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Natural Hazards and Earth System Sciences

Integrated approach for coastal hazards and risks in Sri Lanka

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Abstract. The devastating impact of the tsunami of 26 December 2004 on the shores of the Indian Ocean recalled the importance of knowledge and the taking into account of coastal hazards. Sri Lanka was one of the countries most affected by this tsunami (e.g. 30 000 dead, 1 million people homeless and 70% of the fishing fleet destroyed). Following this tsunami, as part of the French post-tsunami aid, a project to establish a Geographical Information System (GIS) on coastal hazards and risks was funded. This project aims to define, at a pilot site, a methodology for multiple coastal hazards assessment that might be useful for the post-tsunami reconstruction and for development planning. This methodology could be applied to the whole coastline of Sri Lanka.

The multi-hazard approach deals with very different coastal processes in terms of dynamics as well as in terms of return period. The first elements of this study are presented here. We used a set of tools integrating a GIS, numerical simulations and risk scenario modelling. While this action occurred in response to the crisis caused by the tsunami, it was decided to integrate other coastal hazards into the study. Although less dramatic than the tsunami these remain responsible for loss of life and damage. Furthermore, the establishment of such a system could not ignore the longer-term effects of climate change on coastal hazards in Sri Lanka.

This GIS integrates the physical and demographic data available in Sri Lanka that is useful for assessing the coastal hazards and risks. In addition, these data have been used in numerical modelling of the waves generated during periods of monsoon as well as for the December 2004 tsunami. Risk scenarios have also been assessed for test areas and validated by field data acquired during the project. The results obtained from the models can be further integrated into the GIS and contribute to its enrichment and to help in better assessment and mitigation of these risks.

The coastal-hazards-and-risks GIS coupled with modelling thus appears to be a very useful tool that can constitute the skeleton of a coastal zone management system. Decision makers will be able to make informed choices with regards to hazards during reconstruction and urban planning projects.

1 Introduction

The devastating impact of the tsunami of 26 December 2004 on the shores of the Indian Ocean recalled the importance of knowledge of coastal hazards. Sri Lanka was one of the countries most affected by this tsunami (e.g. 30 000 dead, 1 million people affected and 70% of the fishing fleet destroyed). The project described here involves teams from both Sri Lanka and France and has amongst its aims the establishment of a Geographic Information System (GIS) on coastal hazards and risks for a pilot site (Garcin et al., 2007). Thus, the objective is to build a prototype of a coastal-zone management system that could be extended to the whole coast of Sri Lanka. In parallel to the GIS, numerical modelling aiming at better constraining the size of some coastal processes was carried out as well as the simulation of tsunami risk scenarios. This type of approach merging a GIS, numerical and scenario modelling allows the assessment and mapping of the coastal hazards and risks. It also facilitates the taking into account of the coastal hazards in current reconstruction projects and future developments. In the following section, we present the pilot site, the various coastal

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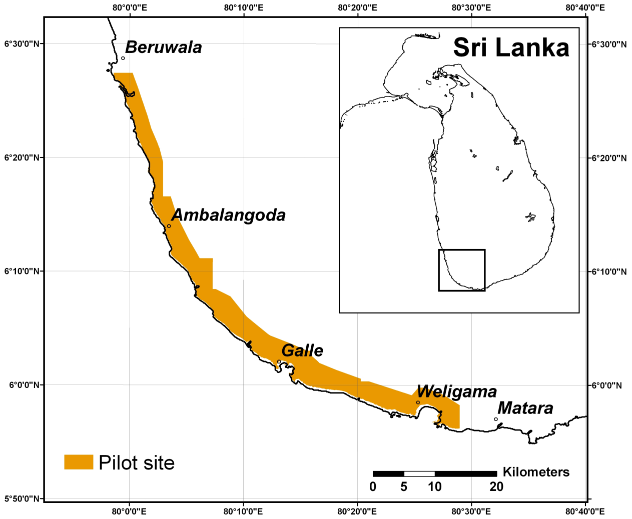

Fig. 1. Location map of the pilot site.

processes and hazards considered in the project and the assets that we have taken into account. Next, the different tools and the methodology used are presented and finally we present some conclusions.

2 The pilot site

The pilot site covers the 2 km wide and 80 km long coastal strip from Beruwala to Welligama Bay on the south-western coast of Sri Lanka (Galle District; Fig. 1). It has been chosen for its representativeness of the Sri Lankan coast in terms of coastal morphology, processes, hazards and human assets (e.g. population density and built environment, fisheries, trade and tourist areas). One of the objectives of this project was to integrate various data sources and format into a single information system. It was, therefore, necessary to identify all existing data from different agencies in Sri Lanka and then to format, digitize geo-reference and integrate them. In addition, some essential missing data were acquired for limited areas for demonstration purposes.

3 Coastal processes and hazards

In order to have a good understanding of the coastal risks, it is essential to understand the chain of processes that lead to them. It is first necessary to identify the coastal processes responsible for hazards. These initial processes can be entirely natural, or can be partially modified by human actions at local, regional or global scales. These processes at the root of hazards can, by way of interactions and feedbacks, minimize or maximize the hazard levels. The same process can play a role in one or more hazards. For example, tsunamis beyond their obvious role in the tsunami hazard can cause significant changes in the coastal morphology and/or the coastline and, therefore, they can have implications for the processes of erosion, transportation and coastal sedimentation leading to a modification of the erosion hazard and morphology of the coastal zone. These changes in the near-shore bathymetry in turn will impact on the tsunami hazard (feedback loop).

The presence of towns, villages and activities in the coastal zone led to a growing exposure to hazards. The evaluation of the assets exposed to hazards is not straightforward because of their diversity (the exposure to tsunami hazard cannot be evaluated in the same way as exposure to erosion).

Additionally, the vulnerability assessment of the asset exposed is dependent on each hazard (the vulnerability of an asset at tsunami is very different to its vulnerability to erosion).

3.1 Coastal processes and hazards typology

3.1.1 Temporal dimension

The coastal processes leading to hazards can be continuous (sea level rise associated with climate change is one example) or discontinuous (e.g. storm surge and tsunami; Table 1). The time scale on which we analyze a process may, in some cases, lead us to consider it as a discontinuous process (e.g. coastal erosion analyzed at a daily time scale) or as a continuous process (e.g. the same coastal erosion analyzed at the decade time scale). Another characteristic of the coastal multi-hazard approach is the variability of the return periods associated with each type of hazard. In the case of Sri Lanka, some of them have an annual return period (e.g. erosion and a storm surge triggered by the monsoon), multi centennial (e.g. a storm surge triggered by cyclones), or even multi centennial to millennial (e.g. a major tsunami).

The sea level rise linked to climate change is specific as it cannot be characterized by a return period but more adequately by a characteristic time of several centuries. This process will be perceptible in few decades and is classically evaluated for 2100.

3.1.2 Effects typology

Three types of effects induced by coastal processes lead to hazards (Table 1):

- Coastline changes (induced by coastal erosion, landslides, mass wasting of the coastal cliffs and by major tsunamis);
- Instantaneous reversible marine inundation of short duration (linked to monsoon, cyclone or tsunami);
- Progressive and irreversible marine inundation (sea level rise linked to climate change).

Table 1. Typology of the coastal processes taken into account in this project.

Process	Type	Time / Return period	Typology of effects	Reversibility
Tsunami	discontinuous	centennial to millennial	submersion & coastline retreat	reversible (submersion), irreversible (coastline retreat)
Storm surge	discontinuous	supra annual	Submersion	reversible
Coastal erosion	discontinuous / continuous	infra annual	Coastline retreat	irreversible
Sea level rise	continuous	century	submersion & coastline retreat	irreversible

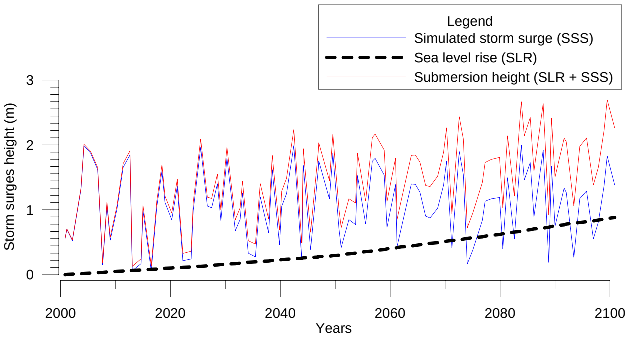

Fig. 2. Example of the interaction between coastal processes: sea level rise and storm surges and the potential impact on extreme surge events.

3.1.3 Superposition of the effects

The effects generated by the processes can overlap and thus increase the hazard level. A very simple example is provided by marine submersion which, if we refer to a perspective of 100 years, must include on the one hand the sea level rise linked to climate change (slow and irreversible) and the other instantaneous and reversible events such as storm surges or tsunamis (Fig. 2). As a result, the evaluation of the marine inundation hazard for the future years must integrate the long-term component of sea level rise.

3.2 The hazards taken into account in this project

The hazards that were included in this project are:

3.2.1 The tsunami hazard

Before 2004, only two historical tsunamis were known in Sri Lanka (NOAA Tsunami Database):

- The 31 December 1881 tsunami with an unknown water height on the eastern coast (at Trincomalee and Batticaloa)
- The 28 August 1883 tsunami with a 1.2 m water height estimated on the eastern coast

These two tsunamis are very modest in comparison with the 2004 tsunami during which water height reached a maximum of 11.3 m and frequently 6 m (11 m at Hambantota, 10 m at Galle Fort and around 6 m in Galle city, for example).

The 26 December 2004 tsunami remains a major event at the scale of the Indian Ocean and it has served as a reference. The lack of information about the return period of such a tsunami has prevented the incorporation of the return period as an element of this hazard. Data about the tsunami that we have included are the maximum inundation limits checked in the field and validated thanks to witnesses. We have also integrated the destruction limit provided by the GSMB, which corresponds to the limit where more than 70% of the buildings have been completely destroyed by the tsunami. Finally, in order to have an evaluation of the submersion height at each location we have developed an empirical model using the maximum elevation of the sea level at the shoreline and the extension of the inundation limit. By interpolation, this empirical model gives us the height of maximum submersion in each cell of a 20×20 m grid. The hazard classes are then defined in relation with the maximum submersion height: high hazard for submersion higher than 3 m, medium hazard for 3 m to 1m and low hazard for submersion less than 1m. This rough model, even if is far from the complexity of the tsunami phenomenon, gives a good evaluation of the maximum submersion height with regards field data and eye-witnesses.

3.2.2 Actual marine submersion hazard

The actual submersion hazard linked to monsoon waves has been taken into account using numerical modelling and is detailed in a specific section of this article.

3.2.3 Future (2100 AD) submersion hazard

The future marine submersion hazard (for the year 2100) includes on one hand, the total surge (sum of storm surge, the wave setup and the tide) and on the other hand the sea level rise caused by climate change. Two total surges were integrated, the first one corresponding to an annual return period (1 m) and the other one to a ten-year return period (2 m).

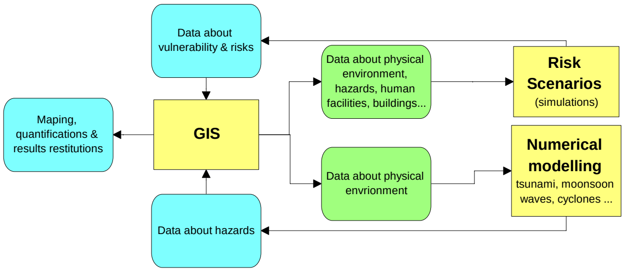

Fig. 3. Schematic representation of the links between the GIS, numerical modelling and scenario approaches.

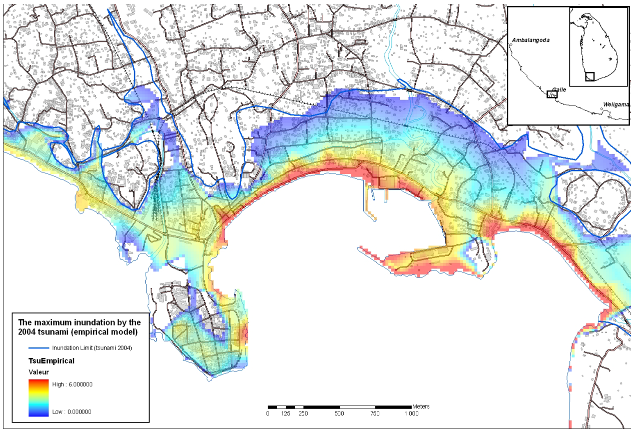

Fig. 4. The tsunami maximum inundation height from the empirical model (grid resolution: 20 m; value in m; the blue line is the tsunami inundation limit from field observations).

Regarding the value of the sea level rise in 2100, we took into account the highest hypothesis of IPCC2001 (0.8 m).

3.2.4 Coastline evolution (1956–2006)

A global approach for the coastline evolution was performed using the evolution of the permanent vegetation line (PVL) as indicator of coastline changes. The PVL is known to be a good marker of coastline evolution on a scale of decades and can be extracted easily from remote sensing data or acquired directly in the field. In order to evaluate the long-term coastline evolution, we imported this limit directly into the GIS using scanned and geo-referenced aerial photos from 1956. We mapped the present day permanent vegetation limit in the field using GPS for the same area covered by the 1956 aerial photos. These points have been integrated into the GIS and the current permanent vegetation line has been drawn using these control points. Thus comparing the 1956 and the 2007 PVL, we have a good idea of the dominant behaviour of the coastline (erosion, stable and accretion) at the scale of the last 50 years.

4 The human assets

The elements at risk in the pilot area are varied: towns, villages and harbours, communication networks, economic and tourist zones. We have integrated high-resolution vectorized data (at a scale of 1:10 000) on buildings, bridges, roads, railways and other infrastructure into the GIS for the pilot area. These data have been produced from maps and data of the Survey Department of Sri Lanka.

In our approach we have only treated buildings, which by their behaviour during tsunamis impact on the danger to the population (building collapse can cause deaths and it does not permit them to be used as refuges). On the other hand, the partial or total destruction of buildings directly contributes to the number of homeless people following the tsunami. The social impact of building damage is, therefore, large and adds to the human and economic losses. The social, political and economic context of the concerned population could be integrated in the future in order to analyze and understand the vulnerability of the communities. However, this is beyond the scope of the current project.

5 The tools and methods used for the hazards and risks characterization

Since they are not sufficient in themselves, three methods and associated tools were used during this project. The first approach was to create a GIS integrating the coastal hazards and the risks using existing or new data. Thus, the GIS includes all data on the physical (bathymetry, topography and hydrography) and human environment (e.g. buildings, facilities, communications networks and land use). The second approach was designed to test a scenario for tsunami risk with the software ARMAGEDOM (Sedan and Mirgon, 2003) and to compare the results with the effect of the 2004 tsunami. In the third approach, we initiated numerical modelling to assess, for example, the surge generated by the waves of monsoons or the 2004 tsunami from its seismic source to flooding of the coast of Sri Lanka. During this project, data were obtained in the field especially following the tsunami (e.g. limits of destruction and inundation, elaboration of a damage scale and the typology of the buildings). We also acquired new field data on the evolution of the coastline (e.g. evolution of the permanent vegetation line during the last 50 years) and other information on the coastal morphology. These data are managed by the GIS and then used by the scenario and numerical modelling as input or validation data (Fig. 3). In return, the results of the modelling can be integrated into the GIS by providing additional data or by clarifying the hazard (from numerical modelling) or risks (from scenario modelling). It is then possible to map, quantify, compare and validate these results.

Table 2. The GIS quantification of the elements exposed to the tsunami hazard and to the sea level rise hazard for the whole pilot area.

Hazard	Tsunami hazard			Total	Sea Level Rise (2100)			Total
Level	Low	Medium	High		Low	Medium	High	
Building (Number)	5166	7097	4821	17084	11 052	4419	1811	17282
Bridge (Number)	50	120	24	194	201	106	41	348
Communication Network (km)	119	278	130	527	340	203	60	603
Road (km)	105	226	107	439	303	186	55	545
Railways (km)	14	52	22	88	36	17	4	58

5.1 The GIS

A part of the GIS data come from various agencies in Sri Lanka (National Aquatic Resources Research and Development Agency; Survey Department; Geological Survey and Mines Bureau, Siriwardana et al., 2005, United Nations University, 2005, Coastal Conservation Department (Sri Lanka), 2004) that are integrated after various treatments (homogenization, reorganization of the data structure and the correction of projection errors). Other data come from field investigations, the interpretation of satellite images or aerial photographs and from empirical models of hazards (tsunami inundation and inundation related to sea level rise).

The GIS data are related to:

- The physical environment such as thematic data (e.g. topography, hydrography and bathymetry) and backgrounds consisting of satellite images of different resolutions (i.e. high resolution: Spot and very high resolution: Ikonos) and digitized old aerial photographs (1956);
- The facilities, infrastructure and the human assets (e.g. buildings, roads and rail networks, defence works and harbour facilities);
- The coastal processes involved in the hazard assessment: data on the 2004 tsunami, data from empirical models for assessing the height of inundation and hazard levels (Figs. 4, 5), assessment of sea level rise impact in 2100 (Fig. 6), erosion and evolution of the coastline, weather and wave climate data.

The intersection of these data with the hazards and assets provided an opportunity to evaluate the assets exposed to tsunami hazard (Fig. 7) and marine inundation hazard in 2100 (Fig. 8).

It is then possible not only to provide a map of elements at risk (Fig. 7) but also to quantify the assets exposed to each risk level by municipality, township and district (Tables 2, 3). In Table 3, we have compared the results from the GIS assessment of the assets exposed to the tsunami risk with data from the Census & Statistics Department of Sri Lanka (CSD). As the GIS evaluation is based on the exposure to a particular hazard level we note some differences with the CSD evaluation, which is based on observed damage. In some cities, the GIS overestimated the number of affected buildings while in others this method provided an underestimate. As the GIS assessment takes into account all the buildings within the inundation limit, we have secondly selected only buildings affected by high to medium hazard levels because it is for these hazards levels that most of the damage occurs. In this case, the number of buildings affected decreases and we underestimate the number of affected buildings. However, our estimation of the number of affected building at the scale of the Galle district is between 117% and 81% of the value from field data provided by CSD. This estimation seems to be relatively satisfying when considering the simplicity of the method used and this method can be useful as a first step.

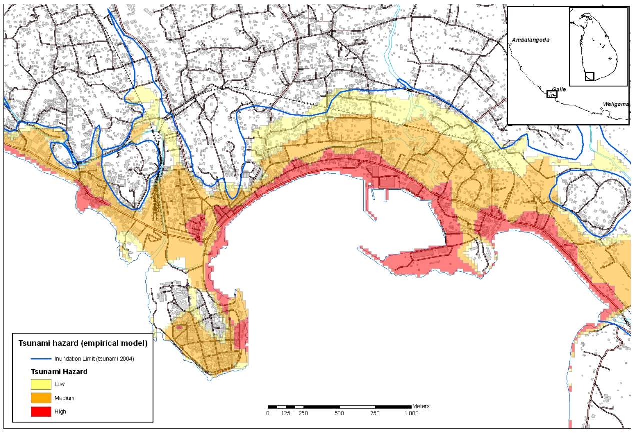

Fig. 5. Tsunami hazard from the empirical model (High hazard: inundation >3 m, medium inundation from 3 m to 1 m and low for inundation <1 m; grid resolution: 20 m).

This mapping is very useful for reconstruction and urban planning or as part of any development project with a coastal risks component. The GIS approach although easily implemented and very useful for the evaluation of the elements at risk does not allow an assessment of the damage that could be caused for a given level of hazard.

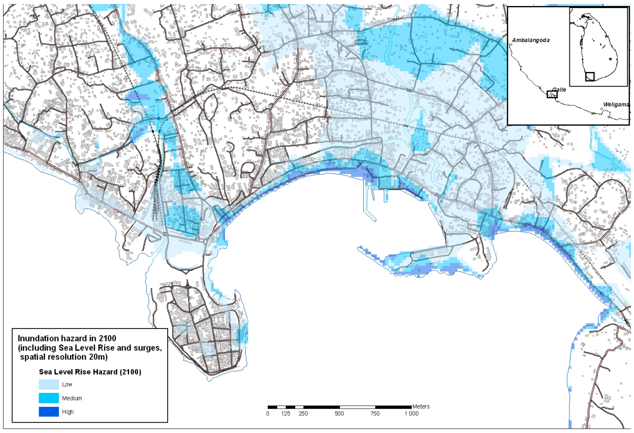

Fig. 6. Sea Level Rise hazard in 2100 (including the SLR and surges; grid resolution: 20 m).

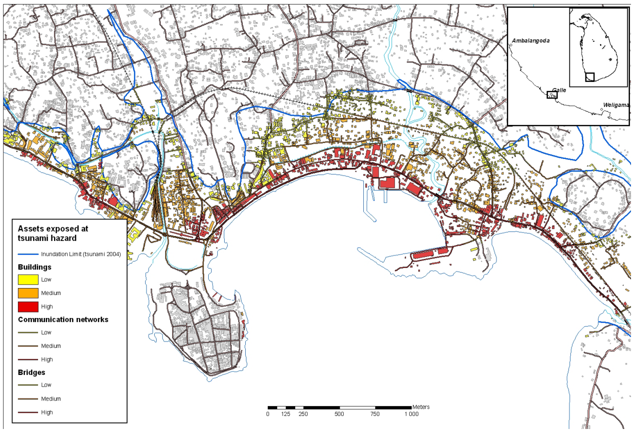

Fig. 7. Assets (buildings, roads & bridges) exposed to tsunami hazard. (Exposure is computed using the position of individual buildings, roads and bridges in the hazard zones of Fig. 5).

5.2 The risk scenarios

A risk scenario consists of assessing the impact of a given magnitude of hazard on the elements at risk. For that, in addition to the definition of the hazard, it is necessary to establish a damage scale which must be consistent with the hazards involved. It is also necessary to define the types of assets and for each type a set of damage functions. The damage functions are therefore dependant on the hazard types and on the assets considered.

In the case of the 2004 tsunami, the data acquired in the field (analyses of damage, testimonies and investigations) and bibliographic data (Peiris, 2006, Papadopoulos et al., 2006, Matsutomi et al., 2006, Ghobarah et al., 2006) have allowed us to develop a damage scale and some damage functions that are appropriate for buildings.

The buildings were divided into seven categories according to their construction type:

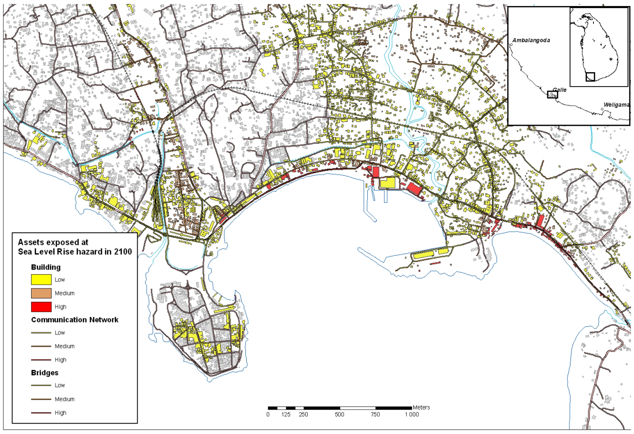

Fig. 8. Assets exposed at the sea level rise hazard in 2100 (sea level rise+storm surge; exposure is computed using the position of individual buildings, roads and bridges in the hazard zones of Fig. 6).

- L: Light (wood, metal);
- B1: light bricks;
- B2: reinforced bricks (2 rows);
- CB1: poor quality cement blocks;
- CB2: cement blocks with concrete columns;
- C: reinforced concrete;
- LB: traditional construction.

The scale of damage has 5 classes (D0 to D4):

- D4: total destruction of the building;
- D3: destruction of several load-bearing walls; scouring important foundations; cannot be rehabilitated;
- D2: collapse of wall panels without damaging the integrity of the building; scouring moderate foundations; uninhabitable but can be rehabilitated;
- D1: cracking, destruction of windows and doors; can be repaired and habitable;
- D0: superficial damage; no structural damage.

A damage function for the tsunami hazard is associated to each type of building. This damage function is a curve with the probability of harm from D1 to D4 on the abscissa plotted against the height of the flooding by the tsunami (Fig. 9).

The software ARMAGEDOM developed by the BRGM (Sedan and Mirgon, 2003) was used to carry out the simulations. It takes the value of aggression linked to the hazard as input. In the case of tsunami the value for the aggression is the maximum inundation height. We used this parameter

Table 3. Comparison of the quantification of elements exposed at the tsunami risk (GIS) with data from Census and Statistic Department of Sri Lanka on building damage (2004 tsunami).

	A	B	C	D	E	F	G
Buildings affected by tsunami	GIS evaluation (all hazard classes)	GIS evaluation (High & medium hazard)	Census & Statistics Dept	A-C	%(A-C)	B-C	%(B-C)
Balapitiya	2074	1097	2574	*−500*	*81%*	*−1477*	*43%*
Ambalagoda	355	137	595	*−240*	*60%*	*−458*	*23%*
Hikkaduwa	5666	4380	5696	*−30*	*99%*	*−1316*	*77%*
Galle city	3528	2158	2066	*1462*	*171%*	*92*	*104%*
Habaraduwa	3149	2413	1668	*1481*	*189%*	*745*	*145%*
GALLE District	14 772	10 185	12 599	*2173*	*117%*	*−2414*	*81%*

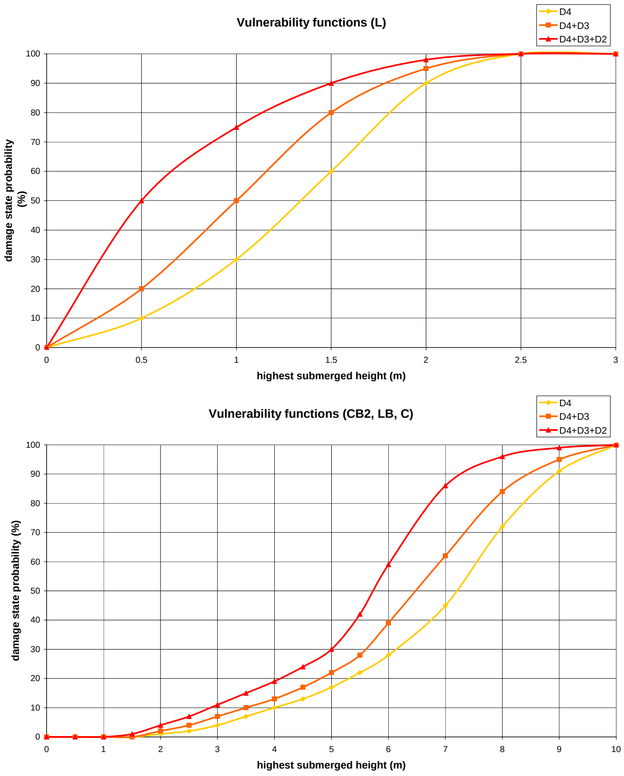

Fig. 9. Examples of the vulnerability curves for the tsunami hazard (top: light buildings, bottom: concrete buildings).

because it is the easiest to estimate and it is fairly representative of the magnitude of the hazard (Peiris 2006) although in fact, the inundation of land by a tsunami is a much more complex process.

This height of flooding has been provided by the inundation model that is integrated in the GIS and which provides the heights of inundation reached throughout the pilot site. The assets analyzed (buildings) come from the GIS layers.

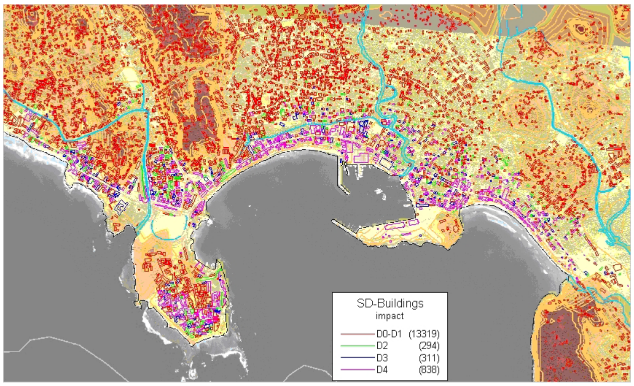

Fig. 10. Buildings damage map from a tsunami scenario simulation (damage scale from D0 to D4).

Each building is assigned a type. This allocation may be done building-by-building following field investigations or by randomly assigning based on the statistical distribution of building types (using data from Census & Statistics Department of Sri Lanka). The result of the simulations is a map in which each building is associated with a damage level (Fig. 10). An assessment of the rehabilitation cost can be realized as a function of the damage level (this was attempted during the project). It is then possible to analyse damage on the scale of a neighbourhood, village, town or district.

The results of this scenario is then compared to those from the GIS assessment (§5.1) and to real data collected in 2005 by the Census & Statistics Department of Sri Lanka.

So we have 2066 buildings affected according to the Census and Statistics Department, 2332 using the GIS and tsunami empirical model and 1443 using ARMAGEDOM.

Considering that the Census and Statistics Department only accounts for damaged buildings (like we did in ARMAGEDOM), and that the results obtained with the other two methods are quite close, the simulation for Galle is

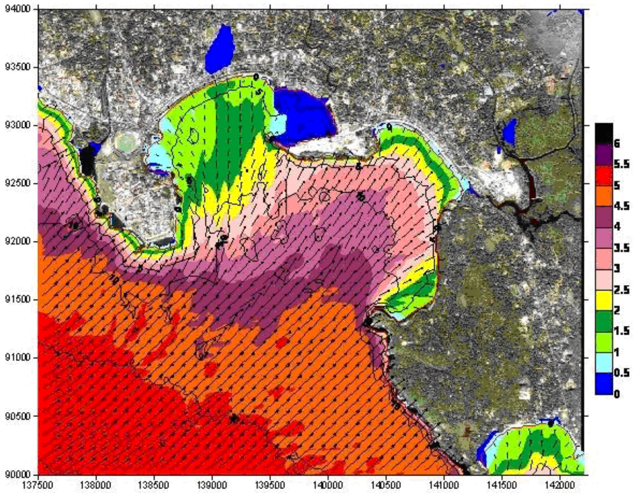

Fig. 11. Significant height (Hs) of wave computed with the high resolution grid, value in m (06/02/1991, Galle Bay, Ikonos image background).

considered to be correct. The underestimation we can observe when comparing our results to those of the Census and Statistics Department and to those coming from GIS is due to:

- the fact that in ARMAGEDOM we cannot, due to the vulnerability functions we defined, include in the 'buildings damaged' those only slightly damaged (D1);
- the area computed with ARMAGEDON is smaller than the administrative Galle city limit.

5.3 Numerical modelling

The previous approaches can be used to assess the risks from each hazard level. However, the hazard assessment can be achieved only for real events that have already occurred or from empirical models based on plausible assumptions. The prediction of long-term risk requires an assessment of the magnitude of each hazard for different return periods even if we are not aware of such an event in the past. This forecast, to be credible, must be based on a scientific understanding of the physical processes involved. This led us to consider the use of numerical modelling.

In the following sections, the first attempts at numerical simulations are presented. They aim to provide a better assessment of the wave hazard.

Two types of wave generate the greatest damage to the south-west of Sri Lanka: the waves associated with monsoons and tsunamis. As one looks at coastal hazards, taking the wave action into account becomes crucial. The wave action affects coastal currents that control the processes of erosion and accretion. In addition, during storms, the run-up and set-up of waves combined with the storm surge due to wind and atmospheric pressure are responsible for the inundation of coastal zones. Finally, the waves directly affect navigation, and are one of the primary parameters to be taken into account for design of structures to protect and manage the coastal zone.

5.3.1 Monsoon waves

For the pilot site, the waves of seasonal monsoons are associated with winds from the south-west or north-east. These waves, in particular, those linked to the south-western monsoons are at the origin in the pilot area of the periodic inundation of and damage to: roads, ocean-front buildings and coastal defence structures and other harbour structures.

The high-resolution bathymetric and topographic data come from the GIS. The waves and wind data result from the analysis and compilation of several databases covering several years (Coastal Conservation Department, the NOAA WaveWatch 3 and ERA40 of the ECMWF).

For example, we present here the modelling for 2 June 1991, on which the highest monsoon waves (HS of 5.5 m for periods around 8s with directions of 240°) were recorded in this area. The computing was made with the SWAN model (Booij et al., 1999) on two nested grids with a resolution of 100×100 m and 20×20 m respectively (Figs. 11 and 12). The result clearly shows the transformation of significant heights from the area of bathymetric depths of 70 m to the shore. The waves rise to 4.5 m at the entrance of the bay from 3 m at the 5 m isobath in Sector E of the bay while they are only 1.5 m in Sector W. At the shore, wave heights reached 1.5 m, while the set-up is 0.3 m. The results for a real event appear to be in quite good accordance with observations. We can consider assessing the wave hazard using statistical analysis on winds and thus simulate the events for different return periods. The impact of the wave can then be interpreted in terms of risk to human facilities, harbour and so forth. This approach also allows us to simulate the future impact of planned harbour or hydraulic work.

These results will be useful for a better quantification of the storm surge in this sector and permit the estimation of the submersion height at each point of the coastline.

5.3.2 Tsunami

The pilot site is a good sector to test and validate the modelling of tsunamis due to the high number of high-resolution data gathered on the 2004 tsunami, such as the inundation limit, the destruction limit and information on the building damage levels. The data that have been used for this modelling are the estimated seismic source (Grilli et al., 2007; Vigny et al., 2005), the topography (Survey Department of Sri Lanka) and the bathymetry at the local scale (National Hydrographic Office) and at the scale of the Indian Ocean (provided by the database ETOPO2). The numerical simulations were performed on a set of nested grids with increasing resolutions using a version of GEOWAVE model (Watts et

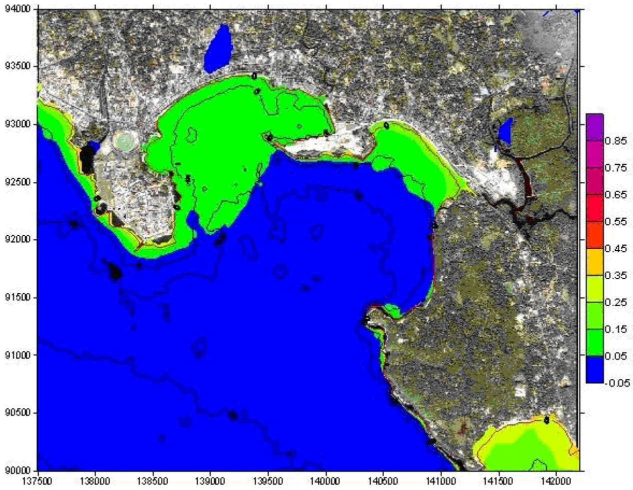

Fig. 12. Wave set-up computed with the high resolution grid, values in m (06/02/1991, Galle Bay, Ikonos image background).

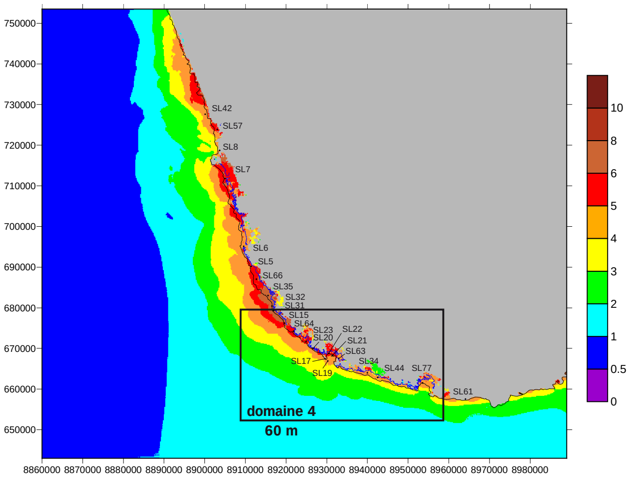

Fig. 14. Maximum elevation of the sea level (in m) from the simulation of the 2004 tsunami (180 m grid resolution).

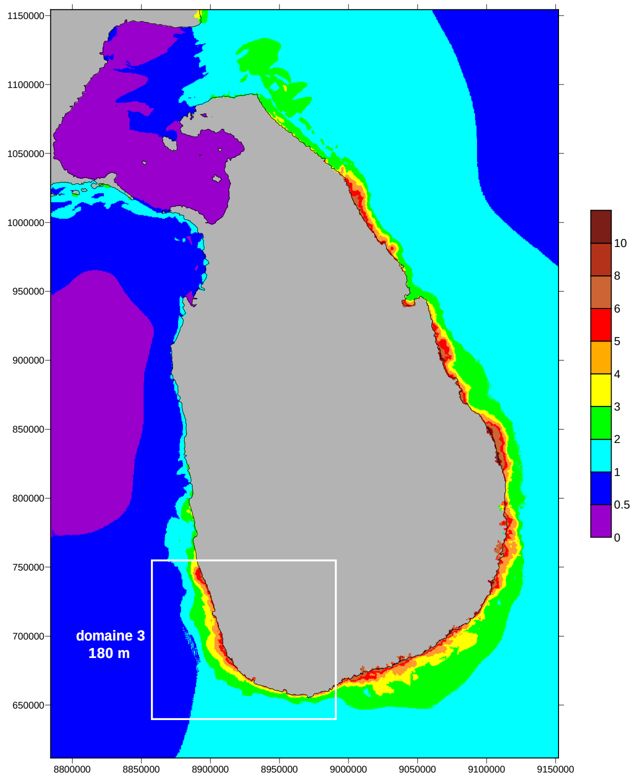

Fig. 13. Maximum elevation of the sea level (in m) from simulation of the 2004 tsunami (540 m grid resolution).

al., 2003) modified by BRGM. The simulations realized give a good restitution of arrival times of the tsunami along the coast of Sri Lanka but also a good evaluation of the heights of waves that have been observed on the periphery of the island (Figs. 13; 14). One of the tasks currently being carried out is the high-resolution (on a 20 m grid) simulation of inundation. The results of this simulation will be compared with field data collected during this project on the extension of the inundation and on the water height at each location and the comparisons will be integrated into the GIS. Once the model is validated on the 2004 tsunami, it will then be possible to assess the impact on the coast of different tsunamis and to assess the risk. The values obtained for each size of tsunamis will be integrated into the hazard maps of the GIS and will be used as different aggressions for the development of other risk scenarios.

6 Conclusions

The coastal zone is characterized by multiple processes (e.g. erosion, marine submersion related to monsoons and cyclones and tsunamis) whose characteristics are very different (in terms of reversibility, rate and return period). Moreover, some of these processes are affected by interactions and feedbacks making the assessment of induced hazards more complex. During this project, three complementary approaches were used together: GIS, risk scenarios and numerical modelling of waves from tsunamis and monsoons. The GIS on the hazards and risks in coastal Sri Lanka was developed by integrating various data (originally heterogeneous) on the land-sea interface. These data, both physical (bathymetry, topography, hydrography, tsunami hazard, erosion and sea level rise hazard) and human (construction, communication networks and land-use) were in a second step analyzed to highlight the exposure of people and property to coastal hazards. The simulation tools (scenario and numerical modelling) used concurrently with the GIS had demonstrated their complementarities in terms of analysis and assessment of hazards and risks. The models use the data from the GIS and in turn, the GIS uses the results from models making it possible to assess numerical quantities, maps and other information useful for communication with decision makers and the general public. The methodology used produces maps of different hazard levels which permits, for example, to define the most suitable areas for rebuilding. In built-up areas that were not destroyed by the tsunami, this approach can also give the level of hazard to which they are subjected. This will help define the risks incurred by the people and properties in these areas but also to define standards for the construction of new buildings or for the upgrading of existing structures in order to reduce their vulnerability.

The multi-hazard approach permits long-term urban development planning taking into account the risks and also to anticipate the retreat strategy in specific areas or for major assets.

The risk scenario approach provides an evaluation of the damage caused to each building affected by the simulated tsunami. Linking the cost of the rehabilitation for each damage level and for each type of building will permit an assessment of the economic cost of such a disaster at, for example, the scale of the district.

The GIS coupled with modelling thus appears to be a very useful tool for decision makers in charge of risk prevention and land-use planning. The GIS reflects the current knowledge of the coastal hazards, land-use and our ability to model phenomena. For it to remain a dynamic tool, it must be updated to reflect the evolution of scientific knowledge, the development in modelling methods and other changes in land-use and facilities.

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