Coastal vulnerability assessment using Fuzzy Logic and Bayesian Belief Network approaches

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INTRODUCTION

Marine drivers such as surge in the context of SLR, are threatening low-lying coastal plains. In order to deal with disturbances a deeper understanding of benefits deriving from **ecosystem services** management and planning (e.g. **the role of dune** in surge mitigation and climate adaptation) can enhance the resilience of coastal systems.

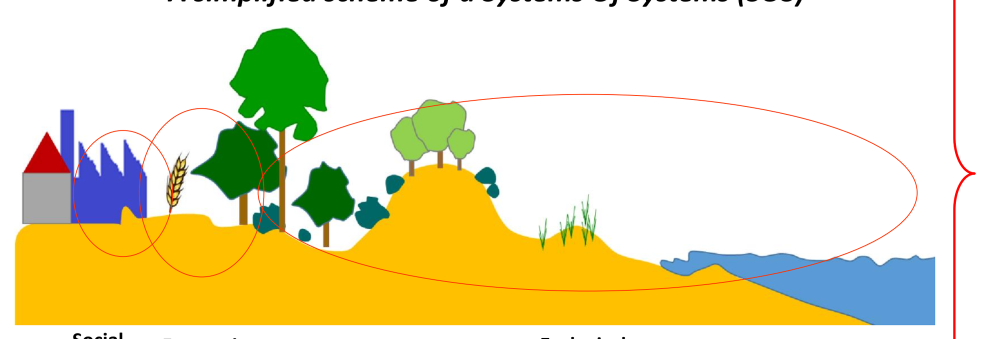
In this frame assessing the vulnerability is a key concern of many **Systems Of Systems SOS (social, ecological, institutional)** that deal with several challenges like the definition of **Essential Variables (EVs).**

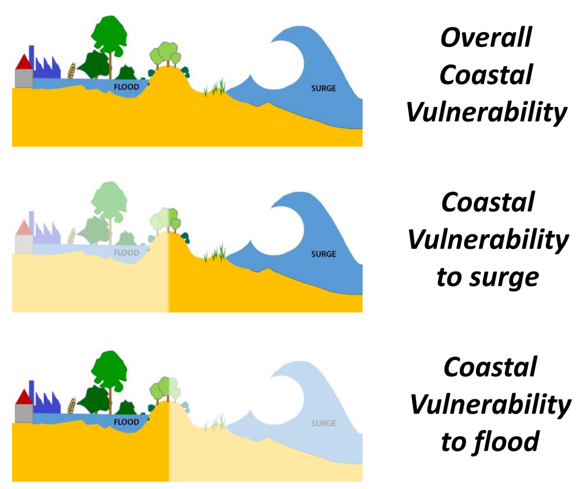
A way to fully exploit ecosystems potential, i.e. their so called **ecopotential** (see H2020 EU funded project "ECOPOTENTIAL"), is the Ecosystem based Adaptation (**EbA**): the use of ecosystem services as part of an adaptation strategy. To provide insight in understanding regulating ecosystem services to surge and to make the best use of EO products, in situ and modeling data), a multi-component surge vulnerability assessment, focusing on coastal sandy dunes as natural barriers is presented. The aim is to combine together eco-geomorphological and socio-economic variables with the hazard component on the base of different approaches:

1) Fuzzy Logic; 2) Bayesian Belief Networks (BBN).

COASTAL VULNERABILITY SYSTEM NETWORK IN AN ECOSYSTEM SERVICES PERSPECTIVE

A simplified scheme of a Systems Of Systems (SOS)





ASSESSING and THUS REDUCING COASTAL VULNERABILITY BY EXPLOITING ECOSYSTEM SERVICES

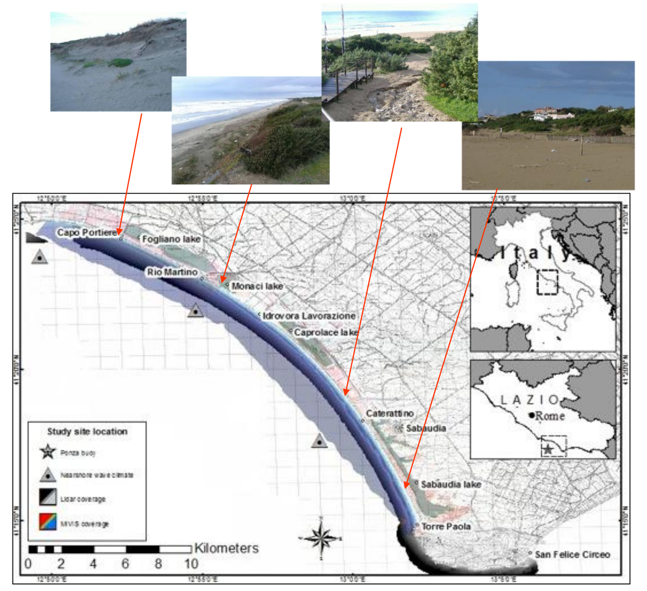
DELIVERED BY DUNES

using 2 approaches

FUZZY BBN

SABAUDIA CASE STUDY: real data and ideal hazard scenarios

A sandy beach characterized by a dune system running parallel to the coastline whose elevation and width increases from north to south reaching the maximum of 28 m and 250m respectively. The dunes are mostly established by specialized coastal vegetation characterized by a linear zonation from the sea to the inward dune slacks that includes seven different community types. Due to the different wind and enlightment exposure, two different sectors can be distinguished: one on the backdune, characterized by the presence of a well-structured tree and shrub vegetation; and one on the foredune facing the sea, characterized by a vegetation mostly xerophytic bush and halophyte, that can stabilize the sands and reduce aeolian transport through specialized root systems, thereby triggering positive feedback mechanisms between the biological and sedimentological components, which give dynamic stability and resilience to the system exposed to natural and manmade disturbances (i.e. sea surge). In the 50's the dynamics of the system, in the direction orthogonal to the shoreline, was blocked by the construction of the coastal road that runs longitudinal to the system at the altitude of the dune crest.



Sabaudia coast area of interest

ECOSYSTEM BASED ADAPTATION APPROACH (EbA): EXPLOITING COASTAL PROTECTION ECOSYSTEM SERVICES

It is widely recognized that healthy ecosystems contribute to human wellbeing and the conservation and increase of their resilience play a key role in reducing climate related risk and vulnerability (Ojea, 2014). The EbA is the use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people adapt to the adverse effects of climate change and natural variability in order to moderate harm or exploit beneficial opportunities. The EbA approach is thus aimed at preserving selected ecosystem services, protecting and enhancing ecosystems (e.g. dune as natural barrier or wetland as natural buffer) and their characteristics (e.g. extent, height, vegetation cover of dune ridge; or extent of wetland) by planning decisions and management practices, gaining at the same time further social (e.g. recreational natural environments) and environmental benefits (e.g. maintenance and creation of key coastal habitats) (Colls et al., 2009).

COASTAL VULNERABILITY ASSESSMENT: GAP FILLING FOR EbA

Current tools range from simple spreadsheet models to complex software packages (coastal vulnerability index, Composite Vulnerability Index, Multi-scale coastal vulnerability index, DESYCO, DIVA, DITTY, SimCLIM, invest, etc.)

Need for: a more comprehensive approach to place-societies vulnerability, trying to move away from approaches strictly hazard/physical phenomena based, approaching vulnerability in a spatially based manner, integrating relevant bio-physical data with related socio-economic data from different sources, integrated systems (SoS), replicable at different scales and in several context , data and variables site specific and whose number and type is not defined *a priori*, stressing the role of ecosystems in surge and flood protection (i.e. mapping ecosystem services) by highlighting ecosystems characteristics.

FUZZY LOGIC BASED VULNERABILITY ASSESSMENT

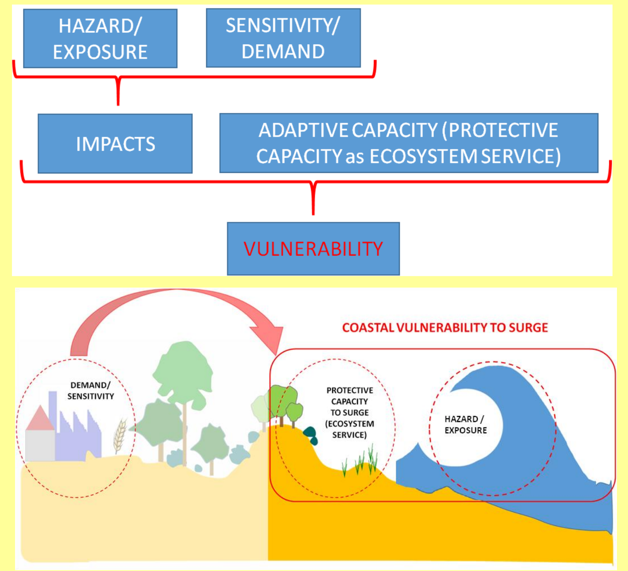
Fuzzy logic applied to complex and imprecise problems enables to handle the non-linearity, which is common in multi-criteria framework, and the vagueness which is common in environmental issues, and has the ability to model complex behaviors as a collection of simple "if–then" rules based on expert knowledge.

Workflow of Fuzzy analysis

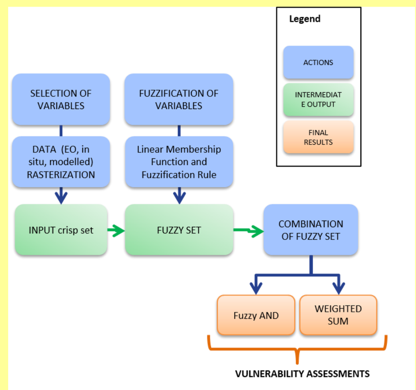
- selection of variables relevant to vulnerability of coastal areas
- fuzzification of variables by choosing a membership function to obtain fuzzy sets;
- combination of selected fuzzy sets using fuzzy operators and raster overlay

In order to avoid to explicitly define inference rules ("if–then") that in the case of many input variables can become a very complex problem we made the implicit assumption that higher membership degree determine higher vulnerability. Therefore fuzzification of each variable was performed adopting the following rule: maximum value (i.e. membership value of 1) corresponds to condition of maximum contribution to vulnerability status and minimum value (i.e. membership value of 0) corresponds to condition of minimum contribution to vulnerability status.

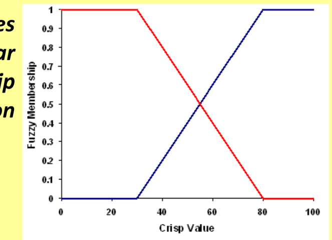
Vulnerability assessment framework adopted (Fussel, 2006; Liquete et al., 2013)



Fuzzy flow chart



Examples of Linear membership function



ESSENTIAL VARIABLES

VARIABLES FOR THE ASSESSMENT			ACQUISITION METHOD or SENSOR, YEAR	DATA or PRODUCT SOURCE	APPROACHES
HAZARD/ EXPOSURE	**Hazard (H)**	Waves (Significant Wave Height)	Buoys and model	Data from 2000 to 2010 ,	FUZZY & BBN
SENSITIVITY/ DEMAND	**Socioeconomic Factors (Fs)**	Population density	Survey	ISTAT, 2011	FUZZY
	Socioeconomic Factors (Fs)	Anthropic (as imperviousness)	EO optical data	ISPRA, 2012	FUZZY
ADAPTIVE CAPACITY (Coastal Protection Ecosystem service)	**Morphology Factors (Fm)**	Elevation	Airborne LiDAR Data, 2009	ISPRA, 2009	FUZZY & BBN
	Morphology Factors (Fm)	Distance (dune-crest coastline)		ISPRA,	FUZZY & BBN
	Coverage Factors (Fc)	Vegetation abundance fractions (trees, shrubs, grass)	Airborne MIVIS data, 2009	ISPRA, 2011	FUZZY & BBN

SWH HAZARD SCENARIOS	DESCRIPTION
Scenario 1	MEDIUM hazard scenario, gradient from north to south, range values: 8.9m-10.1m
Scenario 3	HIGH hazard scenario, gradient from north to south, range values: 17.7m-20.0m
Scenario 2	MEDIUM hazard scenario, fix value from north to south: 9.4m
Scenario 4	HIGH hazard scenario, fix value from north to south: 18.7m

BAYESIAN BELIEVE NETWORK VULNERABILITY ASSESSMENT

A Bayesian Belief network (BBN) is a multivariate statistical model that comprises two structural components:

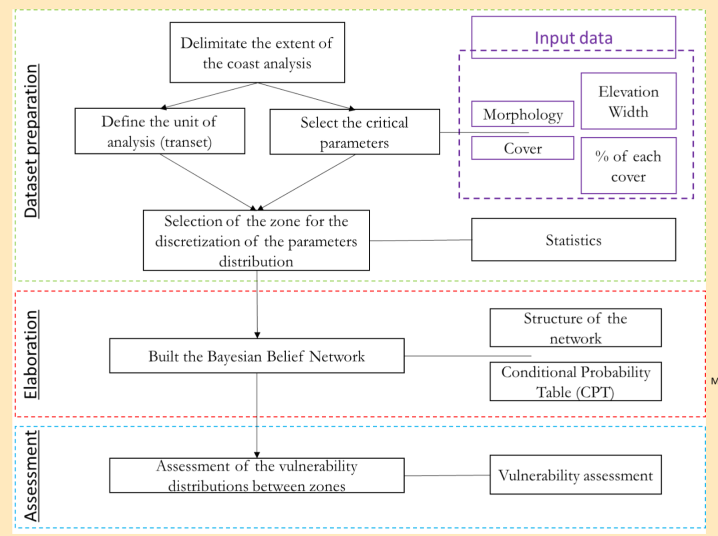
- a causal network, represented as a directed acyclic graph (DAG), and
- conditional probability tables (CPTs) that probabilistically quantify the causal relations in the graph.

In the DAG each vertex represents one of the variables in the model, and a set of arrows, indicating the causal relationships among the system's variables. CPTs express the probability for the states of a child node, given the states of its parent nodes.

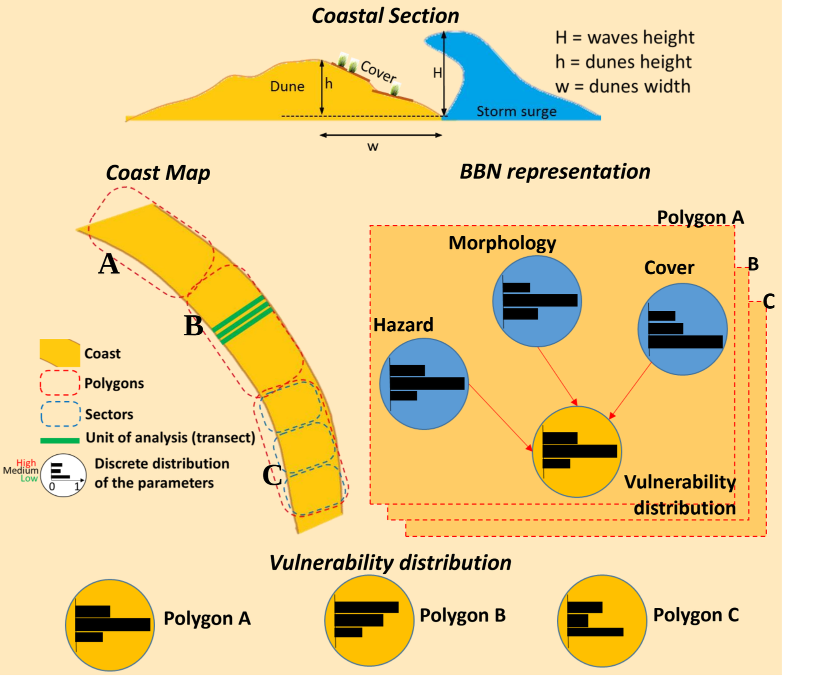
DAG structure and CPT values can be built by specific algorithm in case of data-rich applications. Instead for rare-event applications, like this application, BBNs are typically constructed based on input from expert domain.

BBN use an intuitive graphical representation, provide the possibility of combining diverse sources of information, and the probabilistic framework characterizes uncertainties

BBN flow chart



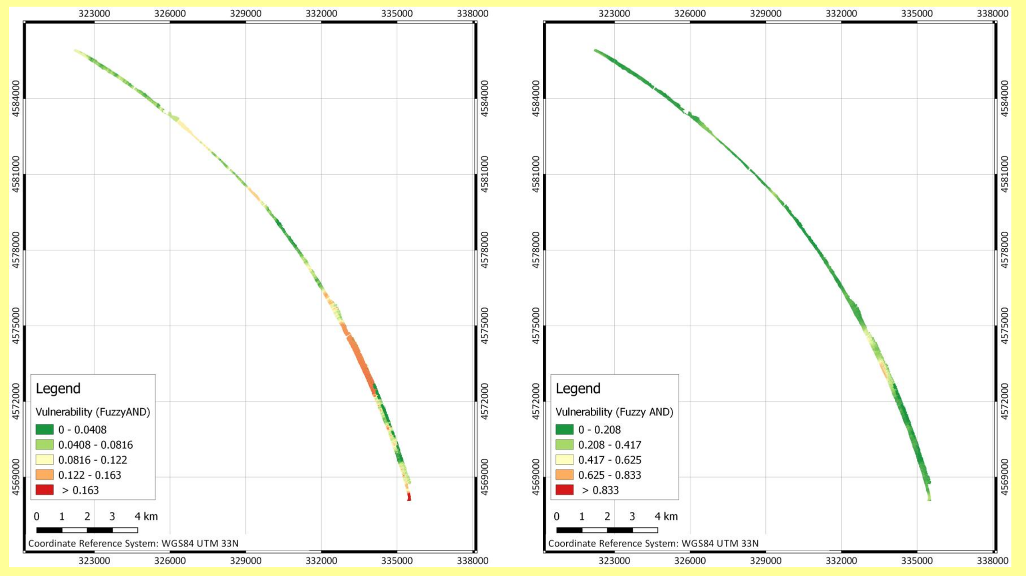
Coastal Section



RESULTS

- Some fuzzy operators (e.g. fuzzy SUM, fuzzy PRODUCT) tend to smooth the vulnerability around respectively very high values and very low values
- Using fuzzy operators - not defining inference system - vulnerability is completeley dependant on parameters values distribution, and does not consider the relation among parameters neither their different relevance
- Comparison among different scenarios using the same operators or among different operators with regard to the same scenario can be very tricky
- Vulnerability results in each case should be read as an information on the maximum and minimum conditions of vulnerability: all the vulnerability degree among these peaks are difficult to be properly interpreted

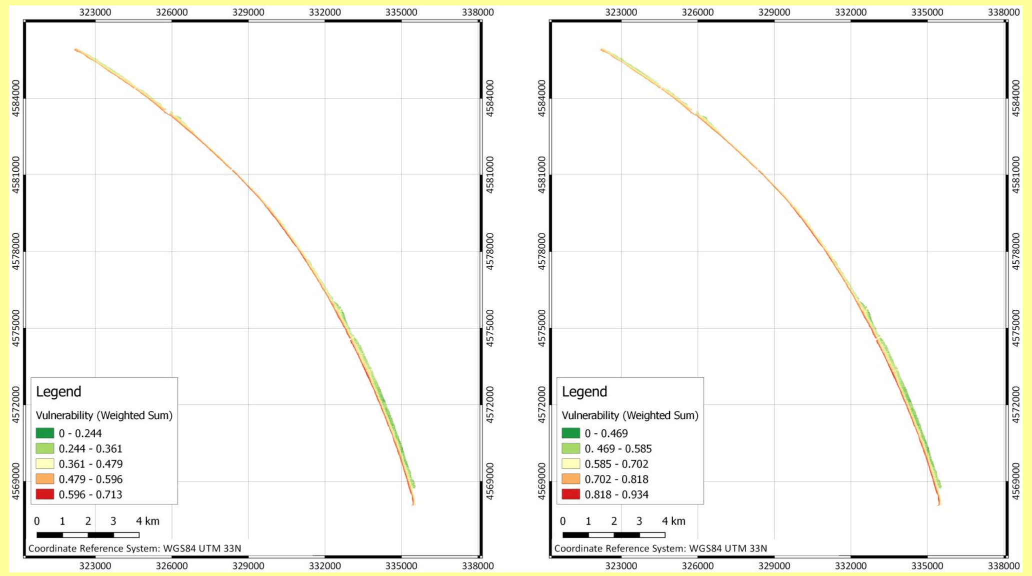
Scenario 1 *Scenario 3*



Fuzzy AND returns the degree of membership among the lowest of the different input maps.

Both scenarios show different degree of vulnerability, but scenario 1 has a lower variability values range than scenario 3. Highest vulnerability degrees, in the southern part of the stretch, have to be mostly attributed to the presence of socieconomic values (i.e. population density and anthropic cover).

Scenario 1 *Scenario 3*



WEIGHTED SUM returns the degree of membership as the sum of all the input maps but weigheted according to expert knowledge.

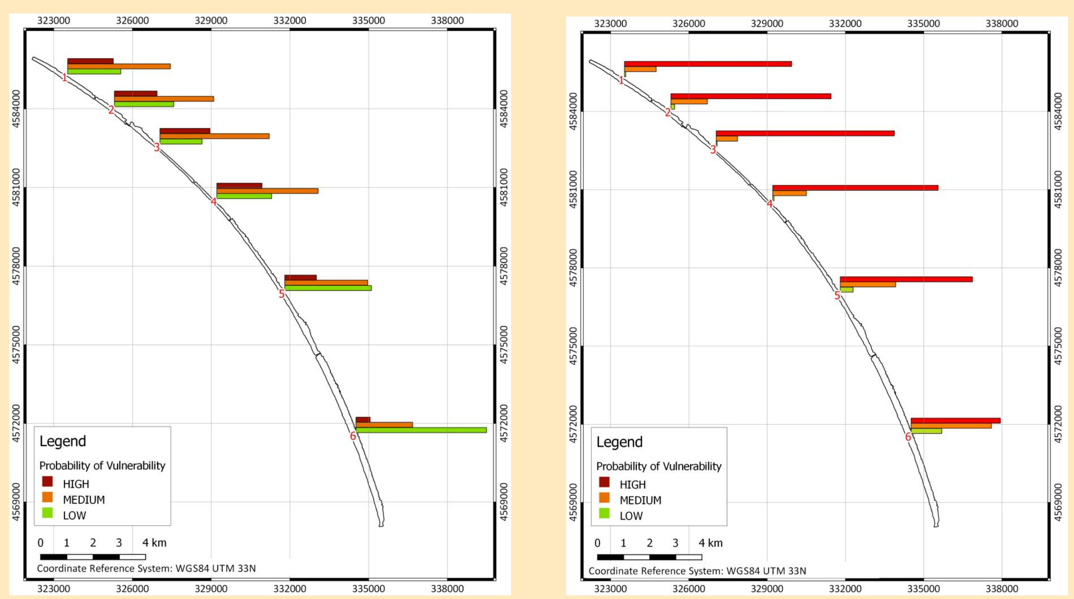
Both scenarios show different degree of vulnerability, and their variability values range are very similar. They show a clear vulnerability gradient moving from coastaline to inland. The definition of weights enables to take into account both the directionality of the hazard and the importance of ecosystem charatheristics.

RESULTS

CPT: Conditional Probability Tables

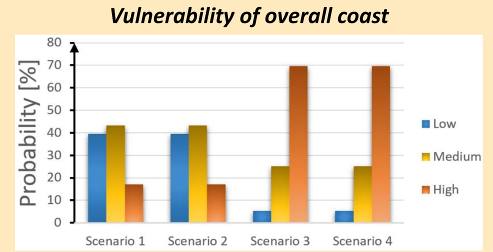
HAZARD		LOW									HIGH								
MORPHOLOGY FACTOR		LOW			MEDIUM			HIGH			LOW			MEDIUM			HIGH		
COVER FACTOR		LOW	MEDIUM	HIGH	LOW	MEDIUM	HIGH	LOW	MEDIUM	HIGH	LOW	MEDIUM	HIGH	LOW	MEDIUM	HIGH	LOW	MEDIUM	HIGH
VULNERABILITY	LOW	0	0	0	0	0.1	0.2	0.2	0.2	0.3	0.1	0.3	0.4	0.3	0.5	0.8	0.7	0.8	1
	MEDIUM	0	0.2	0.3	0.2	0.4	0.4	0.4	0.5	0.6	0.6	0.5	0.4	0.4	0.4	0.2	0.3	0.2	0
	HIGH	1	0.8	0.7	0.8	0.5	0.3	0.4	0.3	0.1	0.3	0.2	0.2	0.2	0.1	0	0	0	0

Scenario 1: 6 Polygons *Scenario 3: 6 Polygons*



In both cases, the vulnerability decrease from north to south, in fact the probability of having low vulnerability increase from north to south.

Vulnerability of overall coast



The four scenarios are merged in two: 1-2 and 3-4 to low and high hazard respectively

Thresholds

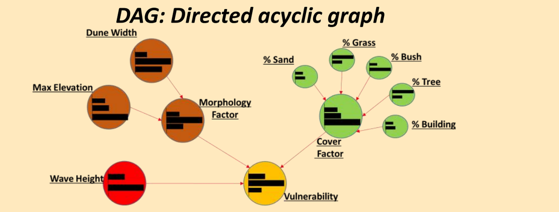
Parameters	Thresholds 1	Thresholds 2
Dunes height	7.95 m	12.51 m
Dunes width	96	138
Parameters	**Thresholds 1**	
Waves height	13.28 m	
% of Sand	20 %	
% of Grass	20 %	
% of Bush	20 %	
% of Three	20 %	
% of Building	20 %	

Thresholds are the boundaries of the discrete distribution of each parameter

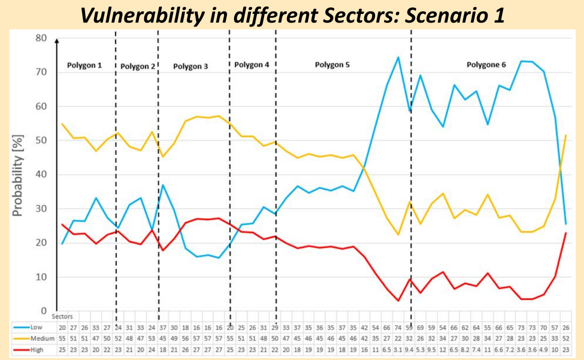
Simulations

Unit of vulnerability analysis	Scenario
Overall coast	1, 2, 3 and 4
6 Polygons	1 and 3
46 Sectors	1 and 3

DAG: Directed acyclic graph

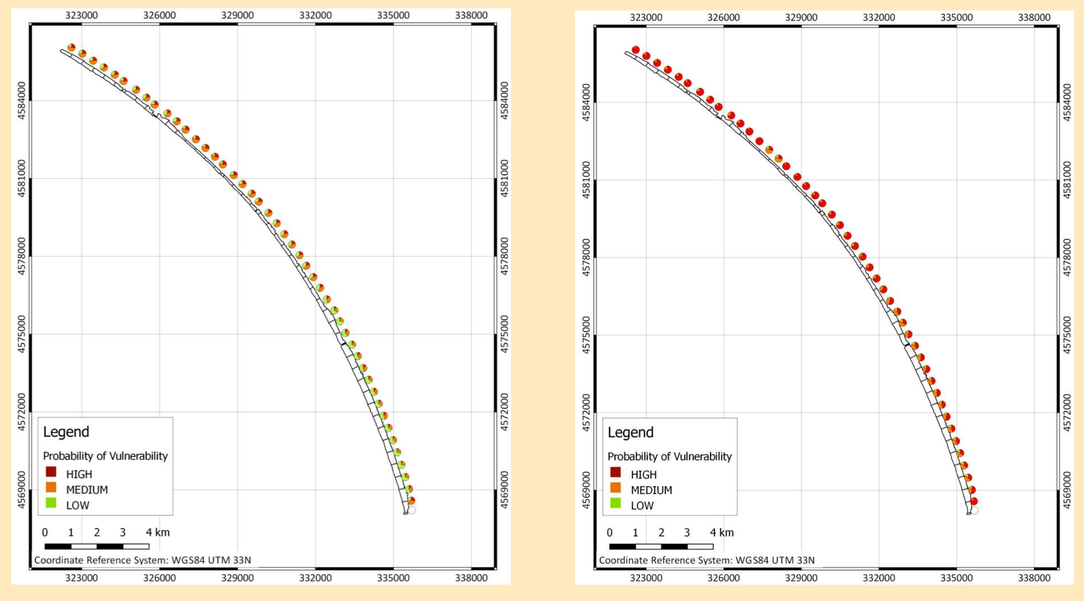


Vulnerability in different Sectors: Scenario 1



The graph shows stretches of coast with characteristic behaviors vulnerabilities, in particular it highlights the polygons 3, 5 and 6

Scenario 1: 46 Sectors *Scenario 3: 46 Sectors*



Also in the sector analysis the vulnerability decrease from north to south, and Scenario 3 shows higher values of high vulnerability compare to the Scenario 1.

CONCLUSIONS

The fuzzy approach is very useful to get a spatialized information whose detail depends on pixel resolution and it can easily manage a great amount of variables coming from different sources. It provides information on vulnerability moving along the stretch (overall coast) and at the same time and through the coast (transect), but result is really reliable if the aim is the definition of the maximum and minimum conditions of vulnerability. According to the results using fuzzy operators, the analysis greatest limit is the incapacity to represent the relation among the different considered variables, which instead can be reached by using the weighted sum or better by using BBN approach (i.e. defining Conditional Probabilities). **The approach based on the Bayesian Belief Networks** has allowed determining the trend of distributions of vulnerability along the coast, highlighting which parts of the coast are most likely to have higher or lower vulnerability than others. By studying the trends of vulnerability distribution obtained by the different sectors it is possible to identify stretches of coast with a vulnerability characteristic behavior. As in the adopted approach the CPT was arbitrary defined, it was not possible to derive the influence of each individual variable.

The two approaches could be used together: the BBN as a preliminary assessment which provides a coarse image of the vulnerability distribution, and the fuzzy as the assessment to provide more space based and detailed information. This fist attempt to adopt a System of Systems perspective is undoubtedly an advantage for the assessment as it help in figuring the complexity of the coastal system, but for the above mentioned reasons is still far away from being able to describe the protective ecosystem services and the variables that influence them. Moreover each systems could be furtherly enriched or better characterized (i.e. choosing other essential variables).

Further development: to improve the testing of both approaches, with the aim of highlight the influence of each variable and especially of those ecosystem related, it suggests the use of large dataset of vulnerability data including information also on vulnerability degree: this would enable to derive inference rules (data based and not expert based) in the fuzzy analysis and to apply the Bayes' Theorem and compute the CPT by specific algorithm in the BBN analysis.

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