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Original
Coupling watershed - coast systems to study evolutionary trends: A review / Malara, G.; Zema, D. A.; Arena, F.; Bombino, G.; Zimbone, S. M.. - In: EARTH-SCIENCE REVIEWS. - ISSN 0012-8252. - 201:103040(2020). [10.1016/j.earscirev.2019.103040]

Published
DOI: http://doi.org/10.1016/j.earscirev.2019.103040

The final published version is available online at:https://www.sciencedirect.

Malara, G., Zema, D. A., Arena, F., Bombino, G., & Zimbone, S. M. (2020). Coupling watershed-coast systems to study evolutionary trends: A review. Earth-Science Reviews, 201, 103040.

10.1016/j.earscirev.2019.103040

(https://www.sciencedirect.com/science/article/pii/S001282521930580X)

Coupling watershed - coast systems to study evolutionary trends: a review

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Abstract

This article proposes a review of the researches dealing with the interaction between watersheds and coastal areas. Watersheds and coasts were traditionally regarded as two separate areas with a contact point in which the output of the watershed constitutes the input of the coastal area. However, the open literature of the last two decades recognized the importance of adopting a holistic perspective in the analysis of these two systems. Such a point of view is so consolidated that nowadays the whole body is designated as the "Watershed-Coast continuum" (WCC).

Despite the fact that this is a consolidated and recognized concept, there are still limited holistic observations. In this review article, we summarize the main findings of the researches on the WCC. Specifically, we provide a state-of-the-art of the researches focusing on the identification of morphological evolutionary trends that are relevant to civil engineering applications by distinguishing three kinds of works: monitoring studies; modelling studies; and monitoring of anthropogenic actions. This article emphasizes the need of developing adequate methodologies for describing the WCC dynamics and suggests planning future monitoring activities by adopting a global perspective.

Keywords: shoreline; hydrological modelling; wave climate; soil erosion; watershed management; coastal infrastructures.

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1. Introduction

1.1 Foreword

Rivers are the most important link between continents and oceans (Walling and Fang, 2003). In river watersheds the terrestrial material eroded from hillslopes by precipitation and surface runoff and from river bed by the channelized stream flow is conveyed along channels and delivered to the sea. The entire drainage area of a river contributes to produce runoff and eroded material (Samaras and Koutitas, 2008), excluding the urban areas. The resulting water and sediment fluxes greatly impact the coastal areas (Syvitski et al., 2009). In this regard, it has been estimated that rivers produce 95% of sediment delivered to the oceans (Syvitski et al., 2003). Moreover, the large spatial and temporal variability of sediment and water discharge rates in rivers strongly influence the coastal morphology evolution. For instance, a decrease in sediment supply from rivers may lead to coast retreat or, vice versa, its increase can determine a downward shift of the coastline. These evolutionary trends pose serious threats to ecosystem sustainability in coastal regions (Li et al., 2018; Wang et al., 2016; Yang et al., 2011). Many studies have also shown that climate change is one of the most important factors influencing water and sediment fluxes of rivers (Huang, 2011; Syvitski et al., 2005b, 2003; Walling and Fang, 2003).

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, which may play an important role in river system transformations (Miao et al., 2011; Milliman et al., 2008; Xu et al., 2016; Zhang et al., 2015). As a matter of fact, from the beginning of past century, natural fluxes of water and sediment in rivers have been strongly impacted by human activities. These latter have generally determined increases in runoff, erosion, and transport of sediments, pollutants and nutrients from the watershed to the coastal waters (Syvitski et al., 2005b). For instance, wildfires, deforestation or extensive cultivation largely increased land erosion rates. Also, the construction of large dams and artificial reservoirs 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 combination of both natural - including climate change - and human-induced changes in river morphology causes land degradation, which in turn determines degradation of the physical and ecological characteristics of the coastal environment (e.g. coastal retreat, sea water intrusion). These 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).

From a marine engineering perspective, it is well known that coastal erosion is one of the main environmental problems in many parts of the world, due to its impacts on coastal areas, which are destructive and visible on the short-term (Andredaki et al., 2014). For instance, about 20% of the continental shorelines face serious erosion problems and this percentage is 80% in the USA (Samaras and Koutitas, 2008; US Geological Survey, 1985). 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) (European Commission, 2004; Samaras and Koutitas, 2014a) 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). As regards these latter, human activities have disturbed the coastal environment since the last century, often with permanent damages and synergistic effects with natural forcing factors (Blott et al., 2006; Klingbeil and Sommerfield, 2005; Tönis et al., 2002; Van Der Wal et al., 2002; Wang et al., 2013). As for river dynamics, the environmental factors contributing to coastal erosion are highly variable, both in time and space (Peychev and Stancheva, 2009). Moreover, also coastal evolutionary dynamics is influenced by climate change, mainly driving wave characteristics, beside modifying storm frequency/intensity and water/sediment flow rates into watersheds (Nicholls et al., 2007; Samaras and Koutitas, 2014b).

Morphological changes, which strongly influence the coastal environment, also have socio-economic implications for riverine populations, particularly in areas at high economic, recreational and ecological values (Wang et al., 2013). Nowadays, the importance of the socio-economic effects of the environmental changes raised up by the evolutionary trends of coastal morphology attracted the attention of environmental engineers, land planners and authorities all around the world (Samaras and Koutitas, 2014c).

1.2 The watershed – coast continuum

A large number of studies has systematically focused, interpreted and reproduced the natural and anthropogenic processes governing the dynamics of both the terrestrial and coastal fields (Samaras and Koutitas, 2012). Consequently, many theoretical studies related to water and sediment transport with different levels of complexity are available. The majority of these studies has been validated in several case studies. Moreover, the comprehension of these evolutionary processes and the capacity of their simulation have been enhanced by the development of computational tools (as the hydrological/hydraulic and coastal/wave models). At present these models allow the simultaneous and intercorrelated description of natural and human-induced evolutionary processes (providing the dynamic sediment budgets) in both coastal areas and watersheds and over small to large spatial and temporal scales (Samaras and Koutitas, 2012). Although coastal areas and watersheds have been the subjects of several investigations and a number of monitoring studies have been conducted, the tendency to consider these systems as two separate entities still remain. In this regard, it is noteworthy that, for instance, most deltas and estuaries are of a river origin in areas with limited tidal ranges and offshore currents, such as in the Mediterranean Sea. In areas with relevant tides the coastal sediments are trapped in the river and are responsible for the need of dredging activities. Therefore, it is important that research looks at the watershed and coastal systems as one sole body, as commonly indicated as the so-called "watershed-coast continuum" (WCC) (Salomons, 2005).

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. In addition, the influence of climatic changes and impacts of natural and anthropogenic actions on socio-economic activities in coastal areas are still poorly understood (Salomons et al., 2005). More specifically, the inter-correlations of continental processes with coastal erosion have not been sufficiently studied (Samaras and Koutitas, 2008), which instead would have provided a thorough comprehension of the geomorphological processes and the reliability of their simulation. As a matter of fact, the studies dealing with the terrestrial field have focused, since long time, on the magnitude and variability of water discharge and sediment yield in time/space, for different distribution of land uses and soils and in several climatic and geomorphological contexts. The environmental impacts of human modifications have been also deepened in a variety of situations worldwide. Furthermore, in the coastal field, the impacts of natural (unmanaged) and human (regulated) actions in watersheds have been often analysed with regards to the erosive and accretive rates on coastlines, the watershed-coast system has not been analysed on its entirety (Samaras and Koutitas, 2014a). It results that literature studies analysing concurrently inland and coastal fields and their quantitative correlation are scarce (Samaras and Koutitas, 2014b). A combined approach to inland and coastal fields has been named

"Integrated Coastal Zone Management" (ICZM). It is expected to bring the solutions of the environmental and socio-economic problems as well as the relevant management actions, not by separate approaches, but over WCC (Samaras and Koutitas, 2012). Furthermore, it is worth-mentioning that the available studies: (i) have adopted monitoring (that is, based on past and/or current measurements) or modelling based approaches, that have focused on either the terrestrial or the coastal fields; (ii) have been carried out at various time and spatial scales (from the event to the millennial and from the local to the oceanic scale, respectively); (iii) and, finally, have analysed both undisturbed and human-influenced watersheds/coastal zones. Therefore, it is evident that such diversity in the adopted approaches requires a systematic analysis.

1.3 Objectives of this review

This review aims at analysing the state-of-the-art of the literature, which has studied the evolutionary morphological trends of WCC. Specifically, the review is structured in: (*i*) a section analysing the literature studies, which have measured the sediment budgets at the land-sea interface; (*ii*) a section dealing with the papers about modelling activities of the watershed/coastline evolution; (*iii*) a section exploring the influence of the anthropogenic factors on the natural morpho-dynamics processes shaping the coastline position. Indications on the additional research needs and future challenges for a more complete analysis of WCC evolutionary trends are given in the last section.

Note that this review does not deepen the concept of morpho-dynamic equilibrium from a theoretical perspective, as a specific review on this topic was recently proposed by (Zhou et al., 2017). Instead, the articles mentioned herein describe numerical and experimental observations conducted in several areas worldwide. In this regard, the global picture about the identified studies is given in **Errore. L'origine riferimento non è stata trovata.**.

2. Monitoring studies

2.1 Experimental observations

A complete empirical description of the WCC dynamics must be based on experimental observations. These latter should be collected using devices measuring both the WCC intrinsic characteristics and the external actions impacting on this system. **Errore. L'origine riferimento non è stata trovata.** gives a general overview of the key elements required for describing by an empirical approach the WCC dynamics. The proposed scheme consists of monitoring of the intrinsic characteristics of WCC and of the external actions. The WCC characteristics are information about morphology, soil, land use and hydrology. The external actions consist of two classes: (*i*) climate forcings, which includes wind action, temperature and precipitation; (*ii*) sea action, which accounts for wave and tidal effects. In addition to the natural factors, also anthropogenic action needs to be monitored. Such an influence can be permanent, such as the construction of a dam in a watershed or a breakwater in the coastal area, or episodic, such as the effects of transient waves propagated by ships.

Errore. L'origine riferimento non è stata trovata. emphasizes the fact that a complete monitoring of WCC can be difficult to be carried out and thus challenging, because of the significant number of elements acting on the inland and sea systems. However, it is worth mentioning that this activity can be simplified by adopting suitable measuring equipment and analytical tools. For instance, satellite images, aerial photographs and cartographic maps provide the morphological characteristics of the entire WCC. Indeed, they may be used for determining both the watershed morphological characteristics and the shoreline displacement. Other tools can provide multiple and simultaneous measurements either in the coast or in the watershed. For instance, stereo-cameras can be employed in the coastal areas for continuously monitoring the shoreline evolution and recording the sea wave characteristics (significant wave height, mean wave direction, etc.) (Benetazzo et al., 2012). On the other hand, it is noteworthy that, although different instruments provide similar measures, these latter may be affected by different sources and levels of errors. An emblematic example is the monitoring of the shoreline evolution. Indeed, this morphological characteristic of the coast is usually determined at the price of significant measurement errors. (Moore, 2000) gave a quite comprehensive overview about the sources of error and the criteria for selecting the appropriate shoreline mapping technique. This author suggested (*i*) to assess the accuracy of historical maps at a preliminary stage; (*ii*) to use the highest quality of the available vertical aerial photographs; (*iii*) to avoid using photographs at a scale smaller than 1:20.000 and, instead, to use the largest possible scale; (*iv*) to avoid post-storm photographs, as they misrepresent long-term trends; (*v*) to perform an overall assessment of the error and quantify its total value. Commonly, the choice of the highest-quality instrumentation can be prohibitively expensive. Therefore, combining in-situ and remotely sensed data can be a reasonable compromise to obtain reliable measures. This strategy was proven to be effective by (Petersen et al., 2008) to get biological measures in the North Sea. These authors demonstrated that information gathered locally can be used for calibrating satellite images providing larger data that otherwise may not be available.

As regards the watershed characterisation, generally morphological, soil and land use data can be easily collected by a proper cartography (e.g., CORINE land cover, soil maps, DTM) and/or field surveys (to measure bed grain size, cross-section geometry, vegetation cover and structure). Conversely, hydrological data can often be unavailable. More specifically, while daily precipitation and temperature data are available almost all over the world, sub-daily values (needed for hydrological modelling) are less frequent, since its collection requires a continuous monitoring by rain gauging stations. Data about stream flows and mainly sediment delivery are rare, because their collection require more advanced equipment (e.g., water level probes, turbidimetries, runoff automatic samplers). This leads to many difficulties in monitoring the water and sediment flows and verifying the runoff and erosion prediction capacity of the hydrological computer models.

The experimental observations obtained by a number of field surveys showed that in the WCC analysis a significant role is played by the transport of water and sediments from the watershed to the coast, as it is one of the main factors of change of beach profiles in the vicinity of the river mouths. In this regard, the holistic view proposed in the monograph of (Milliman and Farnsworth, 2011) is very effective in disseminating the crude numbers. Indeed, these authors estimated that the overall annual discharge of inland sediments to the oceans is about 19 Btons/yr. Currently, this can be viewed only as a rough parameter giving the order of magnitude of the phenomena related to coastline evolutionary trends, as a significant variability is reported in the literature. For instance, the value reported by (Milliman and Farnsworth, 2011) is in reasonable agreement with the early estimates proposed by (Holeman, 1968) and (Milliman and Meade, 1983) and, more recently, with those of (Beusen et al., 2005) and (Peucker-Ehrenbrink, 2009), but it is larger than the estimation, for instance, by (Syvitski et al., 2005b), about 12 Btons/yr. Nevertheless, irrespectively of the specific global estimate, the critical element of these results is that coastal zones are deeply influenced by the surrounding watersheds.

This evidence is also irrespective of the geographical area. Indeed, all continents experience a significant sediment delivery to the ocean. In this regard, **Errore. L'origine riferimento non è stata trovata.** shows the sediment load of each continent as given by (Milliman and Farnsworth, 2011) and the ratio between the sediment load and the continent coast length. These data can be used to quantify the average sediment load impacting on 1-km coast. Although this ratio is affected by a significant variability, as it can vary from

35,15 Mtons/yr/km in Asia to 1,30 Mtons/yr/km in Eurasia, the amount of this impact is quite self-evident and corresponds to an average global estimate of 13,77 Mtons/yr/km.

To quantify *a priori* the sediment load delivered to a coast from a certain watershed, fundamental investigations were carried out with the aim of identifying correlations between the measured sediment loads and other measurable parameters related to watershed characteristics and external actions. In this regard, precipitation, evapo-transpiration as well as watershed morphology and source-rock lithology were found to some extent to be the most influencing parameters on the sediment load. In this context, an important role is also played by human activities, as these may either increase or decrease the total sediment load at the river mouth.

Merely on an intuitive basis, larger watersheds are supposed to have larger loads (Milliman and Meade, 1983). However, this fact is not systematically observed, as a strong variability of sediment delivery rates with the watershed area is found. Instead, a stricter correlation is found with the watershed maximum elevation (Milliman and Syvitski, 1992). Indeed, the sediment load generally increases with the maximum watershed elevation. This fact is particularly proven in small river mountains, because large gradients in watershed morphology in combination with relatively small floodplain areas accommodate the sediment displacement to the rivers and then to the oceans. The source-rock lithology affects the watershed erosion, as, for instance, mudstones are more erodible than sandstones. Also aging is important, as younger rocks are easily eroded compared to old rocks. For this reason, the erodibility of rocks is separated in six classes (Syvitski and Milliman, 2007); this is the reason why the identification of the rock formation era plays a significant role. However, the attempt to directly correlate lithology to sediment load does not provide a clear picture about these observations, because the data demonstrate to be affected by a significant scatter level

(Milliman and Farnsworth, 2011). Instead, runoff data help consolidating this holistic view. In this regard, it is worth mentioning that runoff *per se* is a minor contribution, since its contribution to the total sediment load is about 3% (Syvitski and Milliman, 2007); instead, accounting for runoff in the correlations established between sediment load, watershed morphology and sediment lithology provides clearer trends.

Obviously, coastal areas are exposed to the action of other factors, which on their turn significantly affect their morphology. In this context, an important contribution is given by natural factors (Samaras and Koutitas, 2008): waves; winds; tide; storms; sea level rise; slope stability; and vertical land movement. All these factors impact on the coast either via continuous or episodic actions. In addition, human factors affect the coastal areas by the following actions: coastal structures; dredging activities; ship-induced waves; cultivated areas; coastal vegetation clearing; measures controlling soil erosion; river basin regulation works; and gas mining.

2.2. Case studies

Studies monitoring the evolutionary trends of WCC have been carried out in various locations assumed as case-studies. Several monitoring activities were needed to calibrate/validate hydrological, marine and coupled prediction models. For this reason, an overview of these case-studies is reported in the section 3.

In the Po River (Italy), (Syvitski and Kettner, 2007) showed that the delta experienced a period of rapid progradation in the past years, with a peak in 1800 followed by a rapid decrease due to deforestation, agricultural activities and limited river migration. The study relied on runoff, discharge and sediment load data collected on a monthly basis in conjunction with historical surveys of shoreline evolution. The progradation rate reached a maximum of 150 m/yr in 1800, while in 2000 it was about 4 m/yr. This last rate is associated with a sediment load of about 13 Mtons/yr. In this context, the Apennine coastline experienced a significant erosion, mainly due to reservoir constructions.

(Andredaki et al., 2014) monitored both the watershed and the coastal areas of the Nestor River (Greece) after the construction of a dam. The watershed was characterized via data from 22 rain gauging stations from a meteorological perspective, and via geo-referenced maps from a morphological (area, slope gradients, etc.) point of view. The coastal area was monitored via high-resolution satellite and aerial photograph images. Other data were inferred through a modelling approach.

The Caribbean Magdalena River (Colombia), the largest Colombian watershed (257.000 km^2 with a main course of 1612 km), was the study focus of (Restrepo, 2008), since it is one of the most relevant of the whole east South America as it produces about 9% of the total sediment load (Restrepo and Kjerfve, 2000). Data from a 27 yr long monitoring activity (1972 – 1998) showed that the sediment load is, on average, about 144 Mtons/yr. Aerial and satellite images showed that beach was eroded for a length of about 3.5 km in the period 1936 – 2002 and that the shoreline was subject to retreat rates up to 600 m from 1989 to 2000.

A holistic perspective on the difficulties of conducting a complete monitoring activity and on the consequences of this lack of knowledge is given by (Lukas, 2017). The analysis of historical maps, bathymetric data of about 25 years and satellite images allowed reconstructing the profile variation of the Segara Anakan lagoon (Java, Indonesia) over almost two centuries (from 1857/60 to 2013), also thanks to measures of watershed areas and river courses changes. This analysis depicted a quite dramatic picture of the shoreline evolutionary trend. The water surface area of the lagoon decreased from 8600 to 2200 ha. The author emphasized the fact that the number of factors influencing these evolutionary processes was large and in addition their quantitative estimation is not yet possible.

A specific investigation about the relations between the morphological evolution of a river mouth bar and the fluvial input was proposed by (He et al., 2018) in the Modaomen Estuary of the Pearl River Delta (Southern China). The main data sources were bathymetric data, from four measurement surveys at 1:10.000 scale, and hydrological data, including average daily discharge and sediment concentration. The average annual flow rate was 6150 m^3/s with deviations up to 9525 m^3/s during the flood season. Their measurements highlighted that the main factor controlling the location of the river mouth bar in the estuary are the river floods. The eastern and western channels experienced significant extension rates, associated with reductions in sediment concentration and load (in accordance to (Syvitski et al., 2009)). The maximum recorded values occurred in conjunction with the most intense floods.

The monitoring studies discussed so far are based on the collection of specific experimental data. In some works, the data are correlated with each other via the implementation of theoretical/numerical tools. Section 3 provides a general overview on the most used models and describes the outcomes of the most relevant studies based on their applications.

Overall, we have highlighted that many data are available worldwide, providing a general picture about the correlation between the WCC variables, but they are not enough to definitely delineate the quantitative connections between WCC characteristics, the natural forcing factors and the resulting coastal evolutionary trends. For this purpose, the approach proposed in the LOICZ (Land-Ocean Interactions in the Coastal Zone) project appears as the most reasonable way for achieving this objective. (Ramesh et al., 2015) described the most important achievements of the LOICZ project. This project investigated the WCC from several perspectives, from biology to coastal management, and helped to emphasize the importance of river-mouth systems ecologically and economically. A critical feature of the project is that it adopted a holistic approach, which should be pursued also to build a WCC monitoring system. In other words, it is fundamental to carry out holistic monitoring activities measuring by a simultaneous and integrated way the WCC intrinsic characteristics and the interconnected external actions, in order to quantify input, output and system parameters. In this context, the use of data extrapolated, inferred or fitted by numerical, theoretical or empirical models should be avoided or, at least, minimized, since they necessarily introduce uncertainties in the data interpretation and make more difficult the construction of models aimed at predicting the WCC response. Apart from the difficulties in establishing a complex monitoring system, another challenge is the combination of long-term operation with the resolution required for monitoring episodic events, such as storms. Indeed, long-term trends cover a time span of decades, while episodic events, which may last just a few hours are crucial in the identification of the WCC state.

Another research gap is the limited geographical extent of the monitoring experiences. As we have shown, the majority of case studies proposing the evaluation of the past and current evolutionary trends of WCC and the predictions of future evolution of shoreline position has been carried out at the planetary scale by a low spatial detail or in few regions (China, North America, Europe) by a thicker scale. The large variability of geomorphological (as relates to continental water and sediment flows) and climate (both for watershed and marine systems) characteristics of inland and coastal areas requires a larger effort of researchers, who must provide a database of monitoring case studies able to cover a complete picture of the past evolutionary trends of WCC worldwide.

3. Modelling approaches

As mentioned above, in the last decades several prediction models were developed, both for hydrological/hydraulic and coastal models. At the same time, powerful computational and analytical tools (as the computer models and the Geographic Information Systems, GIS, for information storage, processing and management) were further enhanced. The combination of prediction models and computational and analytical tools made easier and quicker the estimations of water resource dynamics as well as its planning and management, enabling long-term simulations of the related processes with satisfactory reliability (Singh and Woolhiser, 2002). **Errore. L'origine riferimento non è stata trovata.** shows the possible structure of a WCC model, which is the combination of models developed separately in the watershed and coastal fields. Obviously a number of models is available in both fields depending on scale of the analysis and on the data available (**Errore. L'origine riferimento non è stata trovata.**).

For instance, as regards the terrestrial field, a number of watershed-scale models with components able to simulate water runoff, soil erosion and sediment and pollutant transport have been developed that vary in complexity and data input requirement terms (Borah and Bera, 2004). It results that the impacts of natural and anthropogenic changes on land-sea interface dynamics may be effectively assessed using modelling tools, mainly when historic data is available (Jordan et al., 2005). These models, when supported by GIS and geostatistical techniques, can be an important soil management tool to assess wider geographic ranges (Mateos-Molina et al., 2015). However, these models vary depending on different aspects, such as the scope (e.g., erosion, water quality, marine sediment transport), type (e.g., conceptual, empirical, physically-based) (Merritt et al., 2003), temporal (from precipitation/tidal event to millennial) and spatial (from local to continental) scales (Aksoy and Kavvas, 2005).

This section proposes an overview of the modelling studies carried out worldwide about the interactions of sediment fluxes of the watershed-coastline complex. The analysed studies range from theoretical approaches, which develop or integrate new models (Bever et al., 2009; Hu et al., 2009; Samaras and Koutitas, 2014c, 2008), to case studies of application of existing models (Andredaki et al., 2014; Hofmann et al., 2005; Syvitski et al., 1998; Syvitski and Kettner, 2007). Furthermore, the models are applied as analytical tools for watershed management (Bergillos et al., 2016; Samaras and Koutitas, 2014a, 2012) or to study the effects of climate change on coastline evolution dynamics (Luan et al., 2017; Ruggiero et al., 2010; Samaras and Koutitas, 2014b). Finally, modelling experiences have been carried out at different spatial scales (beside individual case studies), from regional applications (Chérubin et al., 2008; Li et al., 2018), to a planetary approach, (Cohen et al., 2013; Syvitski et al., 2003), with the aim of evaluating the prediction capacity of the available models in simulating the interactions between the watershed and marine processes shaping the land-sea interface.

3.1 Theoretical studies

(Hu et al., 2009) proposed a 2D/3D hydrodynamic and sediment transport model (Delft3D-FLOW) to reproduce the storm surge problem and morphological evolution of the Jiuduansha Shoals in the region of Yangtze Estuary (China). Thanks to the model application, the authors demonstrated that the effects of remote wind and waves should be considered to obtain accurate results for storm surges; moreover, the transport of cohesive as well as the non-cohesive fraction of sediment needs to be considered to simulate with reliability the morphological evolution of the shoal.

A “one-line shoreline change model” (PELNCON) was developed by (Samaras and Koutitas, 2008) to study the impact of reservoir construction on coastal morphology evolution of Nestos River (a transboundary basin between Bulgaria and Greece). In more detail, by input the field and wave characteristics (at the breaker line) and the sediment supply rate of the river, the shoreline change was calculated over a given period, demonstrating serious erosion rates of the coastal area due to the high sediment deficit. Despite the easiness of use and reliability of the results of the model, the authors complain the structural weaknesses of the one-line shoreline change theory on which the model is based.

Three formulas to model longshore sediment transport rates (Bayram et al., 2007; Kamphuis, 1991; USACE, 1975) as part of the PELNCON (properly modified) model were properly adapted by (Samaras and Koutitas, 2014c). The main adaption consisted of the description of coastal morphology and sediment transport, and the introduction of sediment sources. These formulas were compared by an application in the Kassandra peninsula (Chalkidiki, Northern Greece) near a stream mouth. The choice of an individual formula affected shoreline evolution, with CERC resulting to the best fitting of PELNCON-M simulations to measured shorelines.

The relationships between physical processes and observed depositional products were simulated by a sediment-transport model applied to the area near the Po river delta (Northern Italy) (Bever et al., 2009). The model couples a 3-D ocean model and sediment-transport calculations including suspended-sediment transport and wave- and current induced resuspension of the fluvial input. The results of the numerical modelling of Po river delta showed that more than half of the discharged sediment remained close to the river distributary mouths, despite the intensive redistribution by winter storms; the remaining sediment was exported from the delta along two transport paths. Sediment transport rates and pathways were controlled by sea wave action and current direction, whereas sediment deposition and reworking near the delta was larger during floods and strong winds.

An application of coupled coastal – fluvial dynamic model was presented by (Ashton et al., 2013). Their application concerned the analysis of the wave induced deltas. Specifically, they coupled a Coastline Evolution Model (CEM) with HydroTrend model. These models demonstrated to predict a two-way interaction between the watershed and the coasts, that manifests itself with long-range interactions between distributary channels connected along the shore.

3.2 Case studies

A combination of mathematical modelling, remote sensing techniques and field surveying was adopted by (Andredaki et al., 2014) to assess the effects of reservoir sedimentation on the coastal erosion and the adjacent shorelines in Nestos river delta. The construction and operation of two reservoirs inversed the erosion/accretion balance in the shorelines (from prevalent accretion before reservoir construction to predominating erosion just after five years), due to the drastic decrease (about 83%) in the sediments supplied to the coast neighbouring the basin outlet.

The model HydroTrend (Syvitski et al., 1998) was widely applied to simulate the sediment loads of the coastal watersheds, also because it is thought to provide important boundary conditions for marine sediment dispersal models using wind, wave and currents data (Syvitski et al., 2005a). These authors applied HydroTrend in Lanyang watershed in northeast Taiwan and found that the modelled suspended sediment concentrations in the river flows to the coast were in close accordance to long-term (1950-1994) observations, except for peak sediment flows. Therefore, it was concluded the tested model may be a useful tool to predict the sediment fluxes across an entire coastline at a high-resolution temporal scale.

The model was also applied to the Po and six Apennine rivers (Metauro, Musone, Potenza, Tronto, Chienti and Pescara), all of which located in the Italian peninsula, to simulate water and sediment supply to the northern Adriatic Sea. A share of about 50% of total sediment flux was quantified to be delivered to the sea by the Po river (carrying solid material of the northern Apennine hinterland), while another 50% was transported by the six modelled rivers, these high fluxes in spite of the numerous small reservoirs that have reduced river sediment loads (Syvitski and Kettner, 2007).

A modelling approach was also used by (Hofmann et al., 2005) in the Elbe river basin (Central Europe) to define the effects of anthropogenic activities carried out in the watershed on eutrophication of the coastal waters of the German Bight. To this purpose, a combination of multi-purpose models was used: MONERIS (MOdelling Nutrient Emissions in RIver Systems), estimating nutrient emissions in the watershed, ERSEM (European Regional Seas Ecosystem Model), evaluating emission effects on the ecosystem of the coastal watersand with the ecosystem, and CENER (Cost-Effective Nutrient Emission Reduction), assessing by a multi-criteria analysis the cost effectiveness of reduction measures. The outcome of the multi-criteria analysis shows that the best alternative to protect the ecological integrity of the coastal waters is the construction of high nutrient retention basins and dams in the catchment.

3.3 Watershed management

It is well known that the construction of artificial basin can induce important changes in watershed morphology and hydrology. Therefore, the mouth dynamics 19-km downstream of reservoir installed in Guadalfeo river (Andalusia, southern Spain) was simulated by a calibrated hydrological model Water Integrated Management for Mediterranean Watersheds (WiMMed) (Herrero et al., 2014; Polo et al., 2009), in a study of (Bergillos et al., 2016). More specifically, the sediment volume transported as bed load and accumulated in the delta was estimated under a managed scenario (with a dam creating the reservoir) and an unmanaged scenario (without the structure). As expected, the mouth lost a large volume of sediments and its position retreated, as a result of sediment transport reduction. The authors used the model as watershed management tool and suggested alternative scenarios to prevent more severe consequences in the delta and the silting of the reservoir. These scenarios consisted of operational schemes modulating the water and sediment flows drained by the dam, in combination with bypassed sediment from the reservoir.

Beside human works, also natural and artificial land use changes may affect the evolution of the coastal morphology through modifications on land erosion rates, requiring suitable strategies for watershed management. The effects of past changes in cultivation practices and the wave actions on the shoreline were modelled by (Samaras and Koutitas, 2014a) in the catchment of the Fourka torrent and the area adjacent to its mouth (Chalkidiki, North Greece), using a combination of Geographic Information Systems, field measurements and numerical modelling (the PELNCON-M model). The model, simulating two sediment discharge rates, showed a shoreline retreat of about 35 m at the torrent's mouth in less than 15 years due to the decrease of the torrent sediment discharge. This reduction was attributed to the abandonment of the grain fields and transformed into grasslands with a lower erodibility and thus of minor contribution to the catchment's sediment yield.

A coupled-calibration approach of watershed and coastal models (namely PELCON-M, SWAT, MOD-C, MOD-D, MEAS-W, MEAS-C models), was carried out by (Samaras and Koutitas, 2012) with an application in an area (mouth of the Fourka torrent) located in the middle of the Kassandra peninsula in Chalkidiki (North Greece). The aim was to promote the synergy of numerical models in both the terrestrial and coastal fields in order to achieve more suitable model selection, more realistic modeling assumptions and better precision in estimating the involved parameters. By this modelling exercise, the impact of three scenarios of data availability (overland sediment transport, estimated by SWAT, and coastal sediment transport and morphology, estimated by PELCON-M) for coast and watershed, the shoreline position was estimated as a function of the changes in the land use distribution in the watershed between 1995 and 2008.

In a subsequent study (Samaras and Koutitas, 2014a), the same authors used the PELCON-M and SWAT models to study the impact of extensive land-use changes (1995 to 2008) in the same watershed as above and severe marine erosion on coastal morphology; more specifically, three longshore sediment transport rate formulae (CERC, BAY and CAM) included in PELCON-M model were applied. CERC formula resulted to the best fitting of simulations to measured shorelines. Furthermore, crop abandonment determined the retreat of about 35 metres in the vicinity of the stream mouth, due to the decrease of sediment discharge at the watershed outlet.

3.4 Climate change

Since climate change has negative impacts on the natural and human environment, modelling is a useful tool to predict the morphological response of coastal areas to the climate evolutionary trends in terms of erosion and accretion rates.

The impacts of climate change on sediment transport and morphology in the WCC was studied by (Samaras and Koutitas, 2014b) through a modelling approach. The SWAT and PELNCON-M models were applied to the Fourka torrent watershed and the coastal zone of the Kassandra peninsula (Chalkidiki, North Greece), respectively. The Global climate projections by the Intergovernmental Panel on Climate Change (IPCC) were assumed as model input and the morphological response of the sandy coast was studied for two climatic scenarios, forecasting increases in precipitation or sea wave extremes, respectively.

The results of the model simulations showed: (*i*) for the first scenario an increase in the watershed sediment discharge at the watershed outlet, leading to a shoreline advance in 10 years; (*ii*) a retreat of the coast position in the same area for the second scenario. Overall, the impacts of the increase of wave extremes on shoreline evolution was milder compared to the forecasted increase of precipitation.

The process-based model system (Delft3D) was applied by (Luan et al., 2017) to the Yangtze Estuary (China) to simulate its past and future decadal morpho-dynamic evolution. First, the model was validated in three separate periods (from 1958 to 2010) with good reliability in reproducing observed erosion and deposition patterns, sediment volume changes, and hypsometry curves. Then, six scenarios of estuarine morphological evolution were analysed from 1958 to 2030 under decreased river inputs and increased relative sea level. The model predictions showed large erosion in the inner and mouth bar area of the estuary. Current net deposition is thought to shift to net erosion in 2030, mainly because of decreasing sediment supply, which will require management strategies. Changes in water discharge will induce lower effects compared to the trend forecasted above.

(Ruggiero et al., 2010) used a simple deterministic one-line shoreline change model (UNIBEST-CL (WL|Delft Hydraulics, 1994), applied in a quasi-probabilistic manner to Columbia River (USA), in order to evaluate the effects of sediment supply and wave climate variability (by simulating six wave climate scenarios) on past and future shoreline change (from 1995 to 2020). The model application showed that shoreline changes were significantly sensitive to changes in incident wave directions (particularly to the largest "El Niño" event magnitude), and to increases in the intensity of the east Pacific wave climate (especially when this increase occurs during the winter storm season). Their analysis suggested that alongshore and cross-shore sediment transport play different roles at decadal-scales and at annual scales, in the sense that the transport is alongshore dominated in the former case and cross-shore dominated in the latter case.

3.5 Regional studies

Coupled watershed-coast evolution models were applied at both regional and planetary scales. One example of regional studies dealing with land–ocean sediment transport processes is presented by a paper of (Li et al., 2018), who applied the Sediment Identity and multiple linear regression approach to nine major rivers of China (Songhua, Liao, Hai, Yellow, Huai, Yangtze, Qiantang, Min, Pearl rivers), all delivering sediment and water into the Southern and Eastern Chinese seas and into the Yellow sea. More specifically, the temporal trends of sediment and water flows delivered to the sea were analysed as the response of anthropogenic and natural pressures occurred during the past six decades. During this period a significant decrease in sediment flows was detected for all the investigated basins. Model results showed that the observed decrease was mainly due to a reduction in sediment concentration because of reservoir construction and secondarily to the soil conservation measures applied in the region.

In the Mesoamerican region a combination of remote sensing techniques and river discharge and numerical ocean circulation models were used by (Chérubin et al., 2008) to study the evolution in time and space of terrestrial runoff in waters. In more detail, monthly overland flows and river discharge, simulated by a land-elevation model, were input to a numerical model simulating the transport of buoyant matter from terrestrial runoff. To this purpose, SeaWiFS images of the period 1997-2006 were processed to produce Colored Detrital Material (CDM) images of the Mesoamerican waters. The modelled plume reproduced well the spatial and temporal patterns of the observed CDM plume. Moreover, the model results showed that the river discharge seasonality was correlated with the CDM images averaged. Finally, the study demonstrated that all the reefs of the Mesoamerican region are strongly influenced by terrestrial runoff on a seasonal basis, with maximum effect during October to January, and minimum from March to April.

3.6 Planetary approach

At the largest spatial scale, the terrestrial sediment flows delivered to the global ocean was quantified in the planetary study of (Syvitski et al., 2003), who applied an original model to a global data set of 340 river basins. The model is based (or, averaged discharge), and basin-averaged temperature. The sediment flows are estimated as a function of basin location, relief and area as well as of the regional climate data through basin temperature and hydrologic runoff; results are provided separately for each of the major hemispheric climate regions (polar, temperate and tropic). While the model prediction capability was found to be satisfactory in the natural basins (that is, in rivers not affected by anthropogenic impacts), the simulated sediment flows were affected by significant uncertainties associated with sediment trapping in reservoirs and dams and land conservation practices, which produced outlier data. However, the model predictions are useful to identify problems of observational data quality and to address the impact of paleo-climate fluctuations (warmer/colder and wetter/drier) on the impact of sediment flows to the coastal ocean.

The BQART and the Psi statistical model were integrated in WBMsed model by (Cohen et al., 2013) to simulate sediment flows towards ocean coasts. More specifically, BQART is a global empirical model that calculates long-term suspended sediment loads, while Psi estimates the intra- and inter-annual variability in BQART sediment flow predictions. WBMsed predictions were compared to the sediment loads observed at the mouth of 95 river mouths and to the original BQART predictions for the same rivers, and to daily sediment flows observations of 11 USGS stations throughout 11 years. WBMsed predictions agreed with the multiyear average, inter-annual and intra-annual trends (produced by BQART), while daily sediment flows (given by Psi) were considerably over- and under-predicted by the model for extreme discharge periods; this latter prediction inaccuracy was determined by the corresponding unsatisfactory water discharge simulations. WBMsed predictions were more reliable for larger watersheds (over 70000 km^2).

From the discussion above, it is evident the significant effort put in the construction of theoretical models able to predict the WCC evolution. We have shown that the current state-of-the-art is a set of hydrological and/or marine simulation models, which have been developed independently in the past in coastal engineering and in watershed related applications, currently often do not interact in a unique evolving system. In other words, these models are joined sequentially, so that the output of the watershed model is the input of the adopted coastal engineering model. Although this approach is reasonably simple, it is inadequate for describing those WCCs with mutual influence between coasts and watersheds. A notable example is given by the evolution of deltas exposed to relevant variations of the tidal levels, where water currents generated by such significant variations affect also the watershed equilibrium. Clearly, the construction of more versatile models derived by regarding the WCC as a whole is desirable. In this context, the concepts elucidated by (Zhou et al., 2017) are of primary importance. Indeed, they pointed out the fundamental distinction between "real" and "virtual" world, that is the word described by the experimental observations and the world modelled by mathematical tools, and outlined the approaches for expressing the concept of equilibrium in estuarine systems (but it can be applied to watersheds and coasts, as well).

4. Anthropogenic effects

It is undeniable that, beside the natural processes, also the anthropogenic actions play a basic role in governing the physical processes shaping the coastline. Often, when the human interventions are introduced into the continuum watershed-coast environment without considering the possible effects on the natural evolutionary processes, the related impacts on the erosion/accretion rates may be of many orders of magnitude compared to the physiological trends. Literature has identified as the most impacting anthropogenic actions the following activities: constructions of artificial reservoirs and dams, mining, human-induced land use changes. A general overview anthropogenic activity – impact is given in **Errore. L'origine riferimento non è stata trovata.**, where the impacts on the morphological evolutionary processes are marked in italics. These actions have been analysed by several studies as acting individually or simultaneously.

4.1 Artificial reservoirs, dams and other engineering works

Generally speaking, the construction of reservoirs and dams to store water for several purposes (e.g., irrigation, energy production, potable uses) modifies the river geomorphological and hydrological processes, since their presence induces alteration of natural water and sediment flow rates downstream of the structures, whose effects are generally not only of large impacts on the natural evolutionary trends, but are also felt at longer distances from the man-works. Sedimentation of solid material in reservoirs reduces their capacity to store water as on-site effect; moreover, also river channels and beaches suffer from the reduction of sediment supply from upstream watershed areas (Batalla, 2003).

In Nestos river (a watershed located at the boundaries between Bulgaria and Greece), the construction and operation of two reservoirs since the end of the 20th century has almost inversed the erosion/accretion rates in the river deltaic as well as the adjacent shorelines, due to a very large decrease in the sediments supplied directly to the basin outlet (Andredaki et al., 2014). In other words, if accretion was prevalent over erosion in the absence of the reservoirs, a combination of modelling and surveying activities carried out just five years after the construction showed a predominance of coastline erosion, due to the reduction of the sediment yield at river outlets.

The effects of the construction of a reservoir, located 19 km upstream of the mouth of the Guadalfeo river delta (in Southern Spain), have been evaluated by (Bergillos et al., 2016) through a comparison of two scenarios, with or without the presence of the structure. Also, in this case study, erosion of the coastline (retreated by about 100 m along coastline 1.4-km long) was detected as the main effect of dam operation, due to the bed sediment deficit of more 2 hm^3 estimated under unmanaged conditions. The authors suggested modulating flows drained by the dam and the construction of a bypass for sediment from the reservoir, to reduce both the delta erosion rates as well as reservoir siltation.

The presence of high erosion in coastline trend since 1950s in the Bradano and Basento basins (Basilicata Region, Southern Italy) suggested a study about the relationship between coastline erosion and natural evolution of the inland system. The combined analysis of local weather changes (precipitation and sea level) as natural factors, presence of five dams, river bend sand extraction as well as land use changes (e.g., desertification process) showed that the natural and anthropogenic forcing factors above mentioned produced different effects. More specifically, while the progressive desertification of the basin and the increase of rainfall erosivity due to the climate changes determined higher erosional trends in the basins with potential coastal accretion, the simultaneous reduction of sediment supply towards the coastline, due to dam presence, caused erosion in the coastline. As a result of the inverse processes (erosion and accretion) balance, coast erosion is now prevalent with a predominant effect played on the coastal dunes, which requires the integrated management of the coastal hinterland and coastline without separating the two systems (inland waters and sea environment) (Bonora et al., 2002).

A dataset of 300-year coastal changes of the Taiwan's largest lagoon (Cigu) was analysed over a 300-year period by (Chang et al., 2018). The study showed that the human activities of the last decades - construction of an upstream reservoir and, hard structures along the coastline (jetties, harbour dykes and offshore breakwaters) has altered the balance of sediment supply with retreat of barrier sandbars along the coast. As shown by a lagoon evolution model, a possible disappearance of the Cigu lagoon is forecasted unless the sediment is recovered from reservoirs and dykes as long-term management strategy.

In another river of the same country (Lanyang River, Hsi) the major anthropogenic action was major road construction. A monitoring activity from 1950 to 1994 showed that the construction of two roads have increased sediment yields by more than tenfold for a period of 2 to 4 years following the disturbance (Kao and Liu, 2002, 2001; Syvitski et al., 2005a).

At a spatial scale larger than those adopted in the previous studies (all of which carried out by a local approach), (Huang, 2011) reported that in Japan the overall erosion rate along the coastline of Japan sharply increased by over 120% since '1980s, as an effect of the construction of a high number of dams. However, a time lag between the sediment supply reduction due to the dam presence and beach erosion was noticed. However, the beach retreat is not always a delayed response of to the dam construction effect. As a matter of fact, the same author demonstrated in a case study (Lower Tenryu river, mid-east Japan) that sand and gravel mining accelerating channel bed erosion was prevalent in inducing coastline erosion compared to sediment deficit due to dam operation. This showed that sediment supply from channel storage may complicate the interpretation of downstream sediment yields.

In Yellow river (China), more than 3000 reservoirs and dams constructed were built since '1950s. It is thus evident how the morphology and the hydrology of this river can be heavily impacted by the human action. The morphological evolution of its estuary has been studied from 1842 to 2006 by (Wang et al., 2013) (see also (Wang et al., 2017)), in order to assess whether the long-term equilibrium has been established under the intense anthropogenic influence. The estuarine areas were affected by several large erosion and deposition episodes, but overall erosion prevailed over the entire 165-year period. At a denser spatial scale, channels became straighter and coastlines were more aligned with the propagation direction of offshore tidal current. The authors concluded that channel development within the estuary is approaching a dynamic equilibrium, resulting from the combination of the anthropogenic effects linked to engineering works around the estuary and the natural evolutionary trends, such as tide propagation and Coriolis force. Compared to these actions, other change factors (e.g., sea level changes and wave climate) had lower effects in the morphological evolution of the estuary.

In the same river, adequate flows of water and sediments are maintained in channels of the main courses by the so-called "Water Sediment Regulation Scheme” (WSRS), in order to control the environmental effects in the large coastal areas of this heavy human-impacted river. More specifically, during selected flood events, large flood discharges from reservoirs are released under river authorities' control on the main stream and tributaries, inducing scouring in the downstream reaches of this river throughout a 10-20 day period (Wang et al., 2010). In order to quantify the hydrological and morphological effects of WSRS on the estuary of this large river, (Xu et al., 2016) discovered a newly formed small delta in the river mouth after the WSRS operated in 2013, thus demonstrating that this new morphologic element altered the distribution of terrestrial material conveyed from upstream zones in the estuarine zone. This study has evidenced how the intentional regulation of water and sediment flows has large impacts in rivers under heavy human control, since it affects by a wide extent coastal hydrodynamics and sediment distribution patterns.

4.2 Gravel mining

Instream gravel mining, beside the construction of reservoirs and dams, are able to interrupt the continuity in sediment transport along a water course and this can strongly damage both river and coastal ecosystems as shown in **Errore. L'origine riferimento non è stata**

trovata.. The resulting sediment deficit has been studied by (Batalla, 2003) in case studies selected in NE Spain (Ebro and other rivers in the Catalan Coastal Ranges and Eastern Pyrenees). In these fluvial systems the sediment extraction due to gravel mining, estimated in several million tons per year, has determined destruction of large portions river ecosystem, undermining of several bridges due to channel incision (with collapse of some structures), groundwater over-drafting; in the downstream coastal areas the high sediment deficit has led to severe erosion of delta and beaches. The author suggested, beside long-term programmes of sediment transfer monitoring in river systems, also short-term actions, consisting of (i) prohibition of solid material extraction in strongly unbalanced rivers (in particular, in reaches downstream of dams), (ii) taxation of gravel mining by charging environmental costs to the gravel price of product (aggregate), and (iii) alternative sources of material (such as concrete recycling, reservoir deposits, especially for low-quality uses).

4.3 Human-induced changes in land use

Changes in land uses due to natural processes and human actions heavily influence the hydrological response of a given territorial unit, since a decrease or an increase in the vegetal cover modifies the runoff generation and soil erosion rates. For a watershed with a coastal mouth these modifications reflect on sediment delivery to coastal waters with consequent changes in shoreline position (**Errore. L'origine riferimento non è stata trovata.**).

Research was aware about the strict relationships between land uses and water/sediment fluxes towards coastal areas since 1993, when the Land–ocean Interactions in the Coastal Zone (LOICZ) project was launched. The main goal of the project was the evaluation of the influence of changes in land use, sea level and climate on coastal systems, and their consequences. The first phase of the LOICZ project (1993–2003) attention was mainly paid to river discharge to the oceans and biogeochemical modelling, while in the following decade

(2004–2014) the anthropogenic actions on the coastal environment were focused, including externalities such as coastal governance, social-ecological systems and ecological economics). In the third decade of its activity, LOICZ has being developing a new vision targeted to support transformation to a sustainable future for society and nature on the coast, deepening research themes about shoreline dynamics, human development of coastal areas and tools to increase sustainability of coastal environment (Ramesh et al., 2015).

Within an application of the LOICZ project to South American and Caribbean Basins, the interactions between the Magdalena watershed (Colombia) and its coastal environment have been studied by (Restrepo, 2008), who evaluated the influence of anthropogenic land use and hydrological changes during the past century in aquatic ecosystems. The land cover changes in the watershed (decrease in forests, increases in cropland, pasture and urban areas as well as unsustainable soil management practices) increased the terrestrial erosion rates in the last 10-20 years. The heavy freshwater and sediment discharges have globally determined a decline of live cover of the coral reef complex in the Caribbean Sea and locally the total disappearance of coral formations beside a large reduction of seagrass cover.

Since land cover can be considered one of the most significant indicator of human alterations on sediment discharges, (Mateos-Molina et al., 2015) used land cover data to estimate changes in sediment fluxes towards the coasts of the Ligurian Sea (northwestern Mediterranean Sea, Italy), which include Marine Protected Areas of high natural value, but very sensitive to the negative effects of water turbidity due to increased sediment delivery. Using a combination of Revised Universal Soil Loss Equation (RUSLE) model and sediment delivery ratio (SDR), the study highlighted heavy changes in marine ecology in two different basins (between 1990 and 2000 as well as 2006 and 2012) and minor environmental damages in several other basins.

The impact of land-use changes in the Fourka watershed (Chalkidiki, North Greece) on erosion of a sandy beach surrounding its mouth has been studied by (Samaras and Koutitas, 2014a) through numerical modelling. Cropland abandonment (determined by a decrease from 23% to 5% in agricultural land cover) led to a decrease in the sediment yield from the contributing drainage area by over 50%, resulting in its turn in a decrease in the sediment discharge by about 10-20% at the watershed outlet. The coastline dynamic response to these variations in water and sediment flows was a coastline retreat of more than 35 metres in the vicinity of the stream mouth.

4.4 Multiple and concurrent anthropogenic change factors

Natural- and human-induced factors of changes in watersheds and coasts can simultaneously act and synergetically regulate the morphology evolution of areas surroundings of river mouths by (Samaras and Koutitas, 2014a).

At a planetary scale and on the long term the inland sediment fluxes from 340 rivers towards the coastal areas of oceans were modelled by (Syvitski et al., 2003). The authors separated the studied basins in major hemispheric climate regions (polar, temperate and tropic) and the monitoring time scale into pre-anthropogenic and anthropogenic periods. The study evidenced that the change factors most influencing the modelled sediment fluxes are sediment trapping in lakes or reservoirs and land use practices. For instance, farming perturbations in the Yellow river (China), road construction in Tseng Wen, Erhain and Lanyang rivers (Taiwan), the combined impacts of landslides and land use in Waipaoa River (New Zealand) and heavy pressure of population in Godavari, Narmanda and Manuk rivers (India) were found to be the most important factors increasing the sediment fluxes to the coastal oceans.

At a smaller spatial scale, the reduction in sediment (mainly gravel and sand) delivery rates from the Figarella and Seccu rivers was analysed as factors of change in beach erosion of Calvi Bay (Corsica, France) during the last three decades. In these coastal streams in-channel gravel-mining since the 1970's and significant land-use changes since the end of the 19th century took place. Less than 50% of the beach sediment deficit resulted directly from mining, while watershed land-use and channel changes determined with evolutionary rates progressively variable throughout the last century the other share of coast erosion, worsening gravel-mining. Currently, since these anthropogenic factors of change are far from under control, management strategies are expected in order to increase sediment delivery and thus protecting the beach from erosion, which is thought to be essential for the tourist industry development (Gaillot and Piegay, 1999).

Overall, this section has emphasized the relevance of human activities on the WCC dynamics. This is a well-known fact, that has been investigated by a number of researches. However, the quantitative consequences of these human activities have not yet been fully described. In this regard, the remarks made in section 2 and 3 apply also in this context, as models must be improved and more data are necessary. Herein, it is noted that the critical consequence is that policy makers are still relying on partial evidences and, consequently, on partial models for making fundamental decisions on environment management. In this context, it is relevant emphasizing that the qualitative impact of these anthropogenic actions is not known by the general public, as well. This is an important issue that has been faced by initiatives, like the LOICZ, that promoted short courses and communication products providing scientific based evidences (Ramesh et al., 2015) to a wider audience.

5. Future challenges and development

To summarize the points discussed above, 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, as the products of a series of natural forcing factors and human-induced pressures (Samaras and Koutitas, 2014a). The scientific research focusing on these evolutionary processes plays a basic role in proposing management strategies and operational tools to avoid, or at least reducing as much as possible, the undesired environmental effects. The efficacy of these strategies and tools is strictly linked to the qualitative and quantitative comprehension of the physical processes taking place in both the terrestrial and coastal fields (Samaras and Koutitas, 2012) as well as of the magnitude of the human pressures modifying the natural watershed-coast environment. Since many decades, these processes have been generally approached by the concept of the "coastal sediment budget", targeted to identify, quantify and hopefully predict the environmental changes in both fields (terrestrial zones and coastal areas) at various scales (spatial and temporal) and by as much reliability as possible (Samaras and Koutitas, 2014a). To understand these changes, 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.

It is widely recognized in literature that there is still a significant lack of information about the connections between watersheds and coasts. In some cases, the physical processes underlying the watershed-coast continuum (WCC) have not been completely understood yet. In this regard, (Lukas, 2017) pointed out that this fact currently is serious limit to policy makers, that cannot rely on objective data for environmental management. In this sense, it is this authors' opinion that the future challenge of the researches in the field must be a unique framework describing the WCC dynamics as one sole body on the basis of integrated monitoring activities and an updating of the theoretical approaches describing the WCC dynamics.

The need of the holistic approach towards a better comprehension of WCC - leading to the concrete possibility to forecast the temporal and spatial coastline evolutionary trends - requires on one hand to establish spatially distributed monitoring systems, targeted to fill the limited geographical extent of the monitoring experiences illustrated above. On the other hand, it is imperative, from a theoretical perspective, the construction of simple models describing the WCC evolution integrating the hydrological and marine simulation models and overcoming the dichotomy between coastal engineering and inland hydrology. These models should be accurate also in the so-called "data-poor environments", that is, in those coastal basins, where the unavailability of hydrological and marine observations (as happen for the majority of ungauged basins, where no data about water and sediment flows can be recorded) prevents the separate verification of model reliability. A possible approach may be the integration of hydrological (e.g., HEC-HMS, SWAT) and coastal (e.g., Genesis, MIKE) prediction models available in literature and often of free and easy use. To overcome these limitations, an indirect validation strategy could be adopted by calibrating through a trial-and-error procedure the coupled inland-coastal models using high-resolution satellite images, caught before and after flood-wave events shaping the coastline.

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TABLES

Table 1 - Continental sediment loads calculated by (Milliman and Farnsworth, 2011) and ratio of the sediment load over the continental coast length.

Continent	**Sediment load (Mtons/yr)**	**Sediment load/coastline length (Mtons/yr/km)**
North/Central America	1900	4,09
South America	2300	15,91
Europe	850	4,13
Africa	1500	20,13
Eurasian	150	1,30
Asia	5300	35,15
Oceania	7100	30,47

Table 2 - Impacts of anthropogenic activities on inland and marine environments (in italics the direct impacts on morphological evolutionary processes). Sources: (Coccossis, 2004; Salomons et al., 2005).

ANTHROPOGENIC ACTIVITY	**IMPACTS**	
	Inland water and environment	**Sea water and marine environment**
Urbanisation and tourism	*Increases in runoff discharge and soil loss* Depletion of surface and groundwater due to water supply Pollution due to sewage and solid waste	Pollution due to sewage and solid waste Eutrophication due to detergents and solvents Loss of biodiversity *Coastal accretion*
Agriculture	*Changes in runoff discharge and increase in soil loss* Depletion of surface and groundwater due to irrigation Pollution due to nutrients, pesticides and herbicides	Pollution due to nutrients, pesticides and herbicides Eutrophication due to nutrients Salt intrusion into ground water Loss of biodiversity *Coastal erosion/accretion*
Industry	Depletion of surface and groundwater Pollution to waste and wastewater disposal and storage	Pollution to waste and wastewater disposal and storage Eutrophication due to detergents and solvents Loss of biodiversity Acidification
Fisheries and aquaculture	-	Eutrophication due to nutrients Loss of biodiversity

Energy production	*Changes in river regime* *Changes in sediment transport and sedimentation rates*	Thermal pollution Loss of biodiversity *Coastal erosion/accretion*
Mining and dredging	*Changes in sediment transport rates* *Subsidence* Pollution to waste disposal and storage	Pollution due to oils Loss of biodiversity *Coastal erosion*
Navigation	-	Pollution to waste and wastewater disposal
Deforestation	*Increases in runoff discharge and soil loss* *Increase of flooding risk*	Pollution due to nutrients Eutrophication due to nutrients Loss of biodiversity *Coastal accretion*
Construction of infrastructures (damming, diversion)	*Changes in runoff discharge and sediment transport rates* Pollution to waste disposal and storage	*Coastal erosion/accretion*
Land reclamation	*Changes in runoff discharge and sediment transport rates*	*Coastal erosion/accretion*

FIGURE CAPTIONS

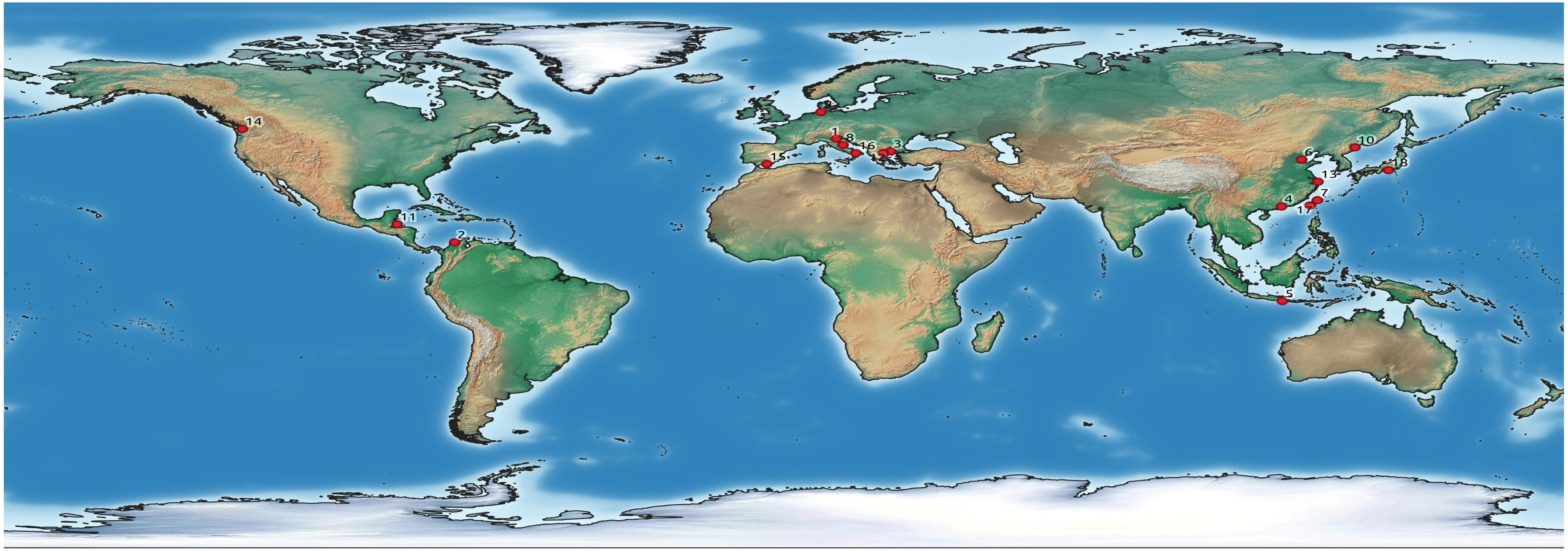

Figure 1 - World map with locations of experimental or theoretical/modelling studies about the WCC.

(Legend: 1. Po River delta (Italy) – Syvitski and Kettner (2007); 2. Magdalena River (Colombia) – (Restrepo, 2008); 3. Nestor River (Greece) - (Andredaki et al., 2014); 4. Modaomen Estuary (Pearl River Delta, China) – He et al. (2018); 5. Segara Anakan lagoon (Java, Indonesia) – Lukas (2017); 6. Yellow River (China) – Wang et al. (2017); 7. Lanyang (Northern Taiwan) – Syvitski et al. (2005a); 8. Po and six Apennine rivers (Metauro, Musone, Potenza, Tronto, Chienti and Pescara) – Syvitski and Kettner (2007); 9. Elbe river basin (Central Europe) – Hofmann et al. (2005); 10. Songhua, Liao, Hai, Yellow, Huai, Yangtze, Qiantang, Min, Pearl rivers (China) – Li et al. (2018); 11. Bay of Honduras – Chérubin et al. (2008); 12. Chalkidiki (North Greece) – Samaras and Koutitas (2014b); 13. Yangtze Estuary (China) – Luan et al. (2017); 14.

Columbia River (USA) – Ruggiero et al. (2010); 15. Guadalfeo river delta (Southern Spain) – Bergillos et al. (2016); 16. Bradano and Basento basins (Basilicata) – Bonora et al. (2002); 17. Cigu (Taiwan) – Chang et al. (2018); 18. Lower Tenryu River (mid-east Japan) – Huang (2011).

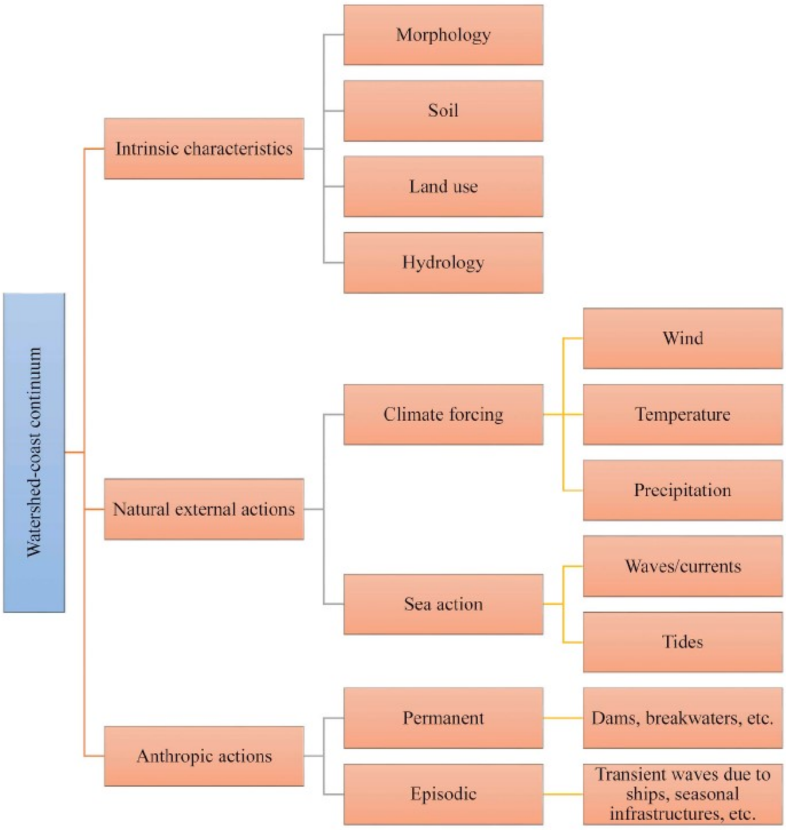

Figure 2 - Overview of the elements to be monitored for describing the watershed-coast continuum dynamics.

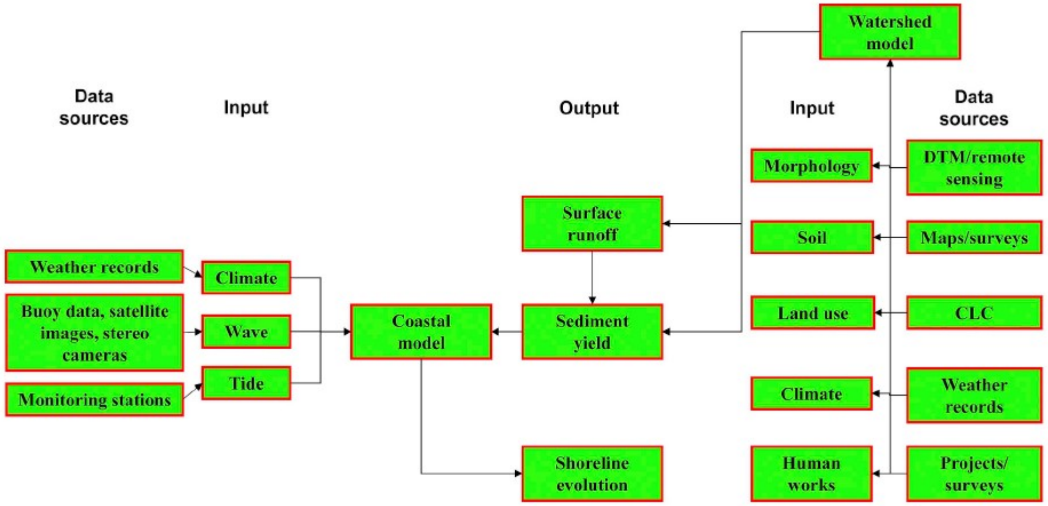

Figure 3 - Structure of a common modelling approach used to evaluate the WCC evolutionary trends.

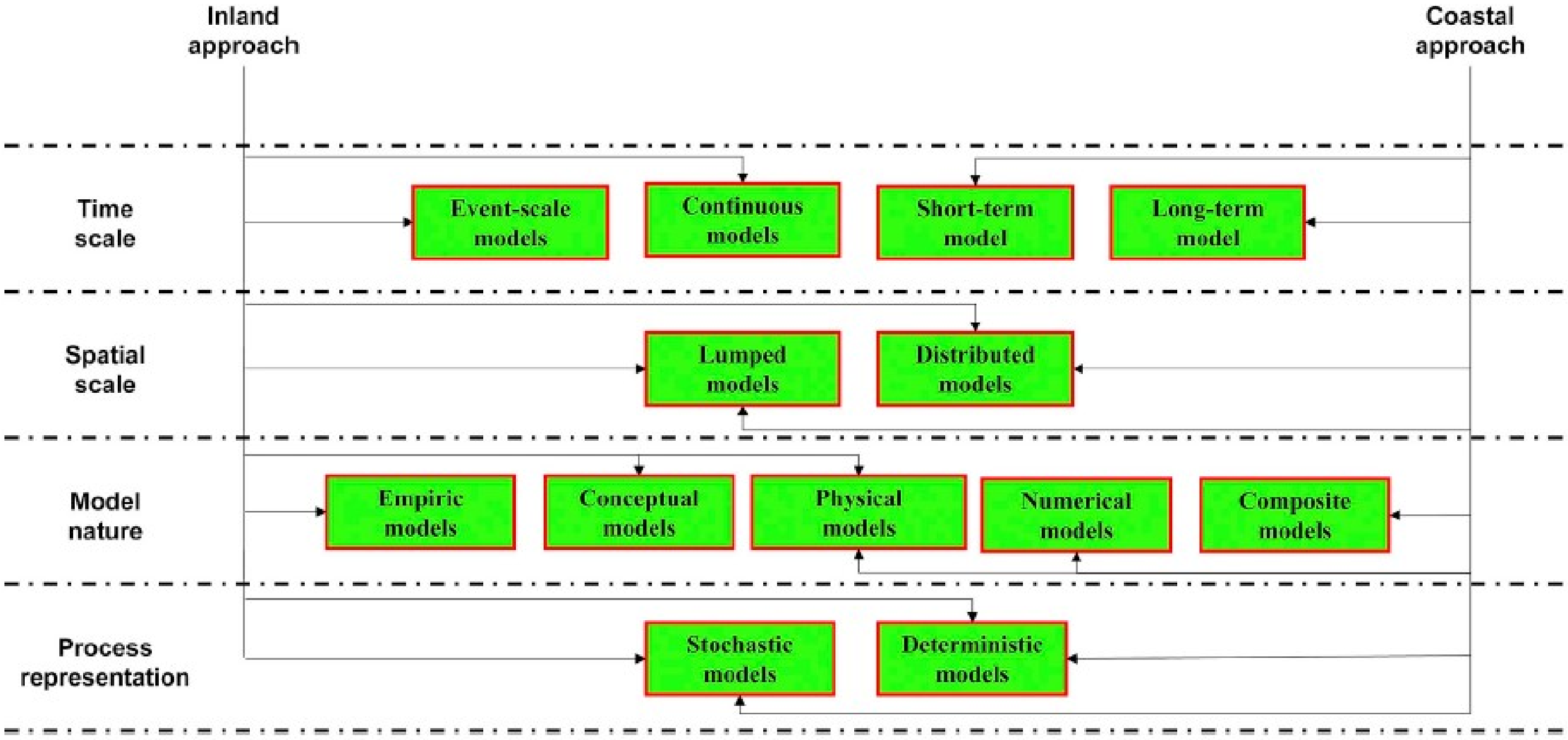

Figure 4 - Classification of the watershed and coastal models.