institute for the Protection and Security of the Citizen
Title: Handbook on Tsunami Hazard and Damage Scenarios
Author(s): S. Tinti, R. Tonini, L. Bressan, A. Armigliato, A. Gardi, R. Guillande, N. Valencia, S. Scheer
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Abstract
The handbook on tsunami scenarios is the result of an intense work performed under the European FP6 co-funded project SCHEMA in a 39 month period from 2007 to 2010 by a Consortium of 11 partners led by Geosciences Consultants (Paris). The handbook is one of the products of the project and has been conceived to illustrate the basic concepts and methods elaborated and applied in the project to produce tsunami scenarios in view of providing tools to assess tsunami hazard and potential damage. One of the main objectives was the elaboration of a general methodology that can be used in all possible cases and that can be easily adapted to the needs of the end users, i.e. chiefly the public administrators responsible for planning of the coastal zone development and protection strategies as well as people and organisations involved in disasters management and mitigation policies. For these reasons, the SCHEMA methodology has been applied to five test sites (Rabat, Morocco; Setúbal, Portugal; Mandelieu, France; Catania, Italy; Balchik, Bulgaria) differing very much from one another, and it has been tested with the active involvement of the end users, so ensuring that it will provide practical and useful tools and it is flexible enough to cover local needs.

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