ANALYSIS OF THE CONCURRENT CONDITIONS OF FLOODS AND SEA STORMS: A CASE STUDY OF CROTONE, ITALY

CATERINA CANALE[1], GIUSEPPE BARBARO[1], OLGA PETRUCCI[2], GIOVANNI BESIO[3], GIANDOMENICO FOTI[1], GIUSEPPINA CHIARA BARILLÀ[1] & PIERFABRIZIO PUNTORIERI[1]
[1]DICEAM Department, Mediterranea University of Reggio Calabria, Italy
[2]National Research Council of Italy, Institute for Geo-Hydrological Protection (CNR-IRPI), Italy
[3]DICAT Department, Genoa University, Italy

ABSTRACT
The considerable anthropogenic pressure that has occurred since the second half of the last century has increased the vulnerability of coastal areas to the effects of natural events such as floods and sea storms, especially if these events occur simultaneously. This paper analyses the conditions that favour the concurrence of floods and sea storms through a case study near Crotone, a city in southern Italy on the Ionian Sea. The study area has a coastal extension of about 34 km, is characterized by typical rivers called "fiumare" and has been hit by several events of concurrent floods and sea storms. The conditions that favour the concurrence of floods and sea storms are mainly related to geomorphologic and climatic factors. Among these latter factors, atmospheric pressure is very important. Indeed the formation of low-pressure areas is the cause of atmospheric disturbances which can affect both the sea and the coast causing heavy rains and intense sea storms. The analysis was divided into two phases. In the first, the concurrence between floods and sea storms was verified. In the second phase, the possible correlations between the main factors involved were identified: the rainfall heights, the maximum significant wave heights and the atmospheric pressure variations observed during each atmospheric disturbance. The analysis showed that the rainfall heights and the maximum significant wave heights, that are both generally independent factors, are related to a common factor, the atmospheric pressure. This result is useful in predicting concurrent events. Indeed, by predicting atmospheric pressure variations, it is possible to estimate the expected rainfall height and the expected maximum significant wave height. The methodology described in this paper can be extended to other areas with geomorphologic and climatic characteristics that are similar to those of Crotone.
Keywords: flood, sea storms, contemporary events, geomorphology, climate, fiumare, Crotone.

1 INTRODUCTION

The causes of hydrogeological instability phenomena can be associated with various factors, which can affect both coastal and river areas and may be directly or indirectly related to human action [1], [2]. Indeed, coastal and river dynamics processes are strongly influenced by natural phenomena, such as wave climate and longshore and river transport [3]–[8], and anthropic interventions [9]–[12]. Therefore, increase knowledge of coastal and river dynamics, and of the factors that influence it, is necessary for proper management and protection of coastal areas [13]–[15]. Examples of anthropic interventions in river basins are the construction of reservoirs, the sediment withdrawal, the reforestation, the hydraulic-forestry arrangements and the subsidence of lowland areas for pumping [16], [17]. Example of anthropic interventions in coastal areas are the construction of port and coastal defence works [18]–[25]. These interventions can trigger intense erosive processes [26]–[38]. Also, anthropogenic pressure can increase the vulnerability of the territory under the action of natural events such as floods and sea storms [39]–[45]. Generally, most studies in the scientific literature treat floods and sea storms in separate ways. However, the most critical aspects of floods and sea storms are observed in the case of concurrent events [46], [47]. Ordinariness of events becomes exceptionality during contemporaneity. Floods and storms

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occur together although they are not dependent events. The link is represented by atmospheric pressure. Lowering of this parameter affects significantly perturbations and winds. The paper describes a case study for the city of Crotone. The analysis of the cumulative rainfall heights and the maximum significant heights, recorded during each concomitant event, returned a good correlation with the atmospheric pressure variation. In a first section, the paper presents the city of Crotone, its geographical, geomorphological and climatic characteristics. The typical rivers of Crotone are the "fiumare". The morphological and granulometric peculiarities of these streams influence the violence of the floods. Exposure to the Grecale wind has a noticeable impact on the waves. The study was conducted by consulting and analysing two databases. The first was provided by the CNR-IRPI of Cosenza and includes all the hydrogeological instability events in Calabria. The second database was provided by the MeteOcean group of the University of Genoa (Italy) and contains meteorological data of Crotone. The two databases allow one to verify the contemporaneity of Crotone events. The paper, in particular, focuses on the analysis of atmospheric pressure variations. In the last section of the paper, the results obtained from the study of the correlation between the different parameters will be presented. The aim of the study is to improve control of events affecting coastal areas, which are particularly fragile.

2 SITE DESCRIPTION

The city of Crotone is located the South of Italy, in the Calabrian region. It is flanked by the Ionian Sea, as shown in Fig. 1. The city is steeped in history. It has many monuments and archaeological sites, near the sea.

Crotone is exposed to Grecale wind (Fig. 2). It is characterized by very strong gusts and can reach 150 km/h, generating windstorms. The Grecale wind is the cause of perturbations in the east. Average annual rainfall is 663 mm, with peaks during the winter season.

Figure 1: Location of the city of Crotone (in red). *(Source: Google Images.)*

Figure 2: Wind rose on the coasts of Crotone. *(Source: Google Images.)*

Regarding geomorphological characteristics, Crotone presents a silty clayey substrate of the Pliocene [48]. Land has a vulnerability and predisposition to soil degradation phenomena. Granulometry in alluvial deposits is variable, depending on the type of sediment. The type of soil influences the instability of the slopes and land, accentuating the risk conditions. Coasts are characterized by continuous beaches. They are exposed to sea storms from East and North-East (Grecale). The solid contributions towards the coast reflect the granulometric characteristics of the lithotypes constituting the underlying basins and they are mainly fine [15]. Typical rivers of the territory are the “fiumare”. The hydrological regime is torrential [49], [50]. River basins are very small, in fact the surface is a few km^2. The proximity of the mountain ranges from the coasts is the cause of very marked steeps. Slope of the river rods is high. This causes very short run-off times. Rains of weak intensity can cause a response from basins, then floods. “Fiumare” have variable granulometry [51]. Sides and beds are easily erodible. The consequence is a large solid transport. Solid flow is added to the fluid flow. The force exerted by the mass has a great destructive power. Most of the soils adjacent to the rivers are characterized by low permeability, with consequent reduction of hydrological losses. All these factors contribute to increasing the hydraulic risk. Geomorphological conditions influence response to atmospheric and climatic events.

3 METHODOLOGY

The analysis was divided into two phases. In the first, the concurrence between floods and sea storms was verified. In the second phase, the possible correlations between the main factors involved were identified: the rainfall heights, the maximum significant wave heights and the atmospheric pressure variations observed during each atmospheric disturbance.

The concurrence between floods and sea storms was verified analysing two databases. The flood events are collected in the ASICal database (Historically Flooded Areas in Calabria), provided by the CNR-IRPI of Cosenza. For each event data, flooded river and damage produced were extrapolated. After identifying the flooded river, the closest gauge was identified, extrapolating the relative rainfall height values. The MeteOcean database of the DICCA Department of Genoa contains meteorological data of Crotone. In this database the Mediterranean Sea has been mapped with a mesh grid of 10 km side, as shown in Fig. 3.

The following data are available for each point: significant wave heights, average and peak periods, wave direction, wind speed components, wind direction and atmospheric pressures. The closest point to Crotone is 6177, as shown in Fig. 4.

Figure 3: Mapping of the Mediterranean Sea with the model proposed by the MeteOcean group.

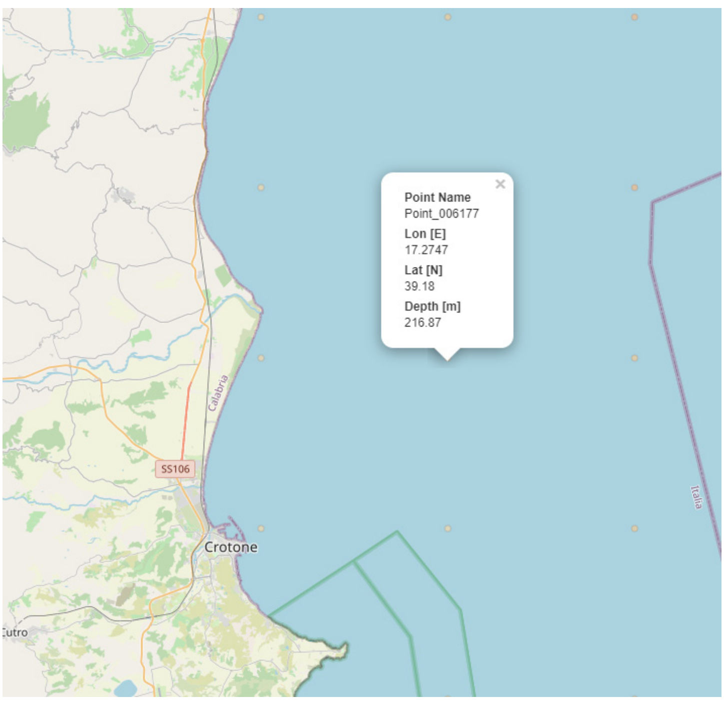

Figure 4: Point chosen for Crotone.

A sea storm is defined as "A sequence of sea states in which H_s (t) exceeds a fixed threshold and does not fall below this threshold for a continuous time interval greater than 12 hours" [52]. The critical threshold was calculated using the following equation [53]:

$$h_{crit} = 1.5\overline{H_s}, \quad (1)$$

where $\overline{H_s}$ is the average of the significant heights recorded for Crotone. Therefore, to verify the concurrence between flood and sea storms, it is necessary that on the date on which a flood events occurred, H_s exceeds the h_{crit} threshold.

The atmospheric pressure variations were analysed on the dates on which the floods and the sea storms occur simultaneously.

Generally, low pressure is related to atmospheric disturbance and a drop of 5–6 hPa can generate intense rainy and windy phenomena. Indeed, air moves from a high-pressure area to a low-pressure area. The atmospheric pressure variations were related to the rainfall height of each flood event and to the maximum significant wave height of each sea storm.

The methodology followed can be summarized into the following steps:

1. analysis of the A.S.I.Cal. database to identify the flood events and their dates;
2. extrapolation of rainfall height of each event from the closest gauge;
3. analysis of the MeteOcean database;
4. estimate of the critical threshold;
5. checking if in the date of the flood H_s has exceeded h_{crit};
6. extrapolation of maximum significant wave height of each sea storm;
7. check of the atmospheric pressure variations in the date on which the floods and the sea storms occur simultaneously;
8. analysis of correlation between atmospheric pressure variations, rainfall height and maximum significant wave height for all events.

4 RESULTS AND DISCUSSION

In the study area, 17 flood events were identified through the analysis of the A.S.I.Cal. database. These events occurred from 1990 to 2017 and the rainfall heights varies between 50 and 300 mm (see the ordinate of the graph in Fig. 5). Through the analysis of the MeteOcean database, it has been verified that a sea storm occurred when each flood event occurred. The maximum significant wave height varies between 1 and 7 m (see the ordinate of the graph in Fig. 6). Also for each concurrent event, the difference between the maximum and the minimum atmospheric pressure value was calculated. These values vary between 300 and 2100 Pa (see the abscissa of the graphs in Figs 5 and 6). In detail, Fig. 5 shows that the most intense rainfall event recorded has a cumulative height of 278.2 mm and an atmospheric pressure drop of 1685 Pa. Also, Fig. 6 shows that the highest significant wave height was 6.833 m and corresponds to an atmospheric pressure drop equal to 2053 Pa.

The graphs in these figures also show that the data are intercepted by a polyline which well approximates the variation trend of the points. Therefore, the correlation between the atmospheric pressure variations and the rainfall heights and the maximum significant wave height is high. It is observed that this correlation is positive. Therefore, when the atmospheric pressure variations increase, the rainfall heights and the maximum significant wave heights also increase. The obtained result shows that two generally independent factors are related to a common factor.

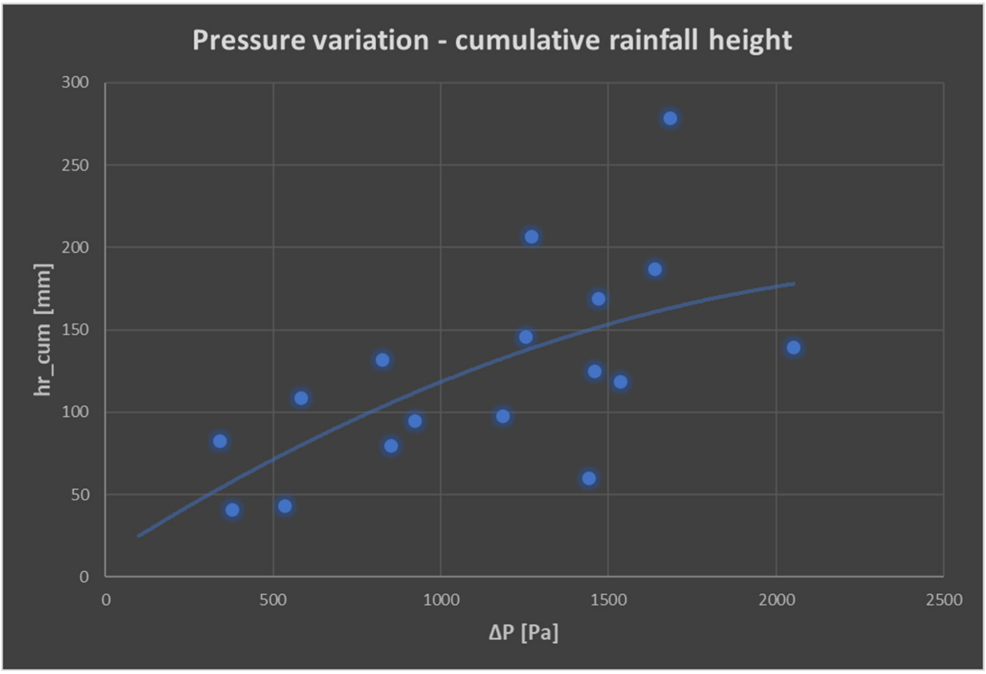

Figure 5: Correlation between pressure variation and cumulative rainfall height.

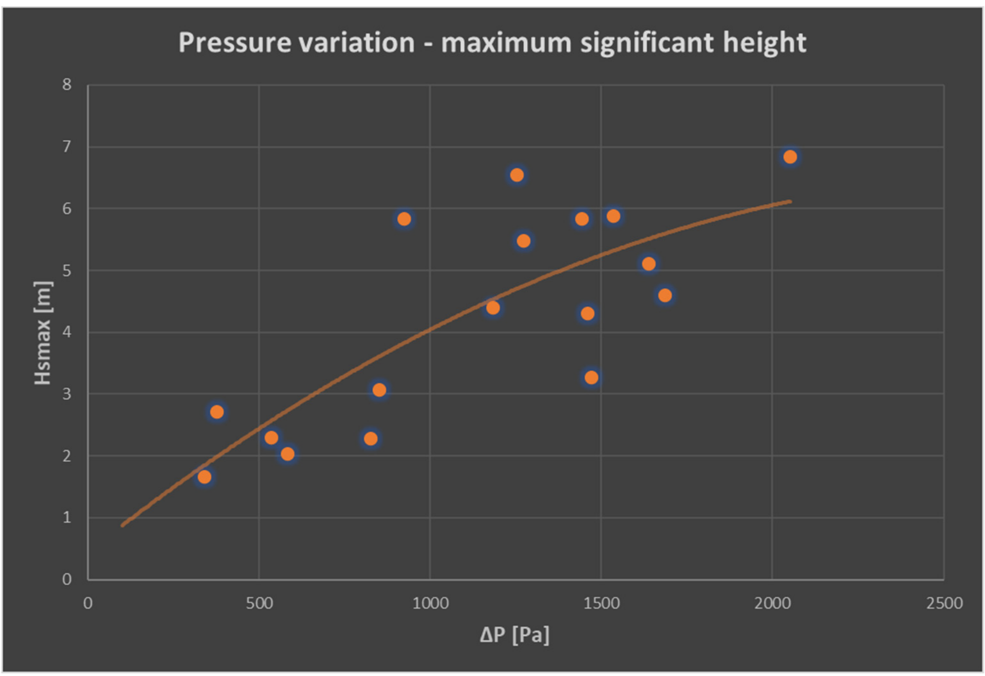

Figure 6: Correlation between pressure variation and maximum significant height.

5 CONCLUSIONS

The analysis of flood and sea storm events has had great importance in scientific literature. If these events occur separately, they can have serious consequences on the territory but, if they occur simultaneously, the consequences can be greatly amplified. The paper analyses the conditions that cause contemporaneity between floods and sea storms through a case study in Crotone, a city in Calabria, in southern Italy. The contemporaneity is ascertained only if the flooding of a river was accompanied by a sea storm. The inverse condition cannot apply. After ascertaining the contemporaneity of these events, attention was paid to the triggering causes. A quantitative analysis of the events has been advanced. Cumulative rainfall heights and maximum significant wave heights are united by the dependence on atmospheric pressure variation. It is possible to study two independent quantities with a significant meteorological variable. Lowering of pressure influences the perturbations and the air masses from which the waves are generated. The variation that occurs during the event is the cause of the simultaneous manifestation of floods and sea storms. This result is useful to predicting concurrent events. Indeed, by predicting atmospheric pressure variations, it is possible to estimate the expected rainfall height and the expected maximum significant wave height.

The analysis described in this paper represents a pilot study that can be extended to other geomorphologically and climatically similar territories to Crotone. This study is interesting in the field of planning and management of coastal areas, especially near river mouths and in the presence of inhabited centres and infrastructures. In fact, the river mouths represent the most vulnerable territories in the presence of concomitant floods and sea storms. The future development of this study concerns a multivariate analysis about correlation between relative humidity and other climatic parameters and rainfall heights and maximum significant wave heights.

REFERENCES

[1] Phillips, M.R. & Jones, A.L., Erosion and tourism infrastructure in the coastal zone: Problems, consequences and management. *Tourism Management*, **27**(3), pp. 517–524, 2006.

[2] Addo, K.A., Shoreline morphological changes and the human factor. Case study of Accra Ghana. *Journal of Coastal Conservation*, **17**(1), pp. 85–91, 2013.

[3] Barbaro, G., Foti, G. & Malara, G., Set-up due to random waves: influence of the directional spectrum. *Proceedings of the 30th International Conference on Ocean, Offshore and Artic Engineering OMAE*, **6**, pp. 789–797, 2011.

[4] Barbaro, G., Foti, G., Mandaglio, G., Mandaglio, M. & Sicilia, C.L., Estimate of sediment transport capacity in the basin of the Fiumara Annunziata (RC). *Rendiconti Online Società Geologica Italiana*, **21**(1), pp. 696–697, 2012.

[5] Barbaro, G., Foti, G. & Malara, G., Set-up due to random waves: influence of the directional spectrum. *International Journal of Maritime Engineering*, **155**, pp. A105–A115, 2013.

[6] Sicilia, C.L., Foti, G. & Campolo, A., Protection and management of the Annunziata river mouth area (Italy). *Journal of Air, Soil and Water Research*, **6**, pp. 107–113, 2013.

[7] Barbaro, G., Foti, G., Sicilia, C.L. & Malara, G., A formula for the calculation of the longshore sediment transport including spectral effects. *Journal of Coastal Research*, **30**, pp. 961–966, 2014.

[8] Tomasicchio, G.R., D'Alessandro, F., Barbaro, G., Musci, E. & De Giosa, T.M., Longshore transport at shingle beaches: an independent verification of the general model. *Coastal Engineering*, **104**, pp. 69–75, 2015.

[9] Walling, D.E., Human impact on land–ocean sediment transfer by the world's rivers. *Geomorphology*, **79**(3–4), pp. 192–216, 2006.

[10] Yang, Z., Wang, T., Voisin, N. & Copping, A., Estuarine response to river flow and sea-level rise under future climate change and human development. *Estuarine, Coastal and Shelf Science*, **156**, pp. 19–30, 2015.

[11] Versaci, R., Minniti, F., Foti, G., Canale, C. & Barillà, G.C., River anthropization, case studies in Reggio Calabria (Italy). *WIT Transactions on Ecology and the Environment*, **217**, pp. 903–912, 2018.

[12] Williams, A.T., Rangel-Buitrago, N., Pranzini, E. & Anfuso, G., The management of coastal erosion. *Ocean & Coastal Management*, **156**, pp. 4–20, 2018.

[13] Jiongxin, X., Sediment flux to the sea as influenced by changing human activities and precipitation: example of the Yellow River, China. *Environmental Management*, **31**(3), pp. 0328–0341, 2003.

[14] Foti, G. & Sicilia, C.L., Analysis, evaluation and innovative methodologies to prevent coastal erosion. *WIT Transactions on Ecology and the Environment*, **169**, pp. 219–230, 2013.

[15] Barbaro, G., Master Plan of solutions to mitigate the risk of coastal erosion in Calabria (Italy), a case study. *Ocean & Coastal Management*, **132**, pp. 24–35, 2016.

[16] Zema, D.A., Bombino, G., Boix-Fayos, C., Tamburino, V., Zimbone, S.M. & Fortugno, D., Evaluation and modeling of scouring and sedimentation around check dams in a Mediterranean torrent in Calabria, Italy. *Journal of Soil and Water Conservation*, **69**(4), pp. 316–329, 2014.

[17] Fortugno, D. et al., Adjustments in channel morphology due to land-use changes and check dam installation in mountain torrents of Calabria (southern Italy). *Earth Surface Processes and Landforms*, **42**(14), pp. 2469–2483, 2017.

[18] Barbaro, G., A new expression for the direct calculation of the maximum wave force on vertical cylinders. *Ocean Engineering*, **34**, pp. 1706–1710, 2007.

[19] Romolo, A., Malara, G., Barbaro, G. & Arena, F., An analytical approach for the calculation of random wave forces on submerged tunnels. *Applied Ocean Research*, **31**(1), pp. 31–36, 2009.

[20] Barbaro, G. & Foti, G., Shoreline behind a breakwater for wave energy absorption in Reggio Calabria: comparison between theoretical models and experimental data. *WIT Transactions on Ecology and the Environment*, **149**, pp. 237–248, 2011.

[21] Barbaro, G., Saline Joniche: a predicted disaster. *Disaster Advances*, **6**(7), pp. 1–3, 2013.

[22] Barbaro, G., Foti, G. & Sicilia, C.L., Wave forces on upright breakwater, evaluation and case study. *Disaster Advances*, **6**, pp. 90–95, 2013.

[23] Prumm, M. & Iglesias, G., Impacts of port development on estuarine morphodynamics: Ribadeo (Spain). *Ocean & Coastal management*, **130**, pp. 58–72, 2016.

[24] Diab, H., Younes, R. & Lafon, P., Survey of research on the optimal design of sea harbours. *International Journal of Naval Architecture and Ocean Engineering*, **9**, pp. 460–472, 2017.

[25] Miduri, M., Foti, G. & Puntorieri, P., Impact generated by Marina of Badolato (Italy) on adjacent coast. *Proceeding of 13th International Congress on Coastal and Marine Sciences, Engineering, Management and Conservation MEDCOAST (Mellieha, Malta)*, **2**, pp. 935–945, 2017.

[26] Boak, E.H. & Turner, I.L., Shoreline definition and detection: a review. *Journal of Coastal Research*, **21**(4), pp. 688–703, 2005.

[27] Mills, J.P., Buckley, S.J., Mitchell, H.L., Clarke, P.J. & Edwards, J., A geomatics data integration technique for coastal change monitoring. *Earth Surface Processes and Landforms*, **30**(6), pp. 651–664, 2005.

[28] Alesheikh, A.A., Ghorbanali, A. & Nouri, N., Coastline change detection using remote sensing. *International Journal of Environmental Science and Technology*, **4**(1), pp. 61–66, 2007.

[29] Maiti, S. & Bhattacharya, A.K., Shoreline change analysis and its application to prediction: A remote sensing and statistics-based approach. *Marine Geology*, **257**(1–4), pp. 11–23, 2009.

[30] Maglione, P., Parente, C. & Vallario, A., Coastline extraction using high resolution WorldView-2 satellite imagery. *European Journal of Remote Sensing*, **47**(1), pp. 685–699, 2014.

[31] Ayadi, K., Boutiba, M., Sabatier, F. & Guettouche, M.S., Detection and analysis of historical variations in the shoreline, using digital aerial photos, satellite images, and topographic surveys DGPS: case of the Bejaia bay (East Algeria). *Arabian Journal of Geosciences*, **9**, pp. 1–18, 2015.

[32] Moussaid, J., Fora, A.A., Zourarah, B., Maanan, M. & Maanan, M., Using automatic computation to analyze the rate of shoreline change on the Kenitra coast, Morocco. *Ocean Engineering*, **102**, pp. 71–77, 2015.

[33] Natesan, U., Parthasarathy, A., Vishnunath, R., Kumar, G.E.J. & Ferrer, V.A., Monitoring longterm shoreline changes along Tamil Nadu, India using geospatial techniques. *Aquatic Procedia*, **4**, pp. 325–332, 2015.

[34] Barbaro, G., Fiamma, V., Barrile, V., Foti, G. & Ielo, G., Analysis of the shoreline changes of Reggio Calabria (Italy). *International Journal of Civil Engineering and Technology*, **8**(10), pp. 1777–1791, 2017.

[35] Borrello, M.M., Foti, G. & Puntorieri, P., Shoreline evolution near the mouth of the Petrace River (Reggio Calabria, Italy). *Proceedings of 9th International Conference on River Basin Management (Prague, Czech Republic), WIT Transactions on Ecology and the Environment*, **221**, pp. 59–67, 2017.

[36] Barbaro, G., Bombino, G., Foti, G., Borrello, M.M. & Puntorieri, P., Shoreline evolution near river mouth: Case study of Petrace River (Calabria, Italy). *Regional Studies in Marine Science*, **29**, article number 100619, 2019.

[37] Foti, G., Barbaro, G., Bombino, G., Fiamma, V., Puntorieri, P., Minniti, F. & Pezzimenti, C., Shoreline changes near river mouth: case study of Sant'Agata River (Reggio Calabria, Italy). *European Journal of Remote Sensing*, **52**(sup.4), pp. 102–112, 2019.

[38] Barbaro, G., Foti, G. & Sicilia, C.L., Coastal erosion in the South of Italy. *Disaster Advances*, **7**, pp. 37–42, 2014.

[39] Fiori, E. et al., Analysis and hindcast simulations of an extreme rainfall event in the Mediterranean area: The Genoa 2011 case. *Atmospheric Research*, **138**, pp. 13–29, 2014.

[40] Boudet, L., Sabatier, F. & Radakovitch, O., Modelling of sediment transport pattern in the mouth of the Rhone delta: Role of storm and flood events. *Estuarine, Coastal and Shelf Science*, **198**, pp. 568–582, 2017.
[41] Nucera, A., Foti, G., Canale, C., Puntorieri, P. & Minniti, F., Coastal flooding: damage classification and case studies in Calabria (Italy). *WIT Transactions on Engineering Sciences*, **121**, pp. 93–103, 2018.
[42] Scionti, F., Miguez, M.G., Barbaro, G., De Sousa, M.M., Foti, G. & Canale, C., An integrated methodology for urban flood risk mitigation: the case study of Cittanova (Italy). *Journal of Water Resources Planning and Management*, **144**(10), 05018013, 2018.
[43] Yashasvini, D.H., Priyanka, S., Vidyashree & Vinutha, S., Urban flood management and monitoring in Vrishabhavathi Valley. *International Journal of Civil Engineering and Technology*, **10**(6), pp. 508–512, 2019.
[44] Barbaro, G. et al., Risk mapping of coastal flooding areas. Case studies: Scilla and Monasterace (Italy). *International Journal of Safety and Security Engineering*, **10**(1), pp. 59–67, 2020.
[45] Schambach, L., Grilli, S.T., Tappin, D.R., Gangemi, M.D., & Barbaro, G., New simulations and understanding of the 1908 Messina tsunami for a dual seismic and deep submarine mass failure source. *Marine Geology*, **421**, 106093, 2020.
[46] Barbaro, G., Petrucci, O., Canale, C., Foti, G., Mancuso, P. & Puntorieri, P., Contemporaneity of floods and storms. A case study of Metropolitan Area of Reggio Calabria in Southern Italy. *Prooceedings of New Metropolitan Perspectives (NMP) (Reggio Calabria, Italy), Smart Innovation, Systems and Technologies*, **101**, pp. 614–620, 2019.
[47] Canale, C., Barbaro, G., Petrucci, O., Fiamma, V., Foti, G., Barillà, G.C., Puntorieri, P., Minniti, F. & Bruzzaniti, L., Analysis of floods and storms: concurrent conditions. *Italian Journal of Engineering, Geology and Environment*, **1**, pp. 23–29, 2020.
[48] Aramini, G., Colloca, C., Corea, A.M., Paone, R., Caruso, A., Bruno, G. & Marsico, T., I suoli della Calabria-Carta dei suoli in scala 1:250000 della Regione Calabria. Programma Interregionale Agricoltura-Qualità – Misura 5, 2003 (in Italian).
[49] Sorriso-Valvo, M. & Terranova, O., The Calabrian fiumara streams. *Zeitschrift für Geomorphologie*, **143**, pp. 109–125, 2006.
[50] Sorriso-Valvo, M., Natural hazards and natural heritage – Common origins and interference with cultural heritage. *Supplementi di Geografia Fisica e Dinamica Quaternaria*, **31**(2), pp. 231–237, 2008.
[51] Sabato, L. & Tropeano, M., Fiumara: a kind of high hazard river. *Physics and Chemistry of the Earth*, **29**, pp. 707–715, 2014.
[52] Boccotti, P., *Wave Mechanics for Ocean Engineering*, Elsevier Oceanography Series, 2000.
[53] Arena, F. & Barbaro, G., Il rischio ondoso nei mari italiani, CNR-GNDCI num. 1965, Editoriale BIOS, Cosenza, pp. 1–136, 1999 (in Italian).