REPUBLIQUE D'HAÏTI

Analysis of Multiple Natural Hazards in Haiti (*NATHAT*)

Port-au-Prince, Haiti
March 26, 2010

Report prepared by the Government of Haiti, with support from the World Bank, the Inter-American Development Bank, and the United Nations System

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Texts, maps, and other documents will be available on the website:
http://community.understandrisk.org/group/haitijanuary12thandbeyond/forum/topics/multihazards-assessments

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(*MULTI-MENACES-HA*)

Haiti Mission, February–March 2010

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Photo 1: Collapsed building in Delmas, Port-au-Prince

FOREWORD

RISK AND RISK MANAGEMENT IN HAITI: NEXT STEPS

Risk is always present, whether it is severe or barely detectable, and must therefore be managed. Some would even say that disasters represent the materialisaton of risks and thus, its poor management. The January 12, 2010 earthquake in Haiti was a sharp reminder of this. It is now time to build the future incorporating proactive risk management principles.

Management of risk requires first identifying and then understanding its causes and consequences. Risk identification and analysis help to clarify how natural hazards are manifested as well as their intensity and spatio-temporal distribution. Moreover, these processes facilitate the assessment of vulnerability to risk and how it builds up, increases and, in addition, provide information on how vulnerability can be reduced. This process must be carried out across the country. The intensity of risk must be evaluated and its uncertainties must be clarified.

Proactive risk management should help to reduce the impact of natural hazards and, more importantly, the sources of vulnerability to a level considered acceptable from a social, economic, and environmental standpoints. As it is impossible to eliminate risk entirely, steps should be taken to protect people and property. Measures must be implemented in advance to permit a rapid response through surveillance, alert and alarm systems, response, rehabilitation (immediate), and reconstruction (in the medium and long terms). In adopting such an approach, replication of previous conditions of vulnerability must be avoided. Instead, priority should be accorded to new conditions that create sustainable resilience, in addition to a culture of prevention to ensure the integration of risk management in all future development programs. This study aims to guide such actions.

Photo 2. The National Palace after the January 12, 2010 earthquake

Summary

On January 12, 2010, Haiti was rocked by a 7.0-magnitude earthquake that caused unprecedented human, social, economic, and environmental destruction across the country and the Latin American and Caribbean region. This earthquake ranks among the most deadly and devastating in the world’s recent history and deals a crippling blow to Haiti's recovery process. The earthquake compounded the hydrometeorological and political upheavals of the past two decades, causing the population additional suffering and presenting an impediment to the restoration of stability and renewal of Haiti's development momentum.

This study aims to identify the spatial and temporal scope as well as the relative intensity of the most severe natural hazards in Haiti. Evidently, the degree of precision and effectiveness of the results of this study directly depend on the quantity and quality of data available. It is hoped that the analyses presented will help to steer emergency recovery efforts and risk management, in addition to land use and development planning. However, these results are preliminary and will be subject to ongoing review in the coming months.

The most imminent natural hazards have been associated with precipitation caused by polar fronts from the northern hemisphere, in addition more rainfall is expected from tropical cyclones and waves, the Intertropical Convergence Zone, convective and orographic activity. El Niño/ENSO has had the tendency to delay the arrival of the rainy season and if extended, can even create drought conditions. Models also indicate that El Niño activity could increase the number and intensity of cyclones; however, it is not possible to predict the route the cyclones will take and if they will approach or even hit the island of Hispaniola.

It is also clear that other natural hazards such as earthquakes, landslides, torrential mudflows, drought, and tsunamis must always be taken into account. As a result, the vision for risk management, which includes emergency management, should be centered around a multi-hazards situation.

Photo 3. Temporary housing settlement, Toussaint l’Ouverture Airport

I -INTRODUCTION

1.1 Background

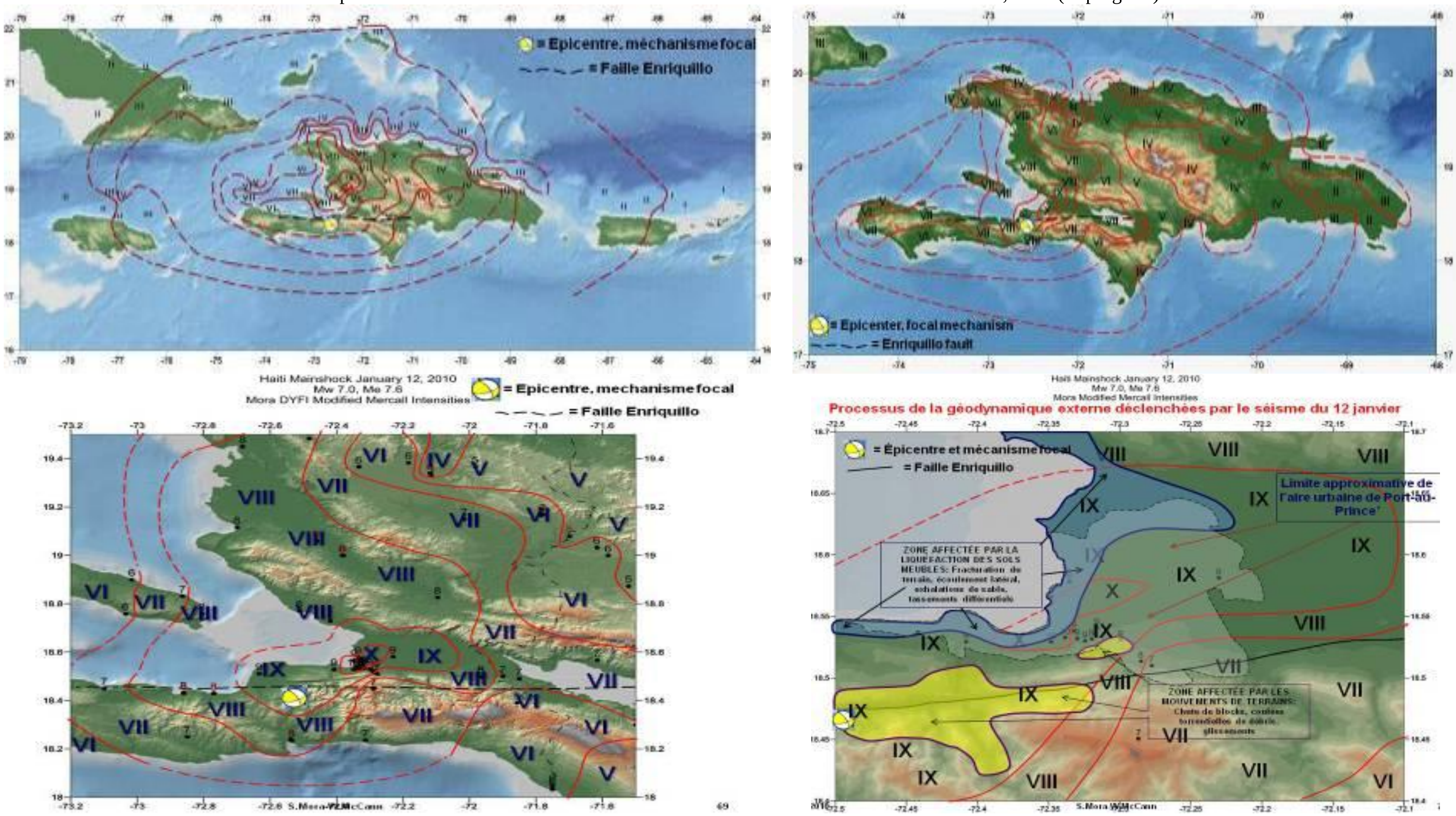
On January 12, 2010, a 7.0-magnitude earthquake took place in Haiti (maximum intensity of X+ on the Modified Mercalli Scale, Figure 1), claiming approximately 230,000 lives and injuring 100,000 people. Almost 600,000 people were left homeless and nearly 300,000 were displaced (Photos 1, 2, 3). These figures are in addition to another sizeable portion of the population in a similar situation as a result of the combined effects of poverty exacerbated by previous disasters and political upheaval, which have plagued Haiti for many years. The earthquake also caused landslides and liquefaction of soft soils over large expanses of the country, and segments of the coast were subject to subsidence and cortical uplift as well as a minor tsunami. This situation has resulted in profound psychosocial trauma in addition to damages and economic losses totaling almost US$8 billion, all of which represents a setback to the country's recovery efforts and development process in the wake of the hydrometeorological and political problems in which Haiti has been mired in recent decades. It is not the first time—nor will it be the last—that a powerful earthquake hits the island of Hispaniola and Haiti in particular. This earthquake is a wake-up call. History, even ancient history, shows that in addition to other hydrometeorological, climatic, and external geodynamic activity, seismic hazards should now be incorporated into daily life and considered in all decision making related to Haiti's development process.

The approach of the rainy season and the next hurricane season threatens to heighten the vulnerability of a population that is already suffering from fatigue, trauma, and conditions exacerbated by poverty and therefore, extreme vulnerability. Rainfall in February and March has affected conditions in the camps and the situation could deteriorate even further as a result of floods, landslides, and heavy mudflows. Furthermore, another severe earthquake, with its associated secondary effects such as liquefaction of soft soils, tsunamis, landslides and mudflows, remains likely. Buildings, especially those that have already been weakened, may sustain further damage. Another earthquake could cause even more harm to a population living in precarious conditions. In light of this situation, the Government of the Republic of Haiti has requested that the World Bank, the Global Facility for Disaster Reduction and Recovery (GFDRR), the United Nations System (UN), and the Inter-American Development Bank (IDB) lend support to its efforts to conduct a study on multiple natural hazards. This study should produce criteria and tools, such as maps and possible scenarios, to assist with decision making by national and subnational authorities and the international community.

The study will also provide a template for dealing with future emergency situations and managing risk in an integrated manner. It will focus in particular on improving security in the camps established for victims and on guiding activities in the early phases of rehabilitation and reconstruction.

The tragic events of January 12, 2010 should also be viewed as an opportunity to increase the long-awaited efforts to improve integrated risk management and to fashion from it an effective instrument of political, social, and managerial decision making. This report aims to analyze the causes and consequences of current and persistent multiple natural hazards in the country.

Figure 1. Isoseismal map (Modified Mercalli Scale) showing the secondary effects of the January 12, 2010 earthquake in Haiti. Based on the determination of intensities gleaned from telephone interviews, interpretation of information in the media and data from USGS/NEIC. McCann & Mora, 2010 (In progress)



1.2 Objectives

The attached study forms part of the Post-disaster Damage and Needs Assessment (PDNA), which aims to:

- Conduct an inventory of hazards across the country;
- Provide an assessment of imminent hazards, which mainly result from the exposure of disaster victims during the approaching rainy season and the possibility of another severe earthquake;
- Summarize recommendations for a medium- and long-term strategy for improving risk management; and
- Formulate an action plan consistent with the strategy developed and offer recommendations to be considered during reconstruction operations.

This analysis is intended to inform a varied target audience —decision makers, the general population, the international community, and scientists and engineers— of the natural hazards and the associated vulnerability currently present in Haiti. In view of the quantity, quality of data collected and the time available, it was necessary to organize the work in the following order of priority:

(i) In the very short term, that is, once humanitarian work is completed and rehabilitation has begun, determine the hazards at the temporary shelters in the Port-au-Prince metropolitan area, in other affected regions and cities in the country, and also in those areas that have been receiving and providing shelter to refugees from disaster-affected areas;

(ii) Considering the likelihood of another major earthquake striking Haiti and Port-au-Prince in the near future, paying particular attention to the possible magnitude, intensity, acceleration, and secondary effects (aftershocks, soil liquefaction, landslides and mudflows, tsunamis);

(iii) Evaluate the hydrometeorological hazards and their secondary effects (e.g. heavy rainfall, tropical cyclones, El Nino/ENSO);

(iv) Analyze the extent and level of risk, taking into account the potential impact of natural hazards (seismic and hydrometeorological/climatic activity, landslides) in the short and medium term, in addition to the current situation and existing vulnerabilities (exposure, fragility, quality of life, economy, environment, etc.);

(v) Determine the conceptual underpinnings for the establishment of procedures and mechanisms for evaluating risk in the major cities and, if possible, across the nation;

(vi) Define the key guidelines for first the macro- and then microzoning of hazards in Port-au-Prince, other selected cities, and also in areas with future potential for urban expansion; and

(vii) Recommend procedures in order to guide the evaluation of vulnerability in the medium term, while taking into account the situation in urban areas and the temporary shelters, the country's main economic activities, and socioeconomic and environmental factors.

II – NATURAL HAZARDS

2.1 The seismic hazard

2.1.1 Seismicity in the Caribbean

The Greater Antilles in general, and Haiti in particular, is an active seismic region. The relative seismic quiescence in Haiti over the last century allowed this inexorable hazard to slip from memory. The island of Hispaniola is in fact located in a zone of major tectonic faults separating the Caribbean and North American plates (Figure 2). Recent geodetic results show that these two plates are sliding past each other at a rate of 2 cm/year: this is the kinematic condition along Haiti's border, according to an initial quantitative degtermination on the seismic hazard (DeMets et al., 2000).

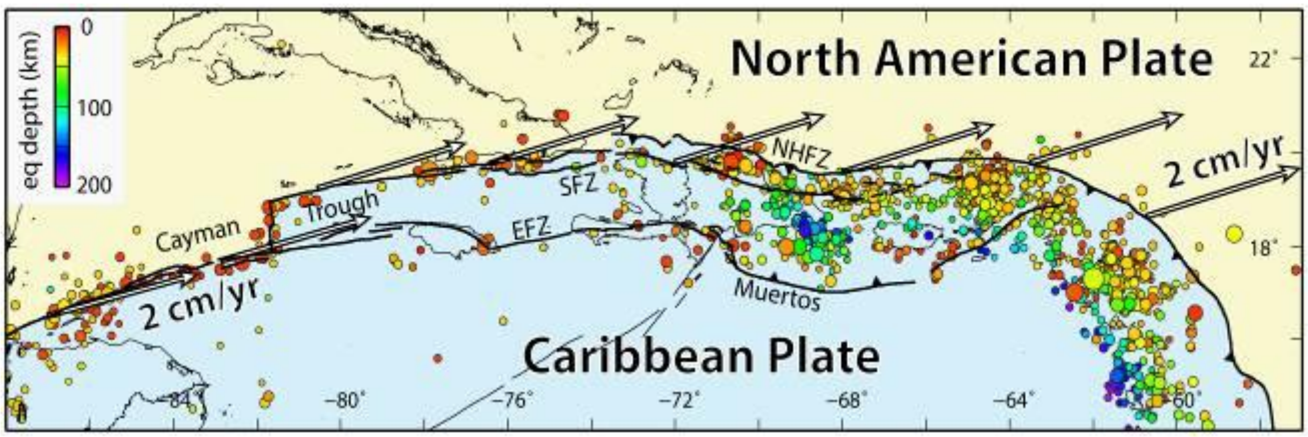


Figure 2: Seismic and tectonic context of Haiti along the boundary of the North American and Caribbean plates. The major and active faults are indicated by black lines. The arrows indicate the relative movement of the Caribbean plate in relation to the North American plate (approximately 2 cm/year). The epicenters of earthquakes in the region since 1974 (source, USGS/NEIC) are indicated by colored circles, which are color-coded by the depth of the earthquake. The northern Caribbean region, including Haiti, is subject to a left-lateral horizontal shearing of 2cm/year, slightly oblique in relation to the general east-west orientation of the plate boundary. EFZ = Enriquillo Fault Zone, SFZ= Septentrional Fault Zone, NHFZ = North Hispaniola Fault Zone.

This slow but persistent movement causes mechanical stresses at the boundary between these two tectonic plates. These stresses affect in particular certain pre-existing fracture zones or tectonic faults. These faults are weaknesses in the earth's crust along which tectonic stresses accumulate inexorably. This accumulation of stress manifests at the surface as an elastic deformation of the earth's crust on both sides of the faults that can be measured by spatial geodesy (GPS, Global Positioning System). When these stresses exceed the mechanical strength of a given segment of a fault, the fault gives away and the compartments on both sides of the fault suddenly slide against each other: this is an earthquake. Tectonic faults are therefore the original source of seismic hazard. Geophysical studies underway show that the earthquake that struck Haiti on January 12, 2010 was caused by an approximately 4-meter displacement that lasted 10 seconds and ruptured a roughly 40 kilometer-long segment of the fault between Petit Goâve and Gressier. This sudden movement triggers seismic waves that propagate over large distances within the earth: these are the vector of the seismic hazard. These waves cause ground motion whose amplitude (and related acceleration) diminishes with distance from the seismic source, but also depends on the geological characteristics of the soil and subsoil: these properties determine the attenuation factor of the seismic waves. Incompetent soils such as unconsolidated sediments or alluvial deposits amplify ground motion in comparison to rocky land. Lastly, ground motion can cause secondary damage after liquefaction, landslides, and tsunami.

2.1.2 Sources of seismic hazard

The main seismic sources in Haiti, as well as their seismological history since the 16th century, are relatively well known and mapped (Figure 3; Mann et al., 2002):

a. **The Enriquillo Fault** crosses the southern Tiburon peninsula to Miragoane and Pétionville, then continues eastward along the southern border of the Cul-de-Sac plain as far as Enriquillo Lake in the Dominican Republic. It is a left-lateral strike-slip fault that is essentially vertical, from which reverse faults branch off (essentially offshore). Geodetic measurements show a small component of shortening across this structure, which is consistent with the classification of the south peninsula as a transpressional ridge. The most recent GPS geodetic measurements show that this fault is accumulating elastic stress at a rate of 6 mm/year. The last major earthquakes along this fault line occurred in November 1751 (M~7.5) and June 1770 (M~8.0), both of which devastated Port-au-Prince (Figures 2 and 3). However, the exact location of the related ruptures has not yet been determined. The accumulation rate of elastic deformation along this fault and the time that has elapsed since the last major earthquake suggested the potential for a 7.2 magnitude earthquake (Manaker et al., 2008).
b. **The Septentrional Fault** runs along Haiti's northern coast, from Môle St Nicolas, canal de la Tortue and Cap Haïtien, and then continues onshore into the Cibao valley in the Dominican Republic. It is a left-lateral, essentially vertical, strike-slip fault. The most recent GPS geodetic measurements show that this fault is accumulating elastic stress at a rate of 12 mm/year. The last major earthquake in Haiti along this fault line occurred in May 1842 (8.0 magnitude). The rate of accumulation of elastic deformation along this fault and the time that has elapsed since the last major earthquake indicate the potential for a 7.5 magnitude earthquake (Manaker et al., 2008). The hazard is probably greater in the Cibao valley in the Dominican Republic, which has not experienced a major earthquake in approximately 900 years. This would be the equivalent of a possible earthquake with a magnitude of over 8 if this lack of movement led to a sudden release of all the stress nowadays. An earthquake of that magnitude would be strongly felt —and of course could cause significant damage— in Haiti.
c. **The North Hispaniola Fault** runs parallel to the island's northern coast at approximately 50 km in the north. It is a reverse fault that is connected in the east to the Puerto Rico Trench that marks the subduction zone of the North American plate under the Caribbean plate. The most recent GPS geodetic measurements show that this fault is accumulating elastic stress at a rate of between 0 mm (west) and 3mm/year (east). There is no record of any major seismic activity on this fault. The associated hazard remains largely unknown.
d. **The Muertos-Neiba-Matheux Fault** is a system of south-dipping reverse faults. Relatively little is known about its seismic activity. Modeling of GPS measurements in Hispaniola shows that the Muertos reverse fault (offshore) could accumulate elastic energy at a rate of 7 mm/year. The accuracy of this value is, however, somewhat doubtful, as the Muertos thrust fault is entirely under the sea and is therefore ill-suited to land-based GPS measurements. Although GPS measurements in Haiti do not indicate any significant movement all along the fault line toward the western segment of the Muertos thrust fault under the Matheux chain, its morphology suggests that it is an active fault. We have assigned it a minimum speed of 1 mm/year, consistent with the uncertainty of the GPS results.

Other faults capable of generating major earthquakes may exist in Haiti, particularly in Plateau Central. Owing to the dearth of adequate scientific information on their seismogenic potential, they have not been covered in this study.

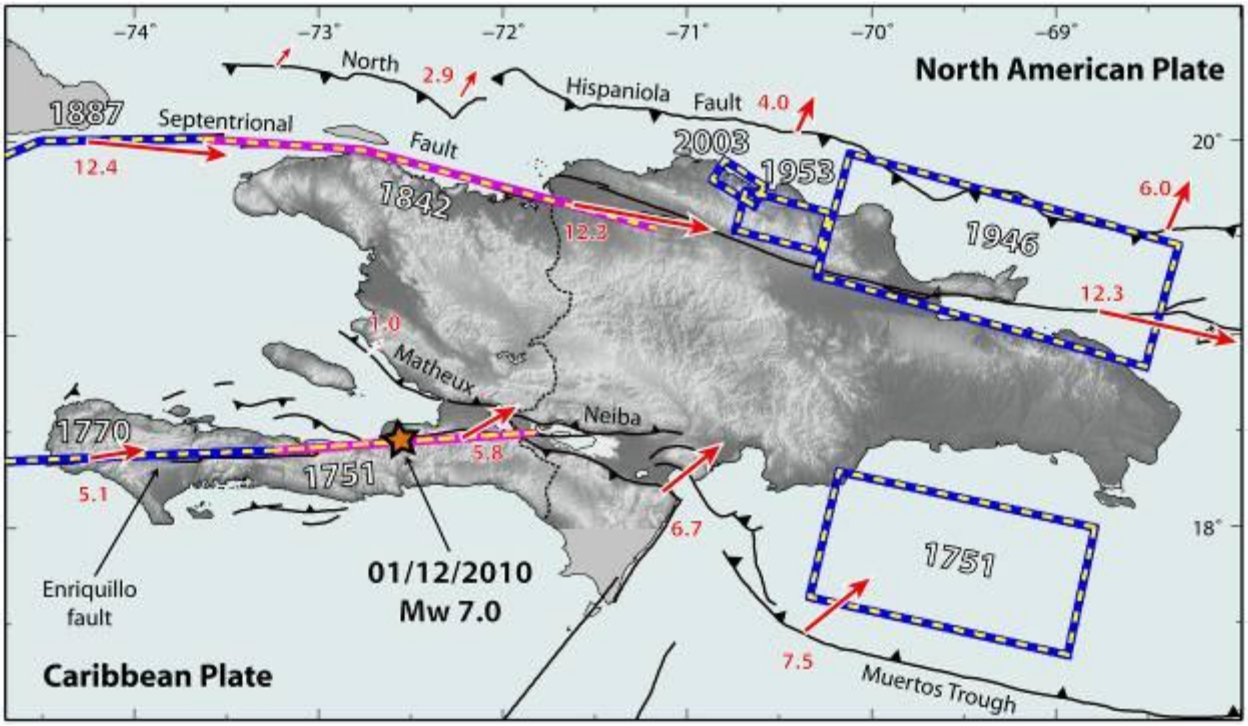


Figure 3: Synthesis of known major and active faults in Hispaniola (black lines), number and direction of slips along these fault lines estimated by GPS (red arrows and values in mm/year) and major historical earthquakes (blue/mauve lines and yellow dotted lines, with the year they occurred. The rectangles indicate thrust earthquakes, while the single lines represent strike-slip earthquakes).

2.1.3 Initial quantification of seismic hazard in Haiti

Based on the assessment of the seismogenic potential of known faults in Haiti using GPS geodetic measurements and the history of earthquakes in the region, the exceedance probability of a given ground motion acceleration was calculated using the Probabilistic Seismic Hazard Analysis (PSHA) methodology of the USGS (http://pubs.usgs.gov/of/2008/1128/, 2008 version). This work was conducted in collaboration with the USGS (Dr. Art Frankel). Potential seismic sources were identified by mapping known active faults. The return time on each fault segment was calculated by either using the rate of seismicity based on the Gutenberg-Richer law (with b=1) or by identifying a characteristic earthquake based on historical seismicity and the slip rate obtained from GPS measurements, or by combining these two approaches. The attenuation laws used were taken from the Next Generation Attenuation of Ground Motions (NGA) Project (http://peer.berkeley.edu/products/nga_project.html). The large-scale site effects are taken into account by introducing the shear wave propagation speed obtained from the empirical relationships linking the shear wave propagation velocity in the upper 30m (Vs30) and the topographic slope (Wald et al., 2007).

Figure 4 shows the 10 percent and 2 percent probabilities of exceedance in 50 years of a given peak ground acceleration (PGA, color coded, from 0 to 180 = 1.8g). This is the first time that a realistic seismic hazard map has ever been prepared for Haiti. The 50-year period corresponds to the average life span of a building. A 10 percent probability over 50 years is equivalent to an annual probability of 1/500, while a 2 percent probability over 50 years is equivalent to an annual probability of 1/2,500. It is important to recognize that the strategy selected in the countries exposed to seismic hazard is one whereby earthquake standards provide protection against low probability events. A 2 percent probability over 50 years should be used to design structures that will protect the lives of their occupants (buildings that will not collapse). A 20 percent probability over 50 years should be used for the design of structures that need to be operational in the aftermath of an earthquake. We converted the probable ground acceleration levels into Modified Mercalli Intensities, in accordance with the criteria established by the USGS project known as Shakemap (http://earthquake.usgs.gov/eqcenter/shakemap/. Potential damage ranges from zero to moderate for intensities I to V (maximum PGA of 0.092 g), from strong to very strong for intensities VI to VII (maximum PGA of 0.34), and from severe to extreme for intensities VIII and above. Categorization thus helps identify three areas of seismic hazard for Haiti: low, moderate, high. This mapping still contains ambiguities related to:

- Uncertainties regarding the identification of seismic sources: the location of all active faults in Haiti and their recurrence intervals are unknown. Although we have used characteristic earthquakes and GPS speeds as a proxy in this study, field work is still required.
- Uncertainties regarding the seismicity rates in Haiti: given that the absence of a seismological network precludes the production of a seismicity catalogue in Haiti, the calculation of parameters "a" and "b" of the Gutenberg-Richter law is therefore highly flawed (and generally not taken into account in this study).
- Uncertainties pertaining to the nature of the soil and subsoil: in Haiti, there are no direct measurements of shear seismic wave velocity in the soil and subsoil. The maps provided in this study take into account the empirical relationship between shear seismic wave velocity in the upper 30m (Vs30) obtained from the topographic slope. This must be improved using the direct measurements of this parameter.
- The fact that the quantity presented here is the peak ground acceleration (PGA). This could easily be replaced by spectral response maps for different periods (which compare the response of buildings to that of a single-degree-of-freedom damped oscillator), a quantity that is more easily assimilated directly by earthquake engineers.

2.1.4 External geodynamic hazards caused by seismicity

Seismicity in Haiti generates two secondary hazards that must be taken into account in development-related decisions:

a. Soil liquefaction

Soil liquefaction is difficult to identify because it has no morphological signature. It occurs in areas that are generally flat with sandy soil materials, with a shallow water table. It bears noting, however, that it only occurs under major seismic stress and that it identifyable through geotechnical procedures.

A detailed description of liquefaction will not be provided here; we will however briefly note that it constitutes a change in soil behavior, from an initial solid state to a liquid state during the strongest seismic vibrations. The soil, particularly when it is composed of fine sands and is saturated or almost saturated, is subject to a temporary increase in the interstitial water pressure and thus in permeability and volume, as well as a simultaneous loss of shear resistance. The "swelling" of liquefied layers typically leads to the mechanical extrusion of volumes of water, combined with soil, to the surface, forming sand volcanoes ("sand blows") and leaving craters and flows everywhere. Liquefaction is sometimes also accompanied by deformation, and even by fracturing of upper soil layers, causing their displacement and lateral spread toward surrounding land depressions (Photo 4). Lastly, the soil's loss of shear resistance also leads to a loss of its load-bearing capacity; buildings and other structures can therefore either sink, with differential settlements, or float owing to the buoyancy effect.

Liquefaction is significant particularly in river basins, alluvial depressions such as the Cul-de-Sac Plain, the deltas of the Froide river (Carrefour) and Momance river (Léogane), where the groundwater aquifer is close to the surface. Numerous examples of this type of effect were observed in the aftermath of the earthquake of January 12, 2010, particularly around port facilities in Port-au-Prince and fuel tanks at the Carrefour power plant, where damage was considerable.

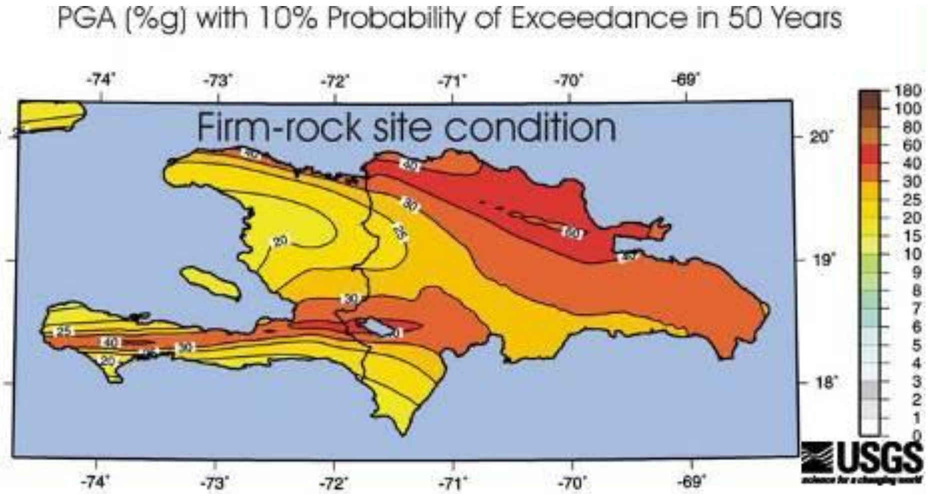
The preliminary map in Figure 5 shows Haiti's susceptibility to liquefaction and was prepared by combining information obtained from the Geological Map of the Republic of Haiti (Bureau of Mines, Ministry of Public Works) and data on shear wave propagation velocity (Vs30), obtained from empirical relationships linking wave celerity in the top 30m of soils and the topographic slope (Wald et al. 2007).

b. Tsunami

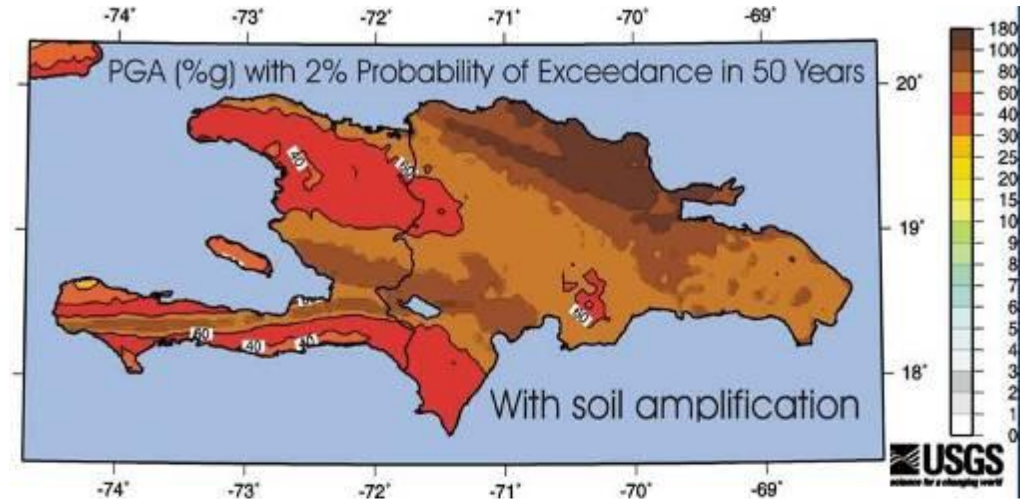
Since the Enriquillo fault line essentially extends across land, the probability of a major tsunami triggered by an earthquake along this fault is low. However, submarine slides or lateral flows can generate local tsunamis, as was observed in the Jacmel and Grand Goave regions during the earthquake of January 12, 2010.

It is to be noted gthat the earthquake of May 1842, which struck northern Haiti, triggered a tsunami that affected the Port de Paix region. The Septentrional fault poses a significant tsunami hazard. It extends along the southern margin of Cuba, where it has a major reverse component and thus a greater capacity to trigger tsunamis. An earthquake on this fault line would pose a considerable hazard to the Port-au-Prince area in particular, but to the coastal areas of Grande Anse, Nippes, and the Artibonite delta as well. A more detailed description of tsunamis is provided in the section entitled "Coastal Hazards."

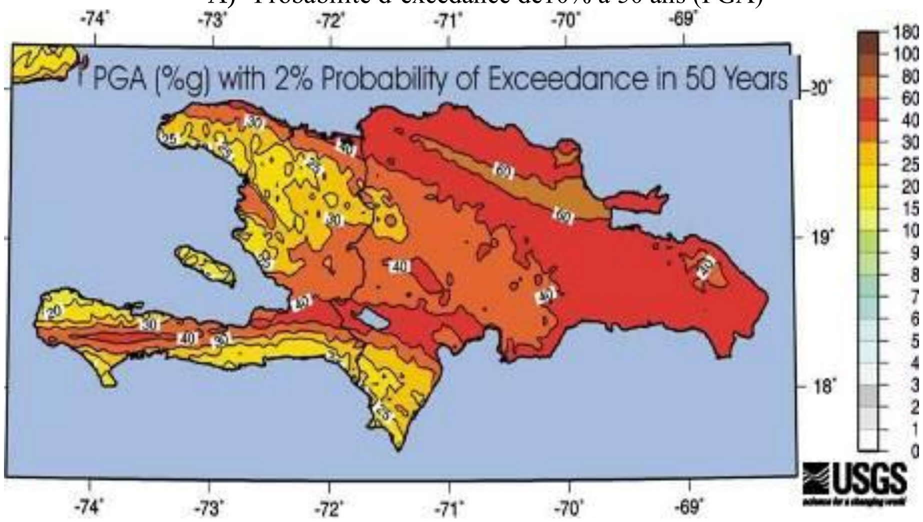
Photo 4. Liquefaction (sand extrusions and lateral spread) of sandy soils in the Port-au-Prince port area



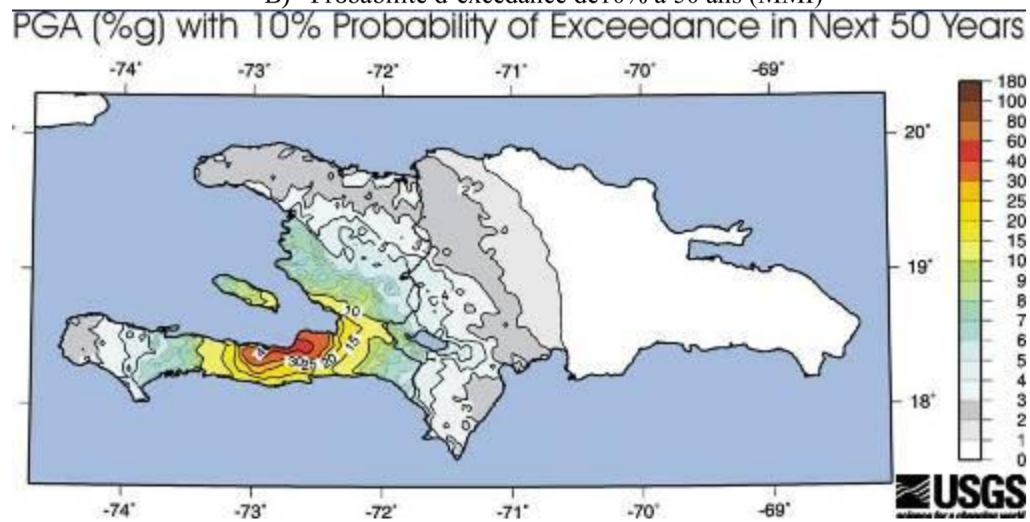
A) Probabilité d'excédance de10% à 50 ans (PGA)



B) Probabilité d'excédance de10% à 50 ans (MMI)



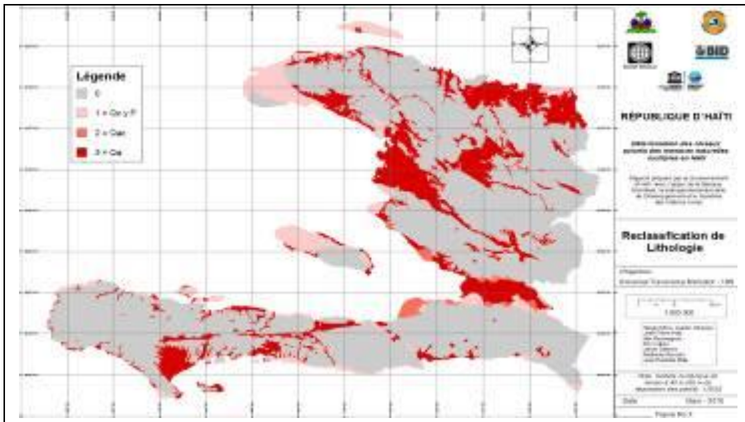
C) Probabilité d'excédance de 2% à 50 ans (PGA)



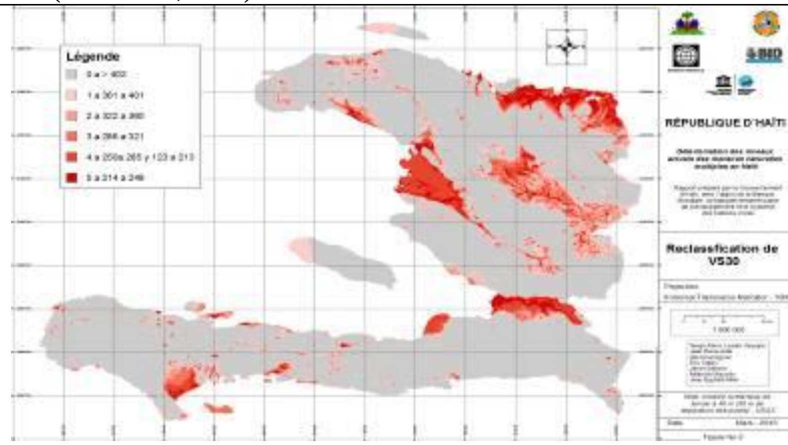
D) Hazards (PGA) from M 5-6.5 aftershocks, since 03/17, 2010 (Morgan Page, USGS)

Figure 4: Maps showing the probability of exceedance in 50 years of a given peak ground acceleration (PGA), provided in "g" values. Explanations and limitations of these maps are provided in the text (in collaboration with Art Frankel and Morgan Page, USGS).

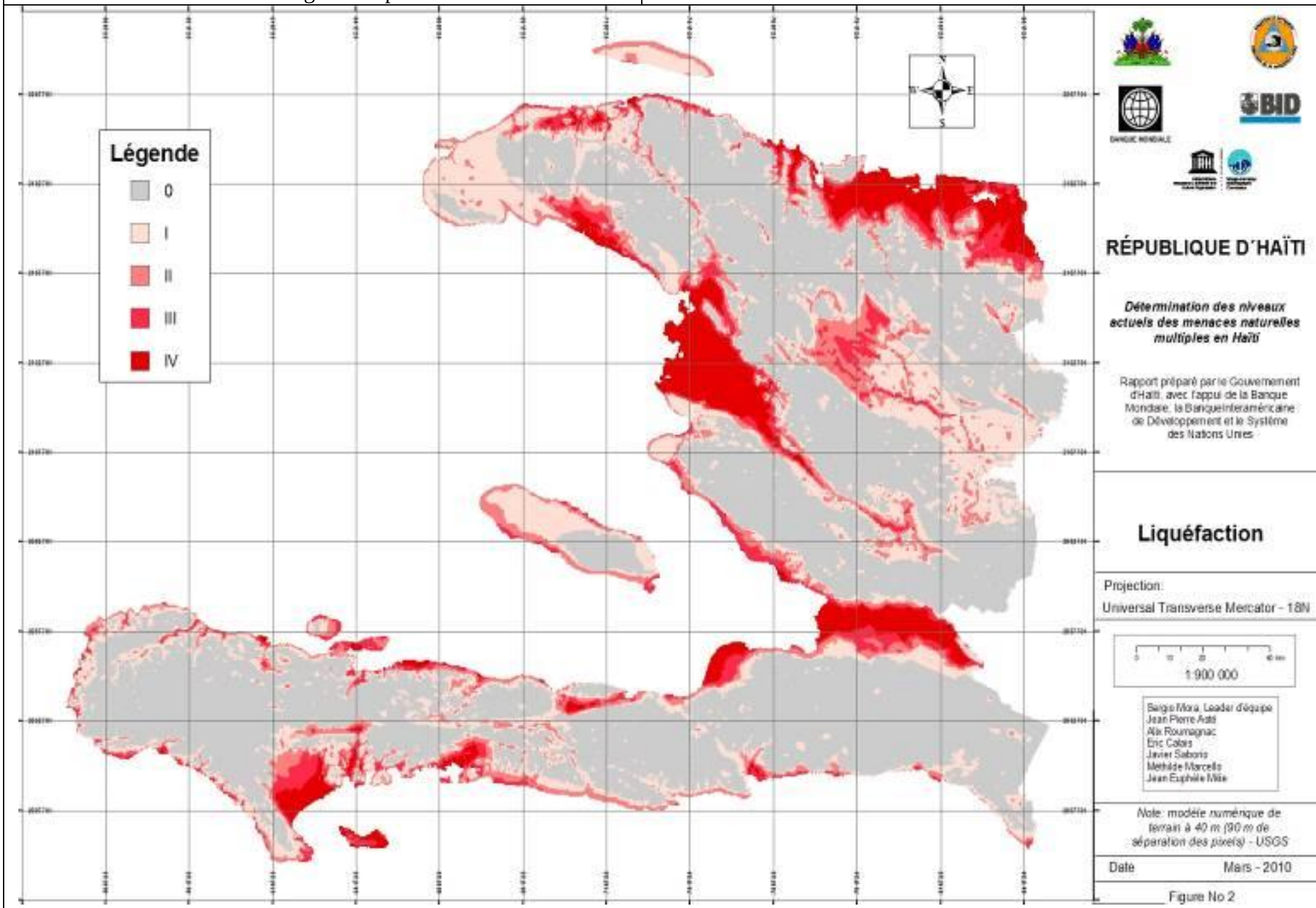
Figure 5. Preliminary map of Haiti's susceptibility to liquefaction; based on information obtained from the Geological Map of Haiti and Vs30 data (Wald et al., 2007)



Susceptibility of soils to liquefaction.
Source: Geological Map of Haiti



Shear wave velocity (Vs30) (Wald et al., 2007)



Preliminary map of Haiti's susceptibility to the liquefaction of soils

2.2 Hydrometeorological and climate-related hazards

Haiti, located in the northern Caribbean, enjoys a tropical climate. The rainy season runs from April to June and intensifies between October and November during the cyclonic season (June until end-November). During the northern winter season, polar fronts can also produce significant rainfall, such as the rains that affected the southern peninsula in late February and early March 2010. During these periods, the atmospheric processes can be intense and cause either significant water balance deficits (i.e. droughts) or heavy rains followed by flooding, landslides and torrential debris flows that are often deadly and devastating. As a result, hazards associated with climate variability are frequent in Haiti and stem from various types of tropical and subtropical atmospheric processes, with a spatio-temporal and varying intensity scales. Available data in Haiti and correlations with countries and neighboring islands indicate that there have been no major changes in rain distribution trends since the early 20th century, beyond the sinusoidal patterns within climate variability limits, mostly controlled by the regional synoptic circulation systems. To date, the influence of climate change has not been detectable in the resolution capabilities of available data.

2.2.1 Droughts

Prolonged water balance deficits occur often in Haiti. During the 20th century, historical documents cite episodes in 1923-24, 1946-47, 1958-59, 1966-68, 1974-1977, 1981-1985 (Mora 1986; NOAA). On several occasions, these periods of drought were accompanied by significant declines in agricultural productivity and drinking water supply, resulting in food vulnerability and even famines. The map in Figure 6 shows the most drought-impacted areas, and the insert box shows the hardest-hit regions that are chronically affected by periods of increased food vulnerability (FAO, 2002). The origin of most droughts in Haiti can be attributed and linked to El Niño/ENSO (warm) episodes.

2.2.2 Heavy rainfall: their causes and effects

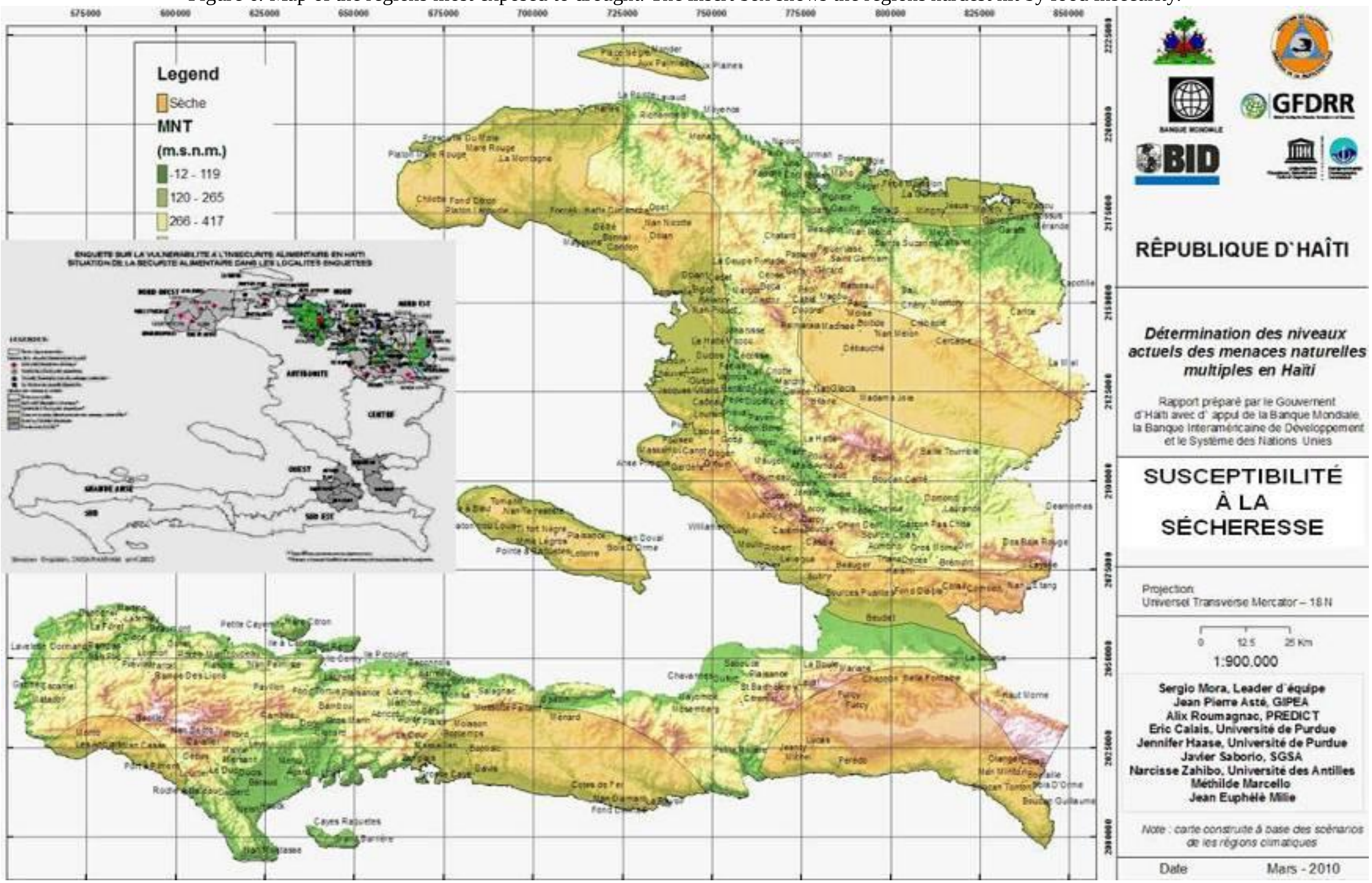
During the rainy season and more specifically the cyclonic season, as is the case throughout the entire Caribbean Basin, Haiti is primarily subject to tropical waves and local and regional disturbances (fairly organized storms), which are sometimes influenced by the Intertropical Convergence Zone and carried from east to west by trade winds (mid-altitude circulation on the atmosphere). These low pressure systems can lead to tropical cyclogenesis and spawn cyclonic systems that produce abundant rainfall and strong winds, which can be qualified in terms of their intensity and structure (Saffir-Simpson scale, Table 1).

Table 1. The Saffir-Simpson Scale

Type of cyclone	Category	Pressure (mbar)	Wind speed (knots)	Wind speed (km/h)	Tidal wave (m)
Tropical depression	TD	-	< 34	< 60	-
Tropical storm	TS	-	34-63	61-113	< 1
Hurricane	1	> 980	64-82	114-148	1-1.6
Hurricane	2	965-980	83-95	149-172	1.7-2.5
Hurricane	3	945-965	96-112	173-203	2.6-3.8
Hurricane	4	920-945	113-135	204-242	3.9-5.6
Hurricane	5	< 920	>135	>242	>5.6

In addition to these synoptic-scale disturbances, the country can also be affected by polar frontal and orographic-convective systems (storms) at the regional level (strengthened by local effects: hilly landscape, exposed capes, etc.), which could also be the root cause of flooding and landslides linked to heavy and intense rainfalls, over a small surface area, such as, for example a watershed.

Figure 6. Map of the regions most exposed to drought. The insert box shows the regions hardest hit by food insecurity.



The Caribbean region is currently influenced by an El Niño-ENSO episode (climate pattern generating large-scale anomalies, linked to the increase in surface temperatures in the Pacific Ocean). This influence could slightly delay the start of the rainy and cyclonic seasons, albeit with a statistical tendency to increase the number and relative intensity of tropical cyclones in the Atlantic.

2.2.3 Average rainfall and climate zones

The map in Figure 7 provides a diagram of Haiti's climate zones, categorized by their exposure to rainfall and their main associated meteorological factors. The entire country is subject to frequent rainfall that generates relatively high annual averages in the hilly areas (orographic effect and strengthened convection). The values in the area extending from Grand'Anse to the southeast are also influenced by increased exposure to tropical waves from the east and disturbances coming from the southwest. The northern section may also be affected by passing frontal systems (cold, extratropical depressions carried in the westerly flow). The entire country is exposed to tropical storms and cyclones.

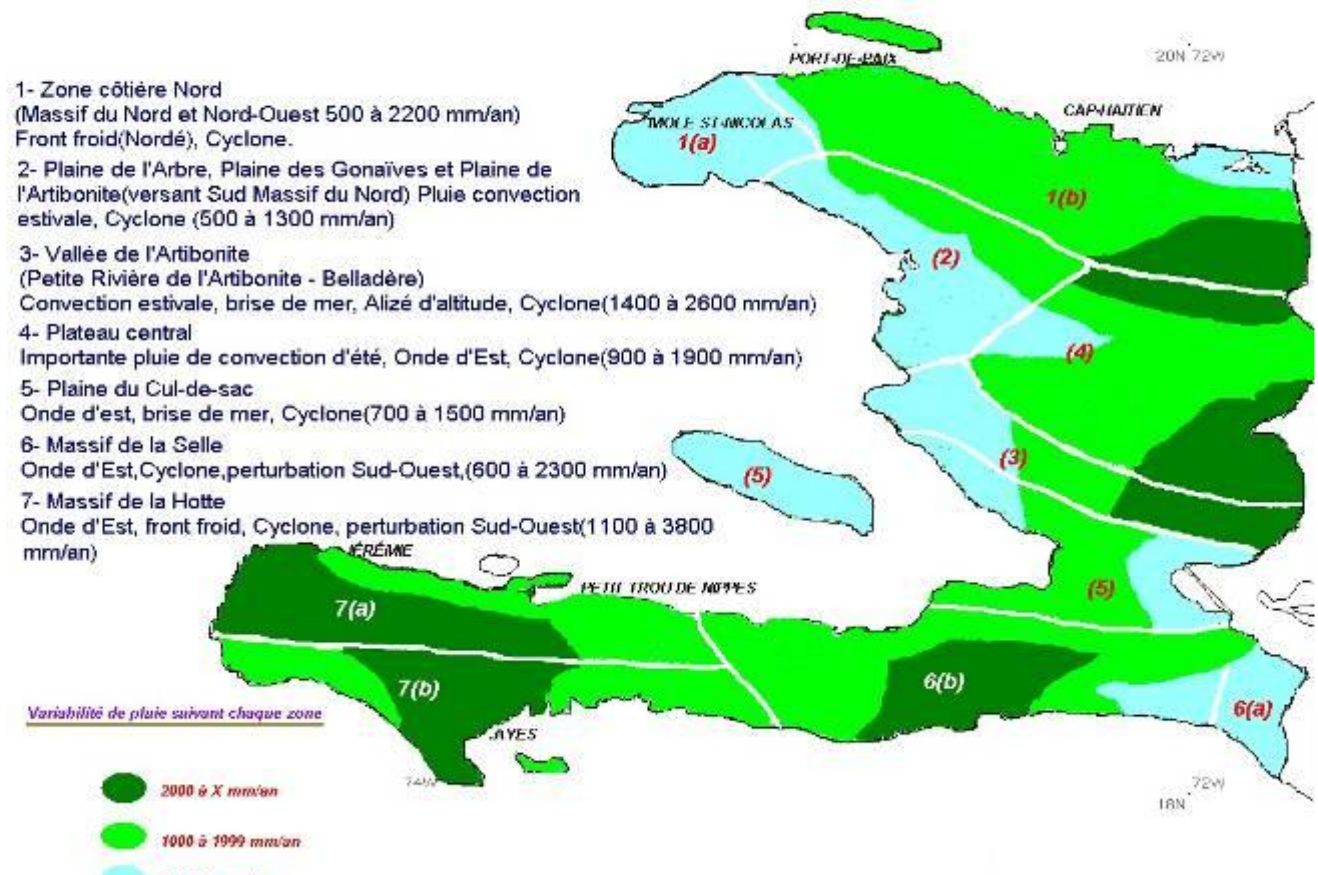


Figure 7. Main sources of rainfall and climate zoning (Source: National Meteorological Center of Haiti)

The graph in Figure 8 below is an extract of the spatio-temporal variability of average rainfall, (between 1953 and 1986) measured in five areas (from north to south).

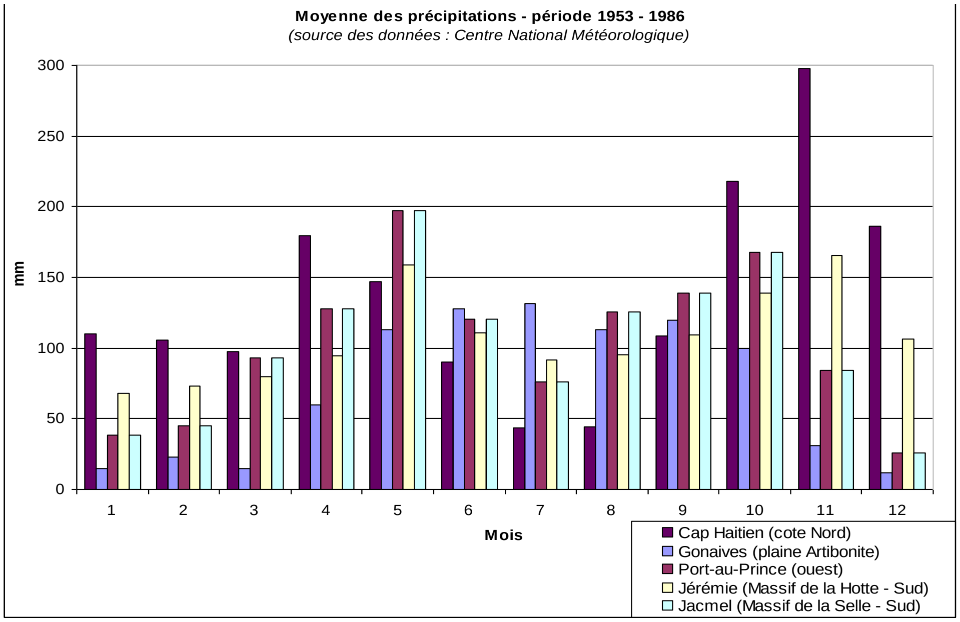


Figure 8. Average rainfall between 1953 and 1986.

2.2.4 The flood hazard in Haiti

The map in Figure 9 shows, between 1998 and 2010, the meteorological events that were the root cause of floods, particularly with the passage of several hurricanes through or near the country (Photos 5a and 5b). Table 2 lists the tropical cyclones that caused significant damage between 1935 and 2008.

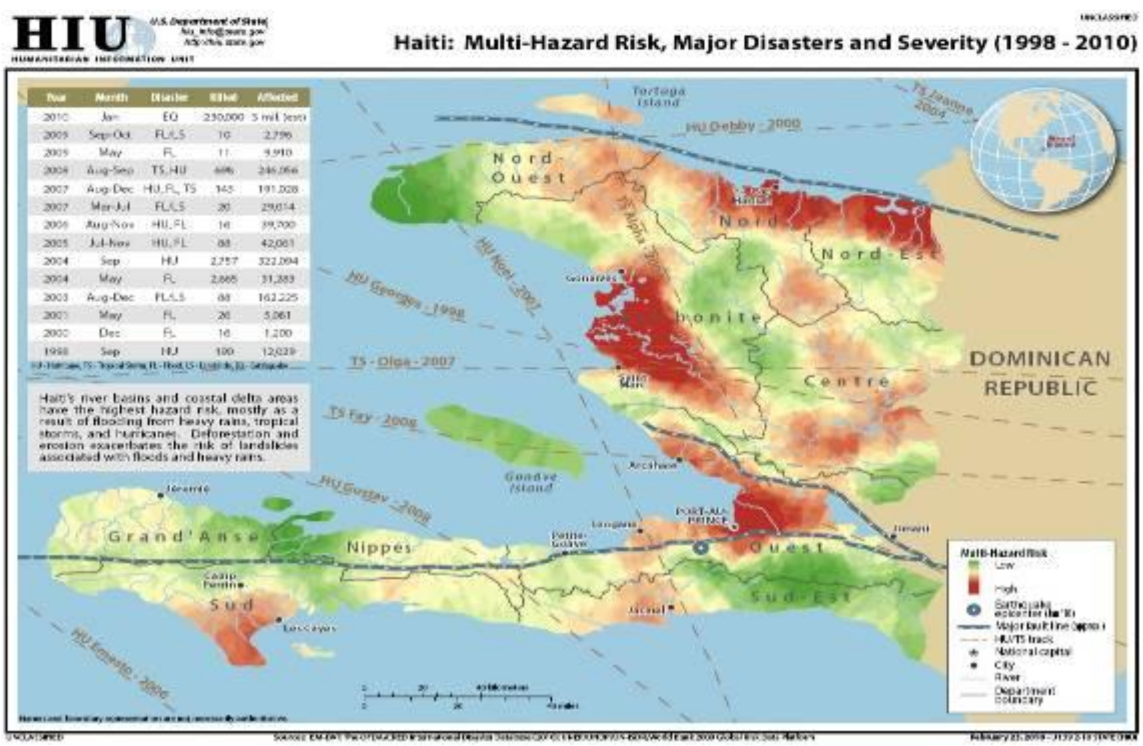


Figure 9. Cyclonic events and floods in Haiti (1998-2010). Source: EM-DAT–International Disaster Database

Table 2. Destructive tropical cyclones (1935-2008). Source: National Meteorological Center of Haiti

Year	Name (hurricane, storm)	Affected areas
1935 (October)	Unnamed	Jérémie (+ 2,000 deaths)
1954 (October)	Hazel	Grande Anse, Ouest, Artibonite, Nord-Ouest (very widespread)
1963 (October)	Flora	Grande Anse, Ouest, Cote sud (Cayes)
1964 (September)	Cleo	Grande Anse
1966 (September)	Inès	Sud and Ouest
1979 (August)	David	Limited impact on Nord-Ouest
1980 (August)	Allen	South coast (Cayes)
1994 (August)	Gordon	Jérémie (192 deaths)
1998 (September)	Georges	Ouest – Centre
2004 (September)	Jeanne	Nord – Haut Artibonite (Gonaïves hard hit)
2008 (August)	Fay	Entire country
2008 (August)	Gustav	Sud and Grande Anse
2008 (August)	Hanna	Artibonite and Nord Est (City of Gonaïves hard hit)
2008 (September)	Ike	Brushed past the north **-** (City of Cabaret affected)

Three types of pluviometric situations that pose a flood hazard can be identified. These categories were applied to determine the relative degree of hazards depiced in figures 11 and 13:

- Convective storms: The Meteorological Centre of Haiti assessed their capacity to produce as much as 200 mm of rainfall in a few hours over very localized areas. This type of precipitation falls into the frequent hazard range.
- Tropical waves relate to much larger disturbances, with accumulations of 400 mm in a 24-hour period. They fall into the less frequent and somewhat rare hazard range.
- Cyclones (storms and hurricanes) can produce as much as 600 mm, and can affect the entire country (e.g. in 1994, Gordon caused nationwide flooding). They fall into the exceptional hazard range.

Cyclones and, to a lesser extent, depressions, can cause problems relating to marine submersion. Based on the type of cyclone (Cape Verde, Barbadian, Caribbean), the value of their atmospheric pressure, the force of their winds, and velocity of their movement, then can influence the affected areas and can generate significant and fluctuating submersion. The southern coast is particularly vulnerable to this type of situation.

a. The spatial distribution of the flood hazard

Haiti is exposed to a significant flood hazard, as shown in the map in Figure 11. Low-lying areas and estuaries are especially exposed to the various levels of hazard. Given the lack of reliable, instrumental and historical data on rainfall and even less on hydrology, in sufficient quantity to provide a probabilistic hazard analysis, this study proposes a spatial distribution of the hazard at three levels: (i) Frequent hazard; (ii) Rare hazard; and (iii) Exceptional hazard as defined in the preceding paragraph. The maps appearing in figure 13 provide details on the various levels of hazard in the areas hardest hit by the earthquake. These three levels can be linked to the various typologies of rainfall, as described before.

b. Aggravating factors of hydrometeorological hazards

The topographic and hydrographic configuration of the country increases its vulnerability to these hazards. Haiti's land mass has 1,700 km of indented coastline, mainly mountainous (80 % of mountains or hills higher than 100 m). The highest peaks are over 2,500m (Massif de la Selle between Jacmel and Port-au-Prince). In the indigenous Taino language, *ayiti-quisqueya* means "high land, mountainous country." Lowland areas therefore account for less than 20 percent of the territory; the coastal lowlands are narrow and rise abruptly within a short distance (Figure 10).

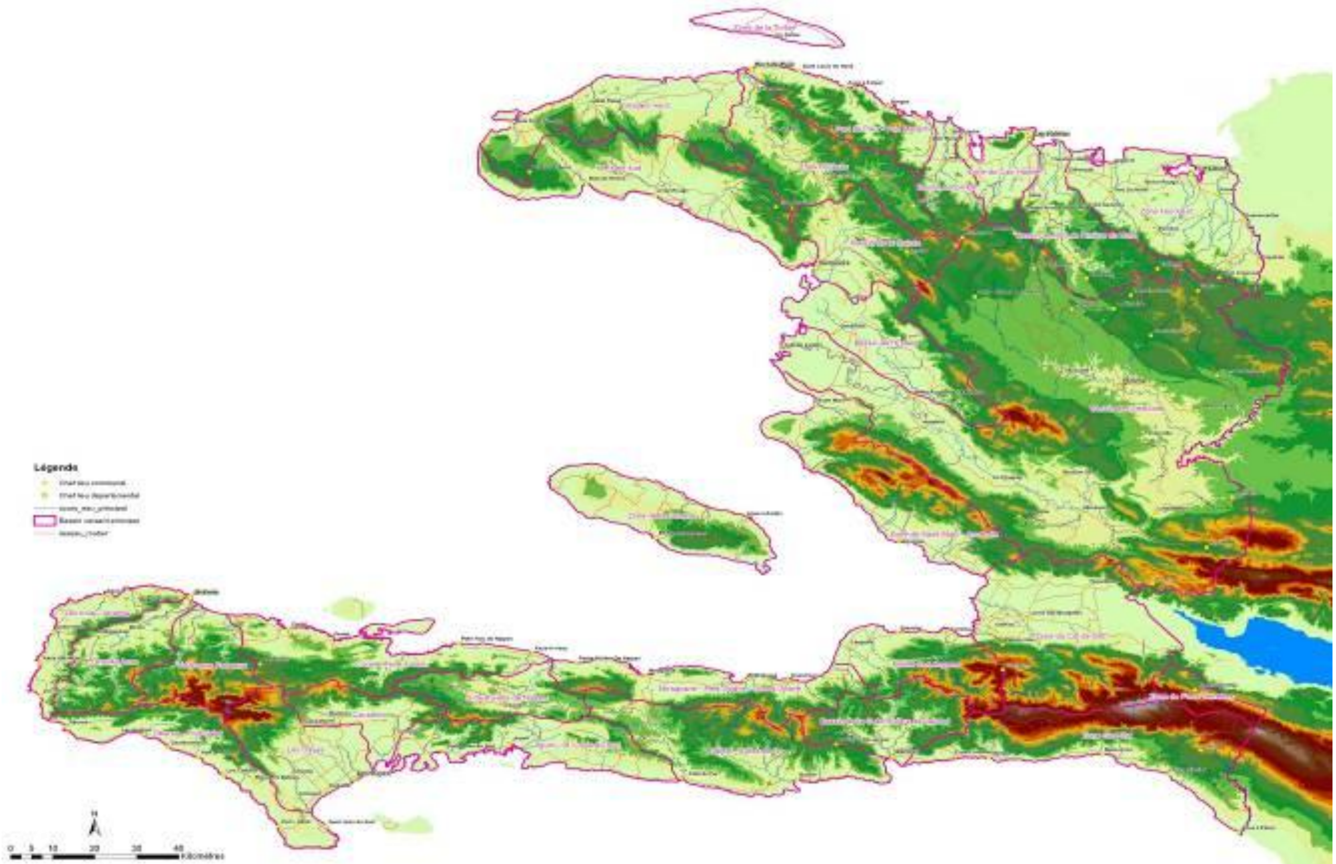


Figure 10. Physiographic map of Haiti. Source: PNAP, BRL ingénierie, 2007.

Photos: Floods at 5a, Gonaïves and 5b, Port à Piment; 2008

Gonaïves, 2008

Port-à-Piment, 2008

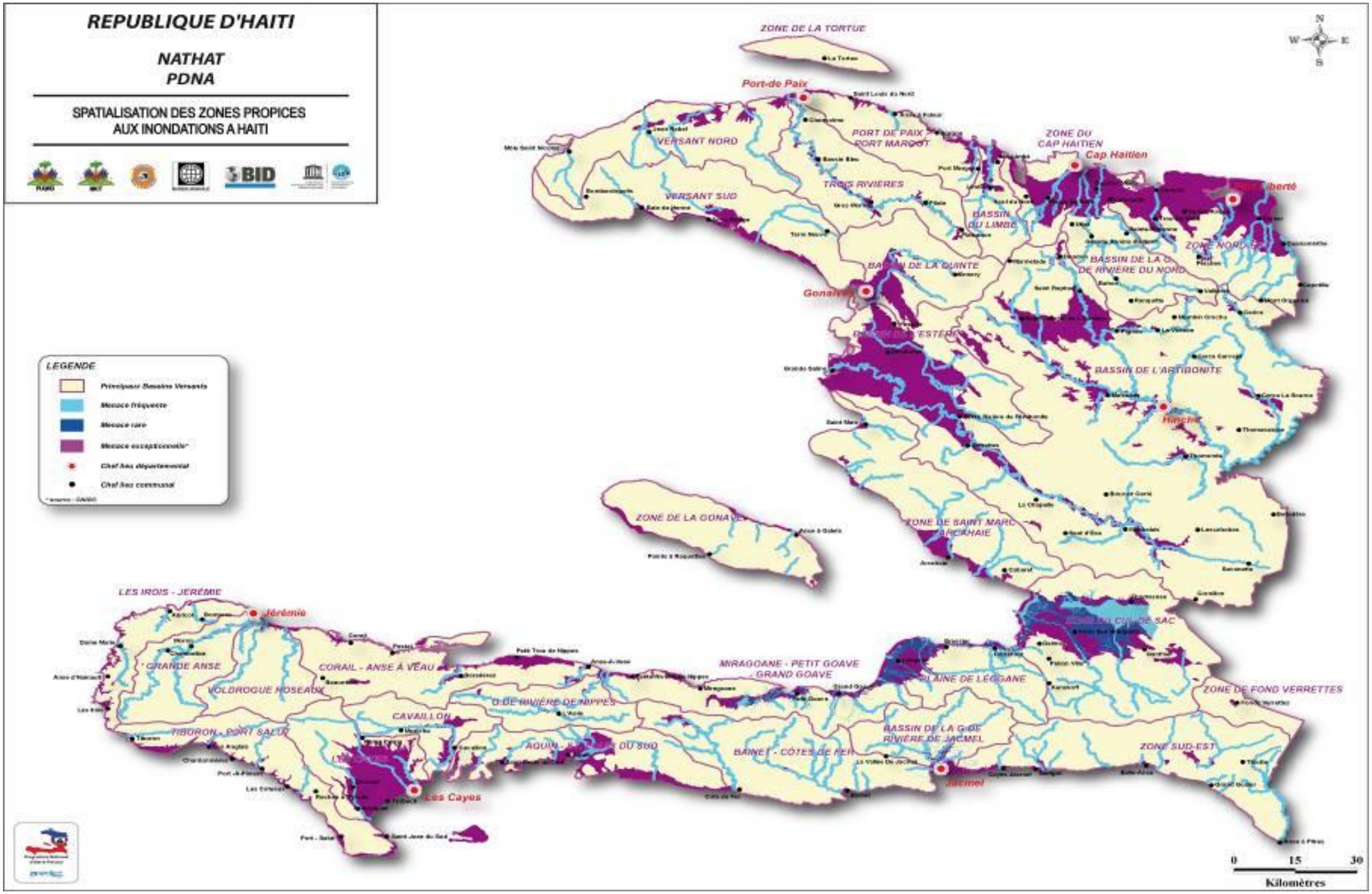


Figure 11. Preliminary map of the hazard of river flooding in Haiti.

These topographic features produce linear watersheds on very steep slopes. The country is drained by 30 major watersheds with an average area of 900 km². The largest watershed is the Artibonite river (6,300 km²), which drains the country's entire central region (Tables 3 and 4; Figure 12).

Table 3. Major watersheds in Haiti.

Basin or Zone (# of sub-basins)	**Drainage area (km^2)**	**Basin or Zone** (# sub-basins)	**Drainage area (km²)**
1. Bombardopolis/Gonaïves (3)	1,130	16. Cayes-Jacmel/Anse à Pitres (3)	1,201
2. Môle St Nicolas/Moustique (4)	975	17. Grande Rivière de Jacmel	561
3. Trois Rivière	898	18. Côte de Fer/Baînet (2)	1,064
4. Port de Paix/Port Margot	547	19. St Louis du Sud/Aquin	714
5. Limbé	313	20. Cavaillon	400
6. Cap Haïtien	325	21. Cayes	661
7. Grande Rivière du Nord	680	22. Tiburon/St Jean	657
8. Limonade/Ouanaminthe (3)	1,085	23. Jérémie/Les Irois	368
9. La Quinte	700	24. Grande Anse	554
10. L'Estère	800	25. Roseaux/Voldrogue	524
11. Artibonite (10)	6,336	26. Corail/Anse à Veau	849
12. Saint Marc/Cabaret (3)	1,118	27. Grande Rivière de Nippes	465
13. Cul-de-Sac	1,598	28. Pte. Riv. de Nippes/Grd. Goâve (3)	691
14. Fonds-Verrettes	189	29. Ile de la Tortue	179
15. Léogane/Carrefour (2)	598	30. Ile de la Gonâve	691

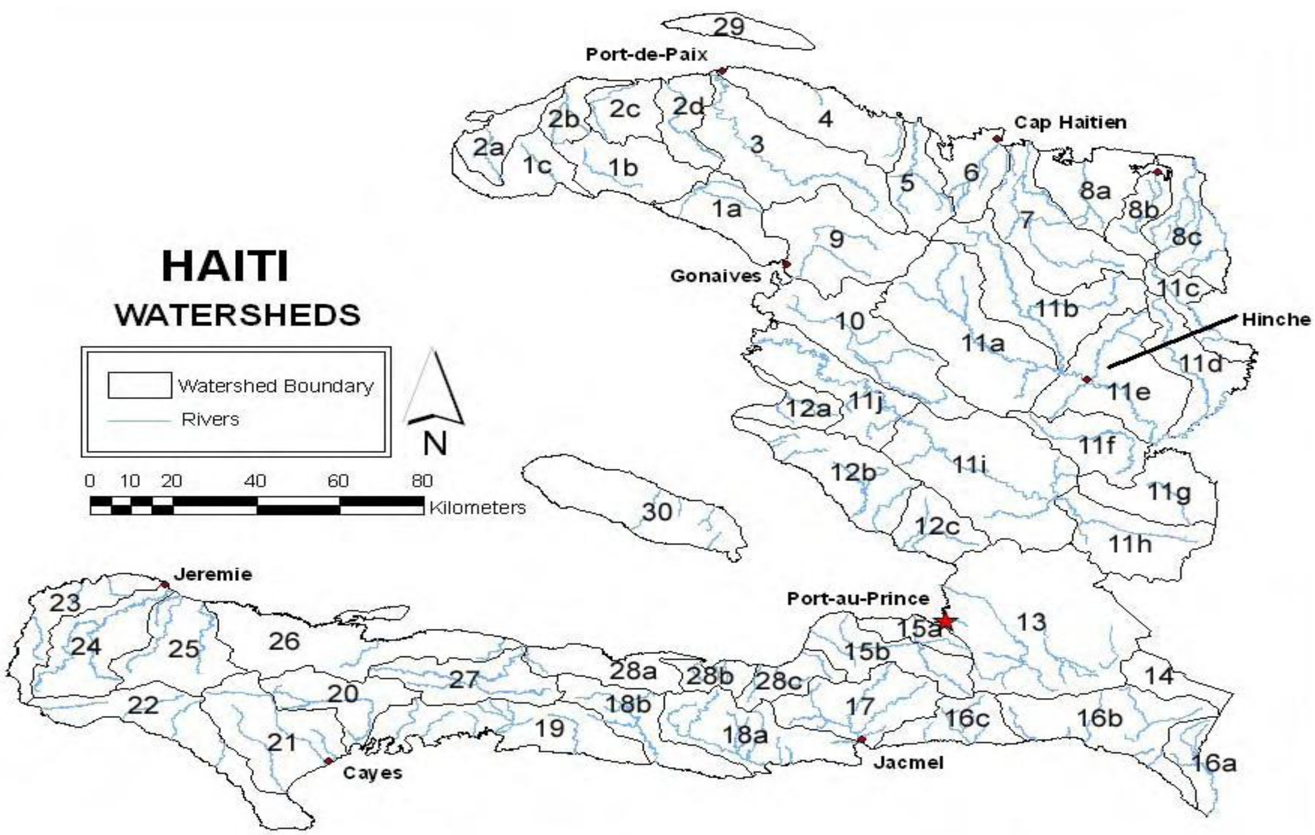


Figure 12. Map of watersheds in Haiti. Source: OAS (1972); UNDP (1998); UTSIG (2001)

Table 4. Major watersheds in Haiti. Source: OAS (1972); UNDP (1998); UTSIG (2001)

Major river systems in Haiti	Drainage area (km^2)	Average Flow (m^3/sec)	Runoff coefficient (%)	Department
Artibonite	6 336	99	22.6	Artibonite & Plateau Central
Trois Rivières	898	6.5	18.6	Nord and Nord-Ouest
L'Estère	800	3.1	12.7	Artibonite
Gde Rivière du Nord	680	5.4	20.5	Nord
Grande Anse	554	12	46.2	Grande Anse
Cavaillon	400	8.0	42.0	Sud
Momance (Léogâne)	437	5.6	-	Ouest
Rivière Grise	290	3.3	24.0	Ouest
Gde Ravine du Sud	205	3.9	32.4	Sud

Flood hazard scenarios in several communes in Haiti are presented in the diagrams of Figures 13a, b, c, d, and e, in map, 2D, and 3D formats. Owing to the paucity of adequate historical and instrumental data, the degree of hazards were modeled and determined by the relative water levels, while taking into account the geometric profiles and spaces of the sections and around minor and major beds of the main ravines, rivers, and streams.

2.3 External geodynamic hazards

2.3.1 **Slope failure**: landslides, rock falls, torrential debris flows

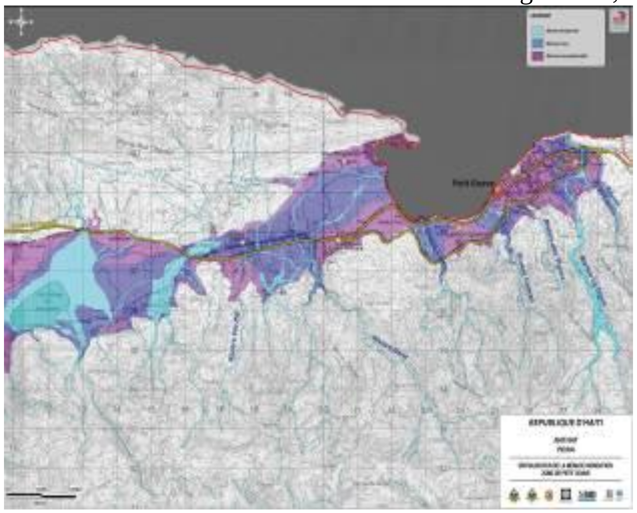
These are hazards created by various forms of instability in the surface layers of rocks and soils, which are generally composed of loose materials or weakned rock masses. These soils naturally tend to shift downward owing to the simple driving force of gravity. This tendency is opposed by resisting forces that are essentially linked to the mechanical resistance of the materials in question (cohesion and friction). The equilibrium between these forces is often limited along steep slopes and can be broken when additional driving forces (variation in the acceleration of gravity linked to the earthquakes or the generation of interstitial water pressure linked primarily to the infiltration of rain) occurr. These imbalances materialize through deformations of varying magnitudes, and subsequently rupture and propagation develops, often with devastating consequences.

2.3.2 Instability, deformation, rupture and propagation

Depending on the nature of the materials and the morphology of the affected areas, imbalance, rupture, and propagation can occur with different forms and celerity, with harmful consequences for all exposed elements (e.g. people, property, activities, natural environment). While we would have liked to describe these processes in terms of intensity or magnitude, we unfortunately lack data to do so. It bears noting, however, that the main elements for assessing their various forms of manifestation are: amplitude, velocity of the deformations, displacement, and the mass of displaced materials.

Rivière Froide (Cold River), Morne l'Hopital; February 2010

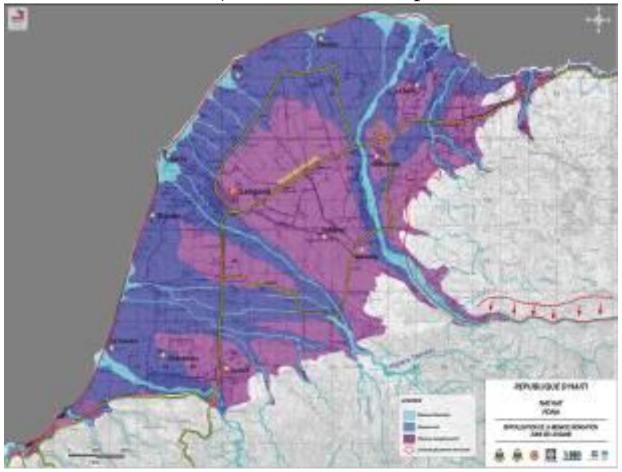
Figure 13a, b, c, d, e. Scenarios presenting the flood hazard in a number of communes in Haiti.



a1)Petite Goâve; map

a2) Petite Goâve; 2D

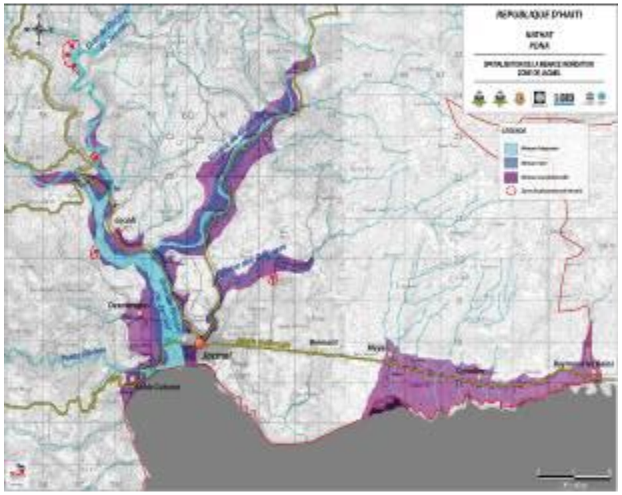
a3) Petite Goâve; 3D



b1) Léogâne; map

b1) Léogâne; 2D

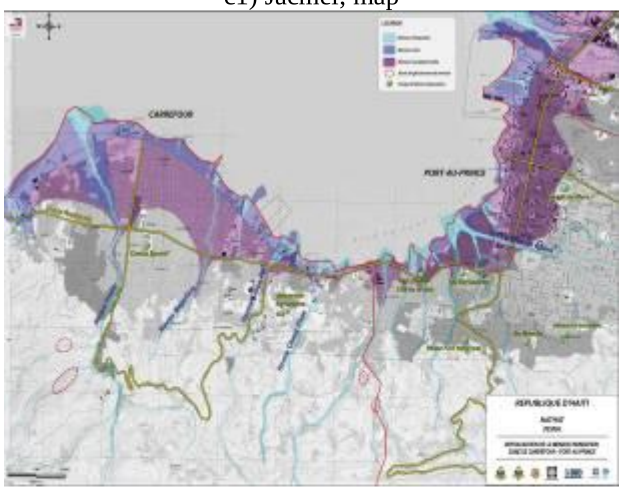
b1) Léogâne; 3D



c1) Jacmel; map

c2) Jacmel; 2D

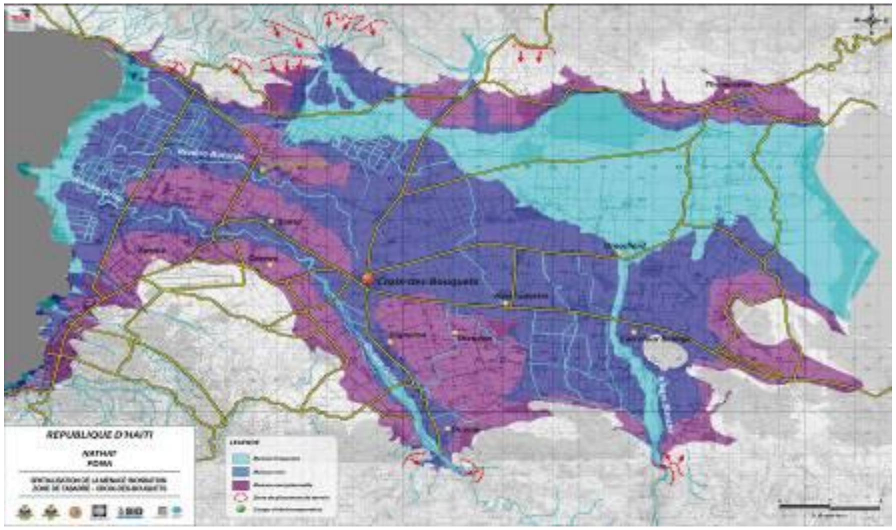
c3) Jacmel; 3D



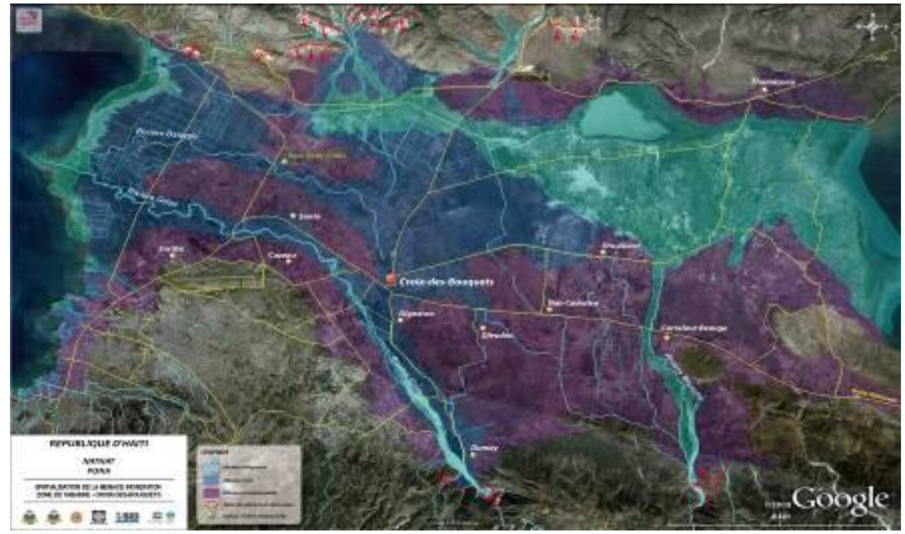
d1) Carrefour; map

d2) Carrefour; 2D

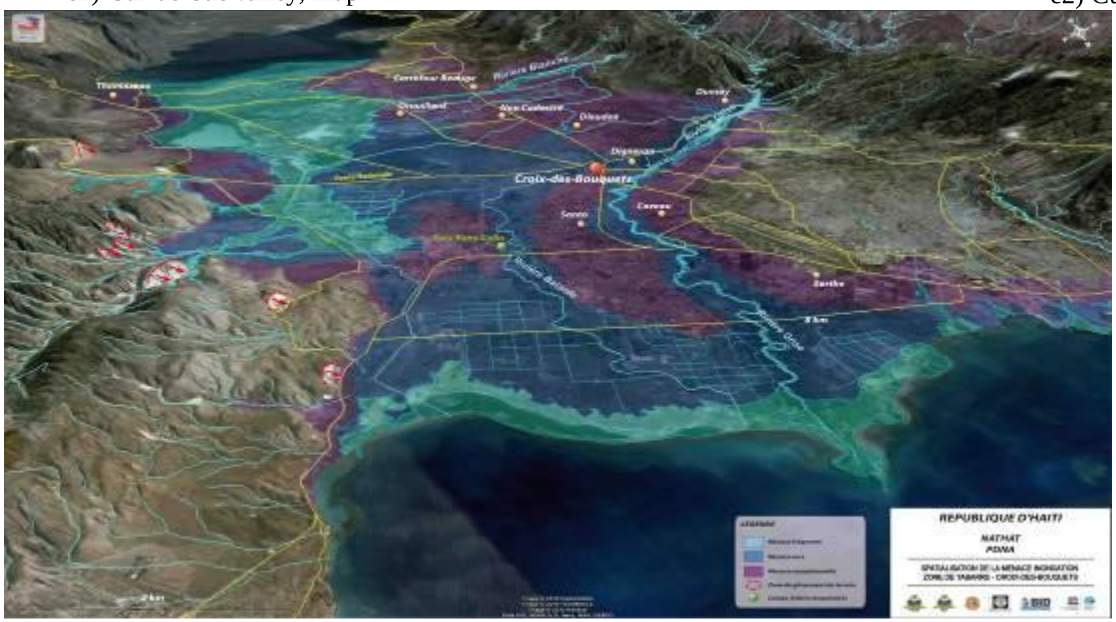
d3) Carrefour; 3D



e1) Cul-de-Sac valley; map



e2) Cul-de-Sac valley; 2D



e3) Cul-de-Sac valley; 3D

Based on their celerity and forms of materialisation, the following slope failure occurrences have bee identified:

- ***Slow, continuous movements***, as evidenced by various types of slow downslope displacements: creep erosion, solifluction, slope settlements. Humidity plays a key role in their activation and continuity.
- ***Rapid, discontinuous movements***: subsidence, landslides, rockfalls, debris flows. Water remains an important factor; seismic shaking is also a trigger and a major accelerator.
- ***Rapid movements***: torrential debris flows and mudflows, corresponding to the mobilization of significant masses of muddy or detrital materials that overcame the limit equilibrium at the top of the slope. The water-solids ratio is high and may at times cause the mass to behave like a thick and viscous liquid.

2.3.3 Status of knowledge on slope failure in Haiti

Prior to January 12, 2010, Haiti possessed only a very incomplete record of landslides, in addition to the survey carried out by the Mining Department in the vicinity of the capital, essentially focusing on cases affecting the Delmas Formation (Pliocène), which is composed of limestone conglomerates in a low resistance marly matrix, with soft clay intercalations with low cohesion.

The post-earthquake reports are still too incomplete. A preliminary assessment can be done, taking into account the large number of surface landslides in the limestone detrital formations, which were observed and which resulted in the devastation of entire neighborhoods. These swarms of destructive landslides may be due in part to land slippage, to the fact that the shaking severely affected the extremely poor structural condition of the buildings and to the related domino effects. Although satellite imagery identified very few large-scale landslides, at least in urban areas, a number of oblique helicopter photographs have revealed worrying situations that call for urgent slope failure assessments.

Moreover, even where landslides are not evident, significant shaking occurred, creating discontinuities of varying widths, where the abundant water flow expected soon during the rainy season could trigger and accelerate ground motion. Other cases of landslides were identified along the main highways (e.g. Léogâne-Jacmel), but once again, no comprehensive, systematic study is yet available.

One last category of hazard, which should be classified as man-made, exists. It is linked to the accumulation and piling of rubble in certain areas in the city. This is the case, for example, with the “clean-up” at the National Financial Administration School (ENAF) and other similar sites. Rubble was piled onto the slope, creating unstable mounds that threaten the adjacent areas. This situation frequently occurs at many other sites.

2.3.4 The filtering method (FIL) and the macrozonation of landslide hazard (Mora-Vahrson)

It is quite clear that the slope failure detection process would be better facilitated and validation if a record of known landslides existed. However, only a few incomplete records existed prior to January 12, 2010. It is to be hoped that specific work, based in particular on field reconnaissances and image processing, will help identify all or a number of the landslides triggered by the earthquake.

Meanwhile, the Mora-Vahrson method (1991) was applied to determine the natural susceptibility to landslide hazard in Haiti (Figures 14a and 14b). This method is based on the superimposition of indicators and parameters related to the intrinsical susceptibility to slope failure, based on its geological-lithologcal characteristics (S_L), the topographic conditions of the hilly area (S_{RR}), and the prevalent humidity (S_H), as well as the trigger drivers caused by seismic activity (D_S) and rain intensity (D_P). A macrozoning scenario of the slope failure hazard (Figures 14a, b, c, d, and e) resulting for each pixel, was obtained based on the following equation:

$$M_{MT} = (S_L * S_{RR} * S_H) * (D_S + D_P)$$

Also applied was the FIL method, a digital land model with a given resolution of between 1 and 100 meters, depending on data availability and the desired final resolution. This model can be used to calculate the gradient for each unit area (pixel). By means of geological and/or pedological maps, the examined territory is divide into homogeneous zones and probable surface layer thickness and traditional mechanical characteristics (cohesion, angle of friction, and density) are identified for each one. Table 5 lists the rules that were provisionally adopted to group the 27 major formations identified on the geological map into a number of homogeneous families, in terms of surface soil formations cover them and which are suceptible to sliding.

Based on each pixel, a safety factor can be calculated for the soil column of a height equivalent to the aforementioned thickness. At the end of the process, an isovalue map of this safety factor is readily available, and the sensitivity of this factor to piezometric variations or seismic accelerations can also be tested. An initial test was conducted, with the assistance from Haitian experts. However, this approach must be repeated in a more detailed manner, especially when more detailed digital models of the country and a better quality assessment of the division of the homogeneous geotechnical areas, in terms of thickness and mechanical behavior of unstable surface layers, are available. This method is a filtering process that is relatively rapid, economical and well adapted to the detection of slope-failure susceptible slopes.

Table 5. Dominant lithologic elements of surface formations

Limestone	Clay	Basalt	Detritus	Marl
A	Gd	Mm	Mu	Cb
Be/ev	Mc	Ms	Ems	Cf
Bm	Cc	Qc	Mi	Mc
Bpa	Ep	Cs	Qac	Ms
Ca	pi	Ev/Be	Qa	O
Es	Qa			Pi

A map of the slopes for which divisions were necessary (slope classification) was prepared based on shapefiles in .shp format. These shapes were superimposed to provide an isovalue map with a I_{pg} landslide predisposition index, expressed in the following four forms (Figures 15a and b):

I_{pgN} corresponding to a dry season, without earthquakes
I_{pgNS} corresponding to a dry season, with an acceleration of 0.2g
I_{pgH} corresponding to a rainy season, without earthquakes
I_{pgHS} corresponding to a rainy season, with an acceleration of 0.2g

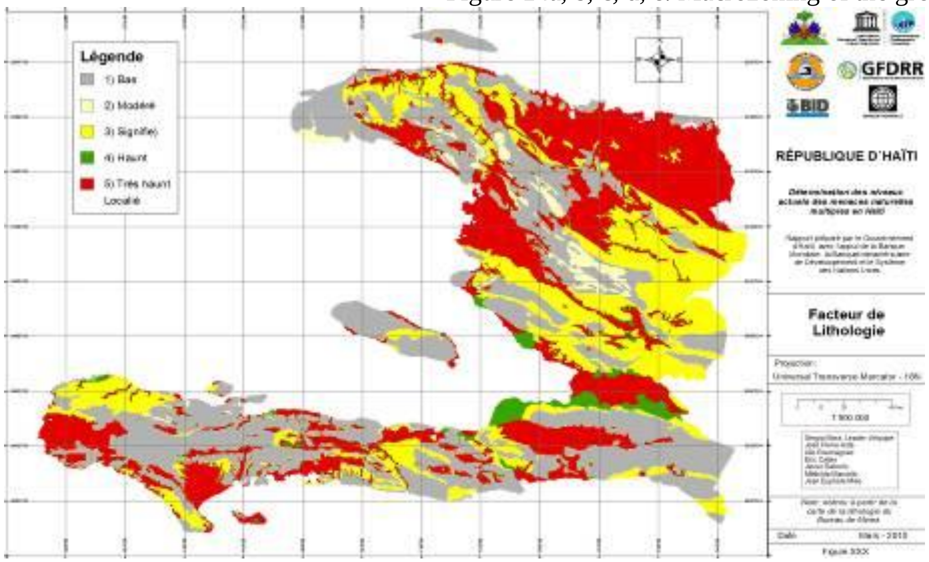
It bears noting that these indices only serve as a filter and do not in any way provide in-depth criteria at the operational level. The maps were prepared at the national level and higher resolution maps at the regional level could also be prepared if more accurate geological and geographical data were acquired, such as, for example, the metric DEM obtained for a section of Port-au-Prince. The division and description process for homogeneous zones, which are an important component of the method, would therefore have to be improved. However, improvements in resolution, and thus operational efficiency, will require a long and thorough endeavor that must be undertaken as soon as possible to guarantee the security and sustainability of the development process that the country needs.

Given these circumstances, this dual filtering process for potentially unstable areas was selected to achieve the short-term objectives of making possible to assign a predisposition index to any relevant area (e.g. a shelter area) for short-term management. For a given polygon representing an area and covering "n" pixels, the average and standard deviation of the instability index values could be calculated and a level of exposure can be determined. Similarly and on a wider scale, an initial detection of all areas exposed to landslides in the country was performed. Despite its rudimentary nature, this method offers valuable opportunities with respect to vulnerability assessments and risk quantification approaches (or the extent of potential losses).

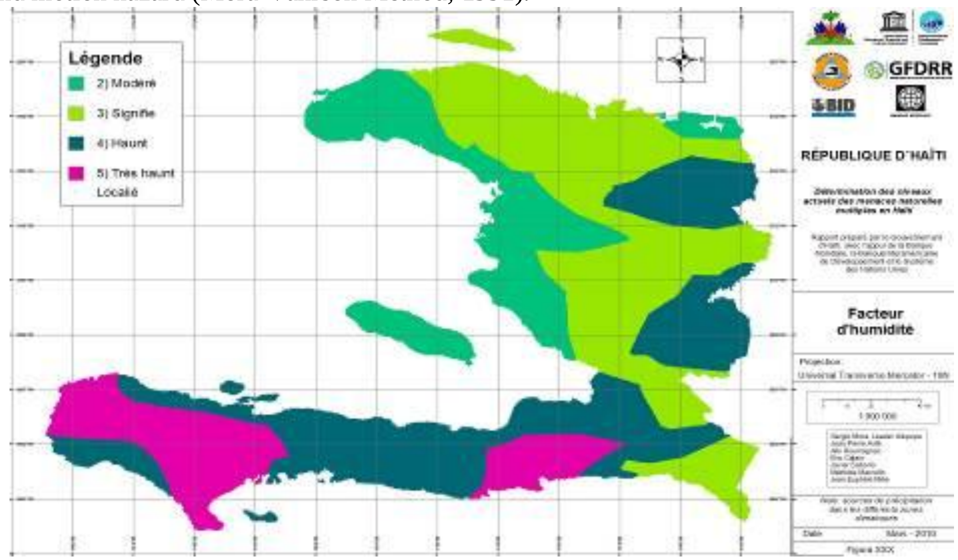
Photo 6. 6a, Le Village commercial center, Montana hotel; December 6, 2009; and 6b, February 16, 2010

Photo 7. Stairway to nowhere; Turgeau, Port-au-Prince; February 21, 2010.

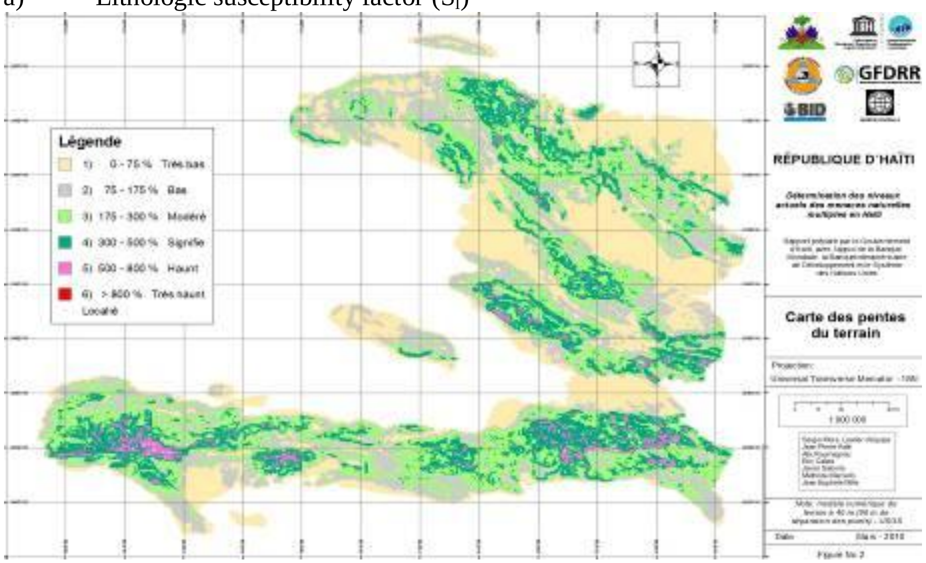
Figure 14a, b, c, d, e. Macrozoning of the ground motion hazard (Mora-Vahrson Method; 1991).



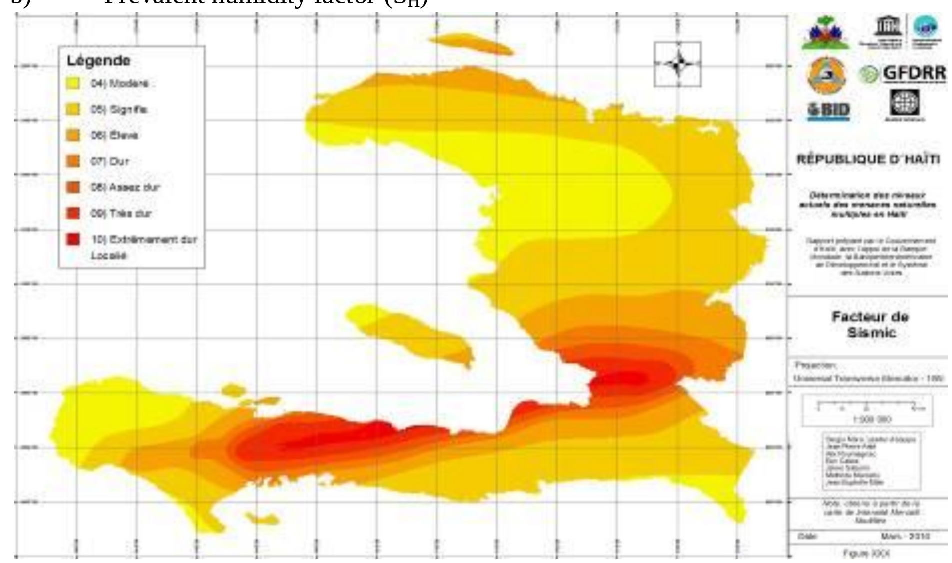
a) Lithologic susceptibility factor (S_l)



b) Prevalent humidity factor (S_H)



c) Topographic factor (S_{RR})



d) Seismic trigger factor (D_S)

Figure 14e. Macrozonation of the slope failure hazard (Mora-Vahrson Method; 1991)

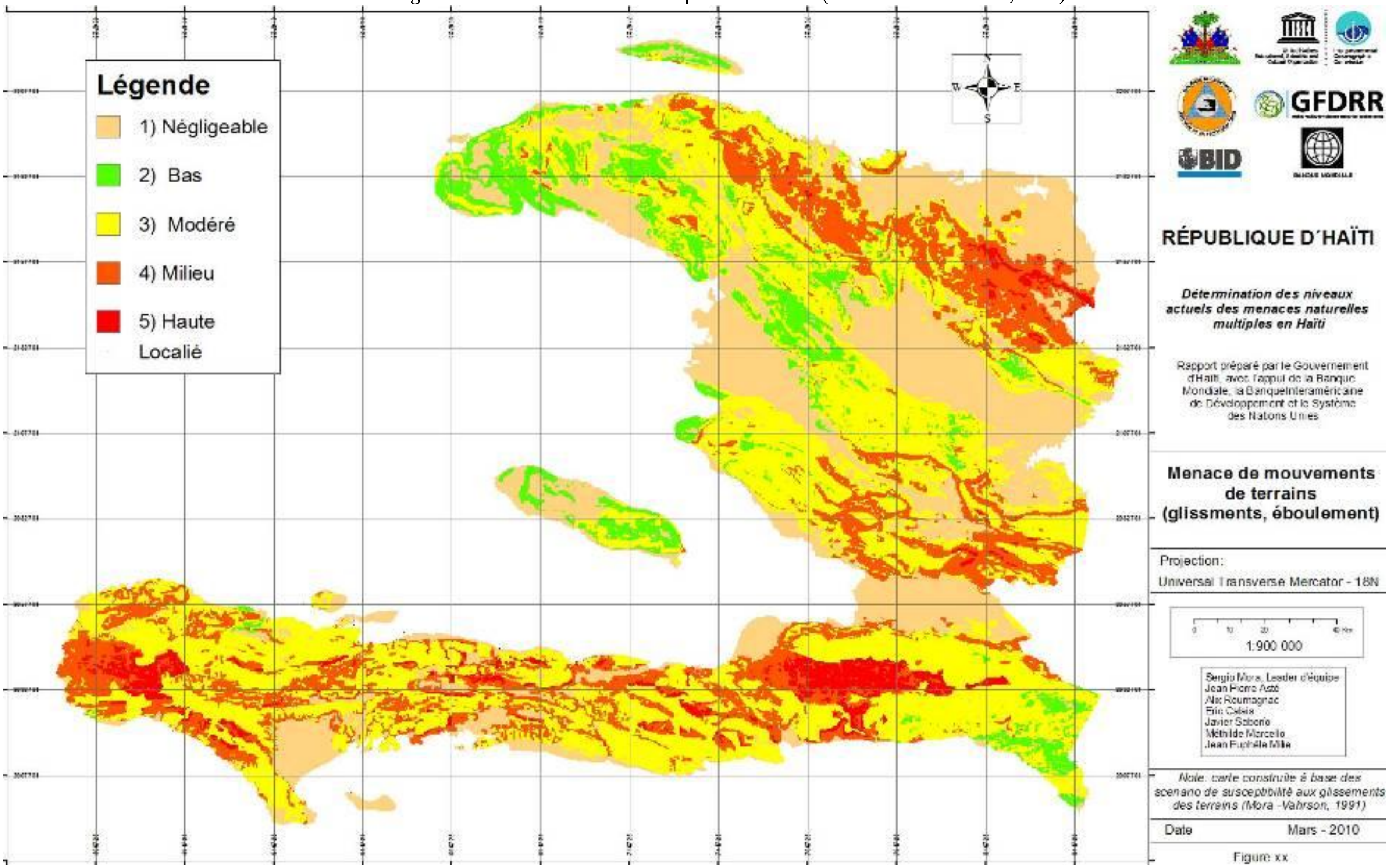


Figure 15a. Macrozoning of the landslide hazards; FIL method. Conditions: dry, without earthquake

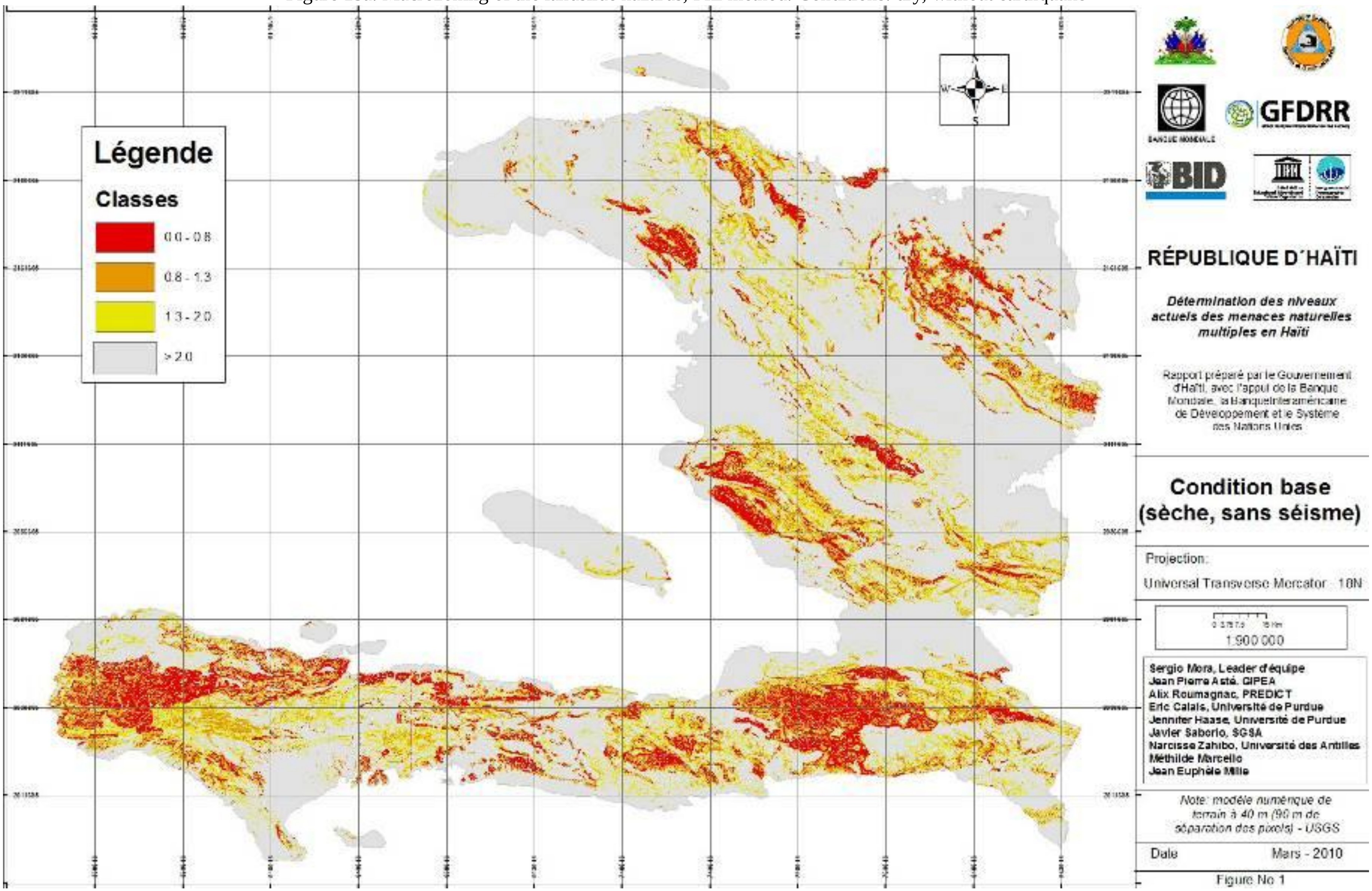
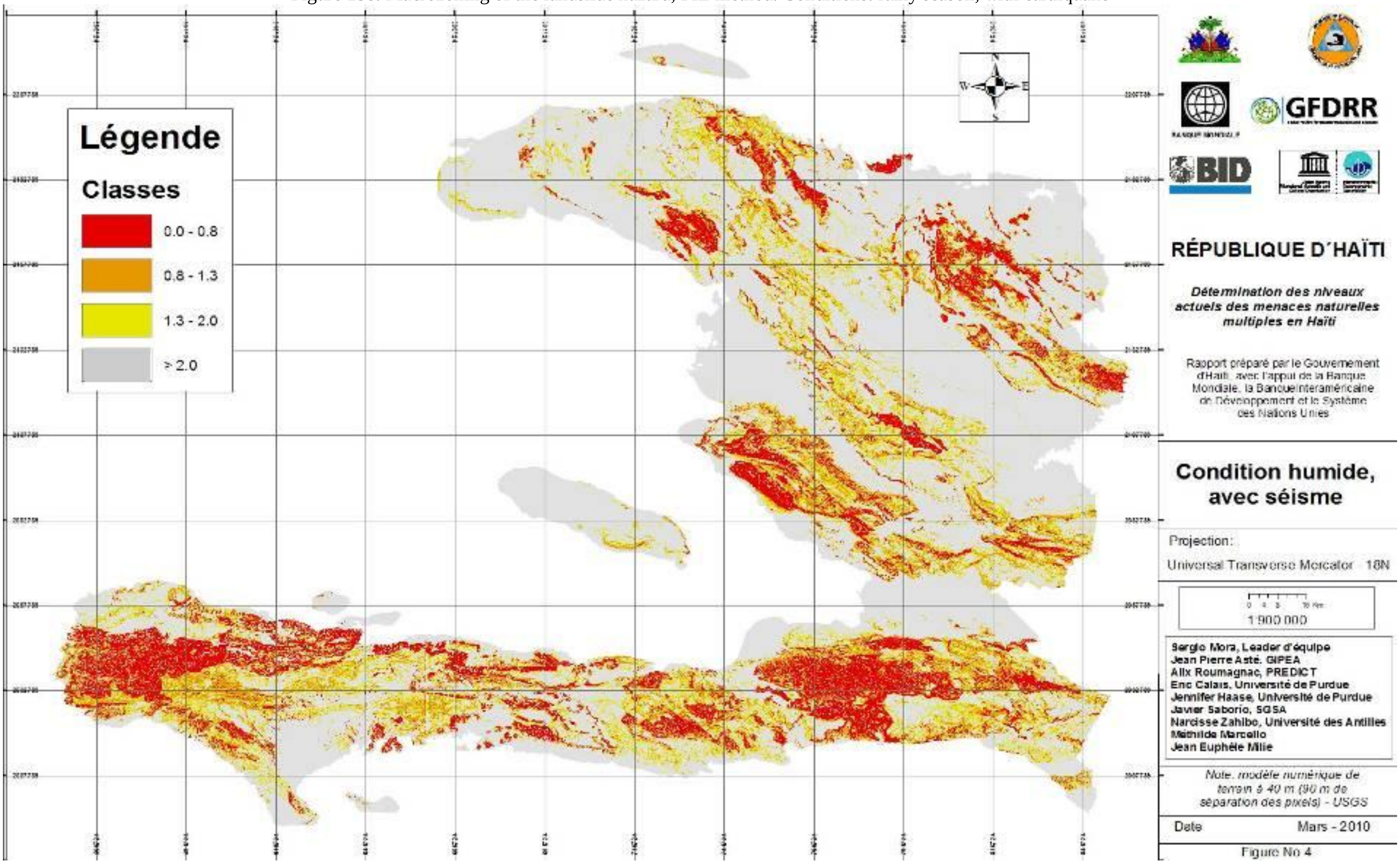


Figure 15b. Macrozoning of the landslide hazard; FIL method. Conditions: rainy season, with earthquake



2.3.5 The geomorphorlogical analysis (MPH)

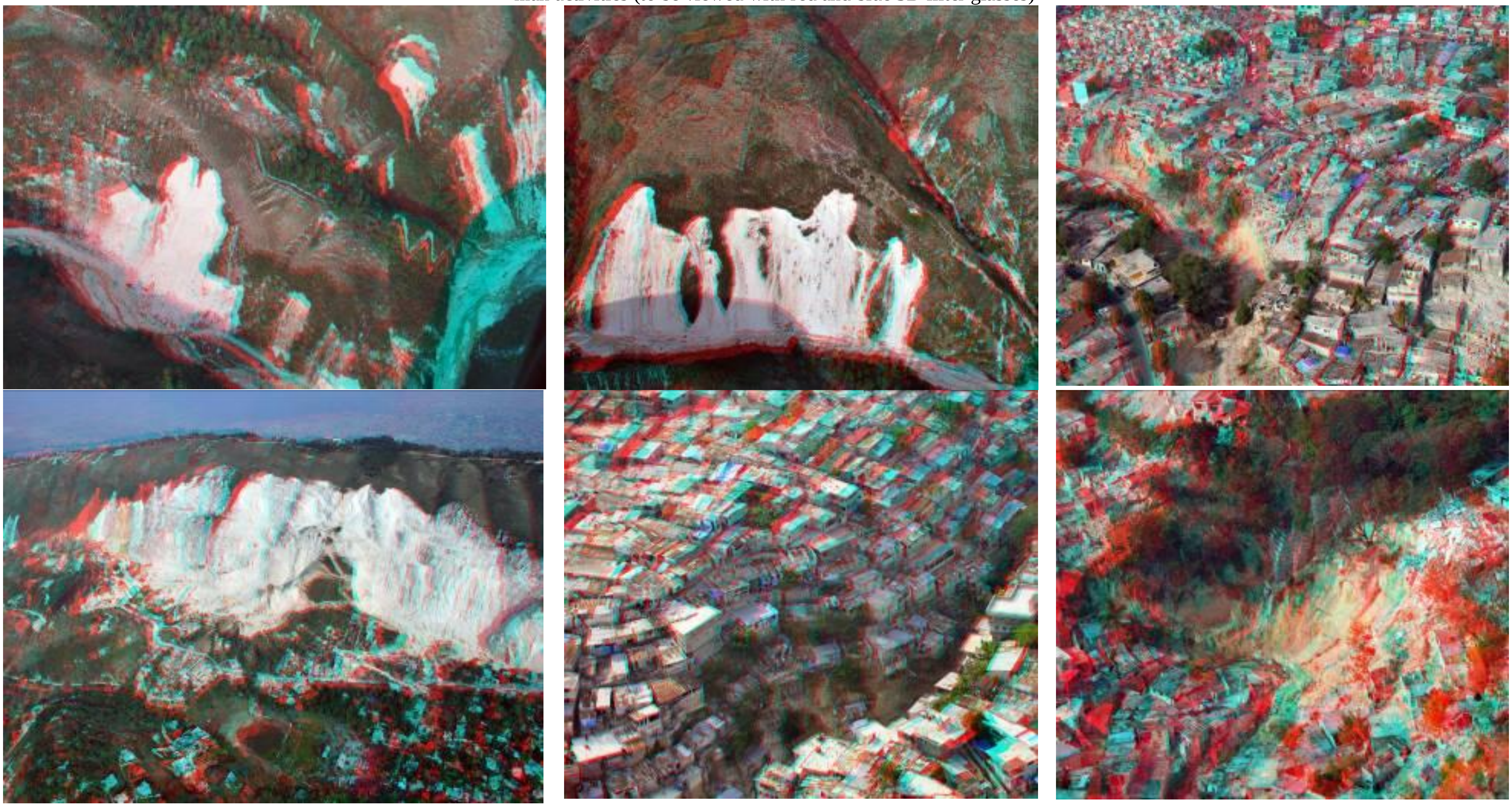
This is a traditional method whose implementation can be considerably facilitated through the use of a three-dimensional representation and visualization. It is based on the principles of stereoscopic photointerpretation. If CNIGS might allow aces to the aerial photographic coverage in digital format and the use of stereophotogrammetric software, this could facilitate the analysis and identification of suspected unstable areas. If photographs taken of certain areas using stereoscopic methods following January 12 were available, it will be possible to provide a more in-depth assessment using morphological criteria or the corresponding potential for landslides, and issue recommendations for the short-term. Second, and most importantly, efforts to differentiate between the various processes grouped under the common term “slope failure” should be initiated. If these areas were also covered by the LiDAR survey at 10 m or 1 m, the forecast will be significantly improved as the assessment of morphological conditions will be quantified instead of simply being qualitative. It bears noting, however, that this alone will not ensure the safety of the exposed populations. All the mitigation measures that must be adopted in parallel require a geoechnical interpretation effort that will take several days, depending on the number of sites covered, and will therefore necessitate specific financial resources. The objective is to have the ability to carry out the following operations as quickly as possible in each relevant area (refugee camps, dangerous zones, urban development areas), and more generally in areas identified as being exposed to slope failure:

- Have access to a stereoscopic view of the areas by indexing photographs;
- Verify (subject to availability of two series of photographs before and after the event) whether a landslide has occurred, or if shaking of the slope suggests that it has been weakened and that it could collapse during the rainy season or owing to additional seismic stress;
- Conduct mandatory field checks;
- Forecast the forms of rupture and possible increased propagation of the unstable masses.

2.3.6 A complement to morphological analysis: 3D modeling (MOD)

The photographs included in Figure 16 (red and blue filter glasses required) were taken using virtual 3D models of slope segments (on the order of 200m to 300 m long and with a spot elevation of the same length) to be able to more closely examine the morphological indices of ruptures and automatically assess the likelyhood of rupture and propagation conditions. It helps provide a closer oblique view and prepare anaglyph images of the photographed scenes. A selection of these images, for which the reader needs red and blue filter glasses, is provided below. Although the slope factor remains essential, emphasis should really be placed on morphological criteria to identify the various types of hazards. In this regard, a very positive development has now placed at least a part of Haiti in a privileged position, with the development of high-resolution, digital elevation models (DEMs) that were not available before. New analytical and detection methods can be used to provide highly effective results based on these models. The technical details will not be developed here; however, the team of experts is available to provide explanations. Future Haitian officials who will be tasked with corresponding responsibilities must therefore be quickly trained in these innovative and effective methods. Moreover, and in terms of a much more traditional approach, there is a need to strengthen the record of landslides across the entire country.

Figure 16. Aerial anaglyph photographs showing slopes in the urban region of Port-au-Prince with instability problems caused by the earthquake and human activities (to be viewed with red and blue 3D filter glasses)



2.4 Coastal hazards

2.4.1 Tsunami

The subduction zone in which the Greater Antilles is located is well known for producing tsunamigenic earthquakes. This was the case on January 12, 2010 when a 7.0-magnitude earthquake occurred in one of the segments of the Enriquillo fault in Haiti. Contrary to early findings, this earthquake actually generated a 2-3 meter tsunami along Port-au-Prince's shoreline, killing three people (Hermann Fritz, Nature, February 25, 2010, doi:10.1038/news.2010.93, http://www.nature.com/news/2010/100225/full/news.2010.93.html), bringing to 10 the number of tsunami recorded on the island since 1752 (Figure 17). A more comprehensive field effort will be necessary to complete the analysis of this case.

In order to evaluate tsunamis capable of being generated by high magnitude earthquakes, NOAA (National Oceanic and Atmospheric Administration, Seattle, USA), following a global geological campaign, recently proposed source models for all subduction zones around the world (http://sift.pmel.noaa.gov), including those in the Caribbean Basin. These source models propose an estimate of several trigger points for subduction earthquakes based on the segmentation of the subducting plate and the overriding plate, and also include all the characteristic functions of the potential earthquake that it could generate. The source model is also linked to a digital simulation of tsunami propagation and flooding (ComMIT/MOST), which therefore helps generate all possible earthquake scenarios in the subduction zone, and study the resulting tsunami. The model was used to study various tsunami scenarios, and evaluate wave heights and probable flooding levels for the coastlines of Haiti's major cities (Figure 18). The study first reveals the need for high-resolution bathymetry. This type of data is indispensable to the preparation of flood maps and assessment of the tsunami hazard. However, by using ETOPO2 for a general bathymetry interpolation for the region, it was possible to analyze wave heights along the coastline, with a bathymetric precision of 3 seconds (approximately 90 m). The results show that the island's coastlines are exposed to the tsunami hazard, with waves sometimes arriving along the coastline in a very short time (approximately 20 minutes), thus necessitating ex-ante risk management activities.

2.4.2 The effects of storms

Owing to their geographical location and synoptic and geographical context, Caribbean islands are frequently exposed to hydrometerological and climate-related hazards caused by atmospheric disturbances (tropical waves and hurricanes, polar fronts, etc.). All of these hazards expose coastal populations to strong winds, storm surges, and wave coastal flooding (Photo 8). These combined hazards, in addition to coastal erosion, make the shoreline particularly vulnerable. The use of scenarios and digital simulations made it possible to establish a series of hypotheses regarding coastal hazard in Haiti posed by tsunami and waves generated by earthquakes and atmospheric disturbances, respectively. The findings can help policymakers identify the targets of their strategy to address coastal hazards and simultaneously implement an education and awareness-building strategy for the population.

2.4.3 Storm surge

An assessment of the hazard caused by atmospheric disturbances was conducted for Haiti's coastlines. Following a statistical analysis of all atmospheric disturbances that, owing to their path, approached or even hit the island over the last 15 years, the scenarios developed facilitated an analysis of the run up heights of these related tidal waves (Figure 18).

Haiti's geographical proximity to Jamaica to the southwest and Cuba to the west reduces the exposure of Port-au-Prince bay to sotrm surges generated by tropical cyclones that usually travel from east to west. Disturbances that move through the passage between Haiti and Jamaica, as was the case with Fay in 2008, may have an impact. The coasts in this bay nonetheless remain exposed to rising sea levels caused by locally generated winds in the region. A simulation of the surge generated by Fay in this bay was conducted and confirmed a very agitated sea producing significant impact on the coast. The simulation of a tropical storm from the north shows that the northern part of the island is protected by Turks and Caicos and by the Mouchoir and Silver banks. This area also remains highly exposed to the locally generated wind.

The southern part of the island has bathymetric features that appear to heighten the hazard. As shallow water areas are only found close to the coastlines, a homogeneous wind in this area is enough for the waves to reach the coasts because they are barely broken in deep waters. The simulation of a disturbance from the south shows wave surges of 8-10 m. Exposed to strong hurricane winds, the island's Caribbean coastline could sustain particularly significant damage from long and strong surges.

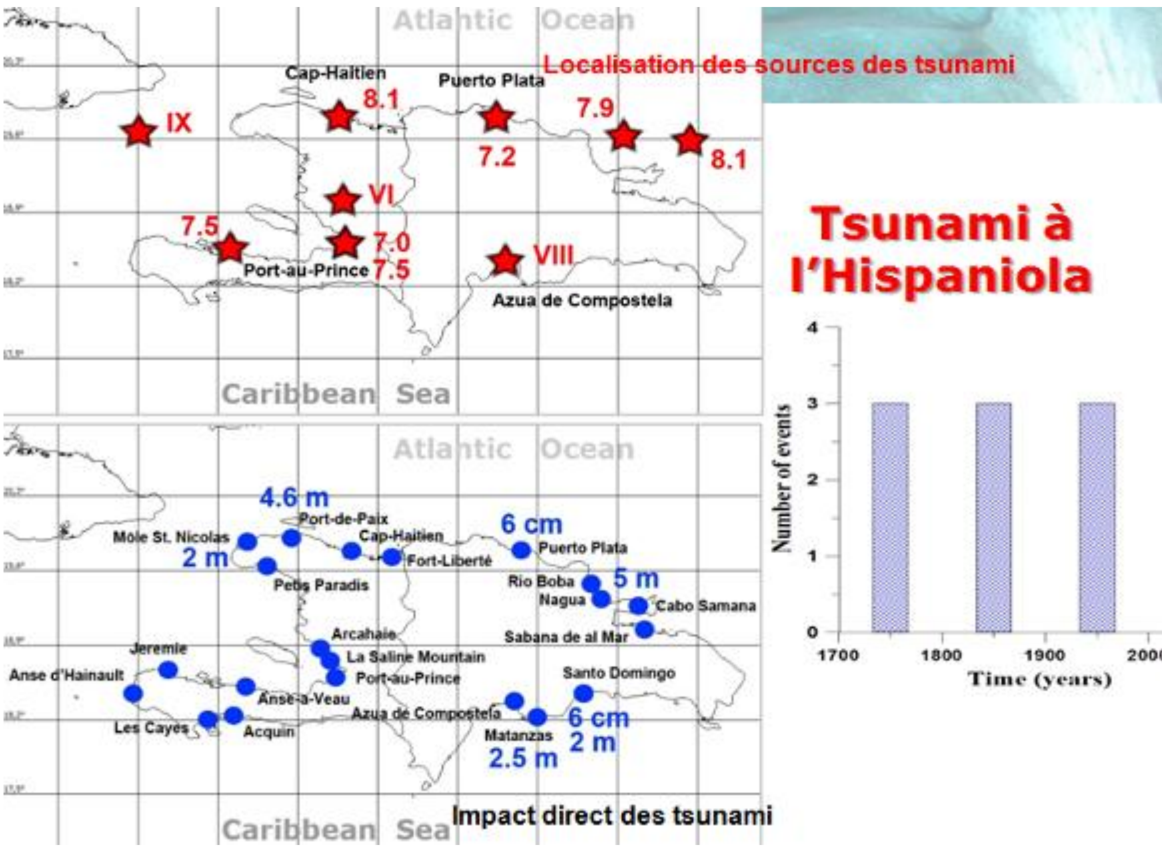


Figure 17. Tsunamigenic earthquakes on the island of Hispaniola

2.4.4 Coastal flooding

The flood hazard linked to rising water levels, caused by tsunami waves, tidal wave surges, and possibly also as a result of rising sea levels accelerated by global warming, should signal the need for consideration of short- and long-term solutions with respect to coastal zone occupation. Decision makers must put in place land-use planning development and mitigation strategies to reduce the aggravating effects of the hazard posed by coastal flooding. The growing number of exposed infrastructure and populations along the coastline makes it increasingly vulnerable.

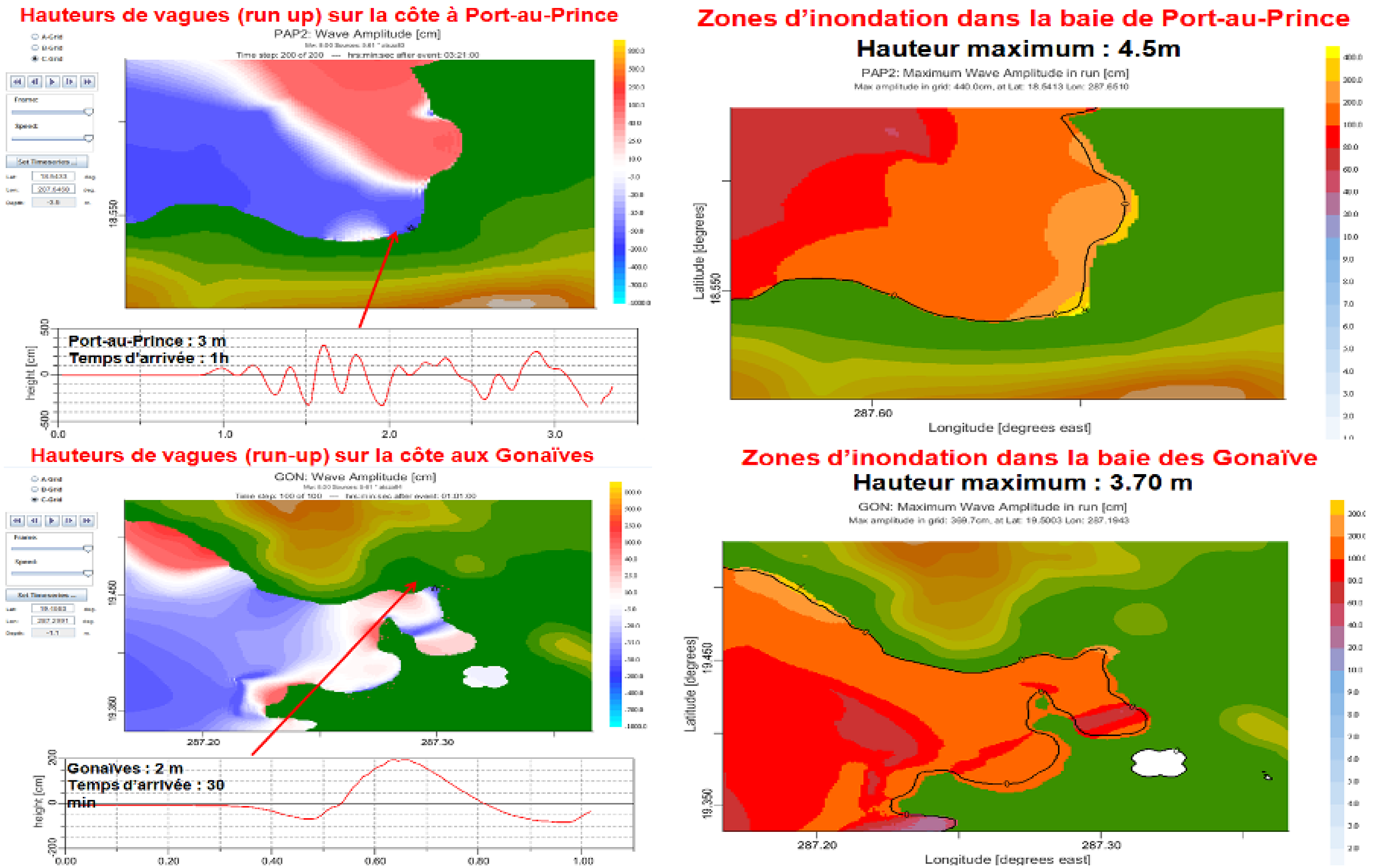
2.4.5 Coastal erosion

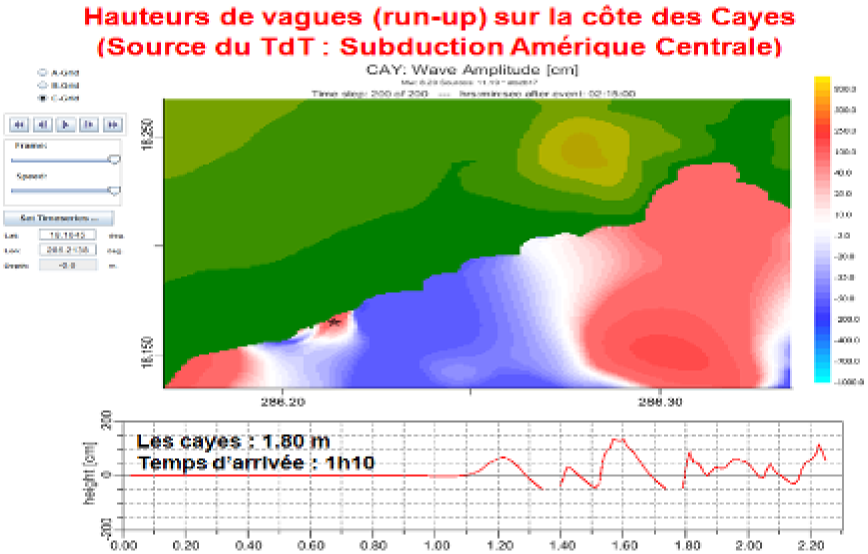
An inspection of a number of sites in Léogane and Saint Marc shows that the coastline is hazardened by coastal erosion. Owing to the ever-present pressure of waves, coupled with the natural erosion process, coastal roads are being eroded. The process could worsen if man-made pressures are combined with natural causes. Solutions such as stone blocks or artificial concrete blocks are urgently needed to provide short-term protection.

Photo 8a. Delta coastline in southeast Port-au-Prince, overrun by urban development.

Photo 8b. Shoreline occupied by shanty towns in the Carrefour area, Port au Prince.

Figure 18. Analysis of tsunami scenarios for several Haitian coastal cities





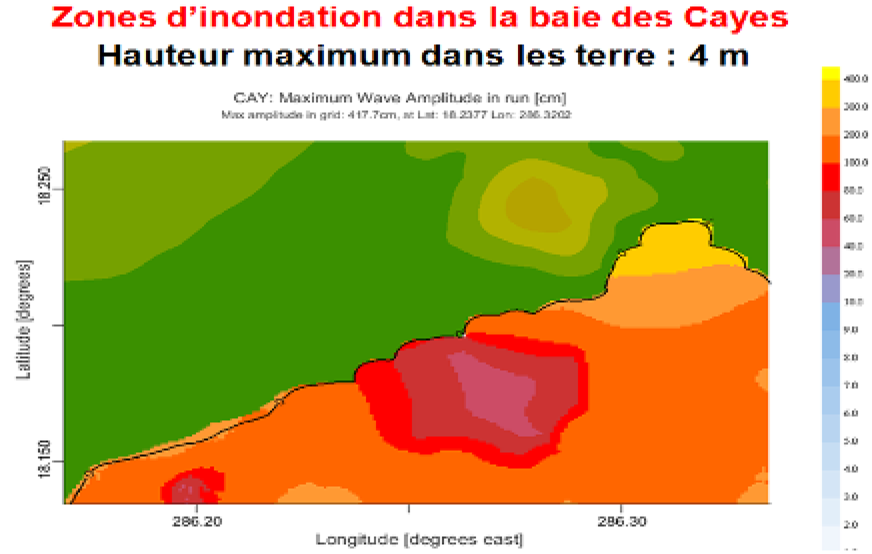
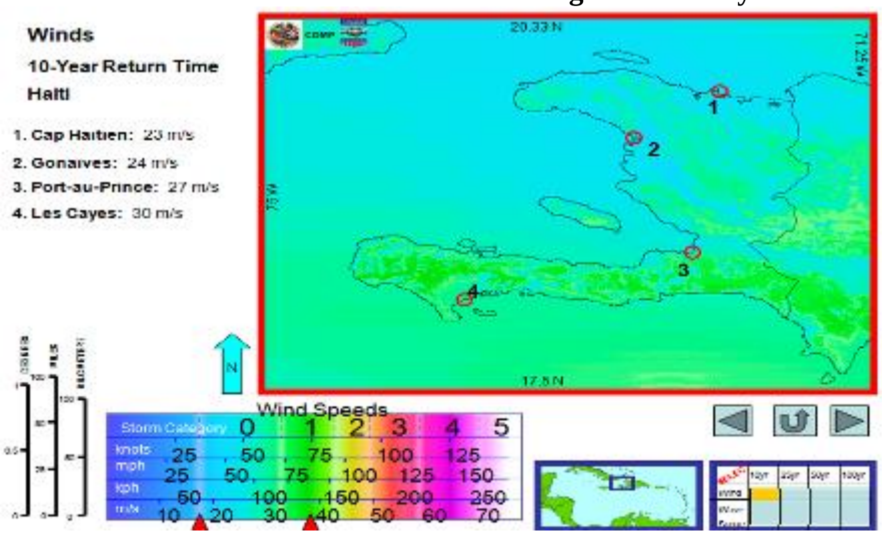
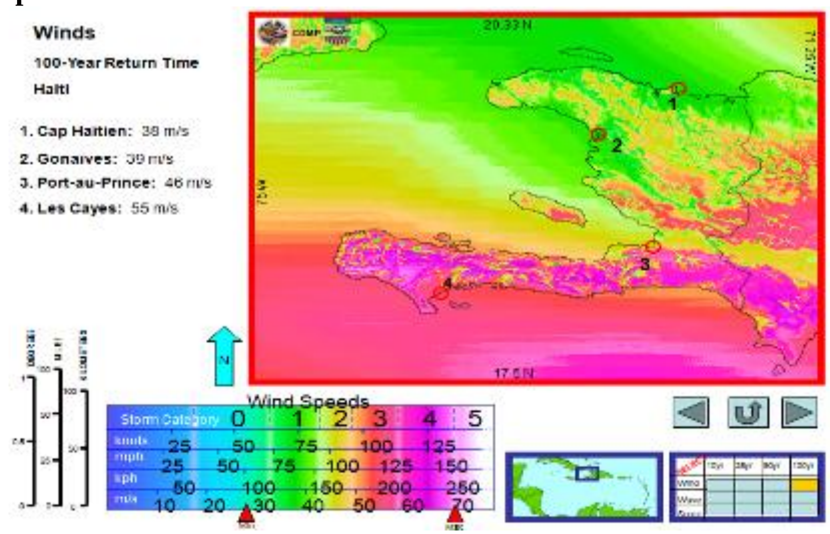


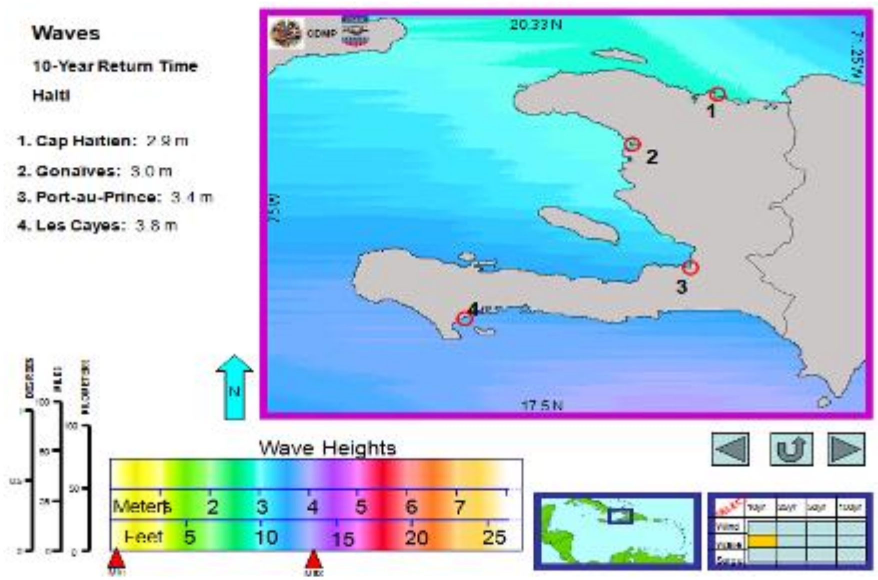
Figure 19. Analysis of storm impact scenarios in Haiti

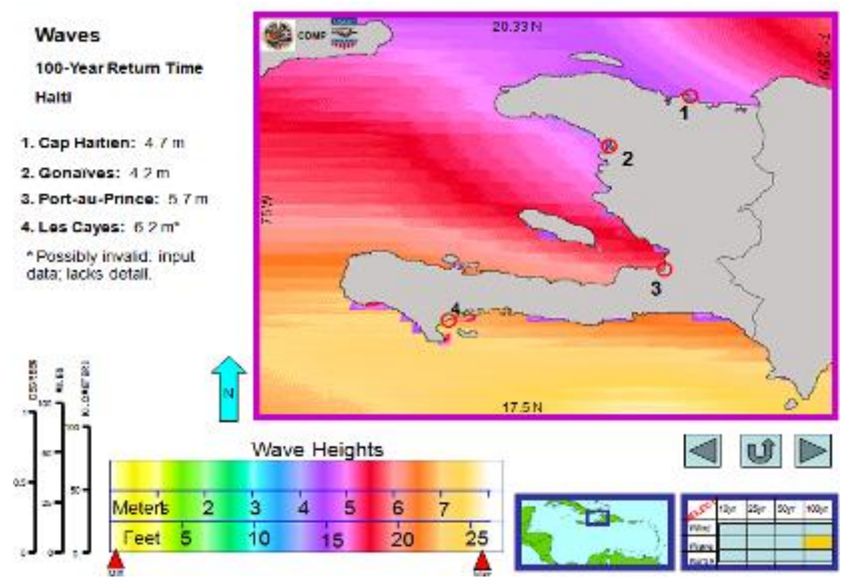


Storm winds; 10-year return time



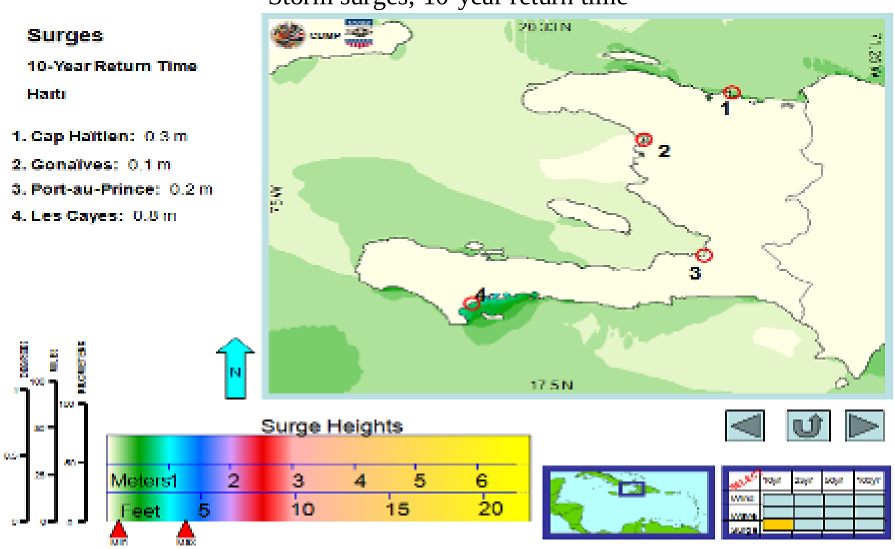
Storm winds; 100-year return time

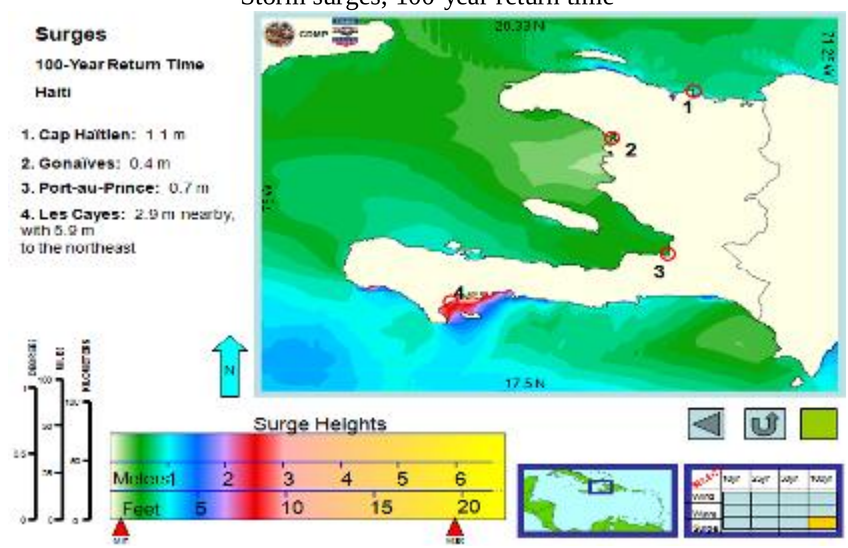




Storm surges; 10-year return time

Storm surges; 100-year return time





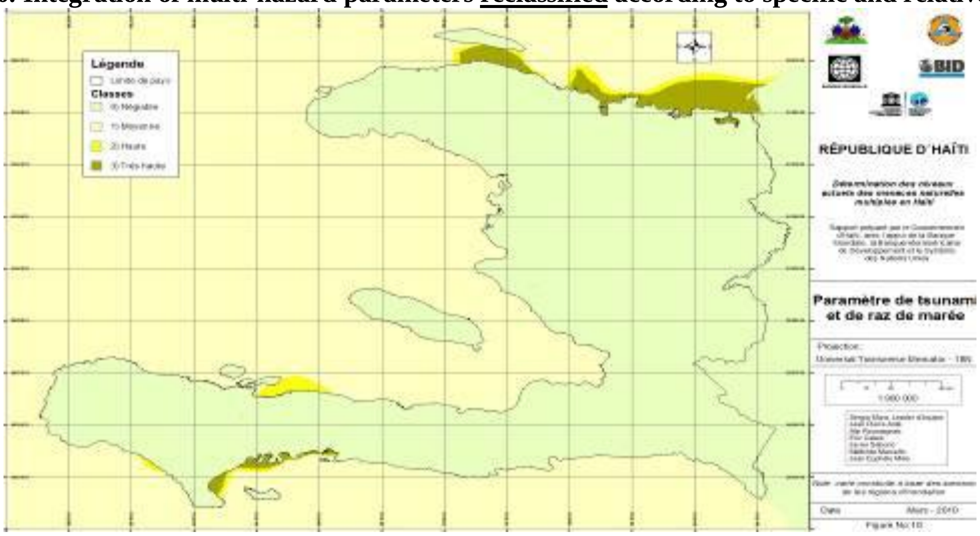
Tidal waves; 10-year return time

Tidal waves; 100-year return time

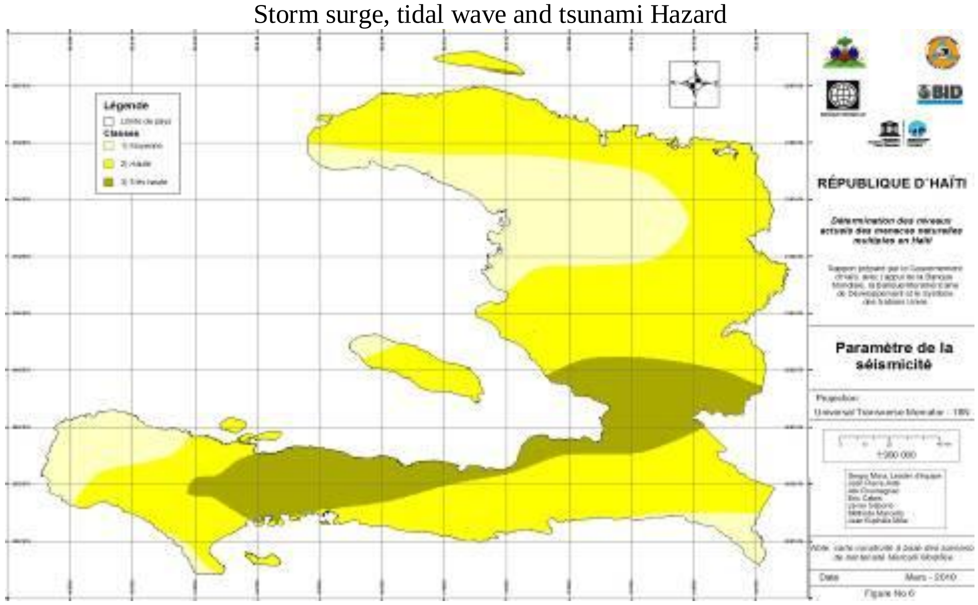
2.5 <u>Superposition model of multi-hazard scenarios, by relative weights</u>

In an effort to understanding the multi-hazard picture in the entire country, a preliminary superposition exercise of natural hazard scenarios in Haiti was conducted. The parametric values of flood hazards, ground motion, liquefaction of soft soils, seismicity, storm and tsunami surges were reclassified in a simple manner to provide roughly equivalent relative weights and make them comparable to each other by preliminarily qualitatively assessing the exposure on the sourrounding areas (no information of quantitative vulnerability is available). Figure 20 shows the partial steps while Figure 21 the overall result. It is clear that this is still a very preliminary exercise requiring review, discussion, and validation. The results are nonetheless consistent with field observations and with information available. As such, it could serve as an instrument and tool to support decision making relating land-use planning in future urban space planning.

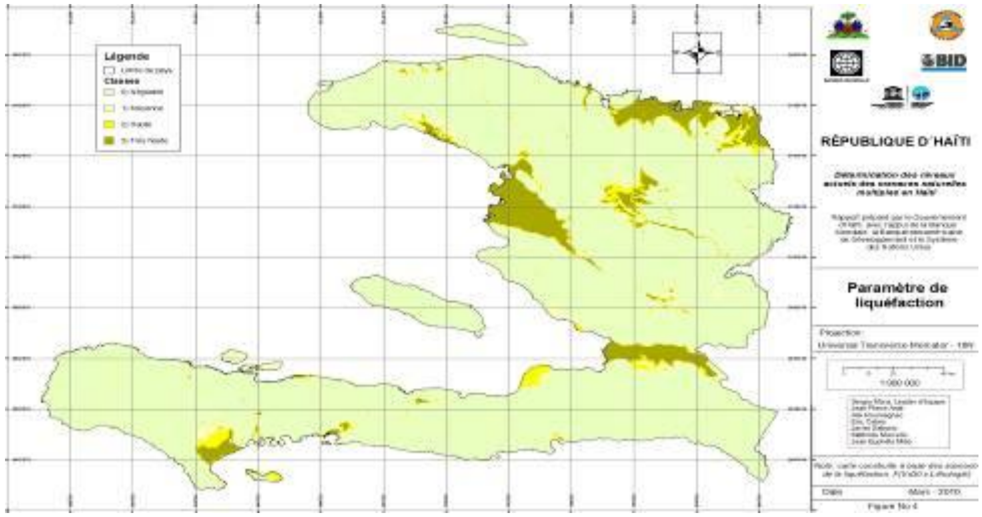
Figure 20. Integration of multi-hazard parameters <u>reclassified</u> according to specific and relative weights



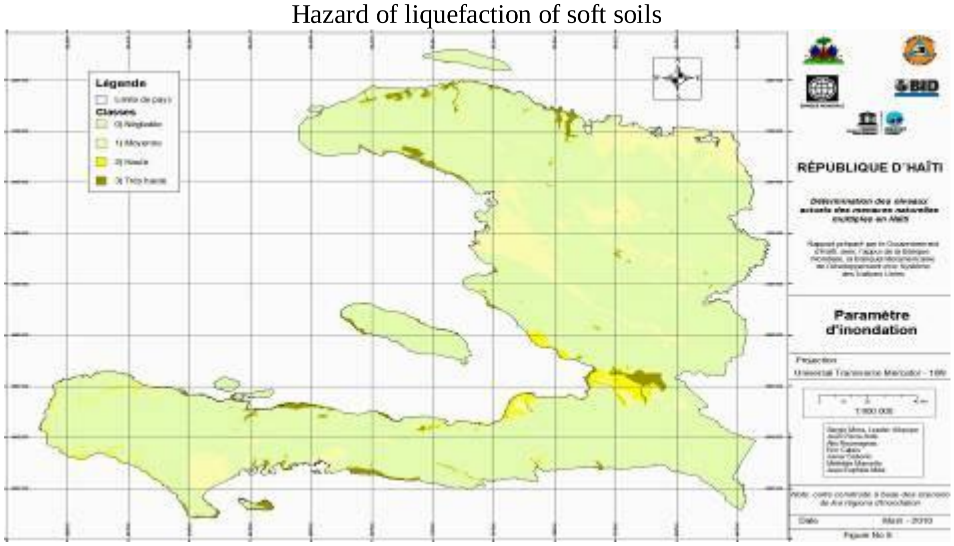
Storm surge, tidal wave and tsunami Hazard



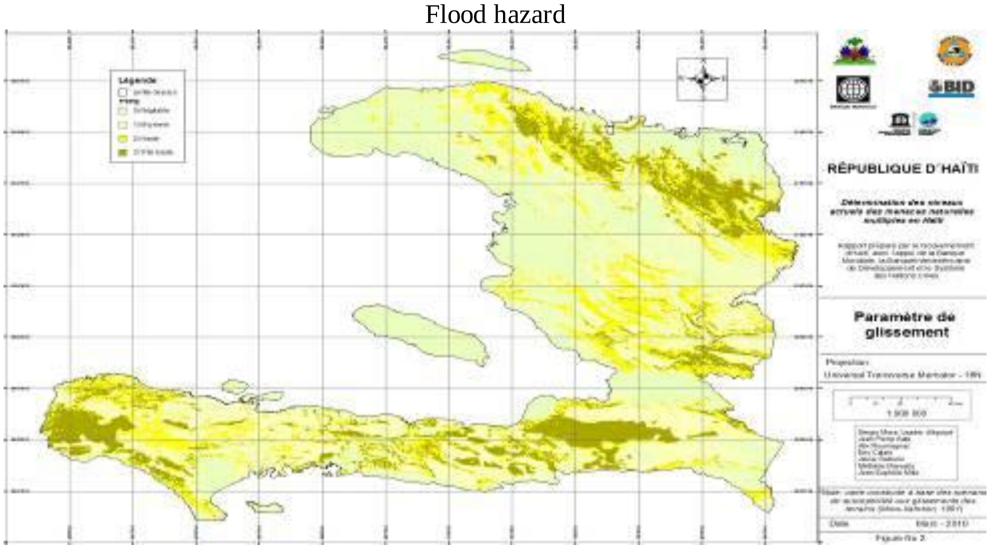
Seismic hazard



Hazard of liquefaction of soft soils

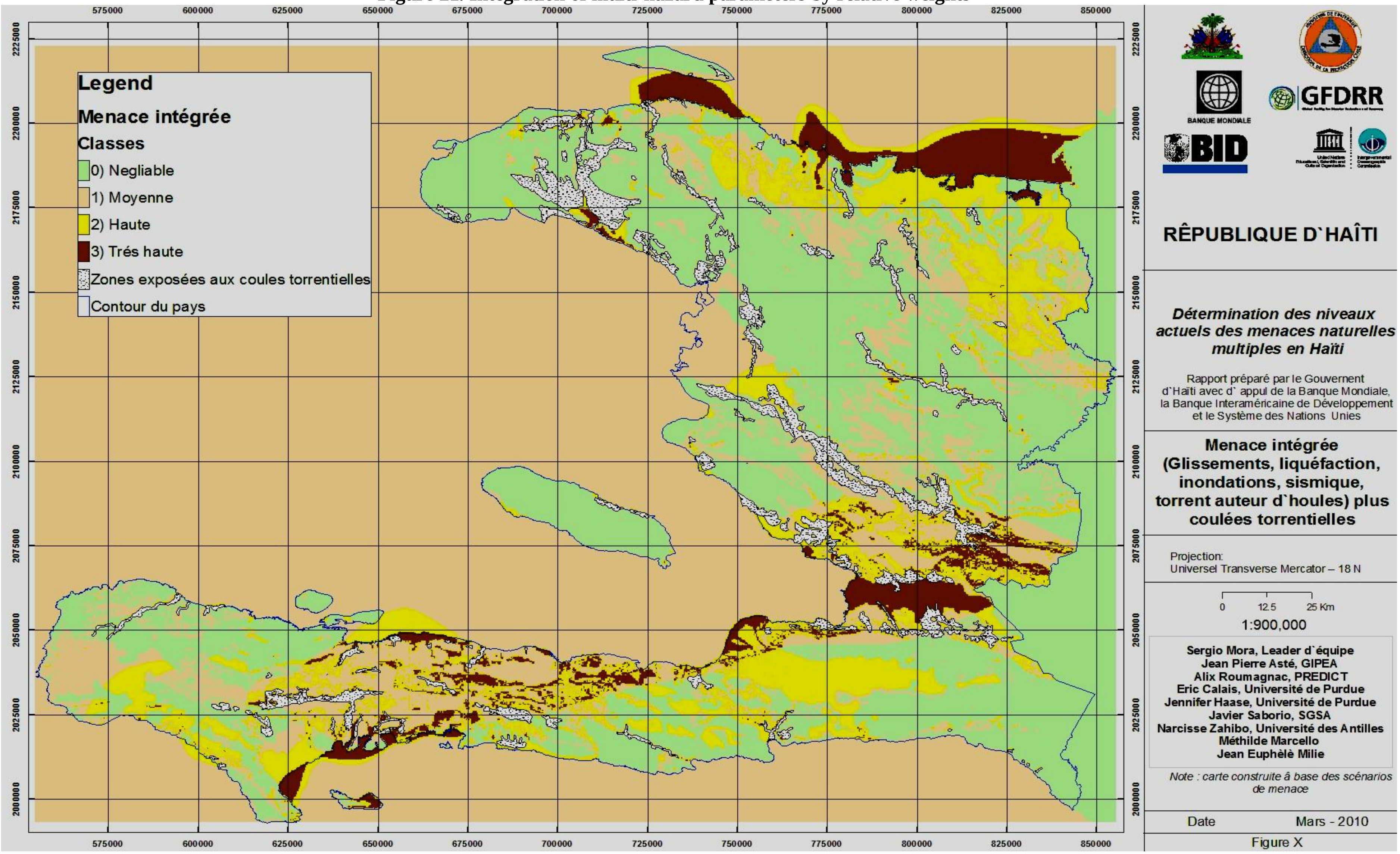


Flood hazard



Slope failure hazard

Figure 21. Integration of multi-hazard parameters by relative weights



III - VULNERABILITY

3.1 Vulnerability and its aggravating factors

Risk is conceptually defined as the complex and concolute relationship between hazards and vulnerability.

$$Risk = Hazard * Vulnerability$$

Hazards are defined on the basis of their intensity, their spatial distribution and their temporal extent (recurrence, celerity at which they materialize). Vulnerability is defined as the level of fragility or inability to face and recover from a critical situations and is determined by the following five quantifiable factors:

- Exposure, defined as the level of exposure to the hazard;
- Fragility, which is the opposite of resilience capacity;
- The socioeconomic values at stake;
- The potential impact on quality of life (deaths, injuries, trauma, forced displacements, loss of subsistence means, etc.); and
- The impact on the environment and natural resources.

3.1.1 The level of exposure

Haiti's population is constantly exposed to the natural hazards as described in the preceding sections. In the aftermath of the January 12, 2010 earthquake, the level of exposure of the population of Port-au-Prince and its environs increased significantly. Houses were already located in exposed areas (ravines, slopes, piedmonts of Morne l'Hôpital, Bourdon), and the Léogâne, Jacmel, Carrefour, Cul-de-Sac Plain and Cité Soleil river floodplains. The number of shelters in Port-au-Prince and its environs has increased. These shelters were set up by the population or local authorities without a preliminary and thorough assessment of the sites. This situation helps further increase the level of exposure of the affected, traumatized, and weakened population.

3.1.2 The level of fragility

Resilience is the capacity to withstand shocks and resume normal activities following a traumatic or devastating event, by mobilizing personnel, family, community-level, and environmental factors. Fragility is the inability of an individual or a community to resume normal activities following a traumatic event. Fragility is therefore the opposite of resilience: $F=1/R$.

The last major earthquake struck Haiti in 1842. The current Haitian population had lost their historical memory of this type of natural hazard and was caught unawares on January 12, 2010. The current authorities from the civil protection services never had to manage this type of emergency and were overwhelmed by the event. The population's level of fragility was already high due to lack of information and training at all levels—youth and adults alike in both urban and rural regions.

Natural hazards are never covered in primary or secondary schools. Opportunities for adults to receive information and training on this subject are rare. In addition, the struggle to daily survival occupies most of their time and efforts, and it is a top priority, thus risk management is of secondary importance to households. Other factors such as illiteracy, difficult access to social services, poverty, anarchic construction, high population density, food insecurity, inadequate use of space, and critical health situation further exacerbate this fragility. All population segments lack adequate information and are ill-equipped to face natural hazards. They are unaware of the types of behavior to be adopted in the event of impact. The earthquake of January 12 only exacerbated an already high level of fragility.

3.1.3 Damage and socioeconomic losses

People and assets (e.g. physical, environmental) that are likely to be affected by a natural hazard constitute the social and economic values in question. The earthquake destroyed a large number of buildings (schools, public utilities, churches, residences, factories, companies, corporate and institutional headquarters) in the three hardest-hit cities, in particular Port-au-Prince. Other persons and property are exposed to further damage by natural hazards that subsequent earthquakes could trigger, and by the rainy season, which could cause flooding, landslides, and torrential mudflows. Natural ecosystems (mangroves, coral reefs, the delta), natural parks and historical sites are also exposed. The pressure on natural resources will intensify owing to growing demand brought on by increased population needs for alternative subsistence means in rural and periurban areas.

3.1.4 Impact on the quality of human life

The earthquake had a significant impact on the quality of life of the Haitian population. While the residents in Port-au-Prince, Léogâne, and Jacmel, among others, bore the brunt, the inhabitants of other towns and communal sections have also suffered the consequences of this disaster. The earthquake killed more than 200,000 people and made over 600,000 homeless—this figure should be added to the number of people who were homeless before the earthquake. The number of amputees is estimated at over 3,000 people. Yet, no plans are in place to provide care for these individuals with limited mobility. Large-scale population relocations occurred, particularly toward Cap Haïtien, Gonaïves, and Hinche. The implications of these population movements are significant from economic and psychosocial standpoints. The overcrouded cohabitation of people in spaces as small as a campsite engenders social tension, disease, and epidemics. In view of the fact that the population's health status was already critical, this situation can only exacerbate health-related problems.

3.1.5 Impact on the environment and natural resources

The precarious living conditions in the makeshift camps and the sudden increase in the population in rural areas will have an effect on the environment and natural resources. Wood is removed to make fires and construct makeshift shelters. The immediate surroundings of the camps are unsanitary, with garbage strewn over the ground nearby. This will lead to clogged sewage drains and blocked ravines. Heavy rainfall will result in overflowing sewers, rising wastewater, and the inundation of low-lying areas of cities, which could increase the number of disaster victims. The disposal of the waste and debris from destroyed buildings is also one of myriad concerns.

3.2 <u>The specific aspect of vulnerability due to slope failure hazards</u>

The impact of slope failure differs from that of other categories of hazards. It can vary, depending on whether consideration is being given to the effect of a block fall, a torrential debris flow, a slow landslide or of a massive rockfall. A slow landslide, for example, can be tolerated for at least a few years. People grow accustomed to this situation in exchange for some discomfort. Activities are adapted to these circumstances. Property is only gradually and slowly damaged, except where their design has been adapted to accommodate slow deformations. Flows and rockfalls are far more devastating, because owing to the speed at which they materialize, one is virtually powerless in these circumstances. The elements in question, which are likely to be affected by hazards, are divided into three main classes: i) people and social structures, ii) property, and iii) activities and services. Vulnerability is reflected in harm to people, damage to property, and disruption of activities. The aforementioned traditional classification clearly shows that the damaging effects of the various hazards will themselves vary considerably. In addition, and unlike floods, these effects will always be irreversible. The basis of the vulnerability lies in two factors: mobility (capacity to escape from the hazardened area) and the capacity to react to the stresses. Naturally, as is always the case with vulnerability, this will depend to a large extent on the structure, social organization, and preparation of exposed societies (Table 6; photos 9a, b, c, and d).

Table 6. Challenges exposed and their different level of vulnerability

Slow, continuous movements	Landslides	Creep, solifluction	Settlement, outcrop bending	Subsidence
Harm	+	+	+	+
Damage	+++	++	++	+++
Disruptions	+++	++	++	+++
Rapid, discontinuous movements	**Block falls**	**Cave-ins**	**Rockfalls**	**Torr. flows**
Harm	++	+++	+++++	+++++
Damage	+	+++	+++++	+++++
Disruptions	+	+++	+++++	+++++

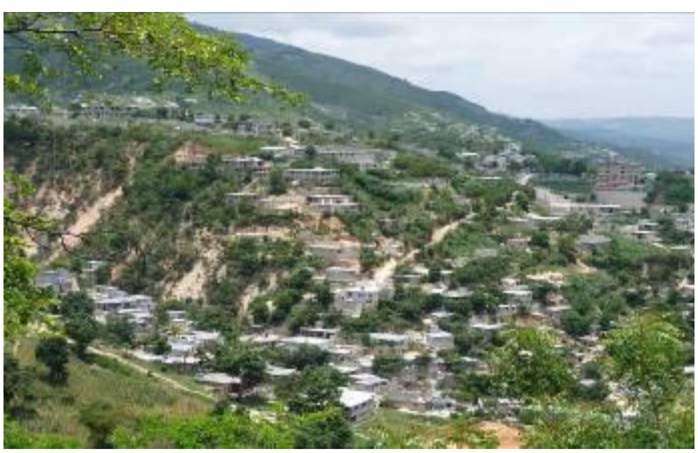
+ Low; ++ Moderate; +++ High; ++++ Very high; +++++ Catastrophic

Vulnerability assessments require a much more complex procedure, particularly in Haiti. The current definition is still extremely rudimentary, resulting in the proposal to decision makers of criteria that are questionable and do not reflect much depth of understanding. Yet, it appears that there are valuable databases at the commune level which could serve as a basis for providing more accurate assessments of the risk posed by each type of hazard and, in particular, by landslides and torrential debris flows (Photo 13).

3.3 Deforestation

One of the aggravating factors with the most serious consequences in terms of flooding is the widespread deforestation occurring in Haiti. The most recent FAO Global Forests Resource Assessment (2005) revealed that Haiti's forest cover (natural or crops) accounts for less than 4 percent of the national territory, compared to 30 percent in the Dominican Republic (22 percent in Cuba, 32 percent in Jamaica) (Photo 10). Deforestation of watersheds increases Haiti's vulnerability to floods, disturbing the water cycle through:

- ***Runoff acceleration*** during torrential rainfall. Denuded slopes provide little or no capacity to intercepting and storing the water flow. This results in high runoff coefficients (sometimes over 40 %), very high specific discharges (discharge per km^2), and shorter concentration times (time between peak rainfall and peak discharge).
- ***Erosion and sediment transport*** by rivers during peak flows. Deforestation, by accelerating soil erosion mechanisms, increases sediment transport (rocks, blocks, gravel, salt, silt, clay, biomass) during floods and poses a genuine hazard to the environment and infrastructure (bridges, roads, homes) located in the bed of water courses. The resulting sedimentation affects watercourses, lakes, and coastal areas (Photos 11, 12 and 13).
- ***Expansion of flood-prone areas***. Excessive sediment deposits in the lowlands generated by erosion lead to the elevation of watercourse drainage channels. During floods, this results in the creation of expanded flood–prone areas (Photos 14 a,b,c, and d).



Juvénat; August 3, 2009

Juvénat; February 13, 2010

Canapé vert; behind ENAF; December 9, 2009 Canapé vert; behind ENAF; February 13, 2010

Photos 9 a, b, c, d. Urban occupation areas along steep slopes; before and after the earthquake of January 12, 2010.

Photo 10. Difference in vegetation cover between Haiti (left) and the Dominican Republic (right). Source : Nasa–Scientific Visualisation Studio http://svs.gsfc.nasa.gov

A)

B)

A) Charcoal saleswoman, Croix de Bouquets market, Aug-09; B) Charcoal makeshift oven, Massif de la Selle National Park, June-08

Photo 11. Ravine in north Jacmel; home hazardened by sediment transport. Source: Predict Services, December 2009

Photo 12. Rouyonne river, Léogane. Very limited water flow space under the bridge of the national highway owing to gravel build-up in the low-flow channel. Source: Predict Services, December 2009

Photo 13. Torrential debris cone in Malpasse.

Photos 14. Examples of problems pertaining to the improper management of water resources.

Croix des Bouquets–Tabarre. Buildings on the Grise river bank; Source: Predict Services, December 2009

Petit Goâve. Structures in the Province ravine bed; Source: Predict Services, December 2009

Carrefour – Port-au-Prince. Blocked or damaged drainage network; Source: Predict Services, December 2009

Carrefour – Port-au-Prince. Blocked or damaged drainage network; Source: Predict Services, December 2009

Petit Goâve. Breach in the La Digue river wall ; Source: Predict Services, December 2009

Jacmel - Structures in the Orangers river bed; Source: Predict Services, December 2009

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IV – RISK MANAGEMENT RECOMMENDATIONS

4.1 Context

The Haitian population is highly vulnerable to natural hazards. Indeed, most densely populated cities are located either in low-lying flood-prone areas or locations close to the sea. This is the case, for example, with Port-au-Prince, Jacmel, and Cayes. Population growth in exposed cities is attributable in particular to rural exodus. The latter has led to the deforestation and clearing of hillsides, and the expansion of cities toward low-lying, swampy and flood-prone areas close to the sea. In addition, this massive influx of people has resulted in anarchic construction using salvaged materials in very exposed areas (e.g. hillsides, river banks, backfilled swamps, natural river outlets, flood-prone lowlands) with either poorly maintained or non-existent drainage networks.

4.2 The aggravating effects of the earthquake

The quantitative cartography of seismic hazards to Haiti shows that:

- Virtually all of Haiti lies in an average to high hazard zone (probability: 1/500) or even a high hazard zone (probability: 1/2,500). It should be borne in mind that a 2 % probability over a 50-year period should be used to design structures that will save the lives of their occupants (buildings that will not collapse). A 20 % probability over a 50-year period should be used for the design of buildings that need to be operational in the aftermath of an earthquake.
- Ground motion levels of 0.18 to 0.34 g correspond to a Modified Mercalli scale of VII, which can lead to significant damage to type D masonry (cf. Annex 2). Given the flimsy nature of buildings in Haiti, this ground motion could lead to fairly widespread destruction of such structures.
- While the hazard is, of course, correlated to the major and active fault lines, all Departments in Haiti face seismic hazard. Violent ground motion of up to 10 km is likely on both sides of the major and active faults (Enriquillo and Septentrional).
- Strong ground motion of up to approximately 30 km is probable on both sides of the major and active faults (Enriquillo and Septentrional). A number of regions along the southern coast of the south peninsula, which are fairly far away from the Enriquillo Fault, such as Gonave Island and the Artibonite delta are located in areas likely to experience strong ground motion.
- The Matheux-Neiba faults, north-dipping reverse structures, pose a hazard to a larger area than do the strike-slip faults. However, the current movements of these faults using GPS measurements remain very poorly defined and call for specific research.

Earthquakes exacerbate the various trigger factors of slope failure and flod hazards. They weaken slopes and cause extensive destruction that can lead to the accumulation of debris in routes and roads. Debris can lead to stream blockage; when subsequent runoffs occur, they submerged areas and generate violent discharges. Earthquakes can also increase overall vulnerability on two fronts: (i) increasing the exposure of people living in camps; and (ii) increase the fragility of houses. In addition, the effects of earthquakes disrupt the organization of the emergency and disaster management chains and reduce or even wipe out subsistence means.

Moreover, flood and slope failure hazards became more conspicuous:

- There is very little accurate information on hazards and vulnerability
- The January 12, 2010 earthquake exacerbated the vulnerability and diminished the resilient capacity.
- These hazards are major and result from the confluence of the topography and the virtually non-existent watershed management processes.
- All the urbanized areas of the country are extremely vulnerable. A very high number of persons are exposed. It is difficult, if not impossible, to relocate these persons to safe areas before the onset of the rainy season or the occurrence of additional earthquakes.

- Risk management is by itself pertinent, but it calls for greater resources and local deployment in a functional and effective manner than it has been done so far in Haiti
- In a broader sense, risk has not been adequately considered in the territorial development process and in public and private investments.
- There are very few areas that offer safe shelter to the population in these exposed spaces. In addition, massive and rapid evacuation is impeded by steep hills, the lack of proper roads, numerous ravines and very congested traffic on the main roadways. A number of protective and safety measures must be adopted to alleviate this situation and need to be applied more widely and made sustainable.

4.2.1 Short-term measures

- Before repairing any damaged buildings, conduct certified expert assessments that take into account:
  - The damage caused by the January 12, 2010 earthquake.
  - The probability of other earthquakes during the life span of buildings.
- Educate the population with respect to aftershocks, which will continue for months. They will become fewer over time but their magnitudes may still be enough to affect already damaged buildings.
- Make recommendations, as soon as possible, regarding temporary housing so that earthquake victims can obtain shelter and protection from the rains, which have already started. The proposed maps indicating hazards were prepared for returned periods under 50 years and are applicable only to this transition period:
  - The life span of temporary housing should allow for periods of reoccupancy (for example 5 years).
  - However, the hazard level remains high for the zone affected by the aftershocks of the January 12, 2010 earthquake (Miragoâne to Carrefour). Consequently, refugee camps should not be set up in these regions.
  - Temporary buildings will have to be lightweight and not vulnerable to seismic hazard.
  - Meteorological and hydrological hazards are the most pressing and, except in the case of the aftershocks mentioned above.

4.2.2 Medium- and long-term measures

- Establish an emergency plan in the case of a new major earthquake.
- Rebuild, taking into account natural hazards such as those measured here.
  - Establish mandatory earthquake standards for all public buildings and major infrastructure, including hospitals and schools, commensurate with the respective hazard levels. Inspect building locations and construction, from the time the architectural plan is prepared to the performance of work by the project supervisor and workers. Prohibit anarchic construction that does not adhere to standards.
  - Educate the population with respect to natural hazards: make it mandatory to include natural hazards in elementary and secondary school curricula. Introduce a course on natural hazards and risk management at the university level.
  - Provide the construction industry (in particular craftsmen) and city councils with the basic regulations on safe construction.
- Develop a national program on natural hazards and risk management:
  - Establish hydrometeorological, seismological and geodesic monitoring networks, integrated to international similar networks in the Caribbean basin
  - Map the geotechnical characteristics of soil and subsoil in major urban zones and establish, at these locations, detailed seismic microzoning.
  - Provide the relevant officials with training (at the Master's and Doctoral levels) in natural hazard and risk management.
  - Provide the appropriate authorities with the information necessary to make decisions related to natural hazards.

- Issue regulations by:
  - Implementing a building code taking into account all sorts of natural hazards. This code could, for example, be based on the code in place in the French Antilles.
  - Prohibit construction in zones most exposed to natural hazards.

It is possible to build structures that withstand all kinds of natural hazards. Civil engineering allows for the design of structures that will withstand damage (such buildings generally cost more) and those that will sustain damage without claiming the lives of their occupants (such buildings cost less).

4.3 Mitigation of slope failure hazards

Haiti must be rebuilt. Everything mentioned above regarding the threats generated by gravity-related processes calls for the implementation of a complex strategy to enhance knowledge of the subsoil, particularly its mechanical and hydraulic characteristics, particularly when they have been altered by society. The reconstruction of the country will lead to extensive territorial development work. The need to acquire knowledge about the subsoil will apply to both the flat and hilly. Despite the existence of a Public Works Laboratory and an office of specialized studies, very little geotechnical data seems to be available. It is therefore important to make arrangements to strengthen the appropriate resources at the national level. This will be essential to cope with the needs linked to the major new construction expected. Situations where future investors have to manage their geotechnical engineering needs autonomously should be avoided. In this effort to strengthen resources, priority should be accorded to data collection and use, which will have to be acquired for purposes of major reconstruction programs. Several complementary activities, aimed at enhancing knowledge of the subsoil and slope failure hazards, should therefore be undertaken as soon as possible.

4.3.1 Active solutions to stabilize unstable slopes

Active solutions are those that make it possible to eliminate or avert hazards by:

- Getting rid of unstable masses, for example, through excavation or blasting (using explosives). Clearly, this can be done only in the case of small masses and volumes under a few tens or hundreds of thousands of m^3. This can be planned, in particular, in cases of preparatory works aimed at the safety of development works
- Stabilizing masses through on-site reinforcement work in areas that are rocky or have loose soil, through drainage work (loose materials). This work can be done only on very small volumes and masses relative to those mentioned above.

4.3.2 Passive solutions

Such solutions entail tackling not the hazard itself, but containing its expansion or the mobility and movement of exposed elements in these expansion areas. Expansion can be controlled through interception works (metal screens, interception ditches and barriers for blocks, barriers to divert heavy flows). The movement and evacuation, even on a provisional basis, of objects and, in particular the most vulnerable population groups, is clearly the most far-reaching solution. However, it spawns a host of other problems. Nonetheless, this is the only foreseeable option in a number of exposed areas, particularly in Port-au-Prince. It is also the most rational solution in the context of rethinking the territorial development process.

4.3.3 General territorial planning principles

While an all-out effort to improve knowledge of the subsoil is required, the approach used should be different from conventional geological approaches used thus far by the Mining Services. Instead of conducting mining research, research should be conducted on the typology and characteristics of the subsoil surface layers, in both flat and hilly areas.

Considerable aerial research resources were quickly deployed after January 12. The hope is that the same momentum can be carried over into a research drive using more modern methods of subsoil examination (radar and related methods). Through the use of traditional methods (land, wells, geophysics), it should be possible to obtain what could be termed a "geotechnical map of Haiti's subsoil," at least for the most heavily populated urban areas. Many areas will see new developments, which will perhaps be quite extensive. Large foreign companies will, in all likelihood, be involved with the design of these developments. A minimum degree of coordination and oversight of these operations will be necessary. One agency, a number of ministries, or specific entities will be designated to oversee and coordinate this work. It would be very unfortunate if all the information compiled for these major projects is not preserved, validated, and organized in operational databases, with a view to enhancing knowledge of geotechnical factors and of the risks faced by the country.

Urban level. It is hoped that oversight of building permits will be effective. However, it would be unrealistic to expect geotechnical studies to be required for each permit. A local engineering infrastructure would have to be developed. In the interim, provisions could be made for a body of inspectors who would be responsible for providing leaders with information on the restrictions to be imposed on applicants, with a view to avoiding the most egregious design flaws. However, beyond these mundane concerns, whether they involve the basic geotechnical or risk management problems, an urban renewal policy will most certainly be implemented. Entire areas will have to be evacuated owing to the level of danger they pose and their populations will have to be relocated. It remains to be seen how and the pace at which this will be done. While hoping for rapid implementation timeframes to avoid further disasters, this effort will certainly have to allow for the time and resources needed to carry out the essential inspections and engineering work to design the urban relocation and recovery areas.

Work that can be done quickly. We are proposing two main activities in the short term:

- The first is a simplified procedure for rapid identification of all the areas in Haiti where the slopes and the nature of the materials point to possible instability. This activity is merely preliminary and represents the first step of a lengthy process.
- The second entails use of 2002 aerial photographs of soil coverage, which the Haitian Geospatial Information Center [*Centre National de l'Information Géospatiale* CNIGS] has in digital form, inasmuch as the Center has not had the time to circulate them. Stereoscopic examination of these aerial photographs using modern tools will make it possible to finetune the list considerably and thus identify and describe hazards.
- A third activity is also possible and can be implemented more readily in the short- and medium-term, provided that the human and financial resources are available. It entails creating virtual dimensional models of the areas in question, using precise targets (a slope, a neighborhood, a new area to be serviced), so as to quantify with precision the stability (or instability) the boundary conditions at these locations and obtain clear and substantiated criteria to determine safety, with possible simulations of rupture and spread, using detailed evaluation methods for losses sustained, and the feasibility of safety solutions.

4.3.4 Specific measures to reduce vulnerability

Individual measures. Given Haiti's current socioeconomic context, it is difficult to envisage the implementation of individual measures to reduce specific vulnerability to earthquakes. Survivors are more concerned with aftershocks without, however, being aware of the heightened risks when they live on sloping terrain. While it is still too early to determine the spread of damage owing to sloping terrain, the fact remains that hillside neighborhoods are the ones most exposed, especially as the rainy season approaches.

Joint measures. Joint measures can be taken only by the different actors concerned, with the assistance of foreign operators (MINUSTAH, civilians, the military, and NGOs). The first measure should entail the relocation of people still living on hillsides. To carry out this task effectively, significant research, which has not yet been conducted, must be done of the terrain. The methods suggested above could be helpful over a two- to three-month period and, while necessary, will not be enough to stave off the dangers feared from the rainy season.

4.3.5 Better knowledge and understanding of risk

This report presents a summary of the knowns and, in particular, the unknowns. In fact, very little is known about Haiti's subsoil or, more specifically, the surface formations that are the source of the stability problems with slopes as well as geotechnical problems. The scope of geotechnical problems has not really been determined, owing to the dearth of real estate investment. However, these problems cannot be overlooked when the new Haiti is being constructed. Obtaining better knowledge and disseminating this knowledge is neither a quick nor easy process. An organizational structure needs to be created and individuals need to be trained and, in particular, provided with modern resources, while avoiding the often outdated methods that remain in place. Clearly, optimal handling of emergency and disaster management calls for: (i) determining, in advance, risk and the factors that heighten this risk (hazards, vulnerability, spatio-temporal distribution, etc.); (ii) obtaining the tools and criteria for reducing vulnerability (prevention, mitigation, etc.); and (iii) having the capacity to determine what level of risk can be borne/tolerated or transferred using financial instruments and mechanisms.

The starting point of emergency management is therefore securing the resources to observe and monitor natural hazards and man-made vulnerability, followed by criteria defining scenarios, intensity thresholds, and the extent of potential damage. Alert/alarm systems also determine the criteria for triggering actions that mobilize the resources to handle emergency situations and the respective actions to be taken by the authorities and the people.

4.4 Improving the response to natural hazards

Risk management in Haiti is based on a system already in place but in need of strengthening. In fact, the entire country needs to have in place a community level local emergency operational process to ensure that the key risk management functions are performed and to enhance efficiency. Consequently, greater involvement of local actors is needed, by providing them with access to information and training. In this regard, a National Early Warning Program [*Programme National d'Alerte Précoce* PNAP] has been established. The mission of this program is to institute an Early Warning Flood System [*Système d'Alerte Précoce Inondation* SAPI], which will operate in a stable and functional institutional framework. The SAPI framework has not yet been determined. Its mission is to develop four main areas, in conjunction with national and local actors:

- Monitoring and forecasting floods, earthquakes and landslides;
- Communicating/providing information to the population on natural hazards;
- Preparing the population to respond in the event that a warning is issued; and
- Conducting a public awareness-building and education campaign.

4.5 Monitoring and alerts

On the other hand, monitoring landslides is feasible but highly complex. It calls, in particular, for sound preliminary assessments of the causes and an equally sound forecast of its form and celerity of materialization, but it can be properly forecasted only if it has been properly monitored. Issuing warnings is also quite a complex process that calls for adequate ex-ante preparation of people receiving the alarm and organization of the resources to be deployed to handle th possible effects and the developments of the alarm. It must also be borne in mind that false warnings can permanently undermine the confidence and cooperation of the persons whose safety is being sought. It is to be reiterated that slope failure is very different from the meteorological processes that often trigger them. The later are recurrent and are clearly identified by the populations concerned. Slope failure hazard of is much more difficult to explain and communicate and even more challenging in the case of torrential debris flows (Photo 13). From the moment of detection of a potentially dangerous event using monitoring resources (cyclone-related, oceanological, seismological, geotechnical, etc.), that is, when the possibility of destruction becomes high, depending on spatiotemporal distribution, the alert level can be raised to the emergency level, thus triggering the activities of the Emergency Operations Center [*Centre d'Opérations des Urgences* COU] and its respective protocols, depending on the situation (Figure 22).

Figure 22. Development of scenarios for observing and monitoring natural hazards. After the intensification and thus possible materialization of damage, the alert is raised to the level of an alarm, thus triggering the activities of the Emergency Operations Center (COU).

The activation of intervention resources either just before an emergency or disaster (in the case of cyclones, drought, and ENSO) or immediately after (in the case of earthquakes) would be triggered by the application of criteria that confirm that a possible destructive hazard or its actual materialization could reach a threshold of causing considerable damage in a determined spatial distribution. Risk assessments and the nature of the response would be based on predetermined baselines (Figure 23) depending, of course, on the nature of the hazard (intensity, speed at which it is materializing, time-space distribution, etc.) as well as vulnerability conditions.

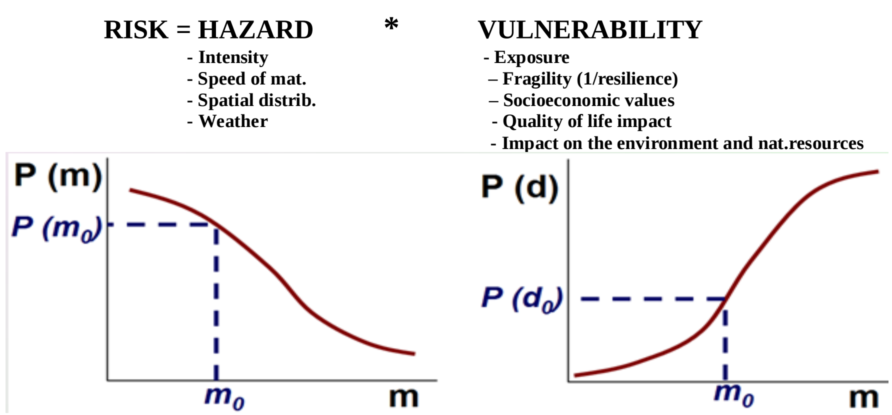

Figure 23. Criteria and factors for determining risk and thus the thresholds for triggering and activating the activities of the Emergency Operations Center (COU)

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Vulnerability, as it relates to each specific hazard, is defined as the level of exposure, the ability to withstand the the shock (or conversely, the level of fragility), the social and economic values at stake, the impact on the quality of human life (deaths, injuries, trauma, forced displacement, loss of subsistence means, etc.) and the impact on the environment and natural resources. The characteristics and specific features of the emergency could raise it to the level of a disaster or even a catastrophe (when damage has mounted to the level of "maximum probable loss") (Figure 24).

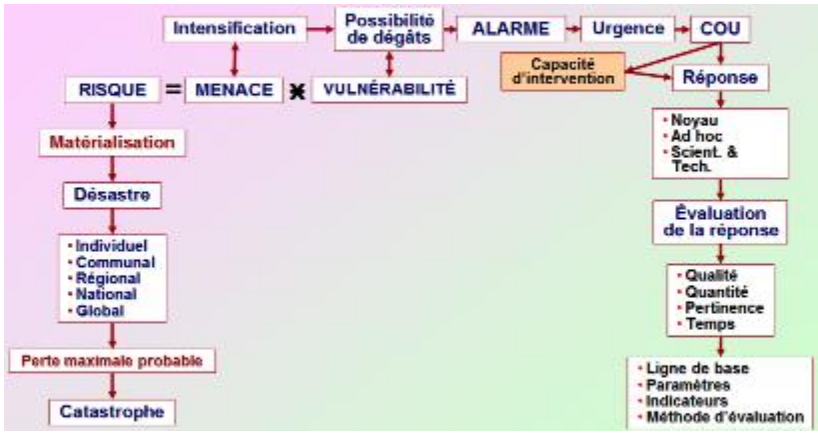

Figure 24. Level and scope of probable damage, outline of the process for calling on the COU, and response assessment criteria in cases of emergency and/or disaster


Photo 15. The true beneficiaries of our work

ANNEX 1: Glossary[1]

Acceptable risk	Level of loss that a society or community considers acceptable, taking into account existing social, economic, political, cultural, technical, and environmental conditions. From an engineering standpoint, acceptable risk is also used to assess structural and non-structural measures to bring potential damage to a level where the danger to persons and property can be reduced, using "accepted practice" and/or codes based, *inter alia*, on a probability estimate and the cost/benefit ratio of these measures.
Alert	Permanent mindset triggered by an announcement or other means of conveying information (*alarm*) issued to warn the population and leaders of an expected event with major implications from a safety standpoint.
Assessment of subsistence means	Methodologies to assess the impact of a crisis (post-conflict or post-disaster) on the means of subsistence, opportunities for recovery, and capacities at the family, community, and local economy levels, from a gender perspective. This includes converting assessment findings into strategic response options (interventions at the project, program, and policy levels). The term refers specifically to the efforts deployed by the FAO and ILO involving tool kits for the overall assessment of subsistence means
Capacity to handle disasters	Different ways in which women and men marshal their capacities and organize themselves to use available resources to cope with the different adverse effects of a disaster. This entails resource management, both in times of normalcy and during crises or adverse situations. In general, building capacity to cope with disasters makes people more resilient in the face of both natural and man-made hazards. This has a gender dimension, given that men and women may have similar or different capacities depending on whether they can gain access to and use of available resources.
Capacity building	Efforts targeting the development of human skills or the infrastructure of a society in a given community or organization, necessary to reduce the level of risk.
Catastrophe	Similar to disaster, but indicative instead of a situation of maximum or extreme loss.
Climate change	The climate of a place or region changes when, over a long period (generally decades or longer), significant and irreversible trends are observed from a statistical standpoint that are beyond a reasonable doubt. Climate change may arise from natural and/or man-made atmospheric processes that span long periods. It should be noted that, in the context of the United Nations Convention on Climate Change, the definition of climate change is narrower, given that it applies only to changes directly or indirectly attributable to human activity. In essence, climate change seems to be linked to an increase in greenhouse gas emissions, although greenhouse gas emissions occur naturally. As a result, the global temperature appears to be rising. Information currently available is not enough to allow for an understanding of the scope of regional and local effects.
Climate variability	This term refers to all atmospheric processes that are cyclical in nature and are linked to physiography and hydrometeorology. It can be described from the standpoint of physics and mathematics. It pertains to the factors and parameters governing the climate, with individual cases and differences, hence the reason it is called climate *variability*. For example, tropical cyclones (depressions, storms, hurricanes), as low pressure vortices, vary each season in terms of their intensity, number, and path. To date, there is no clear-cut evidence that man is capable of influencing this phenomenon.
Destruction (damage)	Negative impact on property, capital, infrastructure on any other type of physical structure (including natural structures) resulting from an external event such as a disaster.
Disaster	Major disruption in the functioning of a community or society, when human, material, economic or environmental losses must be addressed with resources originally earmarked for development. A disaster is the materialization of risk. It is the result of the complex combination of a hazard and the manifestation of vulnerability, when preventive capacities or measures are inadequate to mitigate the negative effects of risk.
Emergency (or disaster) management	Organization and management of resources and responsibilities in the handling of all emergency matters, in particular preparedness, response, and rehabilitation. Emergency management involves the plans, structures, and arrangements established to jumpstart the regular activities of government or volunteer agencies, as well as the private sector, in a comprehensive and coordinated matter, so as to respond to the entire spectrum of emergency needs. This process is also known as disaster management.

[1] Based in part on ISDR and OCHA terminology. See: http://www.unisdr.org/eng/library/lib-terminology

Gender	Specific roles, responsibilities, needs, functions, and interests of women and men, generally based on social influence and specific to a given culture, but different, however, from the concepts of gender that refer to the biological differences between men and women, or to sexual orientation.
Gender analysis	Assessment process of specific, socially influenced differences between men and women that are learned, change over time, and vary from one country to another.
Gender dimension of a disaster	Different effects on and roles of men and women when a disaster occurs. A more complex analysis of gender will also take into account the varying impacts of disasters on different groups, in particular the elderly, infants and children, and persons having special or physical disabilities.
Gender-based needs assessment	Process by which the specific needs of women, girls, men, and boys are identified.
Hazards	For purposes of this study, synonymous with "hazard," with emphasis being placed on probability.
Losses	Decline in economic resources, including means of subsistence (revenue, salaries, profit, private income), following damage caused by an external event such as a disaster).
Mitigation	Structural and non-structural measures applied to contain the negative effects of natural, technological, and environmental hazards.
Needs	Humanitarian interventions in the areas of recovery and development, required to close the gap between the shortages or losses identified and the situation desired by victims in a post-conflict or post-disaster situation. Total needs identified or noted at the local level can be summarized in a recovery framework for a given sector or country.
Needs assessment	This assessment, initiated by humanitarian agencies, entails the identification of basic needs and what is lacking to meet these needs (based on standards, taking into account vulnerabilities, risks, and capacities) and the estimation of the external assistance needed (beyond the community, province, department, or country) to cover these shortages. Needs assessment for recovery purposes (emergency or comprehensive) and for development purposes calls for a broader vision of needs covering institutional, policy-related, and infrastructure areas.
Rehabilitation	Start of a post-crisis recovery process (disaster- or conflict-related). Rehabilitation entails measures intended to restore to the affected community, insofar as possible and as quickly as possible, the pre-disaster quality of life in the areas of governance, subsistence, shelter, the environment, and the social sphere. This includes the reintegration of displaced populations and human safety.
Risk	Literal definitions: PETIT LAROUSSE; 2009 Risk: Masculine noun. (in Italian *risco*, from the Latin *resecum*, something that cuts) • Possibility or probability of an event viewed as negative or damaging. *The risks of war are increasing.* • Exposure to danger or an adverse event that is fairly likely to occur: to run the risk of failure. *A pilot who takes too many risks.* • Engaging in an activity that could be advantageous, but which entails the possibility of danger: *To have an appetite for risk*. • Possible harm or disaster covered by insurance companies in return for a premium. Summary: "…*Possible occurrence of an event that does not depend entirely on the will of the parties and which may result in the loss of an object or any other kind of damage….*" Specific definitions: Risk: • Possibility of damage likely to impact exposed elements, depending on their characteristics, situation, conditions, and spatiotemporal context; consequences and causes are not always predictable. • Combined probability that the occurrence of a situation in a specific time and place will be sufficiently intense to produce damage owing to the intensity of the event and the fragility of the exposed elements, namely, the economy, human life, and the environment.
Risk management	Systematic process for developping administrative and organizational decisions, as well as operational capacities and the overall application of policies and strategies to reduce the impact of natural hazards and environmental degradation linked to man-made activities. This includes the application of the findings of scientific research, observation, and monitoring of natural processes that pose hazards, as well as

	structural and non-structural measures, with a view to avoiding (preventing) or limiting (mitigating or preparing for) the adverse effects of hazards. When a country wishes to protect its population and assets, may establish a risk management policy based upon the following basic strategies, which incorporate ways to understand the causes, consequences and remedies in distinct dimensions: • Risk identification: Incorporates individual and collective understanding and perceptions, social representations and objective evaluations (i.e. scientific, engineering, statistical) of the causes and consequences of risk: hazards (type, intensity, distance, recurrence); vulnerability (degrees of exposure and fragility, socio-economic value of possible losses, potential alterations to the human quality of life - deaths, injuries, trauma, forceful displacements-, and the impact to the environment and natural assets, services and functions • Risk reduction: Includes all ex-ante measures to reduce the physical impact of adverse natural events. Also known as “prevention and mitigation”, it means intervention against the loss generating factors, particularly the vulnerability, since from certain levels of intensity and beyond, it is not possible to reduce the natural hazards • Risk financing, transfer: The ensemble of ex-ante measures aimed at improving the capacity and resilience to cope with the financial consequences of disasters through: reserve funds, contingent credit and insurance. It requires ex-ante assessment of risk in economic terms. This is often done using complex risk models focusing at reducing the impact of natural hazards. To this effect, it is required to establish ex-ante the thresholds for retention/transfer of risk based upon definitions of “accepted” vs. “aceptable” risk. The next step is to build probabilistic scenarios, models and metrics to estimate losses: i) Probable Maximum Loss (PML), ii) Average Annual Loss (AAL) corresponding to the expected loss averaged on a yearly basis, and iii) Loss Exceedance Curves (LEC). These metrics are determined for various return periods (e.g. 50, 100, 250, 500 years). Comparative scenarios can also be performed to demonstrate the effects of intervention versus non-intervention over damage and losses and replacement costs • Emergency and disaster management: Actions, defined ex-ante, to be performed when risk is materialised; they must be as efficient and effective as possible to reintegrate the quality of life of the population affected and avoid rebuilding vulnerability by incorporating preparedness, alert-alarm systems, response, rehabilitation (immediate) and reconstruction (mediate to long term)
Risk management capacity	Combination of all available forces and resources within a community, society, or organization that can mitigate the level of risk or the effects of a disaster. This also includes the development of institutional, financial, policy-related, and other resources, such as technology at different levels and in different sectors of the society.
Subsistence	The capacities and assets (including material and social resources) as well as activities necessary for subsistence purposes. Subsistence is sustainable when, in the face of pressures and shocks, capacity and assets can be preserved in both the present and future, and the natural resource base or financial means that support individuals/families are not undermined. This includes the means to support oneself as well as resources derived from wealth or reserves that can be tapped, should the need arise. This term refers to the resources needed to support a family or a group, their source of income, their resources for survival (the minimum needed for subsistence purposes), and resources to obtain socially acceptable facilities to live “decently.” In post-conflict or post-disaster situations, restoration of employment and subsistence means are government priorities in an emergency recovery context and are therefore part and parcel of the emergency response to lessen the dependence of victims on foreign aid.
Hazard	Physical circumstance or event, natural process, or human activity which, having attained or exceeded a specific intensity, poses a potential danger in terms of the loss of human life, injury, or damage to social and economic goods or environmental degradation. Hazards include latent conditions that may pose a danger in the future, arising from a variety of sources: natural processes (geological, hydrometeorological, biological, etc.) or man-made processes (environmental degradation, technological dangers, etc.). Hazards may be individual, joint, sequential, or combined in terms of their origins and effects.
Vulnerability	Probability, based on the intensity at the time the hazard materializes, that it could cause damage to property, services, and persons, depending on the levels of exposure and fragility. It impacts the quality of human life (deaths, injured persons, victims, displaced persons, psychosocial trauma, etc.), socioeconomic value, and the environment.

ANNEX 2: Definition of the Modified Mercalli Scale (Richter, 1958)

MMI value	Description
I	**Not felt**. Marginal and long period effects of large earthquakes
II	**Felt by persons at rest**, on upper floors, or favorably placed
III	**Felt indoors. Hanging objects swing**. Vibration like passing of light trucks. Duration estimated. May not be recognized as an earthquake
IV	**Hanging objects swing. Windows, dishes, doors rattle.** Vibration like passing of heavy trucks; or sensation of a jolt like a heavy ball striking the walls. Standing motor cars rock. Glasses clink. Crockery clashes. In the upper range of IV, wooden walls and frame creak
V	**Pictures move. Felt outdoors**; direction estimated. Sleepers wakened. Liquids disturbed, some spilled. Small unstable objects displaced or upset. Doors swing, close, open. Shutters, pictures move. Pendulum clocks stop, start, change rate
VI	**Objects Fall. Felt by all**. Many frightened and run outdoors. Persons walk unsteadily. Windows, dishes, glassware broken. Knickknacks, books, etc., off shelves. Pictures off walls. Furniture moved or overturned. Weak plaster and masonry D cracked. Small bells ring (church, school). Trees, bushes shaken (visibly or heard to rustle)
VII	**Nonstructural Damage**. Difficult to stand. Noticed by drivers of motor cars. Hanging objects quiver. Furniture broken. Damage to masonry D, including cracks. Weak chimneys broken at roof line. Fall of plaster, loose bricks, stones, tiles, cornices (also unbraced parapets and architectural ornaments. Some cracks in masonry C. Waves on ponds; water turbid with mud. Small slides and caving in along sand or gravel banks. Large bells ring. Concrete irrigation ditches damaged
VIII	**Moderate Damage**. Steering of motor cars affected. Damage to masonry C; partial collapse. Some damage to masonry B. none to masonry A. Fall of stucco and some masonry walls. Twisting, fall of chimneys, factory stacks, monuments, towers, elevated tanks. Frame houses moved on foundations if not bolted down; Loose panel walls thrown out. Decayed piling broken off. Branches broken from trees. Changes in flow or temperature of springs and wells. Cracks in wet ground and on steep slopes
IX	**Heavy Damage**. General panic. Masonry D destroyed; masonry C heavily damaged, sometimes with complete collapse; masonry B seriously damaged. (General damage to foundations.) Frame structures if not bolted, shifted off foundations. Frames racked. Serious damage to reservoirs. Underground pipes broken. Conspicuous cracks in ground. In alluvial areas sand and mud ejected, earthquake fountains, sand craters
X	**Extreme Damage.** Most masonry and frame structures destroyed with their foundations. Some well-built wooden structures and bridges destroyed. Serious damage to dams, dikes, embankments. Large landslides. Water thrown on banks of canals, rivers, lakes, etc. Sand and mud shifted horizontally on beaches and flat land. Rails bent slightly.
XI	**Rails bent greatly**. Underground pipelines completely out of service
XII	**Damage nearly total**. Large rock masses displaced. Lines of sight and level distorted. Objects thrown into the air

Categories of masonry construction whose performance is used to measure surface movement intensity (Richter 157)

Masonry A	Good workmanship, mortar, and design; reinforced, especially laterally, and bound together by using steel, concrete, etc.; designed to resist lateral forces
Masonry B	Good workmanship and mortar; reinforced, but not designed in detail to resist lateral forces
Masonry C	Ordinary workmanship and mortar; no extreme weaknesses like failing to tie in at corners, but neither reinforced nor designed against horizontal forces
Masonry D	Weak materials, such as adobe; poor mortar; low standards of workmanship; weak horizontally

Relationship between surface movement and the Modified Mercalli Scale (Wald et al., 1999)

PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+