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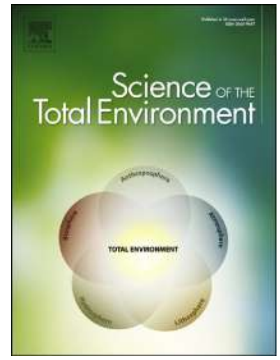

A geomorphological and hydrodynamic approach for beach safety and sea bathing risk estimation

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TITLE PAGE

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A geomorphological and hydrodynamic approach for beach safety and sea bathing risk estimation.

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Abstract

Coastal areas represent one of the most important economic driving forces for entire countries. In the last decades, along coastal areas it has been observed a marked increase in risk of bathing due to the advent of mass tourism, particularly during the summer season. Local and global reports on bathing-related incidents highlight the importance of beach safety in coastal management. This paper describes a cost-effective and semi-quantitative approach for beach safety and sea bathing risk estimation. The methodology was applied to a coastal stretch located in eastern Liguria (north western Italy, Ligurian Sea), which is characterized by high tourism vocation and can be considered indicative of some main features of Mediterranean shores. The peculiar geomorphological and hydrodynamic hazard descriptors and the beach accessibility (i.e., the exposure of bathers to hazard) of the study area have been evaluated by means of open source archive information, field surveys and expert judgement. Subsequently, probability theory was used to estimate the Hazard Index and the Risk of Bathing Index. The resulting zoning maps show that beach safety and risk of bathing do not have a uniform distribution along this coastal sector since both hazard and risk conditioning variables can frequently change from one site to another. Considering the large and rapidly expanding tourism activities in coastal environments, the obtained zoning maps reveal that the proposed method can be a flexible and simple tool for stakeholders in charge of coastal management. The proposed approach may be also adapted to other coastal-type environments by means of an accurate identification of hazard and beach accessibility descriptors that better characterise the stretch of coast under consideration.

Keywords: Beach accessibility; Beach safety; Coastal hazard; Coastal management; Risk assessment.

1. Introduction

Coastal areas represent an important worldwide economic source (Jiménez et al., 2007). In the last decades, many coastal areas have been heavily affected by urban sprawl, favouring the development of numerous commercial, cultural and social activities. Among these activities, tourism sunbathing gained in importance, becoming one of the most significant economic driving forces for villages, cities and sometimes for entire countries as well (European Environment Agency, 2006). However, where an unsafe coastal zone development has occurred, together with an advent of mass tourism, a growing number of people can be exposed to risk (Hall, 2001; Hartmann, 2006; McCool et al., 2009; Pranzini et al., 2018). As reported by Creel (2012), it is relevant to note that about half of the world population live within 200 km of the coast and these figures are likely to double by 2025. Owing to its great economic and social relevance, beach tourism and sunbathing have become increasingly more important aspects of coastal zones management, as reflected in various policy documents (EU Demonostration Programme On Integrated Coastal Zone Management, 1999; European Commission, 1999; World Health Organization, 2003). For Coastal Zone Planning (CZP) purposes, it is important to understand factors that could prejudice bathing safety so as to plan and design interventions (i.e., structural and non-structural measures) aimed to guarantee security and to preserve or enhance tourism (Bush et al., 1999; Morgan et al., 2003; Short, 2007). In this regard, it is essential to take stock of geo-morphological features, sociological settings and infrastructures (Clark, 1997).

Beach safety assessment includes the analysis of a set of circumstances related to boundary conditions (natural and anthropic) that could cause injuries or accidents to the bathers. In literature, some methodological approaches have been proposed by Short (2007) and Williams & Micallef (2009), who defined different hazard factors (natural and anthropic) and boundary conditions for both risk assessment and management. The theme of beach safety has been prevalently addressed for oceanic environments, where peculiar features (e.g., large tidal excursions) exist (Short, 2007;

Williams and Micallef, 2009). However, in the last years beach safety has become an important topic also along Mediterranean coast (De Pippo et al., 2008; Williams, 2011; Pranzini et al., 2018). Numerous water safety and rescue authorities in many regions and countries around the world provided reports on bathing-related incidents. For example, along the Australian coasts, in the 2015-2016 season, 130 drowning fatalities occurred (RLSSA, 2016) while, due to rip currents, 137 and 130 drownings/year were recorded in UK and USA, respectively (Pranzini et al., 2018). In spite of less extreme boundary conditions than in oceanic environments, numerous costal hazards can be also detected in the Mediterranean Sea, where hazard scenarios often derive from geomorphological and hydrodynamic features. In France, along the coast of Marseille, 449 cases of unintentional drownings were identified between 2000 and 2011 while 1235 drownings, resulting in 496 deaths, were recorded in the summer 2012 (Bessereau et al., 2016). Along the Italian coasts, during the summer time, between 90 and 100 drownings are on average detected (Funari and Giustini, 2011). The importance of beach safety along Mediterranean coasts is also highlighted by the strong tourism vocation of this region (Quintiliani, 2009). According to the United Nations World Tourism Organization (UNWTO, 2005), about 20 per cent of international tourist arrivals were recorded in the Mediterranean region in 2004.

The aim of this study is developing a method for beach safety assessment using a probabilistic approach (De Pippo et al., 2008; Wolfgang Fuhs, 1975). The methodology was applied along a 20-km stretch of coast located in eastern Liguria (northwestern Italy, Ligurian Sea), which can be considered indicative of some main features of Mediterranean shores (e.g., cliffs, embayed beaches, pocket beaches, anthropic coasts).The proposed method takes into account some peculiar boundary conditions of Mediterranean coasts, namely the hazard descriptors, and the beach accessibility, which can be assumed as the exposure of the bathers to hazard. We produced beach safety and risk of bathing zoning maps, which can be essential tools for CZP purposes (Bush et al., 2001; De Pippo et al., 2008; Rovere et al., 2015; Rovere et al., 2010). The proposed methodology can be conceived as a semi-quantitative, cost-effective and flexible approach for beach safety and sea-bathing-risk evaluation and mapping at local scale (from 1:10000 to 1:5000 scales). Such methodological approach may be also applied to other coastal-type environments by means of an accurate identification of hazard and beach accessibility descriptors that better characterise the stretch of coast under consideration. The results of this study are expected to give a useful contribute to the improvement of beach and coastal management.

2. Materials and Methods

In this section, we describe in some detail the process we went through to assess sea bathing risk. It is well established by technical terminology that risk is the combination of the probability of an event to occur and its negative consequences (UN-ISDR, 2009). The general definition of risk implies the analysis of hazard in conjunction with risk-exposed elements (Corominas et al., 2014). In terms of sea bathing risk, hazard includes coastal processes that can cause damage, disruption and even casualties while elements at risk can be identified by bathers.

The flowchart in Figure 1 sets out the conceptual strategy followed in defining the proposed approach. The first step consists in identifying the set of variables that, from a geomorphological and hydrodynamic point of view, could be potentially source of hazard for beach-users. The choice of such variables was made according to literature (Bush et al., 1999; Clark, 1997), beach management guidelines (Short, 2007) and based on the geomorphological and hydrodynamic features of the considered coastal areas. For example, we did not take into consideration tidal excursion as usually weak in Mediterranean Sea. The second step describes the conditions that allow to define the accessibility of beach-users to the bathing zone. In general terms, the accessibility can be conceived as an indicator of the presence of people in potentially hazardous bathing zones. Hazard and accessibility descriptors were qualitative evaluated by means of open source information, available data from literature and, in some cases, with observations from field surveys. Eventually, probability theory is used to evaluate the Hazard Index (HI) and the Risk of

Bathing Index (RBI). The outputs of the analysis are beach safety and sea bathing risk zoning maps at 1:10000 scale.

2.1. Hazard Index

Beach hazards were defined as elements of the beach and surf environment that expose people to danger or harm (Short, 2007). By considering geomorphological and hydrodynamic features, we calculated the Hazard Index (HI) according to the following variables:(i) slope stability (St); (ii) wave breaking (W); (iii) rip currents (C); (iv) anthropic structures (A).

2.1.1. Slope Stability

Coastal cliffs can be dangerous environments because of their steepness and geomorphological instability, particularly where rocky coasts are retreating as result of erosion processes (Bird, 1990; Naylor et al., 2010). Since slope mass movements affecting steep cliffs are instantaneous phenomena with virtually no warning signs, coastal cliffs represent a potential threat to people standing on beaches located at the cliff base (Teixeira, 2006; Martino and Mazzanti, 2014). This highlights as slope stability represents a key hazard conditioning variable in performing an effective risk of bathing assessment (Mortimore and Duperret, 2004; Dickson and Perry, 2016). In terms of slope stability, three hazard categories were considered: (i) low, (ii) moderate and (iii) high (Table 1). The stability classification of slopes and landslides was carried out by modifying that provided by Keaton & De Graff (1996). Regarding the state of activity of landslides, we referred to the definitions used in the Multilingual Landslide Glossary (WP/WLI, 1993). In particular, low hazard was assigned to apparently stable slopes/landslides or to coastal stretches where slopes were absent. Potentially unstable slopes and inactive landslides were considered as characterized by moderate hazard. High hazard was assigned to unstable slopes and active, reactivated or suspended landslides. Stability was also considered for protection works, embankments, masonry or concrete walls where they constrain shoreline segments or beaches. According to good, fair or poor stability conditions of protection measures, low, moderate or high class of hazard was assigned, respectively (Table 1).

2.1.2. Wave Breaking

Wave breaking is a direct effect of waves refraction phenomena and represents an important process in beach safety analysis. In the breaker zone, turbulences and currents are capable of underwater drag an unfortunate bather. Furthermore, in this case, the victim can be drag on seaward away from the shore, or towards the shore, where they could be hurt (Short, 2007). The type of wave breaking is influenced by the beach slope and consequently by the grain size (i.e., sediment friction angle). The different types of wave breaking can be classified through the Iribarren's number (ξ_0), which allows to identify four wave breaking types (i.e., spilling, plunging, surging, and collapsing) (Battjes, 1974).

Information on the hazard coming from wave breaking types are reported by Short (2007) (Supplementary material, Table S1 and Figure S2). In case of wave breaking on rocky coasts and in presence of engineering structures, the highest hazard situation can be considered. This assumption comes from the fact that near rocky coast bathers have more difficulties both in getting-in or coming-out the water, independently of the slope steepness and the sea conditions.

In this study, hazard classes related to wave breaking processes are summarized in Table 1 and they were established coupling surf-similarity information provided by Short (2007) (Supplementary material, Figure S2) with sea state conditions (i.e., significant wave height Hs) recorded during rescue operations along the Italian coasts (Funari & Giustini 2011) (Supplementary material, Figure S3).The Italian Health's Superior Institute (ISTISAN) dataset (Funari & Giustini 2011) shows that 36.2% of rescue operations occurred in case of slight sea conditions, 31.6% during moderate swell conditions and 22.6% during calm sea conditions. Only 9.6 % of rescue operations occurred in agitated sea conditions, probably due to the fact that in case of rough sea there is more hazard perception from bathers (Funari and Giustini, 2011). In case of calm or almost calm sea conditions, it can be reasonably deduced that accidents are not strictly related to incident waves, but more likely due to subjective factors (e.g., illnesses and low swimming skills of bathers).

2.1.3. Rip Currents

Rip currents are narrow and concentrated seaward-directed flows of water that originate close to the shoreline and extend seaward across the surf zone, and beyond (Castelle et al., 2016). Moreover, rip currents can occur around groynes and other coastal structures (e.g., breakwaters and rocky headlands), which provide a boundary to the wave-induced flow field (Scott et al., 2016). These rips are known as "boundary-controlled rip" (Castelle et al., 2016). On average, the rip currents velocities range between 0.3 and 0.8 ms^{-1}, usually decreasing in strength toward high tide (Brander and Short, 2001; MacMahan et al., 2005). Rip current pulses are considered major causes of swimmer rescues (Short, 2007). Each year, these phenomena cause hundreds of drowning deaths on beach worldwide and they are therefore the leading deadly hazard to recreational beach-users (Brighton et al., 2013; Castelle et al., 2016). In fact, in high energy environments mega-rips and rip currents can create risky conditions for bathers because of their mean speed may exceed 2 ms^{-1} (Brander and Short, 2000; Short, 2007). Because of rip currents formation strictly depends on coastal geomorphology, we established hazard categories related to rip currents development based on coastal morphological features (Table 1). Accordingly, we assigned low hazard conditions in cases of linear open beaches without morphological indicators of rip currents generation (e.g., bars or cuspids); moderate hazard conditions were attributed to open coasts with barred morphology, where the rip currents can locally persist for days, weeks and even months in association with transverse bar and rip morphologies together with modal wave conditions (Short, 2007); high hazard conditions were considered for coastal stretches affected by anthropic structures (e.g., groynes, breakwaters, jetties, piers) or by natural features (e.g., headlands) (Leatherman and Fletemeyer, 2011), where the topographic rips can be originated (Short, 2007). These currents are persistent (Pattiaratchi et al., 2009) and have stronger and more confined flows than open beach fixed rips, carrying water masses (and swimmers) at greater distances seaward (Short, 2007).

2.1.4. Engineering Structures

Groynes and breakwaters installed for coastal erosion prevention constitute a potential danger for bathers (Reeve et al., 2004; Scott et al., 2016; U.S. Army Corps Of Engineers, 2002; World Health Organization, 2003). Since many decades, detached or nearshore breakwaters have been extensively adopted for coastal protection purposes and for beach creation, also with considerable success, particularly in environments where the tidal range is negligible or small.
Detached breakwaters allow to create a zone of reduced wave energy behind the structure as well as local patterns of wave induced currents that, in turn, create a zone of sand deposition in the lee side of the structure (Reeve et al., 2004). Furthermore, in the external zone of structures, namely towards the open sea, high hazard conditions for bathers can occur due to wave reflection processes or turbulence genesis (Table 1). Groynes can be source of hazard scenarios due to their role in turbulence genesis. However, hazard-related levels can be considered moderate in reason of the absence of a confinement structure between the shore and the open sea. In addition, the contribution of groynes and detached breakwaters to the rip currents generation should not be neglected (see section 2.1.3). Eventually, the presence of anthropogenic hard structures near the surf zone also represents a source of hazard (see section 2.1.2).

2.1.5 Hazard Index assessment

The level of coastal hazard was determined by means of the calculation of the Hazard Index (HI). The considered hazard descriptors were properly combined using basic principles of probability theory (Spiegel & Stephens, 2008). Each presented hazard variable (i.e., St, W, C, A) was considered as an independent event. Therefore, based on the rules of probability of multiple events, the following equations can be written:

$$P(St \cap W \cap C \cap A) = P(St) \cap P(W) \cap P(C) \cap P(A) \qquad (1)$$

$$P(St \cup W \cup C \cup A) = P(St) + P(W) + P(C) + P(A) \qquad (2)$$

Equation 1 gives the probability that all the events will occur simultaneously while equation 2 expresses the probability of a single event occurrence. The probability of occurrence of the opposite event $\bar{X}$ (i.e., probability of non-occurrence) satisfies the following equation:

$$P(\bar{X}) = 1 - P(X) \qquad (3)$$

Consequently, for each combination of the considered hazard descriptors, the Hazard Index was calculated by using the following formula:

$$HI = [1 - (1 - P(St))(1 - P(W))(1 - P(C))(1 - P(A))] \qquad (4)$$

To quantify each hazard descriptor variable three probability values were assigned according to the established hazard levels (Table 1): 0.01 (A-low hazard), 0.50 (B-moderate hazard), 0.99 (C-high hazard).

The Hazard Index provides information on the degree of coastal hazard as a result of geomorphological, hydrodynamic and anthropic coastal features. By applying the equation 4, four classes of coastal hazard were established based on the following conditions (Supplementary material, Table S4):

- Very low hazard ($0.01 \leq HI < 0.50$): all the four independent hazard variables have low hazard (Table 1 - A-Low).

- Low hazard ($0.50 \leq HI \leq 0.65$): one independent hazard variable has moderate hazard (Table 1 - B-Moderate) and the other ones have low hazard (Table 1 - A-Low).
- Moderate hazard ($0.65 < HI \leq 0.997$): at least two independent hazard variables have moderate hazard (Table 1 - B-Moderate) and the other ones have low hazard (Table 1 - A-Low), up to more hazardous conditions where one independent hazard variable has high hazard (Table 1 – C-High), one has moderate hazard (Table 1 – B-Moderate) and the other ones have low hazard (Table 1 - A-Low).
- High hazard ($0.997 < HI < 1$): at least one independent hazard variable has high hazard (Table 1 – C-High), two have moderate hazard (Table 1 - B-Moderate), and one has very low hazard (Table 1 - A-Low), up to the most hazardous condition where all the four independent hazard variables have high hazard (Table 1 – C-High).

The HI values associated to the different classes of hazard are necessary for both the calculation of the Risk of Bathing Index (RBI, see section 2.3) and to make fully automated the procedure for transferring the results on the HI maps (Figure 4, 5, 6 and 7). In fact, Equation 4 can be implemented in a GIS (Geographic Information System) environment and different colours (i.e. green, yellow, orange and red) can be associated to well defined ranges of HI. In this way, the procedure for depicting the different hazard classes on a map results very quick. As shown in Figure 2a, it is reasonable to assume that the hazard decreases as the beach safety increases.

2.2. Accessibility

The opportunity for tourists to enjoy beaches often depends on the quality and availability of accesses such as roads or paths (Williams and Micallef, 2009). The accessibility to the beaches is therefore strictly related to the closeness to urban areas, where the majority of population resides. For this reason, in these areas potential risk conditions for bathers can occur more frequently. On the other hand, in rural areas characterized by low population density, risk scenarios are less frequent, even more where the access points are few, such as along coastal cliffs (Williams and Micallef, 2009). The accessibility plays a key role in the quantification of the risk for bathers. In this study, the accessibility, denoted as X_0, can be therefore assumed as a measure of the elements that are exposed to risk. As an example, in coastal areas where the accessibility is strongly limited or precluded, the risk for beach users was considered to minimum levels. Accordingly, accessibility was considered as the risk conditioning variable. In details, five accessibility levels were considered in order to describe the possible scenarios in terms of coastal crowding: low, low to moderate, moderate, moderate to high, high (Table 2). A weighted value $P(X_0)$ was assigned to each class: 0.01 (1%) - low; 0.25 (25%) - low to moderate; 0.5 (50%) - moderate; 0.75 (75%) - moderate to high; 0.99 (99%) - high.

2.3. Risk of Bathing Index

Risk can be intended as a measure of the probability and severity of an adverse effect to health, property or the environment (Fell et al., 2008). Therefore, risk analysis requires the identification of the elements at risk. Dealing with risk of bathing, the elements exposed to risk can be bathers, tourists or people attending beaches. Nevertheless, a proper sea bathing risk analysis should take into consideration at least one variable, which from here it will be named risk conditioning variable (X_0), capable of influencing the degree of risk along the different shoreline segments. By using the probability theory, combining hazard conditioning variables (i.e., St, W, C, A) with the risk conditioning variable (X_0) (Figure 2), the Risk of Bathing Index (RBI) can be calculated (equations 5 and 6).

$$RBI = P(X_0)[1 - (1 - P(St))(1 - P(W))(1 - P(C))(1 - P(A))] \qquad (5)$$

or equivalently, using the definition of HI in equation (4), one gets

$$RBI = P(X_0)HI \qquad (6)$$

Different classes of risk were established through a matrix in which the classes of coastal hazard were put into relation with the classes of accessibility. In fact, the use of matrices is a common approach useful to conduct subjective risk assessment (Markowski and Mannan, 2008). From the intersection of coastal hazard and accessibility classes the following four risk classes, characterized by RBI numerical values, were identified as follows (Figure 2b): Very low risk (RBI < 0.125); Low risk (0.125 ≤ RBI < 0.250); Medium risk (0.250 ≤ RBI < 0.750); High risk (0.750 ≤ RBI < 1). As for HI (see section 2.1.5), the RBI values associated to the different classes of risk are useful to make fully automated the procedure for transferring the results on the RBI maps (Figure 4, 5, 6 and 7). After different symmetric matrices being tested (e.g. 4x4), the adoption of a matrix consisting of 20 cells (4x5), which comes from a process of re-zoning of cells (Markowski and Mannan, 2008; Ni et al., 2010), was chosen to put forward a more meticulous classification of risk.

2.4. Study Area

The proposed method was applied along a coastal stretch of the Western Mediterranean basin, precisely located along the easternmost sector of the Liguria region (north western Italy), between the municipality of Moneglia and the headland of Punta Mesco (Figure 3). As reviewed by Anthony et al. (2014), Mediterranean coastline consists prevalently of rocky coast (about 54%), commonly with high cliffs, with respect to depositional shores. Low-elevation coasts comprise open-beaches and a variety of embayed beaches (Pranzini et al., 2013), usually enclosed between rocky headlands, which are often associated with sandy-gravelly pocket beaches (Anthony, 2014). According to Anthony (2014), many Mediterranean coastal sectors, especially in the western portions, have been strongly affected by human interventions causing the modification of both the original shore type and morphology, with important effects on sediment dynamics. The selected study area can be considered indicative of some typical geomorphological features of Mediterranean shores. The total length of the study coastal stretch is about 20 km, of which approximately 70% is rocky coast, about 15% is formed by beaches and the remaining 15% consists of artificial coast (Figure 3). The local geomorphology is characterized by a sequence of small coastal basins with the main water divide located very close to the coastline, which is characterized by rocky coasts alternating with embayed beaches, pocket beaches and stretches of artificial coast, which mainly consist of engineering works to protect beaches (Cevasco et al., 2000; Fierro et al., 2015) or wide landslide bodies (Cevasco & De Vita, 2015; Cevasco et al., 2018) against marine coastal erosion. The main towns (i.e., Moneglia, Deiva Marina, Framura, Bonassola and Levanto) are built on small coastal plains and on narrow strips of land close to the mouth of streams, where it can be noted a higher concentration of population and of human activities (Figure 3).

From a geological point of view, the study area is part of the northern Apennines, a mountain belt formed during the Tertiary by the tectonic superimposition of the Ligurid units onto the Adria plate margin. From west to east, along the coastline outcrop sedimentary rock formations, mainly made up of clay-shales and sandstones (Upper Jurassic-Cretaceous) followed by ophiolite rocks (relicts of the Jurassic oceanic crust) and lastly by sedimentary rock formations mainly constituted by claystones and sandstones (Upper Trias–Miocene) (Giammarino et al., 1990).

According to information reported by the Italian Statistics Institute (ISTAT, 2016), the population ranges from about 1,000 inhabitants at Bonassola to a maximum of about 5,500 at Levanto. The four municipalities are well known resort places, where beach tourism represents the main local economic source. Tourist presences are widespread in summer (i.e., June to August) and during weekend in spring and autumn. For example, at Levanto, in 2017 about 350,000 presences were recorded by local tourism agencies. In the last decades, due to the advent of tourism mass, the main city centres have affected by high anthropic impacts, particularly during the summer season when the population can triple (European Environment Agency, 2006). Based on surveys conducted by Regione Liguria Administration (Regione Liguria, 2018), at Levanto, in the period 2010-2017, tourist presences have increased of about 36%. Furthermore, it is relevant to note that, at the regional scale, this sector of Liguria is one of the most affected by tourist impact due to the presence of the near Cinque Terre National Park.

2.5 Method Application

In this section, we briefly describe how each hazard descriptor was evaluated in order to apply the proposed risk of bathing method within the study area. The assessment of slope stability was performed by means of a qualitative approach. Input data were obtained from aerial photo interpretation and open source thematic maps (Regione Liguria, 2018). Firstly, coastal geomorphologic features and anthropic structures were mapped distinguishing slopes, cliffs, landslides bodies and coastal engineering structures. Subsequently, an overall qualitative judgment on slope stability was achieved by considering geological (i.e., lithology, structural features, fracturing degree, weathering) and geomorphological (i.e., slope angle and slope height) factors. For these purposes, high-spatial resolution aerial photographs (at 1:5000 scale) took in 2006, 2008 and 2010 by Regione Liguria Administration, were analysed (Regione Liguria, 2018). Information on landslide activity were collected by means of the analysis of multi-temporal photograph sequences and field surveys, together with findings reported in previous studies (Cevasco et al., 2000; Servizio Geologico Nazionale, 2008). In particular, field surveys consisted in the recognition of the main landslide morphological features (e.g., landslide crowns, main scarps, tension cracks, landslide deposits) that can reveal landslide mechanisms and activity (Fell et al., 2008).
Wave breaking quantification was obtained from information coming from previous studies (Schiaffino et al., 2013). The hazard conditions deriving from breaking waves were analysed based on the breaking type, which was calculated with the surf similarity parameter (Short, 2007). The wave parameters were collected by the buoy of Rete Ondametrica Nazionale (RON) for wave measurements (Bencivenga et al., 2012), which is located approximately 15 nautical miles east of the study area; particularly, we considered the significant wave height value, the wave period and the wave length measured in the bathing season when the beaches are more crowded. In order to assess the surf similarity parameter (i.e., Iribarren's number) and to define the rip currents generation, the nautical maps of Istituto Idrografico della Marina (IIM)

(http://www.mareografico.it/) and the cartographic map dataset of Regione Liguria were used (Regione Liguria, 2018).

As stated above, the rip currents development is strictly correlated to local peculiar geomorphological features and to the presence of anthropic structures (Castelle et al., 2016). It is relevant to note that along the study coastal sector are present a lot of natural and anthropic structures that can favour the generation of rip currents as embayed beaches, headlands, groynes, jetties and detached breakwaters. Eventually, beach accessibility was evaluated taking into account the presence of population centres, roads and trails from open data sources (Regione Liguria, 2018).

3. Results

We applied the proposed approach for beach safety and risk of bathing analysis in four coastal stretches belonging, from west to east, to the municipalities of Moneglia (≈ 5 km), Deiva (≈ 3 km), Bonassola (≈ 4.5 km) and Levanto (≈ 4 km), respectively (Figure 3).

3.1 Moneglia

As can be seen from Figure 4, the coastal stretch of Moneglia is overall characterized by hazard levels from moderate to high. In both the western and eastern sectors, hazard for bathers can be prevalently attributed to poor slope stability conditions while in the central tract hazard is mainly related to the presence of a lot of engineering structures, particularly along the main beach situated in front of the Moneglia urban area. In the western sectors, landslide hazard comes from falls and planar sliding failure mechanisms which affect coastal cliffs cut into heterogeneous rock masses made up of shales and sandstones (Cevasco et al., 2000) while in the eastern ones it is related to residual slow movements of a wide landslide accumulation (Cevasco & De Vita, 2015; Cevasco et al., 2018). Along the Moneglia beach, coastal structures and rip currents represent the two main threats to bathing safety. In fact, this urban sandy beach is characterized by detached breakwaters and groynes which can trigger rip currents. However, it is interesting to note that the hazardous conditions characterizing the western cliffed sectors do not produce severe risk levels of bathing, mainly because of the scarce accessibility of people to these areas. Conversely, along the Moneglia beach, the highest values of risk are reached as a result of the higher probability of presence of bathers (high values of accessibility) coupled with high hazard values (due to coastal structures and rip currents forcing conditions).

3.2 Deiva Marina

Moving eastwards, a different situation can be observed along the coastal area of Deiva Marina (Figure 5). This coastal stretch is free from engineering structures (e.g., groynes or breakwaters) along the wider and more suitable bathing areas located at the final tract of the small coastal plain, in front of the Deiva urban settlement. The Deiva Beach is a natural sandy beach characterized by a very low embayment degree. Here, the low hazard conditions are mainly attributable to the presence of flash rip currents (Castelle et al., 2016), while the medium risk level is favoured by the easiness with which bathers can reach the littoral area. Along the rocky coastal zones, low to moderate values of risk occur, due to the scarce accessibility to these areas.

3.3 Bonassola

The zone of Bonassola (Figure 6), characterized by a natural embayed beach, is one of the few sites of Liguria where anthropic impact was very low since still not affected by intensive engineering structures, except for a sea wall located in the eastern sector. Overall, the majority of this tract is characterized by moderate hazard. In the central zone, which is the main beach, hazard is mainly attributable to the type of breaking wave. It is interesting to observe that the Bonassola beach is the only case where plunging breaking of waves can occur, which is considered the most hazardous hydrodynamic condition according to (Short, 2007).This is mainly related to the bathymetric features (i.e., high slope) of the Bonassola beach, which has been classified as Mixed Sand-Gravel beach (MSG) (Jennings and Shulmeister, 2002) based on sedimentological analyses (Mucerino et al., 2019). Therefore, this peculiar geomorphological and hydrodynamic setting, together with the high exposure of bathers, concur to produce high risk values. The remaining coastal tracts show risk levels ranging from low to very low, prevalently related to the scarce accessibility to sea from rocky cliffs.

3.4 Levanto

The last study case is represented by the small Levanto bay, which is located eastward of Bonassola (Figure 7). This area is somewhat heterogeneous in terms of beach safety. The Levanto beach is an embayed beach that is divided into three sectors (western, central, and eastern) by two groynes. It was observed that the beach, due to the presence of groynes, may be affected by the generation of rip (Schiaffino et al., 2015). In facts, considering also the high probability of presence of bathers, some stretches (e.g., near groynes, where rip currents originate) are characterized by high risk conditions, while risk for bathers is moderate in the other parts of the beach. The rocky coasts show hazard values from moderate to high due to falls and planar sliding affecting cliffs cut on ophiolitic and sedimentary rock masses, respectively. However, due to the low and moderate accessibility, risk is consequently very low and low.

4. Discussions

The large and rapidly expanding tourism activities in coastal environment imposes an urgent need of both beach safety and sea bathing risk zoning. Moreover, the prospect of accelerating sea level rise due to climate changes (Kopp et al., 2014; Rovere et al., 2015) has further increased public awareness of coastal hazards. The main hydro- and geomorphological-related risks for beach users can be identified in drownings due to rip currents (Cervantes et al., 2015; Silva-Cavalcanti et al., 2018), incoming waves (e.g., bathers held under by waves) (Short, 2007; Williamson et al., 2012) and injuries caused by the collision with hard structures (e.g., rocky coasts, coastal structures) (Tipton and Wooler, 2016) or by landslides (Karantanellis et al., 2019; Teixeira, 2014). In the recent decades, the development and constant improvement of remote sensing techniques, together with the considerable amount of freely available data, represent a set of tools that can support researchers and local or regional administrators who are involved in coastal management. In this study, we introduced a semi-quantitative method which offers a flexible and rapid way of estimating and mapping beach safety and sea bathing risk in coastal environments by means of probability theory and GIS-based systems. The general definition of risk implies the analysis of hazard in conjunction with risk-exposed elements (UN-ISDR, 2009; Corominas et al., 2014). In the proposed approach, the geomorphological and hydrodynamic features have been selected as hazard descriptors based on technical guidelines reported in literature (Short, 2007) and on peculiar geomorphological and hydrodynamic coastal features of the Western Mediterranean basin. On the other hand, as emphasized by (Williams and Micallef, 2009), the access to coastal areas has been considered the main factor regulating the presence of beach-users. Thus, we assumed the beach accessibility as the main risk conditioning variable. Furthermore, in this study hazard should be intended as a semi-quantitative evaluation of spatial probability suitable for coastal management, without considering the temporal occurrence of hazard phenomena. The followed approach is somewhat flexible as can be adapted to any specific feature of each coastal stretch. Although it was applied along a particular coastal-type, this methodological approach may be extended to other coastal settings around the world provided that the local sea bathing risk defining variables are properly taken into consideration. Due to the use of open source archive database or information from literature, the implementation of input data is somewhat fast. However, attention should be paid in selecting hazard and accessibility descriptors. In fact, as observed by the application in the study areas, characterized by variable and complex environments represented by cliffs alternating with pocket beaches and embayed beaches and where often coastal engineering structures appear, both hazard and accessibility descriptors can frequently change from one site to another. Nevertheless, the outcomings of the hazard zoning represent a useful tool for coastal planning and management (Balaguer et al., 2008) as they can favour an efficient resources allocation in sea bathing risk prevention strategies. From the hazard maps, it can be noted that sea bathing safety is inversely proportional to the hazard index. The obtained hazard zoning directly highlights the negative role of poor slope stability conditions and of engineering structures in regulating beach safety. In literature, many methods for coastal hazard mapping pointed out the importance of geomorphological instability as key hazard element, both in oceanic (Jongens et al., 2007; Del Río and Gracia, 2009; Nunes et al., 2009) and Mediterranean-type contexts (Fernández et al., 2003; De Vita et al., 2012; Iadanza et al., 2009; Scarpati et al., 2013; Teixeira, 2014; Marinos et al., 2017; Cevasco et al., 2018). Likewise, other methods highlighted the role of coastal structures (De Pippo et al., 2008) and of rip currents (Wind and Vreugdenhil, 1986; Castelle et al., 2016; Scott et al., 2016).

It is relevant to note that in this study the attribution to each hazard or accessibility class has been performed using open source archive information (e.g., aerial photos, thematic maps, etc.), sometimes in conjunction with field surveys. These aspect highlights that required information may depend on the availability of open data. Furthermore, in some cases this operation may require personal judgement of the person carrying out the analysis, leading to a certain degree of subjectivity. Anyway, considering the increasingly availability of detailed open-access data and of geohazard experts, the proposed method can be considered of general application in the future and may be classified as a low-cost method.

Interesting discussion points come also from the sea bathing risk mapping. In this case, it is worth highlighting the role of accessibility, which reflects the amounts of elements at risk (i.e., beach-users or bathers) that may be exposed to hazard. Not surprisingly, from the obtained risk zoning maps, it can be overall observed that where the coastal areas are characterized by moderate to high values of accessibility (e.g., beaches in urban areas or in rural areas with good accessibility as Moneglia or Levanto sites), together with low beach safety conditions, an increase of risk occur. On the contrary, along hazardous coastal stretches, but difficult to reach (i.e., cliffs without accessibility, cliffs or beaches with scarce/moderate accessibility as Moneglia and Bonassola areas), low to very low values of risk were found.

Some difficulties were encountered in validating the obtained zonation maps. It has proven difficult to gather detailed and sufficient data on surf rescues and drowning fatalities attributable to coastal hazards for the study areas. Thus, the obtained results are likely to underestimate the actual level of risk. Nonetheless, in order to qualitative analyse the reliability of the proposed approach, an attempt was performed by comparing sea bathing risk zoning maps with drowning death and surf rescue data provided by ISTISAN (Funari and Giustini, 2011)or collected from local newspaper archives during the 2009-2016 time span. For example, along the Moneglia beach, where high risk levels were mapped, four fatal accident sand numerous rescue operations were registered. This could be related to the presence of detached breakwaters, which in storm surge conditions, as headlands or jetties, might lead to rip currents generation (Castelle et al., 2016)that can mislead an inexpert bather. Furthermore, the easy accessibility to this beach may have contributed to increase the level of sea bathing risk. During the same reference period, along the Levanto coastal stretch one death has been detected, which could be attributable to the presence of rip currents. This would confirm that also in the Mediterranean environment rip currents can be source of hazards for bathers, as well established for oceanic environments (Brander, 2014; Brighton et al., 2013; Castelle et al., 2016). Along the Bonassola beach, witness statements coming from newspapers and from Italian Rescue Agency revealed that rescue operations were rarely performed, and usually in cases of sea adverse conditions. It is interesting to note that this is the only study case affected by *plunging-type* breaking waves. According to Short (2007), this feature is the most hazardous type of wave breaking in storm surge conditions. Despite the above-mentioned lack of information, useful indications on the validity of the proposed approach were obtained. However, further refinements of the validation could benefit from improving completeness of rescue operations archives. In light of these observations, the collection of such data would deserve major attention of national reporting systems, proposing consistent methods that also take into account causes related to rescue operations. As suggested by other authors (Brighton et al., 2013), this will also allow for more accurate global comparisons on sea bathing risk analysis.

5. Conclusions

Sea bathing risk estimation is a crucial and relevant issue in the management of coastal zones. Considering the socio-economic relevance of coastal areas and the advent of mass tourism, sea bathing risk analysis has important implications on the improvements of coastal zone planning policies. In this paper, we proposed a geomorphological and hydrodynamic approach for beach safety and sea bathing risk estimation. The proposed method was applied along a 20-km long Mediterranean stretch of coast located in eastern Liguria (north-western Italy). Hazard and risk conditioning variables were identified by means of open source data, literature and simple field activities. Subsequently, the hazard and risk of bathing indices were calculated and mapped using probability theory and GIS-based systems, respectively. The application of the method along the study area revealed that the resulting zoning maps can provide useful contributions to stakeholders in charge of coastal management. Hazard Index map can aid beach safety practitioners in the establishment of lifeguard and lifesaver services since it allows to detect the most hazardous areas. Moreover, this map can provide useful information to bathers, also contributing to increase their awareness of coastal hazards and their risk perception. Risk zoning maps can support authorities and decision makers in planning and implement appropriate risk mitigation measures, also favouring the optimization of economic resources. Along high-risk areas, these measures could include, for example, reduction of the hazard (e.g., slope stability improvement, engineering coastal structures modifications) or of the exposure of beach-users (e.g., establishing beach accessibility restrictions). Future researches addressed to improve the completeness of database on rescue operations could refine the validity of the proposed approach in estimating sea bathing risk. Nevertheless, considering the increasing availability of open source information, this low-cost approach may have useful implications in pursuing effective integrated coastal management strategies.

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Figure Captions

Figure 1. Flowchart diagram summarizing the general approach adopted in assessing sea-bathing-risk.

Figure 2. Hazard Index (HI) and beach safety classes (a); risk of bathing matrix obtained from the interaction of the hazard index with the beach accessibility (b).

Figure 3. Location map of the study area and of the tested coastal stretches (highlighted by squares named as a, b, c and d).

Figure 4. Mapped distribution of the Hazard Index and of the Risk of Bathing Index along the coastal stretch of Moneglia.

Figure 5. Mapped distribution of the Hazard Index and of the Risk of Bathing Index along the coastal stretch of Deiva Marina.

Figure 6. Mapped distribution of the Hazard Index and of the Risk of Bathing Index along the coastal stretch of Bonassola.

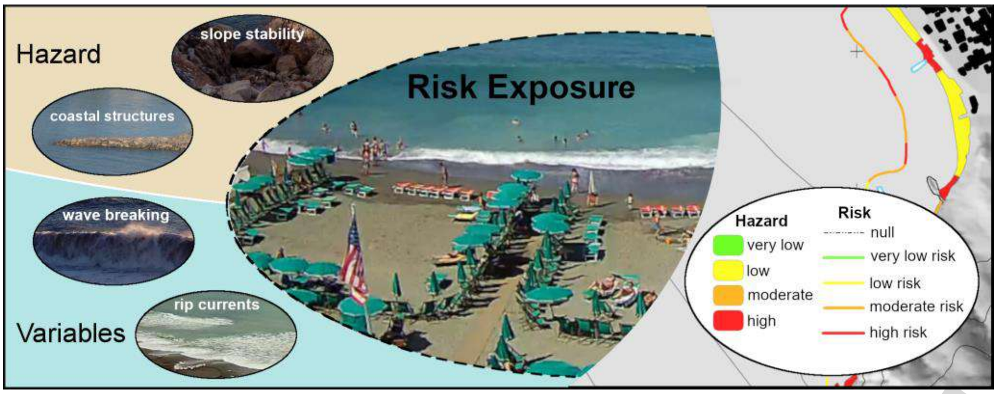
Figure 7. Mapped distribution of the Hazard Index and of the Risk of Bathing Index along the coastal stretch of Levanto.

Table 1. Hazard descriptors and hazard-related levels.

	A-Low	**B-Moderate**	**C-High**
Slope Stability	absence of slopes stable slopes stabilized landslides relict landslides protection works/embankments/masonry/concrete walls in good conditions	potentially unstable slopes dormant landslides protection works/embankments/ masonry/concrete walls in fair conditions	unstable slopes active landslides reactivated landslides protection works/embankments/masonry/concrete walls in poor conditions
Breaking Waves	Every breaking type with Hs < 0.5 m	Spilling ($\xi_0 < 0.5$) Surging and Collapsing ($\xi_0 > 3.3$) Hs > 0.5 m;	Plunging ($0.5 < \xi_0 < 3.3$) Hs > 0.5 m
Rip Currents	open beach (not bars and cuspidate morphologies)	open beach with bars and/or cuspidate morphologies	pocket beach and anthropic structures (groynes, detached breakwaters, jetties, piers)
Engineering Structures	no structures	groynes	breakwaters breakwaters and groynes

Table 2. Risk exposure categories according to accessibility features to coastal areas.

Accessibility				
1-Low	**2-Low/Moderate**	**3-Moderate**	**4-Moderate/High**	**5-High**
cliffs without accessibility	cliffs or beaches with scarce accessibility	cliffs or beaches in rural areas with moderate accessibility	beaches in rural areas with good accessibility	beaches in urban areas



Graphical abstract

Highlights

Sea bathing risk has increased along coastal areas due to mass tourism

A cost-effective approach for sea bathing risk estimation is proposed

Based on geomorphological and hydrodynamic features the Hazard Index was estimated

Exposure of bathers to coastal hazards is regulated by beach accessibility

The Risk of Bathing Index has been assessed using probability theory

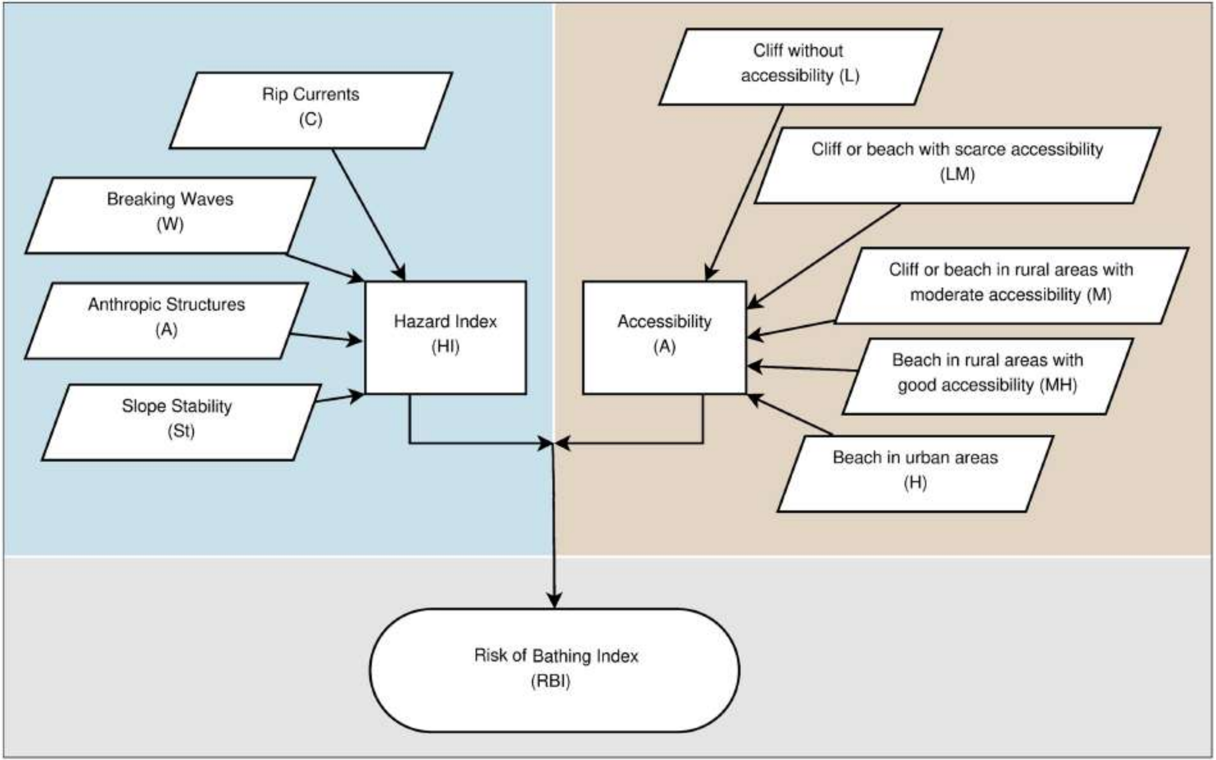

Rip Currents
(C)
Breaking Waves
(W)
Anthropic Structures
(A)
Slope Stability
(St)
Hazard Index
(HI)
Cliff without
accessibility (L)
Cliff or beach with scarce accessibility
(LM)
Cliff or beach in rural areas with
moderate accessibility (M)
Beach in rural areas with
good accessibility (MH)
Beach in urban areas
(H)
Accessibility
(A)
Risk of Bathing Index
(RBI)

Figure 1

(a)

Hazard Index (HI)	Hazard	Beach safety
$0,01 \leq HI < 0,50$	*very low*	*very high*
$0,50 \leq HI \leq 0,65$	*low*	*high*
$0,65 < HI \leq 0,997$	*moderate*	*moderate*
$0,997 < HI < 1,0$	*high*	*low*

(b)

Hazard Index / Accessibility	High	Moderate	Low	Very low
High	*high risk*	*high risk*	*medium risk*	*medium risk*
Moderate to high	*high risk*	*medium risk*	*medium risk*	*medium risk*
Moderate	*medium risk*	*medium risk*	*medium risk*	*low risk*
Low to moderate	*medium risk*	*low risk*	*low risk*	*very low risk*
Low	*very low risk*	*very low risk*	*very low risk*	*very low risk*

Figure 2

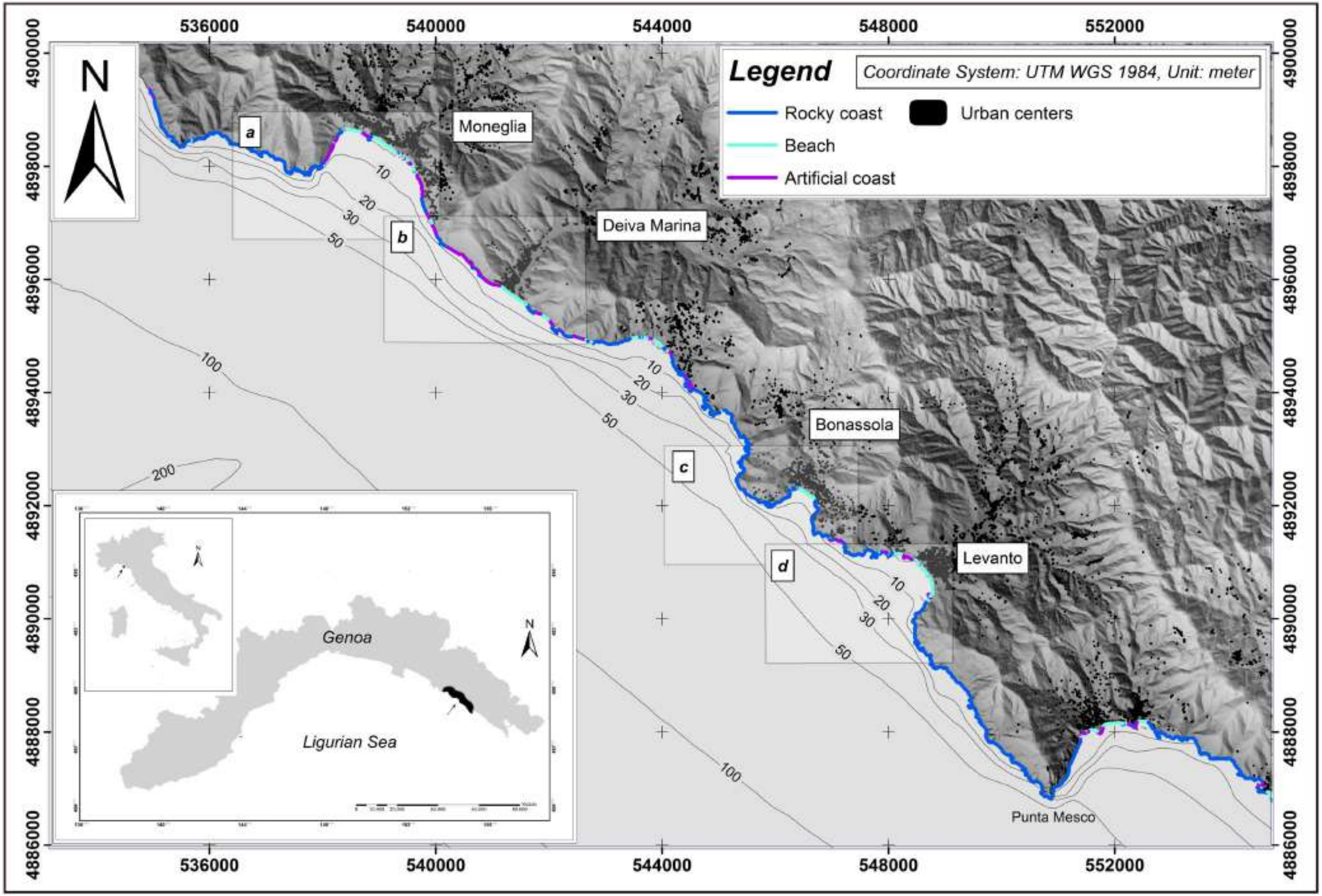
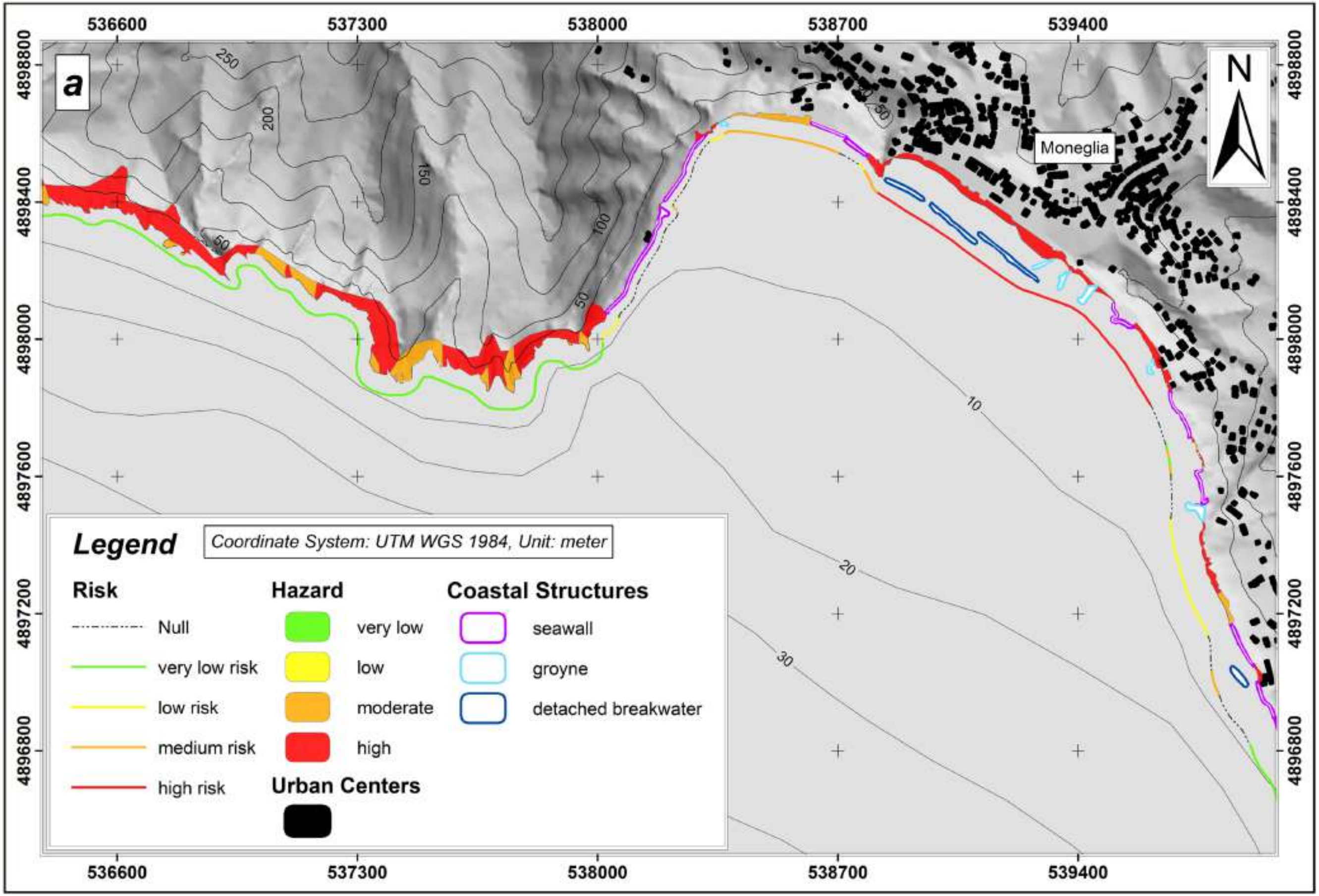
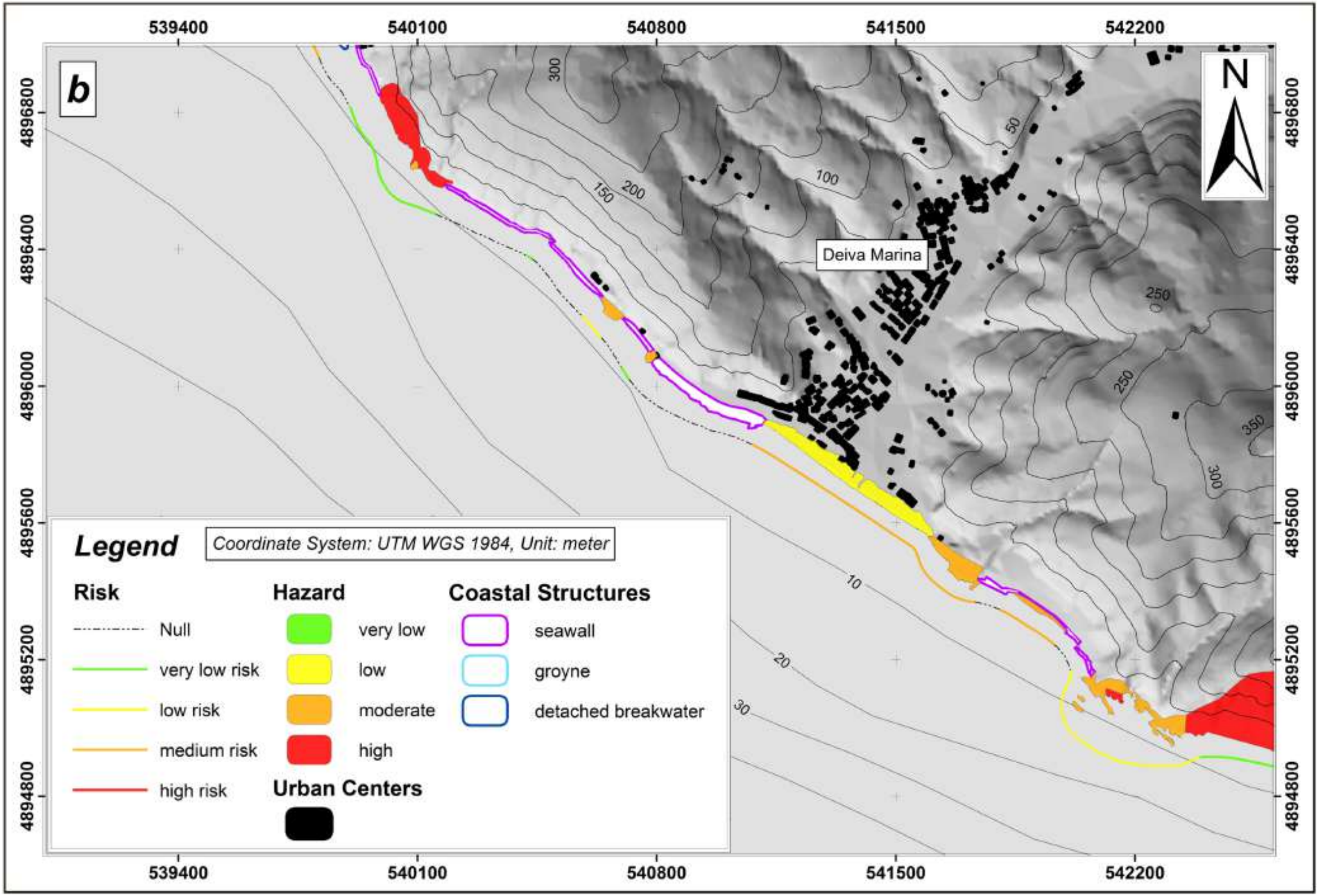

Legend
Coordinate System: UTM WGS 1984, Unit: meter
Rocky coast
Urban centers
Beach
Artificial coast
N
Moneglia
Deiva Marina
Bonassola
Levanto
Punta Mesco
a
b
c
d
Genoa
Ligurian Sea
536000
540000
544000
548000
552000
4900000
4898000
4896000
4894000
4892000
4890000
4888000
4886000
10
20
30
50
100
200

Figure 3



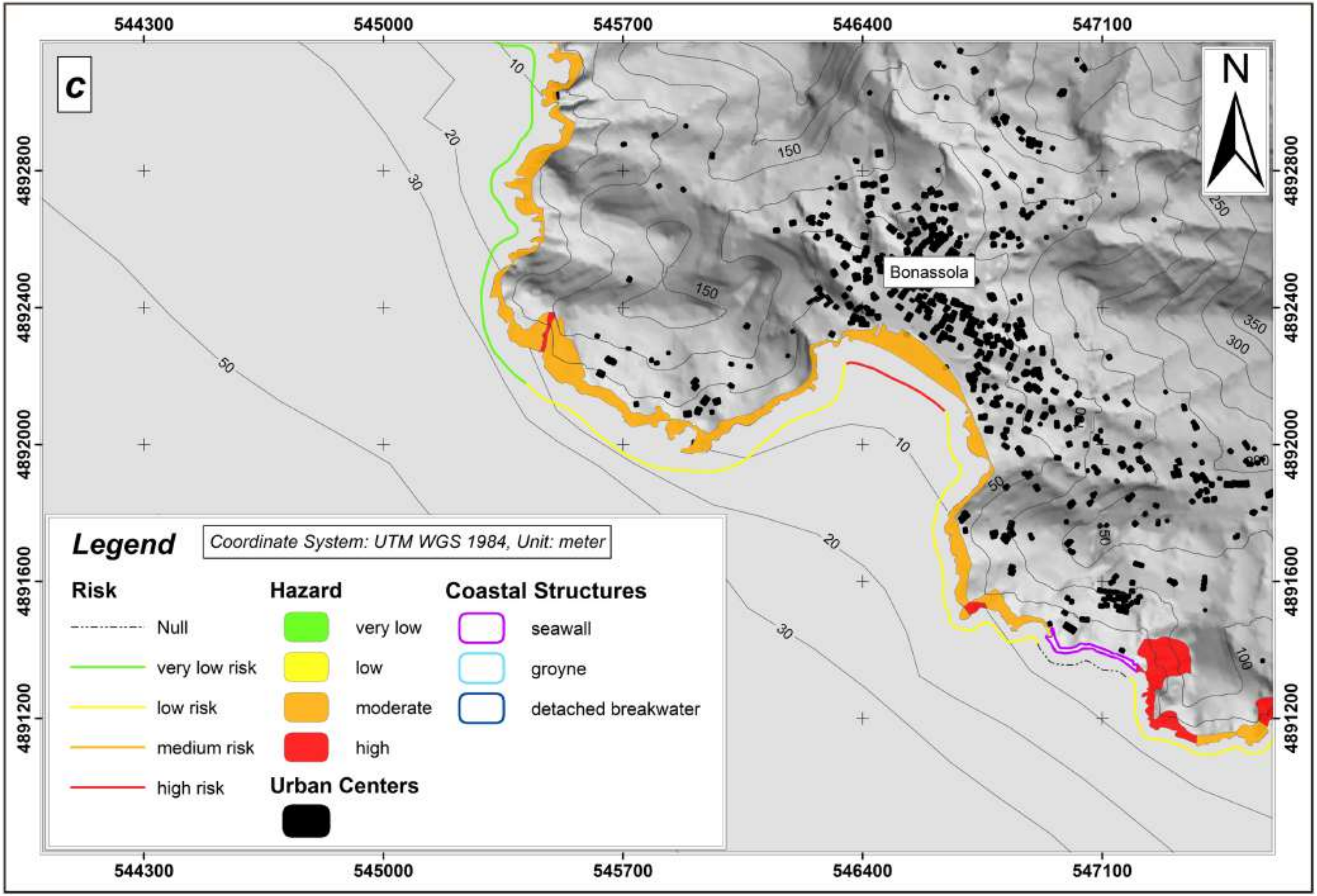
a
Moneglia
N
536600
537300
538000
538700
539400
4898800
4898400
4898000
4897600
4897200
4896800
250
200
150
100
50
10
20
30
Legend
Coordinate System: UTM WGS 1984, Unit: meter
Risk
Null
very low risk
low risk
medium risk
high risk
Hazard
very low
low
moderate
high
Urban Centers
Coastal Structures
seawall
groyne
detached breakwater

Figure 4



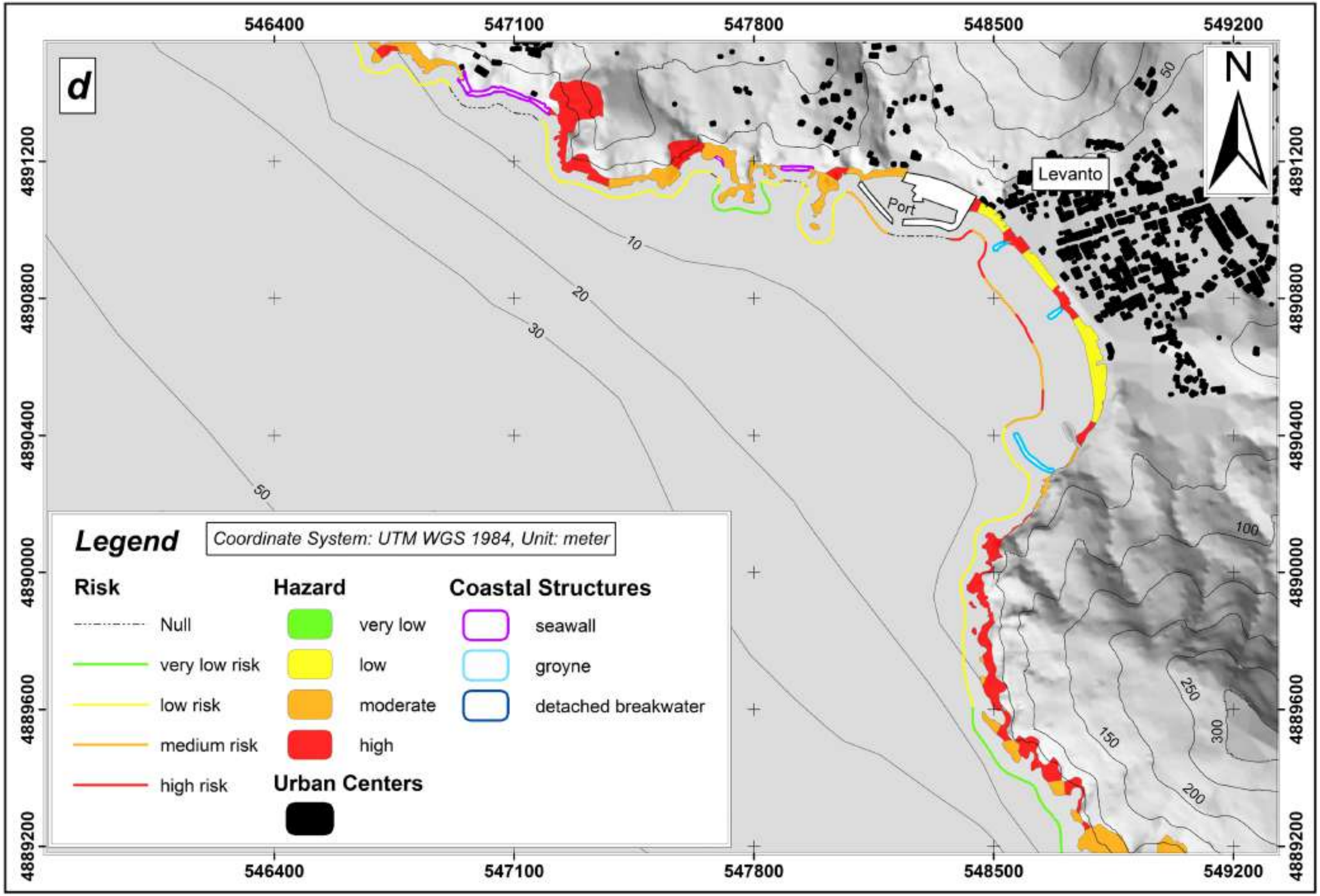
b
N
Deiva Marina
539400
540100
540800
541500
542200
4896800
4896400
4896000
4895600
4895200
4894800
300
50
100
150
200
250
350
10
20
30
Legend
Coordinate System: UTM WGS 1984, Unit: meter
Risk
Null
very low risk
low risk
medium risk
high risk
Hazard
very low
low
moderate
high
Coastal Structures
seawall
groyne
detached breakwater
Urban Centers

Figure 5



544300
545000
545700
546400
547100
4892800
4892400
4892000
4891600
4891200
c
N
Bonassola
10
20
30
50
150
250
300
350
100
Legend
Coordinate System: UTM WGS 1984, Unit: meter
Risk
Null
very low risk
low risk
medium risk
high risk
Hazard
very low
low
moderate
high
Coastal Structures
seawall
groyne
detached breakwater
Urban Centers

Figure 6



d
546400
547100
547800
548500
549200
4891200
4890800
4890400
4890000
4889600
4889200
Levanto
Port
N
10
20
30
50
100
150
200
250
300
Legend
Coordinate System: UTM WGS 1984, Unit: meter
Risk
Null
very low risk
low risk
medium risk
high risk
Hazard
very low
low
moderate
high
Urban Centers
Coastal Structures
seawall
groyne
detached breakwater

Figure 7

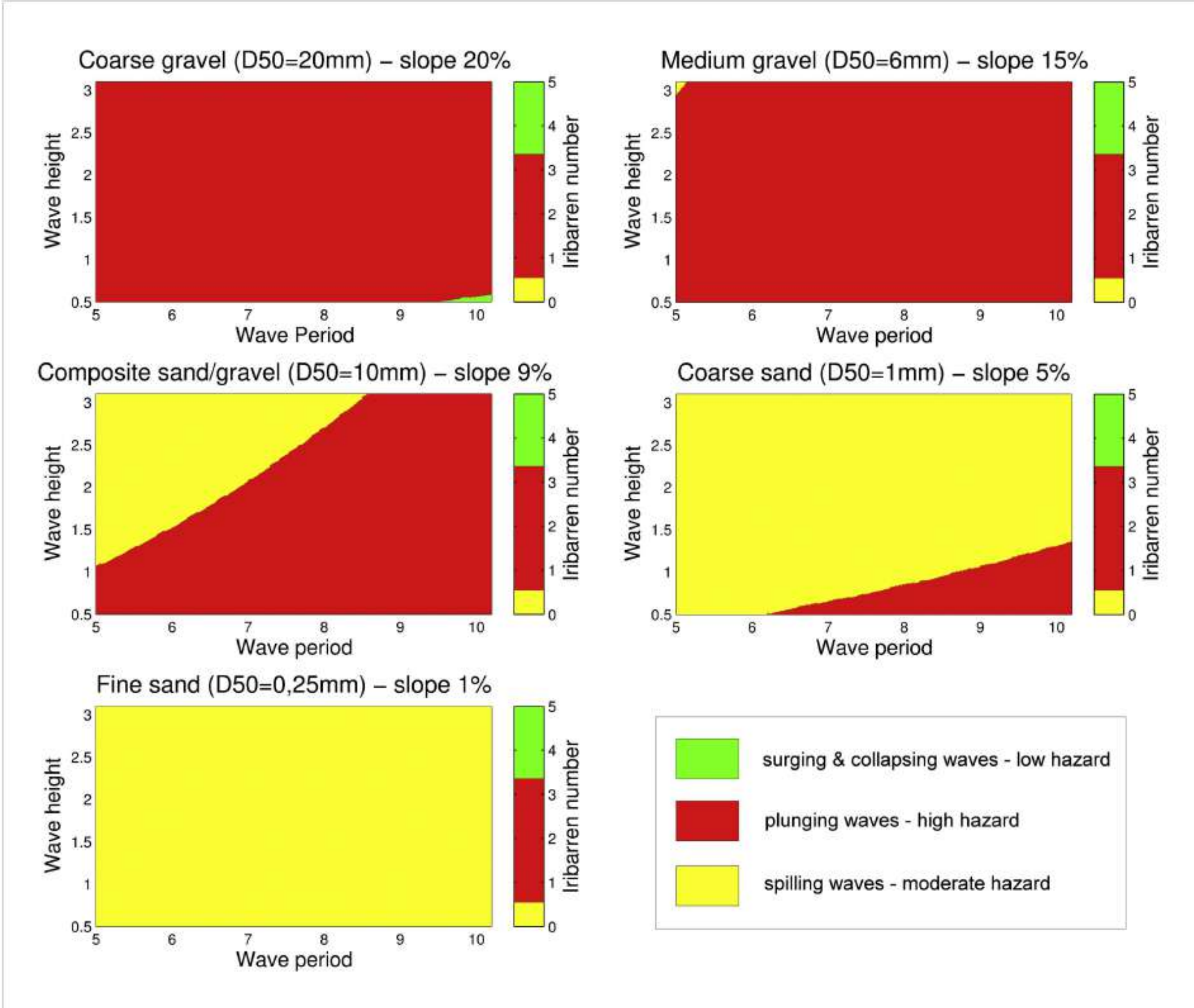
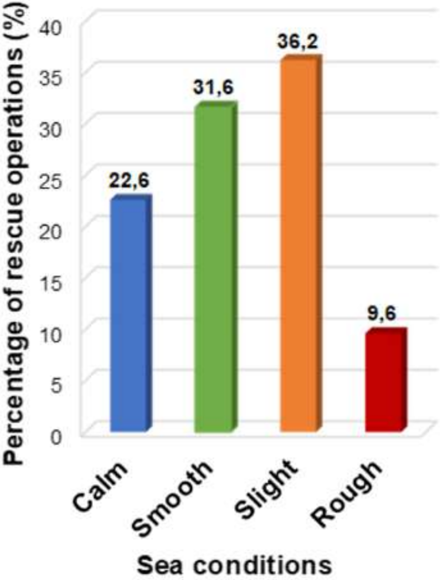

Coarse gravel (D50=20mm) – slope 20%
Medium gravel (D50=6mm) – slope 15%
Composite sand/gravel (D50=10mm) – slope 9%
Coarse sand (D50=1mm) – slope 5%
Fine sand (D50=0,25mm) – slope 1%
Wave height
Wave Period
Wave period
Iribarren number
surging & collapsing waves - low hazard
plunging waves - high hazard
spilling waves - moderate hazard

Figure 8



Douglas Scale		
Degree	***Wave Height (m)***	***Description***
0	no wave	Calm (glassy)
1	0 – 0,10	Calm (rippled)
2	0,10 – 0,50	Smooth
3	0,50 – 1,25	Slight
4	1,25 – 2,50	Moderate
5	2,50 – 4,00	Rough
6	4,00 – 6,00	Very rough
7	6,00 – 9,00	High
8	9,00 – 14,00	Very high
9	> 14,00	Phenomenal

Figure 9

X_1	X_2	X_3	X_4	HI	Hazard
0,01	0,01	0,01	0,01	0,039	very low
0,5	0,01	0,01	0,01	0,515	low
0,5	0,5	0,01	0,01	0,755	moderate
0,5	0,5	0,5	0,01	0,876	
0,5	0,5	0,5	0,5	0,938	
0,99	0,01	0,01	0,01	0,990	
0,99	0,5	0,01	0,01	0,995	
0,99	0,5	0,5	0,01	0,998	high
0,99	0,5	0,5	0,5	0,999	
0,99	0,99	0,01	0,01	1,000	
0,99	0,99	0,5	0,01	1,000	
0,99	0,99	0,5	0,5	1,000	
0,99	0,99	0,99	0,01	1,000	
0,99	0,99	0,99	0,5	1,000	
0,99	0,99	0,99	0,99	1,000	

Figure 10