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Potential tsunamigenic sources in the eastern Mediterranean and a decision matrix for a tsunami early warning system in Israel

Amos Salamon

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Abstract

Understanding the tsunamigenic architecture of the eastern Mediterranean enables formulating a decision matrix that can help determining in near-real-time whether an occurring earthquake is potentially tsunamigenic and, if necessary, issue an early warning message. Such a matrix has already been constructed by the IGC/NEAMTWS (Intergovernmental Coordination Group for the Tsunami Early Warning and Mitigation System in the North Eastern Atlantic, the Mediterranean and Connected Seas, 2009), in accordance with the worldwide experience, and it focuses mainly on large-scale earthquakes that may generate regional and basin-wide tsunamis. However, most of the historical tsunamis that hit the Levant are considered local and as such are outside the mandate of the NEAMTWS and should be considered by the local authorities. This work fills the gap and proposes a decision matrix that is both compatible with NEAMTWS requirements and suites the typical conditions in Israel, especially the need to relate to seismogenic submarine landslides.

The first stage of this work concentrated on reconstructing the tsunamigenic scheme of the eastern Mediterranean. It was found that earthquakes are the major threat for far, basin-wide tsunamis and submarine landslides should be of great concern for near, local tsunamis. Significant basin-wide tsunamis that may reach to the Levant from afar may be generated by strong earthquakes (M~8) in the Hellenic Arc and possibly also from the Cypriot Arc. Interestingly, most of the tsunamis that affected Israel in the past followed on-land earthquakes along the Dead Sea Fault System (DSFS), stressing the role of submarine slumps along the continental slope of the Levant as the source of the tsunami. Potentially, there are also tsunamigenic faults near the Levant coast such as the Beirut thrust, and large tsunamigenic marine slumps far away from the Levant such as in the Nile Cone and the Mt. Etna volcano in Sicily.

Next, the matrix proposed by the NEAMTWS was tested against each of the identified tsunamigenic sources and found capable of covering the regional and basin-wide tsunamis, but missed capturing most of the historical tsunamis that were generated by on-land earthquakes whose origin is further than 30 km away from the coast. Therefore, the matrix was calibrated according to the maximal distance (100 km) and minimal magnitude (M~ 6) of the assumed epicenter of the historical on-land tsunamigenic earthquake that occurred in the Levant (the changes are marked yellow in the following table).

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Decision matrix for Israel

Depth	Location	(Mw)	Tsunami Potential	Tsunami Message Type		
				Local	**Regional**	**Basin**
< 100 km	Sub-sea or very near the sea (< 80-100 km)	**5 to 5.5**	Negligible potential for a local tsunami	**Information**	**Information**	**Information**
		5.5 to 6.0	Low potential for a local tsunami	**Advisory**	**Information**	**Information**
		6.0 to 6.5	Potential for a destructive local tsunami < 100 km	**Watch**	**Advisory**	**Information**
		6.5 to 7.0	Potential for a destructive regional tsunami < 400 km	**Watch**	**Watch**	**Advisory**
		≥ 7.0	Potential for a destructive basin-wide tsunami > 400 km	**Watch**	**Watch**	**Watch**
	Inland (> 100 km)	**5.5 – 7.5**	No tsunami potential	**Information**	**Information**	**Information**
≥ 100 km	All locations	**≥ 5.5**	No tsunami potential	**Information**	**Information**	**Information**

The tsunami warning system is planned to rely on the evaluation of seismic data and therefore non-earthquake tsunamis are not covered. Hence, alerting volcanic and spontaneous tsunamis cannot be considered until a real-time monitoring of sea level is introduced into the warning system. The proposed matrix and the associated maps (Figures 2 and 3 after page 35 in this report) enables issuing a tsunami alert as soon as the preliminary source parameters (magnitude, location and depth) of the occurring earthquake are calculated. It thus supports both alerts coming from any Regional Tsunami Watch Centers (RTWCs) of the NEAMTWS, as well as issuing an independent alert by the National Tsunami Warning Center (NTWC) of

Since the majority (~80%) of the tsunamis that may affect Israel will most probably originate from earthquakes along the DSFS, and the relevant events are expected to reach M6 and above, the first warning signal will be the strong seismic shaking. Therefore, there is no need to wait until a sophisticated warning system gets into operation and people already should be taught to protect themselves from a tsunami by moving away from the sea as soon as they feel the strong shaking. The second natural warning signal, although it may not necessarily always appear, is a drop in the sea level and retreat of the sea. Indeed, some tsunamis may arrive from remote sources that will not be strongly felt in Israel and may start with a rise in sea level, but these are the minority of the events.

The present study was done within the framework of the Inter-ministerial Steering Committee for Earthquake Preparedness in Israel, contract no. 28-02-014, and is complimented by the GSI/24/2009 report on "Areal maps of potential tsunami inundation along the Mediterranean coast of Israel, in Haifa Bay, the Tel-Aviv area, Ashdod and Ashqelon" (Salamon, 2009).

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1 Introduction

With the limited number of modern tsunami records in the Levant and the long repeat time of tsunamigenic earthquakes, the past is the key to the future also for tsunami hazard evaluation. Cross correlating historical earthquakes and tsunamis shows that about 20 tsunamis hit the Levant coasts during the last two millennia, more than half of them followed on-land earthquakes that most probably originated from the continental Dead Sea Fault System (DSFS), four from other on-shore structures, and another four from remote sources, including the Hellenic and the Cypriot arcs and Sicily (Salamon et al., 2007). Three other events are left 'orphaned'. Thus, about 80% of the tsunamis originated from submarine landslides triggered by on-land earthquakes, while only a fifth followed large earthquakes in the eastern Mediterranean (Table 1).

Modern data is limited to the 1956 tsunami that was recorded in Jaffa (Goldsmith and Gilboa, 1986; Van Dorn, 1987) and possibly observed in Haifa (Shalem, 1956). It followed an M7.5 earthquake in the Aegean Sea (Ambraseys, 1960), and was possibly associated also with a large submarine slump (Perissoratis and Papadopoulos, 1999; Beisel et al., 2009). The Thera (Santorini) erupted some 3,600 years ago in the same region and generated the famed Late Minoan tsunami, field evidence of which are already known from Crete, Greece and Turkey (Bruins et al., 2008, and references therein). Analogous to the 1956 case, it is reasonable to assume that the Late Minoan tsunami also reached the Levant. Some evidences in Israel were suggested to support the Thera scenario (Pfannenstiel, 1960; Goodman-Tchernov et al., 2009), although Dominey-Howes (2002) suspected that Pfannenstiel's (1960) evidence is not unequivocal.

Further away, the Messina, Italy, 1908 M7.5 earthquake generated a destructive tsunami that was reported from as far away as western Egypt (Ambraseys, 1962). In earlier times the sector collapse of the nearby Etna volcano produced a large tsunami that possibly reached to the Levant (Pareschi et al., 2006a, 2007), although its alleged fatal impact on the Neolithic village of Atlit-Yam was totally rejected (Galili et al., 2008).

Table 1 Historical and modern tsunamis that affected the Levant coasts

The list includes the significant historical and modern tsunamis that occurred in the eastern Mediterranean basin and affected the Levant coasts, from Egypt in the south to the Bay of Iskenderun in the north, and Cyprus. The Santorini (Thera, Late Minoan) tsunami, although pre-historical, is also included.

Event	Tsunami range*	Tsunamigenic cause	Affected coasts	Comments
1627-1600 BC	Basin wide ?	Eruption of the Santorini (Thera)	Crete, Greece, Turkey	May have affected Israel, but evidence needs to be verified
1365±5 BC	Local	Unknown	Ugarit (Syria) flooded and half destroyed	
Mid 2nd century BC	Local	Unknown	Sea rose between Tyre and Acre	Coast was flooded
23±3 BC	Local	Unknown	Tsunami between Alexandria and Pellusium?	
115 12 13 morning	Local	On-land earthquake in northwestern Syria	Tsunami along the coast between Caesarea and Yavne, Israel	Doubtful tsunami, historical sources are not clear
365 07 21 before sunrise	Basin wide	Strong earthquake in Crete (Hellenic Arc)	Major tsunami in Alexandria, Peloponnesus, Adriatic and Sicilian coasts	Loss of lives and much damage in Alexandria
551 07 09	Local	Earthquake offshore Lebanon	Tsunami in Lebanon, between Tyre and Tripoli	Damage in coastal cities of Lebanon, significant drawback of the sea
746 01 18 morning	Local	Earthquake in the Jordan Valley	Tsunami, possibly on the Levant coasts	Affected coasts were not mentioned, possibly in the Mediterranean
802 12 30 - 803 12 19	Local	Earthquake nearby Massisa	Massisa coasts, near Gulf of Iskenderun	
1033 12 05 before sunset (1034 01 04?)	Local	Earthquake, possibly in the Jordan Valley	Tsunami in Acre, and possibly nearby coast	Port of Acre dried for a while
1036 03 12 - 1037 03 11	Local	Earthquake nearby Cilicia	Sea in Cilicia billowed back and forth	
1068 05 29	Local	Earthquake in southern	Sea in southern Israel receded and	

		Israel?	returned	
1202 05 20 0240 UT	Regional–Local ?	Earthquake in southern Lebanon and northern Israel	Severe tsunami on Levant coast and Cyprus	Damage in Acre
1222 05 11 06:15 UT	Local	Earthquake in southern Cyprus	Tsunami in Cyprus: Limasol and Paphos	Port of Paphos dried for a while
1303 08 08 03:30 UT	Basin wide	Strong earthquake in the Hellenic Arc	Widespread tsunami in eastern Mediterranean, including Acre	Acre was flooded
1408 12 29	Local	On-land (?) earthquake in northwestern Syria	Tsunami, near Mt. Cassius, western Syria	Boats were thrown on shore
1546 01 14 afternoon	Local	Earthquake, possibly in the Jordan Valley	Sea withdrew and returned, southern Israel	
1759 10 30 03:45 LT	Local	Earthquake in southern Lebanon, southern Syria and northern Israel	Sea waves flooded Acre and docks at Tripoli	Streets of Acre were flooded up to 2.5 m
1759 11 25 19:23 LT	Regional–Local ?	Earthquake in southern Lebanon, southern Syria and northern Israel	Sea waves in Acre and as far as the Nile Delta	Damage in Acre
1870 06 24 17:00 UT	Regional	Earthquake in the Aegean Sea?	Port of Alexandria was flooded	
1872 04 03 07:40	Local	On-land earthquake in northwestern Syria	Sea rose and flooded the coast near Antakya	
1908 12 28 05:20 UT	Regional–Local ?	Earthquake (and submarine landslide?) in the Straits of Messina	Tsunami in Messina Straits and nearby seas	Heavy loss of lives and damage in Messina
1953 09 10 04:06 UT	Local	Earthquake southwest of Cyprus	A series of tidal waves in Cyprus	Caused no damage
1956 07 09 03:12	Regional	Earthquake (and submarine landslide?) in the Aegean Sea	Tsunami in the Aegean Sea, recorded in Jaffa	Damage in Aegean Isles, not felt in Jaffa port

* Tsunami range: see definitions in Table 6.

LT: local time; UT: Universal time.

The seismotectonic scheme of the eastern Mediterranean includes additional elements that are not known to have produced historical tsunamis but their tsunamigenic potential cannot be disregarded, mainly due to the presence of submarine slumps. Examples are the northeast African passive margins including the Nile Cone (Garziglia et al., 2007, 2008) and the junction of the Hellenic and the Cypriot arcs (ten Veen et al., 2004). Other structures, further away from the sea, such as the Palmyra in northeastern Syria (the earthquake of 1042 AD), the southern Suez Rift (e.g. the 1969, mb 7.0) and the Gulf of Aqaba (Mw 7.1, 1995), seem less capable of generating submarine landslides in the Mediterranean and therefore may be considered as not tsunamigenic.

Although the average repeat time of significant tsunamis at the Israeli coast is about once in two centuries (Salamon et al., 2007), the potential impact of the next tsunami cannot be underestimated, for the coastal area of Israel has never been so densely inhabited and developed before. It is therefore essential to evaluate the tsunami hazard to Israel.

This work focuses on reconstructing the tsunamigenic framework of the eastern Mediterranean in terms of the location and threshold magnitude of all the potential sources. Understanding this enables formulating a decision matrix that can help determine in near-real-time whether an occurring earthquake is potentially tsunamigenic and issue an early warning message should that be the case.

A decision matrix for the Mediterranean and the northeast Atlantic has already been constructed by working group I of the IGC/NEAMTWS (Intergovernmental Coordination Group for the Tsunami Early Warning and Mitigation System in the North Eastern Atlantic, the Mediterranean and Connected Seas (2009), and for the eastern Mediterranean by Papadopoulos et al. (2007b, 2009). The existing matrix relies on the experience accumulated around the world and other matrices and decision support procedures such as described by the US IOTWS (U.S. Indian Ocean Tsunami Warning System Program), 2007. They all focus mainly on large-scale earthquakes that have generated regional and basin-wide tsunamis. However, most of the historical tsunamis that hit the Levant are local and as such are outside the mandate of the NEAMTWS and should be considered by the local authorities. This work fills the gap and proposes a decision matrix that is both compatible with NEAMTWS requirements (Section 4.2 and Appendix 1) as well as suiting the specific conditions in Israel, including the need to relate to seismogenic submarine landslides.

This work was done within the framework of the Inter-ministerial Steering Committee for Earthquake Preparedness in Israel, contract no. 28-02-014, and is complimented by the report GSI/24/2009 on "Areal maps of potential tsunami inundation along the Mediterranean coast of Israel, in Haifa Bay, the Tel-Aviv area, Ashdod and Ashqelon" (Salamon, 2009).

2 Working approach

The many unknowns and uncertainties do not enable detailed parameterization of tsunami generation for the Levant area. Field evidence is limited, sometimes unequivocal, and so far the constraint is mainly two millennia of descriptive records and a century short of modern records of seismic and tsunami activity. Thus the geometry, orientation, mechanism, location, depth, repeat time and other characteristics of the tsunami generators can only be inferred from the existing data, relying on best judgment.

The seismotectonics and bathymetry of the eastern Mediterranean are reviewed in order to identify and parameterize all the main potential tsunamigenic sources. In most cases, the data is extracted or extrapolated from the published literature. For example, the worst-case scenario is estimated according to the tectonic setting, repeat time is constrained by the geological and seismological findings. Uncertainties regarding submarine landslides are even larger, including the relations between the seismic source and the resulting landslide, the expected volume of the collapsed material and its elevation at start and rest, the slope and the sliding distance, the repeat time of events, etc.

For each of the potential sources we list the past tsunamis it might have generated, describe its probable dimensions, assign its threshold magnitude capable of producing a considerable tsunami, and estimate its return period (Table 2). The collected data was used to formulate the tsunami decision matrix for Israel. For consistency, the scheme of the matrix was adopted from the ICG/NEAMTWS (2009) and tested against the historical tsunamis of the Levant. It was then modified to suit the typical conditions of the Levant and then again validated against the historical list. Parallelly, the basic definitions and terminology suggested by the ICG/NEAMTWS (2009) are also presented and explained (section 4.2 and Appendix 1).

Table 2 **Characteristics of the tsunamigenic sources that may affect the Levant coast**

The table is based on the existing literature as well as on personal judgment where needed. Recurrent rates are conservative and were calibrated with the historical and recorded data. The historical record, two millennia long, is shown for comparison and verification. The table is modified from Thio (2009) and Galanti et al. (2009).

Region	**Tsunamigenic source**	**Estimated tsunami recurrence rates** (in years)	**Comments and references**	**Past reports of tsunamis in Israel**
Continental margins of Israel	Seismogenic landslide, triggered by on-shore M>~6 earthquake, as far as 80-100 km away from the coast	Large ls 1:100,000 Small ls 1: 300	Large volume landslides according to Frey-Martinez et al. (2005). Small landslides: historical records of Israel show 7 local tsunamis in 2,000 years: 2 in south and 5-6 in the north.	115?, 746, 1033, 1068, 1202, 1546, 10/1759, 11/1759
Cypriot Arc	Earthquake	M≥6 1:100	There are five records of M≥~6 events during the last century in and around Cyprus (Salamon et al., 2003), three of them in the sea, some are of strike-slip mechanism. Only the 1953 generated a local tsunami.	None
Crete and the NE Hellenic Arc	Earthquake	M≥8 1: 800-1,000	Shaw et al. (2008): Mw 8.3-8.5 thrust event, estimated repeat time of the 365 is ~ 5,000 yrs, and about 800 yrs if this type is typical to the entire Hellenic Arc (e.g. 1303). Papadopoulos et al. (2009): two M8-8.3 events per 2,000yrs.	1303

Aegean Sea	Earthquake, Landslide, Volcanic	1:25,000	The tsunami of the 1956 M7.5 earthquake was destructive in the Aegean but detected in Israel by instruments only. Perissoratis and Papadopoulos (1999) and Beisel et al. (2009): combined mechanism of earthquake and landslide. Santorini type of tsunami may occur once in 25,000 years.	1956; evidence of the Santorini (1627-1600 BC) are doubtful
Nile Delta	Landslide	1:10,000	Garziglia et al. (2008) estimate for the Rosetta province a rate of 1:27,000 yr for landslides of 3-500 km^3.	None
Offshore Egypt	Earthquake	?	Modern records show 2 M6 earthquakes (per century).	None
Beirut thrust	Earthquake	M7.5 1:1,500	Elias et al. (2007): event per 1,500 – 1,750 yr	551
Italy, Sicily (Messina)	Earthquake	M7.5 1: ~1,000	After Valensise (2004) and Barbano et al. (2007). The 1908 tsunami arrived as far as to Egypt	None
Italy, Sicily (Etna)	Landslide	1: >10,000	After Pareschi et al. (2006a,b, 2007).	~8,000 B.P.

Comments:

The estimated recurrence rates refer to a tsunamigenic event, thus ignoring the unknown relations between the total number of events and the 'successful' tsunamigenic events. Triggers for the 2^{nd} century BC and 23± BC tsunamis are not known. Ls- Landslide.

3 The tsunamigenic framework of the Levant

Following the historical and modern records, active faults and submarine landslides are the two major tsunamigenic sources in the Levant. Several tsunamis (e.g., 1908 and 1956 in Table 1) may have originated from combined sources. Volcano eruptions, although rare, are also possible. Several studies have already examined and simulated the potential tsunamigenic sources in the eastern Mediterranean region (e.g., Papadopoulos et al. (2007a) in the Hellenic Arc; Yaciner et al. (2007) in the Mediterranean; Fokaefs and Papadopoulos (2007) in and around Cyprus; Yolsal et al. (2007) for the eastern Mediterranean; Tinti and Armigliato (2003) in southern Italy; Tinti et al., (2005) in the Mediterranean, Lorito et al. (2008) in southern Italy, including a rupture of the western Hellenic Arc, as was probably the case of 365 AD); yet none of them compiled a comprehensive scheme that is relevant to the Levant.

Herein, the sources are categorized into mainly tectonic and submarine landslides, with subdivisions to near and far sources relative to the Levant coast, main and secondary elements, etc.

3.1 Tectonic sources

As expected, plate boundaries are the major active tectonic elements in the eastern Mediterranean, and those that are in the sea are potentially tsunamigenic, either directly by earthquake sea floor deformation or by the release of submarine landslides. Continental seismogenic structures that are close enough to the continental slope are also capable of triggering submarine slumps and therefore should also be considered.

3.1.1 Far sources

3.1.1.1 The Hellenic Arc

Being the region that has already generated the largest known earthquakes and basin-wide tsunamis, the Hellenic Arc is the most hazardous to the eastern Mediterranean. The tsunamis can be generated by large shallow earthquakes associated with thrust faulting beneath the Hellenic trench.

Many studies discussed the earthquake and tsunami history of the Hellenic Arc and evaluated its potential of generating future activity. For example, Galanopoulos (1960), Papadopoulos and Chalkis (1984) and Papazachos et al. (1986) investigated tsunamis along the Greek coasts, Papazachos and Dimitriu (1991) found that the most devastating tsunamis occurred in areas of shallow normal and thrust faulting, and Papadopoulos et al. (2007a) counted 18 reported tsunamis in the east Hellenic Arc and trench system.

Most notable were the tsunamis of 365 and 1303 AD resulting from possibly the strongest reported earthquakes in the region, ~M>8; the former may have claimed the largest loss of lives and caused extensive devastation in the entire eastern Mediterranean. Shaw et al. (2008) studied the 365 earthquake and tsunami and concluded that this was an Mw 8.3-8.5 thrust event, on a 100 km long fault plane, 30 degree dip, focused at 45 km depth, with a rather large offset of 20 m. In their opinion, the estimated repeat time of such an event on this single fault in western Crete is ~5,000 yrs, and about 800 yrs if this type is typical to the entire Hellenic Arc (e.g., the 1303 event?). This estimate is also compatible with the two millennium years of experience of damaging tsunamis that reached the Levant from the Hellenic Arc (the two events mentioned above), an overall rate of an event per a millennium. The Hellenic Arc has also generated many local tsunamis, but these are not known to have affected the Levant and therefore are not dealt with in this work.

The 2004 Sumatra experience demonstrated the break of a whole arc in an instance, thus portraying the potential break of the whole Hellenic Arc as the worst-case scenario of an earthquake-generated tsunami in the eastern Mediterranean basin. The repeat time of such an extreme scenario, if at all probable, is not known, although the exceptional large offset

(20 m!) suggested by Shaw et al. (2008) for the 365 earthquake is on a scale similar to that of the 2004 Sumatra earthquake.

3.1.1.2 The Cypriot Arc

The Cypriot Arc is the closest subduction zone to the Levant, but evidently is smaller, slower and less active than the Hellenic Arc. Large earthquakes that produce local tsunamis do occur there from time to time but so far no significant basin-wide tsunami is known to have originated from there. Several modern studies have related to tsunamis generated in Cyprus, e.g., Fokaefs and Papadopoulos (2007), but they still seem to include doubtful entries (Salamon et al., 2007). Only the 1222 and 1953 tsunamis, the latter which may have also arrived to Asia Minor but caused no damage, are considered reliable whereas the others mentioned (e.g., 300, 1941) are doubtful.

The arcuate convergent system of the Cypriot Arc (Rotstein and Kafka 1982; Salamon et al., 2003; Wdowinski et al., 2006; Papadimitriou and Karakostas, 2006) produces earthquakes of shallow and intermediate focal depth of several tens of kilometers only, and is interrupted west of Cyprus by the Paphos strike slip tear fault. The largest recorded event was the Mw 6.8, 1996 Paphos earthquake with a strike-slip mechanism. All the other events, including the historical ones, were estimated as weaker (Ambraseys and Adams, 1993; Guidoboni et al., 1994; Guidoboni and Comastri, 2005).

Yet the tectonic setting of the Cypriot Arc does not rule out the potential occurrence of a much larger event that could rupture a large segment of the arc to a depth of several tens of kilpmeters and is capable of generating basin-wide tsunamis. Therefore, the hazard from there should not be overlooked, especially because the Levant coast directly faces large parts of that arc.

3.1.1.3 Sicily and Italy

Sicily and Italy seem to be the most distant tsunamigenic source that may affect the Levant. The tsunami that followed the Mw7.1, 1908 Messina earthquake (Pino et al., 2009) was reported from as far away as western Egypt (Ambraseys, 1962). Favalli et al. (2009)

suggested that the tsunami was driven by a combined seismic and landslide source and this may have intensified its effect.

3.1.2 Near sources

3.1.2.1 The Dead Sea Fault system

Although continental, the Dead Sea Transform (DST) turns out to be the most 'productive' tsunamigenic source, for most of the tsunamis in the Levant followed DST earthquakes, possibly due to the triggering of submarine landslides. Altogether, about 60 moderate to large (M>~6) earthquakes were listed since about the mid 2nd century B.C. in and around the Dead Sea fault system, from the Gulf of Aqaba in the south until it meets with the East Anatolian fault in the north. Of these, about a quarter to a third of the largest and a seventh of the moderate earthquakes were tsunamigenic. Thus the larger events are more likely to produce a tsunami than the smaller ones (Salamon et al., 2007). The most distant coasts affected by a tsunami that originated from an earthquake along the DST were in Cyprus (in 1202) and Egypt (11/1759).

The lowest magnitude and most distant from the Mediterranean coast was probably the tsunamigenic earthquake of 1546, estimated by Ambraseys and Karcz (1992) to be around Ms 6.0. Interestingly, the modern 1927 earthquake which was M_L=6.2 (Shapira, 1979) did not trigger a tsunami. The May 1068 earthquake may also be considered a small magnitude tsunamigenic earthquake (Guidoboni and Comastri, 2005). As no local tsunamis have been observed along the Levant coast during the instrumental period and there are no records of M<~6 historical tsunamigenic earthquakes, it is possible only to approximate the threshold magnitude of tsunamigenic DST earthquakes to be in the range of M6.0-6.5.

A significant number of the tsunamigenic earthquakes, mostly from the central and northern DST, produced surface ruptures, e.g., the 746 (Marco et al., 2003), 1202 (Daëron et al., 2005; Ellenblum et al., 1998; Marco et al., 1997, 2005), October 1759 (Ellenblum et al., 1998; Marco et al., 1997, 2005) and November 1759 (Daëron et al., 2005; Gomez et al., 2001), and these may also indirectly reflect the threshold magnitude for tsunami earthquakes. On the other hand, it appears that many of the strongest and most damaging historical earthquakes, including those that ruptured the surface (e.g., 1837, Nemer and Meghraoui, 2006), did not produce a tsunami. Therefore, there is no such 100% 'successful' tsunamigenic earthquake.

Relating the extent of the tsunamis to the estimated location of the triggering earthquake, it seems that most of the tsunamis struck the coast opposite the area damaged by the earthquake. The largest distance between the DST and the coast affected by a tsunami seems to be about 80-100 km (that is, around the Dead Sea basin), as was probably the case of the May 1068 and 1546 events, but obviously this should also be magnitude dependent.

Overall, experience shows that two similar magnitude earthquakes may in one case trigger a tsunami, whereas in a different configuration, they may not. It is reasonable to assume that the magnitude is not the only factor; and the distance from the coast, the focal mechanism or depth, and the effects of directivity all play a role. Therefore, past experience gives only a rough impression of that threshold and further investigation is needed to determine the typical properties of a tsunamigenic earthquake in the region.

3.1.2.2 Dead Sea Transform secondary structures

Additional parts of the DSFS other than the main transform are also capable of producing a tsunami. Such is the tsunami that followed the 551 earthquake that occurred on the Beirut thrust (Elias et al., 2007). Other tsunamigenic examples are the October and November 1759 events that apparently ruptured the Rachaya and Serghaya faults, respectively (Gomez et al., 2001; Daëron et al., 2005). The motion along the secondary faults is slower than that along the main transform, implying a larger recurrence time of strong earthquakes and tsunamis. The historical experience, however, reflects the cumulative effect of the activity of the whole DSFS and enables estimating the repeat time of tsunamis with no need to resolve the relative contribution of each of the DSFS components.

3.1.2.3 Other nearby seismogenic structures

<u>Northeast Mediterranean Triple Junction</u>: Tsunamis in the Iskenderun Bay (802/3 and 1036/7), whether they originated from the northeastern-most tips of the DST, the Cypriot

Arc, the East Anatolian fault, or any other associated structures, prove the potential of that system in generating tsunamis. Nevertheless, these were local events that did not affect the coast of Israel and therefore can be ignored.

Offshore Egypt and Sinai: So far, there is no record of a tsunami that originated from an earthquake along the northeastern passive margins of Africa. Although M6 earthquakes have already occurred there (Salamon et al., 1996), it is the proximity to the sedimentary cone of the Nile that poses the potential for tsunamis, for vast slumps are well recognized there throughout the recent geological record (e.g., Garziglia et al., 2007, 2008).

Other Possible Local and Distant Sources: The seismotectonic framework of the eastern Mediterranean includes additional on-land elements that are not known to have produced a tsunami in the Mediterranean, but its tsunamigenic potential cannot be disregarded. Such are the Palmyra in northeastern Syria (1042 AD), the southern Suez Rift (mb7.0, 1969) and the Gulf of Aqaba (Mw7.1, 1995), although interestingly, the last two did generate local tsunamis in the gulf (Ben-Menahem, 1991; Wust, 1997). They might not have been strong enough or close enough to the continental slope of the Levant and therefore were not capable of generating submarine landslides. In any case, the potential effect of a larger earthquake on these sources should be further investigated.

3.2 Submarine Landslides

The bathymetry and shallow seismic profiles along and across the continental margins of the Levant south of the Carmel fault show numerous scars typical of landslide morphology, and hilly topography and slide bodies at the foot of the continental slopes (Almagor, 1993). Similarly but on a larger scale, this is also seen around the Nile Cone (Garziglia et al., 2007, 2008, Folkman and Mart, 2008). Papadopoulos et al. (2007) list and discuss the occurrence of submarine landslides in the Mediterranean Sea and conclude that most of them were triggered by earthquakes and a few by volcanic eruptions.

Regarding the driving force of submarine slope failure, Almagor and Wiseman (1977) and Almagor and Garfunkel (1979) suggested that the continental slopes of Israel are stable under static conditions, but may fail under external forces such as earthquakes. Hence, spontaneous failure is excluded. Propagation and response analysis of selected seismic records suggest that indeed large earthquakes are capable of generating slides offshore Israel (Frydman and Talesnik, 1988), and it is mainly the low frequency component of the shaking that causes the failure. In such a case, the minimal threshold acceleration for generating a failure along the submarine slopes should be greater than 0.15g.

Mechanical considerations may suggest that landslide tsunamis could be related to a time-dependent process. The continuous accumulation of sediment loading on the continental slope may result in decreased stability with time, and progressively smaller accelerations would be needed to generate a slope failure. Therefore, the threshold magnitude for tsunamigenic earthquakes may not be constant through time but gradually decrease after the previous tsunami. So far, there is no distance-magnitude relationship determined for tsunami generation from continental earthquakes in the Levant. The only constraint is the historical tsunamis that followed the 1068 and 1546 earthquakes. This relation is discussed in more detail in section 4.3.1 below.

Regarding the critical size of a tsunamigenic submarine slump, ten Brink et al. (2006) examined the sensitivity of slump volume to significant run-up by simulation, and concluded that significant run-up occurs for ≥ 5 km^3 landslide volumes (which is highly dependent on effective slide velocity). Kalderon-Asael et al. (2008) suggested a universal relation between area and volume of landslides, irrespective of slope height and mechanical properties, but in accordance with field observations worldwide. These new understandings will certainly need to be considered in future hazard assessments.

In a predictive sense, since no drastic changes have occurred in the depositional system of the Levant margins in recent times, it is reasonable to assume that slope failure will continue in the future. Learning from the past, future tsunamis will most likely occur opposite the damage zone of future large earthquakes. Interestingly enough, there is a significant seismic hiatus at least along the Jordan Valley, one of the closest sections of the DST to the coast.

3.2.1 Near sources

3.2.1.1 Offshore northern Israel

Almagor (1993) described the narrow margins of the continental shelf offshore Israel north of the Carmel and in Lebanon as a terrace that consists of a "… thick Pliocene-Quaternary sediments wedge that narrows, steepens and deepens from south to north." The morphology resembles cliffs about 1 km high, intensively cut by deep submarine canyons. He also identified large slabs of detached sediments along the Akhziv Canyon, extending in an area of up to 1.5 km x 0.5 km, 80 m thick. Evidently, it reflects intensive failure of the continental slopes, and it is therefore reasonable to assume that this area is vulnerable to tsunami generation.

3.2.1.2 Offshore southern Israel, Gaza and Sinai

Regarding the southern offshore of Israel, Almagor and Garfunkel (1979) described scars that appear all along the continental shelf in water depths of 80 to 450 m. The approximate dimensions of a typical scar are about 3 km wide, 4 km downslope length, and 45 m depth (~0.5 km^3). Chunks of the failed material were sampled as deep as 900 m. The slope attains 1^0 in its upper section, increases to 6^0 at 400 m, and becomes moderate again, back to 2-2.5^0 .

Frey-Martinez et al. (2005) investigated the continental margins of Israel and discovered many slump complexes. The largest group extends over 4,800 km^2, buried within the Late Pliocene succession and reaching a volume of up to 1,000 km^3. An increasing number of smaller slumps appear in younger strata, up to the Holocene. More importantly, the presence of proto-slumps within the very same area suggests that there is still a potential of slope instability.

Deeply rooted rotational slumps, although very impressive and extending along wide areas (e.g., the disturbances of Gaza, Palmahim, Dor), do not seem to be the agents of a catastrophic downslope transport of large volumes and therefore are not considered tsunamigenic (Garfunkel et al., 1979).

3.2.1.3 Repeat time of near sources

There is only limited historical and geological data to constrain the repeat time of landslide tsunamis. There are reports of seven (or eight?) historical events that hit the Israeli coast during the last two millennia, five (or six?) of which occurred in the north and two in the south. As for the large slump complexes, Frey-Martinez et al. (2005) estimated that about 40 of them occurred since the Late Pliocene.

3.2.2 Far sources

3.2.2.1 The Nile Delta

The Nile Cone is the largest submarine body of sediments in the eastern Mediterranean. Sediments are still accumulating there and large scars as well as large volumes of slumps are well known there. Although most of the information derived from research on the western side of the cone, it seems that the eastern side is not different (Folkman and Mart, 2008).

Garziglia et al. (2008) identified seven outstanding mass-transport deposits (MTDs) within the Pleistocene–Holocene sedimentary section (~1200 m thick) of the Rosetta area, western Nile Cone. They distinguished small-scale (~220 km^2 and 10 km^3), medium-scale (400–800 km^2 and 10–50 km^3), and very large scale (at least 5000 km^2, 500 km^3) slumps. Similar dimensions were also suggested by Austin (2006). Garziglia et al. (2008) estimated the recurrence time of large-scale instability events in the Rosetta area to be on the order of 27 ka, and presumed that ground shaking generated by a large remote earthquake (Ms~7.8) in the eastern Mediterranean and even a moderate local earthquake (Ms~6.5) might have been sufficient to trigger failure.

Garziglia et al. (2007) modeled a tsunami scenario based on an MTD found offshore the western Nile margins. This large scale deposit extends over 500 km^2 and involves a volume of 14 km^3 of Pleistocene-Holocene sediments. They estimated the event was between 10 and 9 ka BP.

3.2.2.2 The eastern Mediterranean, Aegean Sea and Italy

It was proposed that the Messina 1908 tsunami (Ortolani et al., 2005; Billi et al., 2008) that was reported from western Egypt (Ambraseys, 1962) and the 1956 tsunami of the Aegean (Perissoratis and Papadopoulos, 1999, Beisel et al., 2009) that was recorded in the Jaffa harbor (Goldsmith and Gilboa, 1986; Van Dorn, 1987) and possibly also in Haifa (Shalem, 1956), were generated by submarine slumps immediately after a large M~7.5 earthquake.

In addition, modeling of a tsunami resulting from the sector collapse of the Etna volcano in prehistoric times (Pareschi et al., 2006a, 2006b, 2007) suggests its arrival to the Levant, although its possible impact on local settlements has been strongly exaggerated (Galili et al., 2008). The estimated volume of the collapsed material is around 20 km^3, and it traveled as far as 20 km offshore. The repeat time of such an event is not known. Another large submarine slide (~2,200 km^2, ~550 km^3) was identified near the Anaximander Seamount (ten Veen et al., 2004), but its tsunamigenic potential has not yet been investigated.

3.3 Tsunamigenic volcanoes

Potential volcano tsunamis may come from the Aegean Sea and Sicily. The most famous event was associated with the Late Minoan (LM) eruption and collapse of the island of Thera (Santorini), for which field evidence were found in the Aegean Sea, Crete and western Turkey (e.g., Yokoyama, 1978; McCoy and Heiken, 2000; Minoura et al., 2000; Bruins et al., 2008). The return time of the LM tsunami is estimated as 25,000 yrs. Another tsunami in the Aegean was reported on September 1650 A.D. and was related to the volcanic activity of Mt. Colombo near Thera (Dominey-Howes et al., 2000; Dominey-Howes, 2002).

Another potential source is the Etna volcano in Sicily. Based on submarine findings, Pareschi et al. (2006, 2007) suggested that collapse of a sector of Mt. Etna into the sea in the early Holocene times which may have been associated with volcanic activity, generated a tsunami that reached the Levant.

3.4 Orphan, spontaneous and asteroid tsunamis

There are several mechanisms capable of generating submarine slope failure. Since the continental slope of the Levant is subject to frequent strong earthquakes, it is reasonable to assume that any accumulated potential for slope failure will be first released by a dynamic shaking before reaching to threshold conditions of static failure. The fact that most of the reported tsunamis in the Levant are associated with on-land earthquakes supports this assumption.

There are three historical ‘orphan’ tsunamis (Ugarit, ca. 1365 BC; mid 2nd century BC in southern Lebanon; and Pellusium 23±3 BC) for which the trigger mechanism is not known. Although seismic shaking would still be the best default mechanism, a spontaneous failure cannot be ruled out.

The 198 BC event on the eastern coastal area of the Mediterranean Sea was noted by Soloviev et al. (2000) as an asteroid-generated tsunami, but this was probably duplicated from an event which occurred in the Gulf of Corinth (Greece) in 373/372 BC (Salamon et al., 2007). Theoretically, this is a plausible mechanism, but practically, there is no data available to predict such an event.

4 The decision matrix

The tsunami decision matrix is an essential tool for determining the potential of tsunami generation from an earthquake as soon as its location, magnitude and depth are determined. At present, preliminary estimates of the source parameters are sufficient for early warning within a few minutes after the earthquake. The decision to issue a tsunami warning is based first on the earthquake signal and then verified or cancelled depending on whether a tsunami was indeed generated or not.

Given the seismic and tsunami histories, the seismotectonic setting and worldwide experience, it is possible to formulate the threshold conditions for tsunami generation in a selected area. Such an analysis enabled the formulation of a tsunami decision matrix for Israel. Firstly, the characteristics of each of the tsunamigenic sources that may affect the Levant coast were determined (Table 2). This was also used for tsunami simulations and hazard assessment for Israel by Thio (2009). Secondly, the decision matrix proposed for the Mediterranean by the NEAMTWS was adopted and tested for the historical record in the Levant (Table 1). Lastly, the decision matrix was modified to conform with the tsunami history of the Levant (Table 4) which in fact refers to 'felt' tsunamis only.

4.1 Unknowns and uncertainties

For the lack of a real-time tsunami monitoring, alerting tsunamis on the basis of tsunami generation is not possible and thus the first message relies on seismological data. Unfortunately, this process is associated with many unknowns. Fast or near-real-time determination of the source parameters, especially of large earthquakes, is based on partial information and therefore is associated with large uncertainties, if not errors. Then, of course, the decision matrix is largely a generalization of the relationship between earthquake and tsunami generation. In the case of the Levant, which involves on-land tsunamigenic earthquakes, not much is known.

Moreover, the size or magnitude of the tsunami cannot be directly inferred from the preliminary determination of the earthquake parameters, for the geometrical dimensions of the earthquake are not known. Gica et al. (2007) found that under the same earthquake magnitude, variations in rake and dip angles, epicenter location, and focal depth do not significantly affect the resulting tsunami, while fault dimensions, strike angle and slip displacement can cause a large change in the wave height in the far field. Less is known about the dependency of submarine landslide generation on earthquakes.

For the above reasons, the decision matrix aims only at a preliminary educated guess of whether a tsunami might have been generated. History shows that not all marine earthquakes generated tsunamis, and therefore 'successful' prediction cannot be promised. It is important to note that the present form of the decision matrix covers only marine and on-land earthquake-associated tsunamis. Volcanic and spontaneous tsunamis are not considered at this stage.

4.2 Definitions and terminology

The decision matrix is expected to be in use by the various warning tsunami centers (Regional Tsunami Watch Centers – RTWCs; national Tsunami Warning Focal Points – TWFPs; and National Tsunami Warning Centers– NTWCs). In order to guide the tsunami watch messaging between these centers, the IOC/NEAMTWS issued recommended users guide responsibilities regarding the roles, requirements and performance indicators of the centers (Appendix 1). The operational guide suggests that the warning centers use uniform terminology in order to avoid possible ambiguities and misunderstanding in sending, receiving and communicating the various types of messages.

The main terms and definitions are explained hereby in short in order to help the reader follow the structure and terminology used in the decision matrix. The following was taken with minor changes from the "*Interim Operational Users Guide for the Tsunami Early Warning and Mitigation System in the North-eastern Atlantic, the Mediterranean and Connected Seas (NEAMTWS)", Version 1.1g,* (http://www.ioc-unesco.org/index.php?option=com_oe&task=viewDocumentRecord&docID=4516).

Types of Messages

Tsunami messages refer to all messages issued by RTWCs in the given region that are destined to the National TWFPs and/or NTWCs for further processing by emergency management agents (directly or second hand). Its content must convey the basic information required by these authorities. If there is a threat of any sort to the coastal areas, the messages related to this threat are called **tsunami alert messages**.

Ideally, the name of the tsunami alert message should already provide 3 of the main instances of information required by the emergency management agencies: **urgency**, **severity**, and **certainty**. The forth required information, the **affected area**, would appear immediately in the text of the message as the list of countries concerned by that particular message type. In this way, the very first few lines of a tsunami message would convey already the basic tsunami information to the recipient. The details of the threat evaluation would appear later in the message. For each information instance, urgency, severity, and certainty, two levels of threat are suggested (Table 3), and for each level there is specific keywords suggested to classify (Table 4):

Table 3 Levels of tsunami threat

Category	Level I (high)	Level II (low)
Urgency	Tsunami to arrive in less than 2* hours	Tsunami to arrive in more than 2* hours
Severity	Tsunami wave height greater than 0.5m and/or tsunami run-up greater than 1m	Tsunami wave height less than 0.5m and/or tsunami run-up less than 1m
Certainty	Tsunami confirmed by sea-level measurements	Tsunami not yet confirmed by sea-level measurements, information based on seismic parameters only

* *Number to be agreed upon by the ICG*

Table 4 Keywords to classify the levels of threat

Level definition for the 3 categories/parameters		
Category	**Level I (high)**	**Level II (low)**
Urgency	Immediate	*More than 2 hours*
Severity *	Watch	Advisory
Certainty	Confirmed	*Not yet confirmed*

* *Already agreed by the ICG/NEAMTWS*

Using all combinations possible we could have 8 message types that are formed by combinations of the words selected for each level in the table above. This is a very high number of messages that could be confusing for the users and so we propose the following simplifications. Firstly, in the NEAM region the reception of a tsunami alert message requires an immediate action to be taken by the agents and so the urgency field can be omitted.

As regards certainty, the information will be provided in the content of the message and proper training of the agents involved will help the emergency managers to grasp fast this content. In fact, the first message related to a tsunami threat will be always based exclusively on seismic information. This information, by itself, is not sufficient to decide if a tsunami was indeed generated and so its certainty is low. The Tsunami Response Plan in each country should define the actions to be taken in this case. When sea-level data is gathered and processed, following messages should confirm, update the threat or cancel it with a very high degree of certainty. And so, in a series of messages related to the same tsunami threat, the sequential order of messages do represent an implicit increase in certainty and this fact should be understood by the message recipients. The certainty level also depends on the magnitude of the tsunamigenic earthquake.

These simplifying options leave us with only two types of tsunami alert messages that convey only the severity information in its name:

Table 5 Types of tsunami alert messages

Message Type	Tsunami Wave	Effects on the coast
Tsunami Watch	Tsunami wave height greater than 0.5m and/or tsunami run-up greater than 1m	Coastal Inundation and decision matrix, indicating the different levels of tsunami advisory messages to be issued on
Tsunami Advisory	Tsunami wave height less than 0.5m and/or tsunami run-up less than 1m	Currents, Bore, recession, damage in harbors, small inundation on beaches

In addition to the tsunami alert messages, we have to consider two additional types of messages, **tsunami information** and **tsunami communication test**.

The **Tsunami Information** is a message issued to advise the NEAM recipients of the occurrence of a major earthquake in the area but with an evaluation that there is no tsunami threat. The thresholds for the issuing of this type of messages are defined in the Decision Matrixes, as agreed by the ICG/NEAMTWS.

For the National Tsunami Warning Centers (NTWCs) it is recommended that a National Tsunami Information message could be sent in the case of an earthquake felt at or close to the coast, of any magnitude. The tsunami information message will then be used to prevent unnecessary evacuations most frequently.

The **Tsunami Communication Test** is a message issued by the RTWCs at unannounced times to test the operation of the tsunami warning systems.

Structure of Messages, Affected Area and Sequence

In the NEAM region, due to its basin structure, there is no tsunami that can affect all countries with the same threat level. However, it could be confusing to send different messages to different countries referring to the same tsunami event. We propose that all National TWFP in the NEAM region will receive the same tsunami message. This means that the same message will contain in the same body more than one type of messages: tsunami watch, tsunami advisory, and tsunami information. We propose that the header part of the tsunami message should contain the sequence of pairs of fields, message type and affected area, by a decreasing order of threat. The type of such a composed message will be the one that corresponds to the highest level of tsunami threat. This means that some coastal area in the NEAM region is subject to that type of tsunami threat. Thus, a Tsunami Watch message will also contain a Tsunami Advisory and a Tsunami Information types of messages, while a Tsunami Advisory will contain also a Tsunami Information type of message.

Thus, the tsunami message type related to one given country is defined by the worst case that can be found on any coastal area of that country, set up according to the Decision Matrix.

The area affected by a certain tsunami threat is defined in the Decision Matrixes agreed by the ICG/NEAMTWS, according to 3 spatial ranges of tsunamis:

Table 6 Spatial ranges of tsunamis

Tsunami range	NE Atlantic	Mediterranean
Local	< 100 km	< 100 km
Regional	100 km to 1000 km	100 km to 400 km
Basin	> 1000 km	> 400 km

4.3 The decision matrix for Israel

The NEAMTWS decision matrix is based on the assumption that a potentially tsunamigenic earthquake should follow the three criteria of depth, location and magnitude (Table 7). Firstly, only earthquakes shallower than 100 km below the surface are considered (leftmost column). Secondly, unless the epicenter is in the sea or very close by (< 30 km), on-land earthquakes are considered incapable of producing a tsunami. Magnitude thresholds are graded according to the spatial range of coasts to be affected by the expected tsunami. Higher magnitudes increase the expected range of the tsunami, from 'local' to 'regional' ('R' in Table 7) and 'basin-wide' ('BW' in Table 7), respectively, and the type of the alert message (Bulletin type) is determined accordingly.

In order to verify the NEAMTWS matrix for the specific conditions in Israel, it was tested against the historical tsunamis to see whether the matrix would have 'captured' them all. Surprisingly, only the marine earthquakes were validated while all on-land tsunamigenic earthquakes were missed (115?, 746, 1033, 1068, 1202, 1546, 1759/10, 1759/11)! The reason is that those earthquakes were most probably originated along the DSFS which is located more than 30 km away from the sea. Thus, the matrix should be specifically modified for Israel. Non-earthquake induced tsunamis, such as the orphan (e.g. the 2nd century BC), volcanic (Late Minoan, Santorini) and spontaneous events, are not meant to be covered by the decision matrix. Once the tsunami warning is based on real-time monitoring of sea level, the matrix can be updated and set to cover the non-earthquake tsunamis.

Table 7 NEAMTWS decision matrix tested against historical tsunamis in the Levant

Depth	**Location**	**(Mw)**	**Tsunami Potential**	**Bulletin Type** (alert message)	**Validation test for the Levant (Israel)**
< 100 km	Sub-sea or very near the sea (< 30 km)	**5.5 to 6.0**	Small potential for a local tsunami	**Information Bulletin**	
		6.0 to 6.5	Potential for a destructive local tsunami < 100 km	**Regional Tsunami Advisory**	
		6.5 to 7.0	Potential for a destructive regional tsunami < 400 km	**Regional Tsunami Watch, Basin-wide Tsunami Advisory**	**R: 1953**
		≥ 7.0	Potential for a destructive basin-wide tsunami > 400 km	**Basin-wide Tsunami Watch**	**BW: 365, 1303, 1908, 1956; R: 551**
	Inland (> 30 km)	**5.5**	No tsunami potential	**Information Bulletin**	
≥ 100 km	All locations	**≥ 5.5**	No tsunami potential	**Information Bulletin**	

4.3.1 Distance-Magnitude relationship for on-land tsunamigenic earthquakes in the Levant

In order to correctly set the NEAMTWS matrix for Israel, there is a need to establish the distance-magnitude relationship for on-land tsunamigenic earthquakes. However, this can not be easily done because location and magnitudes of historical events are a matter of interpretation and associated with very large uncertainties. Thus only a rough estimate can be suggested.

The data used for establishing these relations is arranged in three tables: the first relates to the historical tsunamigenic and non-tsunamigenic earthquakes (Table 8 and the red full circles in Figure 1), for which there are some published estimates of the source parameters. The next (Table 9 and the blue full triangle in Figure 1) relates to the location and magnitude of modern recorded events, for which the source parameters were calculated. Although most of the modern earthquakes have been moderate or far from the Mediterranean, they can establish the threshold for non-tsunamigenic earthquakes. The last, historical data from around the world is limited (Table 10 and the green full diamonds in Figure 1) but seems to agree with the data of the Levant. This is exemplified by the 1169 and 1456 earthquakes and tsunamis in Italy (Guidoboni and Comastri, 2005). Similarly along the California coast, the local tsunamis of 1812, 1865 and 1868 (Chowdhury at al., 2005) followed nearby onshore earthquakes (Dolan and Rockwell, 2001; Toppozada and Branum, 2004). The only exception is the 1373 earthquake in the central Pyrenees-Catalonia region and the tsunami in Barcelona, which seems to have been generated considerably far away from the causative earthquake (rightmost green diamond) and therefore may deserve further investigation to be verified.

All in all, Figure 1 presents the three populations and it appears that the tsunamigenic events (full shapes, excluding the Barcelona tsunami) are clustered above magnitude 6 and bounded by the distance of 100 km. The spread of data is strongly controlled by the tsunamis of 1068 and 1546, and thus the reliability and uncertainty of these events become critical and worth re-evaluation. Interestingly, not all the M>6 events that are closer than 100 km to the sea are tsunamigenic, suggesting that there could be some other factors that control tsunami generation by on-land earthquakes.

Table 8: Historical tsunamigenic and some non-tsunamigenic earthquakes in the Levent

Earthquake (year, month, day**)**	**DST** [a] **Region**	**Estimated magnitude** [b]	**Tsunami?** [c]	**Estimated distance from the sea** (km) [d]	**Source of data and comments** [e]
115 12 13	N	M_W=7.3	?	40	Ambraseys and Jackson (1998): Ms=Large. Guidoboni et al. (1994). Meghraoui et al. (2003): M_W=7.3-7.5, Surface rupture at Missyaf segment, Syria.
363 05 18-19	C	M= ~6.5? Ms=7.4	-	60 - 80	Ambraseys (2006): Ms=7.4. Guidoboni et al. (1994). Shalem (1956): 363 05 24, tsunami in southern Dead Sea.
551 07 09	N	Mw=7.5	551 07 09	0	Ambraseys and Jackson (1998): m. Ambraseys et al. (1994). Ambraseys (1962): "Many writers place… offshore from Lebanon. … us, however, suggest an epicenter in the Jordan Valley". Ambraseys (2006): Ms=7.3. Daëron et al. (2004): Mount Lebanon thrust. Guidoboni et al. (1994). Darawcheh et al. (2000): Roum Fault. Elias et al. (2007): Beirut thrust, Mw=7.5
746 01 18	C	Ms=7.0	746 01 18	60	Ambraseys (2005): 746 01 18. Ambraseys (2006): Ms=7.0. Amiran et al. (1994): 749 01 18. Guidoboni et al. (1994): 749 01 18. Karcz (2004). Marco et al. (2003): Surface rupture in Tiberias (western coast of the Sea of Galilee).
859 12 30 – 869 01 29	N	Ms=7.0	-	30 - 50	Ambraseys et al. (1994): 860 01. Amiran et al. (1994): 859 04 08. Ambraseys (2006): Ms=7.0. Antonopoulos (1980): "a large number of earthquakes prevailed in the east". Guidoboni et al. (1994). Akyuz et al. (2006).
1033 12 05	C	M=~6.5	1033 12 05	60 - 80	Ambraseys and Jackson (1998). Ambraseys et al. (1994). Amiran et al. (1994): 1033/4 winter, a swarm of earthquakes, including the strongest shock on 1033 12 10 and another on 1034 01 04. Probably in the Jordan Valley. Guidoboni and

					Comastri (2005): Me=6.0.
1068 03 18	S	M> 6.6	-	200	Ambraseys and Jackson (1998): L. Ambraseys et al. (1994): Northern Hejaz, near Tabuk (east of the Gulf of Aqaba and the Red Sea). Guidoboni and Comastri (2005): Aila (Elat, Aqaba, northernmost tip of Gulf of Aqaba), first of two events, Me=8.1. Amit et al. (1999), Zilberman et al. (2005): Surface rupture in the southern Arava Valley, M: 6.6-7.
1068 05 29	S-C	M=~6	1068 05 29	60 - 100	Ambraseys et al. (1994). Guidoboni and Comastri (2005): The second of two events, in Ramla, Me=6.0.
1138 10 11	N	M<7	-	60	Seismic sequence from 1138 10 until 1039 06, main-shock on 1138 10 11. Detailed discussion in Ambraseys (2004) and Guidoboni et al. (2004a). Ambraseys (2004): M<7. Guidoboni and Comastri (2005): Me=6.0.
1157 08 12	N	Ms=7.2	-	50	Detailed discussion in Ambraseys (2004), Guidoboni et al. (2004a). Ambraseys and Jackson (1998): V. Ambraseys (2006): Ms=7.2. Guidoboni and Comastri (2005). Possibly the strongest shock of the seismic sequence during 1157 08 09 – 09 07.
1170 06 29	N	Ms=7.3	-	50	Detailed discussion in Ambraseys (2004) and Guidoboni et al. (2004b). Ambraseys and Jackson (1998): L. Ambraseys (2006): Ms=7.3. Ambraseys et al. (1994). Meghraoui et al. (2003): M_W=7.3-7.5, Surface rupture at Missyaf segment, Syria. Guidoboni and Comastri (2005) also hypothesize, though not conclusively, the occurrence of two events rather than of one, Me=7.7.
1202 05 20	C-N	Ms=7.5	1202 05 20	30-50	Ambraseys and Barazangi (1989): Syria-Baalbek, Ms=7.5. Ambraseys and Jackson (1998): L. Ambraseys and Melville (1995). Ambraseys et al. (1994). Ambraseys (2006): Ms=7.2. Daëron et al. (2005): Yammouneh fault. Ellenblum et al. (1998). Guidoboni and Comastri (2005): Me=7.6. Marco et al. (1997, 2005): Surface rupture at Jordan Gorge

					(south of the Hula Valley) segment.
1212 05 01	S	Ms=7.0	-	100 - 200	Ambraseys et al. (1994): 1212 05 01 05 00. Ambraseys (2006): Ms=7.0. Ben-Menahem (1991): 1312 05 01 dawn, heavy destruction at St. Catherine Monastery (Sinai). Guidoboni and Comastri (2005): Me=5.8. Klinger et al. (2000): possible surface rupture in the northern Arava Valley, Mw~7.
1408 12 29	N	Ms=7.0	1408 12 29	30 - 40	Western Syria. Ambraseys and Barazangi (1989): Ms=~7. Ambraseys and Jackson (1998): m, 1408 12 29. Ben-Menahem (1991): 1408 12 30, near Allepo. Guidoboni and Comastri (2005): Me=6.0. Akyuz et al. (2006).
1458 11 08/16	S	Ms=7.1	-	120	Ambraseys et al. (1994): 1458 11 12. Ambraseys (2006): Ms=7.1. Guidoboni and Comastri (2005): Me=5.6. Klinger et al. (2000): Possible surface rupture in the northern Arava Valley, Mw~7.
1546 01 14	C	M_S= ~6.0	1546 01 14	60 – 80	Ambraseys and Karcz (1992): a medium magnitude event of M_S about 6.0, in many respects similar to that of the earthquake of 1927. Ambraseys et al. (1994): 1546 01 14 16 00. Amiran et al. (1994).
1759 10 30	C-N	Ms=6.6	1759 10 30	40 - 50	Ambraseys and Barazangi (1989): S. Bekaa (along the Yammaouneh fault), Ms=6.6. Amiran et al. (1994). Ben-Menahem (1991): seiche in Sea of Galilee. Daëron et al. (2005): Rachaiya fault. Marco et al. (2005): surface rupture at Jordan Gorge segment.
1759 11 25	N	Ms=7.5	1759 11 25	50 - 60	Ambraseys and Barazangi (1989): Syria-Bekaa, Ms=7.4. Ambraseys and Jackson (1998): L. Ambraseys (2006): Ms=7.5. Daëron et al. (2005): Serghaya fault. Gomez et al. (2001): Serghaya fault?
1796 04 26	N	Ms=6.6	-	20 - 40	Ambraseys and Barazangi (1989). Ambraseys and Finkel (1995). Ambraseys and Jackson (1998): Ms=6.6, Syria-

					Ladhikiya (Latakia). Ambraseys (1989).
1822 08 13	N	Ms=7.4	-	50	Ambraseys and Barazangi (1989): Ms=7.4. Aafrine, Turkey-Syria region, the East Anatolian fault where it joins the Dead Sea system. Ambraseys and Jackson (1998): Ms=7.5. Ambraseys (1989). Amiran et al. (1994).
1837 01 01	C-N	Ms=7.0	-	20 – 40	Ambraseys and Jackson (1998): Ms=7.4. Amiran et al. (1994). Ambraseys (2006): Ms=7.0. Ben-Menahem (1991): tsunami in the Sea of Galilee. Ambraseys (1997): Possibly the Roum fault, but no conclusive evidence. Nemer and Meghraoui (2006).
1872 04 03	N	Ms=7.2	1872 04 03	30 - 40	Ambraseys and Barazangi (1989): Ms=7.2, Amik Gulu, the East Anatolian fault where it joins the Dead Sea system. Ambraseys and Jackson (1998), Ambraseys (2006): Ms=7.2. Ambraseys (1989). Ambraseys (2006): Ms=7.0. Akyuz et al. (2006).

The list relates to all the known historical tsunamigenic earthquakes of the Levant as well as to earthquakes for which some estimates of the source parameters appear in the literature. The table and the data were modified from the Electronic Supplement to Salamon et al. (2007).

[a] Location of the earthquakes along the DST system, not necessarily on the main transform: N: northern part, in Syria and Lebanon; C: central part, in Israel, from the Hula Valley to the Dead Sea; S: southern part, in Israel, Arava Valley and southwards.

[b] Estimated magnitudes were taken from historical, geological and paleoseismological studies. If not available, the size was estimated according to best judgment.

[c] The tsunami associated with this earthquake.

[d] Estimated distance of the assumed surface rupture from the Mediterranean Sea, in km. Location of surface rupture adopted from paleoseismological studies, and if not available by best judgment.

[e] ‘Me’: “equivalent magnitude value”, refer to Guidoboni and Comastri (2005) for explanation.

Table 9 **Significant modern tsunamigenic and non-tsunamigenic earthquakes recorded in the eastern Mediterranean**

Earthquake	Magnit.	Region	distance from the Med. (km)	Mechanism	Tsunami?	Source of data and comments
1918 09 29 12:07	M_s=6.3	Between Cyprus and northwest Syria, in the Mediterranean	0	Not known	-	Ambraseys and Adams (1993).
1927 07 11 13:04	M_L=6.2	Dead Sea – Jericho, on land	80	Shear?	Dead Sea, Mediterranean?	Ben-Menahem et al. (1976). Shalem (1956): ‘Probably unclear’ tsunami in the Mediterranean sea.
1953 09 10 04:06	M_L=6.2	Southwestern Cyprus, in the Mediterranean	0	Shear	A series of tidal waves in Cyprus	International Seismological Center (2009). Papazachos and Papaioannou (1999). Soloviev et al. (2000).
1955 09 12 06:09	M_L=6.1	Southeast Mediterranean, in the sea	0	Thrust	-	Shalem (1956): No signal found on mareogram at Haifa Bay. Salamon et al. (2003).
1956 03 16 19:32 1956 03 16 19:43	M_L=5.2 M_L=5.5	Southern Lebanon, on land	20	Shear Shear	-	Shalem (1956): No signal found on mareogram at Haifa Bay. Salamon et al. (2003).
1983 06 12 12 00	M_L=5.4	Gulf of Suez, in the sea	180	Normal	-	International Seismological Center (2009).
1984 08 24 06 02	M_L=5.3	Yizre'el Valley, between the Med. and the DST	20	Transpression	-	International Seismological Center (2009).
1969 03 31 07:16	M_L=6.6, mb=7.0	Gulf of Suez, in the sea	350	Normal	-	International Seismological Center (2009). McKenzie et al. (1970).
1992 10 12 13:09	mb=5.9	Cairo, on land	180	Normal	-	International Seismological Center (2009). Casualties and severe damage in parts of Cairo.
1995 11 22 04 15	Mw=7.1	Gulf of Elat (Aqaba), in the sea	250	Shear	In the Gulf of Elat	International Seismological Center (2009). Wust (1997).
2004 02 11 08 15	M_L=5.2 M_w=5.2	Northeastern Dead Sea	80	Transpression	-	Geophysical Institute of Israel (2009).

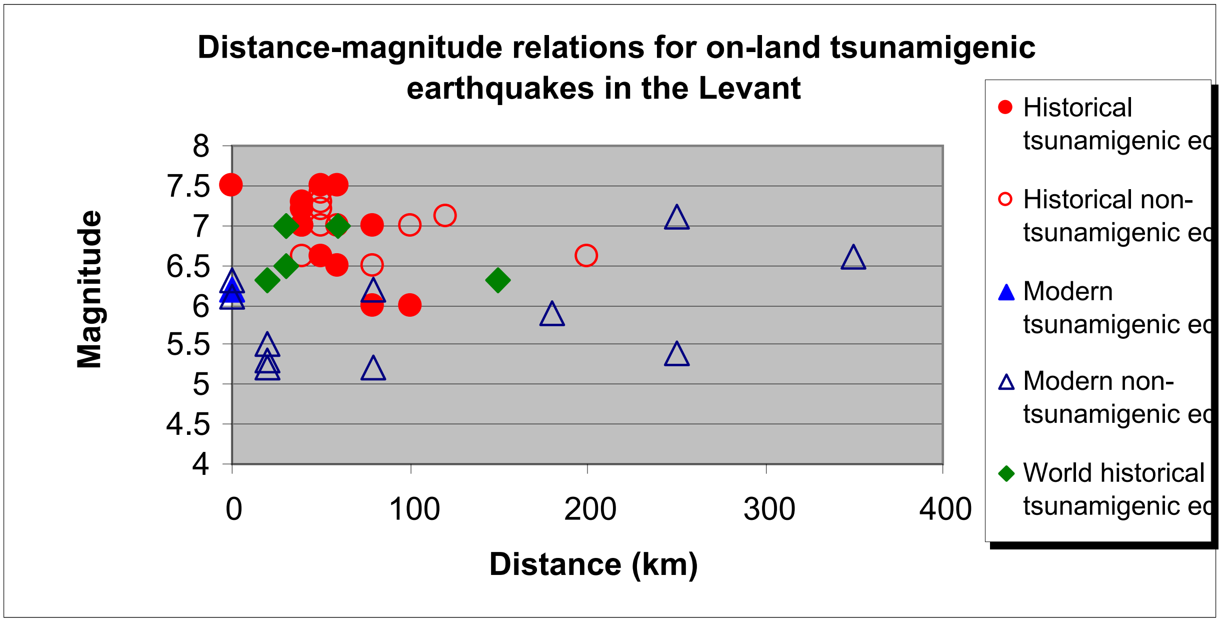
Table 10: Historical on-land tsunamigenic earthquakes in the world

The earthquake (year, month, day, hour)	**Region of the earthquake and the tsunami**	**Estimated earthquake magnitude** [a]	**Estimated distance from the sea** (km) [b]	**Source of data and comments**
1169 02 04	Earthquake in Catania, eastern Sicily (Italy) and a tsunami in Catania, Ionian Sea	Me=6.3	20	Guidoboni and Comastri (2005)
1373 03 03 02	Earthquake in central Pyrenees-Catalonia (Spain) and a tsunami in Barcelona, Mediterranean Sea	Me=6.3	150	Guidoboni and Comastri (2005)
1456 12 05 03	Earthquake in central Italy and a tsunami in Naples, Tyrrhenian Sea	Me=7.0	60	Guidoboni and Comastri (2005), event no. 312.
1812 12 21	Earthquake possibly in the Ventura Basin northwest of Los Angeles and a tsunami in Santa Barbara, California	Mw > 7	30	Chowdhury et al. (2005). Dolan and Rockwell (2001) suggest an earthquake on land, Topozzada and Branum (2004) suggest an offshore event.
1865 10 08	Earthquake in the Santa Cruz Mountains and a tsunami in Santa Cruz, California	6.5	30	Chowdhury et al. (2005). Topozzada and Branum (2004)
1868 10 21	Earthquake on the Hayward fault and a tsunami in San Francisco, California	7.0	30	Chowdhury et al. (2005). Topozzada and Branum (2004)

[a] ‘Me’: “equivalent magnitude value”, refer to Guidoboni and Comastri (2005) for explanation.

[b] Estimated distance of the assumed earthquake epicenter from the sea, in km.

Figure 1 **Distance-Magnitude relations for on-land tsunamigenic earthquakes in the Levant**



4.3.2 The modified decision matrix

Given the distance and magnitude threshold for on-land tsunamigenic earthquakes in the Levant, it is now possible to modify the NEAMTWS decision matrix for the conditions in Israel (Table 11, the modifications are highlighted in yellow). Threshold distance is increased to 100 km and a new row is added in order to introduce a message of tsunami information, advisory and watch in the case of a local tsunami. Testing the matrix against the historical events again, they are all covered now and none escape unnoticed except the non-earthquake tsunamis (Table 1).

For simplicity, the modified matrix is presented also in Table 12 by the tsunami message type, according to the keywords recommended by the NEAMTWS. It is now clear which type of message should be issued, should any type of a tsunamigenic earthquake occur.

Table 11: Modified decision matrix for Israel, tested against the historical events

Depth	Location	(Mw)	Tsunami Potential	Bulletin Type	Validation test for the Levant (Israel)
< 100 km	Sub-sea or very near the sea (< 100 km)	**5 to 5.5**	Negligible potential for a local tsunami	**Information Bulletin**	**-**
		5.5 to 6.0	Small potential for a local tsunami	**Local Tsunami Advisory**	**-**
		6.0 to 6.5	Potential for a destructive local tsunami < 100 km	**Local Tsunami Watch, Regional Tsunami Advisory**	**115?, 551, 746, 802, 1033, 1036, 1068, 1222, 1408, 1546, 10/1759, 1872, 1953**
		6.5 to 7.0	Potential for a destructive regional tsunami < 400 km	**Local Tsunami Watch, Regional Tsunami Watch, Basin-wide Tsunami Advisory**	**1202, 11/1759, 1870**
		≥ 7.0	Potential for a destructive basin-wide tsunami > 400 km	**Local Tsunami Watch, regional Tsunami Watch, Basin-wide Tsunami Watch**	**365, 1303, 1908, 1956**
	Inland (> 100 km)	**5.5 – 7.5**	No tsunami potential	**Information Bulletin**	
≥ 100 km	All locations	**≥ 5.5**	No tsunami potential	**Information Bulletin**	

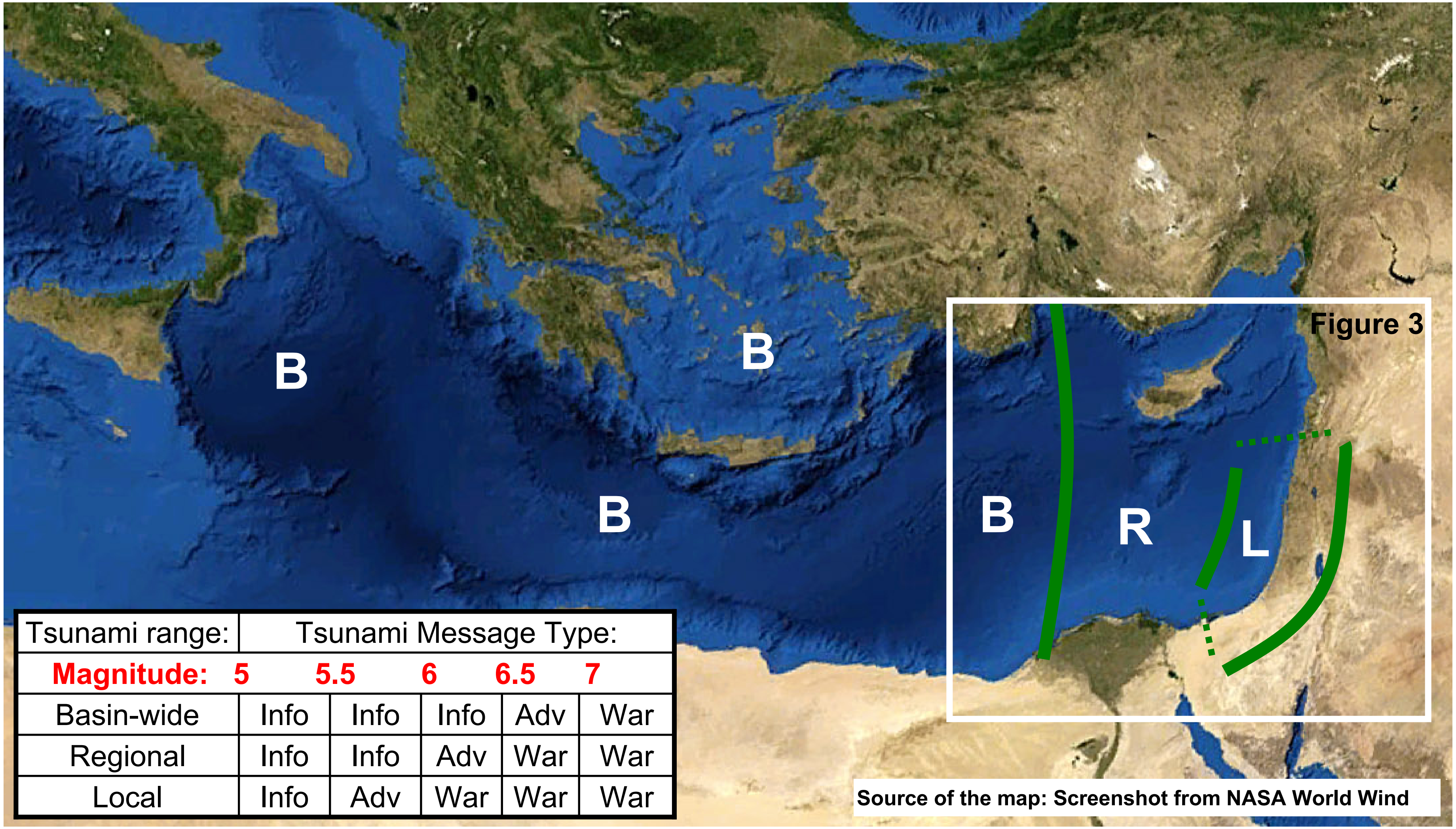
Table 12: The modified decision matrix for Israel, by the type of the tsunami message

Depth	Location	(Mw)	Tsunami Potential	Tsunami Message Type		
				Local	**Regional**	**Basin-wide**
< 100 km	Sub-sea or very near the sea (< 100 km)	**5 to 5.5**	Negligible potential for a local tsunami	**Information**	**Information**	**Information**
		5.5 to 6.0	Small potential for a local tsunami	**Advisory**	**Information**	**Information**
		6.0 to 6.5	Potential for a destructive local tsunami < 100 km	**Watch**	**Advisory**	**Information**
		6.5 to 7.0	Potential for a destructive regional tsunami < 400 km	**Watch**	**Watch**	**Advisory**
		≥ 7.0	Potential for a destructive basin-wide tsunami > 400 km	**Watch**	**Watch**	**Watch**
	Inland (> 100 km)	**5.5 – 7.5**	No tsunami potential	**Information**	**Information**	**Information**
≥ 100 km	All locations	**≥ 5.5**	No tsunami potential	**Information**	**Information**	**Information**

As the matrix is specific to Israel, the location of the potential tsunamigenic events should relate to the Israeli coast. This is presented in Figures 2 and 3. There are three hazard zones on the maps:

- Local (L) - the area vulnerable to earthquakes which may trigger a local tsunami that may affect Israel;
- Regional (R) - the area vulnerable to earthquakes which may trigger a regional tsunami that may affect Israel;
- Basin-wide (B) - the area vulnerable to earthquakes which may trigger a basin-wide tsunami that may affect Israel.

The threshold magnitude for each type of a message set for each of these regions is presented on the map, according to the modified decision matrix (Table 12). Should an event with a magnitude larger than stated occur, a tsunami alert will be issued accordingly. For smaller earthquakes only a tsunami information message is needed.

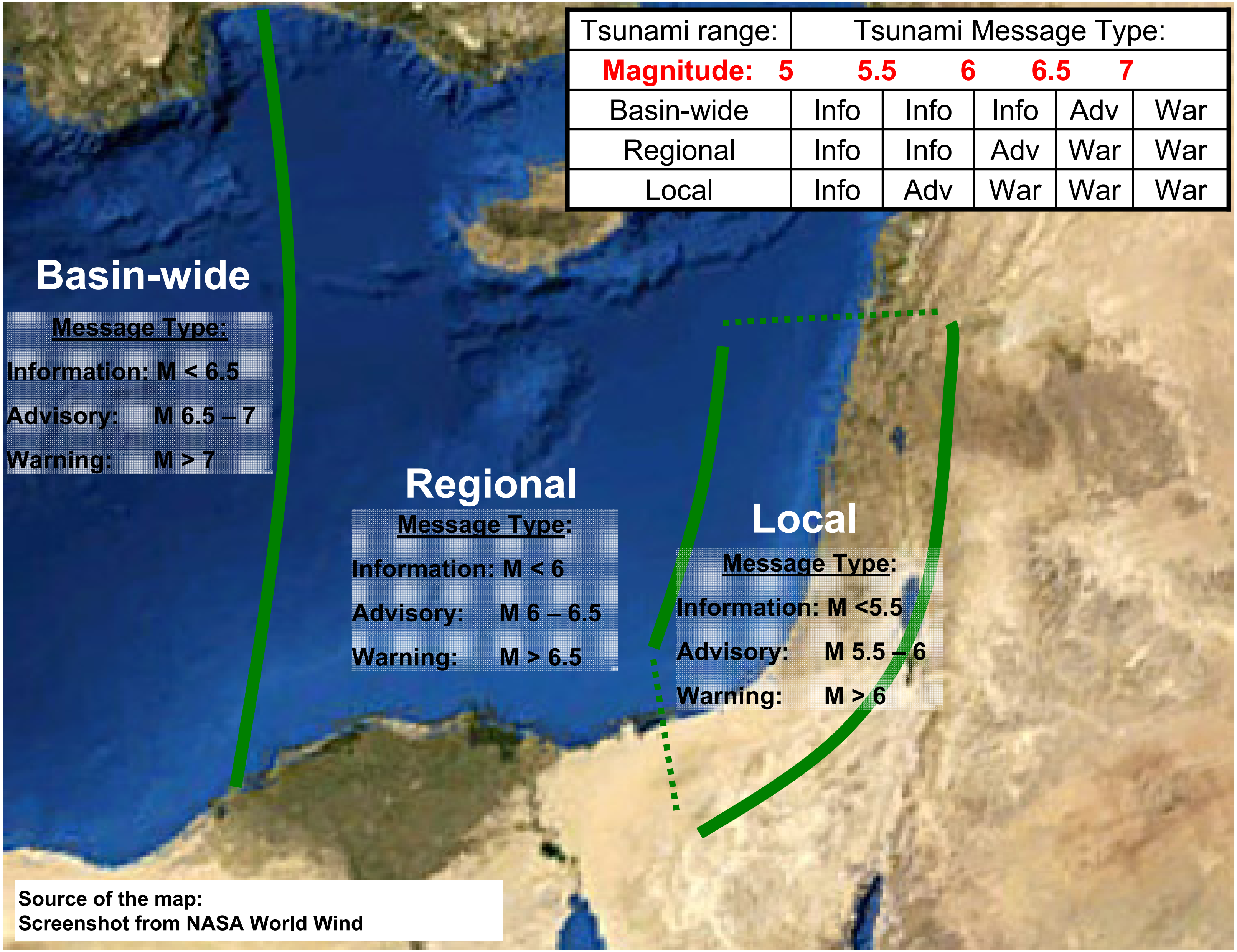


Tsunami range:	Tsunami Message Type:				
Magnitude:	**5**	**5.5**	**6**	**6.5**	**7**
Basin-wide	Info	Info	Info	Adv	War
Regional	Info	Info	Adv	War	War
Local	Info	Adv	War	War	War

Source of the map: Screenshot from NASA World Wind

Figure 2: Threshold magnitude zones for tsunami early warning in Israel, location map

The type of message presented on the map follows the modified decision matrix (Table 12). See Figure 3 for details



Tsunami range:	Tsunami Message Type:				
Magnitude: 5	5.5	6	6.5	7	
Basin-wide	Info	Info	Info	Adv	War
Regional	Info	Info	Adv	War	War
Local	Info	Adv	War	War	War

Source of the map:
Screenshot from NASA World Wind

Figure 3: Threshold magnitude zones for tsunami early warning in Israel, detailed map

The type of message presented on the map follows the modified decision matrix (Table 12).

5 Conclusions

The decision matrix formulated in this work enables issuing a tsunami warning to Israel as soon as the preliminary source parameters (magnitude, location and depth) of the earthquake that has just occurred are calculated. The matrix is based on worldwide experience and conforms to the NEAMTWS recommendation. It was also modified according to the specific seismotectonic setting and the bathymetry of the eastern Mediterranean, and calibrated with the reported historical and recorded modern events that occurred in the Levant (Table 12 and Figures 2 and 3).

The first stage of this work concentrated on reconstructing the tsunamigenic scheme of the eastern Mediterranean. It was found that earthquakes are the major threat for far, basin-wide tsunamis, and submarine landslides should be of great concern for near, local tsunamis. Significant basin-wide tsunamis that may reach to the Levant from afar may originate from strong earthquakes (M~8) in the Hellenic Arc and possibly also in the Cypriot Arc. Interestingly, most of the tsunamis that affected Israel in the past followed on-land earthquakes along the DST, which stresses the role of submarine slumps along the continental slope of the Levant in the generation of the local tsunamis. Potentially, there are also tsunamigenic faults near the Levant coast such as the Beirut thrust, and large tsunamigenic marine slumps far away from the Levant such as in the Nile Cone and the Etna volcano in Sicily. These are also covered by the decision matrix.

The present tsunami warning system is planned to rely on the evaluation of seismic data and therefore tsunamis originating from non-earthquake generators are not covered. Thus, alerting volcanic and spontaneous tsunamis is not considered in the present decision matrix. Introducing real-time monitoring of sea level into the warning system will require modification of the matrix.

Overall, the matrix will support both alerts coming from any Regional Tsunami Watch Center (RTWC) of the NEAMTWS, as well as issuing an independent alert by the National Tsunami Warning Center (NTWC) of Israel.

5.1 Education – the already available tsunami warning system

The repeat time of destructive tsunamis in Israel is long and most chances (80%) are that the tsunami will arrive a few minutes after the earthquake. There are many technological difficulties in preparing and maintaining the warning system, and many uncertainties in issuing and sending a reliable tsunami alert that will reach the authorities in charge and the target population in real time.

Since most of the tsunamis that may affect Israel will probably originate from earthquakes along the DSFS, and the relevant events are expected to reach M6 and above, the first warning signal will be the strong seismic shaking. Therefore, there is no need to wait until a sophisticated warning system is put into operation and people should be taught to protect themselves from a tsunami by moving away from the sea as soon as they feel the strong shaking. The second warning signal, although it may not always appear, is the retreat of the sea. Indeed, some tsunamis may arrive from remote sources that will not be strongly felt in Israel, but these are the minority of events.

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Appendix 1 Structural elements of the tsunami warning system

The following presents the recommended requirements for the structure and roles of the tsunami warning centers to be integrated within the NEAMTWS. It is taken from: "*Interim operational users guide for the tsunami early warning and mitigation system in the north-eastern Atlantic, the Mediterranean and connected seas (NEAMTWS)*", Version 1.1g, http://www.ioc-unesco.org/index.php?option=com_oe&task= viewDocument Record&docID=4516.

2.3 STRUCTURAL ELEMENTS OF THE TWS

Regional Tsunami Watch Centers (RTWCs), Tsunami National Contacts (TNCs), Tsunami Warning Focal Points (TWFPs) and National Tsunami Warning Centers (NTWCs) are basic structural elements of the TWS in the NEAM region. The functions of such components of the NEAMTWS have been adopted by the ICG at the second session of the NEAMTWS held in Nice, 22-24 May 2006. Member States nominated TNCs and TWFPs according to a specific form (Annex II).

2.3.1 Tsunami National Contact (TNCs)

The person designated by an ICG Member State government to represent his/her country in the coordination of international tsunami warning and mitigation activities. The person is part of the main stakeholders of the national tsunami warning and mitigation system program. The person may be the Tsunami Warning Focal Point, from the national disaster management organization, from a technical or scientific institution, or from another agency with tsunami warning and mitigation responsibilities.

2.3.2 Tsunami Warning Focal Point (TWFP)

The Tsunami Warning Focal Point (TWFP) is a 7x24 contact person, or other official point of contact or address designated by a government, available at the national level for rapidly receiving and issuing tsunami event information (such as warnings). The Tsunami Warning Focal Point either is the emergency authority (civil defense or other designated agency responsible for public safety), or has the responsibility of notifying the emergency authority of the event characteristics (earthquake and/or tsunami), in accordance with national standard operating procedures. The Tsunami Warning Focal Point receives international tsunami warnings from the NEAMTWS or other regional warning centers. The TWFP contact information requires 7x24 telephone, facsimile, or e-mail information. The TWFP may be contacted for clarification concerning the designated communication method or in an emergency if all designated communication methods fail.

- Reception of the messages transmitted by the Regional Tsunami Watch Centers
- Evaluate and issue national warnings in accordance with the National Emergency Plan
- Transmission of warning messages to the National Emergency Authorities

- Operating 24/7

2.3.3 Regional Tsunami Watch Centers (RTWCs)

- Collection, record, processing and analysis of earthquake data for the rapid initial assessment (locate the earthquake, the depth, the magnitude, the origin time) as a basis for the alert system
- Computing the arrival time of the tsunami in the forecasting points listed in the Communication Plan
- Collection, record, processing and analysis of sea level data for confirming and monitoring the tsunami or for canceling elements of the alert system
- A decision making process in accordance with the Communication Plan to elaborate messages
- Dissemination to the Member States focal points (and national warning centers) of the messages in accordance with the Communication Plan, included the tsunami travel time, the amplitude and period of tsunami measured, and cancellation messages

2.3.4 National Tsunami Warning Centers (NTWCs)

- Collect, record, and process earthquake data for the rapid initial warning (locate the earthquake, the depth, the magnitude, the origin time)
- Compute the arrival time of the tsunami in the national forecasting points
- Collect, record, and process sea level data for confirming or cancelling the warning

Warning Centers strive to be:

- Rapid, by providing warnings as soon as possible after a potential tsunami generation
- Accurate, by issuing warnings for all destructive tsunamis while minimizing false warnings
- Reliable, by making sure they operate continuously, and that their messages are sent and received promptly and understood by the users of the system.

2.3.5 Backup and Data Collection Centre

- Collect seismic real-time data from public and private sources over Internet and private VSAT hub including the data streams from the dedicated VSAT backbone seismic network
- Operate a global earthquake monitoring system issuing very rapidly automatic solutions

- Provide SeisComP3 software to the RTWCs and to organize operational support
- Provide the collected real-time data feeds and automatic and manual processing results to the RTWCs
- Provide rapid access to its comprehensive seismic data archive of EuroMed and global data
- Provide a platform for the rapid internal exchange of seismic processing results among the RTWCs

2.4 USERS GUIDE RESPONSIBILITIES

The fifth session of the ICG/NEAMTWS (Athens, 3–5 November 2009) adopted roles, requirements and performance indicators for RTWCs and NTWCs, in addition to the roles of TWFPs, as follows. Mandatory requirements are indicated in bold (Table 2-2).

Table 2-2 Roles and requirements for RTWCs, NTWCs and TWFPs

Regional Tsunami Watch Centers (RTWCs)	National Tsunami Warning Centers (NTWCs)	Tsunami Warning Focal Points (TWFPs)
Roles and requirements	Recommended roles and performances	Roles
Watch	**Warning**/Watch	**Warning**
• Reception and interpretation of RT seismic and sea-level measurements **• Determination of seismic parameters** **• Forecasting of tsunami arrival times and level of alert at each forecasting point specified by MS** **• Exchange seismic parameters and information with other RTWCs and NTWCs** **• Disseminate watch and cancellation messages based on the alert-level decision matrix to NTWCs and the TWFPs** **• Monitoring of tsunami propagation and disseminate updated information in priority tsunami amplitude measurements** **• Capability of acting as a backup centre to other RTWCs** **• Function as a NTWC**	• Reception and interpretation of RT seismic & sea level measurements **• Reception of RTWC messages** **• Dissemination of warning and cancellation messages to national authorities according to the national response plan** • Monitoring tsunami propagation and update information to national authorities • Determination of seismic parameters • Forecasting of tsunami arrival time, amplitude and run-up for the national coastline • Provision of information to other national TWCs and RTWCs **• Acting as National Tsunami Warning Focal Point (TWFP)**	**• Reception of the messages transmitted by the Regional Tsunami Watch Centers** **• Evaluate and issue national warnings in accordance with the National Emergency Plan** **• Transmission of warning messages to the National Emergency Authorities**

Regional Tsunami Watch Centers (RTWCs)	**National Tsunami Warning Centers (NTWCs)**	**Tsunami Warning Focal Points (TWFPs)**
Roles and requirements	**Recommended roles and performances**	**Roles**
Above and beyond watch time • Monthly tests of the watch system • Procedures and documentation • Regional tsunami exercises • Conduct training courses with other RTWCs and IOC • Participate actively and report to the ICG and WGs	**Above and beyond watch time** • **National Tsunami Emergency Plan** • **National Procedures (SOP), documentation** • National tsunami exercices • Catalogue of inundation scenarios • National tsunami data base	
Requirements • **Seismic as well as tsunami/oceanographic expertise** • **Direct access to a tsunami and large earthquakes data base** • **Real-time transmission systems for reception of data** • **Real-time alert reception and transmission systems like GTS, Internet…** • **Backup/independent power supply** • **Permanent staff on 24/7 watch** • **Tsunami modeling capacity to produce and update canned scenarios**	**Requirements** • Seismic as well as tsunami/oceanographic expertise • Access to tsunami & large earthquakes data base • Real-time transmission systems for reception of data • **Real-time alert reception system - e.g. GTS** • **Backup/independent power supply** • Permanent staff on 24/7 watch • Inundation modeling capacity	**Requirements** • **Operating 24/7**

הלאומי של ישראל, אשר יופעל באגף סיסמולוגיה שבמכון הגיאופיסי לישראל (בעתיד במסגרת המנהל החדש למדעי הים והאדמה בישראל).

"טבלת ההחלטה" לצונאמי בחופי הים התיכון של ישראל

סוג ההתרעה			הפוטנציאל לצונאמי	מגניטודה (Mw)	מיקום המוקד	עומק המוקד
צונאמי אגני	צונאמי מרחבי	צונאמי מקומי				
מידע	מידע	מידע	פוטנציאל זניח לצונאמי מקומי	5 - 5.5	בים או בקרבתו, עד למרחק של 100 - 80 ק״מ מהחוף	פחות מ- 100 ק״מ
מידע	מידע	עצה	פוטנציאל נמוך לצונאמי מקומי	5.5 - 6.0		
מידע	עצה	אזהרה	פוטנציאל לצונאמי מקומי הרסני < 100 ק״מ	6.0 - 6.5		
עצה	אזהרה	אזהרה	פוטנציאל לצונאמי אזורי הרסני < 400 ק״מ	6.5 - 7.0		
אזהרה	אזהרה	אזהרה	פוטנציאל לצונאמי אגני הרסני > 400 ק״מ	≥ 7.0		
מידע	מידע	מידע	אין פוטנציאל לצונאמי	5.5 - 7.5	ביבשה, במרחק העולה על 100 ק״מ מהחוף	
מידע	מידע	מידע	אין פוטנציאל לצונאמי	≥ 5.5	בכל מקום	מעל 100 ק״מ

מונחים:

צונאמי מקומי: Local, טווח ההשפעה שלו עד 100 ק״מ; צונאמי מרחבי: Regional, טווח השפעה 100 - 400 ק״מ; צונאמי אגני: Basin, טווח השפעה מעל 400 ק״מ; מידע: Information; עצה: Advisory; אזהרה: Watch.

מרבית (כ-80%) ממקרי הצונאמי בישראל, התרחשו לאחר רעידות אדמה יבשתיות, שחלו במערכת ההעתקים של בקע ים המלח. המגניטודה ברעידות אלה הייתה ככל הנראה בדרגה 6 ומעלה. מכאן שקיימת סבירות גבוהה שסימן ההתרעה הראשון לצונאמי בישראל יהיה זעזוע סיסמי חזק.

לפיכך מומלץ כבר כעת, עוד בטרם שתופעל מערכת התרעה מתוחכמת לצונאמי, להדריך את הציבור הרחב להתרחק מהים מיד במקרה שיורגש זעזוע סיסמי חזק. סימן ההתרעה נוסף אשר יופיע רק בחלק מהמקרים, הוא ירידת מהירה במפלס פני הים ונסיגה חריפה של קו המים מערבה. אפשרות נוספת שקיימת, אם כי נדירה יותר, היא שצונאמי יגיע לישראל מרחוק, מבלי שרעידת האדמה שיצרה אותו תורגש וללא נסיגה מקדימה של קו המים.

העבודה הנוכחית נעשתה במסגרת ועדת ההיגוי הבין-משרדית להיערכות לרעידת אדמה בישראל, חוזה מס׳ 28-02-014, והיא משלימה את דוח המכון הגיאולוגי מס׳ GSI/24/2009 בנושא ״מפת האזורים המועדים להצפה מצונאמי לאורך חופי הים התיכון של ישראל במפרץ חיפה, גוש דן, אשדוד ואשקלון״ (סלמון, 2009).

תקציר

הכרת הגורמים היכולים לגרום להתפתחות צונאמי במזרח הים התיכון מסייעת לבנות ״טבלת החלטה״ (Decision matrix) אשר על פיה ניתן לקבוע מיד לאחר רעידת אדמה האם היא מסוגלת ליצור צונאמי ובמידת הצורך לפרסם התרעה מוקדמת. טבלה מסוג זה נבנתה על-ידי קבוצת התיאום הבין-ממשלתית של מדינות צפון מזרח האוקיאנוס האטלנטי ומדינות הים התיכון והימים המקושרים אליו (IGC/NEAMTWS, 2009) הפועלת בחסות אונסקו (UNESCO), לצורך הקמת מערכת התרעה מוקדמת לצונאמי. הטבלה משקפת את הניסיון שנצבר בעולם ומתמקדת ברעידות אדמה חזקות אשר מסוגלות ליצור צונאמי מרחבי (Regional) ואגני (Basin-wide) בים התיכון. אולם, מתברר שמרבית אירועי הצונאמי שקרו באזור הלבנט הם בעלי היקף מקומי (Local) בלבד ועל כן הם מחוץ לתחום האחריות של מערכת ההתרעה הים תיכונית, וצריכים להיות מטופלים על-ידי השלטונות המקומיים. העבודה הנוכחית מגשרת על פער זה ומציעה ״טבלת החלטה״ התואמת במבנה שלה את דרישות המערכת הים תיכונית ובה בעת מותאמת גם לתנאים הייחודיים בישראל, לרבות הצורך להתייחס לצונאמי כתוצאה מגלישות תת ימיות במדרון היבשת של ישראל.

בשלב הראשון של העבודה הוגדרה מערכת הגורמים לצונאמי במזרח הים התיכון, העלולים לפגוע בחוף הלבנט. נמצא שרעידות אדמה חזקות במגניטודה 8 לערך, שמקורן בקשת ההלנית ואולי אף בקשת הקפריסאית, הן הגורם המאיים העיקרי לצונאמי אגני אשר עלול להגיע לישראל מרחוק. במקביל התברר שמרבית אירועי הצונאמי שפגעו בישראל היו בעלי השפעה מקומית בלבד והם התרחשו דווקא לאחר רעידת אדמה יבשתית, שמקורה היה ככל הנראה במערכת ההעתקים של בקע ים המלח. משמעות הדבר היא שגלישות קרקע תת-ימיות שנגרמות מהזעזוע הסיסמי, הן מקור הדאגה העקרי לצונאמי מקומי קרוב בחופי ישראל. חשוב לציין שקיימים גם העתקים יוצרי צונאמי קרובים לישראל כדוגמת העתק ביירות, וכן קיימות גלישות קרקע תת-ימיות רחוקות כמו למשל בדלתא של הנילוס ובהר האטנה בסיציליה, אשר בכוחן לגרום לצונאמי שיגיע לישראל.

בהמשך נבחנה ״טבלת ההחלטה״ שהוצעה על-ידי קבוצת התיאום של מדינות הים התיכון ונמצא שהיא מכסה רק חלק מגורמי הצונאמי הללו ומחטיאה את מרבית אירועי הצונאמי ההיסטוריים שהתרחשו לאחר רעידת אדמה יבשתית, שמוקדה רחוק יותר מ-30 ק״מ מחופי ישראל. לפיכך בעבודה זו נערך כיול (מסומן בצהוב בטבלה שלהלן) על בסיס מיקומן המשוער של רעידות אדמה ההיסטוריות הללו, כך שתנאי הסף לרעידה יבשתית מחוללת צונאמי יהיו מרחק מרבי מהים של כ-100 ק״מ ומגניטודה מינימלית M ~6.

מאחר ומערכת ההתרעה לצונאמי תתבסס בשנים הראשונות על מידע סיסמולוגי בלבד, היא לא תוכל לכסות אירועי צונאמי שאינם קשורים לרעידות אדמה. על כן היכולת להתריע בפני צונאמי ממקור וולקני או אירועים ספונטניים, תתאפשר רק כאשר מידע על גובה מפלס הים ישולב במערכת ההתרעה לצונאמי באופן שוטף ובזמן אמת.

לסיכום, ״טבלת ההחלטה״ והמפות הנלוות אליה (איורים 2, 3 אחרי עמ׳ 35 בדוח זה) המוצעים להלן, יאפשרו להוציא התרעה לצונאמי בישראל מיד לאחר שתתקבל הערכה ראשונית לגבי מימדי הרעידה שהתרחשה (מגניטודה, מיקום ועומק). הטבלה תתמוך הן בהתרעות לצונאמי מרחבי ואגני שיתקבלו ממרכזי ההערכה האזוריים בים התיכון והן במתן התרעות לצונאמי מקומי שיתקבלו במרכז ההערכה

משרד התשתיות הלאומיות
המכון הגיאולוגי

מקורות אפשריים לצונאמי במזרח הים התיכון וטבלת החלטה עבור מערכת התרעה לצונאמי בישראל

עמוס סלמון

מוגש לועדת ההיגוי להיערכות לרעידות אדמה

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