5.1.5 Development of warning systems that decide when meteo-tsunamis (coastal flood) warnings shall be issued based on high resolution air pressure measurements combined with meteo-tsunami (coastal flood) forecast model

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Summary

Abstract

This deliverable analyses recent advances in development of early warning systems for coastal flood and possibility of their integration into decision making process using basic ICT technology. Based on modern achievements, early warning system for coastal flooding developed for the Croatian test site is developed and presented. The system integrates numerical model for assessment of sea level rise due to extreme sea waves in real time, caused by tidal induced oscillations, oscillations due to the barometric pressure changes and wind generated waves, monitoring system for data storage and distribution of the meteorological inputs required to estimate the sea level by numerical model and mobile application that provides information to end users. Special attention of the study is an analysis of the results of real-time prediction of sea level values for different time periods, based on the inputs obtained from a network of sensors installed at the test site and the developed numerical model that allows simulation of coastal flooding. The results are used to disseminate and communicate understandable risk information at the area to end users using the mobile application.

1 Introduction

One of the purpose of PMO-GATE project is *Development of warning systems that decide when meteotsunamis (coastal flood) warnings shall be issued based on high resolution air pressure measurements combined with meteo-tsunami (coastal flood) forecast model* (Deliverable 5.1.5). Warning system is developed for the particular test site of Kaštel Kambelovac. Previous investigations in the project has shown that it seems difficult an occurrence of meteotsunami in the City of Kaštela. Therefore, the warning system is developed for the coastal flood caused by extreme sea waves.

An integrated methodological approach to the development of a coastal flood early warning system is an important key to improve societal preparedness of the people for coastal flood events. It should integrate real time data provided by monitoring system, numerical sea forecasting model for estimation of sea level, historical databases of the model input parameters and application of ICT technology to provide timely and correct information through user-friendly web-based interface. Obtained information are used to reduce potentially affected risks.

The aim of this document is to show the main characteristics and components of early warning system and to present how the basic ICT technology can be integrated into early warning system to assess the real time vulnerability of the coastline to be flooded by the extreme sea waves.

In order to develop efficient early warning system, which will be adapted to the characteristics of the test area, recent advances and achievements in development of early warning systems for coastal flooding and their integration into decision making process have been analysed.

This study integrates the research and main findings of several deliveries of this project, which are important for development of early warning system for coastal flooding at the study area, such as:

- Description of numerical model for assessment of sea level rise due to extreme sea waves in real time, caused by tidal induced oscillations, oscillations due to the barometric pressure changes and wind generated waves (Deliverable 3.2.1 [1]);
- Monitoring system for data storage and distribution of the meteorological inputs required to estimate the sea level by numerical model (Deliverable 5.2.4 [2]);
- Mobile application that provides information to end users [3].

Integration of the mentioned component into a unique early warning system for coastal flooding, based on the modern ICT's tools has been briefly explain and presented.

Special attention of the study is an analysis of the results of real-time prediction of sea level values for different time periods, based on the results obtained from a network of sensors installed at the test site and the developed numerical model that allows simulation of coastal flooding. These results are needed to disseminate and communicate understandable risk information at the area to end users using the mobile application.

1.1 Description of the study area

Coastal flooding is considered one of the major threats for coastal urban areas. Along the Croatian coast, flooding endangers many low-lying coastal areas and the urban settlements potentially exposing the coastal infrastructure and significant number of buildings to flood hazard. Test site of PMO-GATE project, Kaštel Kambelovac, is an example of such area, exposed by sea flood caused by rising sea levels due to climate changes, and by extreme sea waves. Kaštel Kambelovac is one of the seven settlements of City of Kaštela, placed at the north part of the Kaštela Bay (Figure 1), with many cultural and historical buildings and/or areas located near the coastline (Figure 2).

Figure 1. Position of City of Kaštela in Kaštela Bay

Figure 2. The view on a historical centre, Kaštel Kambelovac

All settlements of City of Kaštela are potentially endangered by coastal flooding as well and subject to significant consequences and damage (Figure 3).

Figure 3. Coastal flooding in the City of Kaštela

Consequences of flooding are specially exposed in historical parts of the settlements where the stone historical buildings are placed near the coastline, usually without foundations and with openings at the level of terrain, which affects the penetration of the sea into buildings, both when sea levels rise due to changes in atmospheric pressure and when the extreme sea waves caused by changes in wind direction and speed occur.

Topographic characteristics of the area are essential for analysis of flooding caused by extreme sea waves. Therefore, detailed geodetic survey of terrain has been performed using geodetic drone recording, and the high-resolution geodetic basis of the HR test site has been created (Figure 4).

Figure 4. Geodetic basis of the HR test site

In the present study, the early warning system is developed for coastal flooding caused by simultaneous combination of several mechanisms inducing extreme sea waves, such us tidal induced oscillations, oscillations due to the barometric pressure changes and wind generated waves that have been investigated in the Kaštela Bay.

2 Early warning system

According to United Nation International Strategy for Disaster Reduction (UN ISDR) [4, 5], early warning system is “the set of capacities needed to generate and disseminate timely and meaningful warning information to enable individuals, communities and organizations threatened by a hazard to prepare and to act appropriately and in sufficient time to reduce the possibility of harm or loss”.

2.1 Elements of early warning system

An effective early warning system (Figure 5) is consists of the four elements that have been defined by United Nation International Strategy for Disaster Reduction (UN ISDR). With the aim to achieve people-centred early warning systems, the system should encompass a risk knowledge, technical monitoring and warning service, communication and dissemination of warnings and community response capability [4, 5]. The four elements are explained in the following paragraphs.

Figure 5. Four elements of people-centred early warning systems defined by UN ISDR [4, 5]

Risk knowledge

In order to perform risk assessments, it is necessary to know the characteristics of hazards, vulnerabilities and exposures of people and assets. Risk has a dynamic characteristic, it changes over time, depending on the development of the hazard itself, but also the vulnerability and exposure of people and assets that change (i.e. urbanization, land-use change, environmental degradation, climate change, etc.).

Technical monitoring and warning services

Effective early warning system needed a scientifically based model for predicting hazards and their characteristics (i.e. propagation, intensity etc.), based on the systematic measurements of various parameters via sufficiently dense and reliable network of sensors that operate 24 hours a day. The result of this element is accurate and timely warnings. Warning systems should be coordinated with stakeholders and relevant agencies to gain benefit of shared communication network.

Dissemination and communication services

The main goal of dissemination and communication services is to reach all those at risk and those who need to act to save lives and assets. Therefore, warnings should be easy to understand and recognised as credible (received from a source identified as competent to issue such warnings). In order for alerts to reach as many people as possible, it is necessary to use various communication channels (i.e. radio or television, sirens, electronic media, web and mobile applications) to ensure that alerts will reach even in the event of interruption of some of the channels. In addition, there is a need to use both, video and audio warnings, to reach people with hearing or vision impairment.

Early warning communication system consists of two components: reliable and robust communication infrastructure hardware and appropriate and effective interactions among the main participants in early warning system (scientific community, stakeholders, decision makers, general public, media). Information and communication technology (ICT) has a main role in disaster risk communication and dissemination of information to organization responsible for responding to warnings and to the public.

Community response capability

In order to achieve the best possible response, the local community should be informed in advance about possible risks and ways of acting, as well as about the responsible response agencies and their services. Therefore, emergency response plans are necessary for various disasters and regularly performed exercises and tests of actions, evacuation routes and measures for damage reduction.

2.2 Information and communication technology architecture for early warning system

From the information and communication technology (ICT) point of view, an early warning system integrates all the ICT's tools supporting the four elements: risk assessment, monitoring and prediction, communication services and processes of response. The technologies such as Internet of Things (IoT), Cloud Computing and Artificial Intelligence are used in building elements of early warning systems. For the flooding hazard, various sensors are sensing parameters which influence to the sea level rise and wave formation. The communication networks are transmitting large volume of data in near real time. The wave propagation and the hazards of the area are modelling by fast computing provided by powerful processors and effective algorithms. The artificial intelligence algorithms integrate information and support generation of accurate warnings. Finally, public internet and smart phones are broadcasting timely warnings.

An overview of ICT advanced tools and particular early warning systems architecture based on Internet of Things is given by Esposito et al in [6].

Authors Dongxin B. et al in [7] explains an ICT architecture for early warning system. The architecture consists of four layers:

- *Perceptual layer* includes various sensors (GNSS receiver, rain gauge, strain gauge, camera, etc.) for monitoring hazard parameters and supporting sensors infrastructure for energy supply, communication and protection equipment (battery, chassis, solar panels, etc.).
- *Data layer* includes data receiving and parsing, data storage and data access interfaces.
- *Service layer* is used to include various services. In this layer, data management and complex data analysis are performed (including artificial intelligence and decision support algorithms for storing and using knowledge of risks, detection of false alarms, creation of messages, etc.) as well as standards services such as user and project management.
- Terminal layer represents IT devices for warning dissemination mainly web and mobile applications.

3 Recent advances in coastal flood early warning systems

Coastal floods are recognized as one of the natural disasters that can cause significant damage to coastal cities and local populations. Climate change that increase mean sea levels associated with the occurrence of extreme events [8], fast urbanization of coastal areas and inadequate coastal protection infrastructure require short-term and long-term planning to protect the local community from adverse events, especially in low-lying coastal areas. One of the important short-term measure is the development of early-warning systems that can significantly contribute to the civil protection. The long-term measures aim to reduce risk caused by flood events by developing future scenarios of sea flooding.

The processes that influence to sea flooding and changing of sea-water elevation is a consequence of the phenomenon caused by tidal induced oscillations, oscillations due to the barometric pressure changes and wind generated waves. Additionally, the climate change influence to the increase of mean sea level rise, but also to the frequency and intensity of storms and waves. Therefore, analysis of mentioned effects should consider both short-term sudden changes that affect the formation of high waves, coupled with long-term effect of rising sea levels due to climate change. Numerous studies have shown that the climate change also affect the increased frequency of the occurrence of extreme sea waves.

Coastal events, their occurrence and triggers for the appearance of waves have been investigated to contribute the better understanding of flood events in coastal area as well as efficient risk managing. Recent investigations have studied the occurrence of complex events [9, 10] such as storm and sea waves, the numerical modelling of wave propagation in the coastal area [11], flood water movement over land areas [12], impact of storms on coasts [13] and flood vulnerability [14]. Past flood events have been analysed in many scientific works to predict future flood events and flood risk for coastal area, using various climate change projections.

Some papers deal with problems of short-term forecast of sea level rise. Special attention is paid to the development of an early warning system for timely warning of residents in exposed areas. Early warning systems are also an integral part of coastal flood management plans and contribute to the development of long-term management strategies. An overview of the developments that are needed for an accurate and reliable forecasting system is given by de Kleermaeker et al. [15]. Existing sea-state-monitoring technology, historical database and experience, numerical forecasting models and computer science were the parts of operational coastal flood early warning system developed by Doong et al. [16]. EWS modelling framework, based on a Bayesian network, to link coastal hazards to their socio-economic and environmental consequences has been developed by Bogaard et al. [17]. Operational forecast system connecting available field measurements, data obtained from numerical wave simulations and an empirical wave run-up approach have been presented by Dreier and Fröhle [18].

Early warning system that calculates the total sea level height by combining predictions of tides and sea-level anomalies with wave runup estimates is presented by Merrifield et al. [19]. The system is based on using regional wave and water-level observations, historical beach surveys, and a numerical runup model.

They found that real-time simulations should be incorporated into the early warning system to reduce errors in the forecasts.

Review of the methods in the development of an early warning system of storm wave-driven flooding along coral reef-line coasts, has been presented in the study Winter et al. [20].

Efficient modelling of hydraulic processes in the coastal area and simulation of coastal inundation represent real challenge in establishing a framework for the development of early warning system and significantly influence to efficiency and applicability of the system.

Technological progress in computation and communication sciences in the last decade allows to work with large databases that can store registered meteorological data that affect the occurrence of sea floods. These data represent a basis for developing different forecasting platforms, which use input data and boundary conditions from global or regional scale, open-sea and weather forecast databases, providing wave propagation in the ports [21]. These platforms use a number of effective hydrodynamic numerical models for simulation of storm surge and prediction of sea water level [22]. It is important to notice that the prediction sea water level procedure in real time is time-consuming process which needs significant computational resources, as well as the development and monitoring of a software architecture [23] to model coupling and integration.

Recently, the methodological approaches which involves the implementation and coupling of a hindcast and forecast sea-state data, empirical formulas, wave propagation and hydrodynamic numerical models with an Artificial Neural Network [24–28] has been developed to predict the coastal flood risk and avoid the required implementation of time-consuming numerical models. The model based on Machine Learning [29] and Artificial Intelligence provide easy implementation of numerical models with low computational cost, as well as fast training, validation, testing and evaluation. One such study has been performed for the study area of Rethymno in the Island of Crete, Greece [30].

4 Design of the early warning system for sea flooding risk in the test site Kaštel Kambelovac

4.1 Phases of early warning system for sea flooding

This chapter describes the design of the early warning system for sea flooding in the Kaštel Kambelovac. Sea flooding early warning allows for prevention and minimization of flood induced hazard by extreme sea waves.

The most important phases in a flood early warning system are:

- Collection of input data using real time hydro-meteorological observation obtained by weather radar satellites and automatic hydro-meteorological station network. Provided data are used to evaluate the flood risk.
- Development of scientifically based model for predicting extreme sea waves hazard (i.e. sea level), based on the systematic measurements of various parameters via network of sensors, sufficiently dense and reliable, that operate 24 hours a day.
- Dissemination and communication of risk information by a reliable and robust communication infrastructure hardware and appropriate and effective interactions among the main participants.

In order to realize previous phases, following procedure for early warning systems of extreme sea waves risk is defined:

- The establishment of the monitoring system which includes an installation of hardware at the test site location and appropriate software for real-time data collection. This system will measure the direction and speed of the wind and atmospheric pressure.
- Development of mathematical and numerical model for the transformation of measured parameters (wind speed and direction, atmospheric pressure, tide) into sea level information on the coastline which will include the impact of all measured parameters. Using this approach, real-time information on the magnitude of a potential flood on the coast will be obtained.
- Using a digital terrain model, where each pixel is georeferenced (X, Y coordinates) and assigned an altitude Z, the calculated sea heights will be compared with the altitudes, and if the sea elevation is greater than the altitude Z of a pixel, that pixel will be marked as flooded. Flood edge (land) pixels represent the ultimate extent of land flooding.
- According to the depth of the sea on land, which is the difference between sea level and land level (Z), the risk of flooding for humans will be defined. The risk of flooding for humans will be defined by an analytical function so that it can be easily integrated into the rest of the system. This information is necessary for the input into the early warning system.

- The coastal area of Kaštel Kambelovac is divided into zones in order to define the total sea level. This division is made according to the criteria of the coast type and the coast height, which have a direct impact on the height of the waves.
- Dissemination and communication of risk information to users will realize via the principle of push notifications. Flood warnings will be given to people who have our app installed on their mobile phone and who have enabled that app to send them notifications.

This chapter is structured as follows. Design of information flow is presented to show how information is communicated. The short description of the methodology for the assessment of sea elevation and application of the methodology to study area in Kaštela Bay is given. The implementation details on the system used as a meteorological input for the sea level estimate is described. The web/mobile application implementation details are presented. Finally, the results obtained by web/mobile application are discussed.

4.2 Information flow diagram

Information flow diagram shows how information is communicated from server feeding mobile app, which inform citizens about the flood threat. We use the process or activity model as a basis for description of the information flow. It describes operational activities, input and output flows between different actors, as well as input and output flows to/from concepts within organisation. The purpose of the process model is to:

- Define activities related to the use of sensors, models and the mobile app to alert citizens about flood threat;
- Identify information flows to be implemented in both server and mobile apps;
- Define citizens' activities and roles while using the mobile app.

For this purpose, the Business Process Model and Notation (BPMN) 2.0 notation [31] is used, but limited to the subset which fits the project's purpose (Table 1). Therefore, the activity model is depicted in BPMN notation implemented in Camunda Modeler [32].

Figure 6 shows the information flow diagram for the early warning system developed for sea flooding caused by extreme sea waves. Mobile application alerts and informs citizens about the potential emergency due to sea level-rising, which may be caused by three different phenomena acting together: exchanging of low and high tide, atmospheric pressure and waves. Information about threats is being generated on a server using data from the sensors and algorithms. Sensors provide wind's velocity and direction, as well as atmospheric pressure. The data are processed by the algorithm for the assessment of an absolute sea-level. The results are combined with results from the algorithm for definition of sea level caused by exchanging of low and high tide and the algorithm for prediction of the wave height generated by winds along the coastline.

The study area is divided in ten emergency zones (Figure 7), which are defined taking into account particular coast elevation and wave reflection. The threat is calculated as a difference between predicted sea level and terrain-level for each zone.

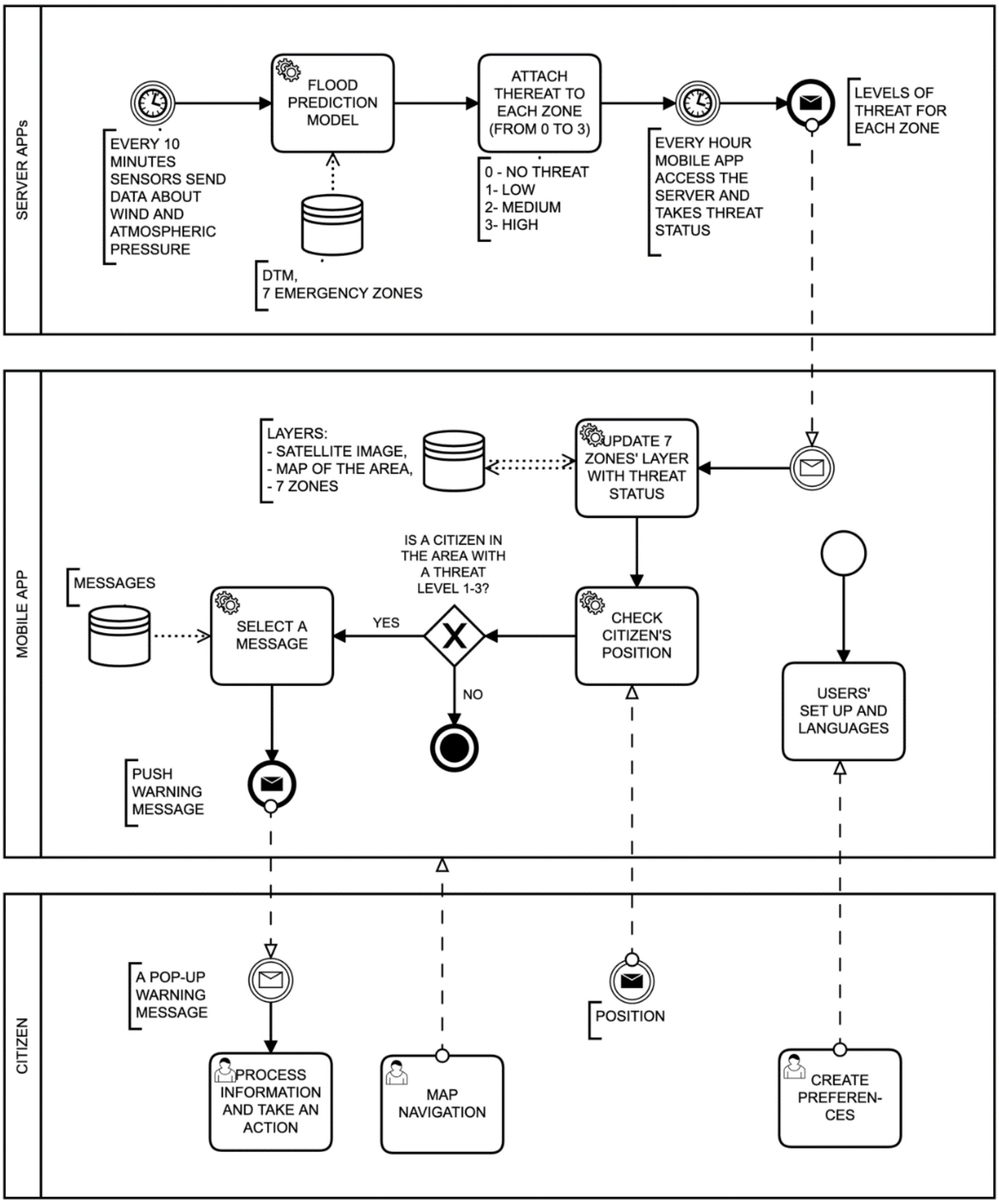
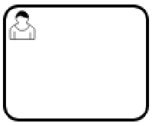
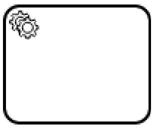
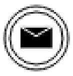
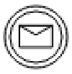
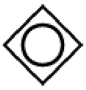
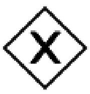
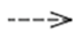


Figure 6. Information flow diagram for the early warning system for sea flooding

Table 1. Legend of used BPMN symbols

Symbol	Meaning
	User task
	Service task
	Data storage
	Signal start event
	Message start event
	Message intermediate throw event
	Message intermediate catch event
	Inclusive gateway (inclusive OR)
	Exclusive gateway (exclusive OR)
	Sequence flow
	Association flow
	Message flow

There are three levels of threat defined as an average predicted flood level for a zone: low, medium and high.

The sensors send the data every 10 minutes and the mobile application accesses the updated threat status every hour.

The mobile application access information about threats and process is further towards citizens. It contains the following layers:

- A satellite image with scales,
- A map of the area (Kaštel Kambelovac, from dr. Franjo Tuđman street southward),
- A transparent map with ten emergency zones.

The mobile application contains adequate messages for each threat level. The messages contain warning about the actual situation and prediction and suggest the action. The application processes the data about the threats in the zones and if the threat is identified it chooses the appropriate messages and sends it to citizens in the corresponding zones. The messages are being sent as a push notification and appears on the mobile phone screen. The notification also includes sound, so blind and visually impaired people can also use it.

The application also allows users to set up their functional preferences and choose the language (Croatian, English and Italian).

Flood hazard classification is defined based on the threat level for potentially exposed citizens located within the endangered area. For each threat level, a flood hazard class is assigned followed with the corresponding warnings. These warnings are primarily focused on preventing citizens' safety so each threat level is defined in relation to water depth and potential human instability in floodwater.

Flood hazard classification in this study is based on the research [33], which conducted different tests to obtain the conditions for the instability of a human body in floodwater. As a result, different stability thresholds are derived for adults and children. The presence of any floodwater in combination with high velocity typical for extreme coastal waves can be dangerous for children due to possible sliding, so the first hazard class is defined as 0 – 0.2 m. As soon as water depth exceeds 0.2 m (second hazard class) it becomes dangerous for adults as well, while exceedance of 0.5 m (third hazard class) can cause severe injuries or even casualties.

Three threat level can be shown as follows:

- *Low threat level presented as yellow warning*: The sea can penetrate into objects having entrance sills lower than 20 cm. Children aged up to 7 years could be endangered. Road traffic can be disrupted in road depressions.

- *Medium threat level presented as orange warning*: The sea can penetrate objects having openings less than 50 cm from the ground. Persons with limited mobility and children could be endangered. Road traffic can be disrupted.

- *High threat level presented as red warning*: The sea can penetrate objects; the sea level is higher than 50 cm. All citizens could be endangered. Road traffic is disrupted. There is a possibility of pollution.

5 Model for assessment of sea elevation in Kaštela Bay

Sea water level is a random process resulting as an outcome of simultaneous combination of several mechanisms of which three of them are dominant, respectively, tidal induced oscillations, oscillations due to the barometric pressure changes and wind generated waves. Although characterized by different time scales, those three mechanism simultaneously contribute to the sea water absolute elevation.

Tidal induced sea water oscillations are driven by the tidal forcing, induced by simultaneous inter gravity forcing between Sun, Moon and Earth. Tidal induced changes are characterized as mixed semidiurnal type at the location of interest, with main periodic intervals corresponding to both semi diurnal and diurnal one. Compared to tidal oscillations, sea level changes caused by barometric pressure changes are aperiodic with time scales corresponding to two main factors: (1) daily barometric pressure changes corresponding to daily scale air temperature change and (2) time scales corresponding to the time necessary for the air mass transfer from different geographic locations to the location of interest to occurred. The latter corresponds to time scale equal to several hours usually. Wind generated waves are characterized by very small time scales, up to 8 seconds in the area of interest and are generated as a result of the air mass kinematic energy transfer to the sea surface.

By coupling those three mechanisms and by neglecting other mechanisms, sea water elevation for the assessment of the coastal flooding vulnerability can be assessed.

Development of the model for assessment of sea elevation is based on the data collected at two meteorological stations and a tide gauge placed nearest to the test site.

The nearest tide gauge near Kaštela Bay is located within the Institute of Oceanography and Fisheries (IOR) in Split (Figure 7), at the western border of peninsula Marjan. Time series of measured sea surface elevations with a total duration of five years have been obtained from the Marjan tide gauge, respectively for the period from 01.01.2010. to 31.12.2014. with the sampling frequency of the tide gauge equal to 1 hour. A continuous time series from 25.01.2010. at 12:00 h to 27.06.2011. at 23:00 h with a total of 12444 data is analysed in order to developed the model.

Barometric pressure data are obtained from two meteorological stations, Split-Marjan, located northwest of the city on the Marjan hill, at the attitude of 122 m a.s.l. and Split-Airport located at 21 m a.s.l. (Figure 7). Measuring system of Split-Marjan location gives barometric pressure data with an hourly measurement frequency, but also wind speed and direction data. The meteorological station Split-Airport records the barometric pressure values three times a day at 7 am, 2 pm and 9 pm. Date needed for calculation of barometric pressure were obtained from both meteorological stations for the period 01.01.2010. to 31.12.2014.

More details can be found in Deliverable 3.2.1 [1].

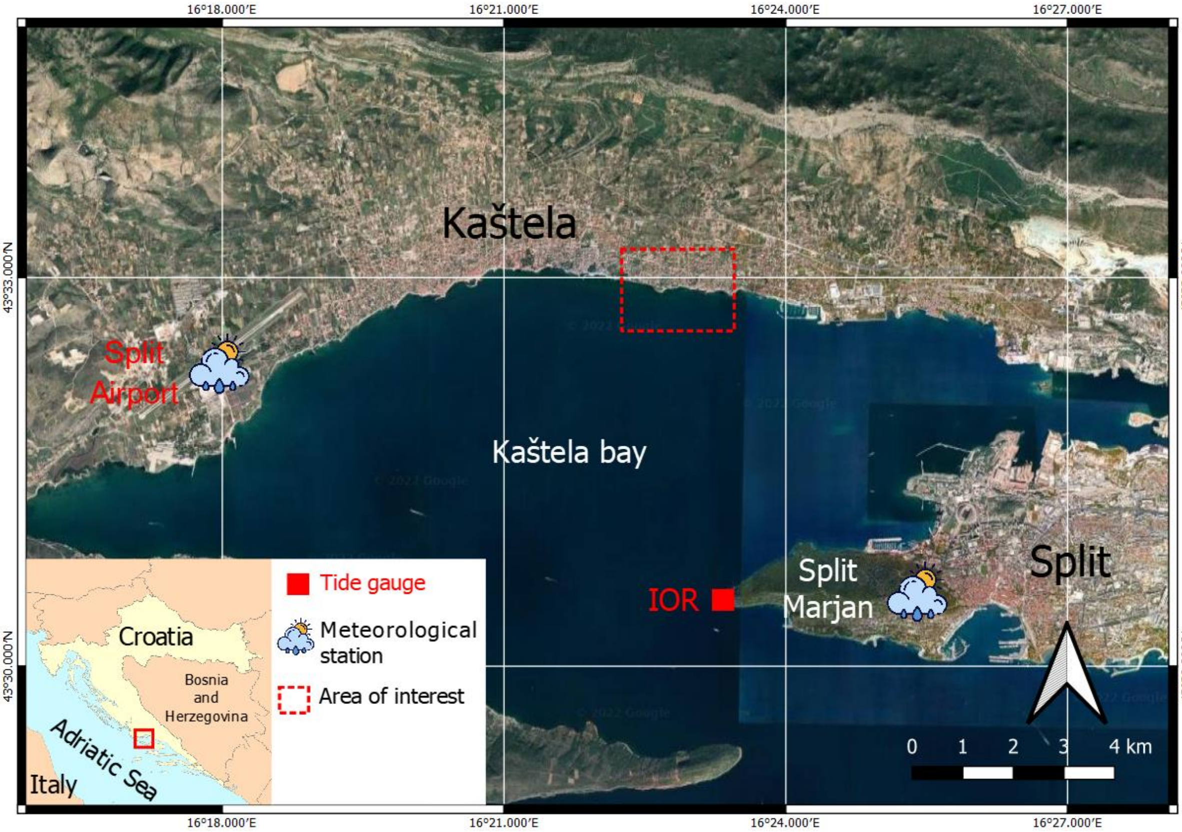


Figure 7. Location of the test site with definition of the tidal gauge and meteorological stations

5.1 Tidal induced oscillations

Analysis of tidal induce oscillacions for the test site is based on previous research [34] of tides characterizing the Adriatic Sea basin. Tidal induced sea level can be simulated using linear superposition of a sinusoidal function corresponding to number of relevant constituents:

$$h_t = \sum_{i=1}^{7} A_i \times \sin\left(\frac{2\pi t}{t_{pi}} + \frac{2\pi\varphi_i}{360}\right), \mathrm{t} = 0, 1, \dots, M \quad (1)$$

where h_t is simulated sea level [m], A_i is amplitude [m], t_{pi} is period [h] and ϕ_i phase [°] of *i-th* constituent, *M* is the sample size and *t* is relative time [h]. Discrete Fourier Transform (DFT) has to applied to determine the unknown values of amplitudes, periods and phases by transformation of original from time to frequency domain. The Fast Fourier Transform incorporated in Python in SciPy library [35] has been applied. More details can be found in Deliverable 3.2.1 [1] of the project PMO-GATE.

Simulated sea level h_{sea} can be calculated as a superposition of tidal harmonics from Eq. (1) and by adding the mean sea level value calculated from the observed sea level signal.

$$h_{sea} = h_t + \bar{h} \quad (2)$$

Detail calculation of tidal induced sea level is shown in Deliverable 3.2.1 [1].

5.2 Barometric pressure induced oscillations

The sea level rise caused by the change of the barometric pressure [1] can be calculated as follows:

$$h_{at} = \frac{-p_a}{\rho g} \quad (3)$$

where h_{at} is sea level change result as a consequence from change in barometric pressure, p_a is barometric pressure [Pa] change, ρ is density of sea water [kg/m^3] and g is gravitational acceleration [m/s^2].

Therefore, simulated sea level incorporating for both tidal oscillations and barometric pressure induced changes is updated from Eq. (3) for value of h_{at} as shown:

$$h_{sea} = h_t + h_{at} + \bar{h} \quad (4)$$

where the third right hand term represents mean sea level values as calculated from the observed signal, h_t represents tidally induced sea level oscillations and h_{at} holds for barometric pressure induced sea level change.

5.3 Wind generated waves

Estimation of the sea wave height at the front of the coastline stars with determination of deep water wave parameters using data sets from neighbouring climatological station (more details in Deliverable 3.2.1 [1]). For the location of interest and relevant incident wave directions following procedure is applied: (1) the lengths of effective fetch are determined; (2) the intensity (speed) and duration of continuous wind occurrence is determined from the wind data; (3) based on the above defined, parameters of deep water wave can be determined; (4) with execution of model analysis, considering depth features, reflection properties of the coastline and the properties of the wave at the distance of 4 meters from the coastline, a significant wave height is defined which is compatible with hundred years return period; (5) by comparing wave heights of realized wave at the distance of 4 meters and wave height of the deep water wave, shoaling coefficient along coastline K_S is determined.

Wave transform analysis needed to generate wave height has been performed by application of SMS CGWAVE software [36]. This software is used to simulate bathymetric refraction, diffraction by structures and the bathymetry, reflection from seawalls, coastlines and from bed slopes, friction, wave breaking and floating docks influence to wave field.

5.4 Sea water elevation assessment

Protocol or the algorithm for the absolute sea level elevation assessment is based on three steps which are presented above and summarized as: (i) sea level caused by tidal forcing, (ii) sea level caused by barotropic pressure forcing and (iii) assessment of wind generated wave height in front of coastline. Sea water elevation assessment as a consequence of simultaneous effects for those three mechanisms is assessed as follows:

- From observed tidally induced oscillations, the first harmonic parameters (amplitude, period and phase) are determined;
- After all harmonic parameters have been determined, tidal induced sea level oscillation is determined by using Eq. (1);
- From observed barometric pressure data the change of sea level induced by the drop/rise of the barometric pressure is determined from Eq. (3);
- From observed tidally induced oscillations, first the harmonic parameters (amplitude, period and phase) are determined;
- Deep water wave parameters are determined depending on incident direction and wind velocity and duration parameters;
- For relevant incident directions numerical simulation of the wave transform has been performed by incorporating shoreline reflection coefficients deter-mined experimentally on site;
- Study area has been divided into ten zones fundamentally different in a way of reflection features;
- For each zone wave parameters have been determined within the zone close to the shoreline (4 m away from the shoreline);
- Final determination of the sea water elevation by incorporating three above-mentioned mechanisms is done by the following equation:

$$h_{sea} = h_t + h_{at} + h_{S(d=4m)} \quad (4)$$

which able to estimate absolute sea level in a simple way, where h_t represents tidally induced component, h_{at} barometric pressure induced component, and $h_{S(d=4m)}$ holds for significant wind generated height as found 4 m offshore.

5.5 Flooding zones

Based on the algorithm for the absolute sea level elevation assessment, the flood exposure maps has been developed using the scenarios associated with the following probability of occurrence [1]: floods with a low probability, or extreme event scenarios; floods with a medium probability (likely return period ≥ 100 years); floods with a high probability, where appropriate.

As a result, sea level for each part of Kaštel Kambelovac coastal area representing cumulative value of tidal, atmospheric pressure and wind impact is estimated. Particular coastal zones are determined based on the coastal area elevation in relation to sea level (Figure 8).

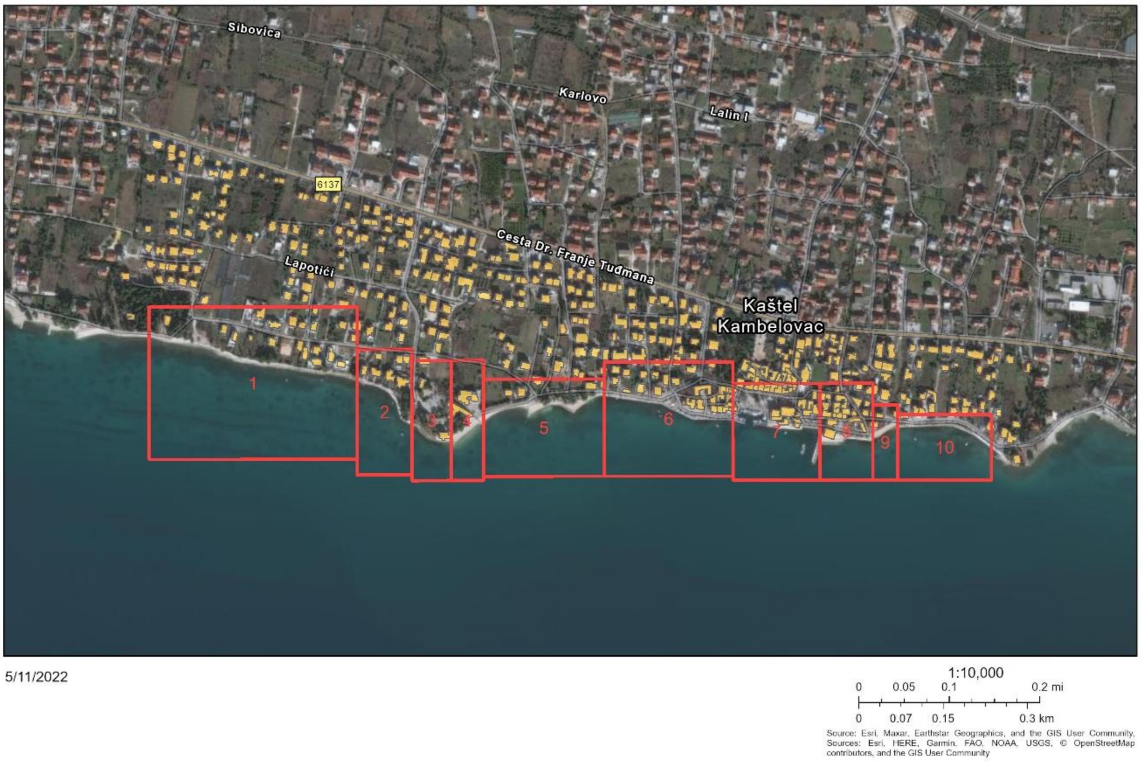


Figure 8. The ten flooding zones in the study area

6 Data collection from sensor devices

The model for sea level assessment caused by extreme sea waves needs real-time input data such as wind speed/direction and atmospheric pressure measurements. Those data are used to determine the wave height in the coastal zone.

Establishing the monitoring system implies an installation of a notification station for data storage and distribution of the data. Data sampling has performed with the specified frequency, while ensuring the possibility of averaging the data in accordance with the needs of the early warning application. Also, in addition to the above measuring equipment, it is necessary to provide the construction infrastructure to place the sensors. This includes the construction of a suitable foundation for the support of the column on which the wind direction and speed sensor and the atmospheric pressure sensor will be placed, the column itself and / or similar infrastructure required for smooth, safe and autonomous operation of the system.

In this case, the monitoring system with optimal, cost-effective, low-power hardware for sea level estimation has been implemented, aiming at real-time wind speed/direction and air pressure measurements. Given equipment has to install at a suitable location that is away from the obstacles, just in the accordance to the manufacturer mounting guidelines. These were necessary in order to obtain accurate readings from the sensors. An existing column at the location of the City of Kaštela, which satisfies the required condition, is used to install the equipment (Figure 9).

Figure 9. Location of installed equipment in the City of Kaštela

Recently, IoT systems for monitoring in different scenarios for purposes of ensure green, sustainable future are widely used to create smart environment tailored for particular human needs [37, 38]. Affordable equipment, miniaturized in its deployment, solar/battery powered are ensuring long lifetime, while the communication ranges are extremely increased and can be measured in kilometres in urban areas, which is especially found in meteorological scenarios [39, 40].

In this study, established sea level monitoring system uses IoT-based, solar powered anemometer (Barani design – Meteo Wind) and solar powered meteo-station (Barani design Meteo-helix) for monitoring air pressure.

The system is deployed to acquire current meteorological information used as an input in the developed model to estimate the sea level. The system is based on Lo-RaWAN IoT radio, which delivers the information to The Things Network (TTN) cloud system, which is then used by the cross-platform web/mobile application, called Waves [3], used as an early warning monitoring system.

LoRaWAN is one of the most widely used Low Power Wide Area technologies that aims to collect and communicate data from an end sensor device at a large distance, making it perfect for a scenario in which sensor devices collect wind and atmospheric data and convey them to a centralized system. LoRaWAN employs a typical star-of-star topology where end devices communicate data in a single hop to one or more gateway devices. These messages are further forwarded to the network and application server for further processing, allowing authorized data to be forwarded to other external services (e.g., using MQTT message forwarding). LoRaWAN allows battery-operated devices to periodically transmit sensor data over large distances, while minimizing consumption during inactive periods. LoRaWAN technology finds its application in smart city / smart agriculture environments where there is no need for real-time (every second) transmission from end devices. During the inactive period, end devices simply cut off the consumption allowing battery lifetime without any external power source up to a couple of years.

Given equipment is capable of sampling the measurements at different rates, starting from 10 minutes readings which are immediately delivered to the server architecture through LoRaWAN network.

The multilanguage system itself implements: (1) the algorithm that defines sea level based on the tidal, wind speed/direction and air pressure information; (2) information on the shore height at the dedicated measurement and early warning zones; (3) push notification logics that can be separately activated based on user's zone of the interest.

Figure 10 depicts the architecture of MeteoHelix weather station from Barani design that utilizes LoRaWAN as a radio technology. MeteoHelix [41] is an automatic all-in-one microweather station which is solar powered and can be active for up to 6 months without sun. It measures air temperature to WMO accuracy, air humidity to WMO accuracy with dew and frost point output, atmospheric pressure, and solar irradiation (pyranometer). Another sensor from Barani design was also installed that utilizes LoRaWAN communication - MeteoWind IoT PRO. MeteoWind [42] is used for wind monitoring and employs two sensors: a separate wind vane and anemometer. MeteoWind allows 4+ months of battery life without sun and maintenance-free service life with long-term measurement stability due to its elliptical cup and metal construction.

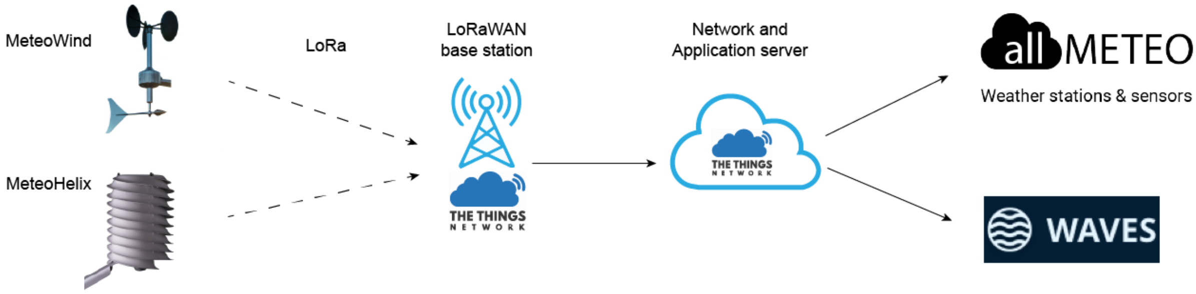


Figure 10. Architecture of LoRaWAN-enabled MeteoHelix and MeteoWind devices from Barani Design

Both devices (Figure 11) are placed at a relatively large height without any object within 50 m (Figure 12) from it, so that both the wind speed and wind direction are not distorted, while both are located in location of Kaštela Bay. Since both MeteoHelix and MeteoWind IoT PRO employ LoRaWAN communications to convey data over the air to the centralized system, The Things Network as a service provider was used to collect data for further processing. As a LoRaWAN gateway, an indoor Sentrius RG1xx LoRaWAN gateway device placed around 150 m from the sensor devices was employed that forward messages to The Things Network (TTN) cloud infrastructure. Once the message arrives at the gateway, it is forwarded to the TTN Network and Application server. Furthermore, TTN allows message forwarding from TTN infrastructure to our dedicated Waves Seafront Monitoring app using MQTT protocol, which is described more in detail in the following section.

Figure 11. Installation of MeteoHelix and MeteoWind IoT Pro devices

Figure 12. Devices placed at a relatively large height

7 Waves seafront monitoring architecture

For the pilot area of Kaštel Kambelovac, a digital sea level monitoring system is developed under the name “Waves Seafront Monitoring”. It also includes location service for the positioning of the user. Short description of the system is summarized from Šolić [3] and given below.

Waves Seafront Monitoring is a cross-platform mobile application that allows users to access and interactively view the current sea level, discretized by coastal segments with respect to coastal height. As shown in Figure 13, it comprises a cloud and client side. At the cloud side, Google Firebase server component is used to execute an evaluation algorithm based on data from the sensor it communicates with, serves as a server for these results, and performs user authentication. Sensor data comprising air pressure, wind speed, and direction are sent to The Things Network (TTN) cloud via LoRaWAN communication channel which is forwarded via MQTT protocol to TTN microservice. Once the packet with sensor data arrives, the TTN microservice captures and stores the LoRaWAN uplink data into the database and forwards the data through PMO algorithm to estimate sea level according to the data arriving from LoRaWAN sensors: wind speed and direction, and atmospheric pressure as well as sea tide level. As can be seen, an alarm notification can be sent to the application if the sea level exceeds a predefined level.

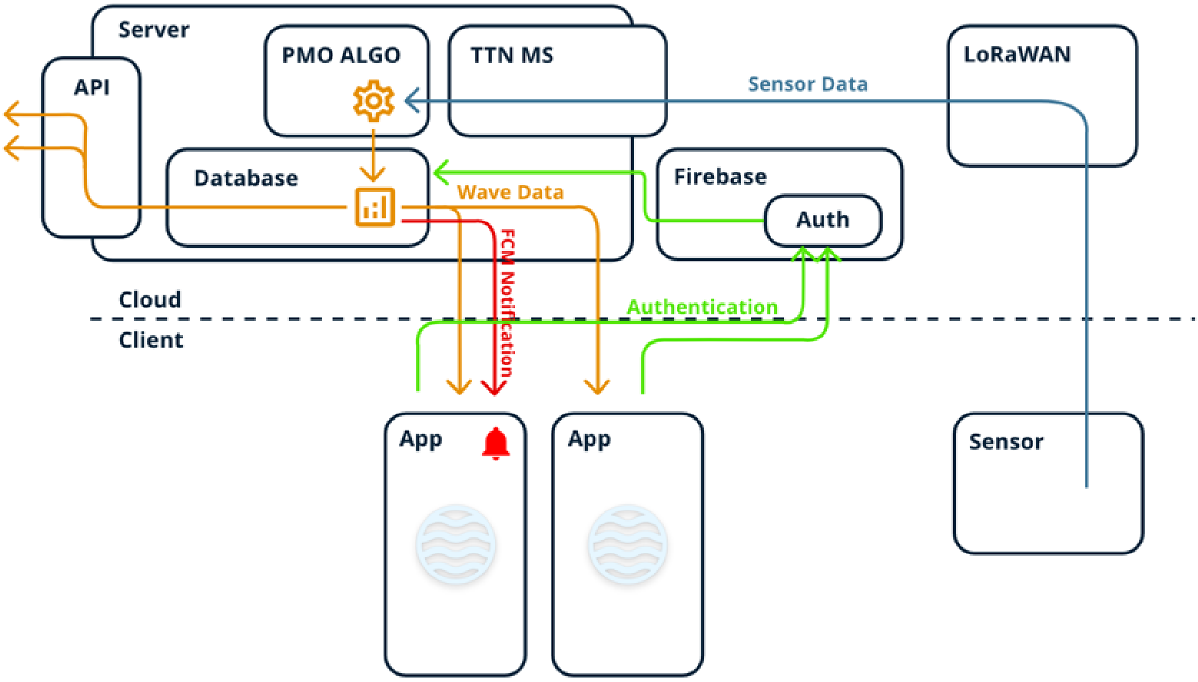


Figure 13. High-level overview of the implementation of the solution

Application front-end comprises the following elements, as depicted in Figure 14:

A. Login interface (Figure 14a) - initial interface for users when opening the application:

   1. Form - the user enters his login details (e-mail and password), and has the option of registration if he does not have an account by clicking on the appropriate link (Figure 14a, number 1),

   2. Logo – which indicate that the mobile application was realized within the Interreg Italy Croatia programme, PMO GATE project (Figure 14a, number 2).

B. Registration Interface (not shown). The login interface is analogous to the login interface, only it allows the user to create an account to access the application by entering login information. To simplify login to the system, there is no special validation of user accounts such as email confirmation.

C. Map interface (Figure 14b) is the central part of the application and contains the basic functionalities:

   1. At the top is a drop-down menu where the user has a choice between three languages: Croatian, English and Italian. By clicking on an option, the interface text adjusts the interface language (Figure 14b, number 3).

   2. Log out button from the application (Figure 14b, number 4).

   3. Values read from the sensor, updated over time depending on how often the data from the TTN arrives. From top to bottom, sea level is the sum of altitudes caused by: sea tide, wind speed and direction, and atmospheric pressure (Figure 14b, number 5). The total amount is calculated based on the algorithm submitted by the Client.

   4. Google maps with plotted polygons that correspond to discretized segments of the coast with regard to their heights (Figure 14b, number 6). The colour of the zone corresponds to the early warning status: green - safe, the sea level is below the coast level. Yellow - warning, the sea can exceed 20 cm above the height of the shore. Orange - dangerous, the sea can rise up to 50 cm above the height of the shore. Red - flooded, the sea exceeds 50 cm above the height of the coast. By clicking on an individual zone, the cards will position themselves next to the corresponding zone, and the map will be centred on the selected zone. Based on the costal height data, monitoring area is divided into 10 zones.

   5. Zone maps showing the names and photos of coastal zones. Here the user can see exactly the height of this segment of the coast, the estimated sea level in relation to the zone, and consequently the situation in that zone, coded in colours analogous to the zones on the map (Figure 14b, number 7). Each zone information contains the sea level in respect to the costal height, where the number with the minus sign shows how much the sea level is below the coastal height. Once the number becomes the positive, zones change the colour since this results with estimated flood. By moving the tabs left or right, the user can focus on a specific zone, and the map will centre on that zone.

6. Notification button (Figure 14b, number 8). By clicking on this button, individually for each zone, the user can indicate whether he wants to receive notifications when the situation in a particular zone changes.

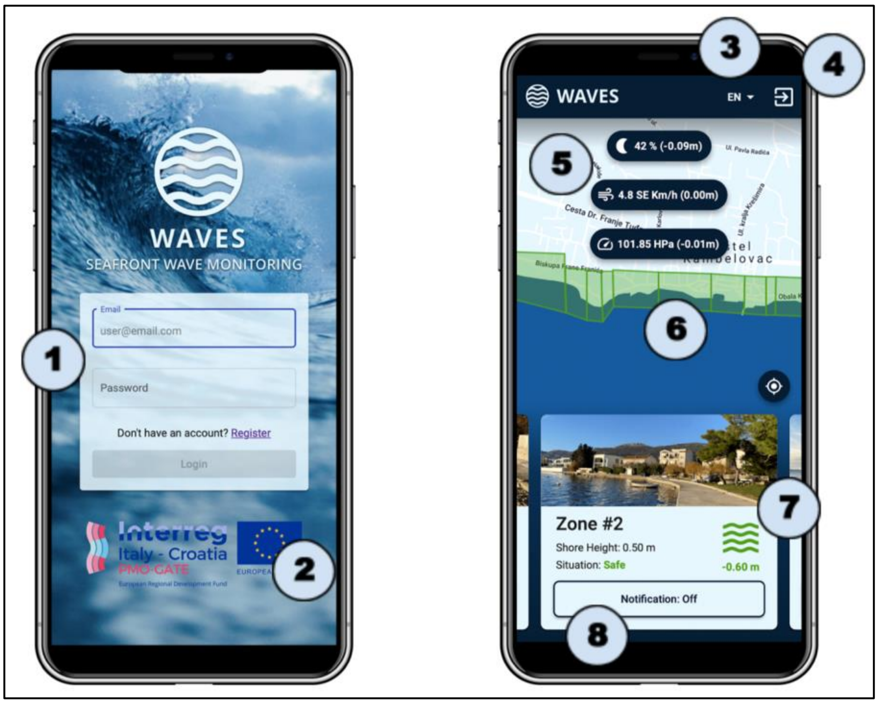


Figure 14. Waves Seafront Monitoring user interface [3]: (a) Login interface; (b) Map interface

8 Results of early warning system for extreme sea waves

8.1 Real-time prediction of sea level

Monitoring system has been installed in Kaštela test site to provide real-time measurement of wind speed, wind direction and atmospheric pressure. Measured data is used for real-time prediction of sea level, based on developed algorithm for estimation of sea level heights and information collected from the monitoring system which has to integrate into the algorithm. Real-time prediction of sea level values is obtained based on tidal simulations, atmospheric pressure values and wind speed and direction.

Resulting sea level values are compared with coastline elevation in order to identify the potential danger of flooding and issue on-time warning.

Figures 15 and 16 show wind speed and air pressure measured during the period of 9 days in February 2022. The data containing air pressure along with wind direction and speed was collected into a database of application. The data was used as an input to an algorithm for estimation of sea level height.

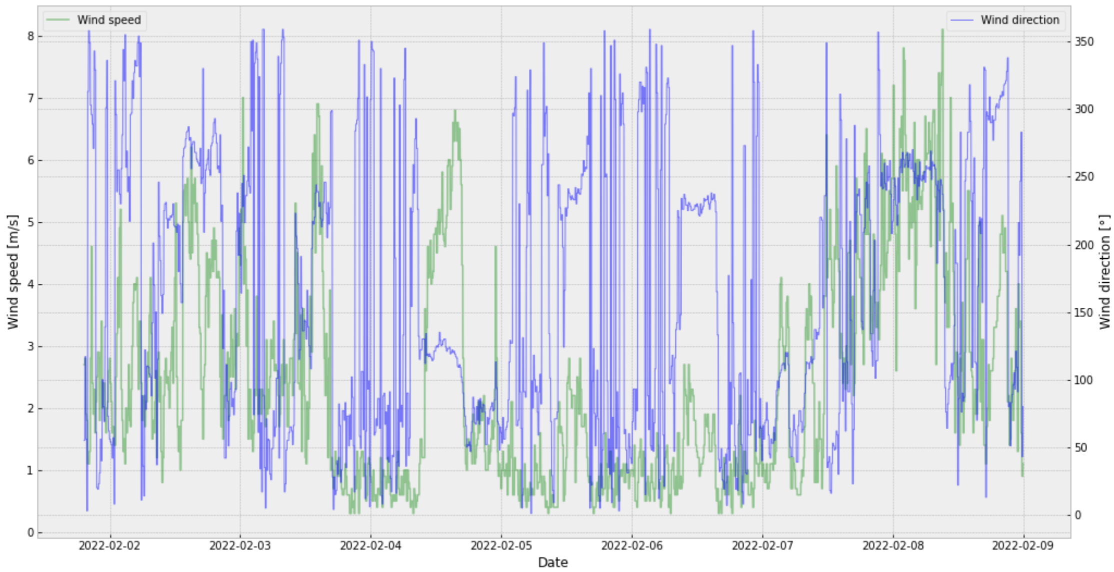


Figure 15. Wind speed obtained from LoRaWAN sensors

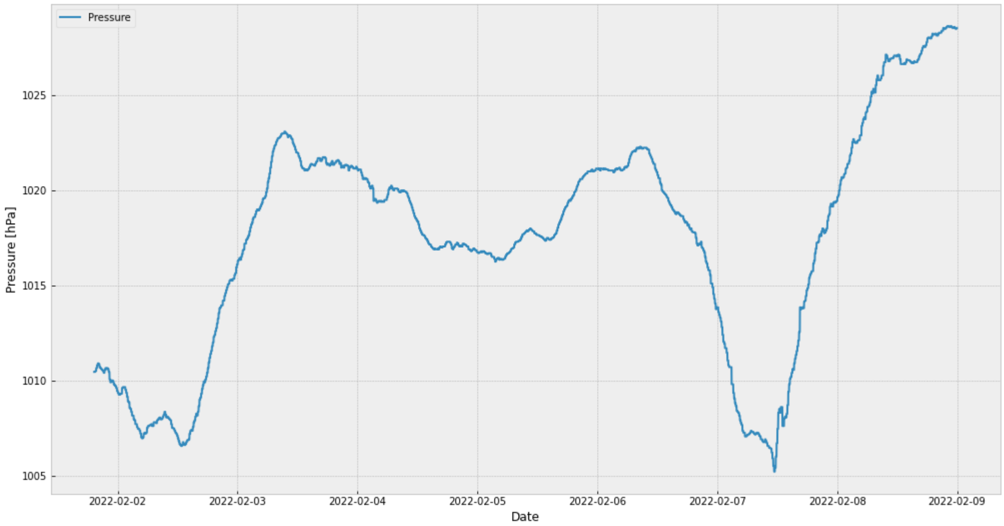
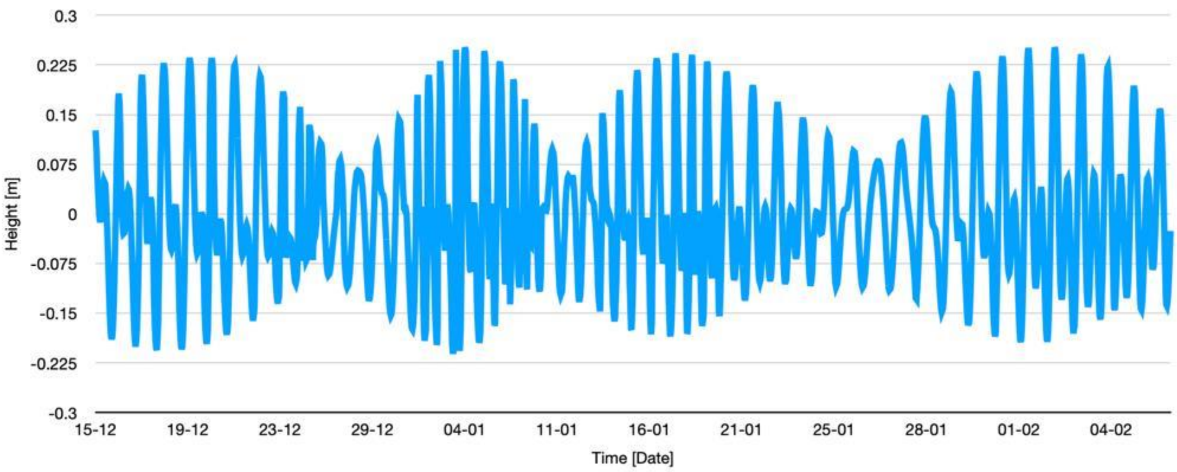
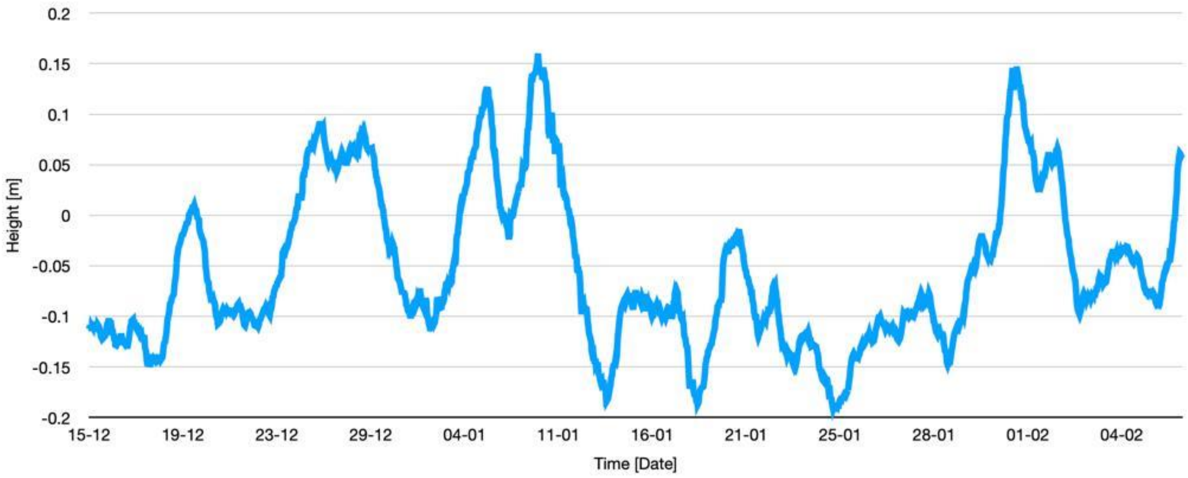


Figure 16. Air pressure obtained from LoRaWAN sensors

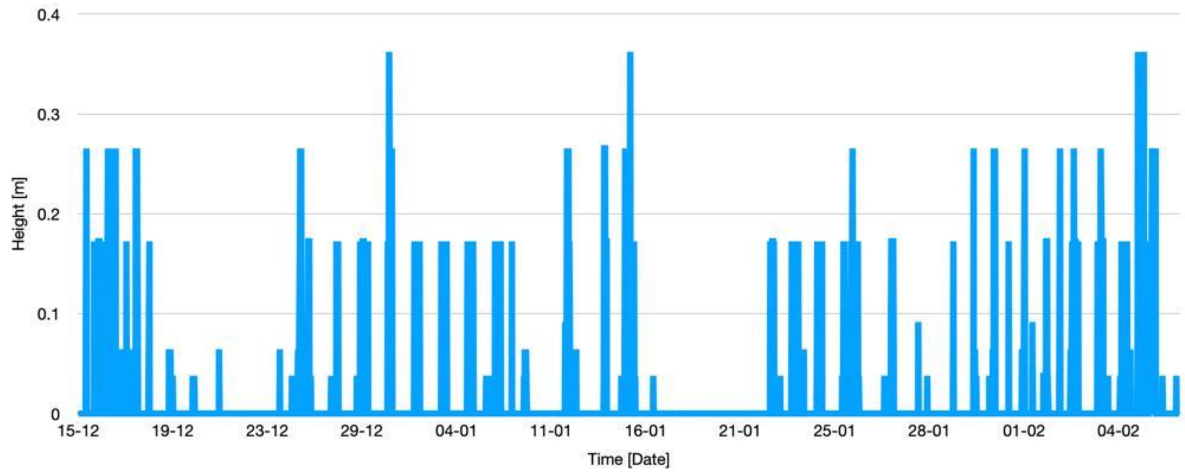
Figure 17 shows sea level height for each of the component (tidal effect, air pressure and wind) as well as total sea height calculated as a sum of the components for the period 15.12.2021-04.02.2022. The results is given for Zone 10. The estimated water level elevation is referred to the HVRS71 vertical reference system determined on the basis of mean sea level. Coastal height in individual zones was also determined in the same reference system. The sea level in respect to the costal height in each zone is calculated as difference between estimated sea level and coastal height. The number with the minus sign shows how much the sea level is below the coastal height and indicates that zone is "safe". The positive numbers show the level of risk depending the height of estimated flood.



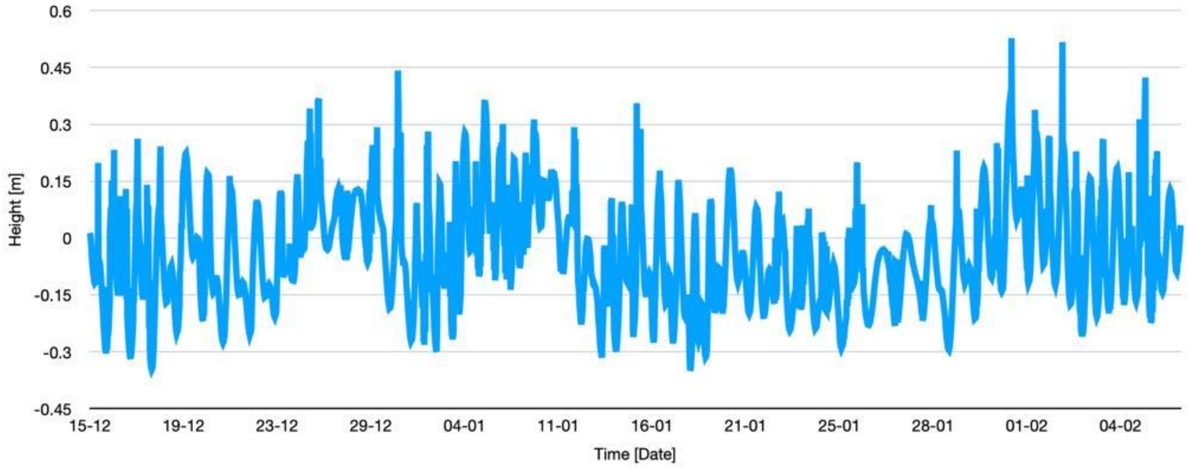
(a)


0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Height [m]
15-12
19-12
23-12
29-12
04-01
11-01
16-01
21-01
25-01
28-01
01-02
04-02
Time [Date]

(b)


0.4
0.3
0.2
0.1
0
Height [m]
15-12
19-12
23-12
29-12
04-01
11-01
16-01
21-01
25-01
28-01
01-02
04-02
Time [Date]

(c)



(d)

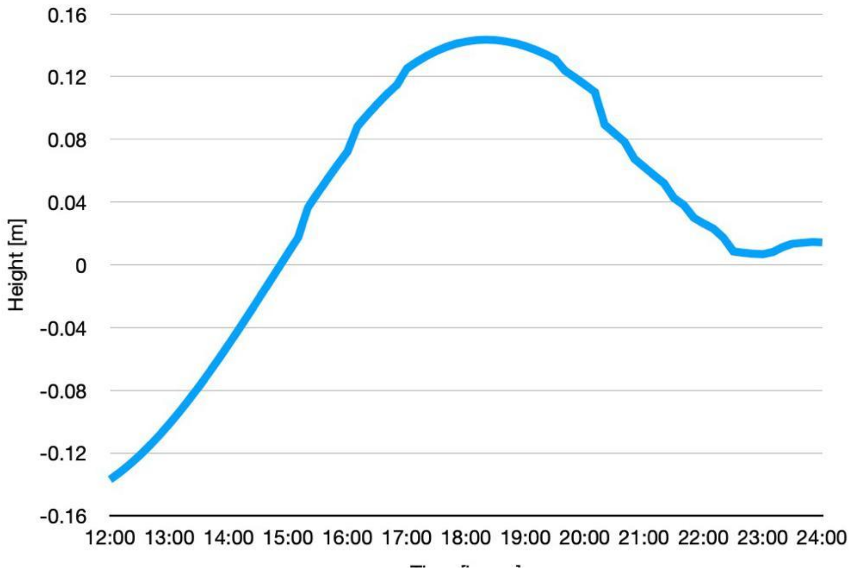
Figure 17. Calculated sea level height in the period 15.12.2021-04.02.2022. caused by: (a) tidal effect, (b) air pressure, (c) wind, (d) total sea level height

The results in Zone 10 in the period 15.12.2021-04.02.2022 show the highest value of estimated sea level equal to 0,525 [m] at January 31st 2022. Considering that the coastal height of Zone 10 is equal to 0,469 [m], the depth of water is 0,056 [m]. This indicates that early warning status is defined as “low level of the coastal flood risk” ($h < 0,20$ [m]).

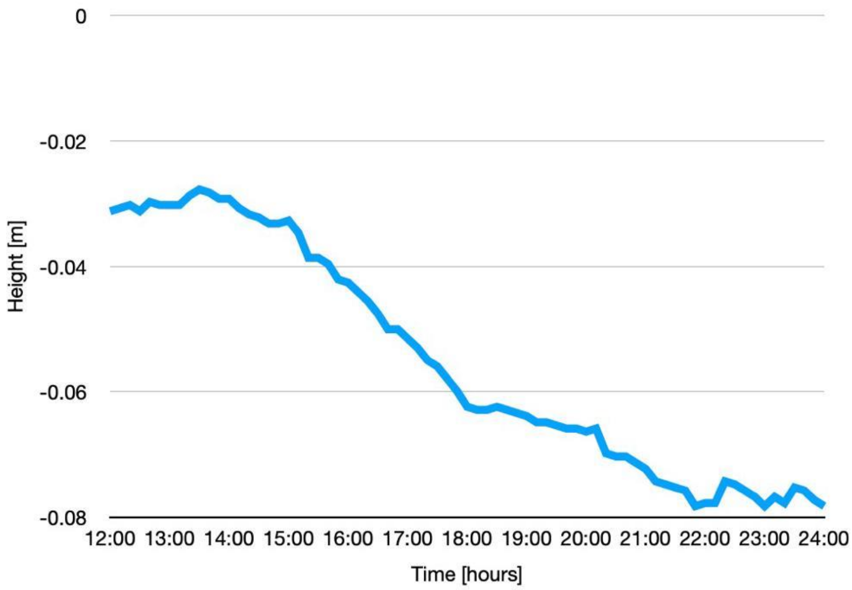
During the whole observed period (15.12.2021-04.02.2022) total sea level height only two times exceeded the coastal height and low level of coastal flood risk was achieved.

Figure 18 shows variation of sea level height during the observed period of 12 hours in February 4th, 2022 for each of the component (tidal effect, air pressure and wind) and the total sea level height calculated as a sum of the components.

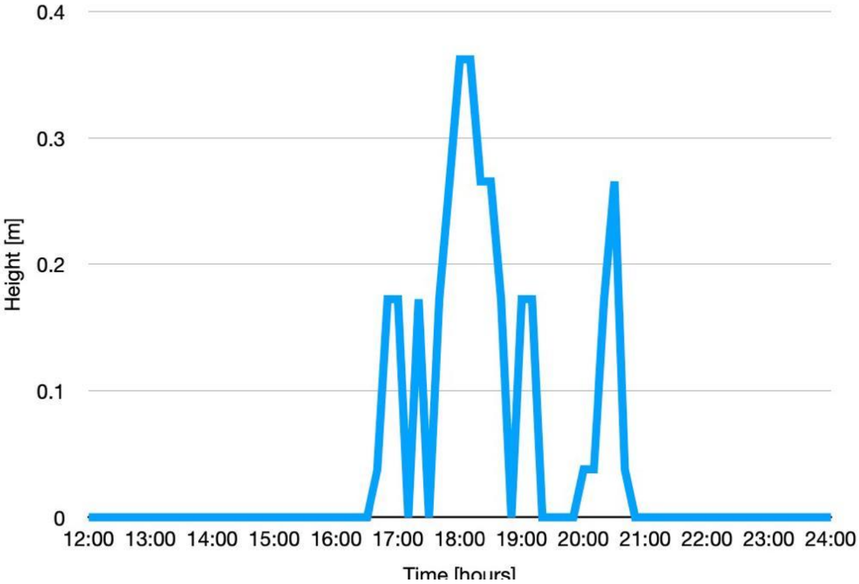
The total sea level height of 0,438 [m] was achieved in 18^{00}, and the depth of water is equal to -0,032 [m]. Therefore, the early warning status in that moment is defined as “safe”.


0.16
0.12
0.08
0.04
0
-0.04
-0.08
-0.12
-0.16
Height [m]
12:00 13:00 14:00 15:00 16:00 17:00 18:00 19:00 20:00 21:00 22:00 23:00 24:00

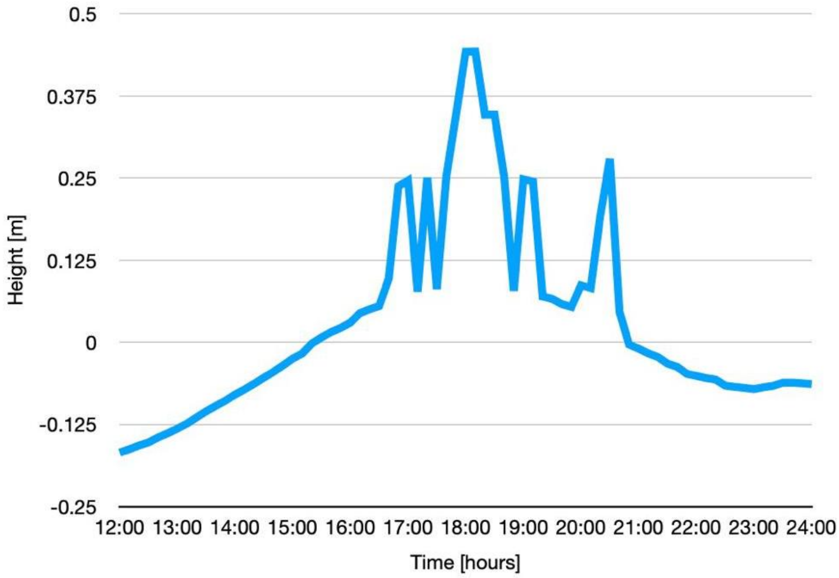
(a)


0
-0.02
-0.04
-0.06
-0.08
Height [m]
12:00 13:00 14:00 15:00 16:00 17:00 18:00 19:00 20:00 21:00 22:00 23:00 24:00
Time [hours]

(b)



(c)



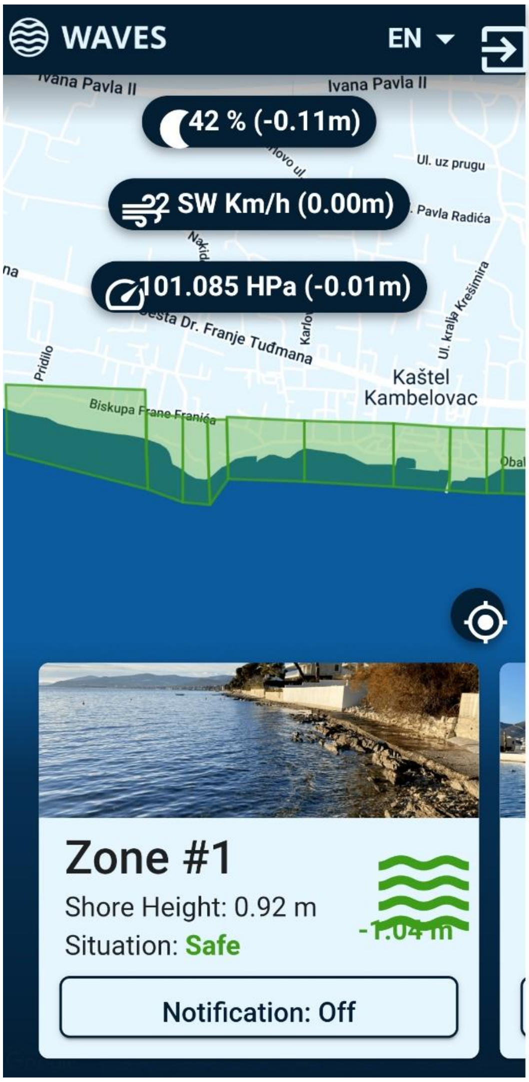
(d)

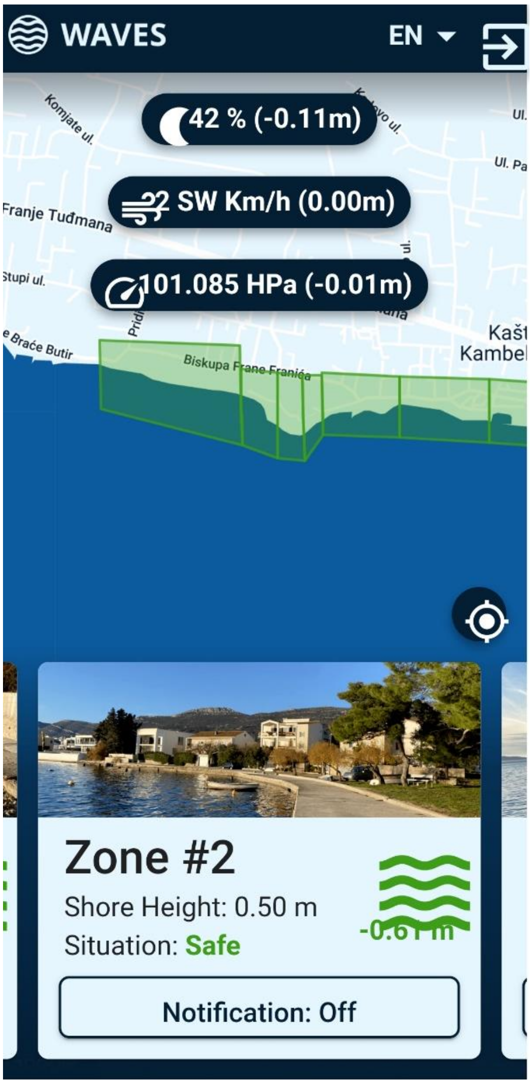
Figure 18. Calculated sea level height during the period of 12 hours (February 4th, 2022) caused by: (a) tidal effect, (b) air pressure, (c) wind, (d) total sea level height

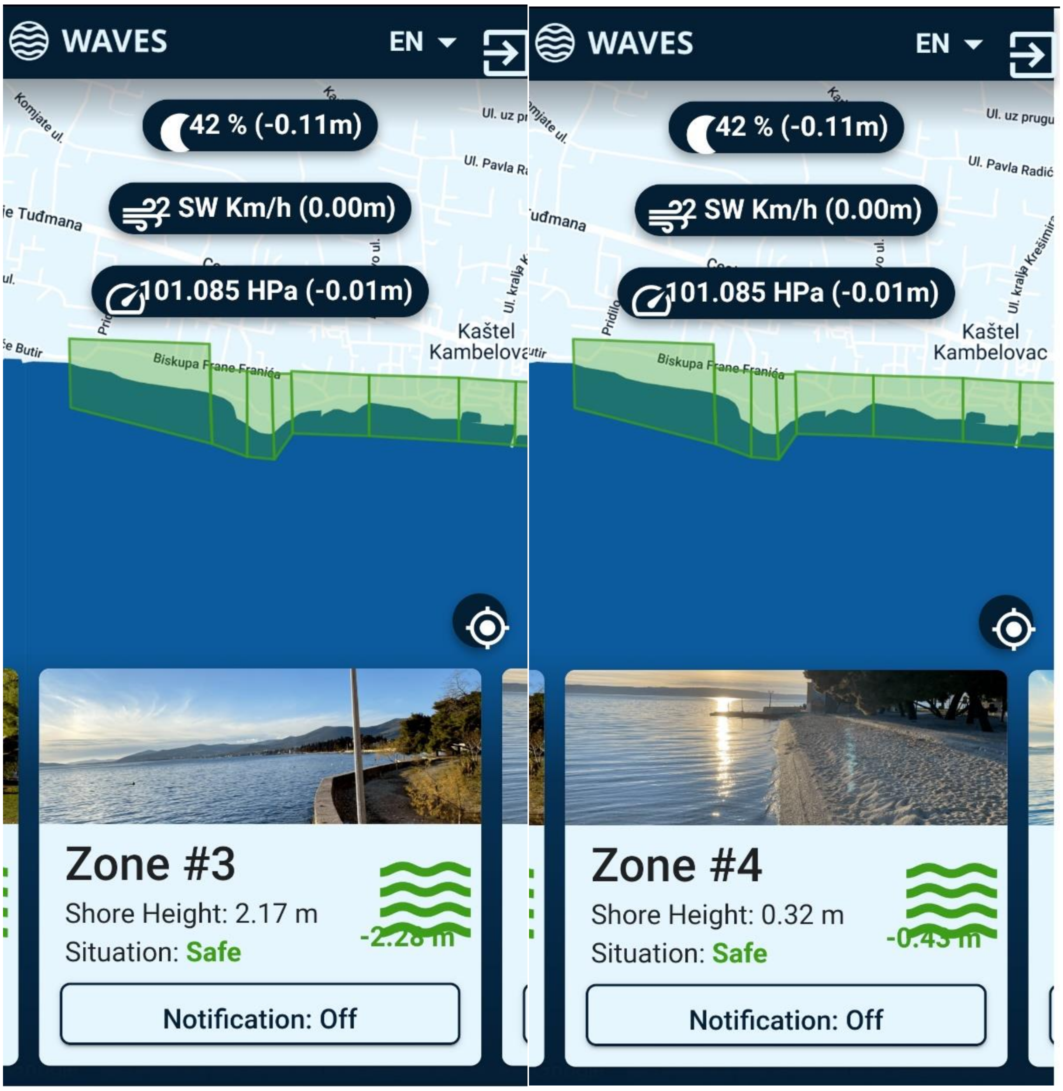
8.2 Results of mobile application

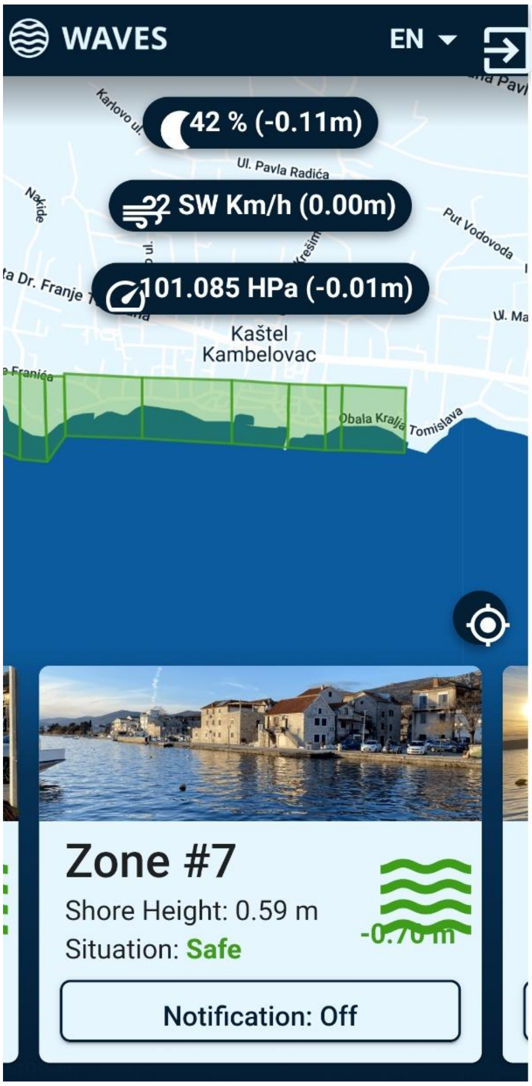
Mobile application shows main meteorological parameters in each zone which are basis for estimation of sea level height. The photo of the zone and shore height are also available to end users. Estimated sea level height is compared to the height of terrain in each zone and the depth of water in each zone is calculated as it was previously shown. Depending on the value of the water depth, the level of the hazard is determined and showed in each zone.

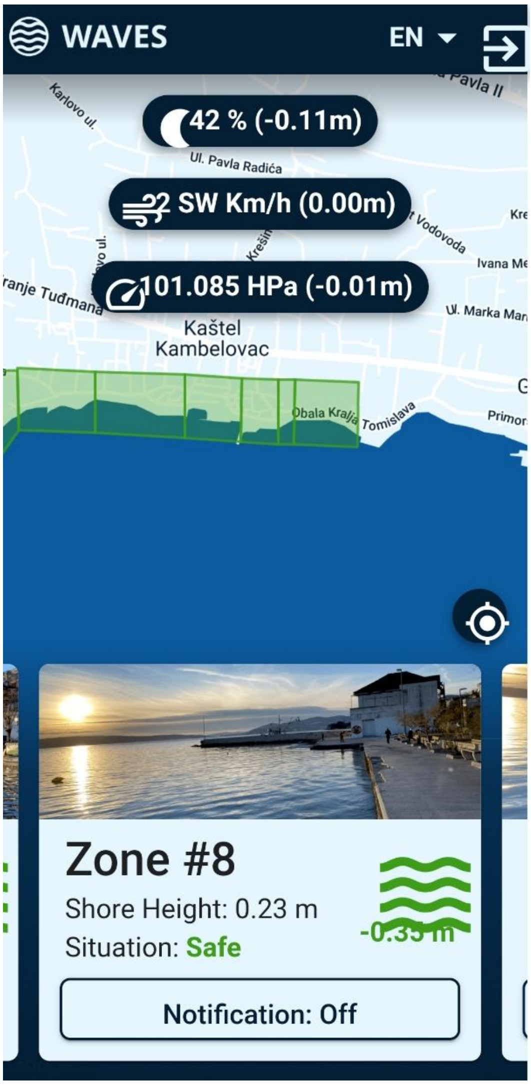
Figure 19 shows main information with the sea level height for 10 zones at June 15th 2022. The colour of the all zones correspond to the early warning status “green – safe”, because the sea level is below the coast level height which is indicated by number with the minus sign.


WAVES
EN
42 % (-0.11m)
SW Km/h (0.00m)
101.085 HPa (-0.01m)
Kaštel Kambelovac
Biskupa Frane Franića
Zone #1
Shore Height: 0.92 m
Situation: Safe
-1.04 m
Notification: Off


WAVES
EN
42 % (-0.11m)
SW Km/h (0.00m)
101.085 HPa (-0.01m)
Biskupa Frane Franića
Zone #2
Shore Height: 0.50 m
Situation: Safe
-0.61 m
Notification: Off


WAVES
EN
42 % (-0.11m)
SW Km/h (0.00m)
101.085 HPa (-0.01m)
Kaštel Kambelovac
Biskupa Frane Franića
Zone #3
Shore Height: 2.17 m
Situation: Safe
Notification: Off
WAVES
EN
42 % (-0.11m)
SW Km/h (0.00m)
101.085 HPa (-0.01m)
Kaštel Kambelovac
Biskupa Frane Franića
Zone #4
Shore Height: 0.32 m
Situation: Safe
Notification: Off


WAVES
EN
42 % (-0.11m)
SW Km/h (0.00m)
101.085 HPa (-0.01m)
Ul. Pavla Radića
Put Vodovoda
Kaštel Kambelovac
Obala Kralja Tomislava
Zone #7
Shore Height: 0.59 m
Situation: Safe
Notification: Off


WAVES
EN
42 % (-0.11m)
SW Km/h (0.00m)
101.085 HPa (-0.01m)
Ul. Pavla Radića
Kaštel Kambelovac
Obala Kralja Tomislava
Zone #8
Shore Height: 0.23 m
Situation: Safe
Notification: Off

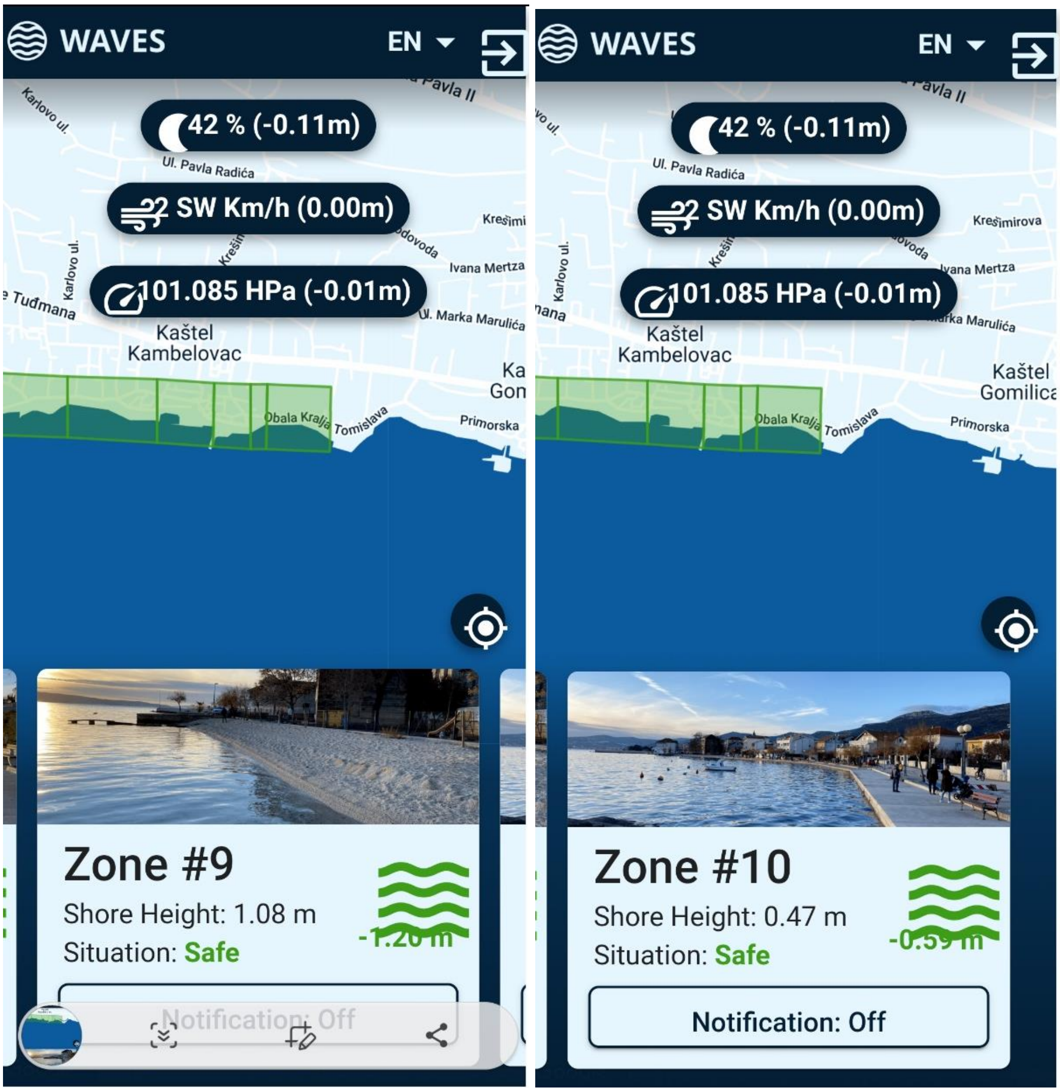


Figure 19. Early warning status of 10 zones, June 15th, 2022.

9 Dissemination and communication of risk information

Information how to install the developed “Waves – seafront monitoring” mobile application, as well as how to use and interpret the results, are available to the citizens, tourists and other users through the information board (Figure 20) placed in a visible place in the test area (Figure 21).

Figure 20. Information board.

Figure 21. Information board at the visible place of “House of Culture” in Kaštel Kambelovac.

10 Conclusion

This document elaborates the design and development of an early warning system for sea flooding in the City of Kaštela, Croatian test site of PMO-GATE project.

Starting from the knowledge about the flood risk in the area caused by extreme sea waves, the main causes of sea waves generation have been analysed and an early warning system has been designed. It includes and connect all important components: risk knowledge, causes of the risk, algorithm for estimation of sea waves height implemented, monitoring system with sensors that ensures input data for the algorithm and the "Waves – seafront monitoring" mobile application which gives information to the users about risk level at the area (low, medium and high).

Mobile application has several important possibilities: (1) to choose between three languages (Croatian, English and Italian), (2) to disseminate and communicate the risk information to users via the principle of push notifications, and (3) to send sound message for the blind and visually impaired people.

Information how to install and use developed "Waves – seafront monitoring" mobile application is available to the citizens, tourists and other users through the signage system placed in a visible place in the test area.

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