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AN INTEGRATED MODEL TO PREDICT TORRENTS MOUTH EVOLUTION IN MEDITERRANEAN CLIMATE CONDITIONS

Ph.D. Thesis

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Summary

Abstract

River mouths dynamics and processes are not much studied, and watersheds and coasts are still considered as two separate entities. In the semi-arid Mediterranean environment, watercourses have a torrential character, with riverbeds that experience short periods of severe and abundant floods during the rainy season, and long periods of absent or extremely low flow during the rest of the year. Despite most of the literature on watershed-coast interaction looks into specific cases under conditions that can vary greatly depending on the climate, in Mediterranean torrents the studies are very poor.

For this reason, this study proposes to identify only some flood events in order to simulate the solid transport in Mediterranean torrents. In addition, a new numerical model for the prediction of coastal evolution near torrents mouth is presented. The model is applied and validated in the case-studies of La Verde, Bruzzano and Spartivento watersheds, in Southern Italy, confirming its reliability through the application to past periods and comparing the shorelines obtained with those captured by satellite images.

Riassunto

Le dinamiche e i processi delle foci fluviali sono poco studiati; inoltre, i bacini idrografici e le coste sono ancora considerati due entità separate. Nell’ambiente semi-arido mediterraneo, i corsi d’acqua hanno un carattere prevalentemente torrentizio, che alterna un breve periodo di piene improvvise e abbondanti durante la stagione delle piogge, e un lungo periodo siccitoso o con deflussi molto scarsi nel resto dell’anno.

Nonostante la maggior parte della letteratura sull’interazione bacino-costa esamina casi specifici in condizioni anche molto variabili a seconda del clima, i corsi d’acqua in ambiente semi-arido mediterraneo sono ancora poco indagati.

Pertanto, questo studio propone di identificare solo alcuni eventi di piena per simulare il trasporto solido dei torrenti mediterranei. Inoltre, viene presentato un nuovo modello numerico per la previsione dell’evoluzione costiera attorno alle foci dei torrenti. Il modello viene applicato e validato nei casi-studio dei bacini La Verde, Bruzzano e Spartivento, nel Sud Italia, confermando la sua affidabilità attraverso l'applicazione a periodi passati e confrontando le linee di costa ottenute con quelle immortalate dalle immagini satellitari.

Keywords

Watershed/coast interaction, Coastal evolution, Numerical modelling, Watershed coast continuum, Mediterranean torrents

1 General introduction

1.1 Forward

The movements and evolution of the coast around the mouths of watercourses are mainly the result of the effects of erosion, transport, and sedimentation processes on both land and sea. The water and sediment fluxes, conveyed along channels and delivered to the sea, greatly impact the coastal areas (Syvitski et al., 2009).

These evolutionary trends pose serious threats to ecosystem sustainability in coastal regions (Yang et al., 2011; Wang et al., 2016). The effects of the natural processes governing water and sediment fluxes in a watershed (such as landslides, precipitation trends, evolution of vegetation cover) can also be enhanced by anthropogenic factors. The latter may play an important role in river system transformations (Milliman et al., 2008; Miao et al., 2011), such as the construction of large dams and artificial reservoirs which resulted in a drastic reduction in river sediment supply (Poulos and Chronis, 1997).

Therefore, management strategies of watersheds, leading to significant alterations of morphology and hydrology of the river system, can result in significant morphological alterations of the coastal zones (Samaras and Koutitas, 2014a). The negative environmental effects have drawn the attention of scientists and land managers to study and assess current sediment delivery rates to coastal and marine habitats (Mateos-Molina et al., 2015).

As for river dynamics, the environmental factors contributing to coastal erosion are highly variable, both in time and space (Peychev and Stancheva, 2009). Indeed, coastal morphology evolves as the combined result of both natural factors (waves, wind, tide, storms, relative sea level rise, slope stability and vertical land movement) and human effects (unsuitable design of coastal structures, dredging, ship-induced waves, coastal vegetation clearing, groundwater over-pumping from coastal aquifers and gas mining) (Samaras and Koutitas, 2014b).

It is evident how the current layout of the land-sea interface is produced by concurrent evolutionary processes acting in both inland and coastal areas (Samaras and Koutitas, 2014a).

Therefore, the efficacy of strategies and tools to predict the evolution of the coastal layout is strictly linked to the qualitative and quantitative comprehension of the physical processes taking place in both the terrestrial and coastal fields. To achieve this goal, scientists have realised that the connections between watersheds (about the terrestrial field/processes) and coastal areas (marine field/processes) cannot be analysed separately, since rivers and coasts dynamically and strictly interact by mixing water and sediment flows, producing the current layout of coastlines.

1.2 State-of-the-art

It is estimated that the total annual discharge of land sediment to the oceans is about 19 Btons/yr (Milliman and Farnsworth, 2011), a value in agreement with estimates by other authors, such as Holeman (1968), Milliman and Meade (1983) and, more recently, with those of Beusen et al. (2005) and Peucker-Ehrenbrink (2009).

The natural parameters that most influence sediment loading are related both to external actions, such as precipitation and evapo-transpiration, and to the intrinsic characteristics of the basins, such as the maximum elevation (Milliman and Syvitski, 1992).

Among the monitoring studies highlighting the effects of artificial structures on coastal morphology, there is that of Andredaki et al. (2014), conducted on the Nestor River (Greece) after the construction of a dam. The characterization of the watershed area was done through the study of rainfall and land morphology, while the monitoring of the shoreline was conducted with satellite imagery and aerial photographs. In this way it was detected, five years after the dam construction, the triggering of an erosion process of the coasts adjacent to the Nestor River mouth.

Concerning other monitoring studies, Syvitski and Kettner (2007) reconstructed the evolutionary history of the Po River (Italy) and its coast, which experienced a period of gradual development, peaking in 1800, followed by a rapid retreat due to deforestation, agricultural activities and construction of reservoirs. The study was based on runoff and water/sediment discharge data, in combination with historical surveys on the shoreline.

Lukas (2017) conducted an analysis of the evolution of the Segara Anakan lagoon (Java, Indonesia) from the mid-1800s to the present day, using historical maps, bathymetric data and more recent satellite imagery, thus bringing to light a high erosion trend of the shoreline.

Regarding the modelling of the watershed-coast system evolution, different models have been developed in the last decades.

For example, the Delft3D-FLOW was proposed by Hu et al. (2009) with the intent to reproduce the morphological evolution of Jiuduansha Shoals at the mouth bar region of the Yangtze river estuary (China). The study demonstrates that, to reliably simulate shoal evolution, transport of the cohesive as well as the non-cohesive fraction of sediment should be considered.

A widely used model for simulating basin sediment fluxes to the coast is HydroTrend (Syvitski et al., 1998; Syvitski et al., 2005), which requires meteorological data and basin characteristics as input. Subsequently, Ashton et al. (2013) coupled HydroTrend with the Coastline Evolution

Model (CEM) for the study of wave-influenced deltas evolution, highlighting that sediment discharge variability can have a significant effect on delta morphology.

Another example is PELNCON (Samaras and Koutitas, 2008), a 1-D model for the simulation of shoreline change, in order to evaluate the impact of the construction of a dam on the beach fed by the Nestos River. The authors demonstrated that the coastline retreat was caused by the sediment deficit due to the dam construction. Furthermore, Samaras and Koutitas (2014c) compared the result of three different empirical formulas for calculating longshore solid transport (Bayram et al., 2007; Kamphuis, 1991; USACE, 1975) in the modified PELNCON model, showing that the best result was obtained with the CERC formula (USACE, 1975).

1.3 Research needs

Although coastal areas and watersheds have been the subjects of several investigations and different monitoring studies have been conducted, the tendency to consider these systems as two separate entities still remain. In this regard, Salomons et al. (2005) has highlighted the importance of looking at the watershed and coastal systems as one sole body, as commonly indicated as the so-called "watershed-coast continuum" (WCC).

From these researches it is evident that, while the evolutionary dynamics of watersheds and coastlines are quite clear and thus can be predicted with acceptable reliability, the connection between watershed and coastal processes are less debated and thus the relevant literature less abundant. Indeed, literature studies analysing concurrently inland and coastal fields and their quantitative correlation are scarce (Samaras and Koutitas, 2014b). In this regard, Lukas (2017) pointed out that this fact currently is a serious limit to policy makers, which cannot rely on objective data for environmental management.

Moreover, a wide lack of information and investigation still exists in Calabria region, where the considerable steepness of the slopes, the low permeability of rocks, the small extension of high-altitude areas, the limited underground water circulation, and, above all, the extreme seasonal variability of meteoric inflows and temperatures are at the origin of a hydrological regime not at all perennial. These characteristics are typical of many southern Italy torrents, also called "fiumare" (Sorriso-Valvo and Terranova, 2006; Bombino, 2010; Sabato and Tropeano, 2014). Their specific characteristics, especially in Calabria, depend on the orography and the Mediterranean semi-arid climate, which implies that the erosion processes are of high magnitude after heavy storms and negligible under not extreme precipitations (Bombino et al., 2009; Zema et al., 2014; Fortugno et al., 2017). These peculiar characteristics, both orographic and climatic, cannot be neglected if we want to fully understand the delicate interactions between inland and coastal areas in such an environment.

1.4 Objectives

To make up for the shortcomings mentioned above, the aim of the PhD Thesis is to evaluate the torrents mouth evolution introducing an original method to identify rainfall (and therefore flood) events that are believed to have a non-negligible influence on coastal evolution in a Mediterranean context. Thus, a new shoreline evolution model is developed and coupled with an existing hydrological model. Moreover, the aim of the project is to validate the new model through the application to three case-studies located in Calabria region (Southern Italy).

Besides, one of the main objectives is to propose a model of easy use, or, in other words, such that the necessary inputs are available and possibly freely accessible, and such that the procedure turns out short and with results of easy interpretation. In this way, the new model could represent a tool that will facilitate the work of authorities and entities involved in territorial management and protection, ensuring also a global vision of the WCC system.

2 Materials and methods

2.1 Theoretical approach

2.1.1 The Hydrologic Modeling System (HEC-HMS)

HEC-HMS, the Hydrological Modeling System developed since 1998 by the "US Army Corps of Engineers" (Feldman, 2000), version 4.3, is chosen in this work to simulate the rainfall-runoff processes and the torrent sediment discharge, since it (i) runs at event scale (and thus the complete temporal diagrams of both water and sediment flows can be simulated) and (ii) takes into account the spatial variability of soil and land uses in a watershed into homogeneous response units, HRUs (Beighley et al., 2005). HEC-HMS allows to apply different rainfall-runoff transformation methods and forecast streamflow of dendritic basin systems in a wide range of geographic areas such as large river basins and small urban or natural watersheds (Abushandi and Merkel, 2013). Moreover, it simulates most of the key hydrologic processes at watershed scale (Abushandi and Merkel, 2013).

HEC-HMS provides a suite of hydrological modelling options, with the main components focusing on determining runoff hydrographs from sub-basins and routing the hydrographs through channels to the study outlet (Beighley et al., 2005; Beighley and Moglen, 2003). Users can select different methods based on existing data and local characteristics. Furthermore, spatial data can be prepared in GIS platform and directly imported into HEC-HMS (Ali et al., 2011).

Concerning the erosion and sediment transport predictions by HEC-HMS, the package provides two erosion models: the Modified Universal Soil Loss Equation (MUSLE) method and the "build-up and wash-off" method. The MUSLE equation was developed by William (1975) to predict sheet and rill erosion from a single rainfall-runoff event and simulates the sediment yield processes from a pervious land segment, while the build-up and wash-off method is a common approach to modelling impervious areas (Pak et al., 2008).

2.1.2 The littoral sediment transport

The sediment transport is the main phenomenon that induces erosion (or advancement) and changes in seabed topography. Sediment transport at any point in the surf zone, in the hypothesis of parallel bathymetric lines, can be seen as a vector with one component longitudinally to the coast (or long-shore) and one transverse (or cross-shore).

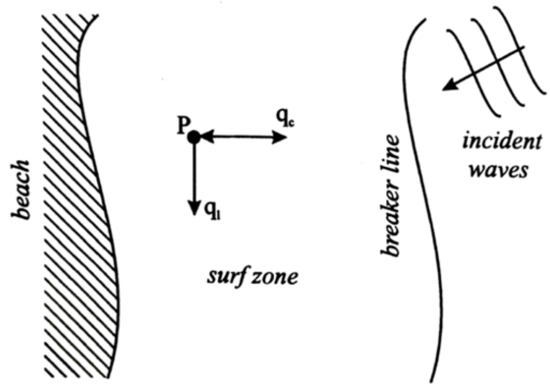


Figure 2.1 - Long-shore (q_l) and cross-shore (q_c) components of littoral solid transport.

The transversal and longitudinal coastal currents, with removal, transport, and storage actions, are responsible for the process of sediment distribution along coasts.

The movement of sediments in the longitudinal direction to the coast is less intuitive, but it is clearly evident whenever this natural movement is hampered by the presence of a coastal work such as a jetty or a groyne. This type of structure cancels or delays the coastal drift causing an accumulation of sediments above the breakwater and triggering an erosion of the beach below the breakwater.

On the other hand, cross-shore solid transport is related to seasonal variations in the coastline position (Kriebel and Dean, 1985; Kriebel, 1986; Nielsen, 1992). Coastal erosion observed during sea storm events, which is also called "acute" (Sorensen et al., 2016), is linked precisely to a movement of sediment in a predominantly transverse direction to the coast. This is the reason why two typical transverse profiles can be identified: a summer and a winter profile, with a continuous movement of sediment deposition and erosion, without implying an irreversible deformation of the beach once an annual sediment balance has been made (Figure 2.2.).

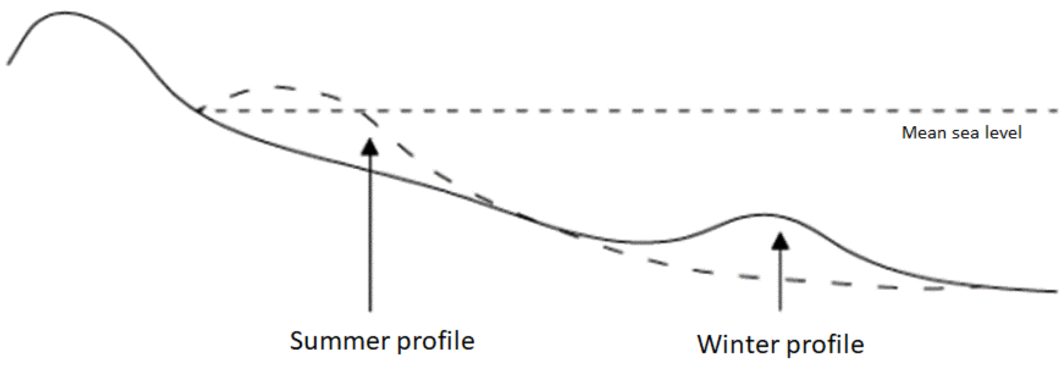


Figure 2.2 - Summer profile (dashed curve); winter profile (solid curve).

In contrast, the long-shore solid transport, along with phenomena such as subsidence and the rise in average sea level, plays a decisive role in "chronic" erosion processes, related to variations in forcing on long time scales (Pelnard-Considère, 1957; Komar and Inman, 1970; Samaras and Koutitas, 2014a; Sorensen et al., 2016).

2.1.3 The equation of sediment conservation

The new model is based on the theory proposed by Pelnard-Considère (1957), whose main hypothesis is that shoreline evolution only depends on spatial and temporal variations of longshore sediment transport; on the other hand, variations in shoreline position due to cross-shore transport caused by extreme events and seasonal changes of the wave climate are negligible, for it is assumed that on- and off-shore transport is balanced in the over-yearly time scale, as explained in the previous paragraph.

The solidity of Pelnard-Considère theory lies in the fact that it derives from a simple mass balance. Given a certain control volume at sea, it is possible to estimate a sediment balance depending on the volume of sand entering and leaving it. If the losses exceed the gains, the deficit will correspond to an erosion of the beach and vice versa. The absence of erosion or progress indicates a state of equilibrium between contributions and losses.

Let us consider a control volume extending from the shoreline to the breaker line, assuming that the bottom material moves only up to a certain depth, called closure depth D_C, and that, up to this depth, the bottom can only move with rigid shifts according to the y-axis (Figure 2.3.).

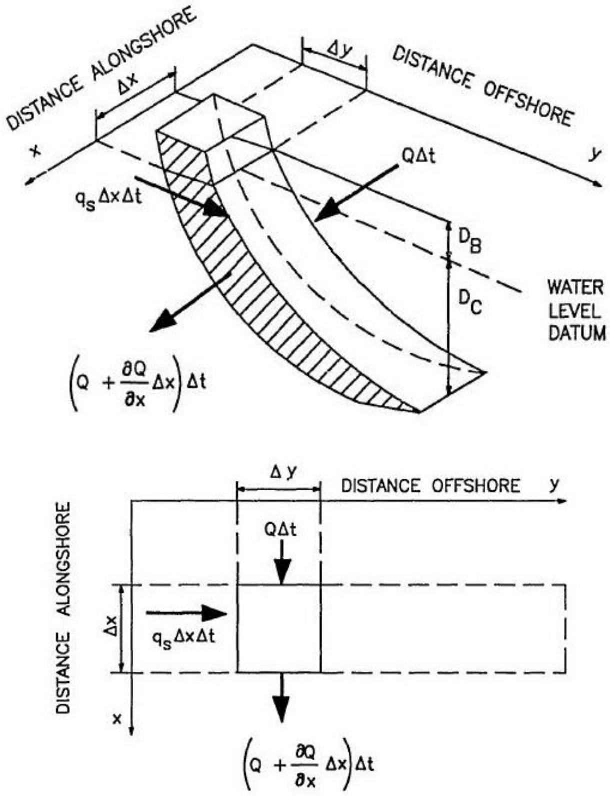


Figure 2.3 - Reference scheme for equation of sediment conservation definition.

Continuity of sand for an infinitely small length, dx, of shoreline can be written as:

$$\frac{\delta y}{\delta t} = -\frac{1}{D_C + D_B}\left(\frac{\delta Q}{\delta x} + q_s\right) \qquad [1]$$

Where *x* and *y* are the shoreline coordinates (m), *t* is the time (s), D_B is the average berm height above the mean water level (m), D_C represents the closure depth (m), *Q* is the long-shore solid transport rate (m^3/s), and q_s stands for the line source (or sink, if it is negative) along the coast ($m^3/s/m$).

Equation 1 is the governing equation for shoreline change, known as “equation of sediment conservation” (Pelnard-Considère, 1957; Dean, 1991). The models that simulate the coastal profile evolution through this equation are called one-line or 1D models, and simulate the changes of the shoreline depending on spatial and temporal variations of longshore sediment transport *Q*.

2.1.4 Coastal Engineering Research Center (CERC) formula

The equation of sediment conservation cannot be solved without knowing the expression of the long-shore sediment transport. Several equations for its calculation are available in literature, such as Kamphuis (1991) and Bayram et al. (2007).

In this study, the CERC formula (USACE, 1984) is adopted. It is based on the principle that solid transport is proportional to wave energy P:

$$Q = KP = \frac{\rho K \sqrt{g/\gamma_b}}{16(\rho_s - \rho)(1-a)} H_{sb}^{2.5} \sin(2\theta_b) \qquad [2]$$

where Q is the rate of solid material in the long-shore direction, K is an empirical coefficient dependent on the material granulometry, ρ is the water density, ρ_s is the density of sediments, g is the gravitational acceleration, a is the porosity index of sediments, H_{sb} is the significant breaking wave height, θ_b is the breaking wave angle with respect to the shoreline and γ_b is the breaking index.

The CERC formula expresses the contribution to long-shore transport due to the inclination of waves; for orthogonal attacks to the coast, the theta sine is, in fact, equal to zero.

2.2 Case-studies

2.2.1 La Verde

La Verde torrent is located in eastern Calabria (South Italy). Its water and sediment flows feed the coast near its mouth, between the coasts of Africo and Bianco (Province of Reggio Calabria, Italy). The watershed covers an area of 115 km^2, with a mainstream of about 30 km and an average altitude of 733 m.

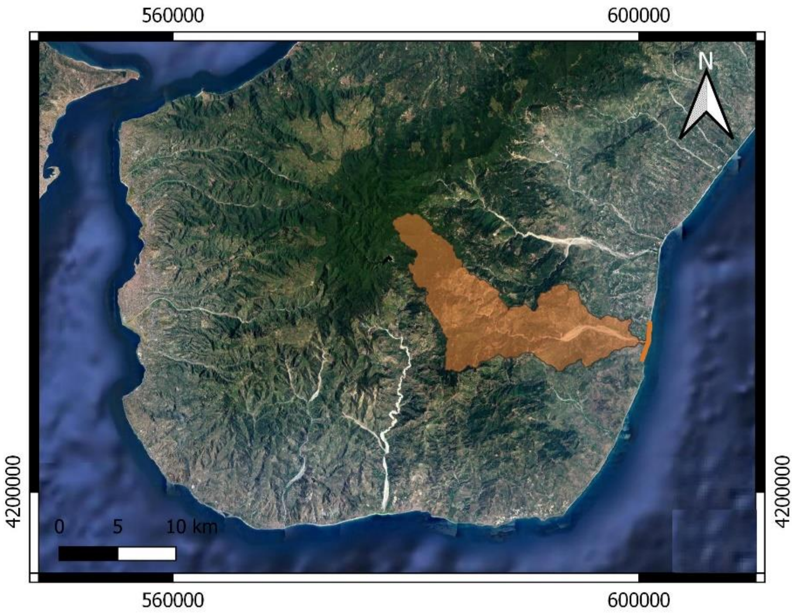
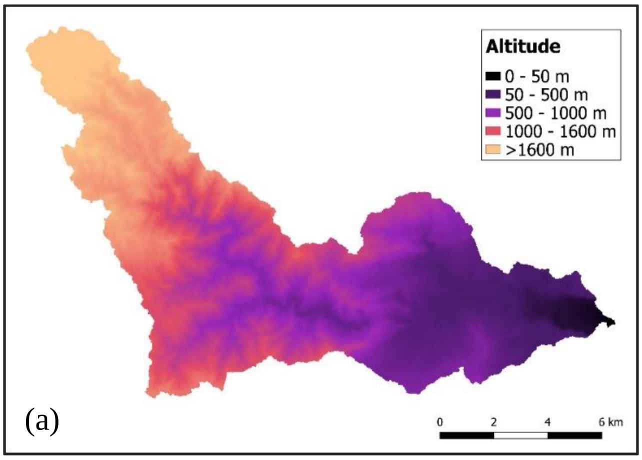


Figure 2.4 - Location of La Verde torrent

The analysis of the basin DEM (Digital Elevation Model) and the *Corine Land Cover* (scale 1:100000, EEA, 2009) shows that the reliefs reach an altitude of 1953 m (Figure 2.5 a); most of the watershed area has a slope greater than 60% (Figure 2.5 b); the forests and semi-natural areas cover 76.5% of the soil, cultivated areas extend for 23.4% and artificial areas for 0.2% (Figure 2.5 c).



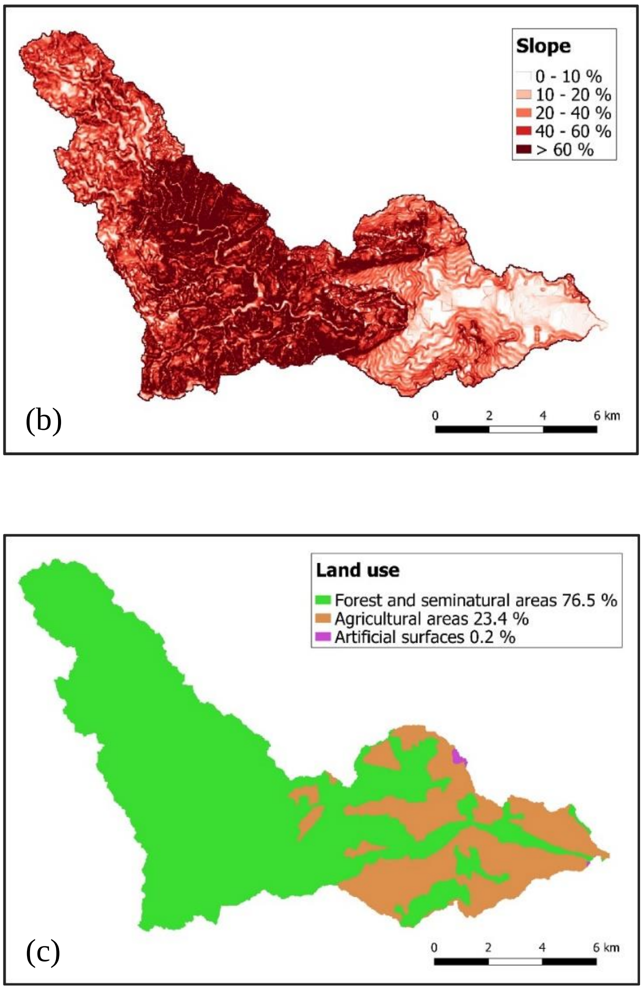


Figure 2.5 – La Verde case-study: (a) altitude, (b) slope and (c) land use.

The beach to which the new model has been applied is flat and sandy, 1.6 km long on the two sides around of La Verde's mouth, with an average slope, up to the depth -20 m, of 1.4%. The satellite images (Google Earth) of the last 20 years shows a growth trend of the beach, strongly accentuated after a severe flood in November 2015 that has led to a massive spill of alluvial material on the coast (reaching an increase of more than 70 metres at the stream's mouth).
Based on MeteOcean datasets (see paragraph 2.4.1) of the last 20 years, the wave height and period depending on mean wave direction, ϑ, have been reconstructed (Figures 2.6 a and b); Figure 2.7 shows the calculated frequency of occurrence for wave height depending on wave direction: the coast face is exposed to scirocco (South-East) and to North-East and South storms; overall the prevalent waves direction is from South to North. Moreover, the main wave sector (the sector with the maximum mean energy flux in N/s) has been calculated, resulting in an average direction of 130° N.

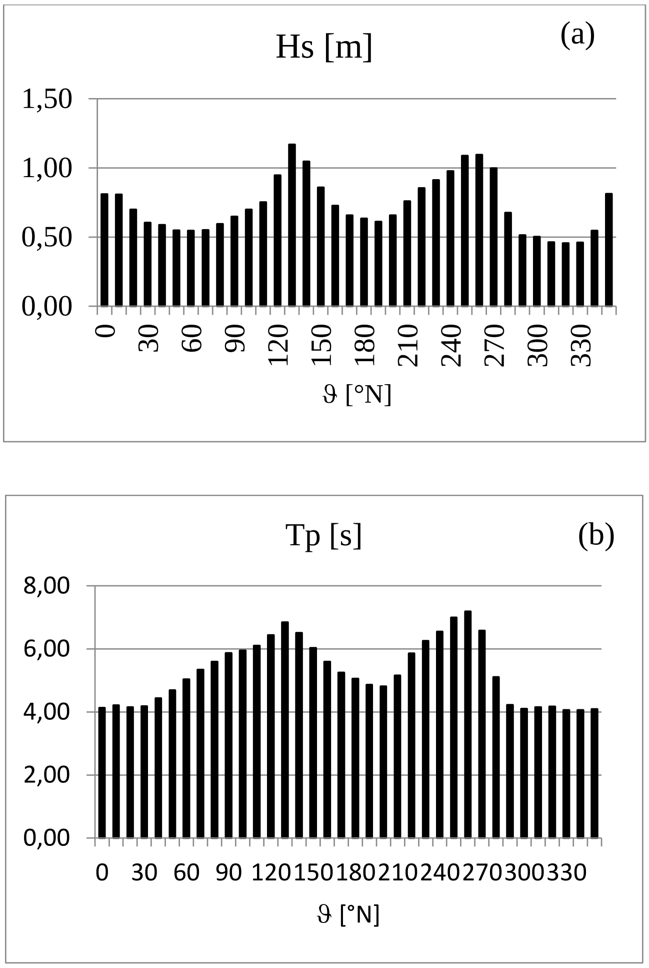


Figure 2.6 - (a) Significant mean wave height [m] depending on mean wave direction [°N]; (b) Peak wave period [s] depending on mean wave direction [°N]

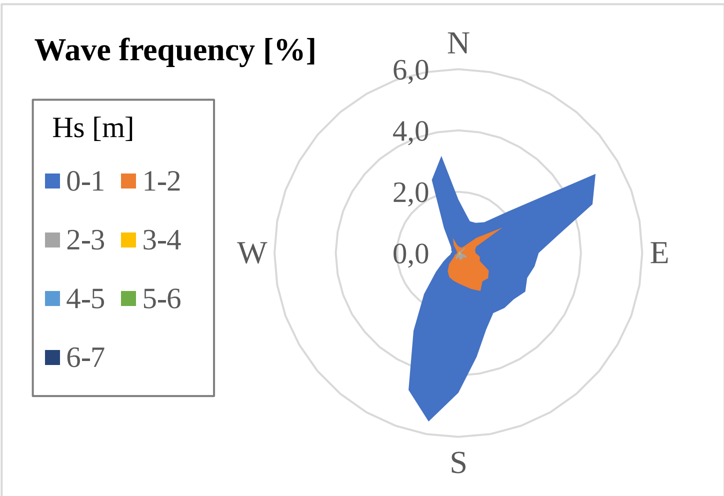


Figure 2.7 – Frequency of occurrence [%] of significant wave height Hs depending on mean wave direction [°N]

2.2.2 Bruzzano

The water basin of Bruzzano torrent is located in eastern Calabria (South Italy). The watershed covers an area of 52 km^2, with a mainstream of about 17 km and an average altitude of 345 m. Its sediment flows feed the coasts of Brancaleone and Bruzzano Zeffirio (Province of Reggio Calabria, Italy).

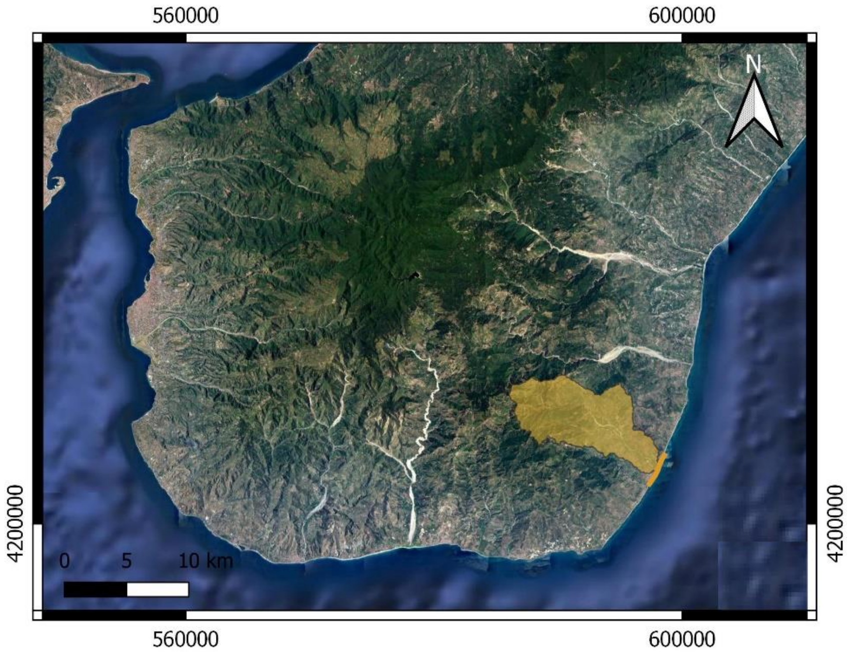


Figure 2.8 – Location of Bruzzano torrent

The altitude ranges from a minimum of 0 metres to a maximum of 1182 metres, with an average of 347 m (Figure 2.9 a). The average slope is 30% (Figure 2.9 b); the forests and semi-natural areas cover 49.3% of the soil, cultivated areas extend for 50% and artificial areas for 0.7% (Figure 2.9 c).

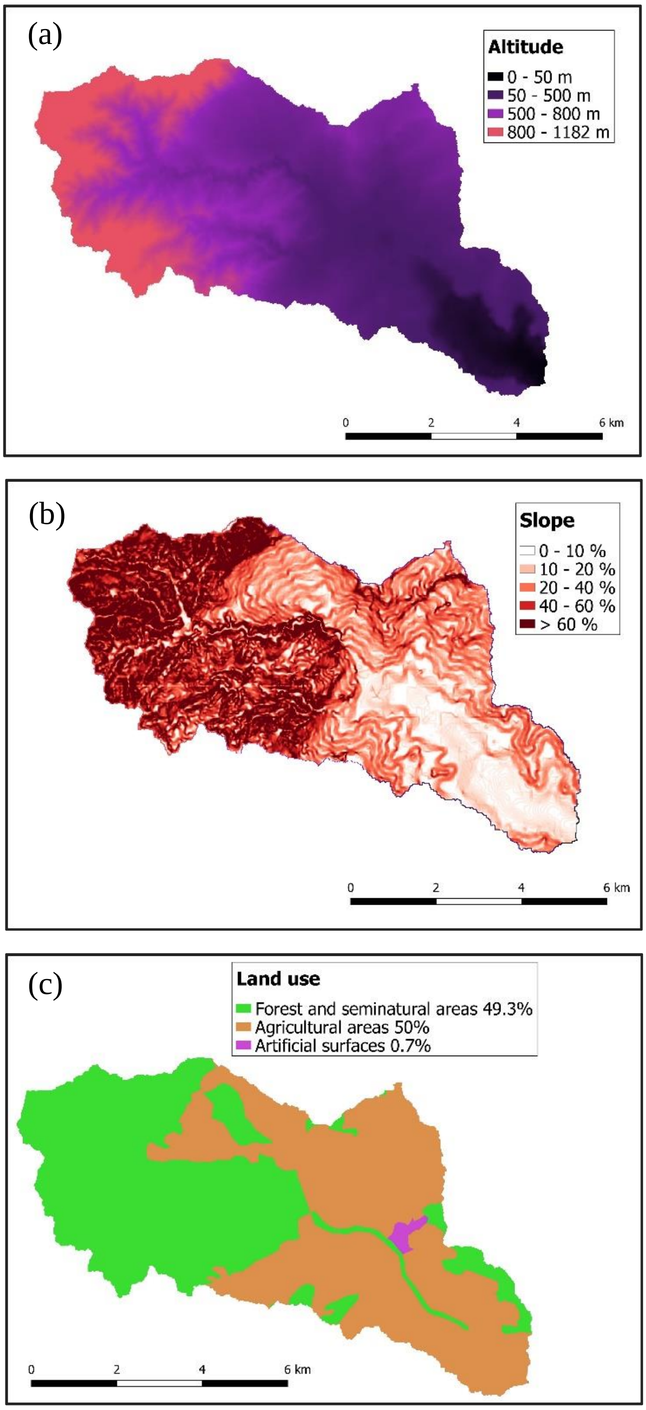
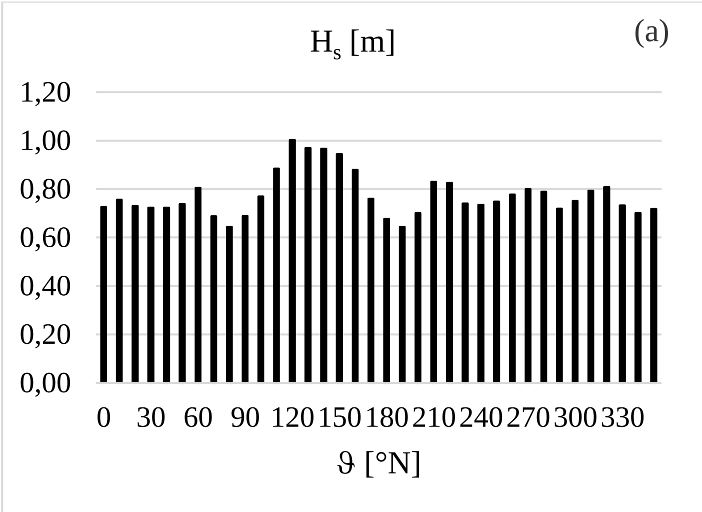


Figure 2.9 – Bruzzano case-study: (a) altitude, (b) slope and (c) land use.

The modelled beach is flat and sandy, 1.6 km long on the two sides around of Bruzzano's mouth, with an average slope, up to the depth -20 m, of 1.4%.

Based on MeteOcean time series of the last 20 years, the wave height and period depending on mean wave direction have been reconstructed (Figures 2.10 a and b); Figure 2.11 shows the calculated frequency of occurrence for wave height depending on wave direction. Moreover, the main wave sector (the sector with the maximum mean energy flux in N/s) has been calculated with an average direction of 70° N.



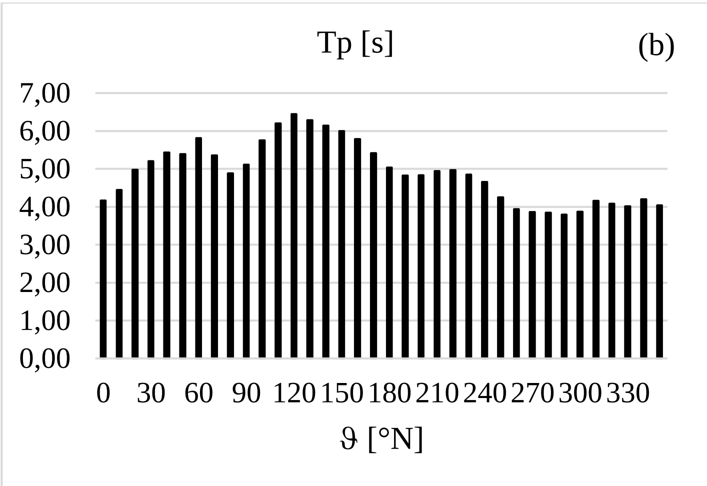


Figure 2.10 - (a) Significant mean wave height [m] depending on mean wave direction [°N]; (b) Peak wave period [s] depending on mean wave direction [°N]

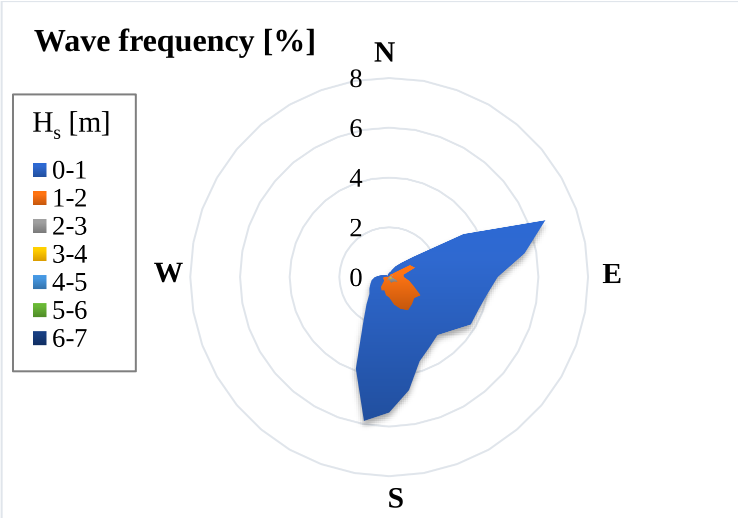


Figure 2.11 – Frequency of occurrence [%] of significant wave height, H_s, depending on mean wave direction [°N]

2.2.3 Spartivento

Spartivento torrent is located in Calabria, Southern Italy, and its watershed covers an area of about 16 km^2, with a mean altitude of 340 m, whereas the mainstream is nearly 13 km long. The stream flows into the Ionian Sea, on the coasts of Galati (Province of Reggio Calabria, Italy).

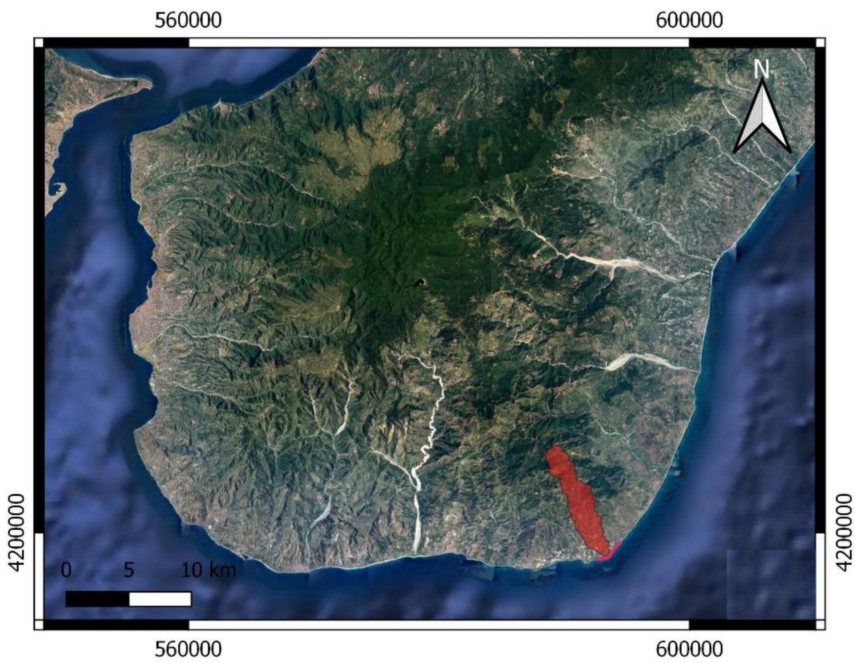


Figure 2.12 – Location of Spartivento torrent

The altitude ranges from a minimum of 0 metres to a maximum of 915 metres, with an average of 340 m (Figure 2.13 a). The average slope is 40% (Figure 2.13 b); the forests and semi-natural areas cover 62.4% of the soil, cultivated areas extend for 37.1% and artificial areas for 0.5% (Figure 2.13 c).

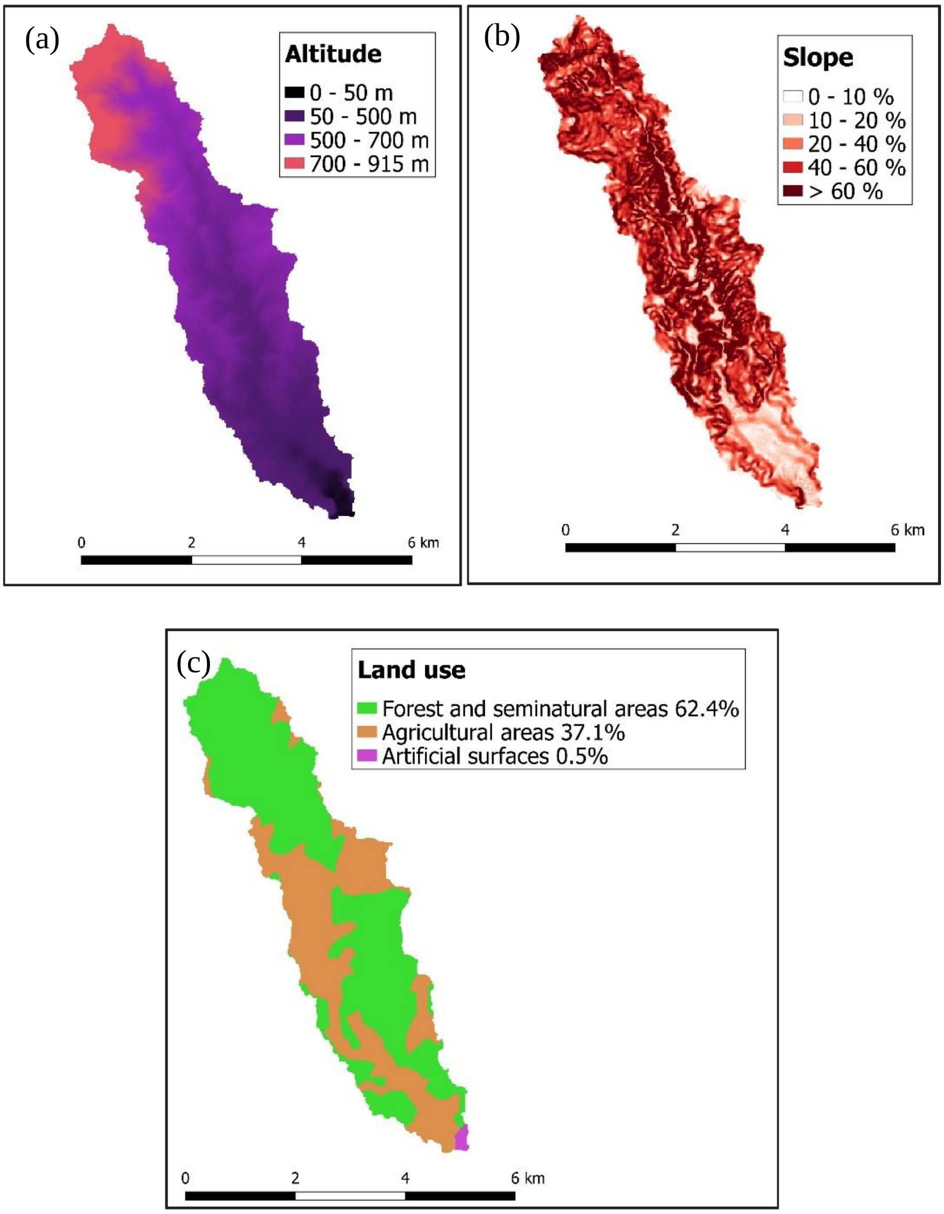


Figure 2.13 – Spartivento case-study: (a) altitude, (b) slope and (c) land use.

The studied coast is sandy, 1.6 km long on the two sides around of Bruzzano’s mouth, with an average slope, up to the depth -20 m, of 1.4%.

Based on the last 20 years of MeteOcean time series, the wave height and period depending on mean wave direction have been reconstructed (Figures 2.14 a and b); Figure 2.15 shows the calculated frequency of occurrence for wave height depending on wave direction. Moreover, the main wave sector (the sector with the maximum mean energy flux in N/s) has been calculated, resulting in an average direction of 70° N.

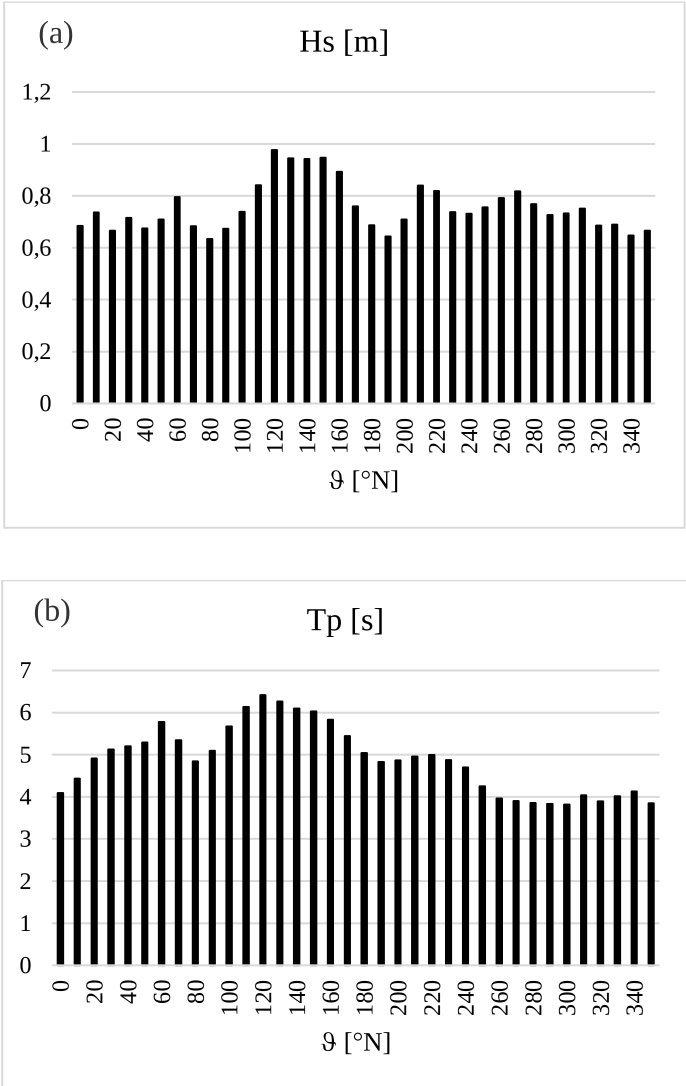


Figure 2.14 - (a) Significant mean wave height [m] depending on mean wave direction [°N]; (b) Peak wave period [s] depending on mean wave direction [°N]

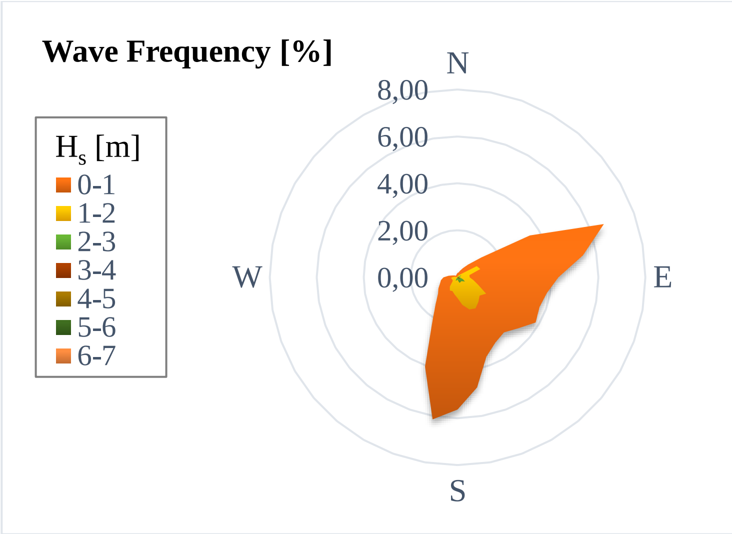


Figure 2.15 – Frequency of occurrence [%] of significant wave height, H_s, depending on mean wave direction [°N]

2.3 Modelling surface soil erosion and sediment transport

2.3.1 Climate and morphological data

The hydrological database ("Regional Agency for Environmental Protection of Calabria") used as input contains the hourly rainfall, collected at the rain gauging stations and related to the period of investigation. Baseflow has been estimated in the observed hydrograph by the "straight-line" method. To spatially scale the rainfall input, Thiessen's polygon method (Thiessen, 1911) has been applied: the polygons have been drawn covering the entire basin area.

Prior to using HEC-HMS, a 20-m resolution Digital Elevation Model (DEM), acquired from the Italian National Geoportal Service (Ministry of Environment), has been adopted to divide the watershed into interconnected subbasins and simulate the stream network by a GIS software (QuantumGIS version 3.8.3). Indeed, QGIS has a set of hydrology tools to automatically delineate a river basin using GRASS tools. The tool "r.watershed" is adopted to autogenerates a set of maps indicating: flow accumulation, drainage direction, location of streams and watersheds, and the LS factor of the Universal Soil Loss Equation.

2.3.2 Selection of rainfall events

The hydrological characteristics of Calabrian torrents, also called “fiumare” (Sorriso-Valvo and Terranova, 2006; Bombino, 2010; Sabato and Tropeano, 2014), depends on the orography and the Mediterranean semi-arid climate: drainage basins are small extending from 8.2 to 159.8 km^2; stream beds are flat, steep and coarse-grained, with braided network; water flow is concentrated in a limited number of winter days, usually on the occasion of intense and sudden floods, while in the late spring and summer, there are accentuated and prolonged low-water with very limited flow, which for the smallest streams may even be absent (Sorriso-Valvo, 2008). Accordingly, the erosion processes are of high magnitude after heavy storms and negligible under not extreme precipitations (Bombino et al., 2009; Zema et al., 2014; Fortugno et al., 2017).

This is the reason why, to evaluate the shoreline evolution, only a finite number of rainfall events are considered, i.e. the N events that (over N years in the past equal to the simulation period) have caused the largest production of sediment volume delivered to the coast. However, within the HEC-HMS package, the Curve Number method has been chosen, and this allows to perform simulations only at event scale. Therefore, to speed up the identification of rain events that have produced the largest volume of sediments, only those with an intensity that exceeds the threshold of 60 mm/day have been taken into account. In addition, two consecutive rainfall events are considered distinct if there are at least 6 hours of zero rain between them.

To sum up, the method to select the rainfall events presents the following steps:

1. Identification of rainfall events with an intensity greater than 60 mm/day within the considered time range of N years.
2. Selection of a number of rainfall events equal to N, which have caused the largest production of sediments (i.e., if the simulation period covers 10 years, the 10 events which have caused the largest production of sediments are considered).

2.3.3 HEC-HMS implementation

The hydrological modelling has been carried out using HEC-HMS, version 4.3. As an example, the sub-watersheds (called subbasins within the software) schematization for La Verde case-study is shown in Figure 2.16.

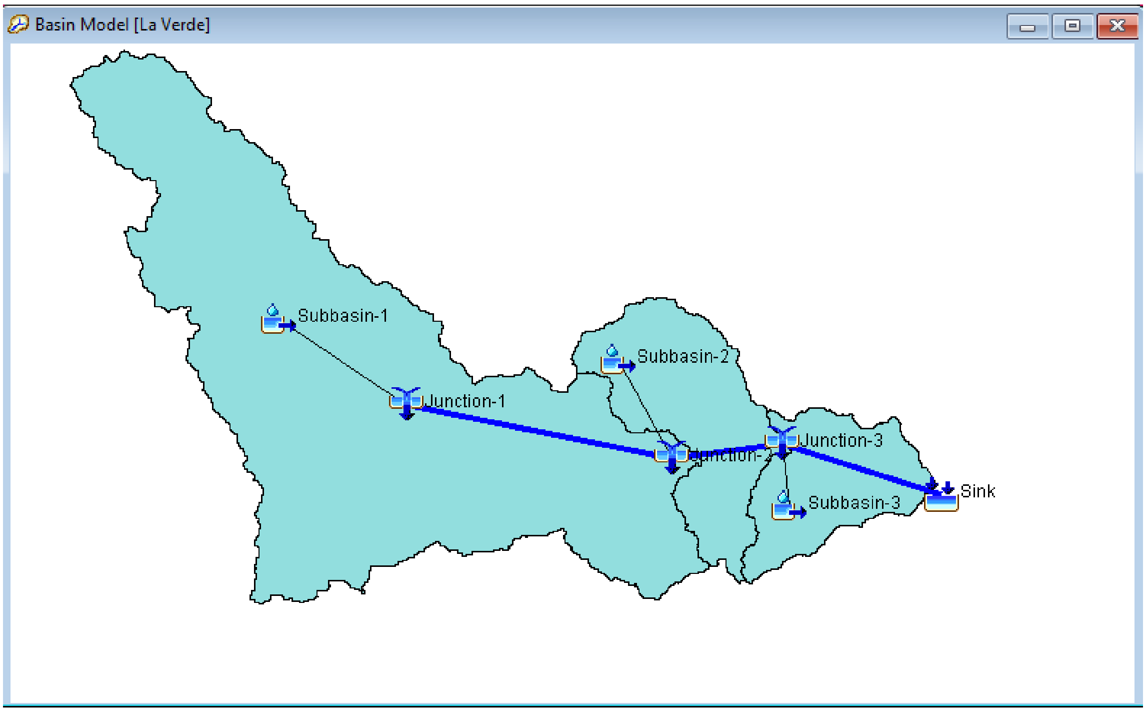


Figure 2.16 - Hydrological modelling of La Verde watershed – subbasins schematization in HEC-HMS

Among the eleven infiltration methods of HEC-HMS, the "SCS-CN" (USDA-SCS, 1972) has been chosen, since the required input parameters are available or can be easily estimated by the database of the studied basin. Moreover, previous studies have shown that the "SCS-CN" method has been used successfully to model flooding (Jin et al., 2015), being conceptually simple. As input of this "SCS-CN" method, the average value of the Curve Number (CN) for each identified sub-basin has been evaluated as a function of soil use ("Corine Land Cover", scale 1:100000, EEA, 2009) and soil texture ("Soil Map of the Calabria Region", scale 1:250000, ARSSA), according to USDA guidelines (USDA, 1972).

A total of seven different rainfall-runoff transformation methods is provided in HEC-HMS. Some of these methods are unsuitable because they require more inputs which are not available for most of the ungauged catchments (Halwatura and Najim, 2013). In this study the "SCS unit hydrograph" (SCS-UH) method has been selected because it requires only the input of lag time. Moreover, Jin et al. (2015) reported good performance in basin hydrological modelling using the SCS-UH for the direct runoff.

The hydrograph simulated through SCS method is used by the software for surface soil erosion and sediment transport modelling based on MUSLE equation (Williams, 1975), which is:

$$Sed = 95 \cdot (Q_{surf} \cdot q_{peak})^{0.56} \cdot E \cdot LS \cdot C \cdot P \qquad [3]$$

being *Sed* the sediment yield for a given event in tons, Q_{surf} the surface runoff volume (m^3), q_{peak} the peak runoff rate (m^3/s), E the soil erodibility factor, LS the topographic factor, C the cover and management factor, and P is the support practice factor.

The terms Q_{surf} and q_{peak} are directly estimated by the software. The soil erodibility factor E represents the difficulty of a soil to erode and has been estimated by the soil erodibility nomograph (Wischmeier et al., 1971) using "Soil Map of the Calabria Region" (scale 1:250000, ARSSA) to extrapolate the required data. The topographic factor LS, which describes the susceptibility to erosion due to slope and length of the slope, has been calculated directly in QuantumGIS (version 3.8.3), through the GRASS tool "r.watershed". The cover factor C, which represents the influence of plant canopy on surface erosion, has been evaluated according to the available land use data ("Corine Land Cover", scale 1:100000, EEA, 2009). The practice factor P has been assumed equal to 1, since no soil conservation practices were adopted in the sub-basins.

The exponent used by the model to distribute the sediment yield into a time-series sedigraph, is assumed equal to 0.75, as suggested by the HEC-HMS Application Guide Manual (2015).

2.4 Modelling torrents mouth evolution

2.4.1 Input data

Three types of data are required by the new model:

- *Torrent sediment discharge*
- *Wave climate*
- *Morphological data*
- *Grain size data*

The *torrent sediment discharge* [m^3/s] for each selected rainfall event has been simulated with HEC-HMS. Then, it is assumed that the transport is zero for the rest of the time, obtaining the solid load time-series for the entire period of the simulation, easily associable with the wave climate time-series.

The *wave climate* required is represented by the time series of wave significant height H_S [m], peak wave period T_P [sec], and mean wave direction ϑ [°N] from the beginning to the end of the simulation timeframe.

In this work, the wave climate has been defined by means of MeteOcean database of DICCA Department (DICCA MeteOcean Re-Analysis, University of Genoa), distributed free of charge for research purposes. The database was reconstructed from 1979 to 2018 thanks to the Wavewatch III model, version 3.14 (Tolman, 2009), built for the simulation of wave generation and propagation, and calibrated using satellite and wave buoy records. The dataset is provided with an hourly time step at all points of a computational grid covering the entire Mediterranean Sea.

The *wave climate* and the *torrent sediment discharge* time-series are directly read by the new code from text files previously prepared.

Morphological data are represented by two shorelines measured on two satellite images at the start and the end point of the simulation. The shorelines have been measured on Google Earth historic satellite images through a series of geo-referenced points, 25 m apart from each other. The points coordinates can be set in any reference system of the user choice.

Grain size data are the D_{50} [mm] of bed material and the sediment porosity. The latter has been assumed to be 0.4 mm, according to local surveys.

2.4.2 Average profile shape

The average profile shape adopted is that of the so-called "equilibrium profile" proposed by Bruun (1954) and Dean (1991). These authors demonstrated that the bathymetry for a wide variety of beaches can in general be represented by the simple mathematical function:

$$d = Ay^{2/3} \qquad [4]$$

In the previous equation *d* is the water depth and *A* is an empirical parameter. The latter depends on the nearshore D_{50} through the following equations:

$$\begin{aligned} A &= 0.41\, {D_{50}}^{0.94}, & D_{50} &< 0.4 \\ A &= 0.23\, {D_{50}}^{0.32}, & 0.4 \le D_{50} &< 10 \\ A &= 0.23\, {D_{50}}^{0.28}, & 10 \le D_{50} &< 40 \\ A &= 0.46\, {D_{50}}^{0.11}, & 40 &\le D_{50} \end{aligned}$$

with D_{50} expressed in mm.

2.4.3 Wave propagation sub-model

An internal model is included to transform waves from the deep-water reference depth to the breaking depth. The reference depth is given in input as the depth of the point where wave conditions (recorded or simulated) are available. The variables to be calculated are depth, wave height and wave angle at breaking.

Waves change their direction as they propagate from deep to shallow water, due to the refraction phenomenon. This transformation can be represented by wave orthogonals and their numerical calculation. Given the wave angle α_0 at the deep-water reference depth, and the origin of wave propagation, the wave orthogonal is calculated with finite increments Δs through the following equations (Griswold, 1963):

$$\alpha(s+\Delta s) = \alpha(s) + \frac{d\alpha}{ds}\Delta s \quad [5a]$$

$$x(s+\Delta s) = x(s) + \cos(\alpha)\,\Delta s - \frac{1}{2}\sin(\alpha)\frac{d\alpha}{ds}\Delta s^2 \quad [5b]$$

$$y(s+\Delta s) = y(s) + \sin(\alpha)\,\Delta s + \frac{1}{2}\cos(\alpha)\frac{d\alpha}{ds}\Delta s^2 \quad [5c]$$

The derivative $d\alpha/ds$ is given by:

$$\frac{d\alpha}{ds} = \frac{2k}{\sinh(2kd)+2kd}\left[\frac{\delta d}{\delta x}\sin(\alpha) - \frac{\delta d}{\delta y}\cos(\alpha)\right] \quad [6]$$

being *k* the wave number and *d* the water depth at node *i, j* with coordinates x_i, y_i of a grid (Δx, Δy) for an arbitrary bottom. Moreover, the partial derivatives $\delta d/\delta x$ and $\delta d/\delta y$ are evaluated by means of the finite difference technique.

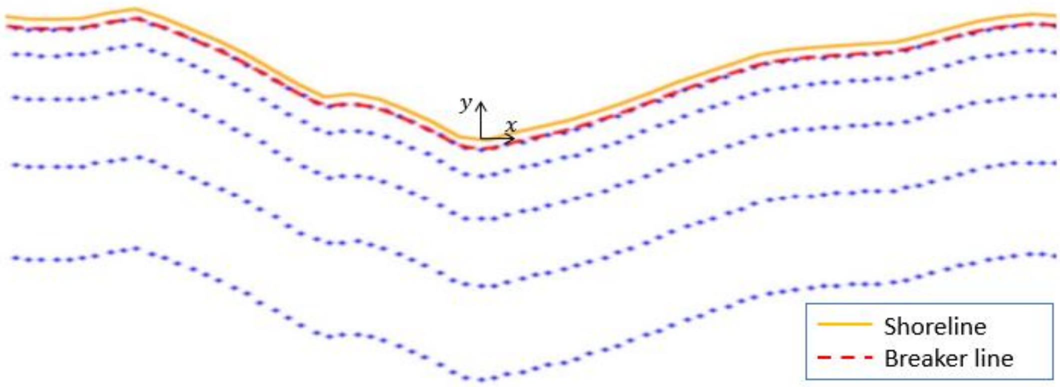


Figure 2.17 - Wave refraction pattern [obtained by eq. 5 and 6] and breaker line for a wave direction on deep water equal to 90°.

The relation between the wave height H and the water depth d is given by:

$$H = H_0 \sqrt{\frac{\sinh(2kd)}{\tanh(kd)[\sinh(2kd) + 2kd]}} \sqrt[4]{\frac{1 - \cos^2(\alpha_0)}{1 - \tanh^2(kd)\cos^2(\alpha_0)}} \quad [7]$$

so that we can get H on depth d, once wave number k and wave height and angle (H_0, α_0) on deep-water are known, bearing in mind that waves on deep-water are defined as waves on depth $d > L_0/2$, being L_0 the wave length on deep-water, defined as the following:

$$L_0 = \frac{gT^2}{2\pi}$$

Furthermore, to calculate the wave number k, the so-called linear dispersion rule is solved through an iterative approach (bisection method):

$$L_i = L_0 \tanh\left(\frac{2\pi d}{L_{i-1}}\right)$$

for i = 1, 2, 3 and so on.

Finally, the problem of braking parameters calculation is solved by the Kamphuis (1991) approach for sea waves. Following this approach, the breaking conditions equations are:

$$H_{sb} = 0.56\, e^{3.5m}\, d_b \quad [8]$$

$$H_{sb} = 0.095\, e^{4m} \tanh\left(\frac{2\pi d_b}{L_{pb}}\right) \cdot L_{pb} \quad [9]$$

where H_{sb} is the significant wave height at breaking depth d_b, L_{pb} is the wave length at breaking and depending on the peak period T_p.

These equations mean that a wave may break for two reasons: when the ratio between the wave height and the water depth exceeds a critical threshold (Equation 8), or when the ratio *H/L* exceeds a critical threshold: in other words, because of the excess of wave steepness (Equation 9).

2.4.4 Implementation of the equation governing shoreline evolution

Coastline dynamics can be simulated using two equations:

- The equation of sediment conservation (Pelnard-Considère, 1957), governing shoreline evolution phenomenon;
- The CERC empirical formula (USACE, 1984), for longshore sediment transport calculation.

The differential equation of sediment conservation (Equation 1) is solved using the finite differences method proposed by Crank in 1975; accordingly, $\delta Q/\delta x$ is expressed as follow:

$$\frac{\delta Q}{\delta x} = \frac{1}{2}\left(\frac{Q_{i+1}(t)-Q_i(t)}{dx} + \frac{Q_{i+1}(t-1)-Q_i(t-1)}{dx}\right) \quad [10]$$

which represents the variation of longshore sediment transport, Q, both in space and time. Thus, Equation 1 becomes:

$$\frac{y_i(t)-y_i(t-1)}{dt} = -\frac{1}{D_B+D_C}\left[\frac{1}{2}\left(\frac{Q_{i+1}(t)-Q_i(t)}{dx} + \frac{Q_{i+1}(t-1)-Q_i(t-1)}{dx}\right) + q_s\right] \quad [11]$$

which represents the shoreline position variation in time, following the finite difference solution scheme reported below (Figure 2.18).

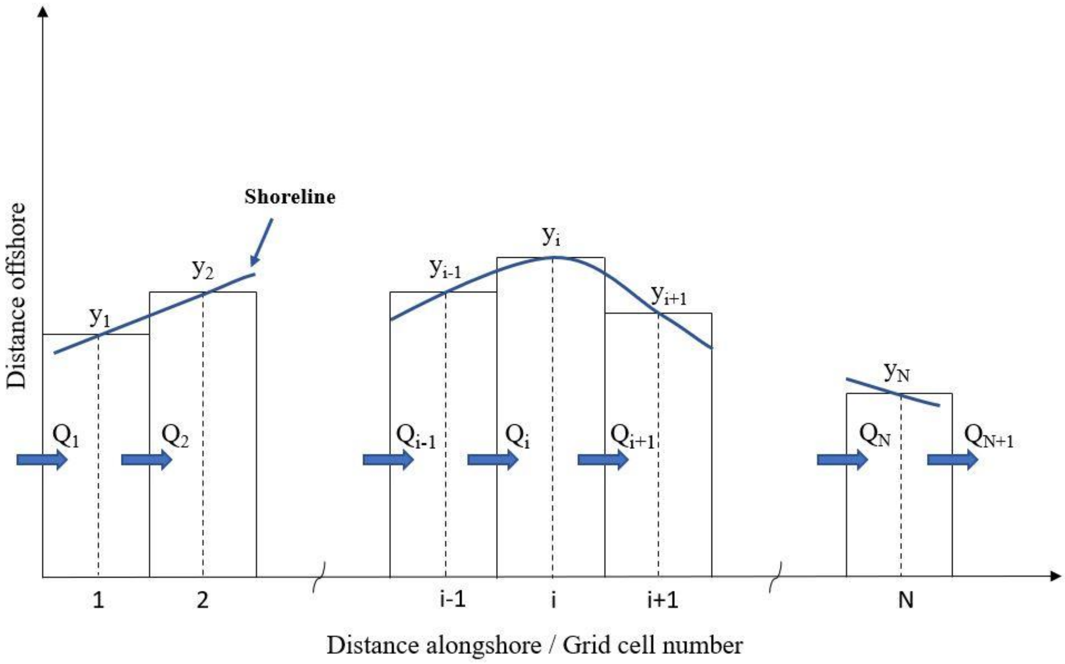


Figure 2.18 - Numerical solution scheme

In this solution scheme, shoreline positions y_i are defined at the center of the grid cells, while transport rates Q_i at the cell sides. In total there are N values of the shoreline position and N+1 values of the longshore sediment transport rate since N+1 cell sides enclose the N cells; Q_1 and Q_{N+1} are the transport rates at the boundaries that must be specified, while all the other Q_i and all y_i will be calculated.

The approach to simulate the torrent sediment discharge is shown in Figure 2.19.

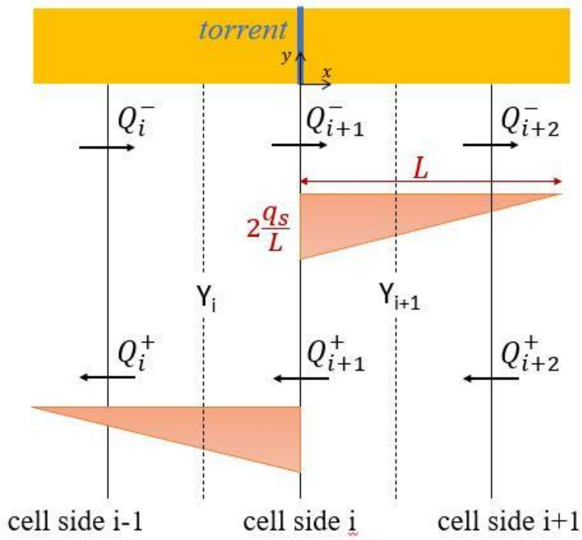


Figure 2.19 – Simulation approach of the torrent sediment discharge distribution.

The torrent mouth is located at the cell side i and can affect the adjacent cells, to the right or left, according to the longshore sediment transport direction (Q^+ or Q^-); this approach is presented by Samaras and Koutitas, 2009.

Moreover, in this work, the torrent discharge q_s from the source point is distributed following a triangular scheme to avoid huge discontinuity in $q_s(x)$. The triangular pattern, in fact, better represents the natural conformation of the sedimentary accumulation at the mouth of a river, which is greater at the mouth and lesser as we move away from it. The triangle base, L, is defined as half the length of the shoreline, while the height is defined as $2\,q_S/L$ (Fig. 2.19), so that the area is exactly equal to q_S.

In a nutshell, the adopted scheme allows river sediment to be distributed along the coast as a function of:

1. Predominant wave direction.
2. Distance from the river mouth.

The other assumption is that sand is transported by the action of breaking waves. Indeed, the new model includes a sub-model, which simulates wave propagation from the offshore point of waves registration to the nearshore. The propagation sub-model allows to calculate all the parameters (depth, wave height and wave angle) at breaking, required by CERC formula (Equation 2) to evaluate the longshore sediment transport rates Q_i. Since the Q_i are a function of wave conditions, all wave quantities are calculated at the cells sides of the resolution scheme (Figure 2.18).

2.4.5 The new shoreline evolution model

The new 1D shoreline evolution model has been developed independently as a software in Python, a programming language built under an OSI-approved open source license.

Its aim is the numerical prediction of a sandy beach erosion/accretion in the over-yearly time scale. The model offers the possibility to consider a stream mouth as a sediment source, allowing the user to simulate the torrent contribution to the sediment budget.

It has been developed using the open-source libraries math, numpy, scipy, pandas, and matplotlib. The Figure 2.20 shows an extract of the code regarding the construction of the equilibrium profile.

```
"Equilibrium profile"

if D50 < 0.4:  # D50 = [mm]
    A = 0.41*D50**0.94  # empirical parameter
elif D50 >= 0.4 and D50 < 10:
    A = 0.23*D50**0.32

def depth(x,y):
    return A*(F(x)- y)**(2/3)
```

Figure 2.20 – An extract of the code.

The model requires as input the torrent solid discharge, the wave climate, the morphological data, and the grain size data. The outputs are the x and y-coordinates (in the reference system chosen by the user) of the shoreline at the end of the simulation time, directly plotted and exportable in a GIS environment.

To summarize the overall approach, a flow chart is proposed in Figure 2.21.

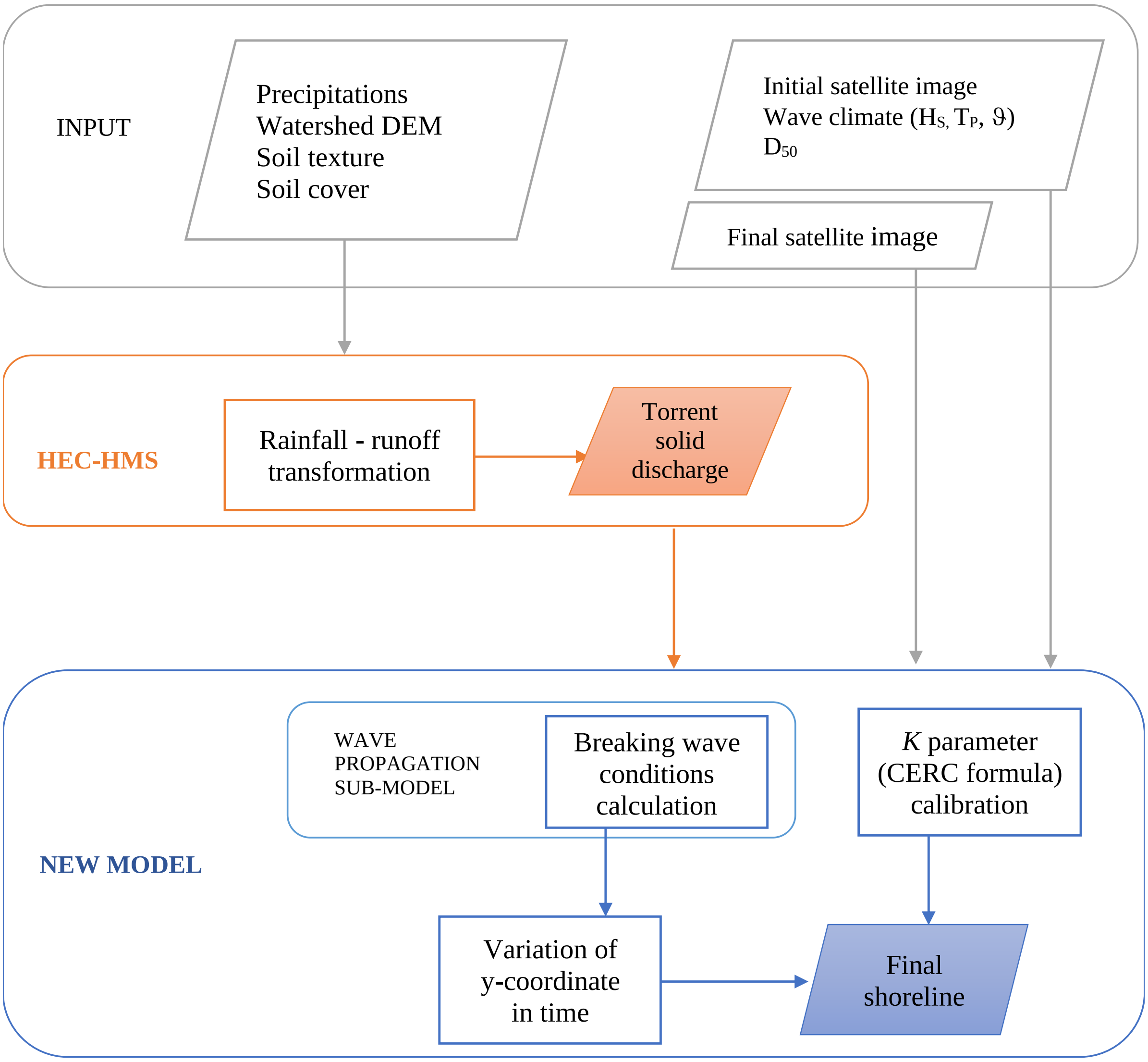


Figure 2.21 - Flow chart of the proposed approach

2.4.6 Calibration and validation of the new model

For the calibration, the model has been applied to a given past timeframe, starting from the morphological data (initial and final measured shorelines), and changing the *K* empirical parameter of CERC formula given in input, until it has returned the position of the shoreline reliably, compared to morphological data observed in the same time interval.

Since an objective parameter was required to identify the accuracy of the result, the mean error of a single simulation run has been defined as the mean cross-shore distance (in meters) between simulated and measured shoreline positions and calculated on a finite number of transects, 25 m apart from each other.

The value of K given for a typical sandy beach is 0.39 (Komar and Inman, 1970), with which, however, an error of the order of thousands is obtained. The value of K is then reduced by attempts; for K = 0.0001, the percentage reduction of the average error is maximum, and is equal to about 99.9% for each case-study.

After the calibration, the new model has been verified to check whether the model, with the parameter determined as mentioned above, was able to reconstruct the shoreline evolution relative to another period of the past. This verification may support its reliability for the prediction of the evolution of that coastline.

For these calibration and validation operations, the satellite images used are distributed free of charge by Google Earth.

3 Results

3.1 Torrent sediment discharge

As an example, Figures 3.1 to 3.3 show the simulated torrent solid discharge in occasion of a specific event for each of the case-studies.

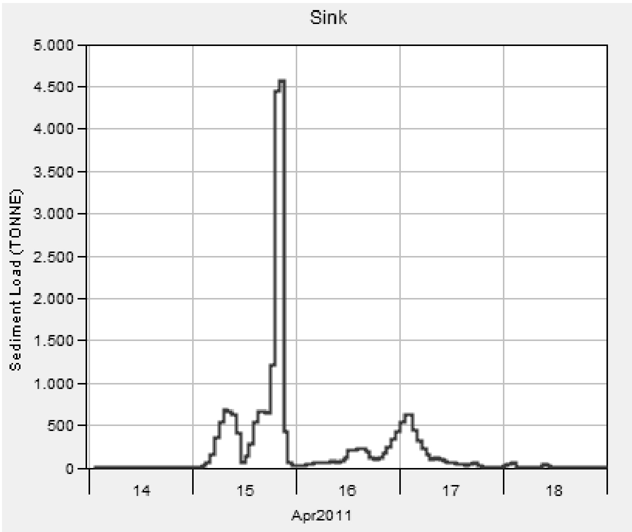


Figure 3.1 – Simulated hourly sediment load at the stream mouth (14-18 April 2011, La Verde torrent).

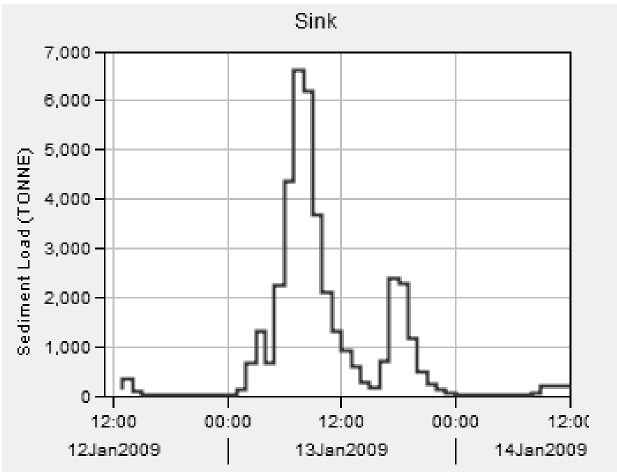


Figure 3.2 - Simulated hourly sediment load at the stream mouth (12-14 January 2009, Bruzzano torrent).

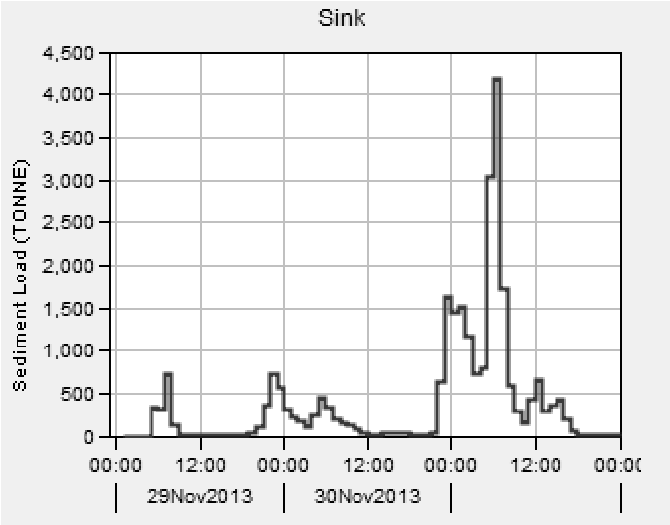


Figure 3.3 - Simulated hourly sediment load at the stream mouth (29 Nov – 1 Dec 2013, Spartivento torrent).

3.2 Torrent mouth evolution

3.2.1 La Verde

The results for La Verde torrent are shown in Figures 3.4 and 3.5 (Run 1 for the period 2005-2011 and Run 2 for the period 2005-2013, respectively).

The Figures show the torrent identified by a light blue line, while the initial position of the shoreline (02/07/2005) is represented by a black geo-referenced line. The dotted red line is the measured shoreline; the solid red line is the simulated one, on 18/06/2011 in Figure 3.4, and 06/08/2013 in Figure 3.5.

For a stretch of the coastline of about 1600 meters around the mouth, the minimum, mean, and maximum error [m] are 1.8, 6.3, 15.2 respectively in Run 1; and 0.2, 9.8, 24.8 in Run 2.

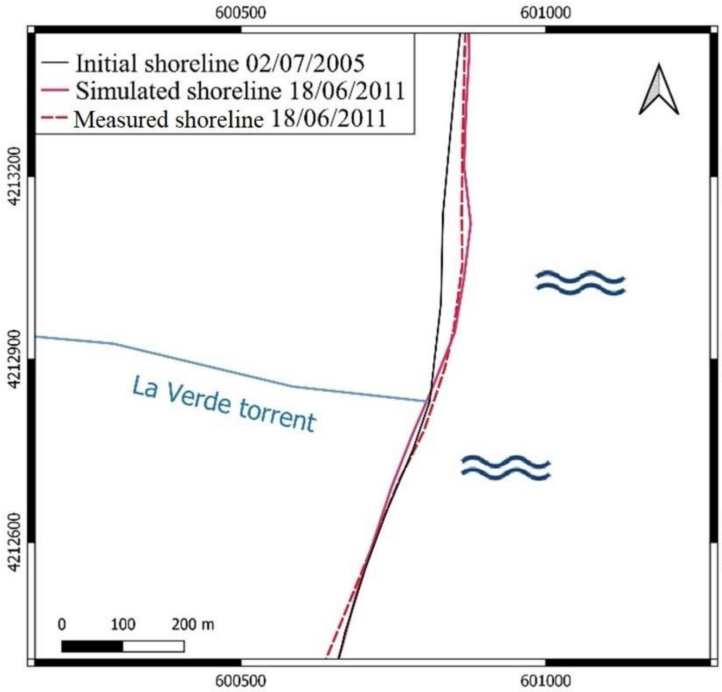


Figure 3.4 – La Verde, Run 1: simulation of coastline evolution from 2005 to 2011.

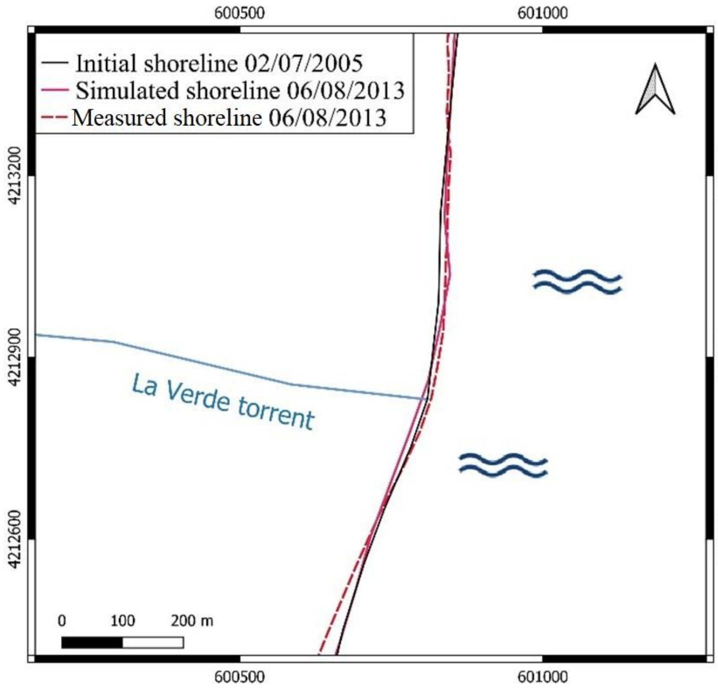


Figure 3.5 – La Verde, Run 2: simulation of coastline evolution from 2005 to 2013.

3.2.2 Bruzzano

Concerning Bruzzano case-study, Figure 3.6 and Figure 3.7 show the results for Run 1 that simulates the time period 2003-2010, and Run 2, that refers to the period 2010-2017.

In particular, the black line is the initial shoreline on 02/10/2003 for Run1, and 09/07/2010 for Run2. The solid red line is the simulated one, on 09/07/2010 in Figure 3.6, and 16/06/2017 in Figure 3.7. The measured shoreline is, again, the dotted and red line.

For a stretch of the coastline of about 1600 meters around the mouth, the minimum, mean, and maximum error [m] are 0.1, 8.4, 23.8 respectively in Run 1; and 0.5, 5.2, 18.1 in Run 2.

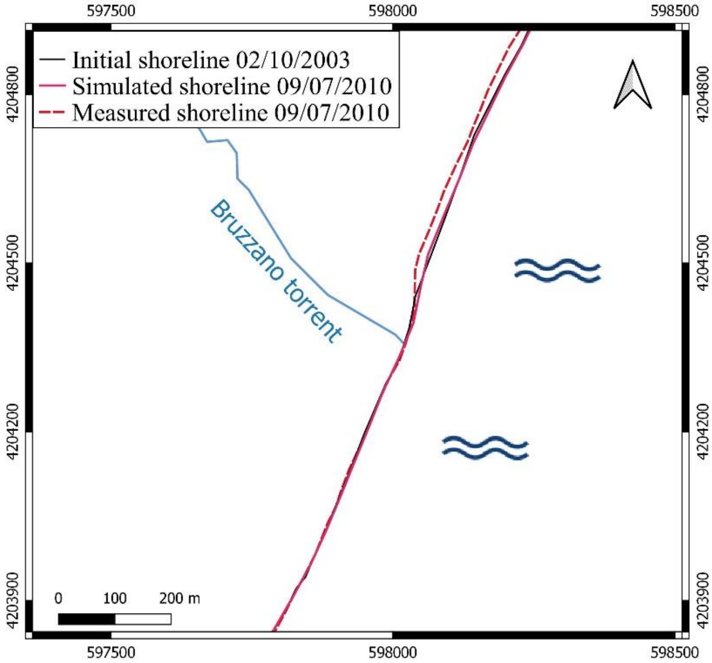


Figure 3.6 – Bruzzano, Run 1: simulation of coastline evolution from 2003 to 2010.

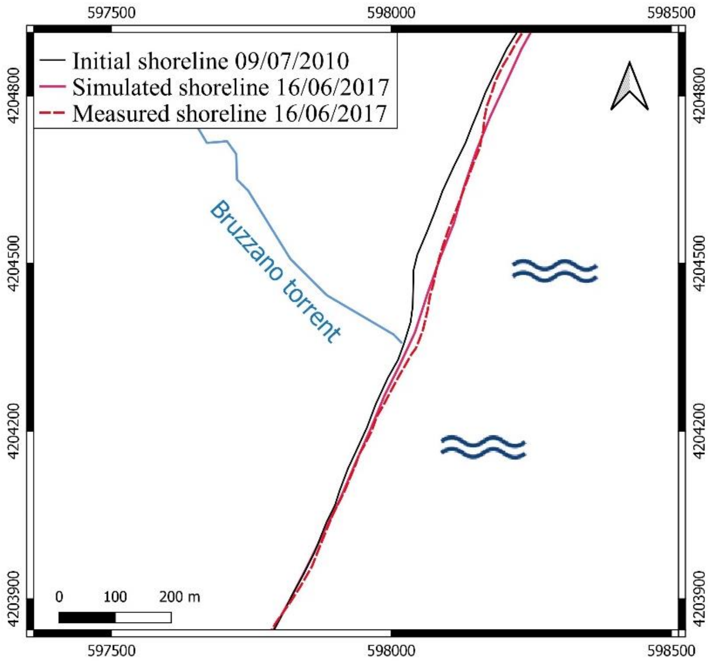


Figure 3.7 – Bruzzano, Run 2: simulation of coastline evolution from 2010 to 2017.

3.2.3 Spartivento

For Spartivento torrent, the third and last case-study, the results are presented in Figure 3.8 and Figure 3.9, where Run 1 simulates the time period 2003-2010, and Run 2 the period 2012-2018. The initial shoreline (02/10/2003 for Run1 and 08/06/2012 for Run2) is represented by a black geo-referenced line. The dotted red line is the measured shoreline; the solid red line is the simulated one, on 09/07/2010 in Figure 3.8, and 21/07/2018 in Figure 3.9, respectively.

For a stretch of the coastline of about 1600 meters around the mouth, the minimum, mean, and maximum error [m] are 1.2, 15.1, 28.5 respectively in Run 1; and 0.6, 11, 25.2 in Run 2.

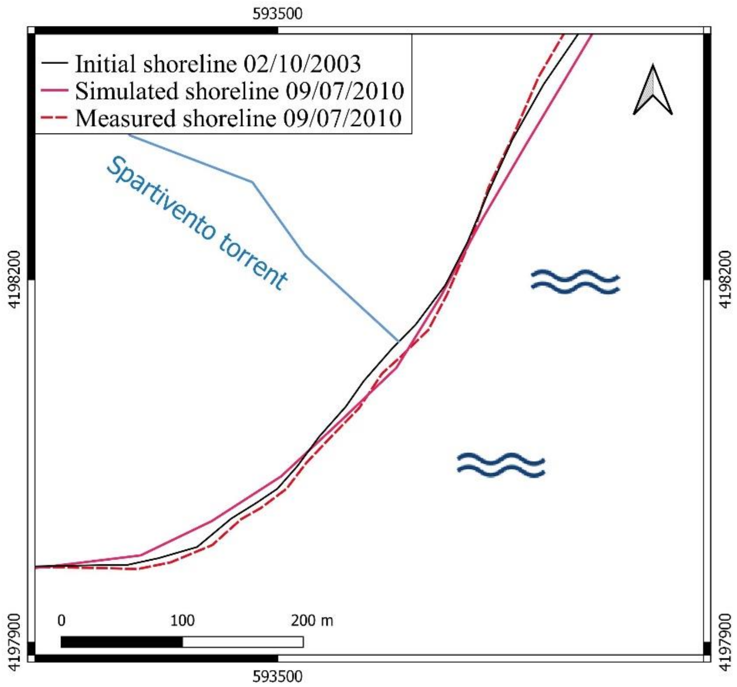


Figure 3.8 – Spartivento, Run 1: simulation of coastline evolution from 2003 to 2010.

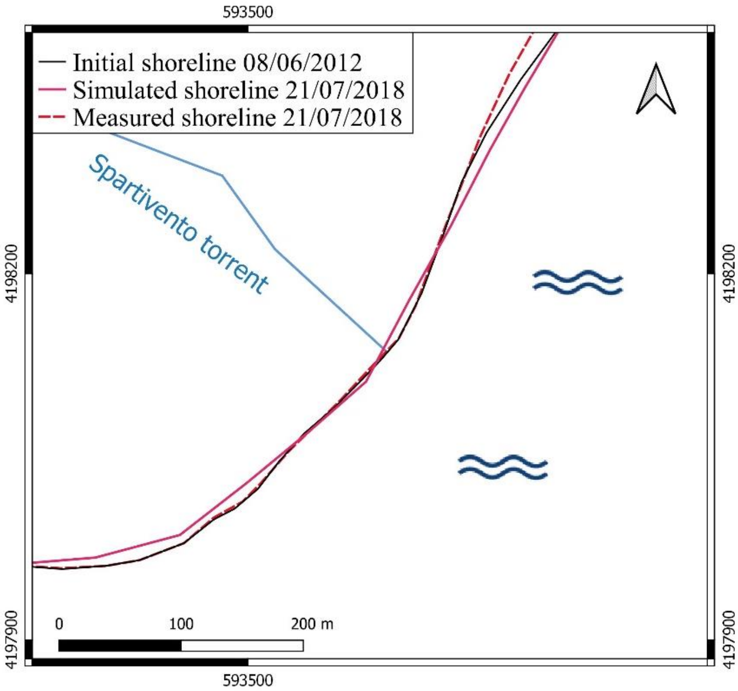


Figure 3.9 – Spartivento, Run 2: simulation of coastline evolution from 2012 to 2018.

3.3 Discussion

As far as La Verde case-study is concerned, Run 1 confirms the growth trend of the coast, which is evident near the mouth and confirmed by historical satellite images. Run 2 proves the slight retreat that took place from 2011 to 2013.

For Bruzzano case-study, in Run1 the forecast south of the mouth is much more accurate than north of the mouth. Finally, Run 2 confirms the growth trend of the coast.

Regarding Spartivento torrent, the error is higher compared to the other case-studies and this is probably due to the coastline shape that is highly curved.

In general, the mean error is reduced by the calibration process and the scheme adopted to distribute the torrents sediment discharge along the coast. Moreover, in accordance with the analysis of wave data, the results of the model Runs confirm the main direction of longshore solid transport. Besides, it is worth mentioning the high computational speed of a single Run of the new model, in comparison with other consolidated models.

However, there are some limitations of the model due to (i) the high variability of the analysed morphological (on the inland and coastal sides) and meteorological processes and the difference in their time scales; (ii) the simplifying hypotheses of the one-line models that exclude the influence of cross-shore solid transport, not negligible if severe storms occur; (iii) the lack of torrent water and sediment discharges observations, which instead forced the use of a hydrological model.

4 Conclusions and Future Perspectives

Starting from Pelnard-Considère theory and introducing an original method to take into account the torrent contribution, the research project has led to the development of a prevision model for coastal dynamics, expanding the knowledge about the delicate relationship between watershed and coast in a Mediterranean semi-arid context.

To summarize, the equation of sediment conservation has been modified with the addition of the torrent sediment discharge, which has been quantified through HEC-HMS, considering only the most severe events in terms of volume because of the peculiar Mediterranean climate conditions. Moreover, the quantity of torrent sediments added to the shoreline has been evaluated depending on the distance from the mouth alongshore and the wave direction, in order to simulate the natural distribution around the torrent mouth. Then, the equation of sediment conservation, which represents the shoreline position variation in time, has been solved using the finite differences method proposed by Crank (1975) and implemented in Python. Finally, the application to three case-studies in Southern Italy, which are La Verde, Bruzzano and Spartivento, has allowed to validate the new model, which is effective to evaluate the evolutionary trend of a beach, fed by torrential watercourses, after a proper calibration.

The new model has been created (i) to become an easy tool to support the management and protection of the basin-coast system for the various subjects and bodies that in Italy deal with environmental issues; (ii) to ensure a global comprehension of the WCC; (iii) to optimize the use of human and financial resources; and (iv) to support preliminary investigation before the activities for mitigation and control of any undesirable effects (both on river basins and coasts).

In this regard, this work will hopefully give rise to a series of researches and in-depth studies that will provide concrete indications on technical developments. The design of hydraulic-forestry works in river basins and the management of sediment deposits along the watercourses, or, again, the planning and design of coastal protection works, with a view to a sustainable balance of the watershed-coast system, are examples of further research paths.

Finally, future research developments should be based on the use of modern remote sensing techniques (drones and satellite imagery) to monitor and update the hydrological and maritime parameters that serve as input to the integrated model. In this way, not only more satisfactory results could be obtained, but also a monitoring campaign useful for land management and protection activities would be started.

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