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Abstract
Coastal environments are featured by high variability, where geomorphological, biological and physical variables show significant spatial and temporal variations induced by both natural and anthropogenic forcing. In particular, sandy coasts are the most vulnerable as they exhibit large responses to low-frequency but high impact/extreme events, such as storm surge flooding events. Against the complex interactions occurring at the land-sea interface, coastal managers and policy makers are increasingly calling for new integrated approaches and tools able to support a multi-scenario evaluation of environmental risks arising from natural and human-induced stressors acting in concert on the same coastal targets (e.g. urban areas, coastal communities and ecosystems). The Integrated Coastal Zone Management (ICZM) approach represents a valuable tool to resolve these issues, providing a structured framework and principles to reduce impacts due to short and long-term pressures, and provide support to sustainable and integrated shoreline management. In the frame of the task 3.5 '*Development of the framework and tool for final users with training*', this report provides an overview of the main tools and methods providing support to policy and decision makers in the implementation of European recommendations and directives for coastal zone risk assessment and management. A set of 44 tools were selected and sorted in indicator and index-based, GIS-based DSS, remote sensing-based methods exploiting potential posed by satellite imagery and Bayesian Network approaches. These methods, with a different level of complexity and detail in the data processing and final outcomes, allow identifying areas and receptors at higher coastal erosion risk, and to simulate future climate and management scenarios, thus allowing to explore the effects induced by multiple measures and climate conditions, with the final aim of supporting the development and implementation of more robust and adaptive coastal erosion risk-based management strategies. A selection of these tools will be applied in the frame of the TRITON pilot cases, in order to evaluate coastal erosion processes and provide the scientific means for cross border operational plan for ICMZ implementation across Greece and Italy.

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Acronyms

BN: Bayesian Network
CC: Climate Change
CM: Coastal Model
CRI-LS: Coastal Risk Index for Local Scale
CSoVI: Coastal Social Vulnerability Index
CVI: Coastal Vulnerability Index
DAG: Directed Acyclic Graph
DPSIR: Driving forces, Pressures, States, Impacts, Responses
DSAS: Digital Shoreline Analysis System
DSS: Decision Support System
EEA: European Environment Agency
FEMA: US Federal Emergency Management Agency
FT: Future scenario
GIS: Geographic Information System
ICZM: Integrated Coastal Zone Management
IPCC: Intergovernmental Panel on Climate Change
KNMI: Royal Netherlands Meteorological Institute
OECD: Organization for Economic Co-operation and Development
PSR: Pressure, State, Response
RaMCo: Rapid Assessment Module for Coastal zone management
RCP: Representative Concentration Pathway
RP: Return Period
RRA: Regional Risk Assessment
RTK: Real-time kinematic
SLR: Sea Level Rise
SoVI: Social Vulnerability Index
SPR: Sources, Pathways, Receptors
SS: Storm Surge
SWH: Significant wave height
TP: Time period

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1. Introduction

Rising sea level and extreme events related to climate change are causing severe threats to coastal areas, affecting both natural and human systems worldwide (IPCC, 2018). Located at the land-sea interface, climate-related impacts will be especially relevant in coastal areas, where a dense interaction between terrestrial and marine systems occurs (IPCC, 2013a). Coastal areas are expected to undergo increasingly intense climate-related impacts and even more severe extreme events. Specifically, rising sea levels, changes in the dynamics and energy distribution of waters, as well as variations in the pattern, frequency and intensity of extreme events are expected to increase future coastal flooding and erosion (MATTM, 2017). Foreseen results consist in diffused environmental and socio-economic damages including the disruption of urban assets and loss of valuable natural areas (EEA, 2017; IPCC, 2014). In this already complicated scenario, coastal areas are also experiencing relevant pressures resulting from multiple human-induced stressors linked with coastal economic development (e.g. touristic activities and infrastructures along the shoreline) and the connected land use changes (e.g. urbanization) (Ramieri *et al.*, 2011). As a consequence, the assessment and management of coastal erosion risks represents a complex task due to the high number of environmental and socio-economic factors at stake, as well as the variety and complexity of interactions that may occur among climate-induced and anthropogenic pressures affecting the same area (Ramieri *et al.*, 2011).

Building on the widely applied Driving force, Pressure, State, Impact, Response –DPSIR- framework (Bidone and Lacerda, 2004; Kristensen, 2004), different tools and methods have been developed so far by the research community in order to provide support in the analysis of coastal erosion risk arising from multiple scenarios, including different management and policy setting, as well as climate conditions. In particular, these tools can be applied both to identify risk-prone areas and receptors and to simulate scenarios, thus allowing to explore the effects induced by different measures, with the final aim of supporting the development and implementation of coastal erosion risk-based policies, robust enough against uncertainties and changes over time.

In the frame of the task 3.5 '*Development of the framework and tool for final users with training*', a DPSIR-based conceptual framework was developed in order to disentangle the complex interactions underpinning coastal erosion phenomena, by defining the relationships between natural and anthropogenic activities, the coastal environment and its ecosystems, and the resulting environmental, physical and socio-economic impacts. Moreover, to operationalize the designed DPSIR-based framework, and provide support in the risk analysis across the TRITON Pilot cases (WP4), an in-depth review of tools and methods dealing with coastal erosion risk mapping and management was also performed, leading to the selection of a set of 44 'key tools'. Selected tools were categorized according to 4 main family of tools (i.e. i) indicators and index-based method; ii)

GIS-based Decision Support Systems; iii) Remote sensing techniques for shoreline detection; iv) Bayesian Networks approaches) and then compared and discussed based on set of comparison criteria (e.g. type of data used for the application of the tool; study area; timeframe scenarios considered in the assessment).

Accordingly, the Section 2 of this document provides a detailed description of the designed DPSIR-based conceptual framework for coastal erosion risk analysis and management, identifying, in a systematic way, the complex relationships between sources and consequences of coastal erosion processes. Then, the Section 3 focuses on the review of the state of art tools and methods for coastal erosion risk mapping and appraisal, including indicators and index-based methods (Paragraph 3.1), GIS-based Decision Support Systems (DSS; Section 3.2), Remote sensing techniques (Section 3.3) and Bayesian Networks approaches (BN; Section 3.4).

2. Conceptual framework for coastal erosion risk assessment and management

Over the last decades numerous and diverse issues leading to ecological implications have challenged both environmental scientists and decision-makers in the understanding of the relationships between social/economic interests and the associated environmental issues, requiring practical evaluation techniques building on interdisciplinary approaches (Neves *et al.*, 2008).

Risk assessment is a rather complex procedure that can help analyzing and managing a wide range of environmental issues, including those related to climate change (Davies & Hope, 2015; Lavasani et al., 2015; Torresan et al., 2016). In many countries and institutions different risk assessment methodologies have been developed in order to understand processes underpinning coastal erosion risks (Falck et al., 2000; Bolado et al. 2012; Skogdalen & Vinnem 2012). Most of these methods apply a stepwise (and cyclic) approach, starting from the definition of the problem, toward the risk identification, analysis and evaluation (ISO, 2009; Defra, 2011). Provide a road map for decision-makers is the final purpose of the methodologies, toward a structured analysis of the complex array of considerations underlying environmental decisions (Marcomini et al., 2010; Defra 2011). Particularly, the definition of the issue of concern, including the identification of all relevant threats (sources of risk), the potential exposure pathways and the harm (losses) that might result from exposure to hazard (impacts), is the first step for an effective risk assessment. In fact, a clear definition of the problem, can help selecting the level and types of methodologies to be applied across the different phases of the risk assessment process (Defra, 2011).

The development of a conceptual framework may help formalizing the issue at hand, showing, in a systematic way, the relationships between the natural and anthropogenic sources of risk, the exposed coastal targets (e.g. coastal dunes, infrastructures and touristic activities) and the resulting environmental, physical and socio-economic impacts. Moreover, conceptual models provide a schematic representation of the limits of the analyzed system (e.g. Defra, 2011) and may help identifying all data sources (physical, environmental and socio-economic information) required to evaluate and understand the multidisciplinary nature of risk (Baldi et al., 2010). In this setting, The **DPSIR framework** developed by the European Environmental Agency (EEA, 1995), with the aim of describing the relationships between the origins and consequences of environmental issues (EEA, 1999; Kristensen, 2004; Khajuria & Ravindranath, 2012), has been widely applied in multiple science domains for supporting the conceptualization of risk assessment problems (Kelble et al., 2013). The framework is an extension of the Pressure-State-Response model (PSR model), developed by the Organization for Economic Co-operation and Development (OECD, 1970) to assess the environmental performance by using key indicators (Khajuria and Ravindranath, 2012).

As represented in Figure 1, the DPSIR framework defines a chain of causal links starting with the identification of the '**driving forces'** representing the natural and anthropogenic forces which can drive variations in the state of the environment and/or human systems. Driving forces, in turn, may exert intentionally or unintentionally '**pressures'**. Pressures can broadly be described as the means through which drivers are actually expressed i.e, in the way they may interfere and perturb the environmental and socio-economic systems (Neves *et al.*, 2008). They can vary among geographic regions, spatial and temporal scales causing changes in the '**state'** of the exposed systems. Finally, changes in the state of the analyzed system can produce several '**impacts'** on the environment, human health and activities, eventually leading to '**responses**', including the re-evaluation of current management policies and, eventually, the setting on of new measures (Kristensen, 2004). Therefore, the DPSIR framework represents a useful tool to identify and classify drivers and pressures at different temporal and spatial scales, and for providing a first-pass screening of potential response management measures and planning strategies.

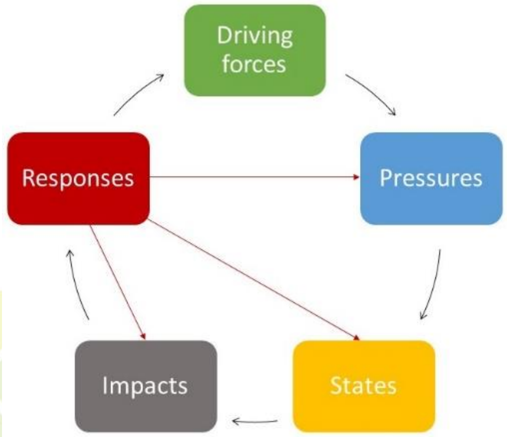

Figure 1: DPSIR conceptual framework

Drawing on this, a DPSIR-based approach is here proposed to formalize the issue of concern of the TRITON project (i.e. coastal erosion), clarifying the possible factors involved in the risk analysis by identifying the main cause-effect relationships and interactions between climate-related and anthropogenic pressures, the exposed coastal systems and the resulting environmental, physical and socio-economic impacts. Figure 2 depicts the designed DPSIR-based framework considering both natural (e.g. solar irradiance and volcanic aerosol changes) and anthropogenic drivers (e.g. population growth and urbanization, land surface changes, socio-economic development), contributing together to shape the global climate system (IPCC, 2013). In turn, these drivers contribute to oceanographic (e.g. winds, tidal range, sea-level rise, wave, storms, coastal currents) and anthropogenic pressures (e.g. tourism, settlement, coastal development, extraction of resources, industries and shipping transports) inducing changes in the state of environmental and human systems exposed (e.g. buildings, infrastructures and people). Specifically, strong tides, waves and winds can lead to structural and physical impacts on buildings and infrastructures (e.g. collapse and disruption of bridges, roads and buildings close to the coast), as well as socio-economic impacts on the activities located at the land-sea interface (i.e. tourism, aquaculture and harbor activities). Similarly, natural ecosystems can be affected as well by both anthropogenic and oceanographic pressures. In fact, costal currents, sea-level rise and storms and, on the other hand, the extraction of resources from the seabed, coastal development and shipping transport can negatively affect coastal ecosystems, causing shoreline retreatment, coastal slope variation and changes in the water quality (environmental and physical impacts), resulting, in concert, in an overall reduction in the ecosystem services flow (socio-economic impacts). People can be affected as well by the considered pressures as a result of coastal extreme events and also landslides. Finally, as possible responses to these impacts, some examples of adaptation (e.g. coastal zone planning, construction of artificial protection like dams, beach nourishment) and mitigation measures (e.g. fuel substitution, conversion of land use, energy taxes and subsidies) are proposed in the conceptual framework in Figure 2, which should be taken into account in order to reduce coastal erosion risk, acting at different levels on drivers, pressures, states and impacts.

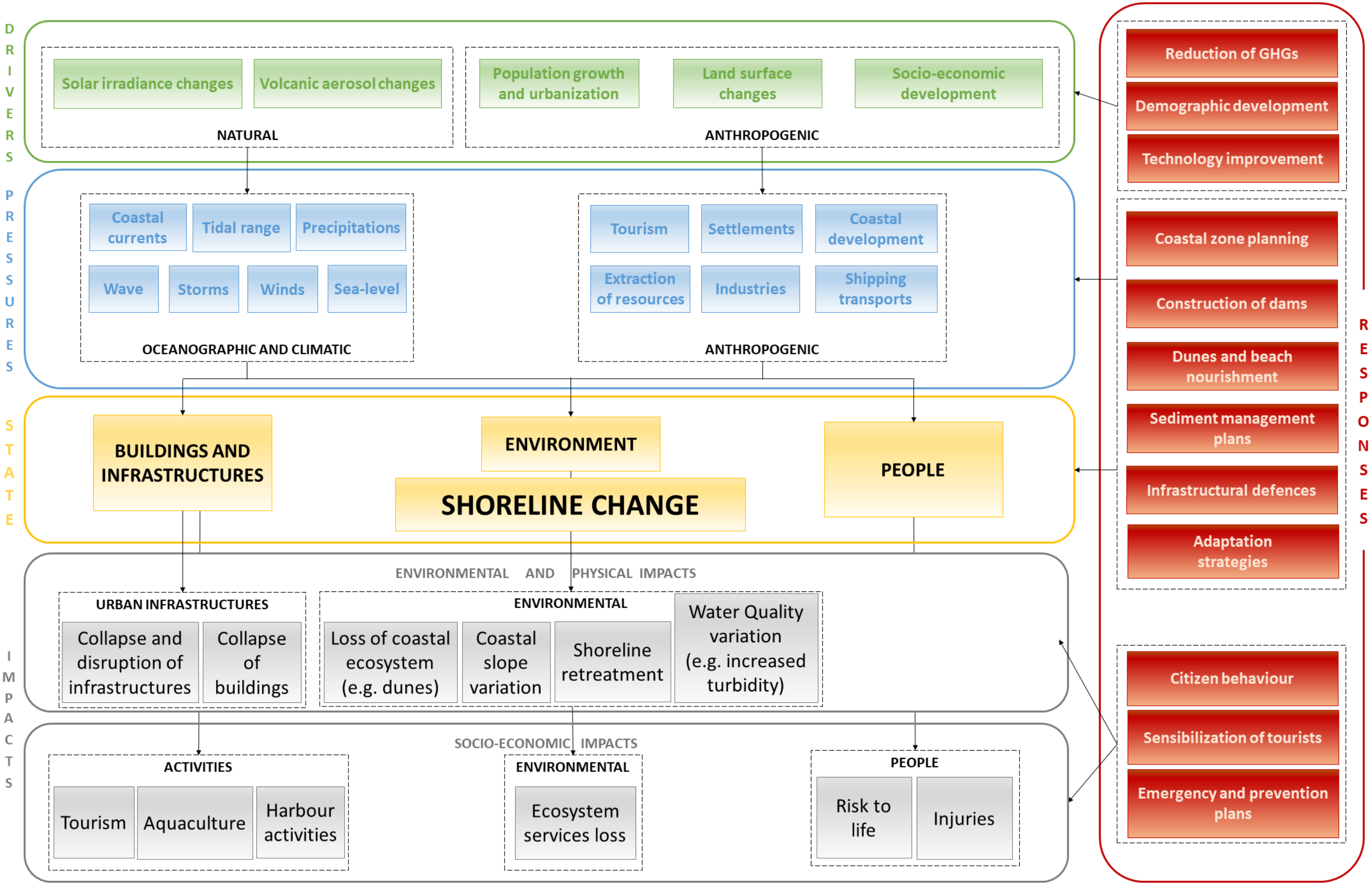

Figure 2: DPSIR-based Conceptual Framework for coastal erosion risk mapping and management

3. State of the art of tools and methods for coastal erosion risk assessment and management

Several tools and methods supporting policy and decision makers in the implementation of European recommendations and directives for coastal zone management have been developed in recent years (UNEP, 2008; EC, 2013). Some of them represent a valuable support for the assessment of coastal vulnerability and risks against future climate change scenarios (e.g. rising sea level, coastal erosion, increase in extreme events such as storm surge flooding) and different socio-economic conditions (e.g. increase of population, land-use changes) (Ramieri et al., 2011). When focusing on coastal erosion processes, more or less sophisticated tools, ranging from indicators and index-based methods (e.g. Coastal Vulnerability Index –CVI) to more complex Decision Support Systems (DSS) (e.g. DESYCO, DIVA SimCLIM), remote sensing and Bayesian Network (BN) approaches, can be applied for understanding processes underpinning the erosion phenomena.

In the frame of the Task 3.5, a set 44 'key tools' dealing with the analysis and management of coastal erosion risks were selected and deeply analyzed by the TRITON partners in order to provide useful information and practical examples of their effectiveness across different coastal case studies. Among these, 24 belong to more simple indicator- and index-based approaches, allowing, with a simple framework, to aggregate multiple heterogeneous variables into a single risk and vulnerability measure; 13 tools relate to DSS supporting decision making processes and facilitating end-users during data pre-processing and integration; finally 7 tools belong to Bayesian Network approaches supporting multiple 'what-if' scenario analysis of coastal erosion risk.

Selected tools for coastal erosion risk assessment and management are summarized in the Table 1 detailing the i) name/acronym of the tool as reported in the related publication; ii) objective of the assessment exercise as explained in the analyzed reference; iii) type of data used for the implementation of the proposed methodology; iv) timeframe scenarios considered in the assessment; v) study area and spatial scale of the analysis; vi) literature reference.

Table 1: Tools and methods for coastal erosion risk mapping and management selected by the TRITON partners

Tools	Name of tool	Objective	Type of data	Scale / study area	Timeframe scenarios	Reference
Indicator and index-based methodologies	**CVI**	Assessing coastal vulnerability to future sea level rise	Geophysical and hydrologic	N / U.S. coasts	/	Gornitz *et al.*, 1991
	CSoVI	Assessing vulnerability in spatial terms using both biophysical and social indicators	Biophysical, chemical, meteo-climatic, socio-economic	L / Georgetown County, South Carolina, US	Flood hazards zones derived by FEMA's Q3 flood data, RP: 100/500 years	Cutter *et al.*, 2003
	PVI	Assessment of physical and social vulnerability of US Coastal Counties	Geophysical, hydrologic, socio-economic	N / US Coastal Counties	/	Boruff *et al.*, 2005
	Composite Vulnerability Index	Vulnerability assessment of coastal natural hazards, introducing parameters for population affected by flooding or living in vulnerable areas, poverty and municipal wealth	Geophysical, hydrologic, socio-economic	R / State of Parà, Brazil	/	Szlafsztein & Sterr, 2007
	CVI for sea level rise impacts	Assessing vulnerability of coastal areas to sea level rise, introducing parameters related to climatic pressures and human-induced pressures	Geophysical, hydrologic, meteo-climatic, anthropic influence	R / Goksu delta	/	Ozyurt *et al.*, 2007
	Vulnerability Indicators for Ecosystems & Natural Resources	Mapping climate change vulnerability in the Sydney Coastal Councils Group	Geophysical, meteo-climatic, socio-economic	L / Sydney Coastal Councils Group	Average, min and max temperature, average rainfall 2030 projections	Preston *et al.*, 2008
	Vulnerability Indicators for Sea-Level Rise and Coastal Management	Mapping climate change vulnerability in the Sydney Coastal Councils Group	Geophysical, socio-economic	L / Sydney Coastal Councils Group	/	Preston *et al.*, 2008
	CVI	Introduction of a multi-scale approach used to provide spatial analysis of the degree of vulnerability, highlighting the implication of scale in the selection of indicators and the degree of simplification	Geophysical, hydrologic, socio-economic	Multi-scale: N, R, L Northern Ireland	/	Mclaughlin & Cooper, 2010
	/	Developed a vulnerability and resilience assessment tool in the ENSURE project context to understand strengths and fragilities of a given territory and community	Physical, socio-economic	L / Sondrio, Italy	/	Menoni *et al.*, 2012

Tools	Name of tool	Objective	Type of data	Scale / study area	Timeframe scenarios	Reference
	CCFVI	Development of a flood vulnerability index for coastal cities, including a politico-administrative sub-index alongside the hydro-geological and socio-economic sub-indices	Geophysical, hydrologic, meteo-climatic, socio-economic, politico-administrative	L / Casablanca (MA), Calcutta (IN), Dhaka (BD), Manila (PHL), Buenos Aires (ARG), Osaka (J), Marseille (FRA), Shanghai (CHN), Rotterdam (NL)	/	Balica *et al.*, 2012
	CSI	Assessing the coastal sensitivity to sea level rise	Geophysical	R / Peloponnese (GR)	/	Karymbalis *et al.*, 2012
	SoVI	Measuring Social Vulnerability to Natural Hazards in the Yangtze River Delta Region, China	Socio-economic	R / Yangtze River Delta Region, China	/	Chen *et al.*, 2013
	SVI	Evaluate social vulnerability of individual cities, capturing at the same time the spatial development of the community	Socio-economic	L / Chiayi, Taiwan	/	Lee *et al.*, 2014
	SVI	Combining hazard and exposure with a social vulnerability index to provide lessons for flood risk management	Hydrologic, socio-economic	L / Rotterdam, The Netherlands	Unembanked areas, B: 2010; FS: 2050 Temperature, river discharge, storm duration and SLR projections from KNMI'06 CC scenarios	Koks *et al.*, 2015
	CCI	Vulnerability assessment for prliminary lood risk mapping and managemnt in coastal areas	Geophysical, hydrologic, socio-economic	L / Ioninan coast of the Basilicata region, Italy	Sea storm RP: 1/30/500 years	Greco & Martino, 2016
	CVI	Assessing coastal vulnerability due to coastal erosion and SLR	Geophysical	N / Indian East coast	/	Ahammed *et al.*, 2016
	SVI	Develope a methodology to assess the social vulnerability and its spatial distribution at the Italian national scale	Socio-economic	N / Italy	/	Frigerio & De Amicis, 2016
	SVI	Develope a GIS-approach to identify the spatial variability of social vulnerability associated to seismic hazards in Italy	Socio-economic	N / Italy	/	Frigerio *et al.*, 2016
	CRI-LS	Assess risk of climate-related hazards in coastal zones	Geophisycal, meteo-climatic, socio-economic	L / Tetouan	SLR and SS RP: 100 years	Satta *et al.*, 2016
	CRI-MED	Assess risk of climate-related hazards in coastal zones at the regional scale	Geophisycal, meteo-climatic, socio-economic	R / Mediterranean	SLR and SWH RP: 100 years	Satta *et al.*, 2017
	CVI	Idetification of potential impacts, vulnerabilities and adaptation strategies for the oil and gas industry against climate-related impacts	Physical, geological, socio-economic	N / Egyptian Coast	SLR, B: 1993-2011; FS: 2021-2050 and 2041-2070 (under RCP4.5 and RCP 8.5 scenarios)	Torresan *et al.*, 2017

Tools	Name of tool	Objective	Type of data	Scale / study area	Timeframe scenarios	Reference
					SS, B: 1970-2000; FS: 2010-2040 and 2070-2100 RCP4.5 + RCP 8.5 scenarios	
	SVI	Examine the spatiotemporal patterns of social vulnerability in Italy for years 1991, 2001, 2011	Socio-economic	N / Italy	TP: 1991 / 2001 / 2011	Frigerio *et al.*, 2018
	/	Assessment of societal resilience indicators using demographic and infrastructure data	Socio-economic	N / Germany	/	Fekete *et al.*, 2018
	CVI and CVI vs. CSI	Assessing the coastal vulnerability of climate change	Geophysical, vegetation	L / Apulian coastline	/	Pantusa *et al.*, 2018
Decision Support Systems (DSS)	**COSMO**	Evaluate coastal management options considering anthropic forcing and climate change impacts	Socio-economic, climatic, environmental, hydrological	N / The Netherlands	100 years	Rijsberman & van Velzen, 1996
	SimLUCIA	assess the vulnerability of low-lying areas in the coastal zones and island to sea-level rise due to climate change	Climatic, environmental, socio-economic	L / Saint Lucia	40 years (1990-2030)	White *et al*, 1997
	RAMCO	Reduce the gap between the present state and the desired state of the coastal zone and support the coastal zone manager(s)	combines GIS with a dynamic system model for the (bio)physical and socio-economic coastal-zone interactions	L / Southwest Sulawesi, Indonesia	2020	Kok *et al.*, 2001
	WADBOS	Support the design and analysis of policy measures in order to achieve an integrated and sustainable management	Socio-economic, hydrological, environmental, ecological	L / Wadden Sea	10 years scenario	Engelen *et al.*, 2005
	CVAT	Assess hazards, vulnerability and risks related to climate change and support hazard mitigation options.	Environmental and socio-economic	L / New Hanover County, Maui County, Rhode Island (USA)	/	Flax *et al.*, 2002
	KRIM DSS	Determine how coastal systems reacts to climate change in order to develop modern coastal management strategies	Climatic, socio-economic, ecological, environmental, hydrological	L / Bremen (Germany)	2050	Kraft, 2003
	DITTY DSS	Preservation, protection and improvement of the quality of the environment through a prudent and rational utilization of the natural resources	biogeochemical, hydrodynamic, ecological, socio-economic models, GIS	L / Sacca di Goro lagoon (Italy)	2/3 years	Mocenni *et al.*, 2009
	IWRM DSS	Explore potential risks on coastal resources due to climate and water management policies	Climatic, environmental, socio-economic, geomorphological	N / Bangladesh	/	Zaman *et al.*, 2009
	DIVA DSS	Assessing coastal vulnerability and explore the effects of climate change impacts on coastal regions	Climatic, socio-economic, geography, morphological	L, N, R, G	2100	Hinkel & Klein, 2009
	SimCLIM	Assessing impacts and risks of climatic extremes in a changing climate	Hydrologic, climatic	R / Southeast Queensland, Australia	2050	Warrick, 2009

Tools	Name of tool	Objective	Type of data	Scale / study area	Timeframe scenarios	Reference
	Coastal Simulator	Long-term assessments of potential coastal impacts and responses	combines a geographical information system with a dynamic system model for the (bio)physical and socio-economic coastal-zone interactions	L / coast of Norfolk, UK	100 years	Mokrech *et al.*, 2011
	THESEUS DSS	Assess risk across a range of spatial and temporal scales to minimize coastal risk	Social, environmental, economic	L / Cesenatico, Italy	2020 (short-term) 2050 (medium-term) 2080 (long-term)	Zanuttigh *et al.*, 2014
	DSS DESYCO	Assessment of vulnerability to natural hazards and climate change	Climatic, biophysical, socio-economic, geomorphological, hydrological	L / Veneto, Friuli-Venezia Giulia, Marche, Apulia (IT)	2070-2100	Torresan *et al.*, 2016b
Remote sensing-based techniques	**Shoreline Identification Techniques**	Assessment and integration of conventional, RTK-GPS and image-derived beach survey methods for daily to decadal coastal monitoring	Real-time kinematic (RTK)-GPS surveys	L/Australia	2005-2008	Harley et al., 2010
		Assessment of beach and dune erosion and accretion using LiDAR: Impact of the stormy 2013–14 winter and longer-term trends on the Sefton Coast, UK	LiDAR	L/ Sefton Coast, UK	2013-2014	Pye and Blott, 2016
		Monitoring beach morphology changes using small-format aerial photography and digital softcopy photogrammetry	Aerial Photography	-	-	Hapke and Richmond,2000
		Science, technology and the future of small autonomous drones	RPAS, unmanned aerial vehicles, UAVs, or drones	-	-	Floreano and Wood, 2015
		Automatic Measurement of Shoreline Change on Djerba Island of Tunisia	Satellite Images	L/Tunisia	1984-2009	Bouchahma and Yan, 2012
	Shoreline Extraction Techniques	Automatic Measurement of Shoreline Change on Djerba Island of Tunisia	NDWI	L/Tunisia	1984-2009	Bouchahma and Yan, 2012
		Semi-automated construction of the Louisiana coastline digital land/water boundary using Landsat Thematic Mapper satellite imagery	Single Band	L/USA	-	Braud and Feng, 1998
		Automatic Coastline Extraction Using Edge Detection and Optimization Procedures	Edge Detection	L/Greece	1929-2000,	Paravolidakis et.al, 2018
	Evaluation of Shoreline Change Analysis	The Digital Shoreline Analysis System (DSAS) version 4.0- an ArcGIS extension for calculating shoreline change	DSAS	US Geological Survey	-	Thieler et.al, 2009

Tools	Name of tool	Objective	Type of data	Scale / study area	Timeframe scenarios	Reference
Bayesian Networks (BN)	**BN**	Assessment of long-term shoreline change due to SLR	Geophysic and hydrologic	N / US Atlantic coast	50/100 years	Gutierrez *et al.*, 2011
	BN	Predicting decadal-scale Chinese coastal erosion due to SLR	Geophysic and hydrologic	N / Chinese coast	'What-if' scenario	Zhan *et al.*, 2014
	BN	Predicting coastal vulnerability to SLR and assessing the interactions between barrier and geomorphic variables	Hydrodynamic, geomorphological	R / Praia de Faro, Portugal	RP: 50 years	Poelhekke *et al.*, 2016
	BN	Assessing coastal vulnerability to storm surge events causing erosion	Geophysical, hydrological, socio-economic, environmental, anthropic influence	R / North Norfolk coast, UK	'What-if' scenario	Jäger *et al.*, 2017
	BN	Evaluate erosion risks and the effect induced by beach nourishment measures	Physical, morphological, ecological, environmental, socio-economic	R / Ria Formosa, Portugal	'What-if' scenario	Plomaritis *et al.*, 2017
	BN	Compare alternatives measures to reduce coastal risk in current and projected future scenarios	Hydro-morphodynamics	R / Tordera Delta, Spain and Lido degli Estensi-Spina, Italy	2100 for the Tordera Delta case study - 2050 for Lido degli Estensi case study	Sanuy *et al.*, 2018
	BERM-N	Quantify the issue of coastal erosion and assess the effectiveness of different nourishment measures in counteracting coastal erosion	Geomorphological	N / Holland coast	5/10 years	Giardino *et al.*, 2019

In the following paragraphs, tools presented in the Table 1 are deeply analyzed providing more details about their technical features and some examples of their application across real coastal case studies. In particular, Paragraph 3.1 reports the review of indicators and index-based methods; Paragraph 3.2 is devoted to the description of models and DSS; Paragraph 3.3 focuses on remote-sensing-based techniques used for the detection of the shoreline evolution; and, finally, Paragraph 3.4 describes BN approaches, also providing some practical examples of their application across different coastal case studies.

3.1 Indicator and index-based methodologies

Different methodologies and tools for risk and vulnerability appraisal have been developed so far by the research community, with the main aim of identifying mostly affected coastal areas due to climate change. Among these, the most commonly applied is the Coastal Vulnerability Index (CVI), an easy to use index-based approach structured to support the integration and combination of multiple physical, morphological and socio-economic variables. The original CVI approach was introduced by Gornitz et al. (1991, 1994), integrating in a single index formulation a range of variables accounting for geological and physical processes, such as resistance to erosion, coastal evolution trends, geological coastal types. The coastal vulnerability is then classified according to the final value of the index, which derives from the mathematical multiplication of the forces contributing to rise vulnerability to climate-related impacts (e.g. erosion and/or inundation) (Equation 1).

$$CVI = \sqrt{\frac{1}{n}(a_1 \times a_2 \times \cdots \times a_n)} \qquad \text{(Equation 1)}$$

where n is the total number of variables a_i considered in the study (e.g. geomorphology, coastal slope, shoreline erosion/accretion rates, relative sea-level change, mean significant wave height, mean tide range, dune, coastal distance, etc..).

The CVI traditional version by Gornitz et al. (1991; 1994) was followed by many other authors which tailored the original framework according to the purposes of their analysis and specific traits of the investigated coastal areas (Abuodha & Woodroffe, 2006; Pendleton et al., 2005; Thieler & Hammar-Klose, 2000). All these studies were mainly focused on coastal geo-physical processes, without investigating other significant phenomena induced by climate forcing and others socio-economic drivers contributing to rise coastal vulnerability. Looking at the Italian Apulia Region shoreline, we also recognize a CVI application to a stretch of the coast between the marinas of Torre Canne and Villa Nova, developed by Pantusa et al. (2018) at the local scale (Figure 3). The study was aimed at

Figure 3: CVI application in the marinas of Torre Canne and Villa Nova (Pantusa et al., 2018)

detecting the most vulnerable shoreline segments to SLR, SS and wave action, in order to provide support for future coastal zone planning and management.

Moving beyond these approaches, Ozyurt (2007) proposed an improvement of the traditional CVI, integrating in its application the evaluation of potential impacts induced by potential Sea Level Rise (SLR) scenarios. Specifically, the index consists of five sub-indices corresponding to a specific impact induced by rising sea level (i.e. coastal erosion, flooding due to storm surge, inundation, salt water intrusion to groundwater resources, salt water intrusion to rivers/estuaries).

Moreover, as the use of socio-economic indicators to measure community vulnerability to natural hazards was becoming more and more common, new CVI-approaches were developed, integrating indicators standing for the socio-economic and politico-administrative dimensions (e.g. Gross Domestic Product – GDP, presence of infrastructures, institutional organization) and community-based adaptive capacity (e.g. percentage of young and foreign people, family income, access to communication networks). In fact, relationships occurring among different systems (i.e. climate, environmental and socio-economic) may strongly influence coastal vulnerability, contributing to rise the overall vulnerability of the analyzed coastal area (McLaughlin and Cooper, 2010). To this aim, Szlafsztein and Sterr (2007) introduced a Composite Vulnerability Index allowing combining 8 variables reflecting the natural dimension of vulnerability (e.g. coastline length, coastal protection measures, fluvial drainage) with 7 other indicators used to depict and evaluate the socio-economic dimension. Specifically, among the socio-economic variables, indicators representing the population potentially affected by flooding, or living in vulnerable areas, as well as information about poverty conditions and municipal wealth were considered. The following year, Preston et al (2008) introduced in his CVI application a set of indicators supporting the spatial modelling of population adaptive capacity to future climate scenarios under the 2030 timeframe (e.g. percentage of young and foreign people, family income, access to communication networks). Few years later, McLaughlin et al. (2010) proposed an advanced CVI methodology integrating three different sub-indices: a i) coastal forcing sub-index characterizing the forcing variables contributing to wave-induced erosion; ii) a coastal characteristics sub-index dealing with the resilience and phisycal and environmental susceptibility of the coast to erosion processes; and a iii) socio-economic sub-index evaluating vulnerability of anthropogenic infrastructures potentially at risk (e.g. settlements, roads, railways) (Figure 4). The peculiarity of this study stands in the multi-scale nature of the approach (i.e. national, regional and local scales), used to provide diversified spatial analysis of the degree of coastal vulnerability, as well as to highlight the implication of scale in the selection of indicators and the degree of simplification in mapping and analytical processes. Indeed, while indicators about coastal characteristics and coastal forcing can be used at broader spatial scale to evaluate the vulnerability of a certain region to morphological changes, indicators concerning socio-economic features require smaller scales of analysis, since societies are strongly connected with their surrounding environments.

Figure 4: General CVI approach proposed by McLaughlin et al. (2010)

Moreover, while at national scale the resolution of the analysis may be coarser, a higher resolution is usually required for local scale analysis, demanding for a more careful data collection and processing for all indicators. In 2012, Balica et al. (2012) enhanced the links of the theoretical concept of flood vulnerability with decision-making process, including in the design of their CVI approach a politico-administrative component (i.e. institutional organization, uncontrolled planning zones and infrastructures for flood protection) alongside the hydro-geological and socio-economic ones. In fact, it is worth noting how the inclusion of politico-administrative and resilience indicators can be used to assess the effects of possible adaptation options, allowing for addressing resources towards the implementation of most promising strategies.

Recent studies further advanced these methodologies introducing, alongside with information on morphology and socio-economic features of the investigated area, the evaluation of potential climate change scenarios. Specifically, in 2016, Greco and Martino (2016) integrated in their CVI approach the study of time-dependent vulnerability, including in the assessment, together with information on morphology and socio-economic features, three sea storm scenarios according to different return periods (i.e. 1 year, 30 years and 500 years). The methodology demonstrated how vulnerability is not static in time but evolves according to changing patterns in the climate system, thus calling for a broader use of future projections for its evaluation. In the same year, Satta et al.

(2017, 2016) expanded the traditional CVI methodology, proposing a Multi-Scale Coastal Risk Index for Local Scale evaluation (CRI-LS) integrating a multi-hazard perspective in the evaluation process. Indeed, impacts arising from SLR, storms, precipitations and drought scenarios were combined in the analysis as meteo-climatic hazards, flanked by socio economic indicators linked with population growth and touristic flows (Satta *et al.*, 2017). The introduction of climate change scenarios in the CVI application can be observed as well in the methodology proposed by Torresan et al. (2017), where a CVI integrating physical, geological and socio-economic indicators was developed taking also into account expected SLR and SS flooding projections for the 2100 timeframe (i.e. Climate-improved CVI).

As previously emerged, the evaluation of social vulnerability is crucial for understanding how a society is able to anticipate, cope with and recover from impacts induced by natural and climate-related hazards. In this setting, as the use of social indicators to measure community vulnerability to natural hazards was becoming more and more common, King & MacGregor (2000) noted that there was the need of isolating appropriate characteristics or variables as community vulnerability indicators, according to some rules. Consequently, they observed that models or constructs were necessary to develop social indicators, which had to be chosen as tools to serve the model. The authors also observed that information on preparedness and awareness was probably going to be excluded from those models, as surveys required to ascertain people attitudes and behavior were difficult to be carried out. So far, few authors specifically investigated, from a socio-economic perspective, the vulnerability of communities themselves to climate, environmental and anthropogenic related hazards. Among these, in 2003, Cutter et al. developed a Coastal Social Vulnerability Index (CSoVI) to assess social vulnerability of United States counties to environmental hazards, using socio-economic and demographic data for the 1990 timeframe, methodology replied also in the Chinese context afterwards (Chen et al., 2013). Both studies considered a wide range of socio-related variables, ranging from age, gender, ethnicity and socio-economic status, to occupation, education, infrastructural network and medical services. A selection of most suitable indicators was consequently extracted according to data availability and characteristics of the investigated area. Starting from the study of Cutter et al. (2003), Boruff et al. (2005) developed a hybrid approach integrating a socio vulnerability index (SoVI), including socio-economic variables, into a CVI, to analyze coastal social vulnerability. As an improvement of the aforementioned indices, Lee (2014) performed an overlay analysis of social vulnerability and patterns of risks associated to national disasters in Chiayi, Taiwan. With the proposed approach, the authors were able to capture the social vulnerability of the analyzed cities, thus transferring to government agencies and local authorities with a valuable knowledge base to address sustainable and strategic environmental planning.

Finally, as vulnerability is strictly connected to resilience, Fekete (2018) observed that only few indicator sets and maps considered in previous methodologies are helpful to directly measure communities resilience, demanding for a specific and independent set of indicators able to capture this aspect of vulnerability in societies. In this setting, within the Italian scene, Menoni et al. (2012) designed a vulnerability and resilience assessment tool supporting the understanding of strengths and fragilities of a territory and its community in facing natural hazards. The framework tool was applied to the city of Sondrio (Italy), highlighting, during the assessment process, sectors for which data were missing, and suggesting suitable policies and actions for disaster risk management and prevention. With the same perspective, always in Italy, Frigerio and De Amicis (Frigerio et al., 2018, 2016; Frigerio & De Amicis, 2016) recently focused on deepening the analysis of social vulnerability to natural hazards. In particular, Frigerio & De Amicis (2016) applied a method to evaluate and spatially model social vulnerability at the national scale, based on socioeconomic and demographic factors driving Italian population pattern. They also integrated social vulnerability into the seismic risk analysis, always focusing on the Italian case (Frigerio et al., 2016). More recently, Frigerio et al. (2018) also examined the spatiotemporal patterns of social vulnerability in Italy, evaluating socioeconomic factors mainly influencing coping capacity of the Italian population to catastrophic natural events (e.g. flood, landslides, wildfires). To this aim he defined a set 16 indicators bringing together, among others, information about education, family structures and employment rate, based on the census data for the years 1991, 2001 and 2011.

3.2 Decision Support Systems (DSS)

Several DSS have been developed in recent years to encourage climate adaptation planning in coastal areas, especially at national to global scale (Torresan *et al.*, 2016a). Computer based information systems showed, in fact, a great potential to support climate change impact and adaptation assessment in coastal zones, by integrating simulation models operating at different scales (climate, ecological and economic models), and by applying increasingly sophisticated methodological approaches and interfaces (Ramieri et al., 2011).
A DSS is a software aimed at assisting planners and policy makers across different phases of the decision-making process, supporting, rather than replacing, their judgment and, at length, improving effectiveness over efficiency (Janssen, 1992). Specifically, a DSS may help to (i) integrate heterogeneous information (e.g. spatial vector and raster data, model outputs); (ii) answer to different management questions (e.g. what is the risk level? What are the mostly affected targets?); (iii) choose among alternative management measures (e.g. prevention, adaptation).
In the environmental resource management sector, DSS are generally classified into two main categories:

- Spatial Decision Support Systems (SDSS): tools specifically designed to provide users with a decision-making environment allowing the analysis of geographical information to be carried out in a flexible manner (Densham, 1991).
- Environmental Decision Supports Systems (EDSS): tools integrating Geographical Information System (GIS), several environmental models (including climate change and impact models), databases and other assessment tools (Fabbri, 1998; Uran and Janssen, 2003; Poch *et al.*, 2004).

DSS addressing climate change are the result of the combination of SDSS and EDSS, and are specifically designed to support decision makers in the sustainable management of natural resources and in the definition of possible adaptation and mitigation measures (Torresan et al., 2010). A key role in these systems is represented by Geographic Information Systems (GIS) allowing to capture, manipulate, process, analyze and display spatial data (Nobre et al., 2010). Focusing on DSS main structure, the following key components can be recognized across conventional DSS:

- Database management system, which allows the organization of basic spatial and thematic data and facilitates their efficient processing.
- Model management system, including several quantitative and qualitative models supporting data analysis.
- Powerful, but simple and user-friendly, interface design, allowing communication with the system and visualization of outcomes.

All reviewed DSSs consider GIS tools as basic media to express their spatially-resolved outcomes in a fast and intuitive, way facilitating communication and understanding also to non-experts (i.e. decision makers and stakeholders).

As reported in the *Table 1*, in the frame of the Task 3.5, a set of 13 DSS for coastal erosion risk mapping and management have been selected by the TRITON partners, as representative of valuable tools for ICZM support in the area of concern. Among these, a first prototype version of an information system for the evaluation of feasible coastal management options, considering anthropogenic and climate forcing, is the so-called **COSMO** (Rijsberman & van Velzen, 1996). It allows integrating environmental, socio-economic and climate data by applying a 4-stage procedure including: i) problem characterization (e.g. coastal erosion, water quality variation); ii) impact evaluation under different development and protection plans; iii) indicators production; iv) GIS-based spatial analysis.

This first release is followed by the DSS ***SimLucia*** (*Simulator model for St Lucia; Figure 5*), developed by the Research Institute of Knowledge System (RIKS), to assess the vulnerability of coastal low-lying areas to SLR, coastal erosion and SS flooding due to climate change. The tools was intended to be applied at the local scale within the St. Lucia case study, taking into account a gradual temperature rise of 2°C and related SLR of 0.8 foot (0.25 m) in a 40 years' time frame scenario (White et al., 1997).

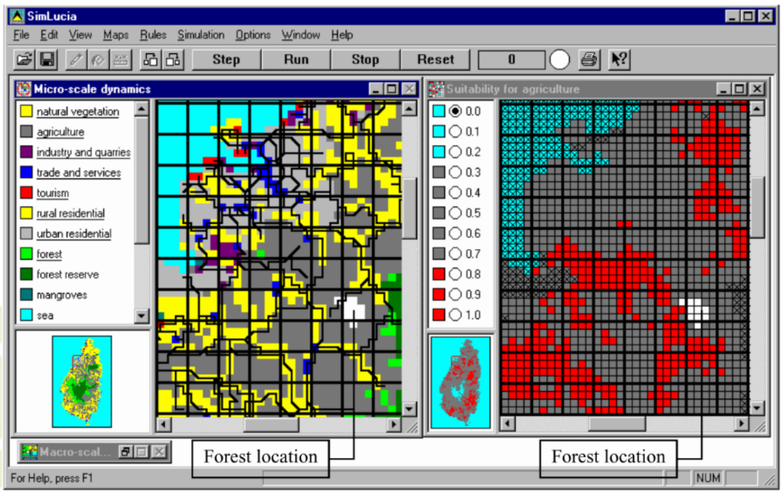

Figure 5: SimLucia application interface (White et al., 1997)

Then, the DSS **RaMCo** (*Rapid Assessment Module for Coastal zone management)* was developed for the rapid and integrated assessment of sustainable solutions for coastal zone management issues at the regional scale. The prototype version of this DSS was developed by de Kok et al. (2001) to explore differences between the current and the desired environmental state for the coastal zone in the Southwest Sulawesi (Indonesia), also in consideration of potential management strategies to be applied.

Another DSS developed by the Research Institute of Knowledge System (RIKS) is the ***WADBOS DSS***, supporting the design and analysis of policy measures in order to achieve an integrated and sustainable local scale management of the Wadden Sea (The Netherlands). It allows integrating socio-economic, hydrological, environmental and ecological data to inform three different sub-models (i.e. socio-economic, ecological and landscape), running for three different possible time steps (a tidal cycle, one month, one year) and a 10-years scenario (Engelen et al., 2005).

The Community Vulnerability Assessment Tool (***CVAT***), was developed with the aim of assessing hazards, vulnerability and risks related to climate change and provide support to hazard mitigation options. With environmental and socio-economic data, as well as observations as input data to characterize the baseline scenario, the tool is able to address multiple climate-related impacts (e.g. SS flooding, coastal erosion, cyclones, typhoons and other extreme events). The tools was applied by Flax et al. (2002) across three different local-scale case study areas located in the United States, evaluating i) community vulnerability and related community-based hazard mitigation strategies to face hurricane hazards in the New Hanover County (North Carolina); ii) the vulnerability of critical facilities, economic sectors, society, and the environment to coastal hazards(e.g. hurricanes, coastal flooding, coastal erosion and tsunami) in the Maui County (Hawaii). The application of the tool in this case, allowed validating the ease of adapting the methodology to other geographic locations and hazard types; iii) risks and vulnerabilities against multiple hazards (i.e. extreme wind events, floods, earthquakes, tornadoes, snow/ice, temperature extremes and environmental hazards) at a state-wide scale, and then the corresponding level of risk in various regions throughout the state.

In order to determine how coastal systems react to climate change impacts, such as SLR, extreme events and coastal erosion, and to develop modern coastal management strategies, the ***KRIM DSS*** was developed as part of the German project KRIM. Kraft (2003) proposed an application of this tool at the scale of the Weser-Jade-Region (Bremen, Germany), with the main aim of providing orientation and action-taking know-how for coastal risk management and protection under climate change conditions. Therefore, the consequences of an accelerated SLR and intensified extreme events, using a 2050 climate scenario, were analyzed together with adaptation options for the natural and the social structures located within the coastal region.

In 2009, another Decision Support System was developed in the frame of the ***DITTY*** EU funded project for the management of Southern European lagoons. The tool builds on a DPSIR-based causal framework allowing to describe the complex interactions between coastal system, society and ecosystems. Moreover, by integrating a GIS database, it allows users to graphically define the area of concern, and to assess the effects of different special allocations under a two- and three-year timeframe scenarios.

Building on the modular and iterative approach for data integration developed in the frame of the DINAS-COAST project (Dynamic and Interactive Assessment of National, Regional and Global Vulnerability of Coastal Zones to Sea-Level Rise), the DSS ***DIVA*** (Dynamic and Interactive Vulnerability Assessment; Figure 6) represents a dynamic, interactive and flexible software tool enabling end-users to produce quantitative information on a range of coastal vulnerability indicators, against user-selected climate and socio-economic scenarios and adaptation strategies, on national, regional and global scales. In the same year Warrick (2009) proposed the ***SimCLIM*** (namely *Simulator model System for Climate Change Impacts and Adaptation*) model, aimed at exploring current and potential risks related to climate change and natural hazards (e.g. SLR, coastal erosion, coastal flooding), with a specific focus on the coastal areas of the South-East Queensland and Brisbane (Australia). The core features of the open-framework

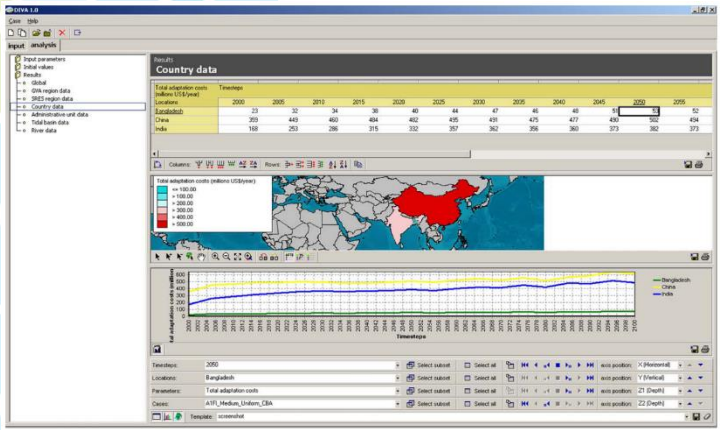

Figure 6: Graphical user interface of the DIVA tool

software modelling system are the scenario periods for extreme events (i.e. heavy daily rainfall events), assessed under both current climate (1961-1990) and future scenarios (drier conditions by 2050). Hence, the model, by considering 30 years of daily rainfall data, produces spatially interpolated risk maps, highlighting risk level according to four categories (i.e. *low or no risk*, *moderate risk*, *high risk*, *extreme high risk*).

Building on a set of coastal models, Mokrech *et al.* (2009) developed the ***Tyndall Coastal Simulator***, supporting the assessment of long-term potential coastal impacts and responses. The simulator is based on a set of linked climate models (CM), included in a nested framework recognizing three spatial scales: (i) the global (GCM) scale; (ii) the regional scale and (iii) the Simulator Domain (a physiographic unit, such as a coastal sub-cell). These models feed into each other and describe a wide array of natural processes and variables linked with coastal dynamics, including: sea level, tides, surges, waves, sediment transport and coastal morphology. Different climate scenarios, as well as the range of uncertainty, can be analyzed through this DSS. Moreover, it allows users to explore the model’s outputs, providing a GIS-based environment to visualize and query geospatial data resulting from the assessment. The DSS was applied along the Norfolk shoreline, where cliffs are easily and well-known to be eroded at an average rate of up to 1 m/yr.

One of the most recent open-source DSS is the ***THESEUS*** *DSS (Figure 7)*, developed in the frame of the THESEUS project by Zanuttigh et al. (2014). It was designed to assess risks across a range of spatial and temporal scales in order to minimize coastal risks and address the design of tailored management measures. The tool can be applied at intermediate spatial scales (10-100 km) and for short (2020), medium (2050) and long-term (2080) scenarios, considering both physical and non-physical drivers, such as climate change, subsidence, population and economic growth. Moreover, it allows integrating in the assessment procedure different mitigation options, such as socio-economic mitigations (i.e. change of land use), ecological solutions (i.e. sea-grasses) and the presence of coastal defenses (i.e. barriers). The DSS tool was tested in the case study area of Cesenatico (Italy), where specific impact functions were developed in order to link economic, social and ecological data to hydraulic

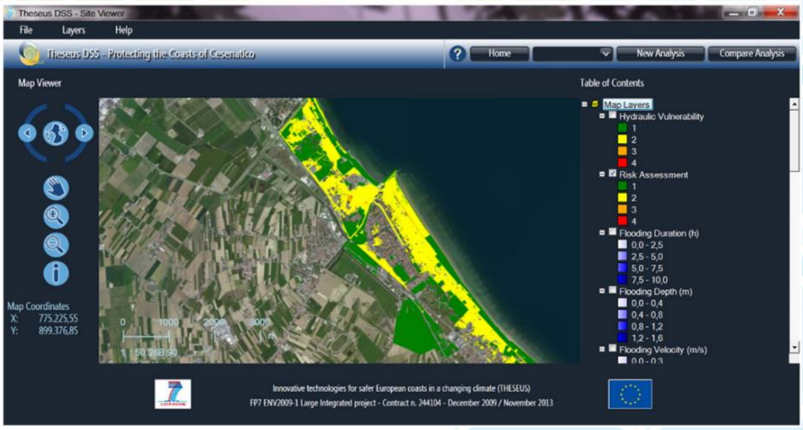

Figure 7: THESEUS integrated risk map (Zanuttigh et al., 2014)

parameters (e.g. beach retreat, flood depth, flood duration, flood velocity) with the main aim of getting spatial maps of social, economic and ecological consequences due to climate change.

Finally, the DSS **DESYCO** is a GIS based decision support system specifically designed to better understand the risks that climate change poses at the regional/subnational scale (e.g. the effect of sea level rise and coastal erosion on human assets and ecosystems) and set the context of strategic adaptation planning within ICZM. It implements a Regional Risk Assessment (RRA) (Landis, 2005; Figure 8) methodology allowing the spatial assessment of multiple climate change impacts in coastal areas and the ranking of key elements at risk (beaches, wetlands, protected areas, urban and agricultural areas). The core of the system is a Multi-Criteria Decision Analysis (MCDA) model used to operationalize the steps of the RRA (hazard, exposure, susceptibility, risk and damage assessment) by integrating a blend of information from climate scenarios (global/ regional climate projections and hydrodynamic/hydrological simulations) and from non-climate vulnerability factors (physical, environmental and socio-economic features of the analyzed system). User-friendly interfaces simplify the interaction with the system, providing guidance for risk mapping, results communication and understanding. DESYCO was widely applied to low-lying coastal plains and islands (i.e. the North Adriatic Sea, the Gulf of Gabes and the Republic of Mauritius), river basins and groundwater systems (i.e. Upper Plain of Veneto and Friuli-Venezia Giulia, Marche Region), and marine areas (North Adriatic Sea).

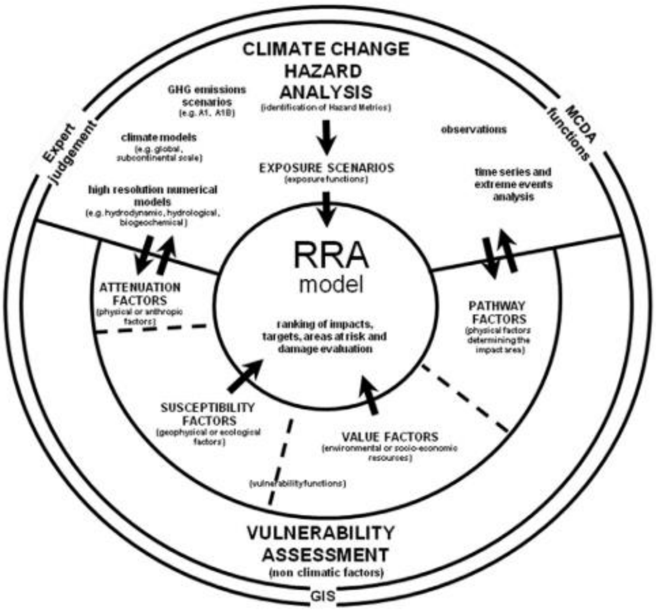

Figure 8: Regional Risk Assessment (RRA) conceptual framework (Torresan et al., 2016b)

3.3 Remote sensing-based techniques for shoreline identification, extraction and analysis

There are several approaches capable to detect the shoreline position and assess the relative shoreline change over a certain time period. These methodologies usually follow a step-wise procedure including the: i) selection of the most effective beach monitoring technique; ii) shoreline digitalization, and c) statistical analysis of shoreline change through the studied years. Various types of data can be considered for monitoring the shoreline change, either using direct (i.e., GPS, Topographic lasers) or indirect (i.e., aerial photography, airborne LiDAR, satellite image analysis) techniques. Using in-situ observation techniques, such as the GPS surveys (Morton et al., 1993; Harley et al., 2010) and the terrestrial laser scanners (Saye et al., 2005; Theuerkauf and Rodriguez, 2012; Lee et al., 2013), researchers may accomplish highly accurate measurements of shoreline position. Such methods are time-consuming to map broader areas, and are inherently limited in temporal coverage, collecting measurements within short time-intervals, thus enabling to report long-term erosion/accretion trends, or widely-spaced in time, or distinguishing seasonal changes (Nadu et. al, 2013). Other techniques, employing remotely sensed data, such as aerial photographs and webcam images (Hapke and Richmond, 2000; Alexander and Holman, 2004; Kroon et al., 2007; Taborda and Silva, 2012; Turki et al., 2013), and airborne LiDAR mapping (Stockdon et al., 2002; Young and Ashford, 2006; Pye and Blott, 2016). Recently, new survey techniques based on remotely piloted aircraft systems (RPAS, also called unmanned aerial vehicles, UAVs, or drones) have begun to be employed in geomorphological and ecological studies (Everaerts, 2008; Colomina and Molina, 2014; Anderson and Gaston, 2013; Floreano and Wood, 2015), and are becoming common survey tools in geosciences. These techniques may cover larger monitoring areas over shorter time intervals. However, their main limitations relate to the relative higher costs and the commonly insufficient availability of images spanning periods of concern. Satellite imagery, on the other hand, has the potential to combine moderate spatial resolution with large spatial coverage and regular and low repeatability in observations. It also provides the advantage of allowing the exploration of shoreline change in remote places with limited coastal observations. Satellite imagery has developed rapidly over the past few decades in terms of spatial resolution, frequency of passage over the same location and overall availability. To date, historical satellite images may cover a time period over 30 years with high spatial resolution. There exist several open-source databases for retrieving satellite images such as: Earth Explorer (https://earthexplorer.usgs.gov/), Copernicus Open Access Hub (https://scihub.copernicus.eu/), and Planet Explorer (https://www.planet.com/explorer/). Furthermore, remote sensing information can be integrated with Geographical Information Systems (GIS), as a helpful tool for analyzing and extracting more reliable and consistent information by using satellite imagery as a base data (Louati et. al., 2015). Over the latest years, remote sensing data from high-resolution satellite sensors (i.e. Landsat, Sentinel, IKONOS) have been widely used across automatic or semi-automatic shoreline extraction and mapping procedures (Figure 9). Specifically, in several studies, techniques such as grey level threshold, level slicing or multi-spectral image classification have been applied using panchromatic bands or a single band or multiple bands combination for Normalized Difference Water Index (NDWI) estimation (Frazier and Page, 2000; Ryu et al., 2002; Braud and Feng, 1998; Kuleli, 2010; Kuleli et al., 2011; Bouchahma and Yan, 2012). For example, Braud and Feng (1998) found that setting a threshold on the Landsat TM Band 5 (Near Infrared) was the most reliable methodology to extract the shoreline. Frazier and Page (2000) quantitatively analyzed the classification accuracy in water body detection and delineation from Landsat TM data in the Wagga Wagga region in Australia.

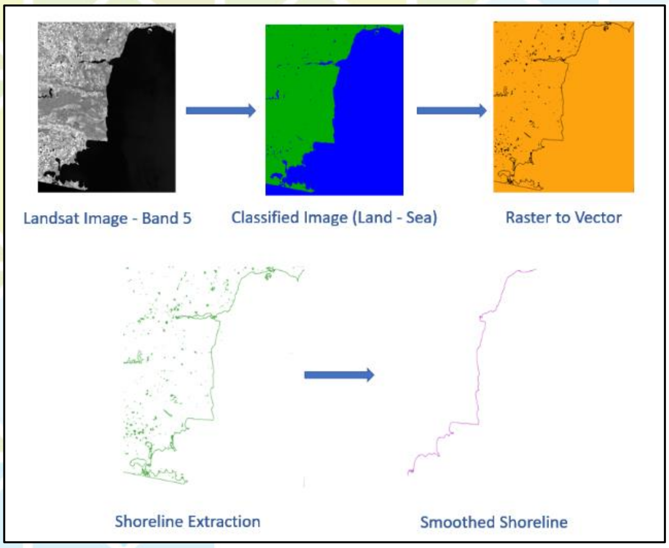

Figure 9: Methodological steps for shoreline extraction from satellite images

In order to evaluate and analyze the shoreline movement in a GIS environment, several techniques can be applied, like the transect-based and the point-based approaches, which allow calculating the short- and long-term shoreline change. The extraction and application of the transect-based approach became easier when combined with GIS-based tools such as the Digital Shoreline Analysis System (DSAS), an open-source extension of the ArcGis Software developed by the United States Geological Survey -USGS- for the multi-temporal analysis of the shoreline evolution (Danforth and Thieler, 1992). Specifically, the DSAS tool is an add-in to Esri ArcGIS desktop enabling potential end-users to calculate rate-of-change statistics from multiple historical shoreline positions. It provides an automated method for establishing measurement locations, performs rate calculations, while providing statistical data required to assess the robustness of the rates. The tool allows developing transects positioned along the investigated shoreline, located in a mutual distance defined by the user according to the possibility to capturing coastal spatial variability across time. Moreover, it supports the development of a set of statistics allowing to summarize the main findings of the analysis. These statistics include: the net shoreline movement (NSM) for reporting the distance between the oldest and the earliest shorelines for each set transect; the End Point Rate (EPR, expressed in m/y) calculated by dividing the distance of the Net Shoreline Movement by the time elapsed between the oldest and the most recent shoreline; the Weighted Linear Regression (WLR, expressed in m/y), in which the weight W is a function of the variance of the measured uncertainty (Genz et al., 2007).

3.4 Bayesian Networks (BN) approaches

Bayesian Networks (also called belief networks or causal probabilistic networks) are probabilistic graphical models, widely used for knowledge representation and reasoning under uncertainty in natural resource management (Pollino and Henderson, 2010).
They rely on Bayes' theorem of probability theory to propagate information between nodes which states that the probability of an event, based on prior knowledge of conditions, might be related to the event, as expressed in the following equation (Bayes, 1763):

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)}$$

where
- $P(A)$ and $P(B)$ are the probabilities of observing A and B without regard to each other;
- $P(A|B)$ is the probability of observing event A given that B is true;
- $P(B|A)$ is the probability of observing event B given that A is true.

BNs represent the system's components (variables) and their relationships (conditional interdependencies) by combining principles of graph and probability theory (Pearl et al., 2011). They are widely used to facilitate the rapid conceptualization of the system to be managed and the evaluation of the dependence or interdependence between data and their inherent uncertainty evaluated as belief probabilities. They allow considering multiple stressors and endpoints in the same framework, thus supporting modelling and analysis of complex coastal environments. Different knowledge domains, expertise and data sources can be integrated in the same BN model, acting as a decision support tool able to inform coastal risk assessment and management.
Being a probabilistic graphical model, BNs include a i) qualitative part, the structure of the network in terms of a Directed Acyclic Graph (DAG), which is composed of nodes representing the set of random variables and arcs between nodes indicating directed probabilistic dependencies between the corresponding variables; ii) a quantitative part, the parameters of the network encoding the conditional and marginal probabilities of the system's variables. Specifically, the marginal probability of a subset of a collection of random variables is the probability distribution of the variables contained in the subset without reference to the values assumed by the other variables. Hence, if a variable has no parents nodes, it is described by a marginal probability distribution (Pollino et al., 2007). On the other hand, the conditional probability gives the probabilities

contingent upon the values of the other variables, thus describing the strength of the causal relationships between all variables connected in the network (Pollino *et al.*, 2007).

The development of a BN requires the implementation of specific operative phases aimed to:

1. Develop the **conceptual model** of the system to be analyzed, by defining the structure of the network and identifying its main variables and relationships represented by using a conceptual/influence 'nodes (variable) and arrow (relationship) diagram;
2. **Parametrize the designed model**, by defining states (also known as bins) for all variables (that can be interval, Boolean, or labelled) and calculating the associated marginal probabilities resulting from data distribution as well relationships between nodes described by the conditional probability distributions;
3. **Evaluate** the performance and prediction accuracy of the BN model through data-based and the qualitative evaluation methods;
4. Perform the **sensitivity analysis**, to evaluate how sensitive are model outcomes to changes in input nodes or other model parameters (e.g. changes in node's type of states);
5. **Define and analyze multiple '*what-if*' scenarios**, by inferring behavior of the variables at stake in the network against different conditions defined by setting specific state/s of a node/s (also known as 'set an evidence') and then propagating information between nodes based on the Bayes theorem (Sperotto *et al.*, 2017). Changes in the simulated scenarios can be analyzed by observing the posterior probabilities of the variable of concern.

Focusing on the application of BNs for coastal erosion risk assessment and management, the first approach was proposed by Gutierrez et al. (2011), to assess long-term shoreline changes associated to SLR at the national scale, in the **Atlantic coast of the United States of America**. As represented in Figure 10, the BN conceptual model designed by Gutierrez et al. (2011) is composed by six nodes, divided into three different categories: i) driving forces (i.e. sea level rise rate, mean wave height and tidal range); ii) boundary conditions (i.e. geometric settings and coastal slope); iii) and response/vulnerability indicator (i.e. long-term shoreline change rate). Each node is sorted in five different states corresponding to increasing risk levels. Results demonstrate that the probability of shoreline retreat increases with higher rates of SLR. Specifically, for scenarios simulating the two

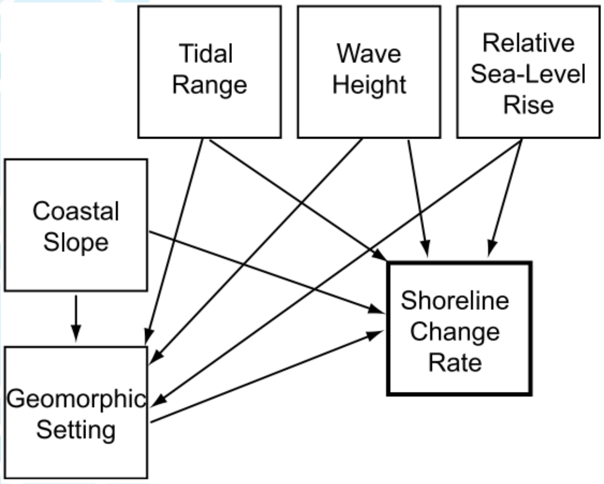

Figure 10: Structure of the Bayesian Network (Gutierrez et al., 2011)

highest relative SLR states in the range of 2.95 - 3.15 m and 3.16 - 4.1 m (set evidence of 100% in these two states, there is nearly 100% probability of resulting in shoreline erosion, while for the other simulated scenario where the rate of sea level rise is maintained low (between 0 and 2.5 m), the probability distribution of all the 4 states associated to the shoreline change variable never exceed the 40%. A key added value of this study is the spatialization of the resulting output from the scenario analysis, building on the historical data used in the hind cast evaluation. The mapping outcomes of this study allow end- users to visualize the probability of shoreline change at each location (from moderate to severe erosion rate) identifying specific location where the BN needs to include more or better information to represent the erosion process. Building on this study, Zhan et al. (2014) developed a similar BN approach defining the relationships between the same six variables (i.e. mean wave height, mean tidal range, relative SLR, coastal slope, coastal geomorphology and shoreline erosion rate) to predict the shoreline evolution in the ***Republic of China*** under different SLR rate. As for the previous study, the authors provided spatially-resolved output from the scenario analysis, showing the the probability of erosion of the Chinese coasts rises as the rate of relative SL increases.

In order to predict coastal vulnerability to SLR, more recently, Poelhekke et al. (2016) designed and applied a BN to the ***Praia de Faro (Portugal)*** case study area. The BN reference model (Figure 11) was selected between three different model's configurations defined by modifying the number of variables concerning the boundary conditions considered in the network (i.e. water level during the peak, max significant wave height, peak period and storm duration), or the number of states classifying the variables themselves (e.g. Configuration 1 was defined by selecting four variables describing the boundary conditions i.e. water level during the peak, max significant wave height, peak period and storm duration, and by classifying their values into in 4 states. Compared to the previous studies, the BN model proposed by Poelhekke et al. (2016) was also validated by analyzing the log-likelihood ratio (LLR) across all the three models' configurations, allowing to determine the prediction accuracy of

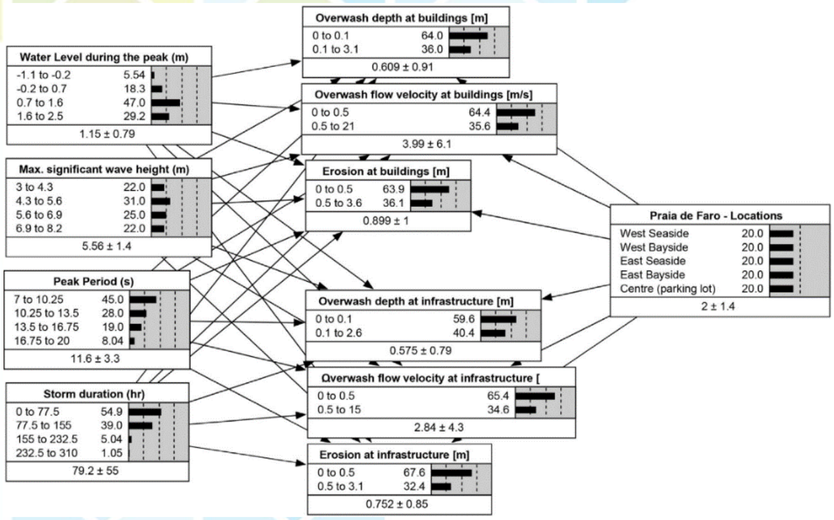

Figure 11: BN Reference scenario for the Praia de fro (Portugal) case study

the BN model. As result of this validation process, the more complex Configuration 2 showed a better performance and was selected as reference BN model for the scenario analysis. This model connect three main groups of variables related to: i) the hydraulic boundary conditions; ii) the characteristics of the coastal zone and; iii) onshore hazards. The key added value of the method proposed by Poelhekke et al. (2016) is that it allows spatializing the investigated case study, integrating in the BN model a node specifically devoted to the 4 zones dividing the overall case study (i.e. West and East Seaside, West and East Bayside, Centre). In this way, by setting the maximum probability on one specific area, the effects of different scenarios on the connected coastal driving forces were observable in the considered area.

Increasing the complexity of the BN applications for coastal erosion risk assessment and management, Jäger et al. (2017), in the frame of the EU FP7 RISC-KIT project, enriched the traditional BN frameworks developed until then, by integrating a set of nodes representing different environmental and human receptors (i.e. residential and commercial properties, people, saltmarshes) associated, in turn, to specific flood-related impacts and damages (e.g. risk to life, commercial damages; Figure 12). Moreover, the case study site of the ***North Norfolk coast*** **(England),** was divided into 6 sub-zones, based on the topographic features and key current flood prevention measures, such as the flood wall and movable flood barrier, located along the investigated coast. The resulting output of the study comprises the analysis of 85 storm surge flooding scenarios representing the range of potential extreme event conditions, including historical storms (8 scenarios), climate change-induced scenarios (18 scenarios) and synthetic events (59 scenarios). As example, climate change scenarios were generated using the DELFT3D-Flow model, modifying the boundary conditions from the historical storm event hindcast mode, including SLR predictions based on the IPCC projections (2013) under the RCP8.5 and for the 2060 timeframe.

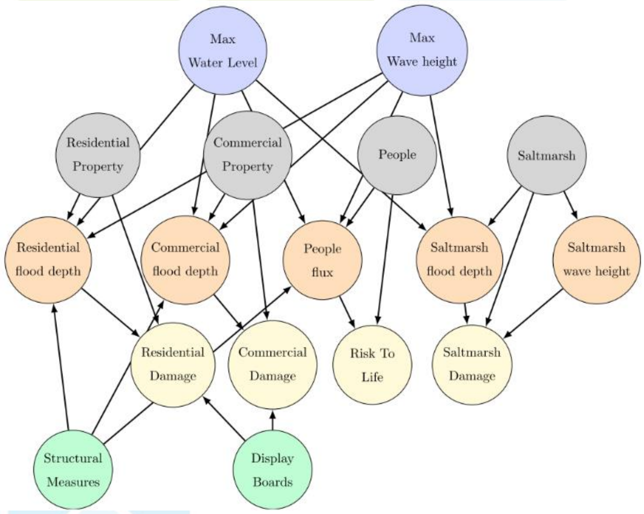

Figure 12: Framework of the Bayesian Network (Jäger et al., 2017)

In the frame of the same EU FP7 RISC-KIT project, Plomaritis et al. (2017) developed a similar BN approach acting as a predictive and working tool able to determine coastal-related impacts on human receptors, and evaluate risk reduction against the implementation of potential management measures. Specifically, the designed BN model focuses on the impact of erosion and overwash to houses and infrastructures, including 4 nodes specifically devoted to management measures (e.g.

beach or dune nourishment, revetments and floodwall). The approach was implemented in the case study of ***Faro Beach (Ria Formosa)***, highlighting, through the scenario analysis, as the implementation of beach nourishment actions would lead to a reduction of houses affected by overwash.

With the main objective of comparing strategic alternatives finalized at reducing erosion and flooding risks under current and future scenarios, Sanuy et al. (2018) designed a flexible BN approach then applied to two different study areas: ***Tordera river delta (Spain)*** (Figure 13) and ***Lido degli Estensi-Spina (Italy)*** (Figure 14). Specifically, the structure of the network is flexible enough to be applied across different coastal settings and tailored according to several boundary conditions, hazards, receptors, impacts/damages, and management measures, depending on the needs driven by research or coastal management objectives. Hence, for very similar, or even for the same case study, the BN model can differ since variables and associated classes/bin may be set in different ways by the end-user for characterizing multiple model configurations. As for the previous studies, both networks developed by Sanuy et al. (2018) was implemented by taking into account management measures (e.g. flood resilience measures, infrastructural defense), contributing to reduce flooding and erosion risks in the investigated areas.

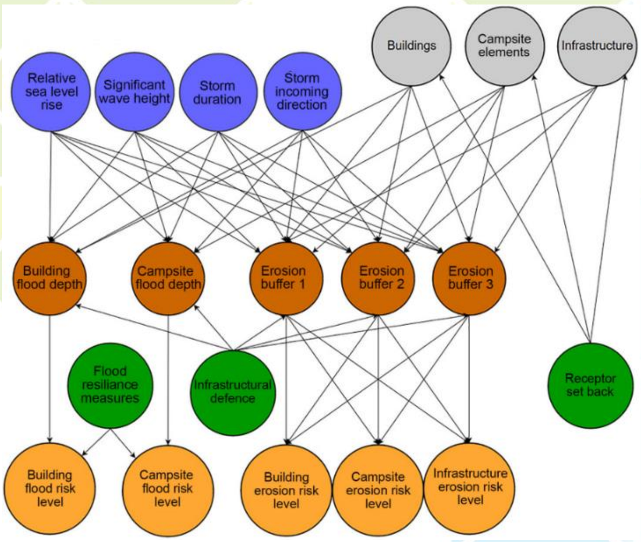

Figure 14: Bayesian network scheme for the Tordera Delta site (Sanuy et al., 2018)

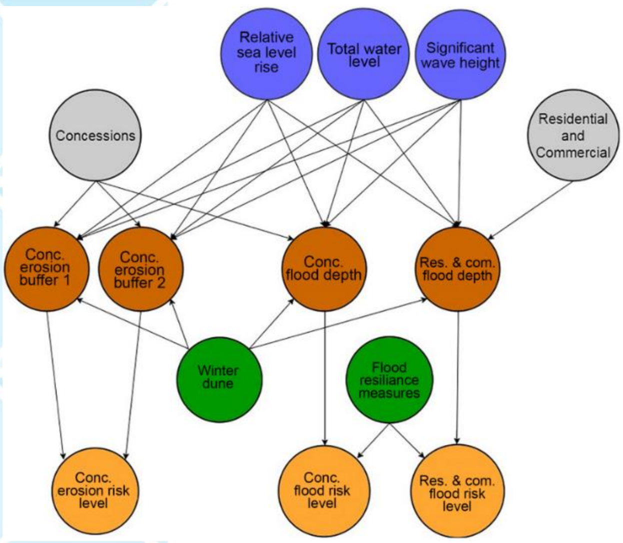

Figure 13: Bayesian network scheme for the Lido degli Estensi–Spina site (Sanuy et al., 2018)

One of the most recent BN application for national-scale coastal erosion risk management is the so-called ***BERM-N*, i.e. Bayesian ERosion Management Network**, developed by Giardino *et al.* (2019). Particularly, main aim of the study was to evaluate the effectiveness of nourishments measures in mitigating coastal erosion processes.

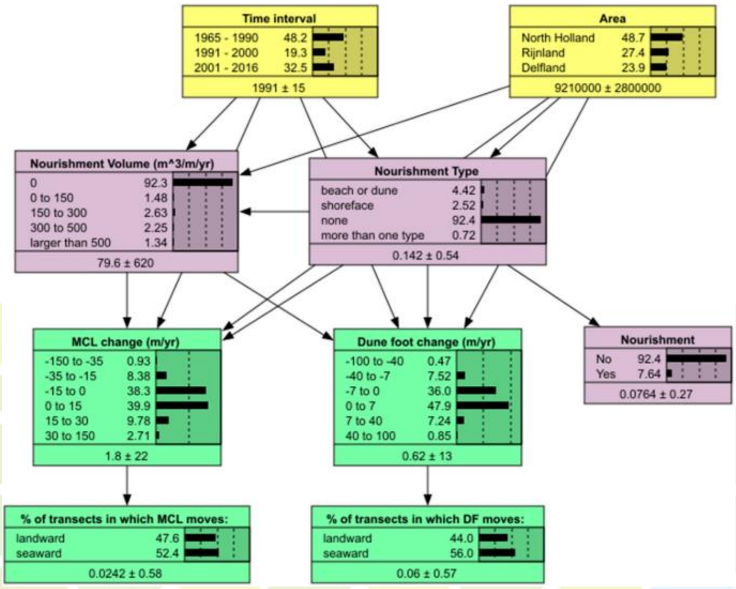

Figure 15: Conceptual model and prior probabilities distribution of the BERM-N (Giardino et al., 2019)

The BN model was organized into three main categories representing the: i) spatial characterization of the study area (e.g. Delftland, North Holland) and the timeframes related to the implementation of beach nourishment measures (e.g. 1965-1990); ii) nourishment types (e.g. beach or dune shoreface) and volumes; effects induced by the implemented measures on the morphological indicators (e.g. dune foot changes) (Figure 15). The BERM-N was trained based on yearly cross-shore profile data available for 604 transects along the **coast of the Netherland**, and representing beach nourishment types (i.e., beach, dune, and shoreface) and volumes implemented during the analyzed time period (1965-2016). The focus of the study by Giardino *et al.* (2019) was on the analysis of the effects of coastal nourishments activities to manage coastal erosion, as major driver of coastal development along the Dutch coast.

4 Conclusions

In the frame of the task 3.5 '*Development of the framework and tool for final users with training*', this deliverable introduces the DPSIR-based conceptual framework highlighting the complex interactions underpinning coastal erosion phenomena, as well as the tools and methods reviewed by the TRITON partners to provide support to policy and decision makers in the implementation of European recommendations and directives for coastal zone risk assessment and management.

Specifically, the report is structured in two main sections: i) the first one briefly describes the developed DPSIR-based conceptual framework defining the relationships between natural and anthropogenic activities, the coastal environment and its ecosystems, and the resulting environmental, physical and socio-economic impacts; ii) the second one focuses on the review of the state of art tools and methods for coastal erosion risk mapping and management, including indicator and index-based methods, Decision Support Systems (DSS), remote sensing-based techniques and Bayesian Belief Networks approaches, revealing a different level of complexity and detail in the data processing and final outcomes.

Specifically, by providing useful information and practical examples of the effectiveness of these tools across different coastal case studies, this deliverable aims at assisting coastal planners and managers in the selection of the most suitable and easy-to-use tool supporting a sound evaluation of coastal erosion risks (e.g. shoreline retreatment, water quality variation) arising from multiple scenarios, including different management and policy setting (e.g. implementation of artificial protection along the coast or nature based solutions to reduce longshore wave power), as well as climate conditions (e.g. sea level rise, increase of coastal flooding events).

These information and tools will be capitalized in the frame of the TRITON pilot cases (i.e. the coast of Ugento, Apulia region (Italy), and the coastal area of Messolongi (Greece)), in order to evaluate, at the local scale, coastal erosion processes and provide the scientific knowledgebase for the development and implementation of more robust and adaptive coastal erosion risk-based management strategies in the project operational area among Greece and Italy.

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