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ANALYSIS OF FLOODS AND STORMS: CONCURRENT CONDITIONS

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EXTENDED ABSTRACT

L'antropizzazione del territorio che ha caratterizzato gli ultimi decenni ha causato un incremento delle superfici impermeabili, con conseguenti ripercussioni sul ciclo idrologico. In particolare, l'impermeabilizzazione del suolo riduce le perdite idrologiche aumentando i deflussi superficiali, a parità di evento atmosferico. Inoltre, i cambiamenti climatici attualmente in atto influiscono in modo significativo sulla circolazione atmosferica e, quindi, sugli eventi atmosferici che generano precipitazioni intense e mareggiate. Nella letteratura scientifica, alluvioni e mareggiate sono quasi sempre studiate e analizzate separatamente. Invece, le maggiori criticità si osservano nel caso di eventi concomitanti ma la maggior parte delle ricerche svolte finora si concentra principalmente sugli effetti prodotti sul territorio piuttosto che sull'analisi delle cause che favoriscono la concomitanza degli eventi. Territori vulnerabili come quelli italiani e calabresi possono risentire maggiormente degli effetti di tali eventi, la cui frequenza e variabilità spaziale e temporale incrementa i possibili rischi.

La memoria analizza le condizioni che favoriscono la contemporaneità tra alluvioni e mareggiate, soffermandosi principalmente sugli aspetti geo-morfologici e climatici del territorio calabrese, ed in particolare della città metropolitana di Reggio Calabria, che, per le sue caratteristiche geomorfologiche e climatiche, può favorire la contemporaneità tra mareggiate ed alluvioni. L'area oggetto di studio si trova nella parte meridionale della Calabria. Tale regione ha una forma stretta e lunga con prevalenza di montagne e colline e con poche pianure (nell'area in esame è presente quella di Gioia Tauro). La Calabria ha una notevole estensione costiera, con circa 750 km di coste (220 dei quali appartenenti all'area di studio) che si affacciano su due mari, Ionio ad Est (soggetto a venti e perturbazioni provenienti prevalentemente da Scirocco e Levante) e Tirreno ad Ovest (soggetto a venti e perturbazioni provenienti prevalentemente da Maestrale). A causa di tale conformazione morfologica, una percentuale elevata di rilievi montuosi è situata a breve distanza dalla costa per cui numerosi corsi d'acqua sono caratterizzati da bacini idrografici di piccola estensione, con pendenze elevate e con bassi tempi di corrivazione. Tali corsi d'acqua sono denominati "fiumare" ed hanno regime idrologico torrentizio, con lunghi periodi secchi e con piene improvvise ed impetuose. La maggior parte dei suoli adiacenti le fiumare è caratterizzato da bassa permeabilità, con conseguente riduzione delle perdite idrologiche. Tutti questi fattori contribuiscono ad incrementare il rischio idraulico. Dal punto di vista costiero, sia il Mar Ionio che il Mar Tirreno sono caratterizzati da grande variabilità spaziale dei fetch geografici, con alcune direzioni (le stesse da cui arrivano le perturbazioni sopra citate) in cui i fetch sono dell'ordine di 500-1000 km. Pertanto, anche il rischio di inondazione costiera assume notevole importanza ed il verificarsi in contemporanea di alluvioni e mareggiate può avere notevoli ripercussioni sul territorio.

La contemporaneità delle alluvioni e delle mareggiate è stata analizzata prendendo in esame i dati contenuti in due database. Il primo è quello dell'Istituto di Ricerca per la Protezione Idrogeologica del Consiglio Nazionale delle Ricerche di Cosenza (CNR-IRPI), che fornisce informazioni sugli eventi di dissesto idrogeologico avvenuti in Calabria negli ultimi secoli. In dettaglio, il database contiene data, localizzazione e descrizione dell'evento e dei relativi danni, raggruppati per comune. Il secondo database è quello del MeteOcean del Dipartimento DICCA dell'Università di Genova che fornisce dati ondosi e climatici dell'intero Mar Mediterraneo (scomposto in una griglia a maglia quadrata di 10 km per lato) degli ultimi 40 anni, dal 1979 al 2019, ricostruiti a partire dai dati del Climate Forecast System Reanalysis (CFSR). In dettaglio, il database contiene, ad intervalli orari e per ciascun punto, altezze significative, periodi medio e di picco, lunghezze d'onda, velocità del vento alla quota di 10 m e direzioni di provenienza del moto ondoso e del vento.

Nell'area di studio è stata osservata una elevata contemporaneità, pari al 97%, nella macro-area ionica mentre nella macro-area tirrenica la contemporaneità è minore, 73%, ma sempre rilevante. Questo studio rappresenta uno studio pilota che può essere esteso in altri territori geomorfologicamente e climaticamente simili all'area oggetto di studio (per esempio Liguria, Basilicata, Sicilia etc.). Lo studio è di notevole interesse nel campo della pianificazione e gestione delle aree costiere, soprattutto in prossimità delle foci fluviali ed in presenza di centri abitati ed infrastrutture. Infatti, le foci fluviali rappresentano i territori maggiormente vulnerabili in presenza di alluvioni e mareggiate concomitanti.

ABSTRACT

The geomorphological characteristics and the seismic, landslide and erosive dynamism of the Italian territory, meant studies on the hydrogeological risk were necessary. Floods and sea storms, combined with anthropic factors, are causes of instability. Under particular climatic, geographical and geomorphological conditions, these events occur simultaneously, increasing their effects. Reggio Calabria, a metropolitan city in the south of Italy, is located in a particularly complex context. The city is flanked by the Tyrrhenian Sea and by the Ionian Sea. The territory is exposed to the risk of intense sea storms. Moreover, the torrential nature of the rivers and intense rainfall favour the formation of floods. This paper analyse the conditions that favour the concurrence between floods and sea storms in the territory of Reggio Calabria. This analysis can be extended to other areas with characteristics that are similar to those of Reggio Calabria.

***Keywords**: flood, sea storms, hydrogeological instability phenomena, contemporary events, geomorphology, climate, fiumare.*

INTRODUCTION

The causes of hydrogeological instability phenomena can be associated with various factors, directly and indirectly related to human action (Addo, 2013; Phillips & Jones, 2006). For example, growing anthropization causes irreversible processes of soil consumption, with increase in river and urban flow discharge. Furthermore, over the decades there has been a slow and gradual climate change that has strongly affected rainfall. This change also affects the coasts, causing sea level rise and extreme events with consequent sea storms, run-up, overtopping and flooding (Komar, 2000; Breil *et alii*, 2007; Lionello *et alii*, 2010; Barbaro *et alii*, 2019b; Schambach *et alii*, 2019a). The intensity and frequency of sea storms strongly affect the coastal erosion process (Boccotti *et alii*, 2011; Barbaro *et alii*, 2013) and coastal structures, very often, are insufficient to counteract sea storms (Barbaro *et alii*, 2014a). Studies in the literature treat floods and sea storms in separate ways. About floods, both river and urban floods are studied, analyzing hydraulic interventions and water disposal systems and carrying out the studies using mainly two-dimensional models (Mascarenhas *et alii*, 2002; Prestininzi & Fiori, 2006; Kim *et alii* 2007; Scionti *et alii*, 2018). Regarding sea storms, various researches focus on coastal hydrodynamics, on coastal erosion and on sediment transport (Maiti *et alii*, 2009; Tomasicchio *et alii*, 2015; Barbaro *et alii*, 2017). However, the most critical aspects of floods and sea storms are observed in the case of concurrent events (Barbaro *et alii*, 2019c). The context in concurrent events is more complex and it is conditioned by particular meteorological features and complex orographies. Reggio Calabria, in Southern Italy, is located in this context. The territory is flanked by the Ionian Sea and the Tyrrhenian Sea. The typical rivers are called "fiumare". They have a torrential hydrological character that favours the formation of floods in a short time. The exposure of the metropolitan city to the winds of Scirocco, Levante and Maestrale, influences the characteristics of precipitations and of the sea storms. This paper analyse the conditions that favour the concurrence between floods and sea storms in the territory of Reggio Calabria. Also, the paper describe the territory from the geomorphological and climatic point of view and analyse the concurrent events that have affected the metropolitan city of Reggio Calabria. The analysis was carried out by analysing two databases. The first was provided by the CNR-IRPI of Cosenza. It contains all the events of hydrogeological instability in Calabria. The second database was provided by the Meteocean group of the DICCA department of Genoa and contain wave data of the last 40 years. For every flood event, the presence of a simultaneous sea storm was verified. This analysis can be extended to other areas with characteristics that are similar to those of Reggio Calabria.

SITE DESCRIPTION

The metropolitan city of Reggio Calabria is in the Calabria region and is located the south of Italy, as shown in Fig. 1.

The city is located in the centre of the Mediterranean and is flanked by the Tyrrhenian Sea and the Ionian Sea. The length of the coasts is about 210 km. Reggio Calabria has 97 municipalities, of which 37 are coastal. It represents the second biggest city of the Calabria region by number of inhabitants (about 548000). The most important massif is the Aspromonte, part of the Calabrian Apennines and very close to the coast. So, there are many coastal areas without plains, except for the Gioia Tauro Plain in Tyrrhenian area, as shown in Fig.2. The territory is subject to numerous hydrogeological instability phenomena, including floods and sea storms.

Fig. 1 - Location of the metropolitan city of Reggio Calabria (in red).

Fig. 2 - Extension of the Aspromonte massif along the territory of Reggio Calabria.

GEOMORPHOLOGICAL CHARACTERISTICS

The tectonic history of Calabria has influenced and determined the present geology of this region. The whole territory is contained in the Calabrian-Peloritan arch, considered a fragment of the Alpine chain and divided into two units, one southern and one northern. It represents a link between the Eurasian and African plates. Although there are ancient rocks, it can be assumed that Calabria, and even more so the metropolitan city of Reggio Calabria, is geologically young. In fact, the layout of the strata making up the territorial structure has occurred in recent times and the slopes are constantly evolving due to the lifting of the plates (Mandaglio, 2016). The degradation of the soil depends very much on the type of outcropping layers. The ARSSA (Regional Agency for Development and Services in Agriculture) has carried out a classification of soils for the whole of Calabria (Aramini *et alii*, 2003). The coastal area of the metropolitan city of Reggio Calabria is part of the Soil Region 62.3 and 66.5, as shown in Fig.3a and 3b.

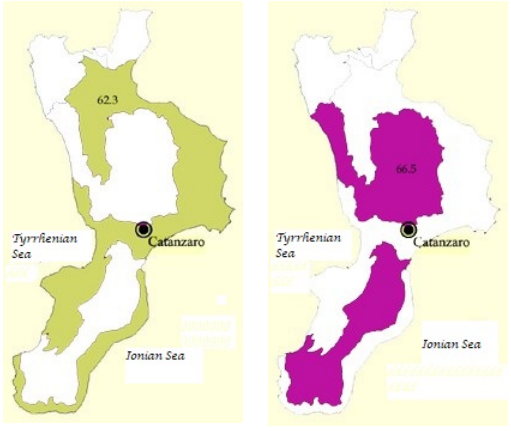

Fig. 3 - (a) Type of soil 62.3 characterizing the Ionian coast and part of the Tyrrhenian. (b) Type of soil 66.5 characterizing the remaining coastal area of the territory of Reggio Calabria.

The type of soil 62.3 presents a silty clayey substrate of the Pliocene. This means the land has a vulnerability and predisposition to soil degradation phenomena. The areas of alluvial deposits have a variable granulometry, depending on the type of sediment. Type 66.5 concerns a restricted area of the Tyrrhenian coastal area. These are coarse soils with variable thickness. The risk of erosion is due to the export of vegetation cover. They are soils with good drainage capacity. The types of soil exposed affect the instability of slopes and land, affecting the risk conditions.

The typical rivers are called "fiumare". The hydrographic configuration of these rivers is influenced by the Calabrian tectonic history. Many reliefs are close to the coast, with several coastal areas without coastal plains. Therefore, most of the basins are characterized by a small catchment area (from 8.2 to 159.8 km^2) and, due to the small distance between mountain and sea, longitudinal slopes of the rivers are very high. The latter parameter causing frequent landslides and increasing solid transport, that affect the coastal morphology (Sicilia *et alii,* 2013; Barbaro *et alii*, 2014b; Barbaro *et alii*, 2019a; Barbaro *et alii*, 2019d; Foti *et alii*, 2019). Other peculiarities of this rivers include the presence of very wide beds with coarse grain size from a few cm up to 2 m and the presence of sand and silt is low (Sabato & Tropeano, 2014). The hydrological regime is torrential (Sorriso *et alii*, 2006; Petrucci *et alii*, 2012) with short run-off times (Sorriso & Valvo, 2008). The river flow is almost nil during the summer but grows very quickly during the flood events.

Regarding the characteristics of coastal sediments, along the Ionian area the beaches are pebbly and sand of alluvial origin, due to the river transport. The presence on the seabed of geological formations, similar to canyons, favours the distribution and dispersion of solid material during extreme events. The Tyrrhenian area has very different characteristics. There are many high coasts and pocket beaches and the coast of the Gioia Tauro Plain is characterized by a very large dune system. Finally, the concurrence of floods and sea storms affects the coastal morphology.

CLIMATIC CHARACTERISTICS

Reggio Calabria has some geographical and morphological peculiarities. The spatial variability of climatic conditions and of extreme events can be attributed to the particular conformation of the peninsula, flanked by two seas: the Ionian Sea and the Tyrrhenian Sea (Terranova *et alii*, 2013). This peculiarity is associated with an orography that contrasts the humid currents, favouring the ascent of air masses and generates rainfall events. Generally, the climate conditions and the atmospheric disturbances affecting the Tyrrhenian coast are different from those affecting the Ionian coast. The Ionian coast is exposed to Levante and Scirocco winds (Fig. 4). The atmospheric disturbances associated

with these winds can be intense and persistent and, in some cases, are similar to a kind of hurricane, also called Medicane (Mediterranean Hurricane) or Tropical Like Cyclones (TLC). The Tyrrhenian coast is exposed to the Mistral wind (Fig. 4), that is very strong in the winter period due to the thermal contrast that is generated between the pole and the equator. The disturbances associated with the Mistral wind are of the Atlantic type, with frequent rains similar to a flash flood but they are almost never persistent (Buttafuoco *et alii*, 2007). These disturbances explain the greater rainfall in the Tyrrhenian area, as compared to the Ionian one. The average annual rainfall is about 1150 mm, higher than the Italian average value of 970 mm. The spatial distribution of the average annual rainfall as shown in Fig.5.

The winds also influence the wave climate. In the following polar graphs, the mean energy flux and the wind velocity are shown for the Ionian coast. Very high flux values are observed along the sectors between 50° and 60°, related to the Grecale winds, and between 110° and 140°, related to the Scirocco and Southern winds. Regarding the wind velocity, the trend is similar to that of the mean energy flux and are in perfect correlation with the exposure of the coasts. The Tyrrhenian area is subject by a wave climate that is concentrated in a specific sector (about 300° in the North), perfectly oriented with the direction of the NW disturbances (Barbaro, 2016). In both areas, the fetches can reach lengths of the order of a thousand kilometres.

METHODOLOGY

The concurrence of floods and sea storms was verified by analysing two databases. The first was the ASICal database (Historically Flooded Areas in Calabria), provided by the CNR-IRPI of Cosenza. It contains the date, description and location of all the events of hydrogeological instability in Calabria. The second database was provided by the Meteocean group of the DICCA department of Genoa. This database contain wave and climate data, mainly significant height, average period, peak period, average direction, peak direction, wind velocity, of the Mediterranean Sea of the last 40 years, from 1979 to 2019. The Mediterranean has been divided into a square mesh of about 10 km long (Fig. 8). For each flood event that occurred in this time interval, the presence of a simultaneous sea storm was verified. First, it was necessary to associate each grid point with the corresponding coastal municipalities.

A 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" (Boccotti, 2000). The critical threshold depends on the location and was calculated for each grid point using the following expression (Arena & Barbaro, 1999):

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

$\overline{H_s}$ represents the average significant wave heights of the entire time series of each grid point. To verify the concurrence, if in the date of the flood H_s has exceeded h_{crit}, then the sea storm has also occurred.

RESULTS

A significant case study of the concurrence between floods and sea storms is the event that occurred from October 31st to November 2nd 2015 in Bruzzano Zeffirio, a town in southern Ionian Calabria. The event consisted of both a flood, which caused the flooding of the Bruzzano river, and a sea storm. The joint action of both phenomena may have caused the collapse of the highway bridge and of the railway bridge, both located near the river mouth. Figure 9 shows the effects of the concurrent events.

The analysis carried out for Reggio Calabria includes 35 coastal municipalities out of 37. The study excluded the municipalities which, due to reduced coastal length, do not

Fig. 4 - Wind rose on the coasts of Reggio Calabria.

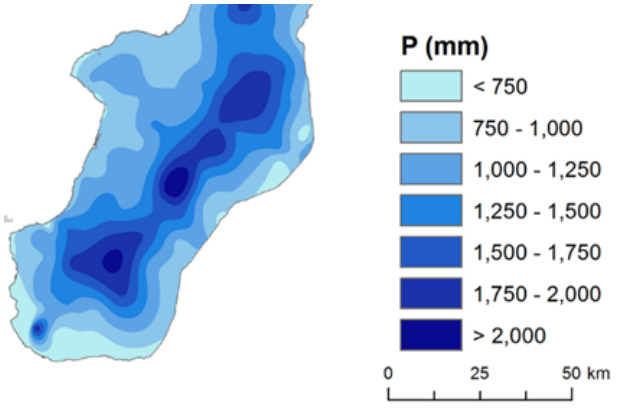

Fig. 5 - Spatial distribution of the average annual rainfall (P).

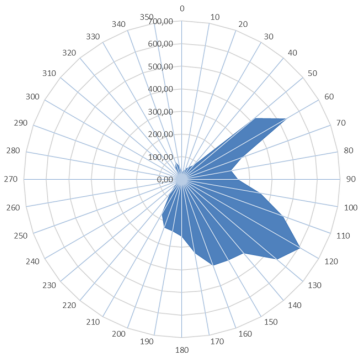

Fig. 6 - Polar graph of the energy flux for the Ionian coast. The values are in N/s.

have rivers in their territory. Due to the geomorphological and climatic differences between the Ionian and the Tyrrhenian coasts, the study was divided into these two macro areas. There are 29 municipalities on the Ionian area (from Monasterace to Reggio Calabria) and 6 on the Tyrrhenian area (from Villa San Giovanni to San Ferdinando). The analysis shows a high concomitance. Indeed, from 1979 to 2019 there were 252 flood events that affected the coastal municipalities of Reggio Calabria. Of these events, 231 are concurrent. The total percentage of concurrent events is 92%, with higher values on the Ionian coast, 97%, compared to the Tyrrhenian coast, 73%. In the latter area, the concomitance occurs most in the winter period. Table 1 shows the results obtained for the two macro areas. In Table 2, the detailed study of each coastal municipalities analysed is shown. From this Table it is possible to observe a perfect concurrence of events for most Ionian municipalities, 24 out of 35, and the municipality with the lowest percentage of concurrence is Africo, 80%. In the Tyrrhenian area, the municipality with the highest percentage of concurrence is San Ferdinando, 86%, and the municipality with the lowest percentage of concurrence is Bagnara Calabra, 59%.

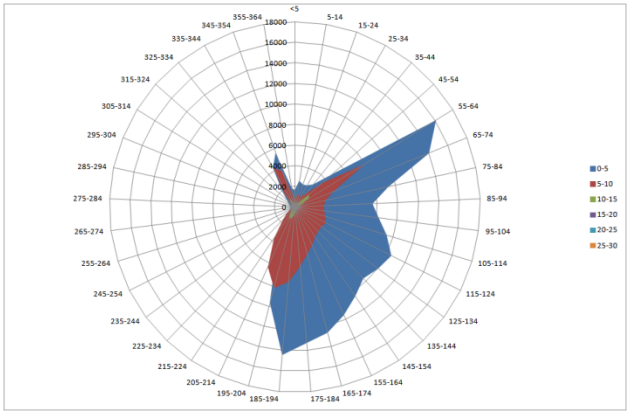

Fig. 7 - Polar graph of the wind velocity for the Ionian coast. The values are in m/s.

Location	Flood events	Concurrent sea storms	% concurrent events
Ionian coast	193	188	97
Tyrrhenian coast	59	43	73
Total	252	231	92

Tab. 1 - Number of analysed events and percentage of concurrent events.

Location	Flood events	Concurrent sea storms	% concurrent events
Monasterace	8	8	100
Stilo	4	4	100
Camini	2	2	100
Riace	1	1	100
Stignano	3	3	100
Caulonia	15	15	100
Roccella Ionica	5	5	100
Marina di Gioiosa Ionica	5	5	100
Grotteria	4	4	100
Siderno	6	6	100
Locri	6	6	100
Portigliola	4	4	100
Sant'Ilario dello Ionio	2	2	100
Ardore	10	10	100
Bovalino	11	11	100
Casignana	2	2	100
Bianco	11	11	100
Africo	5	4	80
Ferruzzano	8	7	88
Bruzzano Zeffiro	7	6	86
Brancaleone	6	6	100
Palizzi	5	5	100
Bova Marina	13	13	100
Condofuri	17	16	94
San Lorenzo	2	2	100
Melito	8	8	100
Montebello Ionico	10	9	90
Motta San Giovanni	8	8	100
Reggio Calabria	5	5	100
Villa San Giovanni	3	2	67
Scilla	10	8	80
Bagnara Calabra	17	10	59
Palmi	4	3	75
Gioia Tauro	18	14	78
San Ferdinando	7	6	86

Tab. 2 - Analysed events and concurrent events for each municipality of the metropolitan city of Reggio Calabria.

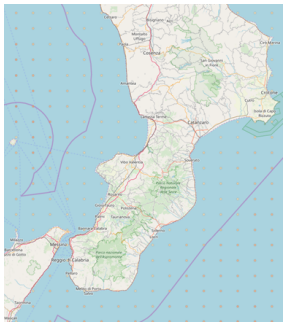

Fig. 8 - Squadre mesh of the Meteocean database.

Fig. 9 - The suspended railway tracks at Bruzzano Zeffirio following the event of 31th October-2nd November.

CONCLUSIONS

This paper analyse the conditions that favour the concurrence between floods and sea storms in the territory of Reggio Calabria. Also, the paper describe the territory from the geomorphological and climatic point of view and analyse the concurrent events that have affected the metropolitan city of Reggio Calabria. The analysis was carried out by analysing two databases. The first was provided by the CNR-IRPI of Cosenza. It contains all the events of hydrogeological instability in Calabria. The second database was provided by the Meteocean group of the DICCA department of Genoa and contain wave and climate data of the last 40 years. For every flood event, the presence of a simultaneous sea storm was verified.

The exposure of the coasts to atmospheric disturbance and the characteristics of the river basins are the main factors for the concurrence between floods and sea storms. Atmospheric disturbance have variable extension but to generate concurrent events it is necessary that the extension of the atmospheric disturbance is such that it affects both the sea and the soil.

Generally, the atmospheric disturbances affecting the Tyrrhenian coast are different from those affecting the Ionian coast. The Tyrrhenian disturbances are of the Atlantic type, with frequent rains similar to a flash flood but they are almost never persistent. The Ionian disturbances are more extensive and, in some cases, are similar to a kind of hurricane, also called Medicane (Mediterranean Hurricane) or Tropical Like Cyclones (TLC).

The analysis described in this paper can be extended to other areas with characteristics that are similar to those of Reggio Calabria, for example the Italian regions of Liguria, Sicily and Basilicata. Some possible future developments concern the analysis of the extent of the events, in terms of rainfall heights and intensity, in terms of the maximum significant wave heights of the sea storms and of the durations of both events. Finally, this study is also of considerable interest for the planning and management of the river mouth areas.

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