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LOCAL SITE CONDITIONS INFLUENCING EARTHQUAKE INTENSITIES AND SECONDARY COLLATERAL IMPACTS IN THE SEA OF MARMARA REGION - Application of Standardized Remote Sensing and GIS-Methods in Detecting Potentially Vulnerable Areas to Earthquakes, Tsunamis and Other Hazards

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ABSTRACT

The destructive earthquake that struck near the Gulf of Izmit along the North Anatolian fault in Northwest Turkey on August 17, 1999, not only generated a local tsunami that was destructive at Golcuk and other coastal cities in the eastern portion of the enclosed Sea of Marmara, but was also responsible for extensive damage from collateral hazards such as subsidence, landslides, ground liquefaction, soil amplifications, compaction and underwater slumping of unconsolidated sediments. This disaster brought attention in the need to identify in this highly populated region, local conditions that enhance earthquake intensities, tsunami run-up and other collateral disaster impacts. The focus of the present study is to illustrate briefly how standardized remote sensing techniques and GIS-methods can help detect areas that are potentially vulnerable, so that disaster mitigation strategies can be implemented more effectively. Apparently, local site conditions exacerbate earthquake intensities and collateral disaster destruction in the Marmara Sea region. However, using remote sensing data, the causal factors can be determined systematically. With proper evaluation of satellite imageries and digital topographic data, specific geomorphologic/topographic settings that enhance disaster impacts can be identified. With a systematic GIS approach - based on Digital Elevation Model (DEM) data - geomorphometric parameters that influence the local site conditions can be determined. Digital

elevation data, such as SRTM (Shuttle Radar Topography Mission, with 90m spatial resolution) and ASTER-data with 30m resolution, interpolated up to 15 m) is readily available. Areas with the steepest slopes can be identified from slope gradient maps. Areas with highest curvatures susceptible to landslides can be identified from curvature maps. Coastal areas below the 10 m elevation susceptible to tsunami inundation can be clearly delineated. Height level maps can also help locate topographic depressions, filled with recently formed sediments, which are often linked with higher groundwater tables. Such areas are particularly susceptible to higher earthquake intensities and damage. The sum of risk GIS factors increases the susceptibility of local soils in amplifying seismic ground motions. Areas most susceptible to higher earthquake impacts can be identified using a systematic GIS approach, the weighted–overlay-method implemented in ArcGIS. Finally, the data obtained by remote sensing can be converted into Google Earth-kml-format and become available at no cost, to raise public disaster awareness and preparedness in the Sea of Marmara region.

Keywords: *Sea of Marmara, Bosporus, Dardanelles, 1999 Izmit earthquake, tsunami, landslides, remote sensing, GIS methods, Digital Elevation Model, Shuttle Radar Topography.*

1. INTRODUCTION

On August 17, 1999, a large destructive earthquake (named as the "Kocaeli earthquake") struck northwest Turkey and generated a destructive tsunami within the enclosed Sea of Marmara. This was the strongest earthquake to strike Northern Turkey since 1967. Its epicenter was near the Gulf of Izmit, a densely populated area. Official estimates indicated that about 17,000 people lost their lives and thousands more were injured. Most of the destruction and deaths resulted from secondary collateral impacts at locations along coastal area of the Sea of Marmara that were particularly vulnerable because local geologic site conditions exacerbated earthquake intensities. Following the disaster it was determined that there was a need to identify and map such vulnerable sites.

The present study provides a background of the disaster, the geologic setting that makes this region vulnerable and an analysis of how standardized remote sensing techniques, satellite imageries, digital topographic data and a systematic GIS approach that is based on Digital Elevation Model (DEM) data, can be integrated to help determine geomorphologic/topographic settings and identify specific geomorphometric parameters that influence local site conditions which enhance secondary, collateral, disaster impacts.

2. THE IZMIT EARTHQUAKE OF AUGUST 17, 1999

Many seismic stations around the world measured the earthquake. Its origin time was 00:01:39.80 (UTC), 03:01:37 am (local time) and its focal depth was shallow (17 km)(USGS). The epicenter was at 40.702 N, 29.987 E (USGS), near the town of Gölcük on the western segment of the North Anatolian Fault. There were small differences in magnitude determinations. The surface wave magnitude was given as 7.8 (USGS). The Moment Magnitude was given as Mw=7.4 (USGS; Kandilli). The Duration Magnitude was given as 6.7 (Kandilli) and the Body Wave Magnitude at 6.3

(USGS) and 6.8 (British Geological Survey), respectively. The earthquake resulted from right-lateral strike-slip movement on the fault. Numerous aftershocks with magnitude above 4 were recorded after the main earthquake. The first of the aftershocks (magnitude of 4.6) occurred 20 minutes later. Several others followed in subsequent days. According to the USGS and Kandilli most of the aftershock activity was confined to the region bounded by 40.5-40.8N and 29.8-30.0E, which covers the area between Izmit and Adapazari to the east of the epicenter (Pararas-Carayannis, 1999). However there was a cluster of aftershocks near Akyazi and Izmit.

On 31 August, a strong aftershock killed one person, injured about 166 others and knocked down some of the buildings that were already weakened by the main quake. Surprisingly the aftershocks caused a great deal of damage, which indicated that local conditions, exacerbated earthquake intensities of even weaker events to have secondary collateral impacts.

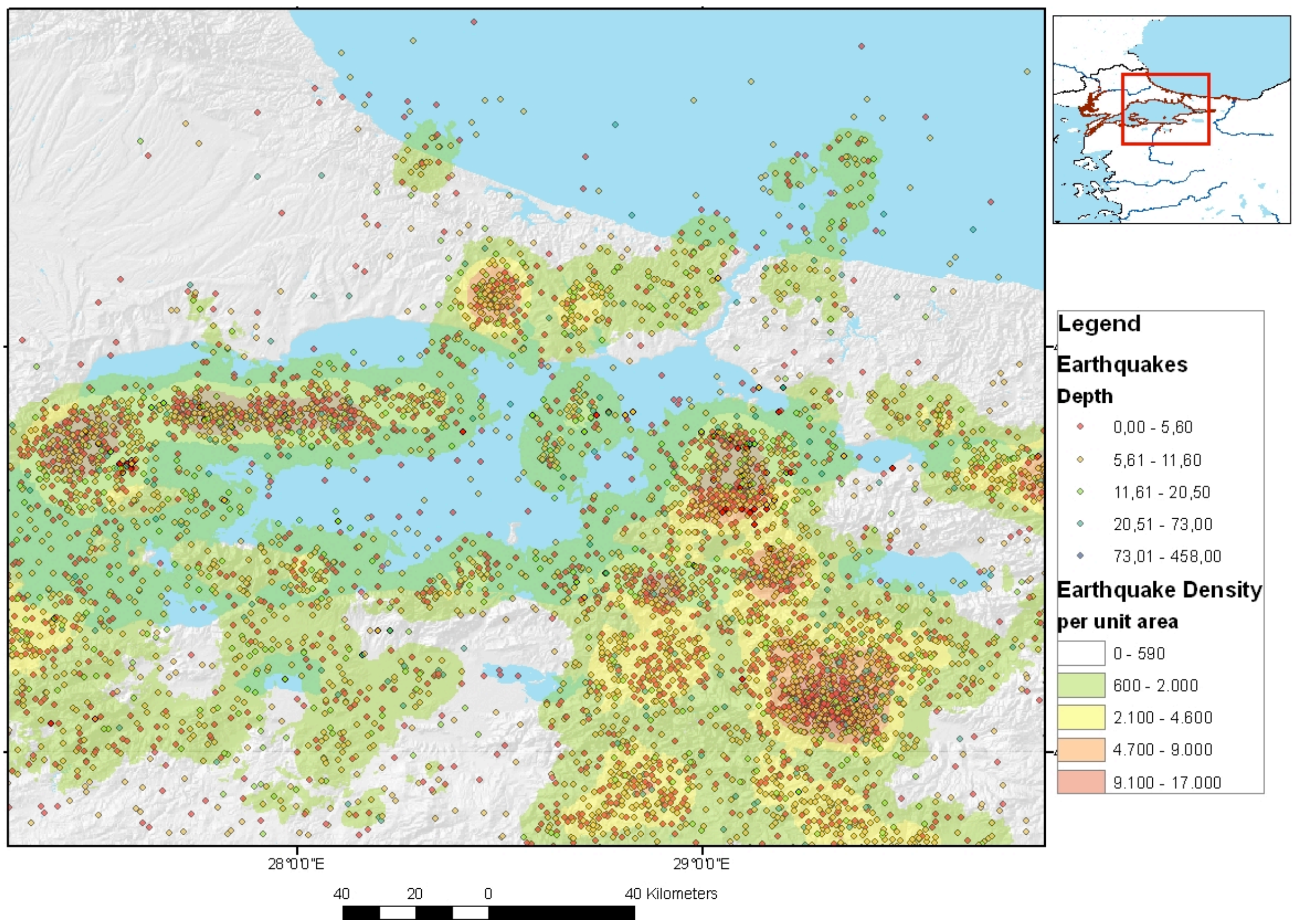

Fig. 1. Earthquake density in Sea of Marmara Region, Earthquake data: ISC, Bogazici University, Kandilli Observatory & Earthquake Research Institute, World Stress Data.

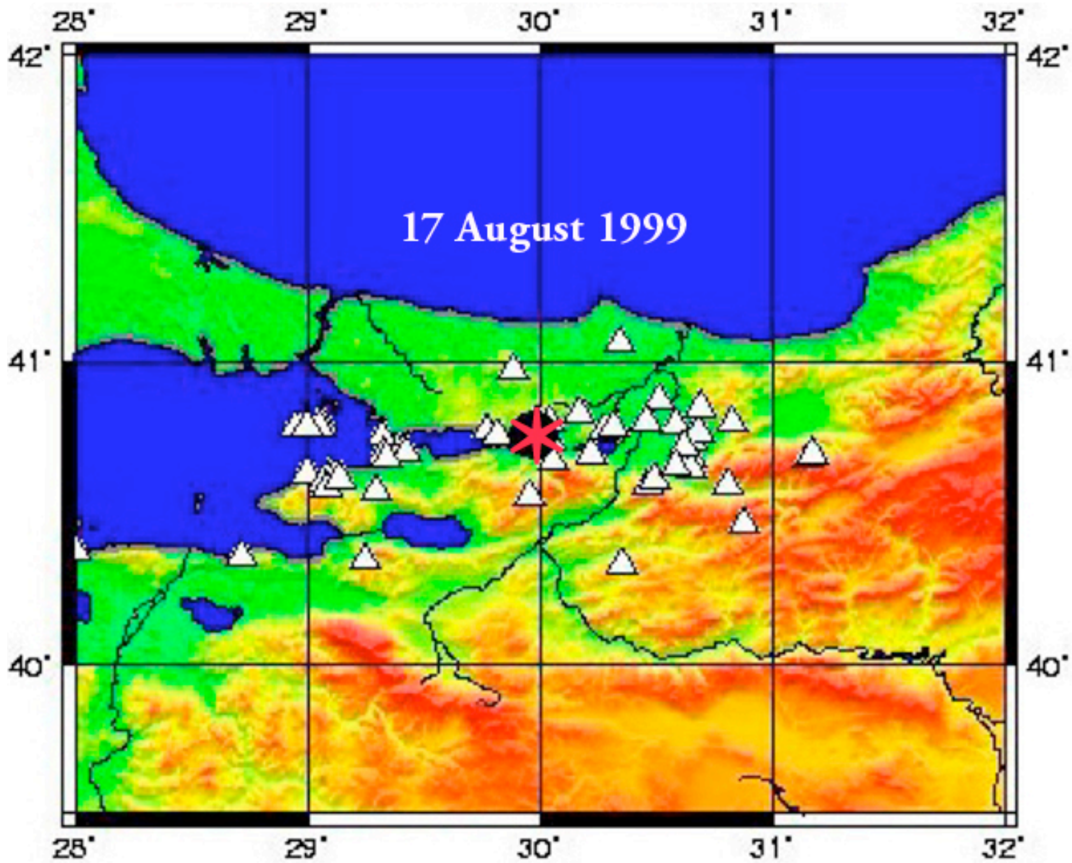

Figure 2. Epicenter and distribution of large aftershocks of the 17 August 1999 earthquake (modified after KOERPI)

3. THE TSUNAMI OF AUGUST 17, 1999 IN THE SEA OF MARMARA

Although the earthquake involved primarily horizontal ground displacements, slumping and landslides triggered tsunami waves which were particularly damaging in the Gulf of Izmit, perhaps because of convergence and a funneling effect. The long duration of the earthquake's ground motions (45 seconds), the directivity of the surface seismic waves, the proximity of the epicenter to the Sea of Marmara and the Gulf of Izmit, and the overall orientation of the affected area, strongly support that the tsunami was generated in the Gulf of Izmit, in the eastern portion of the Sea of Marmara. The tsunami waves had an extremely short period of less than a minute, which also supports the premise that the source was the localized subsidence of coastal areas and the underwater slumping of unconsolidated sediments, rather than larger scale tectonic movements which involved primarily lateral motions (Pararas-Carayannis, 1999). An initial recession of the water was observed at both sides of Izmit Bay immediately after the quake, followed by tsunami waves which had an average run-up of 2.5 m. along the coast. Maximum run-up was 4 m in Golcuk where there was considerable damage to the naval base facilities. In fact, Golcuk and several coastal areas are now flooded permanently as a result of tectonic subsidence and landslides. Also, large coastal portions of the town of Degirmendere remained flooded as a result of subsidence - with sea level reaching the second floors of apartment buildings. Similar permanent flooding, but to a lesser extent, occurred also at Karamursel.

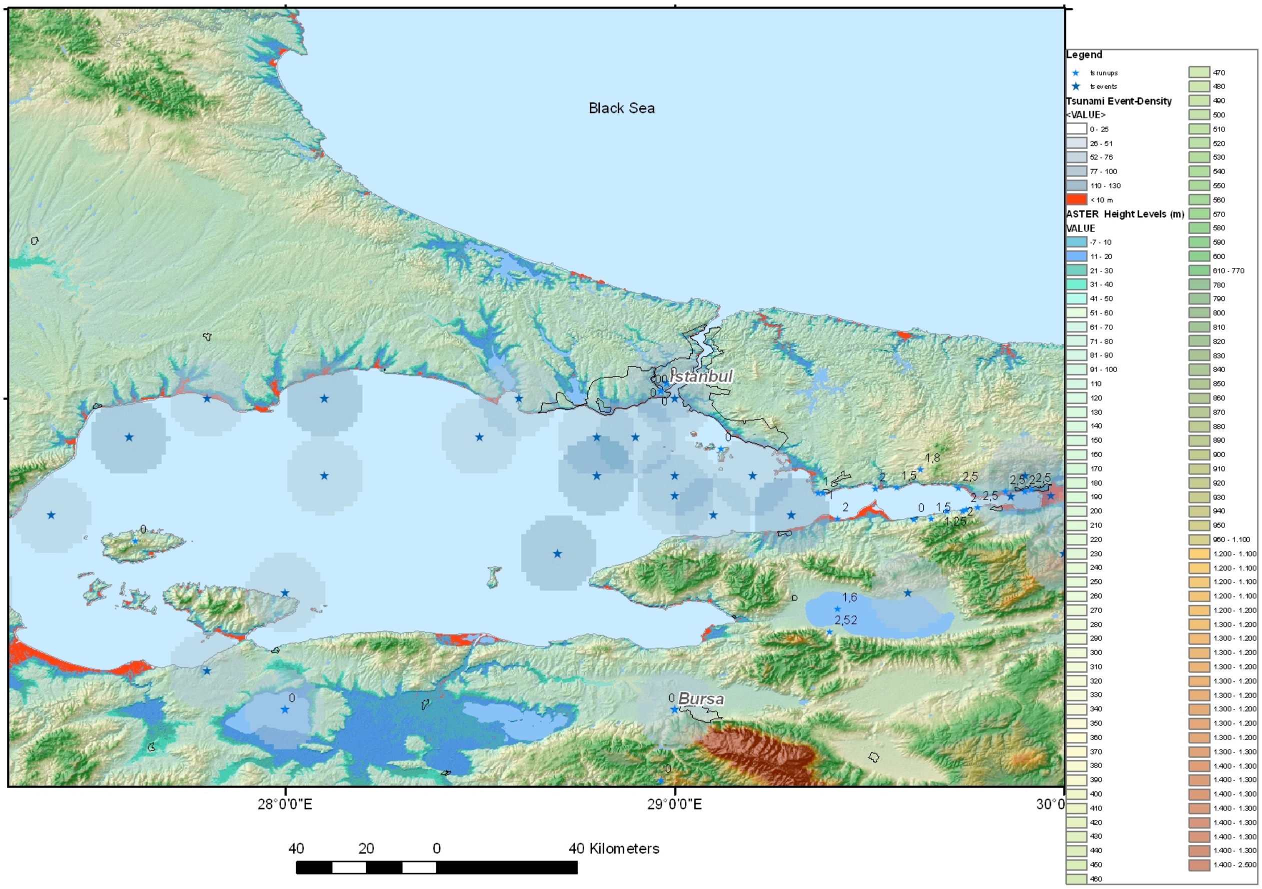

Figure 3: Overview of tsunami events and run-up heights according to NASA tsunami catalogue. The red areas indicate heights below 5 m.

The westward propagation of the seismic ruptures along the North Anatolian Fault (NAF) during the 20th century has increased the probability that the next rupture will be located offshore, in the Marmara Sea, in the prolongation of the 1999 Izmit earthquake faulting. Also, there is a high probability that a destructive tsunami will be generated. Historical records indicate that that more than 90 tsunamis have occurred along the Turkish coasts between 1410±100 BC and 1999 AD. Near Izmit Bay, tsunamis occurred in: 325; 24 August 358; 8 November 447; 26 September 488; 15 September

553; 15-16 August 555; 14 December 557; 715; 740; 19 April 1878; 10 May 1878; and 18 September 1963 (Altinok et. al., 1999). Strong earthquakes in the Marmara Sea in 1509, and in May 1766, broke submarine parts of the NAF, in the vicinity of Istanbul and generated tsunamis. Future tsunamis may be triggered either by submarine co seismic displacements or by landsliding (Hebert, 2005).

The lesson learned from this event is that tsunamis can occur in any body of water since a variety of mechanisms can generate them. Even earthquakes involving primarily horizontal ground motions (strike-slip type of faulting) can generate tsunamis by triggering slope failures and underwater landslides. Obviously the susceptibility of coastal regions along the Sea of Marmara needs to be carefully evaluated.

Figure 4: Extreme destruction from collateral ground liquefaction and subsidence (source:)

4. SEISMOTECTONIC AND GEOLOGIC SETTING

Before discussing how standardized remote sensing and GIS methods can be applied in the identification of sites potentially vulnerable to earthquakes, tsunamis and other collateral hazards, we must first review briefly the seismotectonic and geologic setting of this region.

The Sea of Marmara is an inland sea separating Asia Minor from Europe. It is 280 km (175 miles) long and almost 80 km (50 miles) wide at its greatest width. On its northeast end, it connects with the Black Sea through the Bosporus Strait. On its southwest end it connects with the Aegean Sea through the Dardanelles. Although its total area is only 11,350 square km (4,382 square miles), its average depth is about 494 m (1,620 feet), reaching a maximum of 1,355 m (4,446 feet) in the center.

The sea was formed as a result of tectonic movements that occurred about 2.5 million years ago, in the Late Pliocene (Pararas-Carayannis, 1999).

The excessive seismicity of this particular region can be explained by current geophysical knowledge of its structural development. Turkey is being squeezed sideways to the west as the Arabian plate pushes into the Eurasian plate. The north Anatolian fault forms the edge of this Turkish (Anatolian) crustal block so that destructive earthquakes happen regularly along it as different sections break (Pararas-Carayannis, 1999).

The earthquake of August 17, 1999 occurred along the long, east-west trending, great North Anatolian Fault Zone (NAFZ) - known to be the most prominent active fault system in Northwestern Turkey. The NAFZ is a major fracture that traverses the Northern part of Asia Minor and marks the boundary between the Anatolian tectonic plate and the larger Eurasian continental block. It has been the source of numerous large earthquakes throughout history. The NAFZ splits into three strands at the eastern part of the Marmara Sea. The northern strand passes through Izmit Bay, traverses Marmara Sea and reaches to the Saros Gulf (Barka and Kadinsky-Cade, 1988). The central fault zone passes through Izmit Bay, traverses the Sea of Marmara and reaches the Saros Gulf to the southeast. This great fault system has many similarities to the San Andreas fault system in California. Earthquakes involve primarily horizontal ground motions (strike-slip type of faulting). Because of this unstable tectonic system, the area is considered as one of the most seismically active zones of the world. In the last hundred years, numerous large earthquakes have also occurred along the NAF, in the western part of the country. Beginning with an earthquake in 1939, several more quakes - with Richter magnitudes greater than 6.7 - struck in progression along adjacent segments of the great fault (Pararas-Carayannis, 1999). The August 17, 1999 Izmit earthquake was the eleventh of such a series that have broken segments of the NAF, in both eastward and westward direction. Fig. 5 shows the epicenter of the earthquake near Izmit, as well as the location and sequence of previous events. The sequence of historic events indicates that the next destructive tsunamigenic earthquake could occur west of the 1999 event, in the Sea of Marmara.

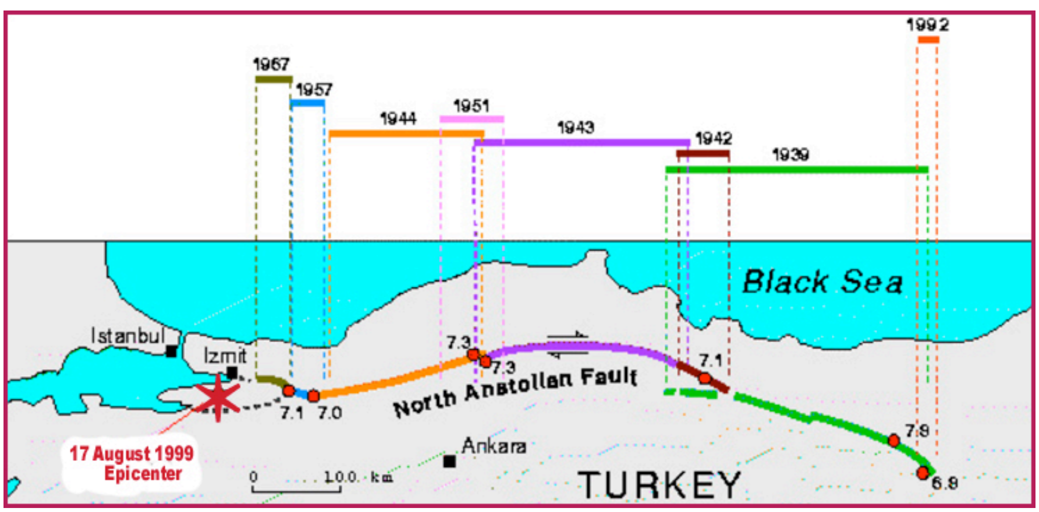

Figure 5: Historical Earthquake Activity Along the Northern Anatolian Fault (modified after Kandilli)

5.1 Earthquake's Surface Rupture and Ground Displacements

The earthquake's surface rupture extended for about 100 km east of Golcuk, but did not continue southeast and did not join the rupture of the 1967 earthquake - the last event in this region. Instead, the rupture turned northeast near Akyazi, where a cluster of aftershocks subsequently occurred. Ground displacements of about 1.5 m were measured in this area. Subsequent field studies indicated right lateral ground displacements ranging from 2.5-3 m up to 4 m, with a maximum of 4.2 m east of Lake Sapanca. Ground displacements between Lake Sapanca and the Gulf of Izmit were about 2.60 m. Additionally, there was evidence of about 2 meters subsidence along the north side of the fault's block - which was particularly evident along the coastline at Golcuk, where tsunami waves and major flooding occurred (Pararas-Carayannis, 1999). Such tectonic ground displacements are characteristic of major earthquakes along the NAF and have been responsible for the development of local geologic conditions, which exacerbate earthquake intensities and the potential impact of collateral hazards in the Sea of Marmara region.

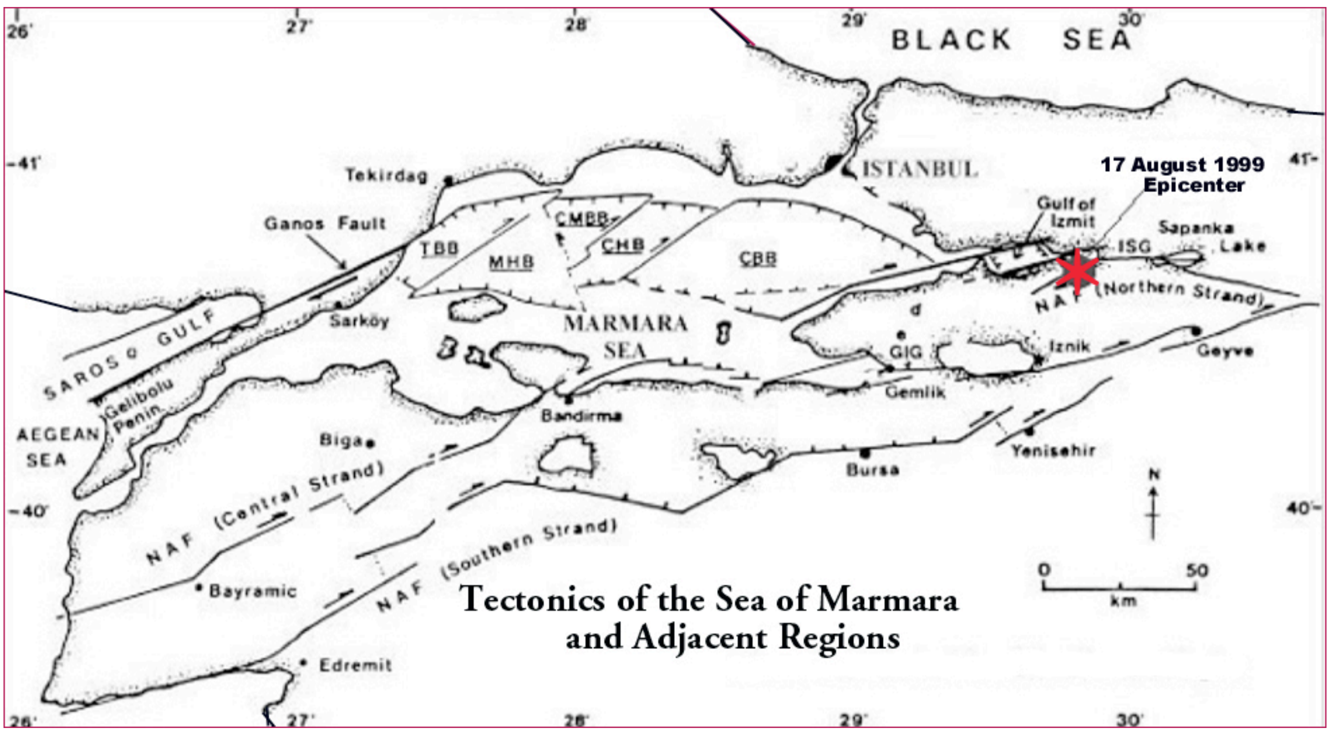

Fig. 6: Tectonic Map of the Marmara Region and location of the earthquake (source:).

6. POTENTIAL COLLATERAL HAZARDS ASSOCIATED WITH EARTHQUAKES AND TSUNAMIS IN THE SEA OF MARMARA REGION

The entire Sea of Marmara is traversed by numerous deformed and offset branches and strands of the NAF, where destructive tsunamigenic earthquakes can occur. The 1999 earthquake occurred near the Gulf of Izmit along an offset central branch of the NAF. The E-W trending Izmit Bay is a tectonically active basin which is particularly susceptible to earthquakes, tsunamis and collateral hazards such as subsidence, landslides, ground liquefaction, soil amplifications, compaction and underwater slumping of unconsolidated sediments. The entire bay area is covered mainly by fine-grained sediments from fluvial and littoral processes. When the 1999 earthquake struck, the local geologic site conditions exacerbated earthquake intensities.

During the first two days following this earthquake and tsunami, the severity of destruction and the losses of human lives in the region were grossly underestimated because of problems with access and communications. Almost the entire infrastructure of the region and all industrial facilities located along the coastal area of Izmit Bay were severely damaged. There was great destruction within 20 km of Gölcük that ranged from small displacements to complete collapses of coastal structures such as ports, jetties, cranes and piping systems. The navy base and shipbuilding yard at Gölcük were considerably damaged and at least 400 sailors and high ranking officers were killed. Rescue operations were delayed because of heavy damage on the major highway connecting Istanbul to Ankara and alternate roads were blocked. Many apartment blocks collapsed completely, causing the death of thousands of people. A fire at the Tupras oil refineries, which refine almost 90% of Turkey's oil, threatened to take over other industrial sites and took five and a half days to contain and extinguish (ERDIK, 2000). Also, subsidence, coastal landslides and tsunami waves caused destruction at Degirmendere and Karamursel.

If an earthquake and tsunami disaster similar to the 1999 or 1509 were to strike again the Sea of Marmara region, closer to metropolitan Istanbul, thousands of people could lose their lives and the destruction to infrastructure facilities and cultural sites would be severe. It would take many years to recover from the economic damage and to repair the infrastructure. There could be major damage to trains and stations. The Strait of Bosporus is of great economic importance. Five times the amount of ships pass through it than the Panama Canal every year. Two million people commute across it every day. Another severe earthquake could seriously damage the three major bridges and tunnel across the Golden Horn. Also, since they are sections of the Bosporus that are only 700 meters wide an earthquake-induced landslide or a collateral hazard could render it non-navigable.

Because of the economic consequences, such potential collateral disaster scenarios cannot be overlooked. When the Treaty of Montreux was signed in 1936 (to provide unrestricted passage of the Bosporus in time of peace), an average of 17 ships crossed each day the Bosporus, usually carrying grain and weighing about 13 tons. Presently, about 100-110 ships weighing as much as 200,000 tons, often carrying oil, gas, chemicals, nuclear waste, and other hazardous materials, pass through the strait each day. The question therefore arises as to what would happen if an oil tanker was sunk by a tsunami in the Bosporus? Even a minor disaster unrelated to an earthquake could have severe economic consequences for the region. There have been at least ten major oil spills in recent times on the waterway. On 15 November 1979 the Greek ship "Eviriali" collided with the Romanian ship "Independenta", killing 43 people and releasing 94,600 tons of crude oil into the strait, with fires which burned for almost a month. Twenty-two days after this collision and a failed containment attempt by the Turkish Navy, the "Independenta" exploded, dumping 380 barrels of oil to the port of Hydarpasa. More recently, in March of 1994, the Cyprian oil tanker "Nassia", carrying 19 million gallons of crude oil from the Russian port of Novorssyisk, collided with an empty cargo ship at the entrance of the Bosporus, resulting in 30 deaths. Three of its ten tanks ruptured, the ship drifted unguided and burned for more than a hundred hours. The accident resulted in $1 billion in damages, and forced the closing of the waterway for a week. Certainly an earthquake or a tsunami could cause greater economic disasters from collateral impacts in the narrow strait.

Similar hazard vulnerability can be expected on the other side of the Sea of Marmara. The Dardanelles strait, or Hellespont, connecting with the Northern Aegean Sea, is 61 kilometers long but only 1.2 to 6 kilometers wide, with depth averaging 55 meters deep (maximum depth of 82 meters). A major branch of the North Anatolian Fault Zone, the Ganos Fault traverses the Gallipoli Peninsula along the Gulf of Saros. A large-scale landslide induced by an earthquake, or the sinking of a large ship, could render this important waterway non-navigable. Losing either of the straits on opposites sides of the Sea of Marmara would have considerable economic consequences, not only for Turkey, but for Russia, Central Asia and Europe. Thus, it becomes obvious that a program of disaster preparedness for the entire region requires proper identification of specific site vulnerabilities to natural disasters and to the potential impact of collateral hazards.

7. APPLICATION OF STANDARDIZED REMOTE SENSING AND GIS-METHODS IN DETECTING POTENTIALLY VULNERABLE AREAS TO EARTHQUAKES, TSUNAMIS AND OTHER HAZARDS IN THE SEA OF MARMARA REGION.

As the 1999 disaster demonstrated, local site conditions exacerbate earthquake intensities and can result in collateral destruction. Generative causes may include a combination of tectonic movements associated with an earthquake or major sub aerial or underwater slides which can generate destructive local tsunamis. Secondary phenomena associated with a large earthquake will depend on the energy release, the physical rupture along the fault, the propagation path of surface seismic waves and the magnitude and duration of the dynamic, near-field, strong motions. Earthquake ground motions of high intensity could result in strong accelerations or ground liquefaction (Pararas-Carayannis, 1999) which can also trigger landslides, sudden subsidences, slumping or the generation of destructive waves.

However, a systematic GIS approach based on SRTM data (Shuttle Radar Topography Mission, with 90m spatial resolution) and ASTER-data (with 30m resolution, interpolated up to 15 m), or data from the Digital Elevation Model (DEM), can help extract geomorphometric factors and thus identify sites that are potentially vulnerable in the Sea of Marmara region. For a geomorphologic overview and for deriving the characteristic, geomorphologic features of vulnerable sites, terrain parameters and morphometric maps can be extracted from SRTM and ASTER DEM data, such as shaded relief, aspect and slope degree, minimum and maximum curvature, or profile convexity maps, using ENVI / CREASO and ArcGIS / ESRI software. Such methods can help identify sites with steep slope gradients, sites characterized by flat depressions, or sites covered by unconsolidated sediments.

With the use of remote sensing data, the causal factors can be determined systematically. With proper evaluation of satellite imageries and of digital topographic data, specific geomorphologic/topographic settings that enhance disaster impacts, can be identified. Areas with the steepest slopes can be identified from slope gradient maps. Areas with highest curvatures susceptible to landslides can be identified from curvature maps. Factors such as height levels, slope gradients, terrain curvature and traces of faults are combined with lithologic and seismotectonic information in a GIS database. Of course, many other factors play an important role and, if available, should be included in the database. The approach presented here is meant to serve as a first basic data stock in getting a perception of potential sites susceptible to higher earthquake shock and for the planning of additional geotechnical investigations.

LANDSAT ETM and DEM data can also be used as layers in generating a Hazard GIS database for the Sea of Marmara region. To enhance the LANDSAT ETM data, digital image processing procedures can be carried out. With digital image processing techniques, maps can be generated to meet specific requirements and for risk site mapping. As a complementary tool, Google Earth Pro Software can be used in order to benefit from the high-resolution 3D imageries of the coastal areas (http://earth.google.com/).

Coastal areas below the 10 m elevation susceptible to tsunami inundation can be clearly delineated from hypsographic maps. The same maps can help locate topographic depressions that may be filled with alluvial deposits, which are often linked with higher groundwater tables. Such areas are particularly susceptible to higher earthquake shock and damage. The sum of risk factors characterizes the susceptibility of local soils in amplifying seismic ground motions. Areas most susceptible to higher earthquake impacts can be identified using a systematic ArcGIS approach, map software and the weighted–overlay-method. Finally, the data obtained by remote sensing can be converted into Google Earth-kml-format and become available at no cost, to raise public disaster awareness in the Sea of Marmara region.

The present study provides only a few examples of the methodology that could be adopted to generate maps that can illustrate susceptible sites to secondarily induced, collateral hazards in the region. Figure 7 illustrates the systematic GIS-Aproach that can be used in developing earthquake susceptibility maps. Figure 8 indicates the causal factors that influence earthquake ground intensities, particularly for sites that have unconsolidated sedimentary covers or steep slope gradients and how these factors can be extracted, based on SRTM and ASTER data, geologic maps and evaluations of LANDSAT data. Finally, Figure 9 illustrates areas of the Eastern Sea of Marmara that are susceptible to higher earthquake shock according to morphometric and geologic surface properties.

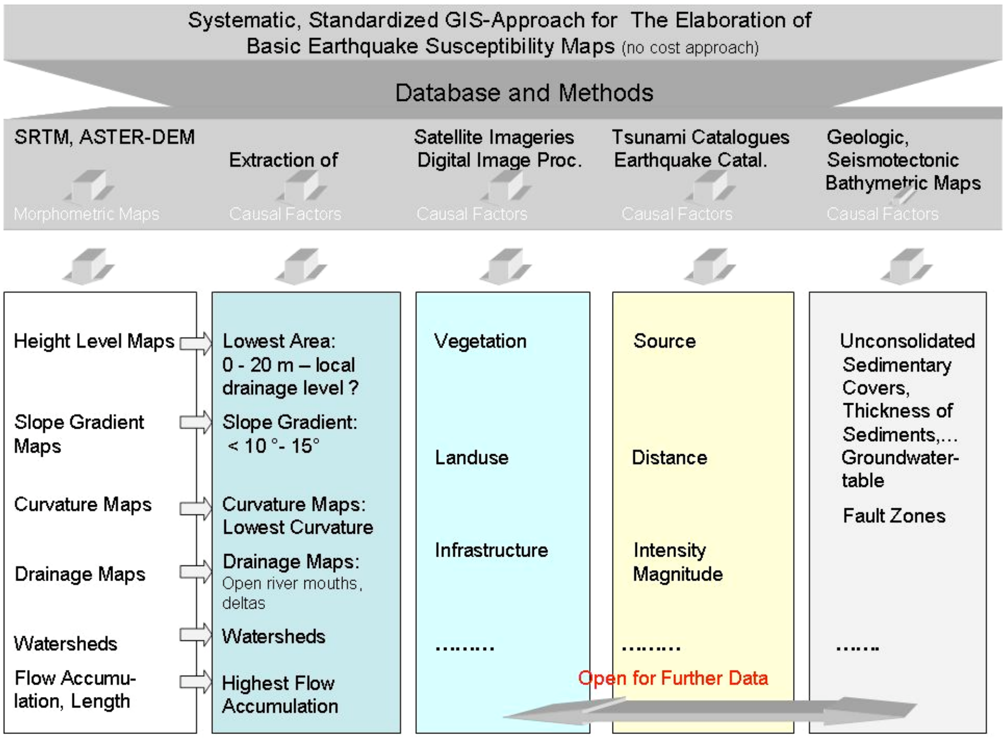

Fig. 7: Basic GIS approach.

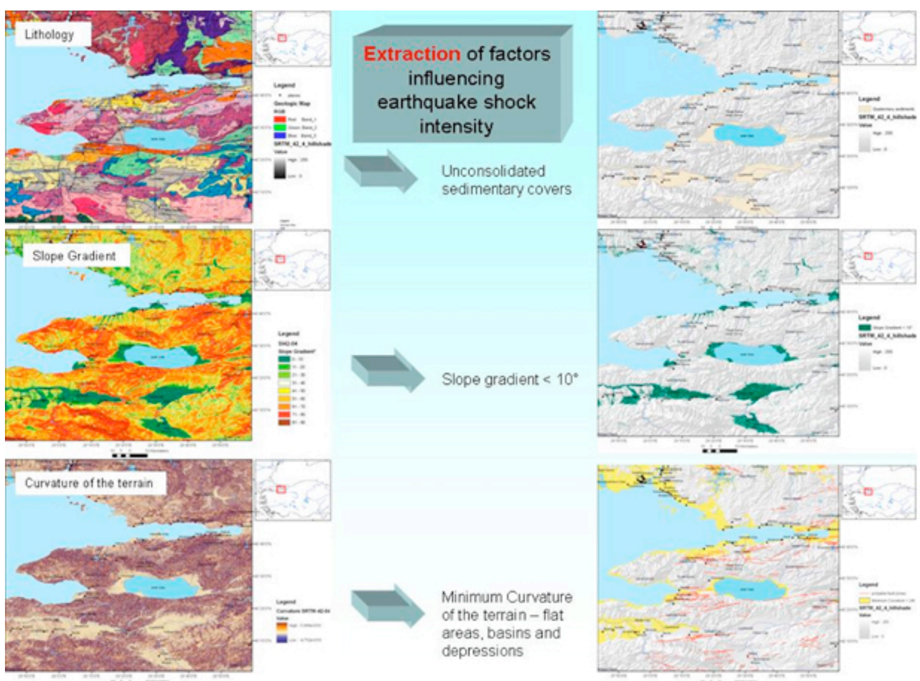

Fig.8: Extraction of some causal factors based on SRTM and ASTER data, geologic maps and evaluations of LANDSAT data.

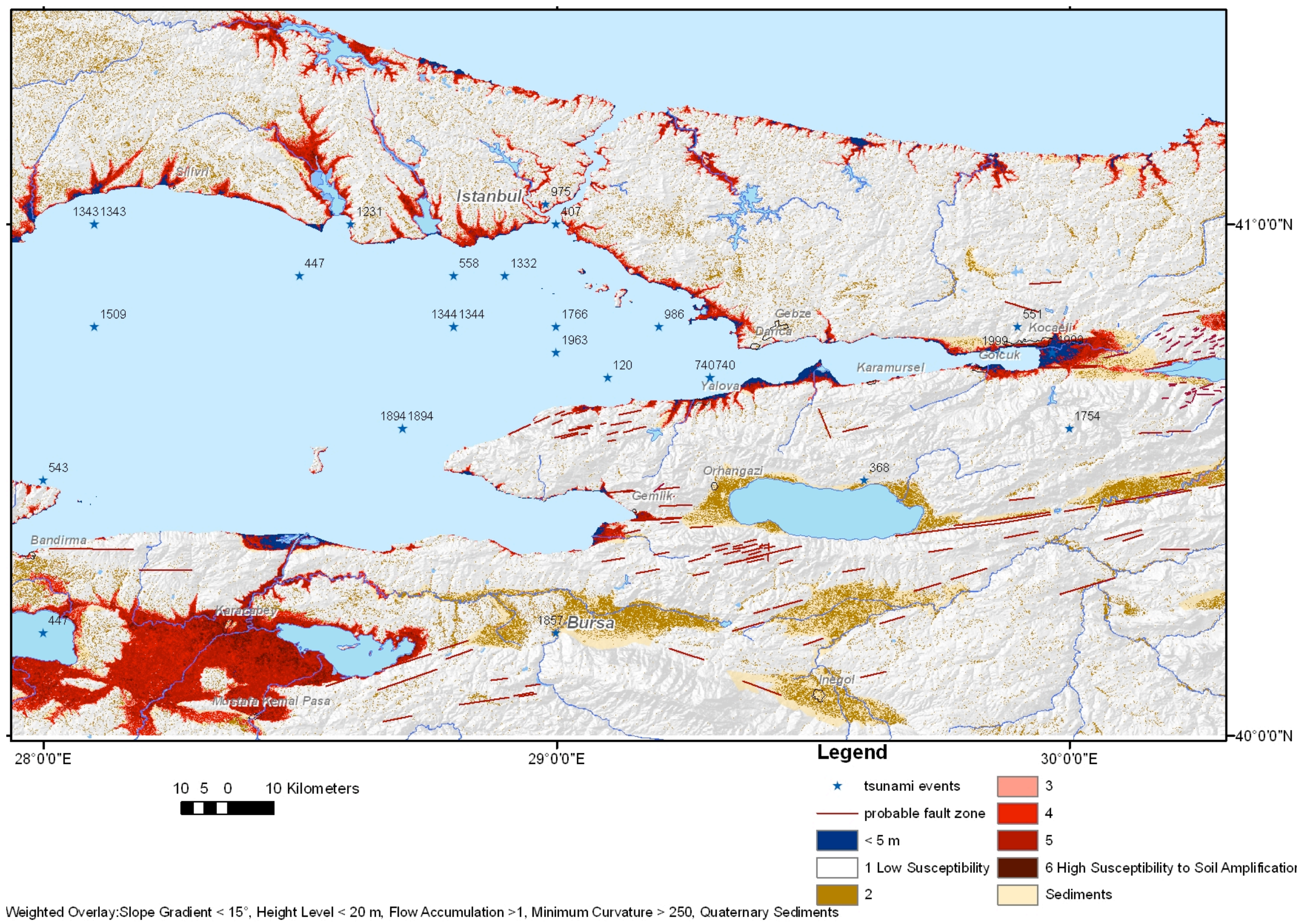

Fig. 9: Areas susceptible to higher earthquake shock according to morphometric and geologic surface properties.

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