# ADDRESSING CHALLENGES AND REQUIREMENTS FOR LOCAL TSUNAMI AWARENESS, WARNING AND MITIGATION: A "LAST MILE" CASE STUDY FOR BODRUM-TURKEY

**Necmioğlu Ö.[1], Yalçıner A.C.[2], Kalafat D.[1], Süzen L.[3], Tanırcan G.[4], Annunziato A.[5], Santini M.[6], Güney Doğan G.[7], Tüfekçi Enginar D.[8], Güneş Y.[9],Yelkenci Necmioğlu S.[10], Bali S.[11], Özener H.[12]**

[1] *Dr., Kandilli Observatory and Earthquake Research Institute, Boğaziçi University, İstanbul*
[2] *Prof. Dr., Department of Civil Engineering, METU, Ankara*
[3] *Prof. Dr., Department of Geological Engineering, METU, Ankara*
[4] *Assoc. Prof. Dr., Earthquake Engineering Department-KOERI, Boğaziçi University, İstanbul*
[5] *Dr., European Commission – Joint Research Centre, Ispra*
[6] *Expert of the Italian Civil Protection Department seconded to the , European Commission – Joint Research Centre, Ispra*
[7] *Project Assistant., Department of Civil Engineering, METU, Ankara*
[8] *Res. Ass., Department of Geological Engineering, METU, Ankara*
[9] *Eng., Kandilli Observatory and Earthquake Research Institute, Boğaziçi University, İstanbul*
[10] *Dr., Kandilli Observatory and Earthquake Research Institute, Boğaziçi University, İstanbul*
[11] *Civil Engineer, Bodrum*
[12] *Prof. Dr., Geodesy Department-KOERI, Boğaziçi University, İstanbul*
*Email: birgore@boun.edu.tr*

## ABSTRACT:

Kandilli Observatory and Earthquake Research Institute's (KOERI) Regional Earthquake and Tsunami Monitoring Center (RETMC) is an accredited 24/7 operational National Tsunami Warning Centre for Turkey under the Intergovernmental Coordination Group for the Tsunami Early Warning and Mitigation System in the North-eastern Atlantic, the Mediterranean and connected seas (ICG/NEAMTWS) initiative, providing services to Eastern Mediterranean and its Connected Seas since 2012. The 20 July 2017 Bodrum-Kos (Mw 6.6) earthquake and resulted tsunami with the nearshore maximum water elevations around 30-40 cm and maximum run-up of 1.9 m was a wake-up call for the NEAMTWS and a bitter reminder for the need to address local and near-field tsunami warning in the Eastern Mediterranean. Simulations indicated that the nearshore maximum water elevations could have been doubled if the Mw would have been 6.8, which is not an unlikely scenario for the Bodrum-Kos area. In addition to that, tsunami could have resulted in loss of lives if the earthquake would have happened during the day-time in the middle of the high-touristic season. To address local/near-field tsunami warning, awareness and preparations, the European Commission (EC) funded a new project through the EC-Joint Research Center (JRC) and involving KOERI and Middle East Technical University (METU), in close connection with a wide range of local stake-holders. In this context a collaborative action "Last Mile - Bodrum" for the installation of a local earthquake monitoring-tsunami warning system, preparation of high-resolution tsunami inundation and evacuation maps, and awareness and preparations activities, such as seminars, workshops and a tsunami exercise in Bodrum to be realized all in 2019. This presentation will focus on the achievements of this initiative, as an example of pilot local-tsunami mitigation system.

**KEYWORDS:** tsunami, early warning, Bodrum-Kos Earthquake

## 1. TSUNAMI WARNING SYSTEM FOR TURKEY AND ITS SURROUNDINGS

An overview of historical tsunamis in an around Turkey and history of the establishment of a Tsunami Warning System serving Turkey and its surroundings can be found in Ozel et al., 2011. A large set of historical studies reveal also clear evidence for the so far underestimated tsunami hazard in the region (Altınok and Ersoy, 2000; Altınok et al., 2011; Ambraseys, 2009; Fokaefs and Papadopoulos, 2009; Guidoboni and Comastri, 1997; Okal et al, 2004; Papadopoulos at al., 2007; Solovev et al., 2000; Yalçıner et al., 2004). A comprehensive assessment of tsunami hazard in the same area based on a large set of deterministic tsunami scenarios is available in Necmioglu and Ozel, 2015. Results from 2,415 scenarios show that in the Eastern Mediterranean and its connected seas (Aegean and Black Sea), shallow earthquakes with Mw ≥ 6.5 may result in coastal wave heights of 0.5 m, whereas the same wave height would be expected only from intermediate-depth earthquakes with Mw ≥ 7.0. The distribution of maximum wave heights calculated indicate that tsunami wave heights up to 1 m could be expected in the northern Aegean, whereas in the Black Sea, Cyprus, Levantine coasts, northern Libya, eastern Sicily, southern Italy, and western Greece, up to 3-m wave height could be possible. Crete, the southern Aegean, and the area between northeast Libya and Alexandria (Egypt) is prone to maximum tsunami wave heights of > 3 m. Considering that calculations were performed at a minimum bathymetry depth of 20 m in this study, these wave heights may, according to Green's Law, be amplified by a factor of 2 at the coastline.

KOERI-RETMC is the 24/7 operational National Tsunami Warning Centre for Turkey accredited by the ICG/NEAMTWS in 2016, providing tsunami warning services to Eastern Mediterranean, Aegean, Marmara and Black Seas since 1 July 2012 (Figure 1).

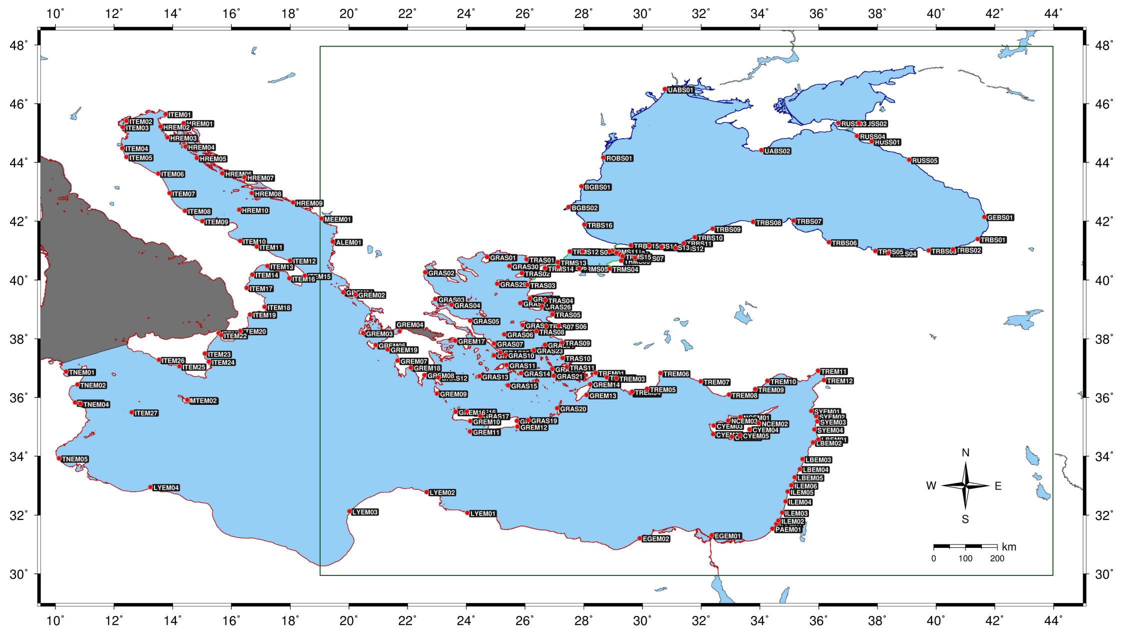
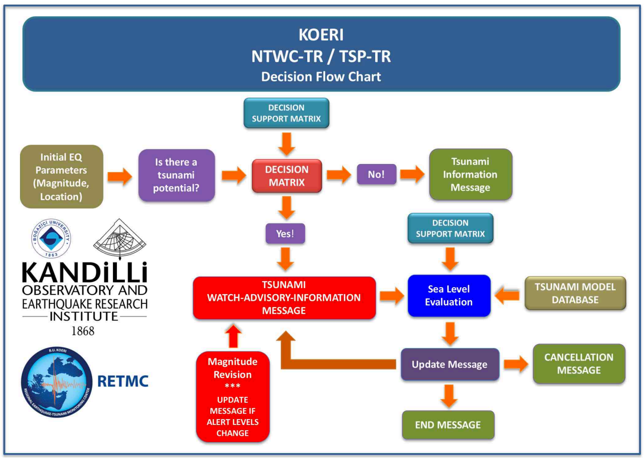



Figure 1: KOERI-RETMC Service Area. Earthquake monitoring area is shown in green rectangle as the area monitored by KOERI to assess the tsunamigenic potential of an earthquake (30°-48° N, 19°-44°E), whereas disseminated messages include Tsunami Forecast Points as indicated on the map. Grey zones are not included in the service area.

The decision flow chart of the system is presented in Figure 2a. The system relies on early determination of earthquake magnitude which allows the duty officer to issue a tsunami information bulletin or warning with corresponding alert levels through a Decision Matrix (Figure 2b).




(a)

| TSP-TR (KOERI) | | | | | | |
|---|---|---|---|---|---|---|
| Decision Matrix for the Eastern Mediterranean, Aegean and Black Seas | | | | | | |
| Depth (km) | Epicentre Location | Earthquake Magnitude | Tsunami Potential | Type of Tsunami Message | | |
| | | | | Local | Regional | Basin-wide |
| | | | | < 100 km | ≥100 - ≤400 | > 400 |
| < 100 | Offshore or close to the coast (≤ 40 km inland) | 5.5 ≤ Mwp or mb ≤ 5.9 | Low tsunami potential | Information | Information | Information |
| | | 6.0 ≤ Mwp ≤ 6.4 | Tsunami potential | Advisory | Information | Information |
| | Offshore or close to the coast (≤ 100 km inland) | 6.5 ≤ Mwp ≤ 6.9 | Potential for a destructive tsunami | Watch | Advisory | Information |
| | | 7.0 ≤ Mwp or Mwpd ≤ 7.4 | Potential for a destructive tsunami | Watch | Watch | Advisory |
| | | Mwpd ≥ 7.5 | Potential for a destructive tsunami | Watch | Watch | Watch |
| | Inland (>40km and < 100km) | 6.0 ≤ Mwp ≤ 6.4 | Low tsunami potential | Information | Information | Information |
| ≥ 100 | offshore or inland (≤ 100 km) | Mwp ≥ 5.5 | Low tsunami potential | Information | Information | Information |

| NEAMTWS Decision Support Matrix | | |
|---|---|---|
| Alert Level | Advisory | Watch |
| Wave Amplitude | 0.2-0.5 m | > 0.5 m |
| Run-up | < 1m | > 1 m |
| Impact | Current, bore, damage in water; possible minor inundation in beaches | Watch impact + inundation of the low-lying coastal land |

(b)

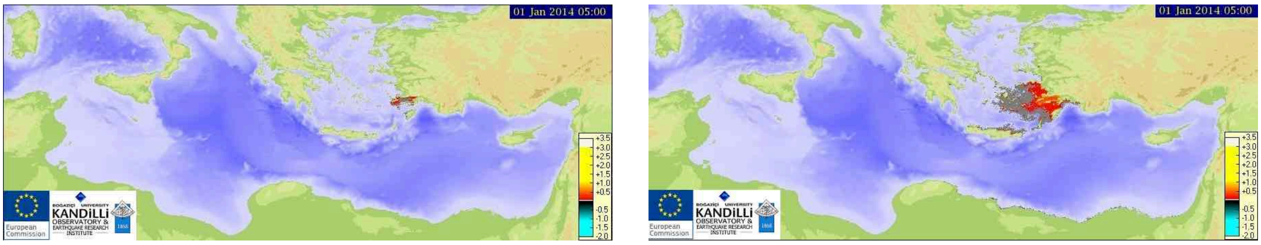
Figure 2: (a) KOERI-RETMC Decision Flow Chart used in its Tsunami Service Provision. (b) KOERI-RETMC Decision Matrix used for issuing tsunami information or tsunami warning messages with corresponding alert levels.

## 2. 21 JULY 2017 BODRUM-KOS TSUNAMI AND LIMITATIONS OF THE REGIONAL APPROACH IN ADRESSING LOCAL TSUNAMI THREAT

The effectiveness of the services provided during the 20 July 2017 Bodrum-Kos earthquake and tsunami by various ICG/NEAMTWS Tsunami Service Providers (TSPs) within the Mediterranean Basin, namely CAT-INGV (Italy), KOERI-RETMC (Turkey), and NOA/HL-NTWC (Greece), has been discussed in detail in Heidarzadeh et al., 2017. Although the Bodrum–Kos tsunami was moderate with little damage to properties, it was the first noticeable tsunami in the Mediterranean Basin since the 21 May 2003 western Mediterranean tsunami. Different TSPs provided tsunami warnings at 10 min (CAT-INGV), 19 min (KOERI-RETMC), and 18 min (NOA/HL-NTWC) after the earthquake origin time. Apart from CAT-INGV, whose initial Mw estimation differed 0.2 units with respect to the final value, the response from the other two TSPs came relatively late compared to the desired warning time of ~ 10 min, given the difficulties for timely and accurate calculation of earthquake magnitude and tsunami impact assessment. It is justifiably argued that even if a warning time of ~ 10 min was achieved, it might not have been sufficient for addressing near-field tsunami hazards.

Figure 3: Images from the 20 July 2017 Bodrum-Kos earthquake and tsunami impact in Bodrum (Dogan et al., 2019).

In that respect, the 20 July 2017 Bodrum-Kos (Mw 6.6) earthquake and resulted tsunami with the nearshore maximum water elevations need around 30-40 cm and maximum run-up of 1.9 m (Dogan et al., 2019) was a wake-up call for the NEAMTWS and a bitter reminder for the to address local and near-field tsunami warning in the Eastern Mediterranean (Figure 3). Simulations indicated that the nearshore maximum water elevations could have been doubled if the Mw would have been 6.8 (Figure 4), which is not an unlikely scenario for the Bodrum-Kos area. In addition to that, tsunami could have resulted in loss of lives if the earthquake would have happened during the day-time in the middle of the high-touristic season.




(a) (b)

Figure 4: Comparison of maximum wave height distributions for an earthquake of Mw 6.6 (a) and maximum credible earthquake with Mw 7.1 (b) derived in Necmioglu (2014). Simulation results indicated that the nearshore maximum water elevations would be 0.36 m for Mw 6.6, 0.68 m for Mw 6.8, and 2.66 m for Mw 7.1

Despite considerable progress and achievements made within the upstream components of NEAMTWS, the experience from this moderate tsunami highlighted the need for improving operational capabilities of TSPs, but more importantly for effectively integrating civil protection authorities into NEAMTWS and strengthening tsunami education programs to address local tsunami threat. Inspired from the 20 July 2017 Bodrum-Kos earthquake-tsunami and earlier event on 12 June 2017 in Lesvos, EC-JRC organized an International Conference on the Recent Tsunami Events in the Aegean Sea during 12-13 December 2017, which highlighted the shortcomings of the existing system and provided a range of suggestions on improvements ranging from awareness programs at various levels to stand-alone local tsunami warning systems, from tsunami inundation maps to evacuation maps and tsunami signage installation. In both of these events in the Aegean Sea, there was no alert to the population. In fact, most of the population reacted in the worst possible way to the earthquake and to the consequent tsunami: remaining in the area, taking images and videos, walking inside the tsunami waves. Apparently, no information was provided by any civil protection authority to the people which resulted in this most irrational behaviour. As a follow up, to address local/near-field tsunami warning, awareness and preparations, the European Commission funded a new project through the EC-JRC and involving KOERI and METU, in close connection with a wide range of local stake-holders. In this context a collaborative action “Last Mile - Bodrum” for the installation of a local earthquake monitoring-tsunami warning system, preparation of high-resolution tsunami inundation and evacuation maps, and awareness and preparedness activities, such as seminars, workshops and a tsunami exercise in Bodrum to be realized all in 2019.

## 3. CONCEPTUAL STRUCTURE OF THE PROPOSED LOCAL TSUNAMI WARNING SYSTEM

As discussed by Heidarzadeh et al., 2017, for most of the Eastern Mediterranean, tsunami hazard is a local (near-field) phenomenon and while the international and intergovernmental tsunami warning system (i.e., NEAMTWS) addresses the requirements for basinwide tsunami threats, special focus is necessary for nearfield tsunami threat due to its short arrival time (e.g., Synolakis and Kong 2006; Synolakis and Bernard 2006; Papadopoulos and Fokaefs 2013). The near-field tsunami threats are a challenge for tsunami warning systems around the world because of the short tsunami travel times and incapability of the current technologies to accurately estimate earthquake magnitudes in such a short time (e.g., Ozaki 2011). It is believed that the earthquake ground shaking is the first warning message for the coastal communities in the area emphasizing the importance of tsunami awareness and education for coastal communities (e.g., Synolakis and Okal 2005; Satake 2014). The components of tsunami warning systems in the near-field conditions of the Mediterranean Basin have been discussed by a number of authors among which are Ozel et al. (2011), Papadopoulos and Fokaefs (2013), and Necmioglu (2016). The proposed tsunami early-warning system for Bodrum, as shown in Figure 5, is inspired from the conceptual model designed for Marmara (Necmioglu, 2016), where the system will make use of strong ground motion parameters for warning and sea-level measurements for verification purposes.

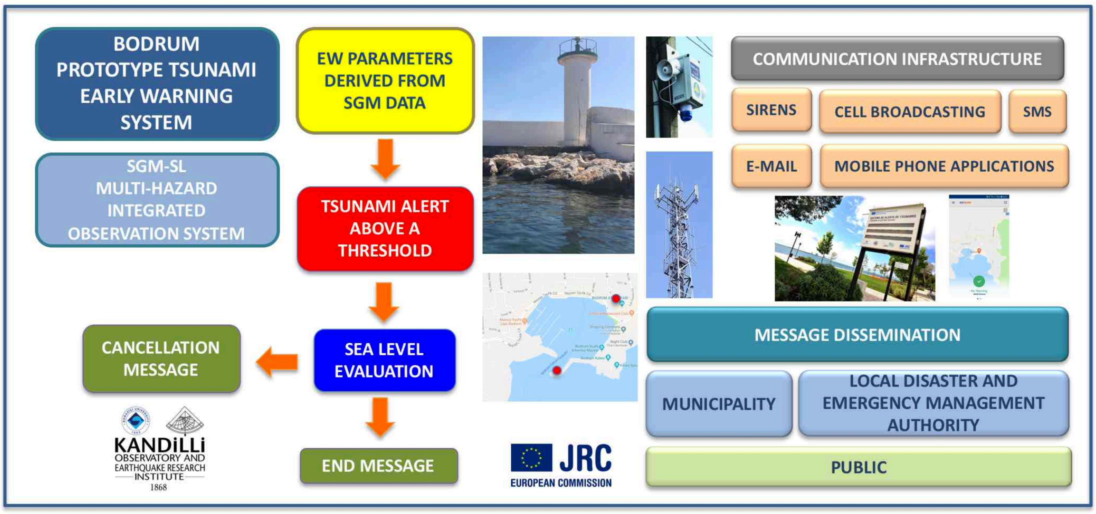



Figure 5: Proposed tsunami early-warning system for Bodrum.

The system is expected to be installed during summer 2019. It should be noted that this system does not replace the national system, but is thought to be integrated within. At the beginning, it will operate as an independent/stand-alone early warning system, but later on, it is considered to become part of the national system, capable of receiving and diffusing additional tsunami messages to the population. The system will be triggered by the exceedance of a threshold PGA value to be determined through strong ground motion simulation of the 20 July 2017 Bodrum-Kos earthquake and a set of hypothetical scenarios in the range of 5 magnitudes levels between Mw 5.5 and Mw 7.5 for three different site conditions using two ground motion prediction equations available for Turkey (Tanircan and Yelkenci-Necmioglu, 2019). Once triggered, the system may function in automatic mode, namely the alert will be disseminated through dedicated/available systems or in semi-automatic mode, where an authorized user, such a as a representative of the local Civil Protection Unit or Disaster and Emergency Management Presidency, may activate the alert system. The system will be capable of disseminating alerts via sirens, SMS, cell-broadcasting, e-mail and mobile phone applications. Public speaker system network already established at the Mosques may also be utilized. In automatic mode, it is expected that the alert would be disseminated in less than 1 min, whereas in the semi-automatic mode a maximum time limit, such as 3min, could be defined to either pass or block the automatic alerting.

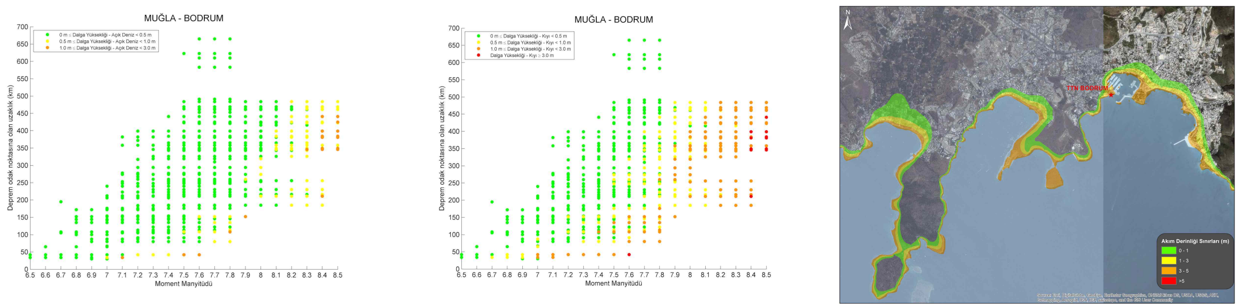
## 4. SUPPORTING ELEMENTS OF A LOCAL TSUNAMI SYSTEM: INUNDATION AND EVACUATION MAPS

A very useful overview of the requirements on the elements for reducing and managing the risk of tsunamis can be found in the ICG/NEAMTWS guidance for National Civil Protection Agencies and Disaster Management Offices (2011). According to this guidance, the key element of the emergency response in anticipation of a tsunami impact is the evacuation of the exposed people and mobile assets (e.g., vehicles and important information) to tsunami-safe areas, or, in the case of harbour craft, offshore to deep water. The trigger for the evacuation process at the local community level may be the receipt of a Warning message through the centralized Civil Protection

Authority, from the National Tsunami Warning Centre, or through a local/in-situ system as proposed for Bodrum. Alternatively, in seismically active coastal areas, the trigger for response could be that a strong earthquake has been felt by the coastal community. In such cases, although the magnitude and location of such an earthquake and the likelihood of a consequent damaging tsunami may be unknown to that community at the time of the receipt of a warning, precautionary evacuation procedures should be considered. In that respect, evacuation planning is essential for tsunami mitigation and preparedness.

Evacuation planning is a lengthy process and should be considered as an ongoing endeavour which continues to improve in successive iterations. Consideration may be given to embedding such planning in the Integrated Coastal Area Management process. The time and resources taken for planning activities will be directly related to the geographical size of the management area, regional topography, regional hazards and vulnerabilities, demographics, size, density and temporal variation of the population, number of agencies involved in the planning process, and resources available.  The elevations and methods used to establish evacuation zones should be developed based on local hazard analysis and inundation modelling. Better results are obtained from detailed analysis at local level, with high resolution bathymetric and topographic data. Ideally, zones need to represent an envelope around all possible inundations from all known tsunami sources, considering all of the ways each of those sources may generate a tsunami. Use of a single tsunami evacuation zone has the advantage of simplicity for both emergency planning and public understanding. However, because a single evacuation zone must accommodate the very wide range of local risk scenarios that may exist, this can result in regular "over-evacuation" of the entire zone for common, small-scale events. Recurrent over-evacuation is likely to result in decreasing levels of community trust in emergency managers. Use of more than three or four evacuation zones may better reflect the range of local tsunami risk scenarios. However, such differentiation requires far greater resources and a higher degree of coordination for planning and response, and the complexity of information may create public misunderstanding.

Evacuation routes have to be designed to permit human and vehicle movement to safe places and evacuation structures. The design should be based on the expected volume of humans and vehicles, speed of evacuation and safety. The design should primarily present the number of routes required, the width and the overall safety of the evacuation process. The design must ensure the safe passage of evacuation and consider the risk of failure of the route itself under disaster conditions. Such an approach will identify weak links which may have to be rectified in advance and also recommend alternative routes in the event of failure of a prescribed route.




(a) (b) (c)

Figure 6. Offshore (a) and coastal (b) tsunami height-earthquake magnitude (Mw)-distance relationship for Bodrum obtained from a large set of deterministic scenarios excluding any possible associated submarine landslide (Necmioglu and Ozel, 2015), which show coastal wave heights of less than 50 cm for earthquakes Mw < 6.7, well in accordance with the observations made during the 21 July 2019 Bodrum-Kos earthquake of Mw 6.6. Tsunami inundation map for Bodrum (c) communicated to AFAD in 2017 based on 150m resolution bathymetry and 3m resolution topography maps. Colours indicate flow-depth boundaries (green 0-1m, yellow 1-3m, orange 3-5 m, red > 5m). Due to the number of scenarios considered, higher resolution of bathymetry-topography data and building inventory, this study will result in considerable improvements in the currently available inundation map for Bodrum.

Tsunami signage is an integral part of practical tsunami risk management. Signage depicting evacuation zones and routes raises public awareness of local tsunami risk and provides information to increase the efficiency and effectiveness of an evacuation, and serves as an element of tsunami awareness. Well placed evacuation signage is the critical link between an actual event and the emergency response plan. The maintenance of the evacuation route should be given high priority. In the case of Bodrum, the possible installation of the tsunami signage will be decided by the local authorities upon completion of the pilot project.

In this project, evacuation maps for the city of Bodrum will be produced based on tsunami modelling of the 20th July 2017 Mw 6.6 earthquake and the study of the possible maximum credible events both within the Gökova Bay and Southern Aegean-Hellenic Arc. The proposed study will also guide the emergency managers for the optimum deployment of the sea-level observation network. Once finalized, they will replace the inundation maps for Bodrum communicated to AFAD in 2017, shown in Figure 6.

## 5. AWARENESS AND PREPAREDNESS AT LOCAL LEVEL: TOWARDS INTEGRATED EMERGENCY MANAGEMENT PLANS AND TSUNAMI EXERCISES

A dedicated meeting with the wide participation of local stakeholders, ranging from public offices to various local associations took place on 25 February 2019. During this meeting, it was identified that the earthquake of 20 July 2017 and associated tsunami, also together with various related meetings and workshops organized afterwards, resulted in awareness concerning tsunami disaster in the region. The need to consider tsunamis in the determination of post-earthquake assembly areas and preparation of tsunami inundation and evacuation maps based on an integrated/multi-hazard approach was identified. It was furthermore noted as especially important to give priority to provide public education and awareness in schools. During the tsunami on 20 July 2017, various difficulties in the ports and marinas were experienced by local marina operators, and some subsequent improvements were made. Seaside and coastal port facilities were recognized as of critical importance in tsunami preparedness, but additional studies are considered to be necessary in the context of preparing for the worst-case scenario. An agreement was made to execute a table-top exercise in Bodrum on 5 November 2019, as part of national activities under the World Tsunami Awareness Day. A follow-up meeting was organized on 25 May 2019 with selected local stakeholders, where draft tsunami modeling results and evacuation maps were presented. A dedicated working group was established to work on the planning, conduct and evaluation of the tsunami exercise. This exercise is expected to provide not only an opportunity to make use and disseminate the outcomes of the project, but will also serve the local stake-holders to obtain a gap analysis concerning the existing emergency plans, resources and remedy actions towards possible improvements in local disaster awareness and preparedness in an integrated approach.

## 6. CONCLUSIONS

The 20 July 2017 Bodrum-Kos (Mw 6.6) earthquake and resulted tsunami with coastal wave heights around 30-40 cm and maximum run-up of 1.9 m was a wake-up call and a bitter reminder for the need to address local and near-field tsunami warning within NEAMTWS. Although the Bodrum–Kos tsunami was moderate with little damage to properties, it was the first noticeable tsunami in the Mediterranean Basin since the 21 May 2003 western Mediterranean tsunami, and could have resulted in loss of lives if the earthquake would have happened during the day-time in the middle of the high-touristic season. Inspired from the Bodrum-Kos earthquake-tsunami and earlier event on 12 June 2017 in Lesvos, EC-JRC organized an International Conference on the Recent Tsunami Events in the Aegean Sea during 12-13 December 2017, which highlighted the shortcomings of the existing system and provided a range of suggestions on improvements ranging from awareness programs at various levels to stand-alone local tsunami warning systems, from tsunami inundation maps to evacuation maps and tsunami signage installation. As a follow up, the EC funded a new project through the JRC involving KOERI and METU, in close connection with a wide range of local stake-holders. In this context a collaborative action “Last Mile - Bodrum” for the installation of a local earthquake monitoring-tsunami warning system, preparation of high-resolution tsunami inundation and evacuation maps, and awareness and preparations activities, such as seminars, workshops and a tsunami exercise in Bodrum to be realized all in 2019. This pilot initiative, upon successful completion, is expected to serve as a model for other places in southwestern Turkey, such as Datça, Didim, Fethiye, Marmaris and Kaş.

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