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Triton

Tools and methods for assessing coastal vulnerability to climate change – Part. 1

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Lecture OUTLINE:

- Overview of climate change impacts in coastal zones;
- Coastal Vulnerability to climate change in Europe;
- Assessment methods:

  - Indicator-based approaches;
  - Index-based methods.

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Part 1:

Indicator and index-based methods.

Part 2:

Decision support systems (DSSs) and complex system methods.

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Climate change and coastal zones

COASTAL ZONES are complex systems of strategic importance in different sectors:

- they are **home** to a large percentage of **citizens** worldwide;
- they are a major source of **food** and **raw materials;**
- they are a crucial link for **transport** and **trade;**
- they include valuable **habitats** and **natural resources;**
- they are favoured destination for **leisure time** and **recreational activities.**

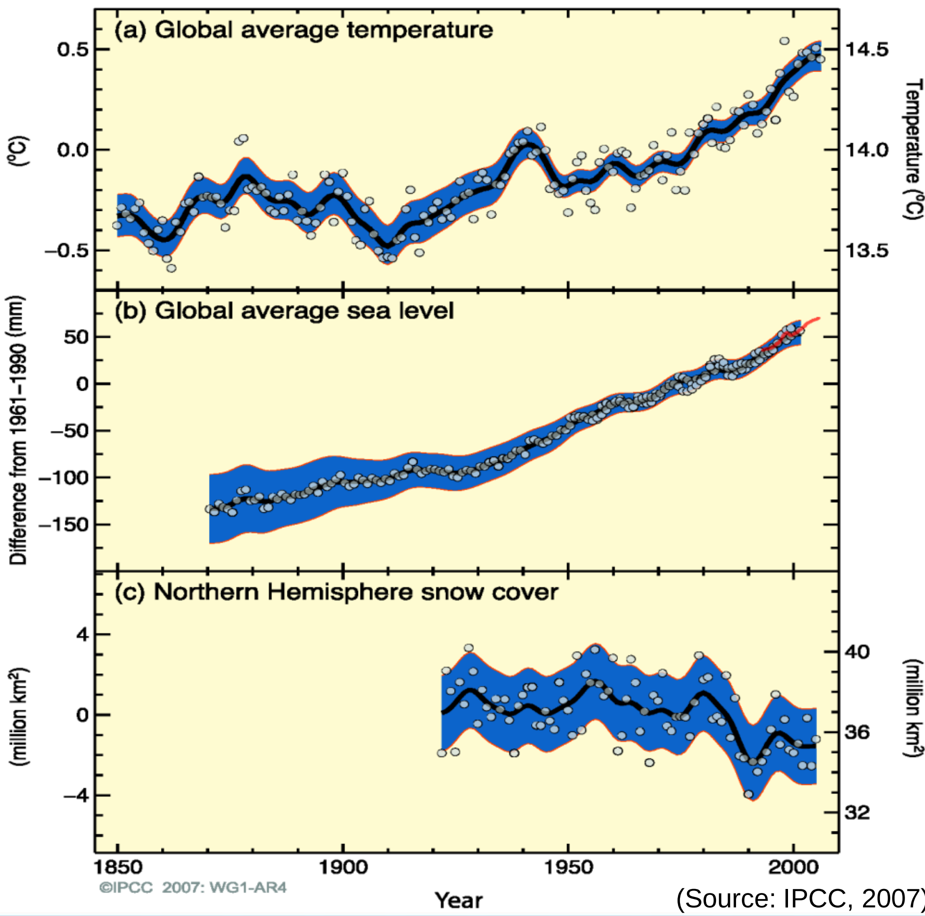
In the last decades **urbanization**, **agriculture**, **industry**, **energy production**, **transportation** and **tourism** posed **increasing pressures** on coastal areas

habitat destruction, **water** and **soil contamination,** coastal **erosion** and **resource depletion**

the depletion of the limited resources of coastal zones and the limited physical space is leading to **increasing conflicts of interests** among different **stakeholders** (e.g. aquaculture and tourism)

importance of ICZM

Coastal systems are projected to be increasingly at risk due to global climate change trough the 21th century and beyond (IPCC, 2007 and 2014).



(Source: IPCC, 2007)

BIOGEOPHYSICAL IMPACTS:

- Sea-level rise.
- Increasing flood-frequency probabilities.
- Erosion.
- Inundation.
- Rising water tables.
- Saltwater intrusion.
- Negative consequences for biodiversity and ecosystems.
- ….

SOCIO-ECONOMIC IMPACTS:

- Direct loss of economic, cultural and subsistence values through loss of land, infrastructure and coastal habitats.
- Increased flood risk of people, land and infrastructure.
- Damage to coastal protection works and other infrastructure.
- Impacts related to changes in water management, salinity and biological activity.
- Impacts on agriculture and aquaculture.….

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Bio-geophysical impacts including relevant interacting climate and non-climate drivers

Bio-geophysical effect		Other relevant factors	
		Climate	**Non-climate**
Permanent inundation		Sea level rise	Vertical land movement (uplift and subsidence), land use and land planning
Flooding and storm damage	Surge (open coast)	Wave and storm climate, morphological change, sediment supply	Sediment supply, flood management, morphological change, land claim
	Backwater effect (river)	Run-off	Catchment management and land use
Wetland loss (and change)		CO_2 fertilisation, sediment supply	Sediment supply, migration space, direct destruction
Erosion	Direct effect (open coast)	Sediment supply, wave and storm climate	Sediment supply
	Indirect effect (near inlets)		
Saltwater Intrusion	Surface waters	Run-off	Catchment management and land use
	Groundwater	Rainfall	Land use, aquifer use
Rising water tables/impeded drainage		Rainfall	Land use, aquifer use

(source: modified from Nicholls and Klein, 2005)

Climate change impacts result from the interaction between climate and **non-climate drivers** and have significant regional variations (Nicholls et al., 2008).

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A **strategic** approach is needed to ensure that **timely** and **effective adaptation measures** are taken, ensuring **coherency** across **different sectors** and **levels of governance.**

The **challenge for policy-makers** is to **understand climate change impacts** and to **develop** and **implement policies** to ensure an **optimal level** of **adaptation.**

The aims for the **scientific community** are to **improve** the **knowledge** on **climate impact** and **vulnerability** and to **provide methodologies** and **tools** in order to guide the development of appropriate **adaptation measures.**

EC, 2009.

Coastal Vulnerability to climate change in Europe

A significant and increasing share of the EU population lives in coastal areas:

- Approximately 40.8% of the EU population lives 50 km or less from the coast (ESTAT, 2011).

- 20% of the EU population (86 million people) lives within a 10 km coastal strip (EEA, 2013).

- Approximately 140,000 km^2 of EU land is currently within 1 m of mean sea level (REGIONS 2020, EU Commission).

↓

- growing demands on coastal resources and increasing people's exposure to coastal hazards;

- the assessment of coastal vulnerability to climate change is therefore a key issue at the European level.

Ramieri et al. (2011)

Methodological aspects of coastal vulnerability assessment:

- Coastal vulnerability assessment initially needs the clear definition of **policy** and **decision making objectives** and related questions;
- **Different tools** may be indicated to approach coastal vulnerability assessment at **different spatial** and **temporal scales**, in different regions and for different policy purposes;
- A **multi-hazard approach** is required, evaluating impacts induced by various drivers, such as changes in sea-level, storms, salinity, waves, temperature and sedimentation patterns;
- Vulnerability assessment should consider also the analysis of **current** and **future adaptation strategies** and measures, significantly influencing coastal vulnerability;
- **Data availability** is still a **key issue**: globally available data (e.g. sea level rise projections or digital elevation models) need to be corrected or detailed to address regional specificities.

Ramieri et al. (2011)

Climate change vulnerability and adaptation at the regional and sub-regional level.

Number	European marine regions and sub-regions
1	Baltic Sea
2	North-east Atlantic Ocean: Greater North Sea
3	North-east Atlantic Ocean: Celtic Seas
4	North-east Atlantic Ocean: Bay of Biscay and Iberian Coast
5	North-east Atlantic Ocean: Macaronesian biogeographic region
6	Mediterranean Sea: Western Mediterranean Sea
7	Mediterranean Sea: Adriatic Sea, Ionian Sea and Central Mediterranean Sea
8	Mediterranean: Aegean-Levantine Sea (Eastern Mediterranean)
9	Black Sea

Location of European Marine Regions and sub-regions as defined by the Marine Strategy Framework Directive 2008/56/EC.

Ramieri et al. (2011)

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Main climate change hazards and vulnerabilities in different European Marine Regions and sub-regions.

European marine sub-regions	Main hazards and vulnerabilities
Baltic Sea (1)	Storms surges River flooding Salt water intrusion Loss of marine habitats, ecosystems and biodiversity Socio-economic vulnerabilities (fisheries, tourism)
North-east Atlantic Ocean Greater North Sea (2)	Storm surges Coastal flooding Coastal erosion Altered salinity Salt water intrusion Loss of marine habitats, ecosystems and biodiversity Loss of property and infrastructure
North-east Atlantic Ocean Celtic Seas (3)	Coastal flooding Coastal erosion Loss of marine habitats, ecosystems and biodiversity Decrease of salmon production Loss of property and infrastructure
North-east Atlantic Ocean Bay of Biscay and Iberian Coast (4)	Coastal flooding Coastal erosion Loss of marine habitats, ecosystems and biodiversity
North-east Atlantic Ocean: Macaronesian bio-geographic region (5)	Salt water intrusion Loss of marine habitats, ecosystems and biodiversity Socio-economic vulnerabilities (fisheries, aquaculture, tourism, health)

Ramieri et al. (2011)

Main climate change hazards and vulnerabilities in different European Marine Regions and sub-regions

European marine sub-regions	Main hazards and vulnerabilities
Mediterranean Sea: Western Mediterranean Sea (6)	Coastal flooding Coastal erosion Altered salinity Salt water intrusion Freshwater scarcity Loss of marine habitats, ecosystems and biodiversity Socio-economic vulnerabilities (fisheries, tourism, health)
Mediterranean Sea: Adriatic Sea, Ionian Sea and Central Mediterranean Sea (7)	Coastal flooding Coastal erosion Salt water intrusion Loss of marine habitats, ecosystems and biodiversity Socio-economic vulnerabilities (heritage, tourism, health)
Mediterranean Sea: Aegean - Levantine Sea (8)	Coastal erosion Coastal flooding Salt water intrusion Introduction of alien species Socio-economic vulnerabilities (agriculture, tourism)
Black Sea (9)	Coastal flooding Coastal erosion Loss of marine habitats, ecosystems and biodiversity Socio-economic vulnerabilities (fisheries)

Ramieri et al. (2011)

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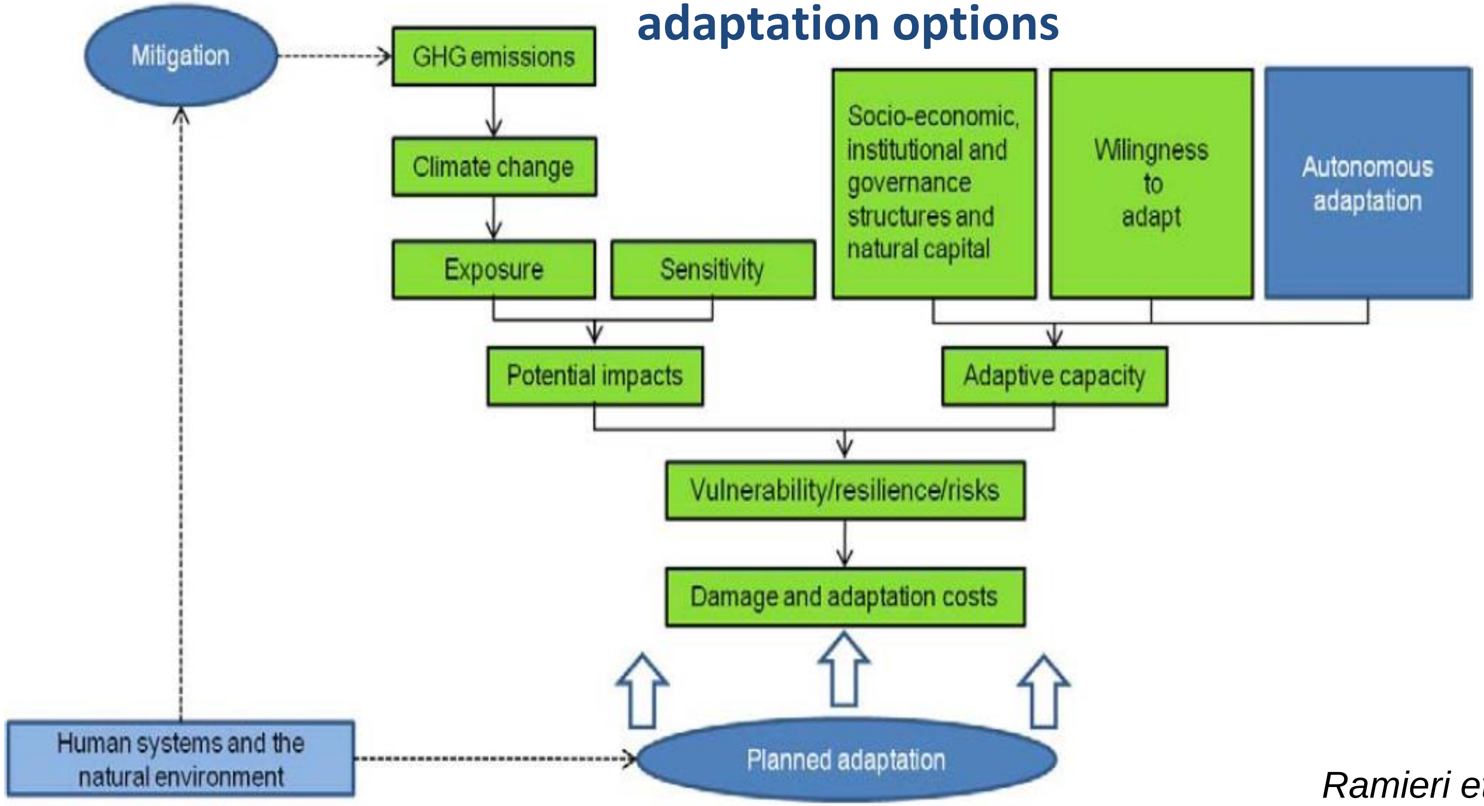
Conceptual framework for climate change impacts, vulnerability, disaster risks and adaptation options



Ramieri et al. (2011)

(source: EEA, 2010a; ETC-ACC, 2010b)

The **IPCC definitions** of vulnerability to climate change, and its related components (exposure, sensitivity, and adaptive capacity) provide a suitable starting position to explore possibilities for vulnerability assessment but they **are not operational.**

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Methodological aspects of coastal vulnerability assessment:

- The **operational definition** of the vulnerability concept is related to the specific issue and/or context (e.g. the coastal area) addressed by the analysis.

- **Key steps** in the operationalization phase include:

1. Identification of application context: objectives and scenarios.
2. Data availability.
3. Indicator selection.
4. Normalization.
5. Weighting.
6. Aggregation.
7. Uncertainty.

(adapted from Balbi et al., 2012).

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Criteria for evaluating methods for coastal vulnerability assessment at the European scale

- **Possibility to address different temporal scenarios.**

  e.g. 2050 and 2100.
- **Relevance for assessing vulnerability related to one or more key climate change impacts.**
- e.g. permanent inundation, change in the frequency and intensity of costal flooding; coastal erosion, saltwater intrusion in rivers and groundwater, impacts on wetlands.
- **Applicability to different typologies of coastal systems**. e.g. wetlands, beaches, rocky coasts, and estuaries.
- **Possibility to assess social, economic and ecological risks of climate change in coastal regions.**

  e.g. systems at risk include population, built infrastructure, and economic activities but also natural ecosystems.
- **Consideration of adaptation measures.**

  e.g. already implemented measures as well as scenarios of future adaptation.

Ramieri et al. (2011)

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Criteria for evaluating methods for coastal vulnerability assessment at the European scale

- **Possibility to vary assumptions and scenarios.**

  e.g. maps and/or indicators showing how the vulnerability varies in relation to sea level rise scenarios, time horizons, socio-economic dynamic scenarios, adaptation/no adaptation options.

- **Consideration of regional climate change scenarios.**

  e.g. consider regional information about sea level rise, subsidence rates, etc., rather than global or European averages.

- **Assessment of uncertainties.**

  e.g. related to climate change scenarios, current environmental and socioeconomic conditions

- **Availability of underlying data and/or models.**

  e.g. computer models should be publicly available or available at a reasonable cost.

Ramieri et al. (2011)

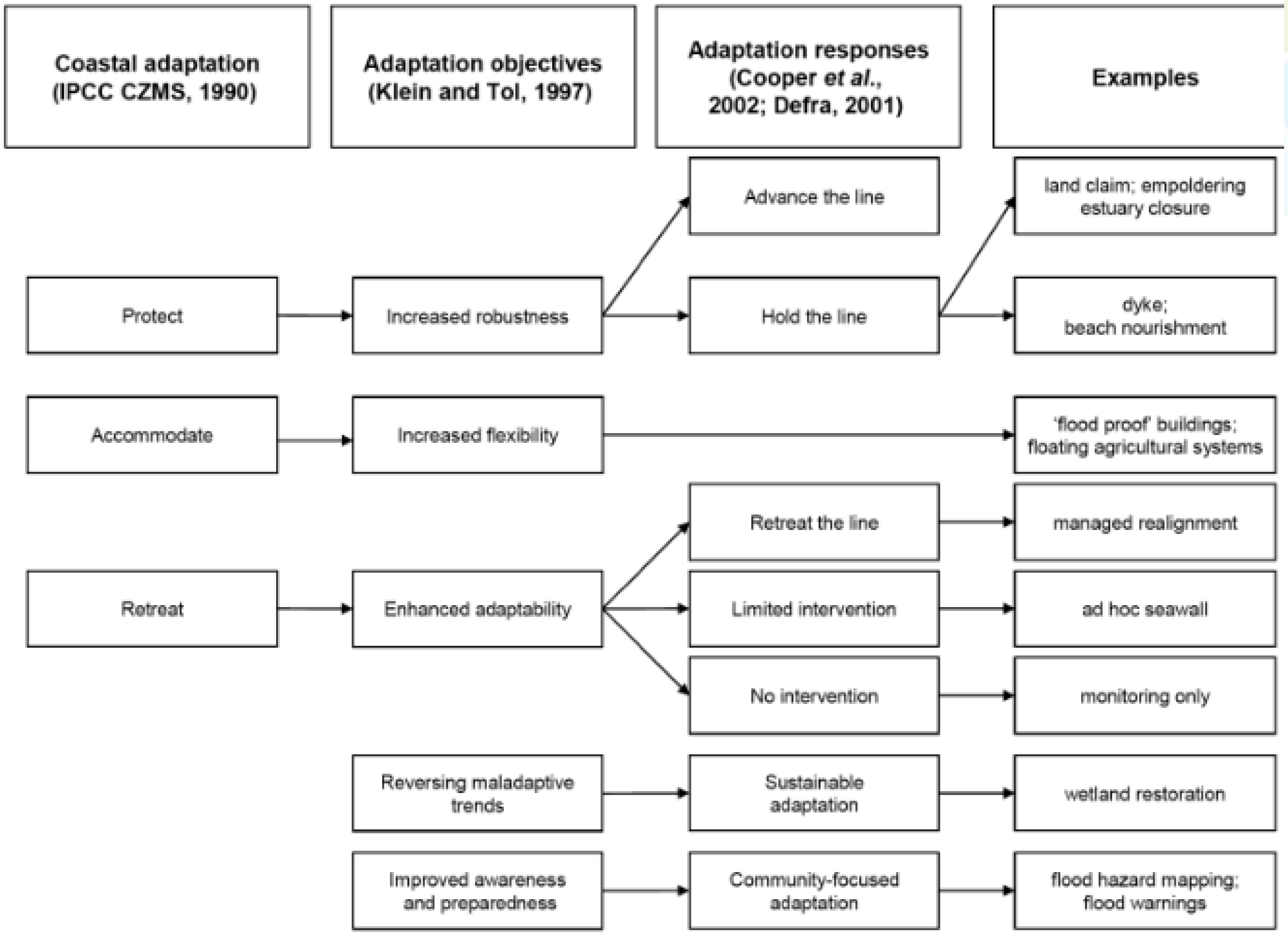
The main purpose of vulnerability assessment is to provide information to guide the process of adaptation.

Coastal adaptation is a complex and iterative process, three basic adaptation strategies are often used:

- **Protect** - to reduce the risk of the event by decreasing the probability of its occurrence;
- **Accommodate** - to increase society's ability to cope with the effects of the event;
- **Retreat** - to reduce the risk of the event by limiting its potential effects.

Ramieri et al. (2011)

Coastal adaptation



Evolution of planned adaptation practices in coastal zones (source: Nicholls et al., 2007)

Ramieri et al. (2011)

Project co-funded by European Union, European Regional Development Funds (E.R.D.F.) and by National Funds of Greece and Italy

Projects

FP7

RISC-KIT (2013-2017)

Resilience-Increasing Strategies for Coasts - toolKIT

In the frame of RISC-KIT project have been developed methods, tools and management approaches to reduce risk and increase resilience to low-frequency, high-impact hydro-meteorological events in the coastal zone

→ DSS as a **Bayesian Network Approach**, built on a Source-Pathway-Receptor (SPR) concept

Jäger et al., 2018
Plomaritis et al., 2018

THESEUS (2009-2013)

Innovative technologies for safer European coasts in a changing climate

Examine the application of innovative combined coastal mitigation and adaptation technologies generally aiming at delivering a safe (or low-risk) coast for human use/development and healthy coastal habitats as sea levels rise and climate changes (and the European economy continues to grow)

→ **GIS-based tool: THESEUS DSS**

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Projects

FP7

BASE (2012-2016)

Bottom-Up Climate Adaptation Strategies Toward a Sustainable Europe

The BASE project aims to foster sustainable adaptation in Europe by improving the knowledge based on adaptation and making this information easier to access, understand and act upon.

SIM.COAST (2010-2014)

Numerical Simulation Tools for Protection of Coasts against Flooding and Erosion

The project aims to contribute to protection of coasts against flooding and erosion, through research and training of researchers

PEGASO (2010-2014)

People for Ecosystem-based Governance in Assessing Sustainable development of Ocean and coast

- Constructing an ICZM governance platform as a bridge between scientist and end-user communities;
- Refine and further develop efficient and easy to use tools for making sustainability assessments in the coastal zone (indicators, accounting methods, models and scenarios);
- Implementation of a Spatial Data Infrastructure (SDI), following the INSPIRE Directive, to organize and standardize spatial data to make it available to the ICZM Platform.

Projects

FP7

MICORE (2008-2011)

Morphological Impacts and Coastal Risk induced by Extreme storm events

Innovations in coastal storm risk management and coastal civil protection schemes.

→ on-line tool based on real-time data acquisition

→ state-of-the-art hydrodynamic and morphological models is feasible for vulnerable areas across Europe

RISES-AM (2013-2016)

Responses to coastal climate change: Innovative Strategies for high End Scenarios - Adaptation and Mitigation

Develops sustainable adaptation pathways for coastal zones under high-end climate change and sea-level rise scenarios.

NEMO (2012-2016)

Nearshore Monitoring and Modelling: Inter-scale Coastal Behaviour

Gain unprecedented insights into the complex processes in natural coastal environments, and to use these to develop, test and use an innovative new physics-based model capable of providing robust forecasts of large scale, long term coastal change.

Assessment methods:

INCREASING COMPLEXITY

- Indicator-based approaches;
- Index-based methods
- Software based on GIS applications (e.g. decision support systems, DSSs)
- Complex system methods (e.g. Bayesian network, agent-based model)

Ramieri et al. (2011)

* Indicator and indices *

An indicator is a **value** that represents a **phenomenon** that cannot be directly measured and may aggregate different types of data.

An Index is a set of aggregated or weighted **parameters or indicators.**

A measurement of a specific variable is the basis for the characterization of an indicator, which in turn can be the basis for the construction of an index.

* Indicator and indices *

Three functions:

- Reduce the **number of parameters** that normally would be required to represent a situation;
- Simplify the **process of results** communication to the users;
- Quantify **abstract concepts** such as ecosystem health or biotic integrity that are not measurable.

In the specific context of climate change:

- Monitoring **climate variations;**
- Characterising **spatial and temporal distributions** of stressors and drivers;
- Identifying **strategic vulnerabilities**.

Climate change indicators should consider specific attributes:

Routinely collected: indicators must be based on routinely collected, clearly defined, verifiable and scientifically acceptable data.

Representative at national scale: as far as possible, it should be possible to make valid comparisons between countries using the indicators selected;

Methodologically well founded: the methodology should be clear, well defined and relatively simple. Indicators should be measurable in an accurate and affordable way, and constitute part of a sustainable monitoring system. Data should be collected using standard methods.

Show cause-effect relationship: information on cause-effect relationships should be achievable and quantifiable in order to link pressures, state and response indicators.

EEA, 2012

Indicators and indices

Climate change related indicators should consider specific attributes:

Sensible to changes: indicators should show trends and be able to detect changes in systems in timeframes and on scales that are relevant to the decision makers.

Policy Relevant: indicators should send a clear message and provide information at a level appropriate for policy and management decision-making;

Broadly accepted and intelligible: the power of an indicator depends on its broad acceptance and on its easy communication.

EEA, 2012

Need to identify a broadly accepted definition of indicators and indexes, also considering how they relate to the concepts of vulnerability and risk.

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Indicator-based approaches:

- Indicator-based approaches, express the vulnerability of the coast by a set of **independent elements** (i.e. the indicators) that characterize key **coastal issues**.

- These approaches allow the evaluation of **different aspects related to coastal vulnerability** (e.g. coastal drivers, pressures, state, impacts, responses, exposure, sensitivity, risk and damage) within a consistent assessment context.

- These indicators are in some cases combined into a final **summary indicator**.

Eurosion project: http://www.eurosion.org/index.html

13 indicators based on the DPSIR approach (EEA, 1995) to support the assessment of **coastal erosion risk** throughout Europe:

9 sensitivity indicators (referred to pressure and state indicators):

1) Relative sea level rise;
2) Shoreline evolution trend status;
3) Shoreline changes from stability to erosion or accretion;
4) Highest water level;
5) Coastal urbanisation (in the 10 km land strip);
6) Reduction of river sediment supply;
7) Geological coastal type;
8) Elevation;
9) Engineered frontage (including protection structure).

4 impact indicators:

10) Population living within the RICE (Radius of influence of coastal erosion and flooding);
11) Coastal urbanisation (in the 10 km land strip);
12) Urbanised and industrial areas within the RICE;
13) Areas of high ecological value within the RICE.

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Eurosion project: http://www.eurosion.org/index.html

Each indicator is calculated at the regional (subnational) level in the RICE area:

From the shoreline, the Radius of Influence of Coastal Erosion and flooding (RICE) is defined as :

- all areas located **within 500m** from the shoreline;

- areas lying **under 5 meter** contour line.

Eurosion project: http://www.eurosion.org/index.html

Each indicator was evaluated according to a **semi-quantitative score** that represents low, medium and high level of concern about the **expected future risk or impact erosion** (Eurosion, 2004).

The **evaluation** of the identified indicators was supported by the **Eurosion database**, structured in various **spatial data layers** covering the **European scale**.

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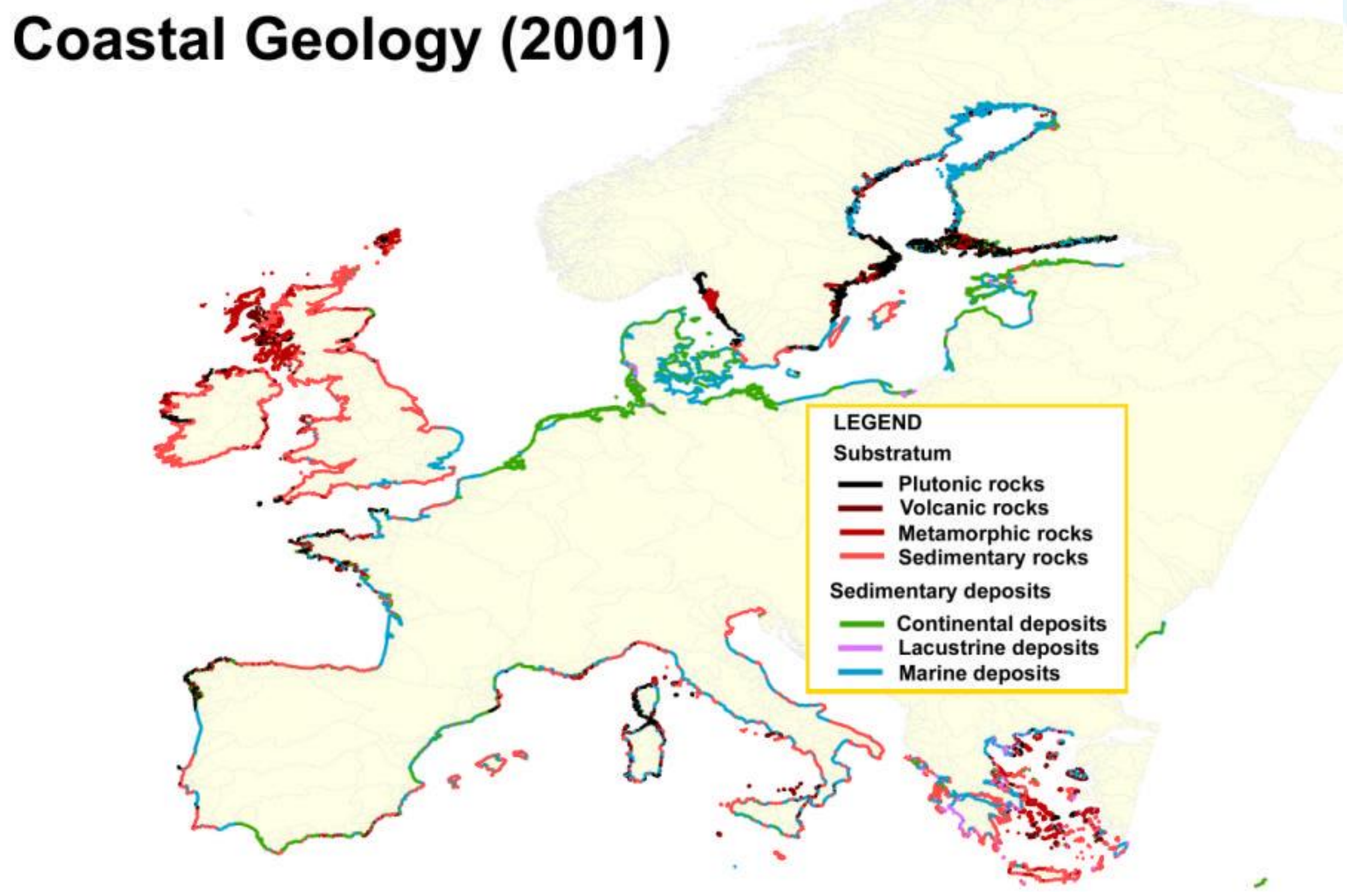
Eurosion project: http://www.eurosion.org/index.html



(Source: EUROSION project [website](http://www.eurosion.org/index.html))

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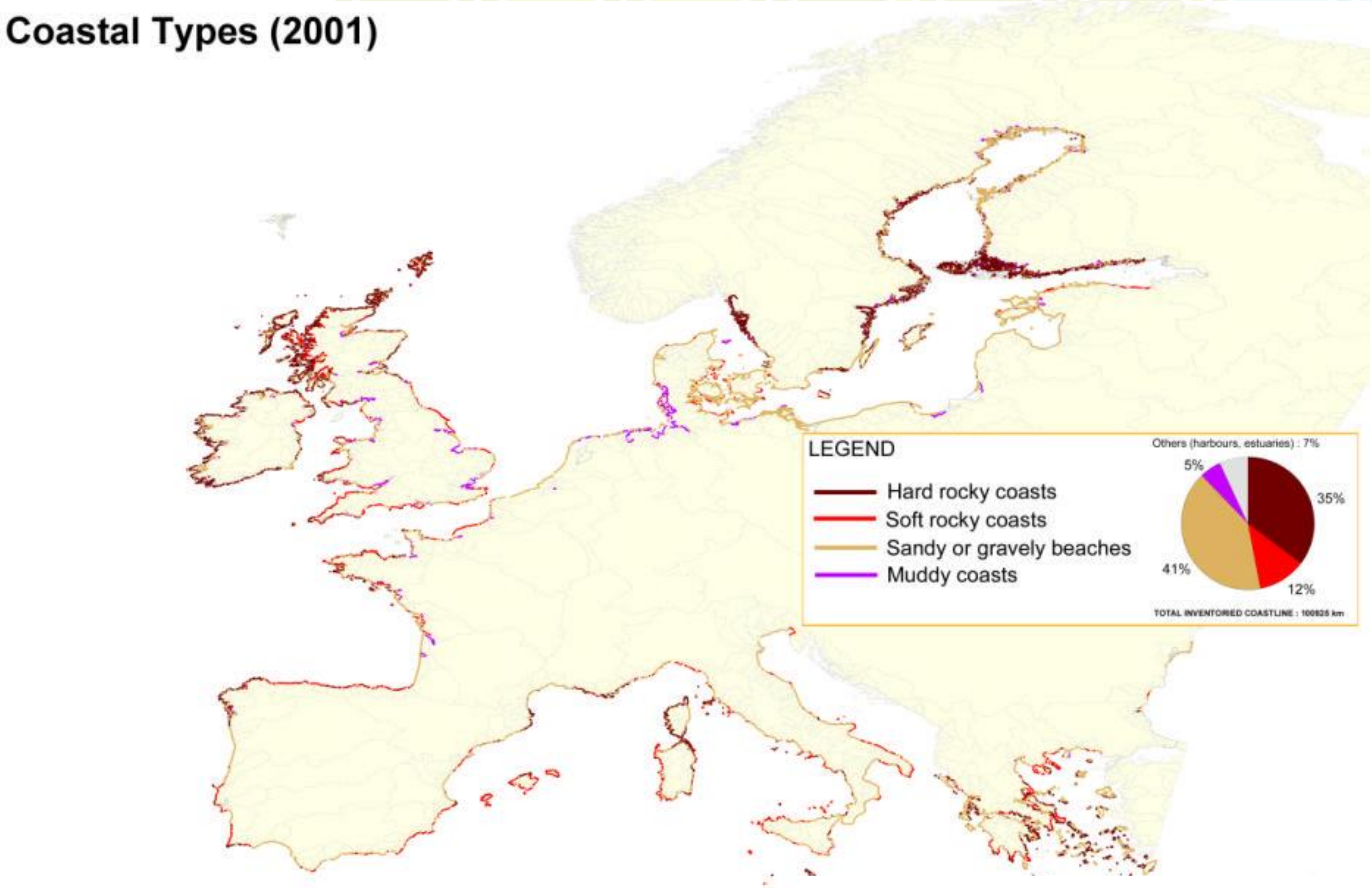

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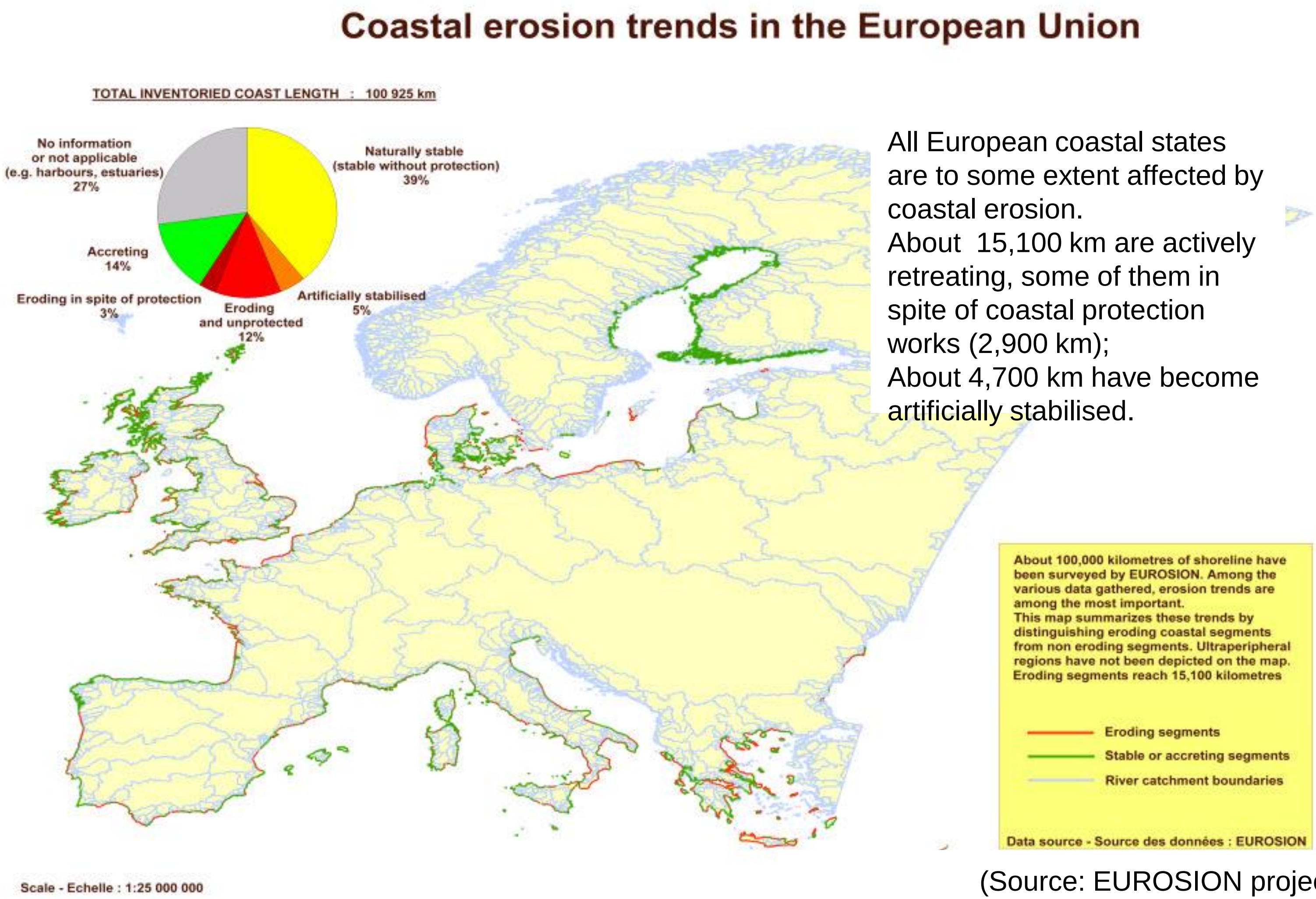


All European coastal states are to some extent affected by coastal erosion.
About 15,100 km are actively retreating, some of them in spite of coastal protection works (2,900 km);
About 4,700 km have become artificially stabilised.

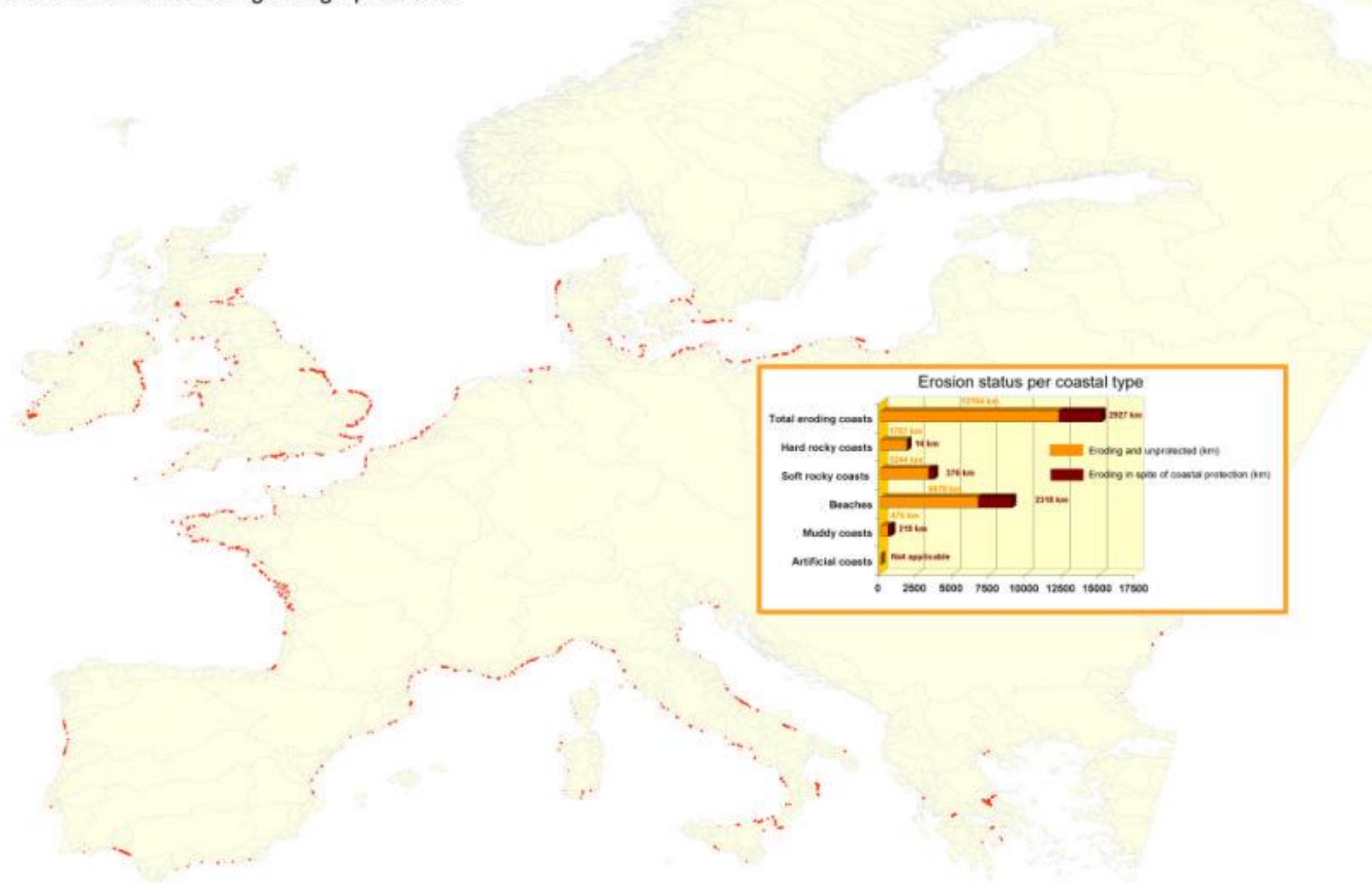
(Source: EUROSION project website)

Project co-funded by European Union, European Regional Development Funds (E.R.D.F.) and by National Funds of Greece and Italy

Eurosion project: http://www.eurosion.org/index.html

Coastal erosion despite coastal protection (2001)

Red spots depict areas which are eroding though protected



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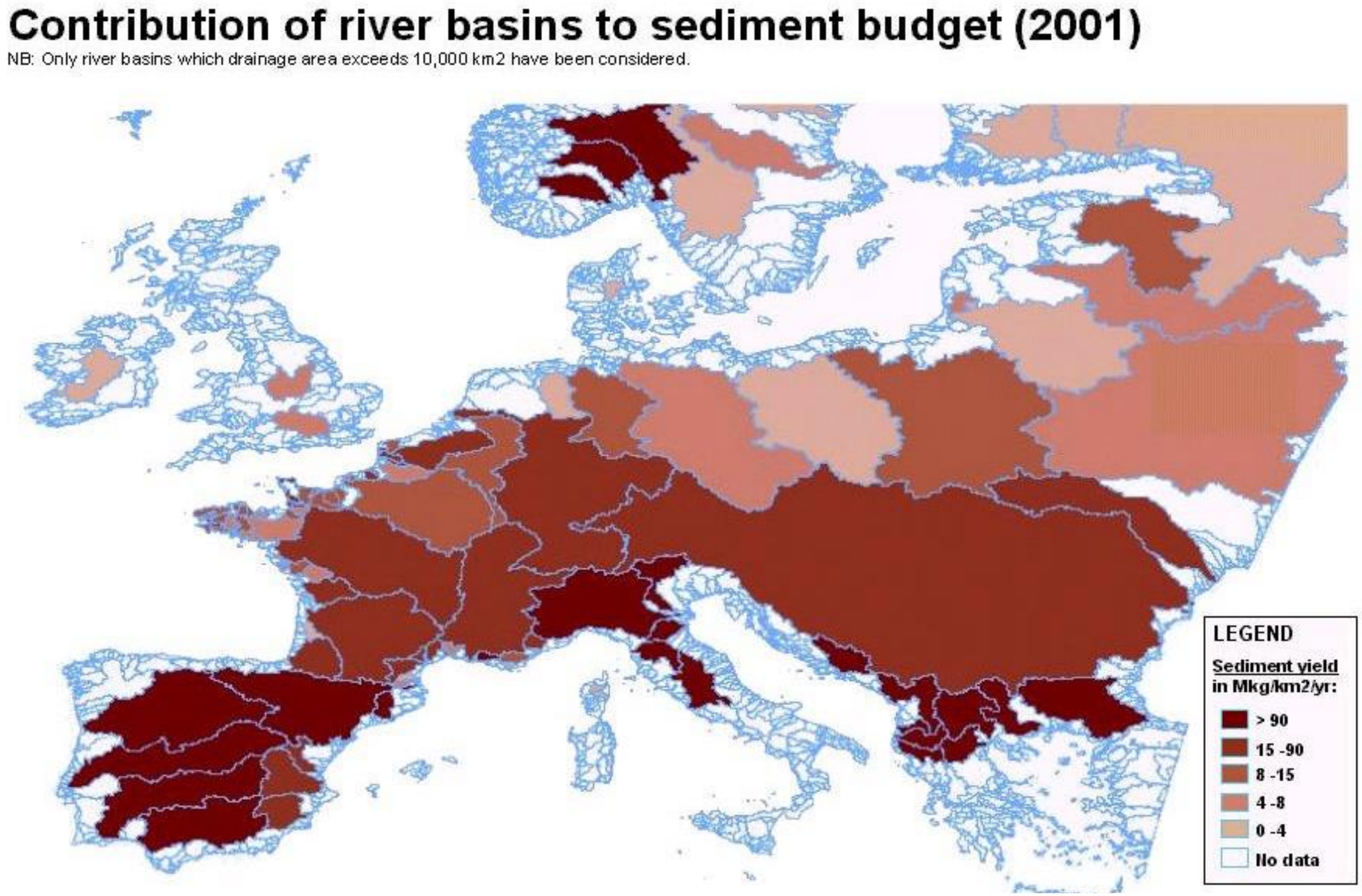

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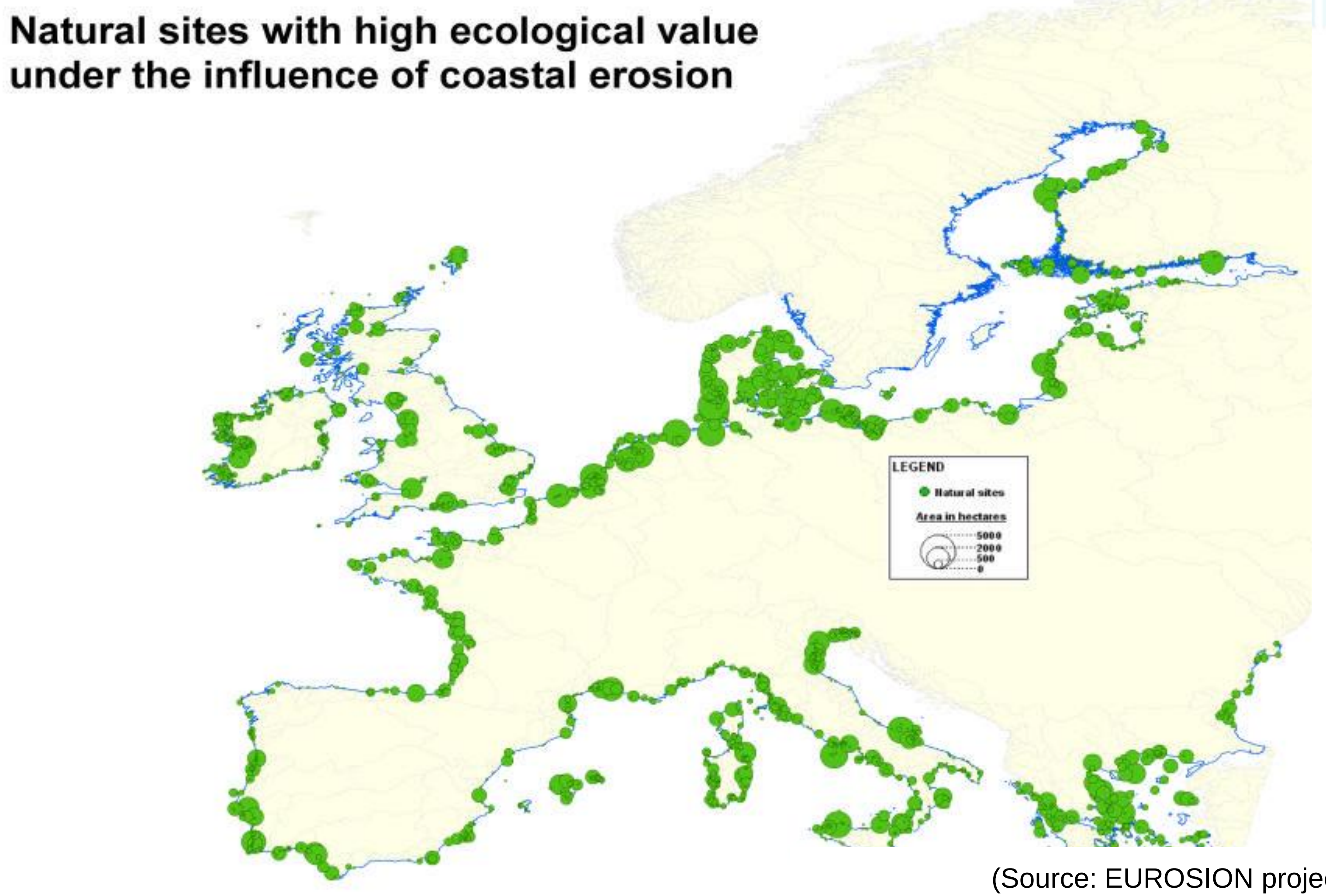

(Source: EUROSION project [website](http://www.eurosion.org/index.html))

Eurosion project: http://www.eurosion.org/index.html

METHODOLOGY FOR RATING EUROPEAN REGIONS IN TERMS OF COASTAL EROSION AND FLOODING			
Indicator	**0 point**	**1 point**	**2 points**
PRESSURE SCORING			
1) Relative sea level rise (best estimate for the next 100 years)	*< 0 cm (per region)*	*BETWEEN 0 AND 40CM (PER REGION)*	*> 40 CM (PER REGION)*
2) Shoreline evolution trend status	*Less than 20% of the shoreline is eroding (per region)*	*Between 20% and 60% of the shoreline is eroding (per region)*	*More than 60% of the shoreline is eroding (per region)*
3) Shoreline changes from stability to erosion or accretion between the most recent and the previous version of the database	*Less than 10% of the shoreline changes between the 2 versions (CCEr and CEL)*	*Between 10 and 30% of the shoreline have changed between the 2 versions (CCEr and CEL)*	*More than 30% of the shoreline have changed between the 2 versions (CCEr and CEL)*
4) Highest water level	*Less than 1,5 meters*	*Between 1,5 and 3 meters*	*More than 3 meters*
5) Coastal urbanization (in the 10 km land strip)	*Urban areas (in km2) have increased of less than 5% between 1975 and present*	*Urban areas (in km2) have increased of 5 to 10% between 1975 and present*	*Urban areas (in km2) have increased of more than 10% between 1975 and present*
6) Reduction of river sediment supply (ratio)	*Ratio between effective volume of river sediment discharged and theoretical volume (i.e. without dams) is superior to 80%*	*Ratio between 50 and 80%*	*Ratio is less than 50%*
7) Geological coastal type	*> 70% of "likely non erodable" segments*[13]	*"likely non erodable segments" between 40% and 70%*	*< 40% of "likely non erodable segments"*
8) Elevation	*< 5% of the region area lies below 5 meters*	*Between 5 and 10% of the region area lies below 5 meters*	*> 10% of the region area lies below 5 meters*
9) Engineered frontage (including protection structure)	*< 5% of engineered frontage along the regional coastline*	*Between 5% and 35% of engineered frontage along the regional coastline*	*> 35% of engineered frontage along the regional coastline*

(Source: EUROSION project website)

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Eurosion project: http://www.eurosion.org/index.html

METHODOLOGY FOR RATING EUROPEAN REGIONS IN TERMS OF COASTAL EROSION AND FLOODING			
Indicator	**0 point**	**1 point**	**2 points**

IMPACT SCORING

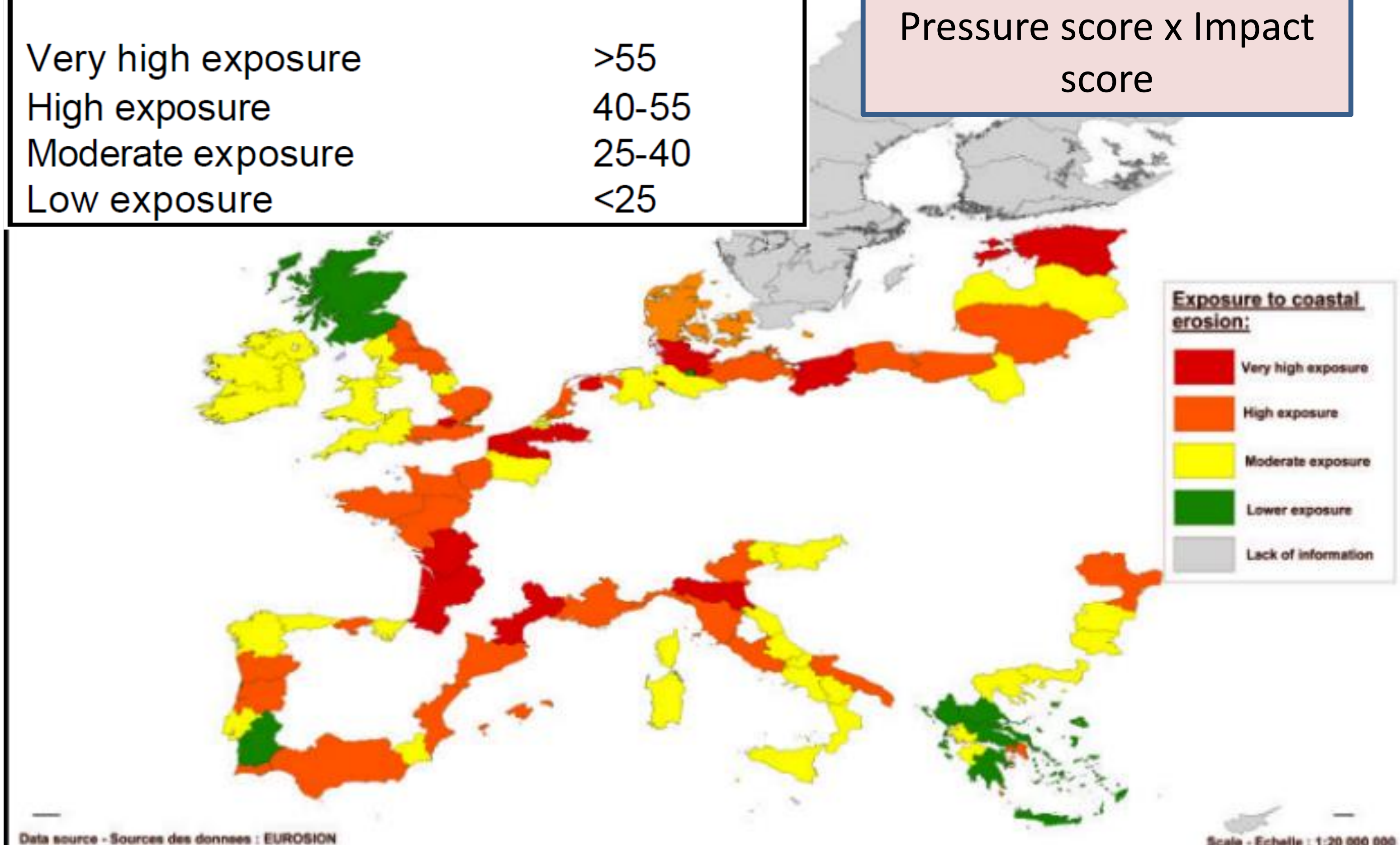
10) Population living within the RICE[14]	*< 50,000 inhabitants per region*	*Between 50,000 and 200,000 inhabitants per region*	*> 200,000 inhabitants per region*
11) Coastal urbanization (in the 10 km land strip)	*Urban areas (in km2) have increased of less than 5% between 1975 and present*	*Urban areas (in km2) have increased of 5 to 10% between 1975 and present*	*Urban areas (in km2) have increased of more than 10% between 1975 and present*
12) Urban and industrial living within the RICE	*< 10% of the land cover within the RICE is occupied by urban and industrial areas (per region)*	*Between 10% and 40% of the land cover within the RICE is occupied by urban and industrial areas (per region)*	*> 40% of the land cover within the RICE is occupied by urban and industrial areas (per region)*
13) Areas of high ecological value within the RICE*	*< 5 % of areas of high ecological value within the RICE per region*	*Between 5% and 30% of areas of high ecological value within the RICE per region*	*> 30% of areas of high ecological value within the RICE per region*

(Source: EUROSION project website)

Exposure of European regions to coastal erosion

Classes	***Exposure***
Very high exposure	>55
High exposure	40-55
Moderate exposure	25-40
Low exposure	<25

Exposure =
Pressure score x Impact score



(Source: EUROSION project website)

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Eurosion project: http://www.eurosion.org/index.html

Class 1 – Very high exposure: Regions of class 1 should deserve **immediate attention** from the European Commission, the Member State and the Regional Authority concerned. **Coastal sediment management plans (CSMP)** covering class 1 regions should be established before end of **2006** and their achievements **monitored** and evaluated on a **yearly basis**. Due to their significance at the European level, elaboration of coastal sediment management plans for class 1 regions should receive **financial and technical support** from **European** and **national authorities**;

Class 2 – High exposure: Regions of class 2 deserve **attention** from the European Commission, the Member State and the Regional Authority concerned. Coastal sediment management plans covering class 2 regions should be established before end of 2008 and their achievements monitored and evaluated on a **3-year basis**. Due to their significance at the national level, elaboration of shore and sediment management plans for class 2 regions should receive **financial and technical support** from **national authorities**;

Class 3 – Moderate exposure: Regions of class 3 should deserve **attention** from the Member State and the Regional Authority concerned. Coastal sediment management plans covering class 3 regions should be established before end of **2008** and their achievements monitored and evaluated on a **5-year basis**;

Class 4 – Low exposure: Regions of class 4 do **not deserve short term attention** from the European Commission nor the Member State with respect to coastal erosion. shore and sediment management plans covering class 3 regions should however be established before end of **2010** and their achievements be monitored and evaluated on a **10-year basis**;

Index-based methods:

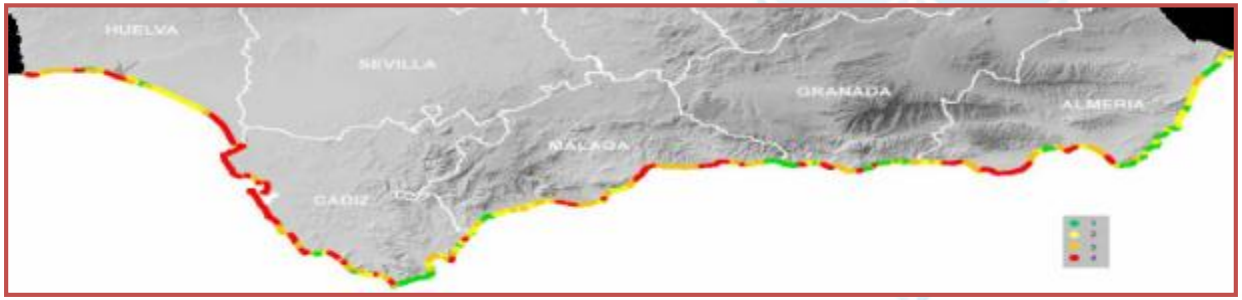
- Express coastal vulnerability by a **one-dimensional**, and generally **unitless**, risk/vulnerability **index**.
- This index is calculated through the **quantitative** or **semi-quantitative** evaluation and **combination** of **different variables**.
- The ranking of variables is a somewhat **subjective exercise**, and the criteria by which they are ranked must be **clearly defined**.
- A vulnerability index **aims to simplify** a number of **complex** and **interacting** parameters, represented by diverse data types, to a form that is **more readily understood** and therefore has **greater utility** as a **management tool**.

Coastal Vulnerability Index – CVI

The CVI is one of the **most commonly used** and **simple** methods to **assess coastal vulnerability** to **sea level rise**, in particular due to **erosion** and/or **inundation** (Gornitz et al., 1991).

The CVI provides a **simple numerical basis** for **ranking sections** of **coastline** in terms of their **potential for change** that can be used by **managers** to **identify** regions where **risks** may be **relatively high**.

The CVI **results** can be displayed on **maps** to highlight **regions** where the factors that contribute to shoreline changes may have the greatest potential to contribute to **changes** to **shoreline retreat** (Gutierrez et al., 2009).



Coastal Vulnerability Index – CVI

The **first** methodological step deals with the **identification** of **key variables** representing **significant driving processes** influencing the coastal vulnerability and the coastal evolution in general.

The **number** and **typology** of **key variables** can be slightly modified according to specific needs; in general CVI formulation includes 6 or 7 variables.

The **second** step deals with the **quantification** of **key variables:** generally based on semi-quantitative scores according to a 1-5 scale (1 low contribution to coastal vulnerability of a specific key variable, 5 high contribution).

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CVI (USGS, 2004)

Table 1: Ranges for Vulnerability Ranking of Variables on the Pacific Coast.

Variables	Very Low 1	Low 2	Moderate 3	High 4	Very High 5
GEOMORPHOLOGY	Rocky cliffed coasts, Fj[illegible]	Medium cliffs, [illegible]	Low cliffs, Glacial drift, [illegible]	Cobble Beaches, [illegible]	Barrier beaches, Sand beaches, Salt marsh, Mud flats, [illegible] grove, [illegible] efs
SHORELINE EROSION/ACCRETION (m/yr)	> 2.0	[illegible]	[illegible]	[illegible]	[illegible]
COASTAL SLOPE (%)	> 14.7	10.9 – 14.65	7.75 – 10.85	4.6 – 7.7	< 4.55
RELATIVE SEA-LEVEL CHANGE (mm/yr)	< 1.8	[illegible]	[illegible]	[illegible]	[illegible]
MEAN WAVE HEIGHT (m)	< 1.1	[illegible]	[illegible]	[illegible]	[illegible]
MEAN TIDE RANGE (m)	> 6.0	4.0 - 6.0	2.0 - 4.0	1.0 - 2.0	< 1.0

GEOLOGIC VARIABLES: they account for a shoreline's relative resistance to erosion and its susceptibility to flooding,

PHYSICAL PROCESS VARIABLES: contribute to the inundation hazards of a particular section of coastline over time scales from hours to centuries.

Key variables and scores used in the USGS CVI for the Pacific Coast.

CVI (USGS, 2004)

Table 1: Ranges for Vulnerability Ranking of Variables on the Pacific Coast.

Variables	Very Low 1	Low 2	Moderate 3	High 4	Very High 5
GEOMORPHOLOGY	Rocky cliffed coasts, Fjords	Medium cliffs, Indented coasts	Low cliffs, Glacial drift, Alluvial plains	Cobble Beaches, Estuary, Lagoon	Barrier beaches, Sand beaches, Salt marsh, Mud flats, Deltas, Mangrove, Coral reefs
SHORELINE EROSION/ACCRETION (m/yr)	> 2.0	1.0 - 2.0	-1.0 - 1.0	-2.0 - -1.0	< -2.0
COASTAL SLOPE (%)	> 14.7	10.9 – 14.65	7.75 – 10.85	4.6 –7.7	< 4.55
RELATIVE SEA-LEVEL CHANGE (mm/yr)	< 1.8	1.8 - 2.5	2.5 - 3.0	3.0 - 3.4	> 3.4
MEAN WAVE HEIGHT (m)	< 1.1	1.1 – 2.0	2.0 – 2.25	2.25 – 2.60	> 2.6
MEAN TIDE RANGE (m)	> 6.0	4.0 - 6.0	2.0 - 4.0	1.0 - 2.0	< 1.0

Key variables and scores used in the USGS CVI for the Pacific Coast.

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CVI (Abuodha and Woodroffe, 2006)

	Very Low	Low	Moderate	High	Very high
Variable	**1**	**2**	**3**	**4**	**5**
Dune height (m)	> 30.1	20.1 - 30.0	10.1 - 20.0	5.1 - 10.0	0 - 5.0
Barrier types	Transg[illegible]	[illegible]	[illegible]	[illegible]	Mainland beach
Beach types	Dissipa[illegible] Longshore bar trough (LBT)	Rhythmic bar beach (RBB)	Transverse bar rip (TBR)	Low tide terrace (LTT)	Reflective (R)
Relative sea-level change (mm/yr)	≤ -1.1 Land rising	-1.0 - 0.99	1.0 - 2.0 Eustatic rise	2.1 - 4.0	≥ 4.1 Land sinking
Shoreline erosion accretion (m/yr)	≥ +2.1 Accretion	1.0 – 2.0 Stable	-1.0 - +1.0 Erosion	-1.1 - -2.0 Erosion	≤ -2.1 Erosion
Mean tidal range (m)	≤ 0.99 Microtidal	1.0 – 1.9 Microtidal	2.0 – 4.0 Mesotidal	4.1 – 6.0 Mesotidal	≥ 6.1 Macrotidal
Mean wave height (m)	0 – 2.9	3.0 – 4.9	5.0 – 5.9	6.0 – 6.9	≥ 7.0

The first three variables replaced the geomorphology and coastal slope, variables identified by USGS (2004).

Key variables and scores used in a CVI for the Australian beach case.

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Coastal Sensitivity Index (CSI) (Shleupner, 2005)

Sensitivity to Inundation and Erosion	*1*	*2*	*3*
	Low	**Intermediate**	**High**
1. **Morphology and Elevations**			
a. Relative elevation	High (>20 m, mountainous inland area)	Intermediate (>10 to ≤ 20 m, hilly inland area)	Low (0 to 10m, flat land, lake, wetlands)
b. Coastal morphology	steep coast protected through rubble	active cliffs	sand beaches
	lifted steep coast (>100m)	low steep coast	muddy bays
	lifted rocky shore	stone beach, rocky shore	
		mangroves	
c. $a^2 + b^2 / 2$	1 to 3	4 to 6	7 to 9
2. Erodibility (based on geology)	**Low**	**Intermediate**	**High**
	volcano cones	lime	alluvium
	lava flows	unconsolidated volcanic breccia	deeply weathered volcanites
		heat tuff	pumice
			tuff
3. Exposition to wind regime	leeward	other coast	windward
4. Natural protection	sheltered by bay/island/reef	partly sheltered	open coastal area
5. Sedimentation	**High**	**Intermediate**	**Low**
	shelf area with sedimentation	shelf without sedimentation	shelf without sedimentation

Key variables and scores used in the CSI in Martinique.

Coastal Vulnerability Index – CVI

The **third** step deals with the **integration** of the **key variables** in a **single index** (i.e. the final CVI) using different formulas:

Product mean: $$CVI_1 = \frac{(x_1 * x_2 * x_3 * x_4 * \ldots x_n)}{n},$$

Modified product mean: $$CVI_2 = \frac{[x_1 * x_2 * ½(x_3 + x_4) * x_5 * ½(x_6 + x_7)]}{n - 2},$$

Average sum of squares: $$CVI_3 = \frac{(x_1^2 + x_2^2 + x_3^2 + x_4^2 + \ldots x_n^2)}{n},$$

Modified product mean (2): $$CVI_4 = \frac{(x_1 * x_2 * x_3 * x_4 * \ldots x_n)}{5^{(n-4)}},$$

Square root of product mean: $$CVI_5 = [\,CVI_1\,]^{½},$$ and

Sum of products: $$CVI_6 = 4x_1 + 4x_2 + 2(x_3 + x_4) + 4x_5 + 2(x_6 + x_7).$$

Where: n =variables present; x_1=mean elevation; x_2=local subsidence trend; x_3=geology; x_4=geomorphology; x_5=mean shoreline displacement; x_6=maximum wave height; x_7=mean tidal range.

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Coastal Vulnerability Index – CVI

The CVI formulation based on the square root of product mean (CVI_5) has been widely used in applications at the local, regional and supra-regional level (Thieler and Hammar-Klose, 1999; Thieler et al., 2002).

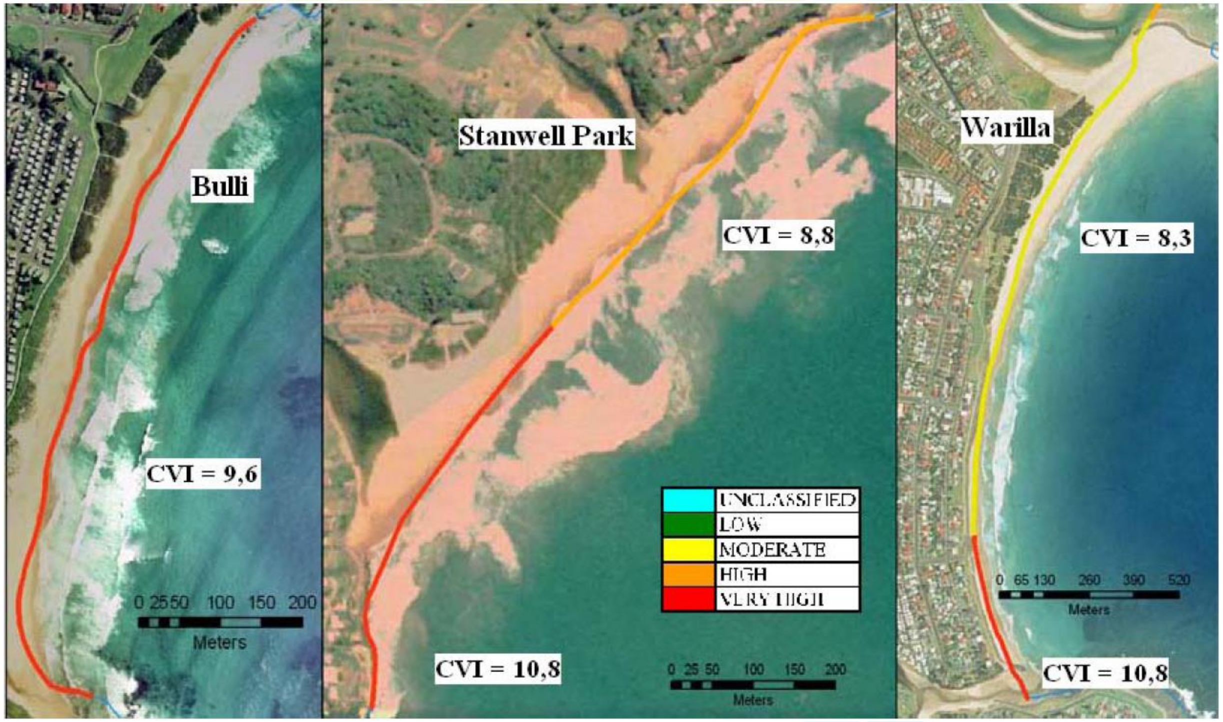
United States Geological Survey (USGS) uses 6 variables combined through the following equation:

$$CVI = \sqrt[2]{\frac{a \cdot b \cdot c \cdot d \cdot e \cdot f}{6}}$$

a = geomorphology;
b = shoreline change rates;
c = coastal slope;
d = relative sea level rate;
e = mean significant wave height;
f = mean tidal range.

Coastal Vulnerability Index – CVI

In the **fourth** step CVI values are **classified** in n different groups (e.g. 3, 4 or 5) using n-1 percentiles as limits (e.g. 25%, 50%, 75%).
This classification enables the **evaluation** of the **relative coastal vulnerability** of the different studied coastal parcels (such as sub-areas included in a wider coastal system).



(Source: Abuodha and Woodroffe, 2006)

CVI for sea level rise impacts (Özyurt, 2007)

Aim: to assess impacts induced by sea level rise.

The index is determined through the **integration** of **5 sub-indices**, each one **corresponding** to a **specific sea level rise related impact:**

- coastal erosion;
- flooding due to storm surges;
- permanent inundation;
- salt water intrusion to groundwater resources;
- salt water intrusion to rivers/estuaries).

Each **sub-index** is determined by the **semi-quantitative** assessment of both **physical** and **human** influence parameters.

Source: Özyurt (2007) and Özyurt et al. (2008)

Interreg Greece-Italy
European Regional Development Fund
EUROPEAN UNION
Triton

TRITON
Development of management tools and directives for immediate protection of biodiversity in coastal areas affected by sea erosion and establishment of appropriate environmental control systems

CVI for sea level rise impacts (Özyurt, 2007)



Physical parameters

- Rate of SLR;
- Geomorphology;
- Coastal slope;
- Significant wave height;
- Sediment budget;
- Tidal range;
- Proximity to coast;
- Type of aquifer;
- Hydraulic conductivity;
- Depth to groundwater level above sea;
- River discharge;
- Water depth at downstream.



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CVI for sea level rise impacts (Özyurt, 2007)

Parameters of human influence

- Reduction of sediment supply;
- River flow regulation;
- Engineered frontage;
- Groundwater consumption;
- Land use pattern;
- Natural protection degradation;
- Coastal protection structures.

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CVI for sea level rise impacts (Özyurt, 2007)

		Range				
		Very low	**Low**	**Moderate**	**High**	**Very high**
Physical Parameters		**1**	**2**	**3**	**4**	**5**
Rate of SLR	mm/yr	<1	1-2	2-5	5-7	7-9 and over
Geomorphology		Rocky cliff coasts, fiords	Medium cliffs, indented coasts	Low cliffs, glacial drift, alluvial plains	Cobble beaches, estuary, lagoon	Barrier beach, sand beach, salt marsh, mudflats, deltas, mangrove, coral reefs
Coastal slope		>1/10	1/10-1/20	1/20-1/30	1/30-1/50	1/50-1/100
Significant wave high	m	<0.5	0.5-3.0	3.0-6.0	6.0-8.0	>8.0
Sediment budget		More than 50% of the shoreline is in accretion	Between 10-30% of the shoreline is in accretion	Less than 10% of the shoreline is in erosion or in accretion	Between 10-30% of the shoreline is in erosion	More than 50% of the shoreline is in erosion

Physical parameters and corresponding ranges (source: Özyurt, 2007).

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CVI for sea level rise impacts (Özyurt, 2007)

		Range				
		Very low	**Low**	**Moderate**	**High**	**Very high**
Physical Parameters		**1**	**2**	**3**	**4**	**5**
Tidal range	m	>6.0	4.0-6.0	2.0-4.0	0.5-2.0	<0.5
Proximity to coast	m	>1000	700-1000	400-700	100-400	<100
Type of aquifer		Leaky confined		Confined		Unconfined
Hydraulic conductivity	m/day	0-12	12-28	28-41	41-81	>81
Depth to groundwater level above sea	m	>2.00	1.25-2.00	0.75-1.25	0.00-0.75	<0,00
River discharge	m^3/s	>500	250-500	150-250	50-150	0-50
Water depth at downstream	m	≤1	2	3	4-5	>5

Physical parameters and corresponding ranges (source: Özyurt, 2007).

CVI for sea level rise impacts (Özyurt, 2007)

Range					
	Very low	**Low**	**Moderate**	**High**	**Very high**
Human Parameters	**1**	**2**	**3**	**4**	**5**
Reduction of sediment supply	>80%	60-80%	40-60%	20-40%	<20%
River flow regulation	Not affected		Moderate affected		Strongly affected
Engineered frontage	<5%	5-20%	20-30%	30-50%	>50%
Groundwater consumption	>20%	20-30%	30-40%	40-40%	>50%
Land use pattern	Protected area	Unclaimed	Settlement	Industrial	Agricultural
Natural protection degradation	>80%	60-80%	40-60%	20-40%	<20%
Coastal protection structures	>50%	30-50%	20-30%	5-20%	<5%

Parameters of human influence and the corresponding ranges (source: Özyurt, 2007).

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Parameters used to calculate the sub-indeces of each impact of sea level rise (source: Özyurt, 2007)

Impacts of Sea Level Rise	Physical Parameters	Human Influence Parameters
Coastal Erosion	1. **Rate of Sea Level Rise** 2. Geomorphology 3. Coastal Slope 4. Significant Wave Height 5. Sediment Budget 6. Tidal Range	1. Reduction of Sediment Supply 2. River Flow Regulation 3. Engineered Frontage 4. Natural Protection Degradation 5. Coastal Protection Structures
Flooding due to Storm Surges	1. **Rate of Sea Level Rise** 2. Coastal Slope 3. Significant Wave Height 4. Tidal Range	1. Engineered Frontage 2. Natural Protection Degradation 3. Coastal Protection Structures
Inundation	1. **Rate of Sea Level Rise** 2. Coastal Slope 3. Tidal Range	1. Natural Protection Degradation 2. Coastal Protection Structures
Salt Water Intrusion to Groundwater Resources	1. **Rate of Sea Level Rise** 2. Proximity to Coast 3. Type of Aquifer 4. Hydraulic Conductivity 5. Depth to Groundwater Level Above Sea	1. Groundwater consumption 2. Land Use Pattern
Salt Water Intrusion to Rivers/Estuaries	1. **Rate of Sea Level Rise** 2. Tidal Range 3. Water Depth at Downstream 4. Discharge	1. River Flow Regulation 2. Engineered Frontage 3. Land Use Pattern

(Source: Özyurt, 2007)

CVI for sea level rise impacts (Özyurt, 2007)

$$CVI_{impact} = \frac{(0{,}5 \times \sum_{1}^{n} PP_n) + (0{,}5 \times \sum_{1}^{m} HP_m)}{CVI_{least\ vulnerable}}$$

PP = Physical Parameters;
HP = Human Influence Parameters;
n and **m** = the number of physical and human influence parameters, respectively, considered for a particular impact;
$CVI_{least\ vulnerable}$ = the value of the sub-index for the least vulnerable theoretical case, meaning all parameters equal to 1.

Fine-tuning of the method can include **weighting** of individual parameters and of groups of parameters (physical PP and human influence HP groups).

In the above formula no weight definition is considered; meaning that parameters contribute equally to the definition of the sub-indices.

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CVI for sea level rise impacts (Özyurt, 2007)

CVI index values vary between 1 and 5, and can be integrated in an **overall final index CVI (SLR),** according to the following formula:

$$\mathrm{CVI(SLR)}=\frac{\sum_{i=1}^{5}\text{Total Impact}_i}{\sum_{i=1}^{5}\text{Least Vulnerable Case}_i}$$

The formula may integrate **all the five sub-indexes** or only **a subset** of the five considered impacts, those playing a more relevant role in the vulnerability of the studied coastal system.

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Composite Vulnerability Index (Szlafsztein and Sterr, 2007)

It combines a number of **separate variables** that reflect **natural** and **socio-economic characteristics** that contribute to **coastal vulnerability** due to natural hazards;

Selected **indicators** can **differ** in **number**, **typology** and **scales** of evaluation according to the study area.

Data for each variable are placed into **classes**, assigning a rank between 1 and 5 according to their relative vulnerability (i.e. very low, low, moderate, high and very high).

Each indicator is then **weighted** according to its importance in determining the vulnerability of coastal areas to natural hazards.

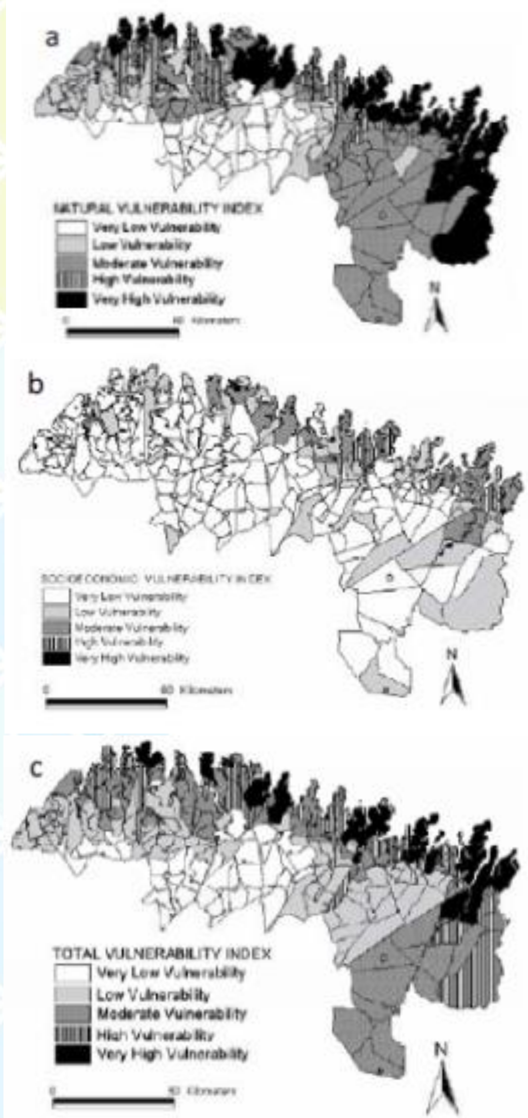
Indicators are then **aggregated** according to an appropriate set of **weights**.

Composite Vulnerability Index

Natural parameters:
- coastline length and sinuosity;
- continentality in terms of coastline density into municipal areas;
- coastal feature (estuarine, beach etc.);
- coastal protection measures;
- fluvial drainage;
-flooding areas.

Socio-economic parameters:
- total population and total population affected by floods (both divided into age classes);
- density of population;
- non-local population (i.e. born elsewhere but living in considered areas);
- poverty;
- municipal wealth.

Separated **GIS-layers** are overlaid and the variable scores combined into natural and socio-economic vulnerability indices, which when combined represent the **total vulnerability index.**



(Source: Szlafsztein and Sterr, 2007)

Multi-scale coastal vulnerability index (McLaughlin and Cooper (2010)

Basic assumptions:

- Indices incorporating a diversity of indicators have been used extensively to provide **spatial analyses** of the degree of **vulnerability**.
- Such indices are typically applied at global and national scales, and they involve **varying degrees** of **simplification** and **aggregation** of information.
- The **degree of simplification** that is desirable depends on the **management scale**, and higher resolution is required at the local compared to the global scale.

Importance of **spatial scale** in developing indices of vulnerability:

while a **common** index **architecture** can be applied, the **selection of variables** must take account of the scale at which the hazard is to be assessed.

Multi-scale coastal vulnerability index (McLaughlin and Cooper (2010).

The index integrates three sub-indices:

- a **coastal characteristic sub-index**, describing the resilience and coastal susceptibility to erosion;
- a **coastal forcing sub-index**, characterizing the forcing variables contributing to wave-induced erosion;
- a **socio-economic sub-index**, describing targets potentially at risk.

The computation of each sub-index is determined on the basis of various **variables**, whose specific **identification** (number and typology) **depends** on the considered **application scale** (i.e. national, regional or local).

(Source: McLaughlin and Cooper, 2010)

The identified variables are **ranked** according to a **1-5 scale** in order to express their contribution to the coastal system vulnerability; with 5 being the highest value and 1 the lowest.

Sub-index	Variable	1	2	3	4	5
CC	Shoreline type	High cliff (>40 m)	Medium cliff (20-40 m)	Low cliff (10-20 m)	Shingle ridge/bar	Sand beach/dune
	Rivers	Absent				
	Solid geology	Plutonic, volca high–medium metamorphics				sediment,
	Drift Geology	Bedrock, urba				, peat, glacial lacial outwash
	Elevation	>30				
	Orientation	Not relevant, e.g. sea loughs		Easterly		Northerly
	Inland buffer	500-1000 m inlan				d
CF	Significant wave height (m)	0-0.74 N 0-0.24 E				
	Tidal range (m)	>5				
	Difference in modal and storm waves (m)	<0.10 N <0.10 S	0.10-1.70 N 0.10-0.25 S	1.70-3.30 N 0.25-0.40 S	3.30-4.90 N 0.40-0.55 S	>4.9 N >0.55 S
	Frequency of onshore storms (%)	0-2.8	2.8-5.6	5.6-8.4	8.4-11.2	>11.2
SE	Settlement	No settlement	Village	Small town	Large town	City
	Cultural heritage	Absent				Present

At the national scale geology was deemed as essential variable to distinguish areas of potential vulnerability to erosion: there is a wide variation in the types of solid and drift geology.

Were considered important at the National and borough council scale but not included in the local scale index (little local variations)

National scale application in Northern Ireland (McLaughlin and Cooper, 2010). Resolution: 500 x 500 mq.

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At the **borough council** scale it was possible to use a more relevant **landform variable** integrating both the solid and drift geology.

Landform are classified according to their **slope**, **volume** and **lithology**.

	Variable	1	2	3	4	5
Characteristics	Landform				ridges	
	Elevation (m)	>30	20 to <30	10 to <20	5 to <10	<5
	Rivers	Absent	Stream	Small river	Medium river	Large river
	Inland buffer (m from the MHWM)	300 to >1000		50 to <300		0 to <50
Forcing	Tidal range (m)	>5	3.5 to <5	2 to <3.5	1 to <2	<1
	Storm probability (based on coastal orientation)	North easterly	Northerly Easterly	North westerly South easterly	Southerly South westerly	Westerly
	Morpho-dynamic state (Dean's parameter)	Rocky coasts and gravel beaches	<1.5 or >5.5	<1.5 to <5.5	>1.5 to >5.5	<1.5 to >5.5
Socio-economic	Cultural heritage	Absent				Present
	Landuse	Water bodies Marsh/bog and moor Sparsely vegetated areas Bare rocks	Natural grasslands Coastal areas	Forest	Agriculture	Urban and industrial Infrastructure
	Population	0 to <5	5 to <20	20 to <50	50 to <100	100 to >200
	Roads	Absent	Minor roads (<4 m)	Minor roads (>4 m)	B-class roads	A-class roads
	Railways	Absent				Present
	Conservation designation	Absent		European International		National

Regional scale (McLaughlin and Cooper, 2010). Resolution: 25 x 25 mq.

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A number of variables could be used in all three index scales, with the level of detail increasing with the resolution of the study area.

TABLE 3 Local vulnerability ranking

	Variable	1	2	3	4	5
Coastal characterisitcs	Landform	High resistance cliff Seawall	Low resistance cliff	Multiple sand dune ridges	Single sand dune ridges Gravel and	Mudflat Saltmarsh Beach –
	Elevation (m)					
	Rivers					
	Inland buffer (m from MHWM)					
Coastal forcing	Storm probability (based on coastal orientation)	North easterly	Northerly Easterly	North westerly South easterly	Southerly South westerly	Westerly
	Morphodynamic state (Dean's parameter)	Inland areas and rocky cliffs	Dissipative or Reflective	Intermediate	Reflective Intermediate Dissipative	Dissipative Reflective
Socio-economic	Cultural heritage	Absent				Present
	Landuse	Rocky cliffs	Scrub	Beach Sand dunes	Agricultural land	Urban Residential
	Population					
	Roads					

At the National scale only major rivers were identified; at the local scale the influence of smaller rivers becomes of increasing importance.

Increasing detail for population and roads from the national to the local scale:

1. from the identification of cities settlements/villages to the census of number of people (houses);
2. from main national roads to minor roads and footpaths.

(McLaughlin and Cooper, 2010). Resolution: 1 x 1mq.

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Multi-scale coastal vulnerability index

- Sub-indices are calculated by the **sum** of the values of the relative **variables**;
- the results were then **normalized** by working the results out as a **percentage** of the **maximum** and **minimum scores;**
- the obtained number is then standardized to the **range 0-100**.

Coastal Characterization (CC) sub-index = {[(sum of CC var.) – 7]/28} x 100

Coastal Forcing (CF) sub-index = {[(sum of CF var.) – 4]/16}·x 100

Socio-Economic (SE) sub-index = {[(sum of SE var.) – 6]/24}·x 100

The final CVI index is computed through the **average** of the three sub-index values, as shown in the formula below:

CVI = (CC sub-index + CF sub-index + SE sub-index) / 3

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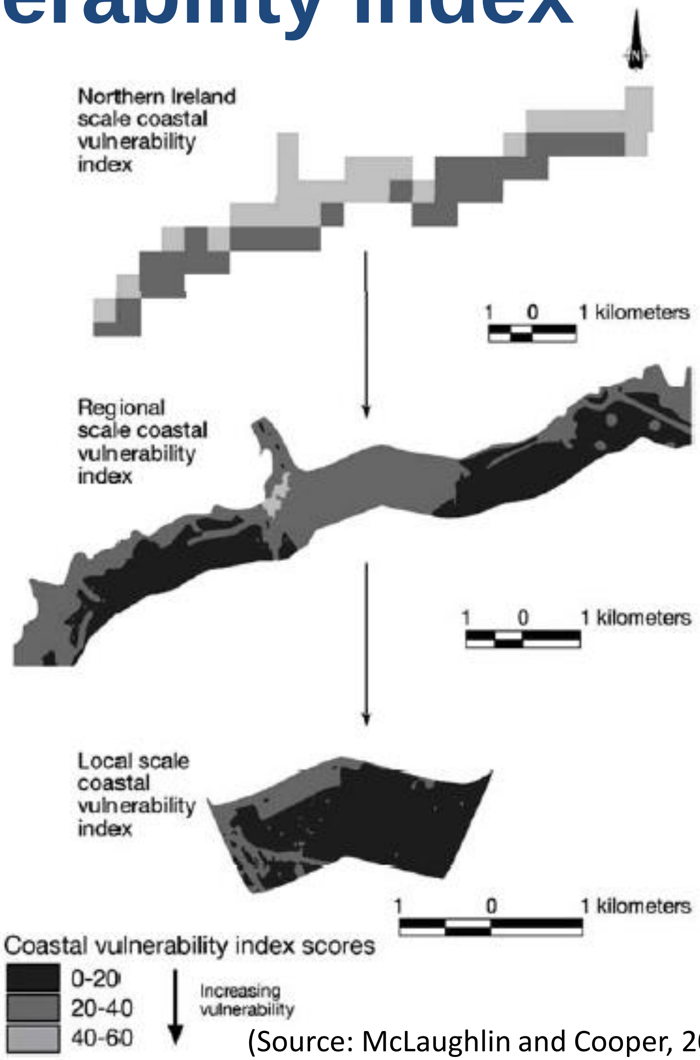
Multi-scale coastal vulnerability index

CVI values can be visualized as a colour-coded **vulnerability maps**.

The CVI index is easy to calculate and can be applied to various spatial scales, thus supporting multiscale analysis important for costal planning and management.



(Source: McLaughlin and Cooper, 2010)

Multi-scale coastal vulnerability index

There is no ‘one size fits all’ index of coastal vulnerability that can be applied at all scales:

Global-scale : enable international approaches to be coordinated and global policies to be debated;

National scale : allow the definition of national level policy and the prioritization of resources;

Local scale : is commonly implemented to define the practical response to coastal hazards.

Review: assessment of coastal risk of climate related hazards

(Satta et al., 2016; Satta et al., 2017)

Climatic threat/issue	Name of indicator	Purpose	Scale	Methods/tools aggregation	Highlights
Sea level rise, storms, erosion, droughts	Multi-Scale Coastal Risk Index for Local Scale (CRI-LS), 2016	Identify areas where the risk is relatively high at the local scale, identifying the most suitable adaptation measures.	Local scale	Variable ranked and weighted through an expert judgement elicitation. Resulting values are hosted in a geographic information system (GIS) platform: enables the individual variables and aggregated risk scores to be color-coded and mapped across the coastal hazard zone.	Interesting choice of indicators & methodology for multi-hazard scenario. However, it is not possible to apply it due to stakeholders involvement phase in identification of weights: the case study area is too wide to apply such methodology.
	Coastal Risk Index for risk assessment in the Mediterranean region (CRI-MED), 2017	Assess coastal risks and vulnerabilities associated with the physical and socioeconomic impacts of climate change in all Mediterranean coastal zones	Regional scale	Based on a GIS application; aggregation based on classification & ranking into sub-indices, consequently merged to calculate the overall index	

Satta et al., 2016: CRI-LS

- **Hotspot** of the Mediterranean Moroccan coast: **Coastal zone of Tetouan**
- Provides a set of maps that allow **identifying areas** within the coastal hazard zone with **relative higher risk** from climate-related hazards
- Can be used to **support coastal planning** and **management** process in selecting the most **suitable adaptation measures**

Satta et al., 2017: CRI-MED

- **Spatial risk index**, which combines variables representing **different aspects of risk**: coastal areas of relatively higher risk emerge from the **integration of the variables**
- Creates an **interface** between **theoretical concepts** of risk and the **decision-making process** relating to disaster risk reduction
- Allow researchers and policy-makers to identify coastal areas most at risk from coastal erosion and coastal flooding: resulting risk maps enable **identification** of **suitable** and **less suitable areas** for urban settlements, infrastructures and economic activities.

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Review: assessment of coastal risk of climate related hazards

(Satta et al., 2017)

CRI-MED Case study: Mediterranean Sea

- Identify areas at risk of coastal erosion and inundation
- 62% low or extremely low
- 19% moderate
- 18% high or extremely high

Mediterranean coastal zone risk map

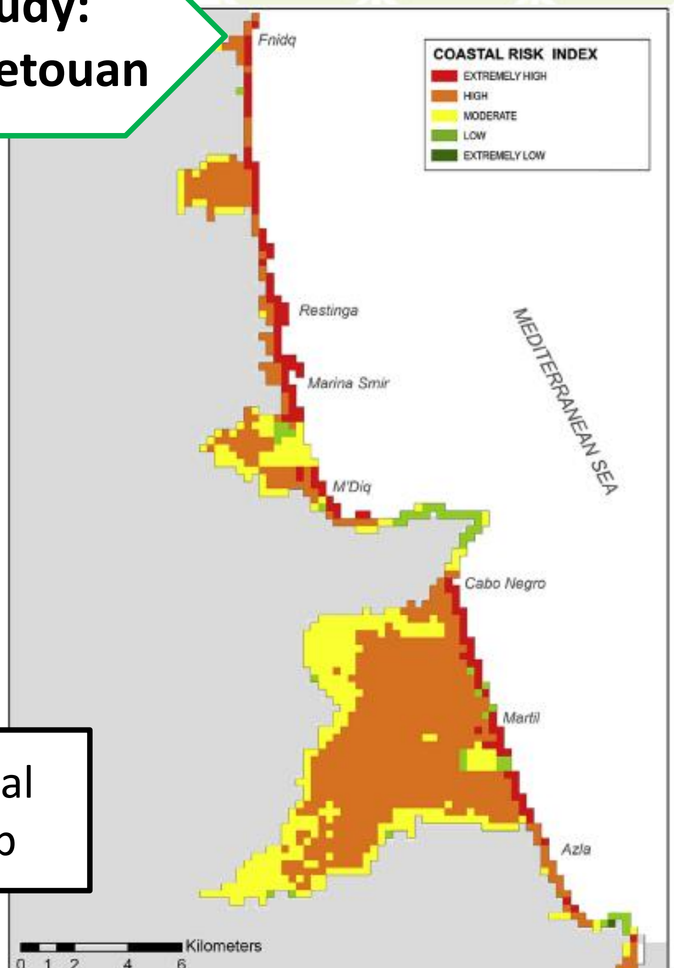
The map shows that a relatively small number of areas are at extremely high risk (4%)

(Source: Satta et al., 2017)

Review: assessment of coastal risk of climate related hazards

(Satta et al., 2016)

CRI-LS Case study: Coastal area of Tetouan



Tetouan coastal zone risk map

- Identify levels of risk for the shoreline and hinterland areas potentially affected by flooding
- 3 sub-indices (hazard, vulnerability and exposure)
- Qualitative risk classes (extremely high, high, medium, low, extremely low)

(Source: Satta et al., 2016)

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Application of a Coastal Vulnerability Index. A case study along the Apulian Coastline, Italy

(Pantusa et al., 2018)

- Based on the methodology proposed by Gornitz et al., 1990,1991

$$CVI = \sqrt{(a \cdot b \cdot c \cdot d \cdot e \cdot f \cdot g \cdot h \cdot i \cdot l)/10}$$

- Considers 10 variables divided into 3 groups:
    - **Geological** (geomorphology, coastal slope, shoreline erosion/accresion, emerged beach width, dune width)
    - **Physical process** (relative sea level change, mean significant wave height, mean tide range)
    - **Vegetation** (width of vegetation behind the beach, Posidonia oceanica)

- Geography Information System (GIS) platform to better process the data
    - The coast has been divided into 24 transects
    - Each transect is classified with the respective CVI category

- A comparison with the Coastal Sensitivity Index (CSI) shows quite similar results

- FUTURE AIMS:
compare this CVI with more complex numerical models

(Source: Pantusa, 2018)

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Conclusions

- Indicators and index-based approaches are generally **simple to implement**.

- Their **application** at the scale of Europe and Regional Seas essentially **depends on data availability** that could be a limiting factor in the practical application.

- **Adjustments** of the methodology should be needed in order to address relevant characteristics **in different regions** and/or to make best use of available data.

- Indicators or index-based approaches are useful tools for a scoping or **“first look” assessment** - thus supporting identification of **priority vulnerable coastal areas and systems**.

Conclusions

- They are not useful for a more detailed quantitative assessment of costal vulnerability and the related identification of adaptation measures.

- Due to their simplified approaches, indicators and indices can be also very useful for communication purposes.

- Index-based approaches are not immediately transparent since the final computed indices do not allow the user to understand the assumptions and evaluation that led to its calculation.

- A clear explanation of the adopted methodology is therefore essential to support the proper use of these methods.

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Thanks for your attention!

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Proactive adaptation

Aims to reduce a system’s vulnerability by minimizing risk and/or enhancing the system’s resilience.

5 objectives of proactive adaptation for coastal zones (Nicholls and Klein; 2005) :

- increasing **robustness** of **infrastructural designs** and long-term investments;
- increasing **flexibility** of vulnerable managed systems;
- enhancing **adaptability** of vulnerable natural systems;
- **reversing maladaptive** trends;
- improving **societal awareness** and **preparedness**.

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Overview table of main indicators and index-based characteristics

Method	Spatial scale	Spatial resolution	Temporal scale	Main driver of changes	Main climate change impacts	Coastal systems	Assessment targets	Adaptation measures	Main data input	Output
Eurosion	European scale	Indicators and indexes were calculated at the regional level, i.e. NUTS 1 or NUTS 2 depending on the country	Depending on time scale and resolution of input data	Sensitivity indicators, e.g. sea level rise, shoreline evolution, sediment budget, etc.	Coastal vulnerability to erosion	Coastal zone in general	Targets represented by the impact indictors, i.e. population, urban and industrial areas and areas of high ecological value	Partially addressed by the indicator "engineered frontage", also including protection structure	Eurosion database: terrestrial boundaries, maritime boundaries, shoreline, bathymetry, elevation, geomorphology and geology, erosion trends and coastal deference works, hydrograph, infrastructure, wave and wind climate, tidal regime, sea level rise, land cover, areas of high ecological values	Sensitivity score Impact score Finale score, i.e. exposure to coastal erosion
CVI Index	Applied at the local, regional, supra-regional scale. Theoretically it can be applied to any spatial scale; it depends on data availability	Depending on the considered spatial level and data availability	Depending on time scale and resolution of input data	Sea level rise	Coastal vulnerability to sea level rise, in particular due to erosion and/or inundation	Coastal zone in general	Physical system	Not addressed by the index	Data input depends on key variables used to calculate the CVI index. Most common ones include: geomorphology, geology, elevation, coastal slope, shoreline change rates, significant wave height, relative sea level change, tidal range	CVI tables and maps; CVI is classified in groups using percentage limits
CVI (SLR)	Applied at the local scale. It appears to be suitable for the regional scale as well. Actually spatial scale of application depends on data availability	Depending on the considered spatial level and data availability	Depending on time scale and resolution of input data	Sea level rise	Coastal erosion, flooding due to storm surges, permanent inundation, salt water intrusion to groundwater resources and salt water intrusion to rivers/estuaries	Applied to a delta area by Özyurt (2007) and Özyurt *et al.* (2008). Theoretically it can be applied to the coastal zone in general	Physical system; some component of the socio-economic (i.e. land use) and ecological systems (i.e. natural protection degradation) are considered	Considered in terms of evaluation of coastal protection structures	12 physical (e.g. geomorphology, sediment budget and water depth at downstream) and 7 human influence (e.g. reduction of sediment supply and land use pattern) parameters	5 CVI sub-indices, each one related to a specific sea level rise impact. These are integrated in a final CVI (SRL) index.
Composite Vulnerability Index	Applied at the regional scale in Brazil (State of Para). Spatial scale of application depends on data availability	Depending on the considered spatial level and data availability. In the application to the State of Para, spatial resolution was the census collection area (343 in total)	Depending on time scale and resolution of input data	Natural and socio-economic parameters used to derive the index	The index assesses coastal vulnerability in general, i.e. not specifically referring to climate change vulnerability. It also considers coastal flooding that can be strongly influenced by climate changes drivers.	Coastal zone in general	Physical and socio-economic targets	Considered in terms of evaluation of coastal protection measures	Natural parameters: coastline length and sinuosity, continentality in terms of coastline density into municipal areas, coastal features (estuarine, beach etc.), coastal protection measures, fluvial drainage, flooding areas. Socioeconomic parameters: population and population affected by floods, density of population, non-local population (i.e. born elsewhere but living in considered areas), poverty, municipal wealth	Three different indices: natural, socio-economic and total vulnerability index. Indexes can be represented in maps
Multi-scale CVI	Applied from the local to the national scale. Actually spatial scale of application depends on data availability	National scale: 500 X 500 m² grid cells Regional scale: 25 X 25 m² grid cells Local scale: 1 X 1 m² grid cells Spatial resolution depends also on data availability	Depending on time scale and resolution of input data	Forcing variables contributing to wave-induced erosion, i.e.: significant wave height, tidal range, storm and modal wave height, storm frequency	Coastal erosion	Different typologies of coast (e.g. cliff, sandy beaches)	Mainly socio-economic targets	Not addressed by the index	Key variables are defined according to the specific application (location and scale). Variables refer to: (i) resilience and coastal susceptibility to erosion, (ii) forcing variables contributing to wave-induced erosion, (iii) socio-economic target potentially at risk	Three sub-indices: (i) coastal characteristic sub-index, (ii) coastal forcing sub-index, (iii) socio-economic sub-index. Final CVI index. Indices can be represented in maps

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Methods for assessing coastal vulnerability to climate change

ETC CCA Technical Paper 1/2011

Emiliano Ramieri, Andrew Hartley, Andrea Barbanti, Filipe Duarte Santos, Ana Gomes, Mikael Hilden, Pasi Laihonen, Natasha Marinova, Monia Santini

European Environment Agency

European Topic Centre on Climate Change Impacts, Vulnerability and Adaptation

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Tools and methods for assessing coastal vulnerability to climate change – Part. 2

<u>Dr. Elisa Furlan</u>

Dr. Silvia Torresan, Maria Katherina Dal Barco,
Prof. Andrea Critto

Summer School
Bari, Italy, 2nd October 2019

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Part 1:

Indicator and index-based methods.

Part 2:

Decision support systems (DSSs) and complex system methods.

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OUTLINE

- Decision Support Systems (DSS): basic concepts and objectives
- The DSS DESYCO: functionalities across case studies
- Introduction to Bayesian Networks (BN)
- Methodological steps for BN implementation
- BN for coastal erosion risk assessment and management
- BN Strengths and Weaknesses
- Bayesian Network application in the frame of the TRITON project
- Future developments...

Vulnerability assessment methods

INCREASING COMPLEXITY

- Indicator-based approaches;
- Index-based methods
- Software based on GIS applications (e.g. decision support systems, DSSs)
- Complex system methods (e.g. Bayesian network, agent-based model)

Source: Ramieri et al., 2011

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Why DSS??

- **Complex** environmental **problems**;
- Need to provide **solutions**.

Growing desire to develop **effective** and **efficient computational methods** and **tools** that facilitate **environmental analysis**, **evaluation** and **problem solving**

Decision Support Systems (DSS)

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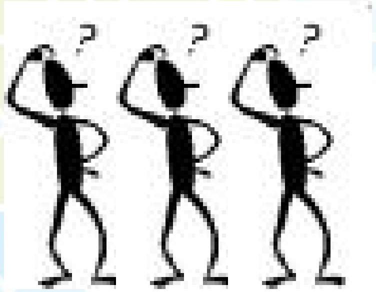
What are we talking about?

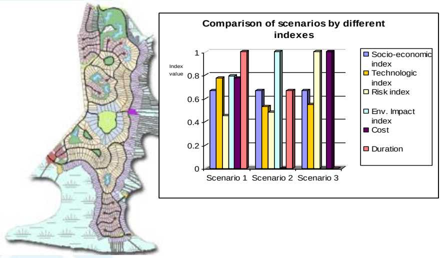
Decision

Problem
People



Support

Providing answers
Aiding not deciding



Systems

Complexity
Computer assisted

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DSS properties and characteristics

Decision Support Systems should focus on effective support and not on automatic selection

↓

They require direct use involvement in the analysis of the decision problem, evaluation of decision outcomes and preference specification

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Decision making and DSS

Decision Support Systems can aid and assist decision makers in **one or more phases** of the decision making process

Functionalities, components and other characteristics are tuned to the goals of the considered assessment/management phase(s)

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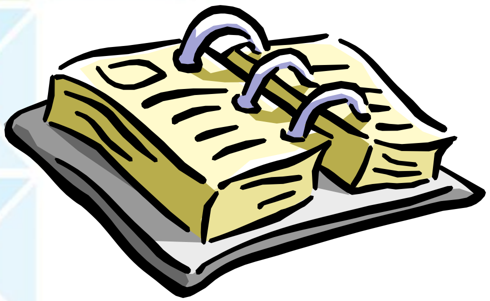
Evolvement of DSSs in relation to technology

STAGE	APPROXIMATE PERIOD	DOMINANT CONCEPT OF DSS	TECHNOLOGIES
I	60s-70s	Data modelling	Databases and MIS (Management Information System)
II	80s	Collabortive & group decision support	Knowledge bases, expert systems, EIS (Executive Information Systems)
III	90s	Knowledge management	OLAP (On Line Analytical Processing), data warehouse, data mining
IV	2000s	Web-based and active DSS	Internet, client-server tools, software agents

DSS framework and structure

The **decisional or conceptual FRAMEWORK** allows to identify and frame the problem of interest by defining main functionalities and methodologies of the system



The **STRUCTURE** is intended as the description of the technical characteristics and links of the components of the DSS (eg. databases, models, user interfaces, GIS)

DSS functionalities

A DSS may help:

- To **integrate different** types of **information** (e.g. GIS data, model outputs)

- To **answer** different **management questions** (e.g. What is the level of risk? What are the remedial technology options? What are the costs? Will the regulatory targets be achieved?)

- To **choose** among **alternative actions** (e.g. prevention, adaptation)

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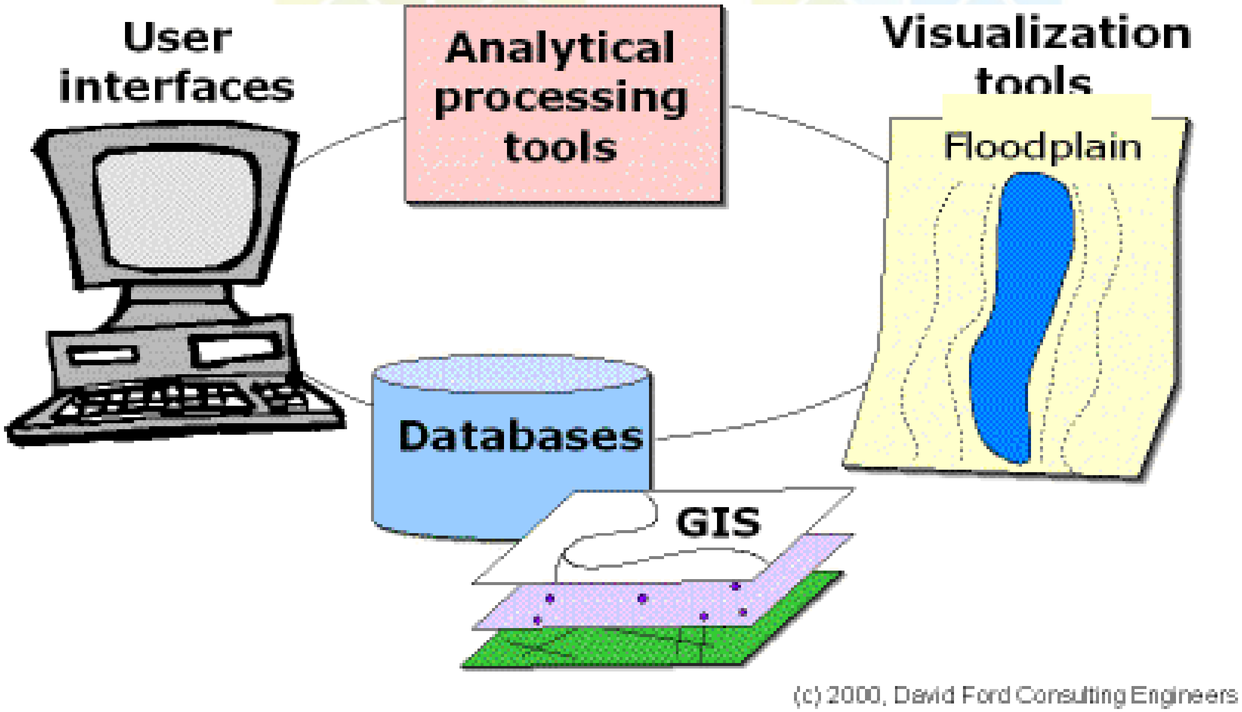
DSS structure/components

Conventional DSSs consist of components for database management, powerful modeling functions and powerful (but simple) user interface designs.
(Shim et al, 2002; Ascough et al., 2002)



DSS outputs

Current, timely information that is accurate, relevant and complete:

- quantitative results from models
  (es. projections and forecasts, "what if?" results)
- analyses and displays of historical data
- displays of facts in various formats
  (es. trend analysis, performance monitoring)
- recommendations
- retrieved relevant documents
- shared content and interaction

a map
a chart
a tabular data summary
a printed report
a data file

Types of DSSs

A DSS can be designed that is:

- very **specific to a particular decision** or component of a particular decision (e.g., a watershed nutrient loading model built for a specific watershed, a Brownfield revitalization model built for a specific industrial site)

- a **framework that allows a particular type of application to be modeled** (e.g., watershed management, site revitalization, sustainable land reuse)

- a **generic framework** for modeling any type of decision (e.g., Analytica (lumina.com), GoldSim, (goldsim.com))

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Spatial DSSs

Spatial Decision Support Systems (SDSS) are decision support systems where **the spatial properties of the data** to be analyzed play a major role in the decision making. Usually, these properties refer to the data's location on the Earth's surface – the so-called **georeferenced data**
(Woods et al, 1999)

SDSS were created to support the analysis of complex spatial problems

SDSS are explicitly designed to provide the user with a decision-making environment that enables the **analysis of geographical information** to be carried out in a flexible manner
(Densham, 1991)

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Spatial DSSs

Spatial decision support relies heavily on maps: the backbone upon which plans and policies are defined

Problems can roughly be classified into:

- **Siting**, i.e. **WHERE** to place some given object (e.g. a dam, a house, a park)
- **Spatial allocation**, i.e. for a predefined location, **WHAT** is the best object among a class of objects to place there (e.g. a crop or a building type)

In the first case, the main issue is **determining** the **location**, whereas in the spatial allocation the unknown is the object itself.

Some problems may require combination of both characteristics (e.g. urban planning)

(Woods et al, 1999)

Spatial DSSs

Environmental decision making through a **Geographic Information System** (GIS) corresponds to **defining** and **calibrating** a model by using the **GIS' functions** to construct a set of **maps**.

Map generation is a partially ordered sequence of activities, which are related by data and control links.

(Source: Woods et al, 1999)

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Spatial DSSs

A **GIS** is a software that provides mechanisms to **store**, **analyze**, **manipulate** and **visualize georeferenced** data.

GIS is used to help decision makers in:

- **Identifying** geographic regions that satisfy one or more criteria;
- **Exploring spatial** and **temporal** relations among georeferenced data;
- Providing **data** for **analysis** and **simulation** models.

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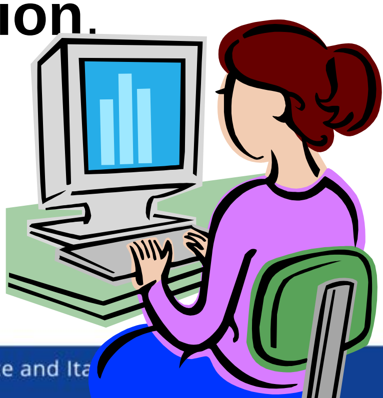
Advantages/benefits for use - 1

- **Structured approach** to problem solving;
- **Summary** of **information**;
- **Integration** of many **information** sources;
- **Enhancement** of effectiveness of **decision process**;
- **Improvement** of interpersonal **communication**, active **participation** and **consensus** building;
- Inclusion of **uncertainty analysis**.



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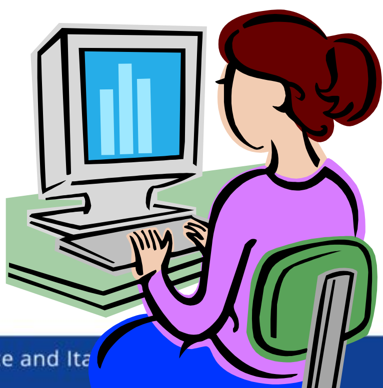
Advantages/benefits for use - 2

- **Identifying** preferred **options** for further discussion;

- **Dealing** with **trade-offs**: social, economic, biophysical, legislation;

- **Flexibility** and **adaptability** to accommodate changes in the environment and in the decision making approach;

- Promoting **learning**.



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Disadvantages/limits of use - 1

- DSS **complexity**;
- Information **overload**;
- Users find the system **too detailed**, **time consuming** and **costly to use**;
- No end **user input before** and **during** the DSS development;
- **Unclear** definition of the **beneficiaries**.

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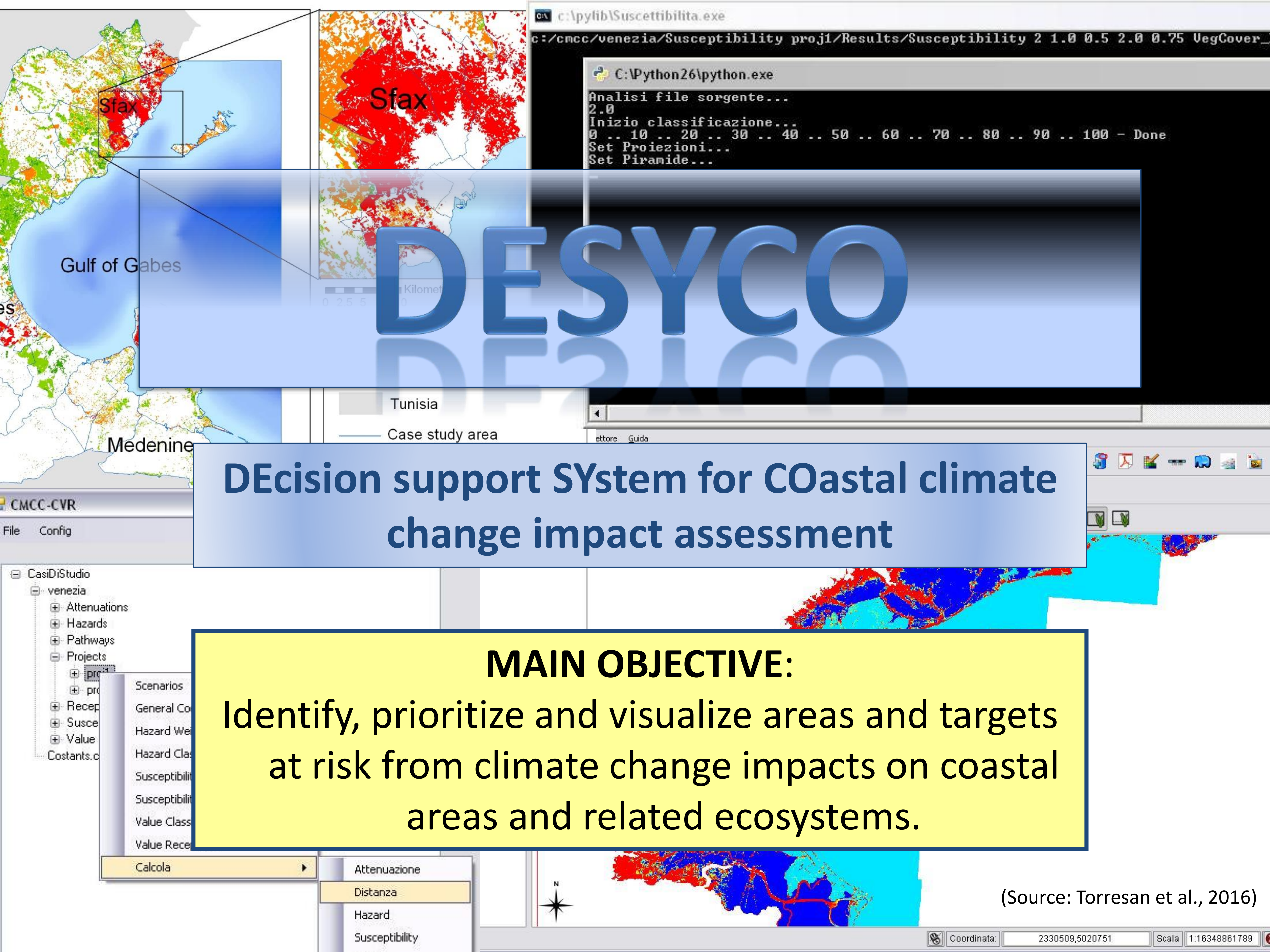
Disadvantages/limits of use - 2

- **Difficulty** in gaining **acceptability** and trust for the **outputs**;
- “**Transfer of power**” perception;
- Need to be **continuously updated**;
- **Uncertainty** of the **model output** and of the **appropriateness** for **solving** the decision question;
- **Limited** computer **ownership** among users;
- **Userfriendliness** is **low**;
- **Lack** of **fields testing**.



DESYCO

DEcision support SYstem for COastal climate change impact assessment

MAIN OBJECTIVE:
Identify, prioritize and visualize areas and targets at risk from climate change impacts on coastal areas and related ecosystems.

(Source: Torresan et al., 2016)

DESYCO can be used to:

- Adopt a **Source-Pathway-Receptor-Consequence** risk assessment approach.
- Analyse long-term **climate change hazard scenarios**.
- **Rank** coastal **receptors** and **areas** vulnerable to or at risk from different climate change impacts.
- Produce **interactive GIS-based maps** (i.e. vulnerability, exposure, risk and damage maps).
- **Transfer information** about potential climate change impacts for **adaptation actions.**

(Source: Torresan et al., 2016)

Specific technical features of DESYCO

- **Two-dimensional visualization** of vulnerability and risk based on raster maps;
- **Multi-target** vulnerability and risk assessment;
- Analysis of **different** climate change **impacts** (e.g. sea level rise inundation, storm surge flooding, water quality variations);
- Integrates **GIS spatial analysis** to calculate indicators: distance and surface calculation, vector analysis (e.g. intersection, union, merge);
- **MCDA module** integrating multiple vulnerability indicators with **expert** and **stakeholder judgment**;
- Flexibility to manage **different input** data (i.e. raster or shape files) provided by different **scenarios models** and **vulnerability datasets**.

(Source: Torresan et al., 2016)

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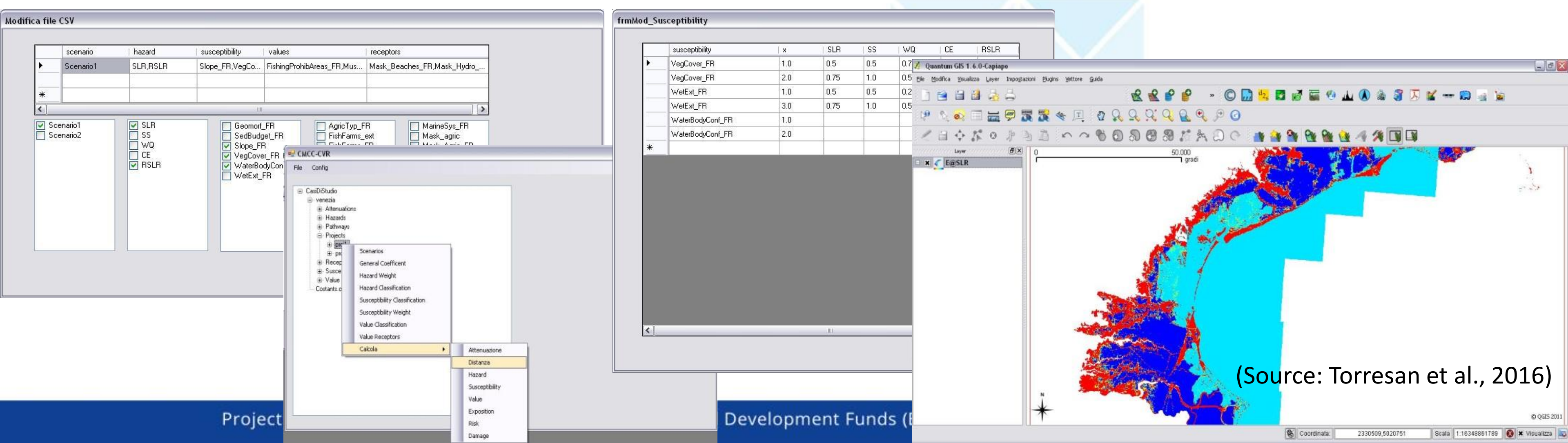
DESYCO: structure

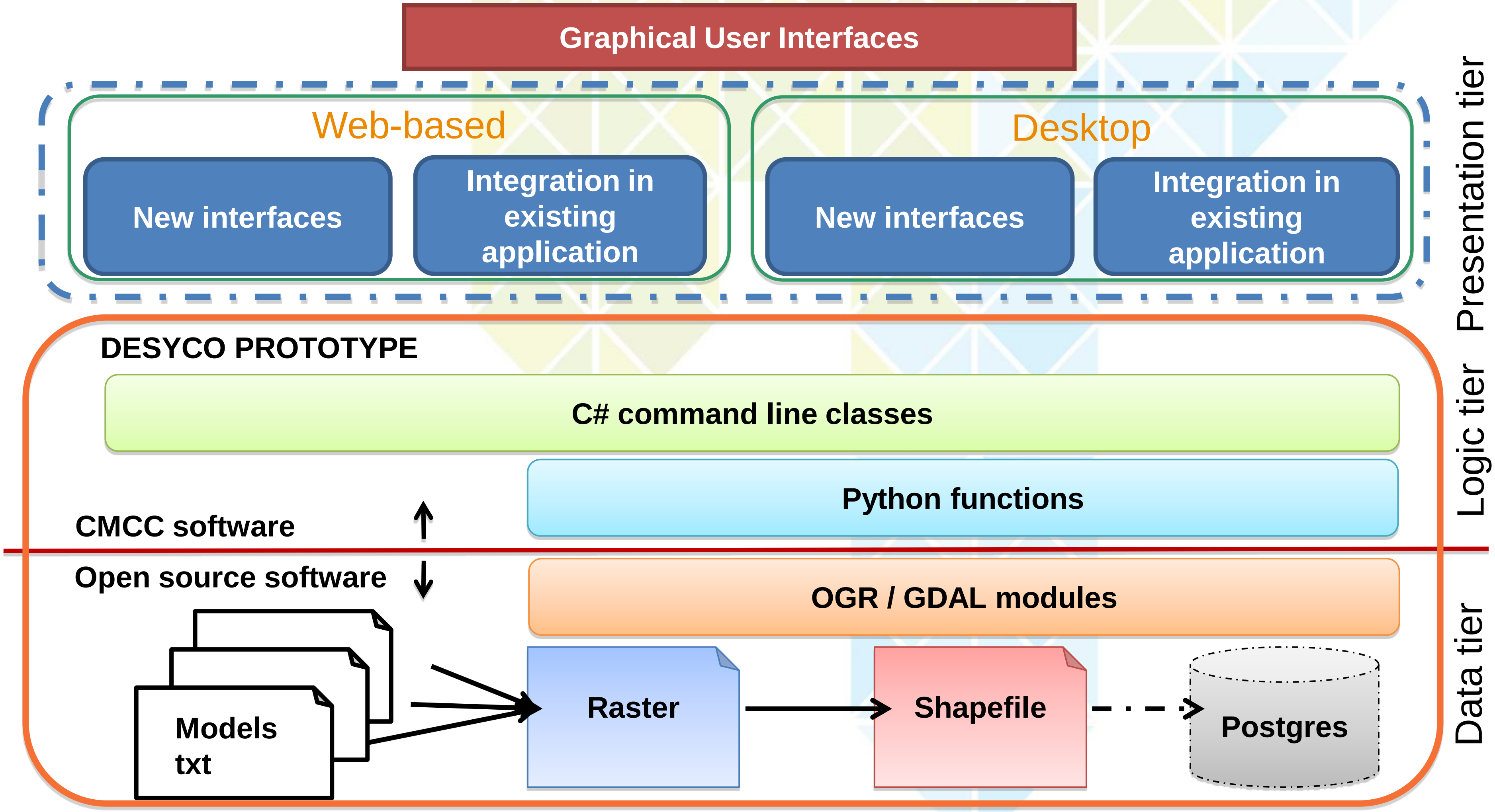
The structure of DESYCO consists of 3 main components:

- **A GEODATABASE with bio-physical and socio-economic data for the investigated coastal area.**
- **Multi-scale SCENARIOS Module, provided by numerical models simulations or time series analysis.**
- **A Relative Risk Model (RRM) for the application of the Regional Risk Assessment (RRA) methodology.**



(Source: Torresan et al., 2016)

DESYCO Software architecture



(Source: Torresan et al., 2016)

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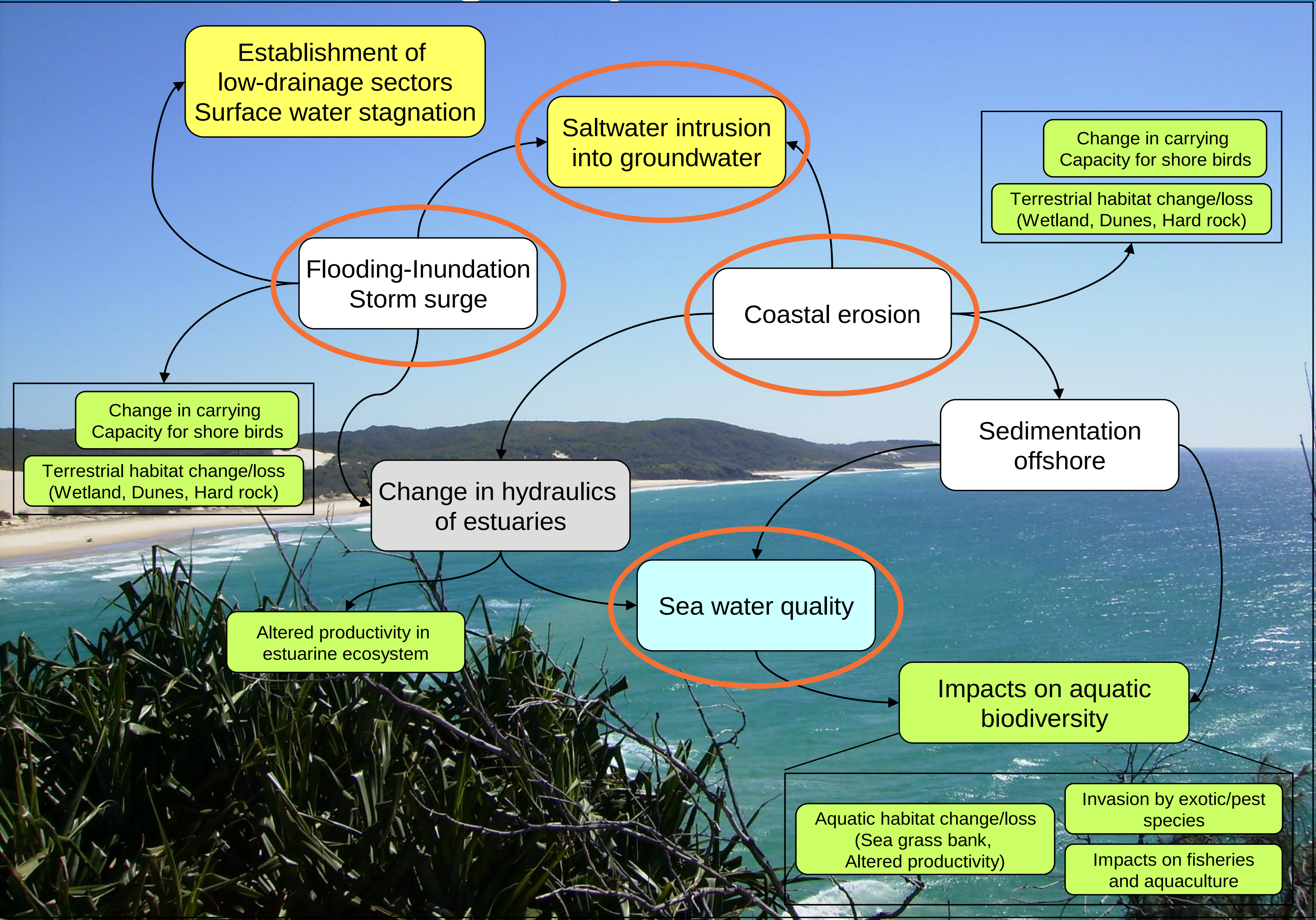
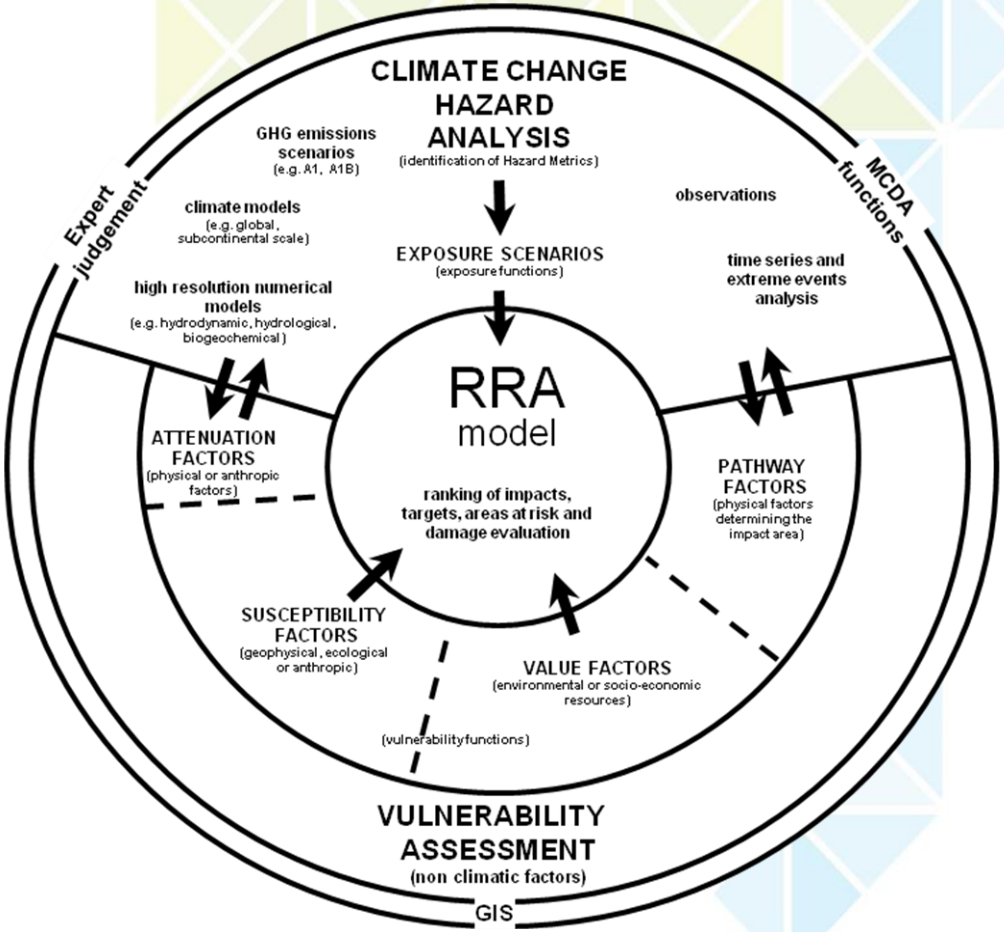
Climate change impacts in coastal zones

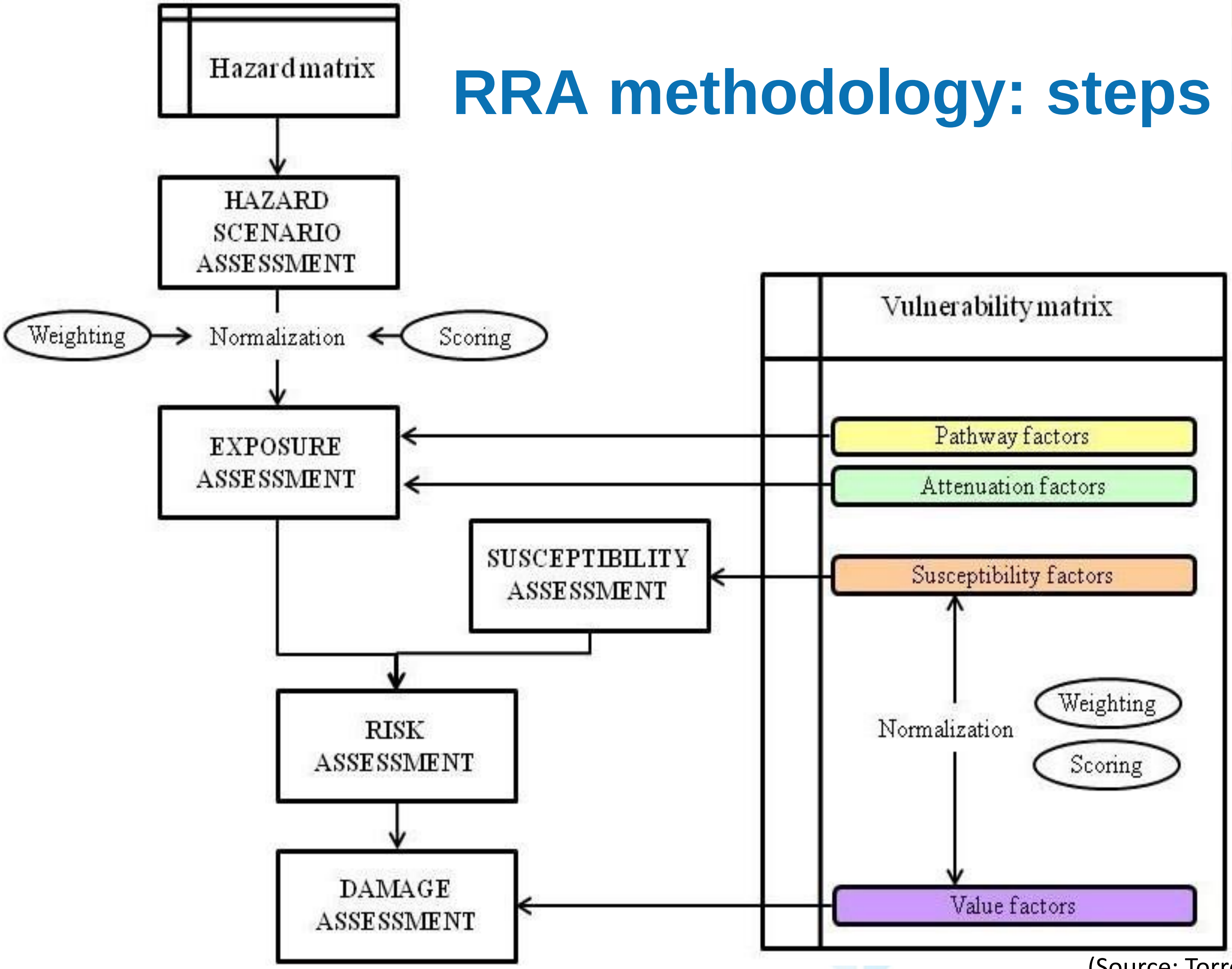


Regional Risk Assessment (RRA) conceptual framework



(Source: Torresan et al., 2016)

RRA methodology: steps



(Source: Torresan et al., 2016)

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Input data

HAZARD MATRIX

BOTTOM STRESS	EXTREME STORMS SURGE	SEA LEVEL RI	TIDE	WAVE	CLIMATE CHANGE IMPACTS
					HYDRODYNAMIC IMPACTS
		Projected water level			SLR Inundation
		Projected water level			
	Water levels associated to extreme events with different return periods	Projected water level			Storm surge flooding
Bottom stress		Projected water levels		Height	Coastal erosion

HAZARD METRICS

VULNERABILITY MATRIX

	RIVER MOUTHS	WETLANDS	AL SYSTEMS
	- Elevation	- Elevation	- Elevation
el	- Protection level	- Protection level	- Water body configuration
	- Urban typology	- Extension of wetlands	- Protection level
	- Agricultural typology		
- Elevation	- Elevation	- Elevation	- Elevation
- Distan coastlin			
- Artific protecti			
- Vegeta cover			
- Coasta			
- Geomorphology	- Geomorphology	- Protection level	
- Dunes	- Protection level		

Storm surge flooding

VULNERABILITY FACTORS:

- **Susceptibility factors;**
- **Pathway factors;**
- **Value factors;**
- **Attenuation factors.**

(Source: Torresan et al., 2016)

RRA output

HAZARD METRICS
PATHWAY FACTORS
ATTENUATION FACTORS
} Exposure maps

SUSCEPTIBILITY FACTORS → Susceptibility maps

Exposure maps + Susceptibility maps } Risk maps

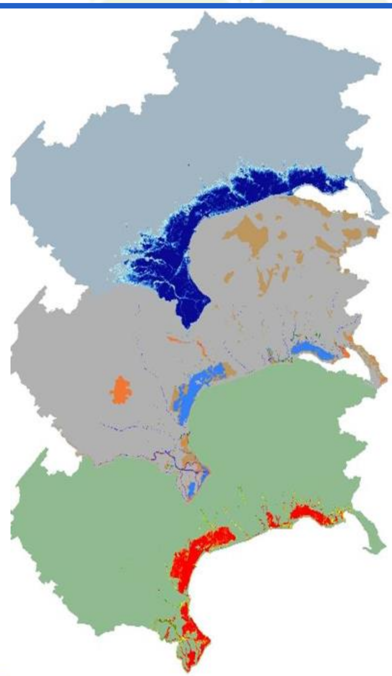
VALUE FACTORS → Value maps

Risk maps + Value maps } Damage maps

Exposure map

Susceptibility map

Risk map



decision support tools useful to guide the impact/risk management phase.

Adapted from: http://www.adrc.or.jp/publications/Venten/HP/herath4.jpg

(Source: Torresan et al., 2016)

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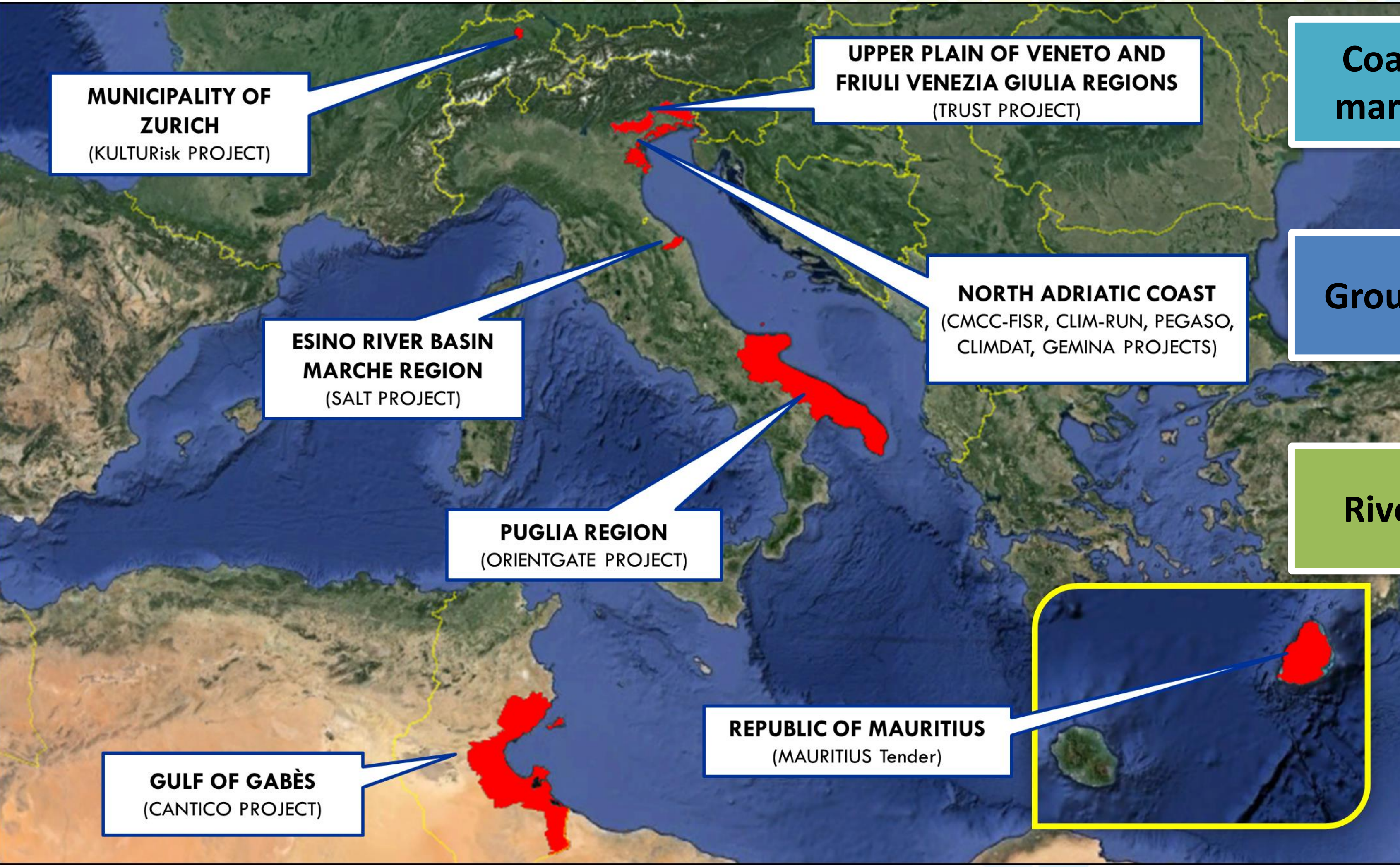


Coastal and marine areas

Groundwaters

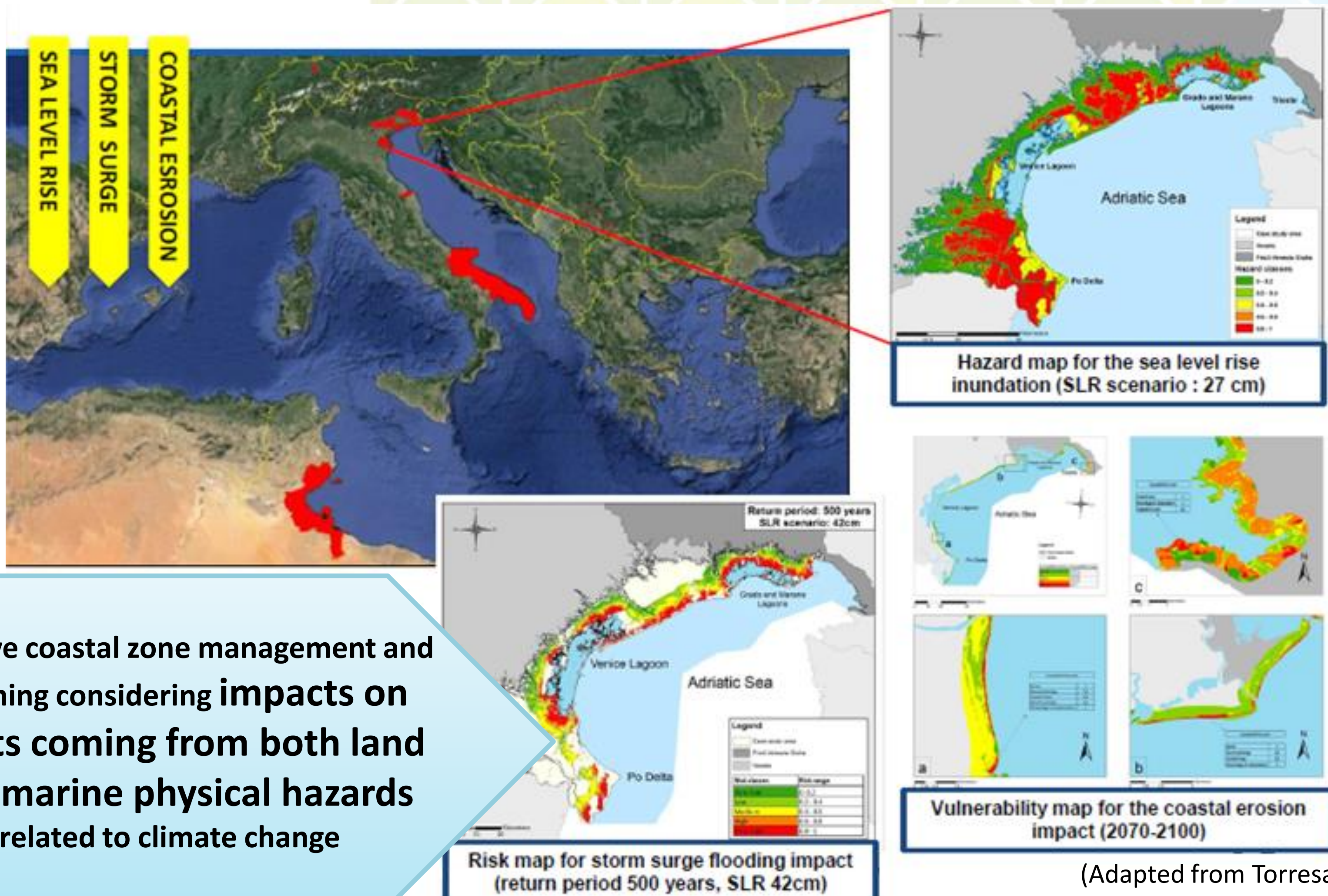
River basins

(Source: Torresan et al., 2016)

Coastal and marine areas




North Adriatic coastal areas

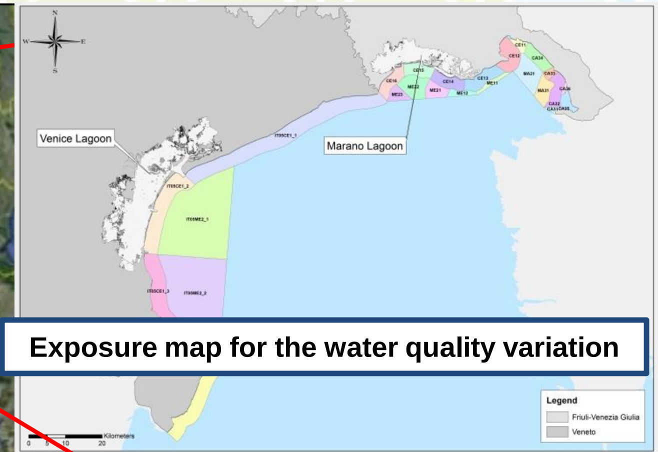


Improve coastal zone management and planning considering **impacts on coasts coming from both land and marine physical hazards** related to climate change

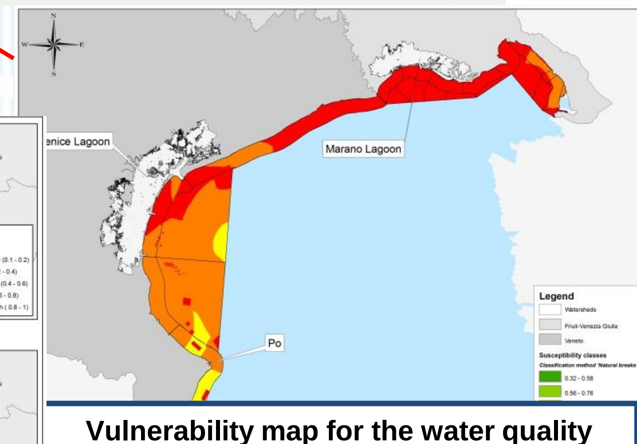
(Adapted from Torresan et al., 2016)

North Adriatic coastal water bodies

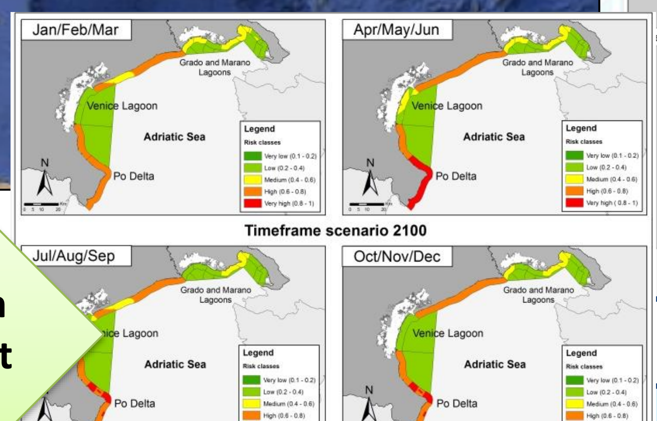
SEAWATER QUALITY VARIATION



Exposure map for the water quality variation



Vulnerability map for the water quality variation



Risk map for the water quality variation (emission scenario A1B, 2100).

Identify measures and policies for **maintaning marine ecosystems in a healthy, productive and resilient condition** in wiev of climate change

(Adapted from Rizzi et al., 2016)

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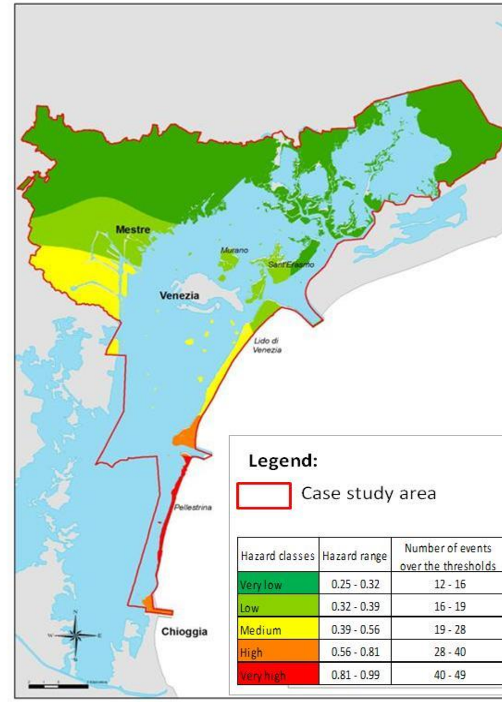
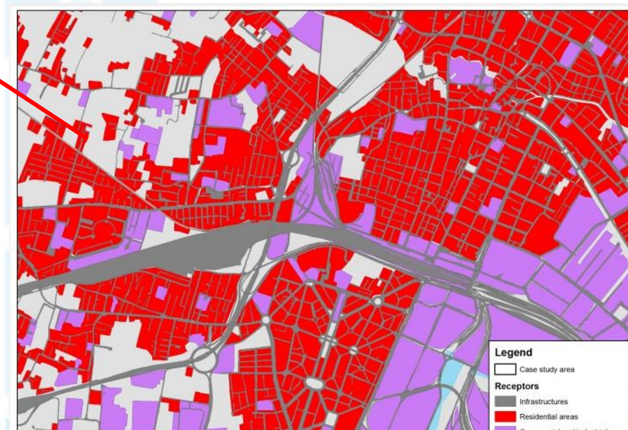
Municipality of Venice (Italy)

PLUVIAL FLOODS



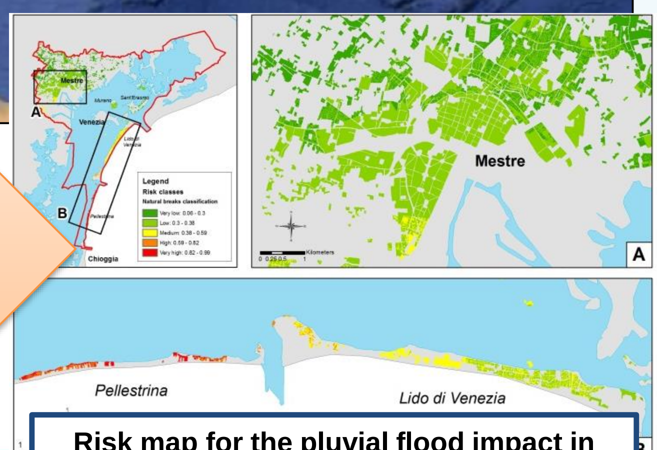
Hazard map for the pluvial flood impact



Exposure map for the pluvial flood impact

(Adapted from Sperotto et al., 2016)

Integrate informations concerning future climate change scenarios in the development of **new building regulations and urban plans** as well as in the definition of **action plan for risk reduction**



Risk map for the pluvial flood impact in residential areas

Groundwaters

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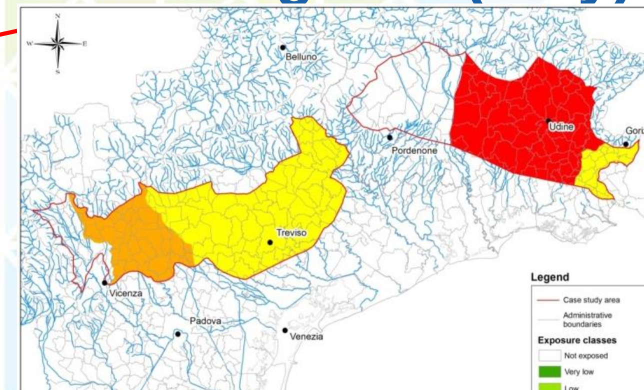
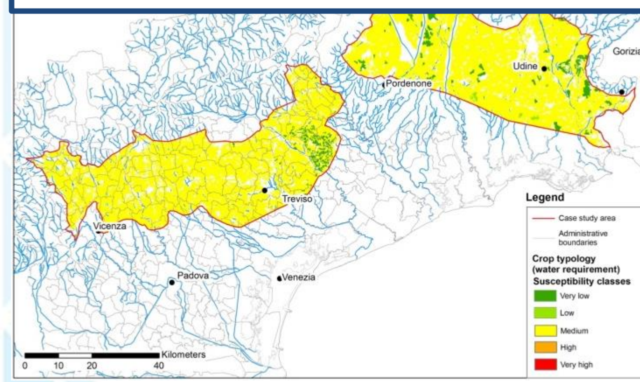
Upper plain of Veneto and Friuli Venezia Giulia regions (Italy)

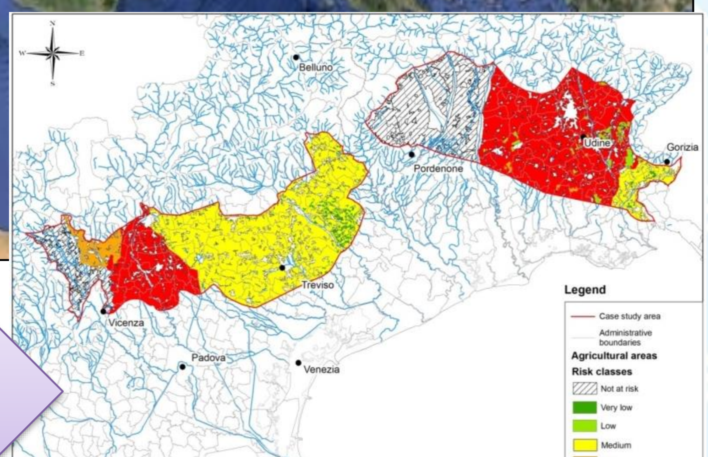


Hazard map for changes in water availability for irrigation related to agricultural areas

Susceptibility map for changes in water availability for irrigation related to agricultural areas



Implement concerted and coordinated climate adaptation actions in order to **improve water resources management and planning**



Risk map for changes in water availability for irrigation related to agricultural areas

(Adapted from Pasini et al., 2012)

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Groundwaters

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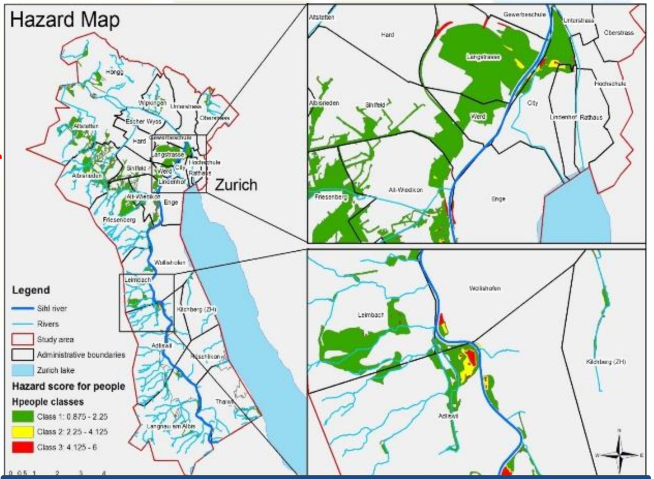
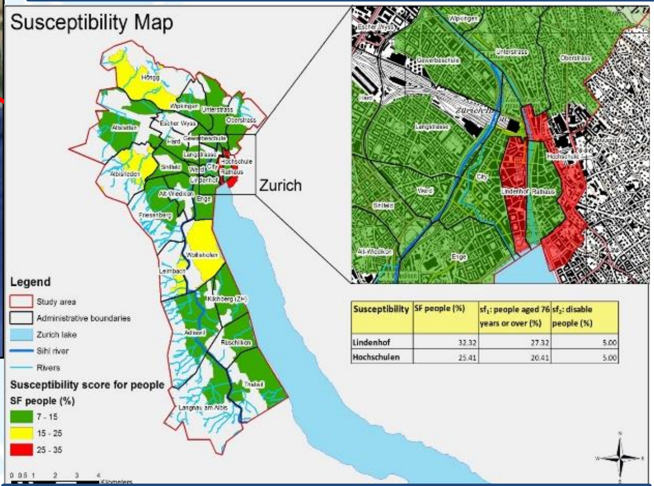
Sihl river, Zurigo (Switzerland)

RIVER FLOODS

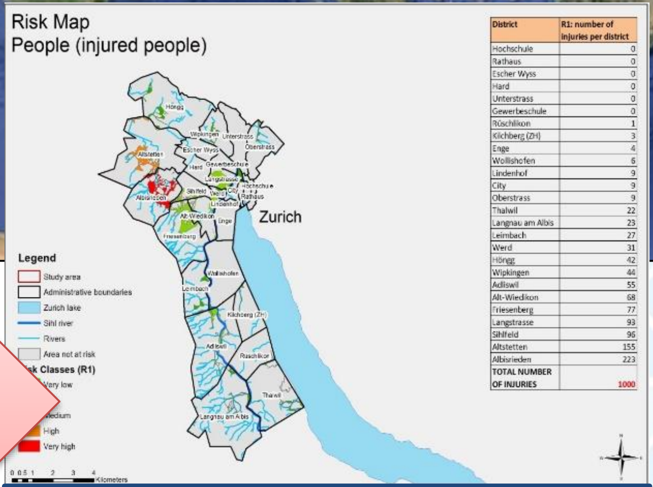


Hazard map for the urban floods impact



Susceptibility	SF people (%)	sf_1: people aged 76 years or over (%)	sf_2: disable people (%)
Lindenhof	32.32	27.32	5.00
Hochschulen	25.41	20.41	5.00

Vulnerability map for the urban floods impact



District	R1: number of injuries per district
Hochschule	0
Rathaus	0
Escher Wyss	0
Hard	0
Unterstrass	0
Gewerbeschule	0
Rüschlikon	1
Kilchberg (ZH)	3
Enge	4
Wollishofen	6
Lindenhof	9
City	9
Oberstrass	9
Thalwil	22
Langnau am Albis	23
Leimbach	27
Werd	31
Höngg	42
Wipkingen	44
Adliswil	55
Alt-Wiedikon	68
Friesenberg	77
Langstrasse	93
Sihlfeld	96
Altstetten	155
Albisrieden	223
TOTAL NUMBER OF INJURIES	1000

Risk map for the urban floods impact related to the receptor 'people'

Identify risk hotspots requiring the implementation of specific **early warning systems and preparadness actions** for disaster risk reduction

(Adapted from Ronco et al., 2015)

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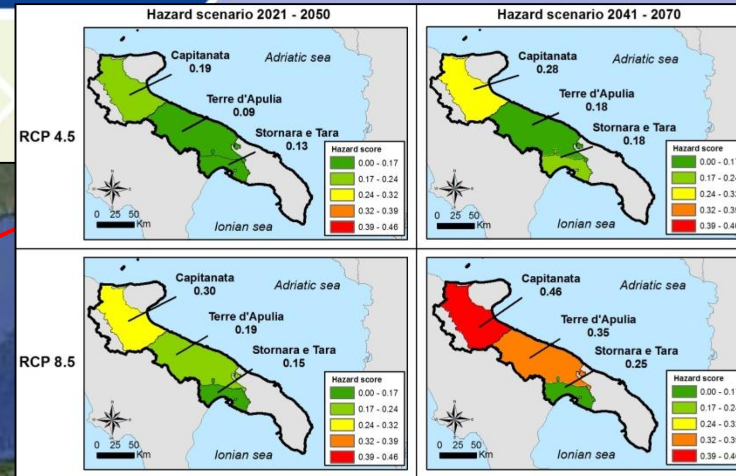
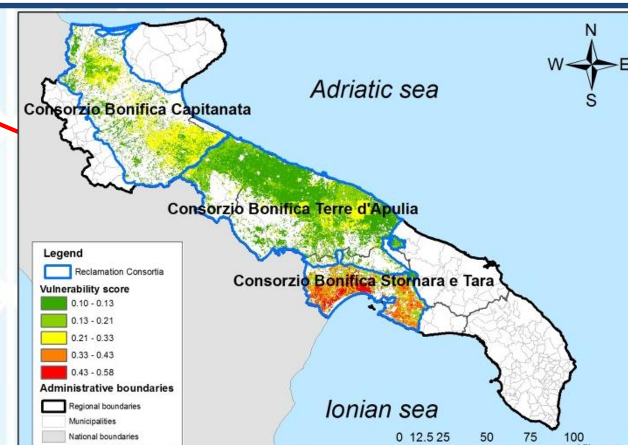
Puglia region (Italy)

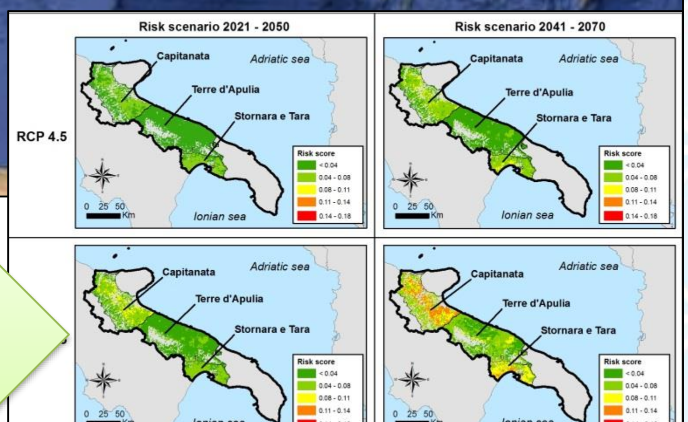
HYDROLOGICAL DROUGHTS



Hazard map for the hydrological droughts on water quantity



Vulnerability map for the hydrological droughts on water quantity



Risk map for the hydrological droughts on water quantity

Support **management of the agricultural sector in order to reduce economic losses** in future climate change scenarios (implementatin of diversified and drought-resistent crops).

(Adapted from Ronco et al., 2017)

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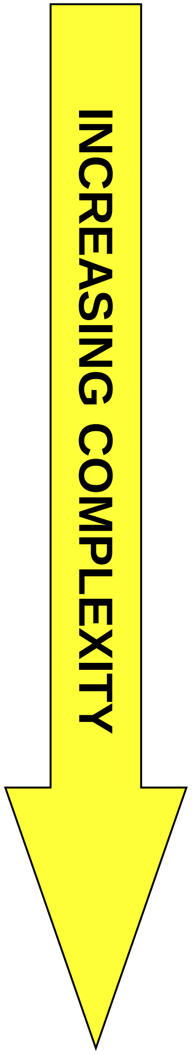
Vulnerability assessment methods



- Indicator-based approaches;
- Index-based methods
- Software based on GIS applications (e.g. decision support systems, DSSs)
- Complex system methods (e.g. Bayesian network, agent-based model)

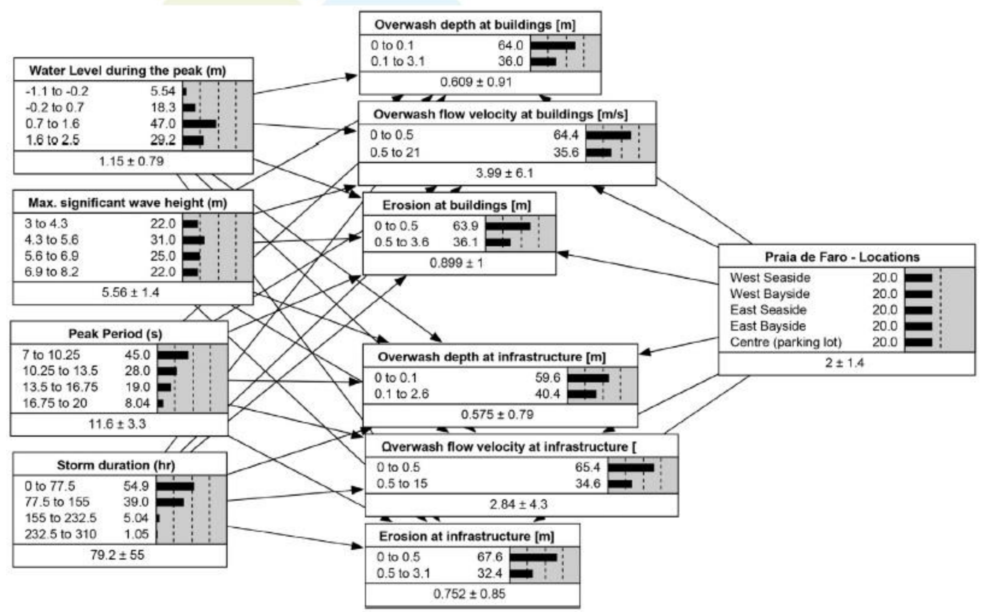
Introduction to Bayesian Network

- **BBNs are probabilistic graphical models** representing the system's components (variables) and their relationships (conditional interdependencies) by combining principles of Graph theory and Probability theory (Pearl, 2011).

- They are **graphically-based to facilitate the rapid conceptualization of the sys**tem to be managed (e.g. marine region) and the evaluation of the dependence/independence between data and their inherent uncertainty evaluated as belief probabilities.

- They allow to c**onsider multiple stressors and endpoints in the same framework**, supporting modelling and analysis of complex marine environments.

- **They integrate different knowledge domains, expertise and data sources** (e.g. GIS data, MCDA and environmental indicators) into a complex system acting as a **decision support tool** informing coastal risk assessment and management.



(Source: Poelhekke et al., 2016)

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The Bayes Theorem

The probability of an event, based on prior knowledge of conditions that might be related to the event:

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

- **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.

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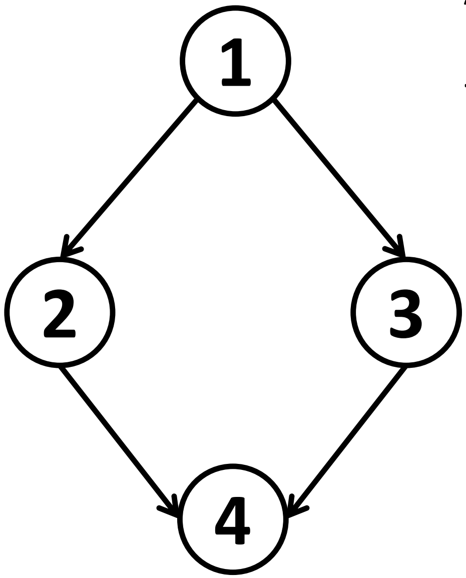
Basic concepts



A Bayesian Network is a probabilistic graphical model consisting of:

- a **qualitative part**, the **structure of the network** in terms of a Directed Acyclic Graph (**DAG**)

The DAG is composed of:

- **nodes** representing the set of random variables $\mathbf{X}=(X_1, X_2,\dots, X_d)$;
- **arcs** between nodes in the form of $\mathbf{X_i} \rightarrow \mathbf{X_k}$, indicating directed probabilistic dependencies between the corresponding variables.

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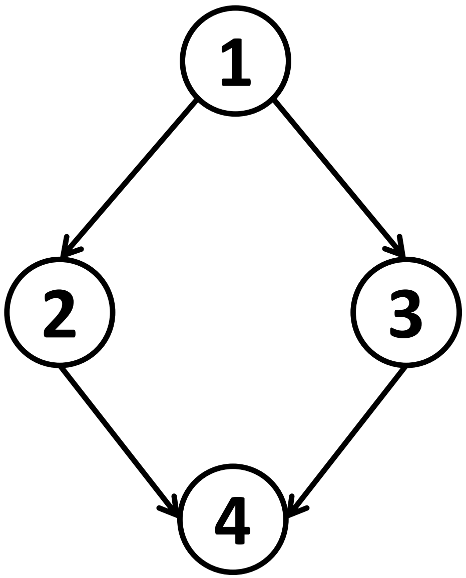
Basic concepts

A Bayesian Network is a probabilistic graphical model consisting of:

- a **quantitative part**, the parameters of the network encoding the **conditional and marginal probabilities** of the system variables.



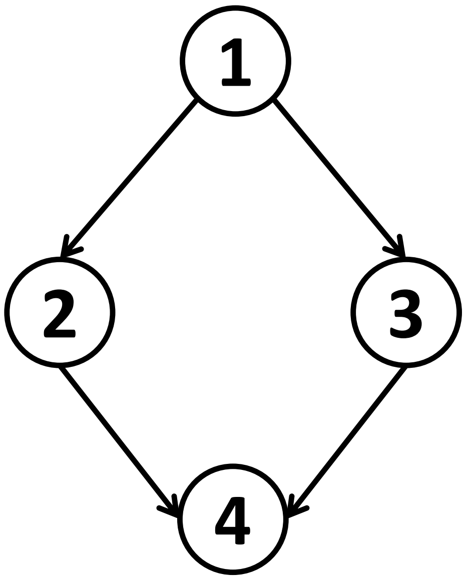
The **marginal probability** of a subset of a collection of a random variables is the probability distribution of the variables contained in the subset. It gives the probabilities of various values of the variables in the subset without reference to the values of the other variables.

If a variable has no parents, it is described by a marginal probability distribution. *Pollino et al., 2007*

Basic concepts

A Bayesian Network is a probabilistic graphical model consisting of:

- a **quantitative part**, the parameters of the network encoding the **conditional and marginal probabilities** of the system variables.



A **conditional probability** gives the probabilities contingent upon the values of the other variables.

The conditional probability describes the probability of each value of the child node, conditioned on every possible combination of values of its parent nodes. These describe the strength of the causal relationships between variables.

Pollino et al., 2007

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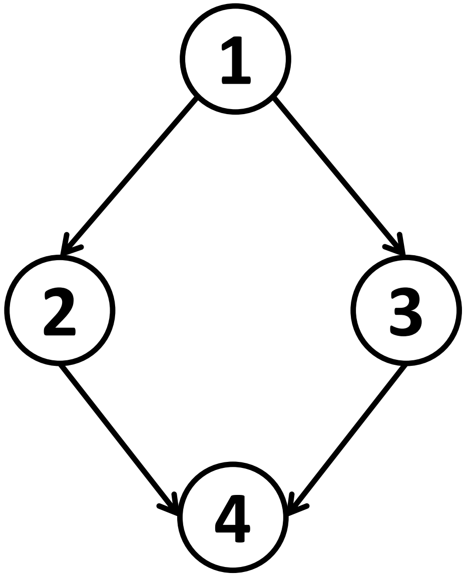
Basic concepts



The structure of the network and the conditional probabilities can be inferred both from **expert knowledge** and **observed data**.

Once the BN has been inferred, it can be used to perform probabilistic inference or belief updating (also known as scenario analysis).

Probabilistic inference in BN generally consist in:

- assessing the probability that a variable assumes one of its values, conditioned to specific values of other variables

  $P(X_i=x_{ij}|X_k=x_{kj},\ldots, X_m=x_{mj})$

- Identifying the values of a given set of variables that lead to the highest posterior probability when a set of other variables are set to fixed values: $x^*_{ij}=\arg\max P(X_i=x_{ij}|X_k=x_{kj},\ldots, X_m=x_{mj})$

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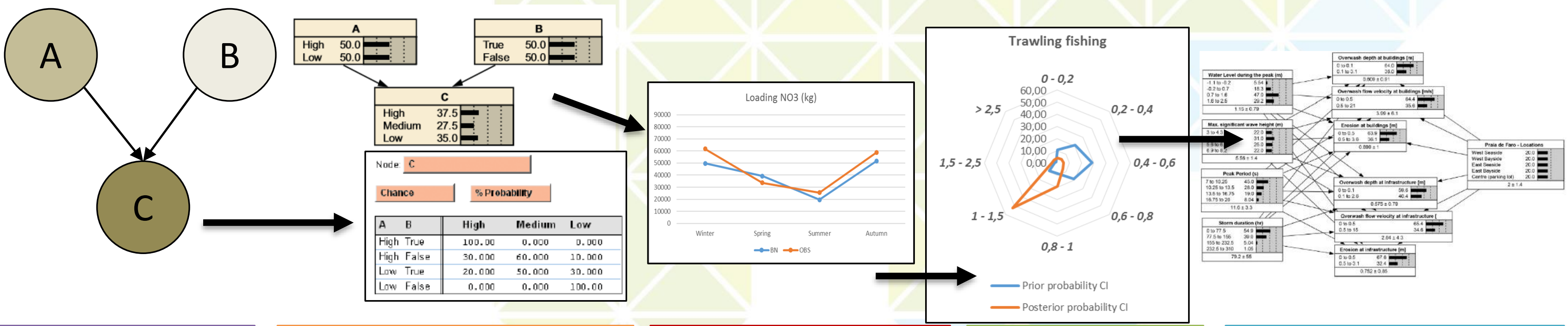
Lead Partner: REGIONE PUGLIA
Technical support: a·r·t·i
Project Partners: cmcc · ΠΑΝΕΠΙΣΤΗΜΙΟ ΠΑΤΡΩΝ

Methodological steps for BN implementation



CONCEPTUAL MODEL:	MODEL PARAMETRIZATION:	VALIDATION:	SENSITIVITY ANALYSIS:	SCENARIOS ANALYSIS:
Define the structure of the network and identify its main variables and relationships represented by using a conceptual/influence **'nodes and arrow'** diagram.	Define **states** for all variables (interval, boolean, labelled) and calculate the associated **prior probability** resulting from data distribution as well relationships between nodes described by the **conditional probability** distributions.	**Evaluate the performance/prediction accuracy of the BN** model through two different types of validation methods: - the data-based validation; - the qualitative evaluation.	Evaluate **how sensitive are model outcomes** to changes in input nodes or other model parameters (e.g. changes in node's type of states.	By inferring behavior of the variables at stake against different conditions defined by setting specific state/s of a node/s (**evidence**) and then propagating information between nodes based on the Bayes theorem, thus resulting in **the posterior probability.**

(Source: Sperotto et al., 2017; Furlan et al., 2020)

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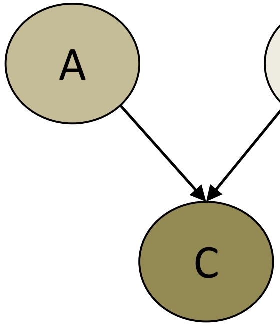
Methodological steps:
DESIGN OF THE BN CONCEPTUAL MODEL



AIM:

Identify the casual structure of the BN model (design the DAG)

- The **casual structure** of the model should represent as much as possible the **reality of the system to be investigated (e.g. natural or socio economic systems)**.
- In the case of complex and heterogeneous environments, **multidisciplinary** expert systems and **knowledge-based models** is crucial to create the most appropriate BN model configuration.

- Definition of **final objectives (i.e. assessment endpoints)** of the model;
- **Identification** of relevant **system variables (i.e. nodes) by means e.g. of the DPSIR Framework** and representation of their **causal-relationships (i.e. arcs).**

(Source: Sperotto et al., 2017; Furlan et al., 2020)

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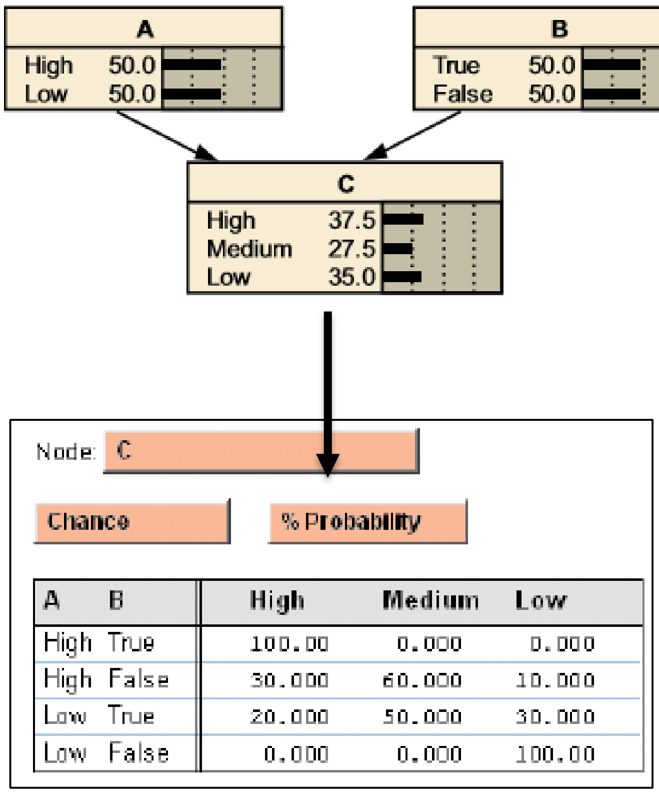
Methodological steps:
BN MODEL PARAMETRIZATION



AIM:
Assign states to each variable of the system and compute the conditional probabilities representing the strength of relationships between the system components

- Definition of **states for all variables** (i.e. range of potential values the variable can assume)
- **Identification** of **prior probability** (i.e. initial conditions of the system)
- Computation of **conditional probabilities** (i.e. strength of relationships between systems variables)

(Source: Sperotto et al., 2017; Furlan et al., 2020)

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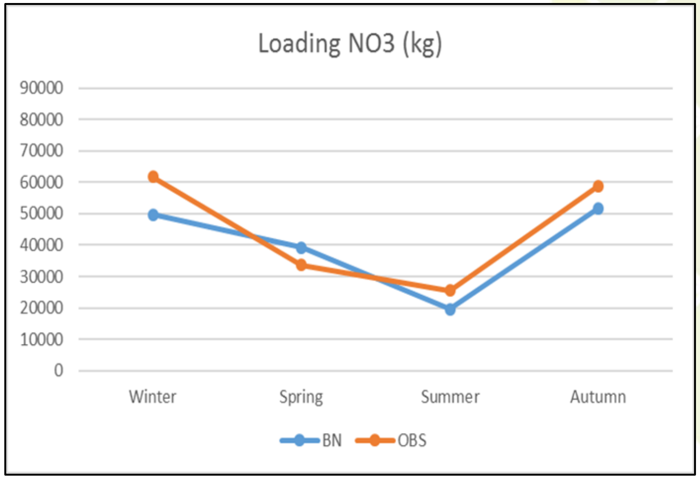
Methodological steps:

MODEL EVALUATION



AIM:

Assess if the BN model purses the objective for which it was designed and if the results are consistent with the outcome of other similar models or monitoring data

➢ **DATA-BASED EVALUATION**

It measures the predictive accuracy of the model by calculating the error rates comparing the frequency of the predicted node state (i.e. the node with the highest probability) with a test or an independent set of observed data.

➢ **QUALITATIVE EVALUATION**

It uses expert judgement or compare results with peer reviewed literature or similar model results.

(Source: Sperotto et al., 2017; Furlan et al., 2020)

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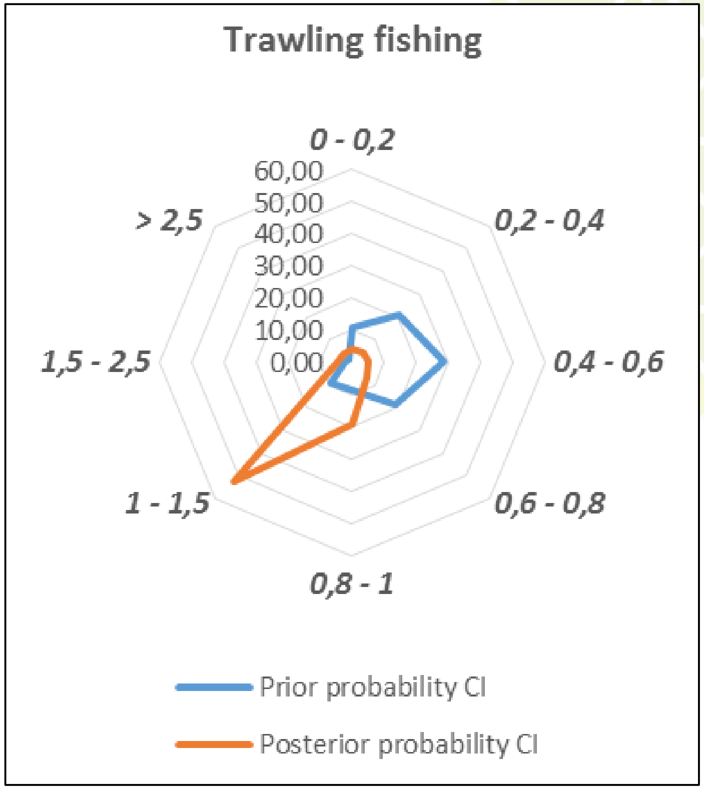
Methodological steps: SENSITIVITY ANALYSIS



AIMS:

- Test the sensitivity of model outputs to variation in the model input parameters;
- Identify the most relevant variables: key variables driving changes in the assessment endpoint.

(Source: Sperotto et al., 2017; Furlan et al., 2020)

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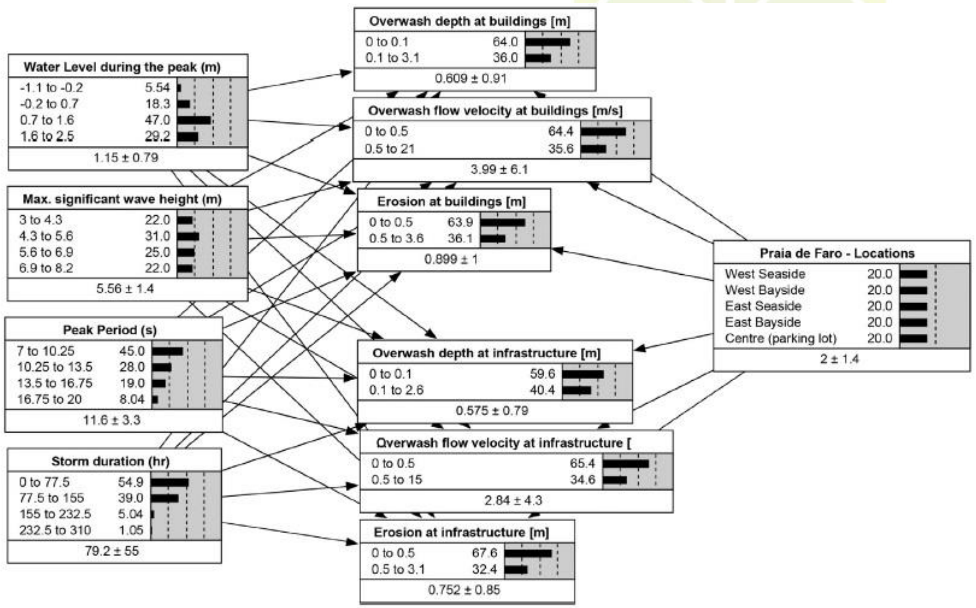
Methodological steps: SCENARIO ANALYSIS

AIMS:

- Assess the relative changes in outcomes probabilities associated with changes in input variables;
- Define the state in which state input variable should be to obtain the desired outcome.



➢ Development of **scenarios fixing the probability of inputs variables' states** (e.g. assigning 100% probability for one state) and observing the relative changes in the outcome probabilities of output nodes (e.g. nutrient loading).

(Source: Sperotto et al., 2017; Poelhekke et al., 2016; Furlan et al., 2020)

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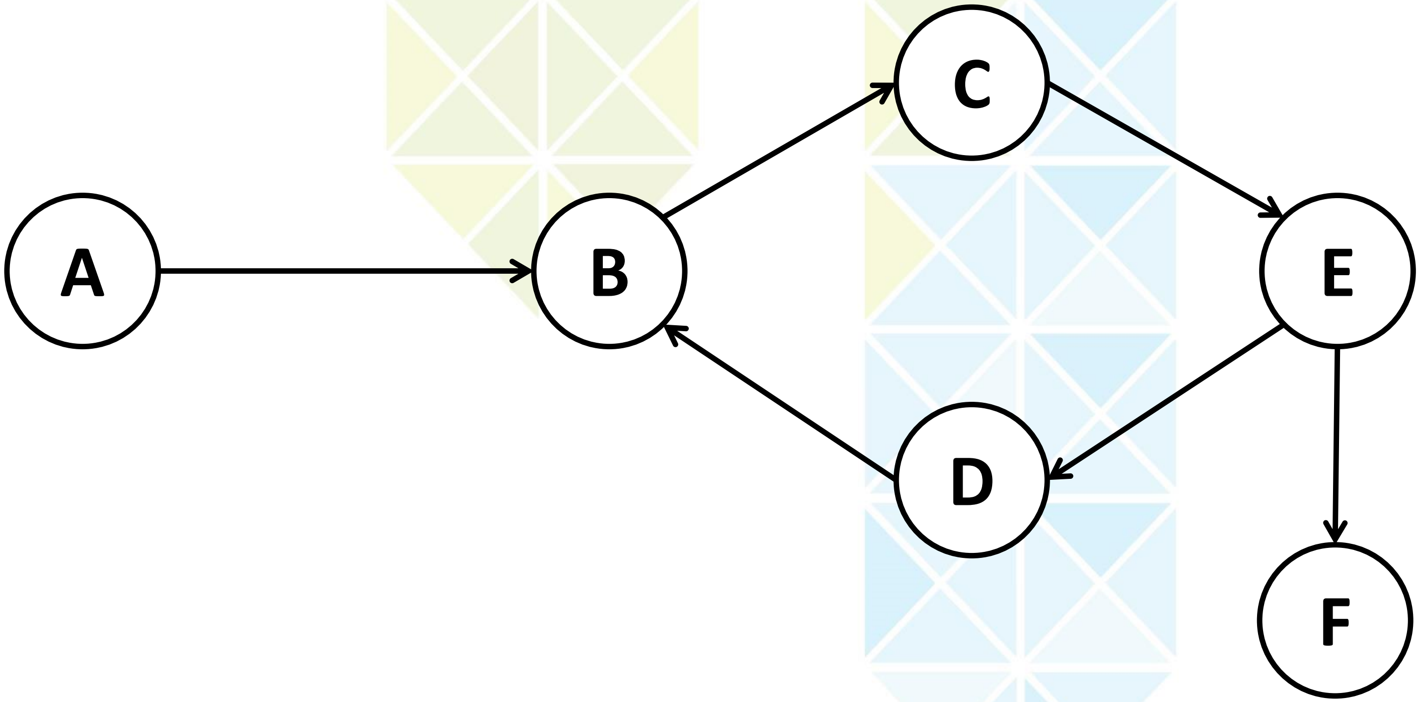
Available softwares for Bayesian Network design



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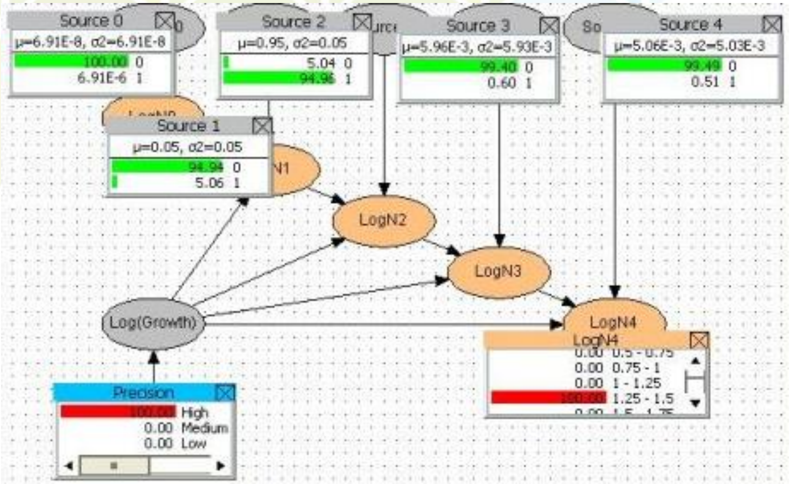
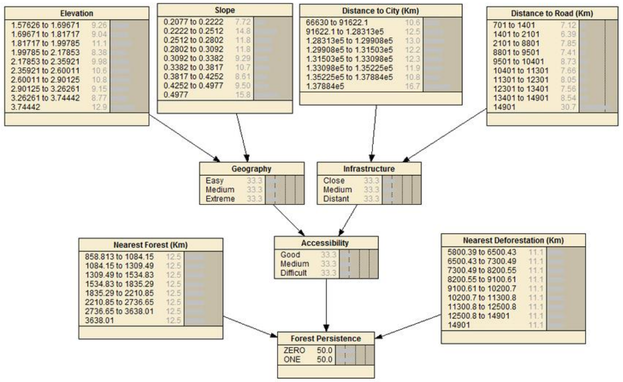
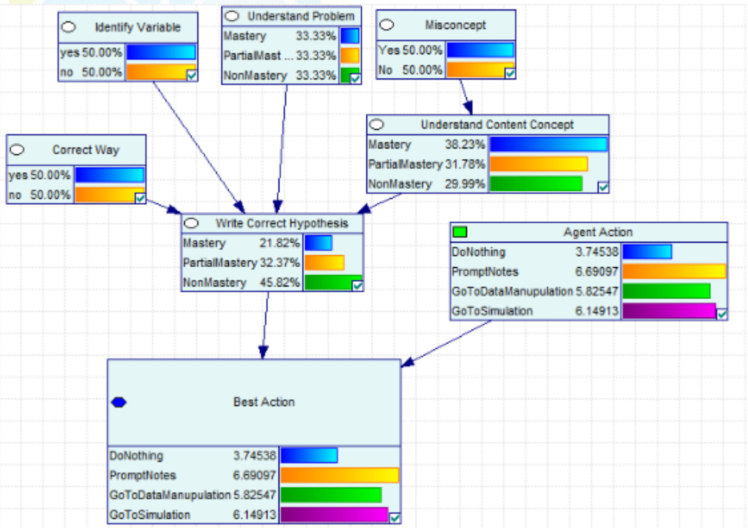
Available softwares for Bayesian Network design

Softwares:

- Netica: https://www.norsys.com/netica.html
- Hugin: www.hugin.com
- GeNIe: www.bayesfusion.com
- BN learn (R-package): www.bnlearn.com
- Infert.NET: https://dotnet.github.io/infer/
- SamIam: http://reasoning.cs.ucla.edu/samiam/
- JavaBayes: www.cs.cmu.edu/_javabayes/Home/
- Bayesware: www.bayesware.com
- R: Blearn library







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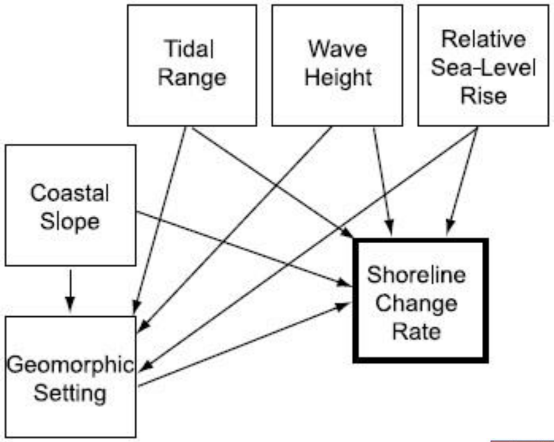
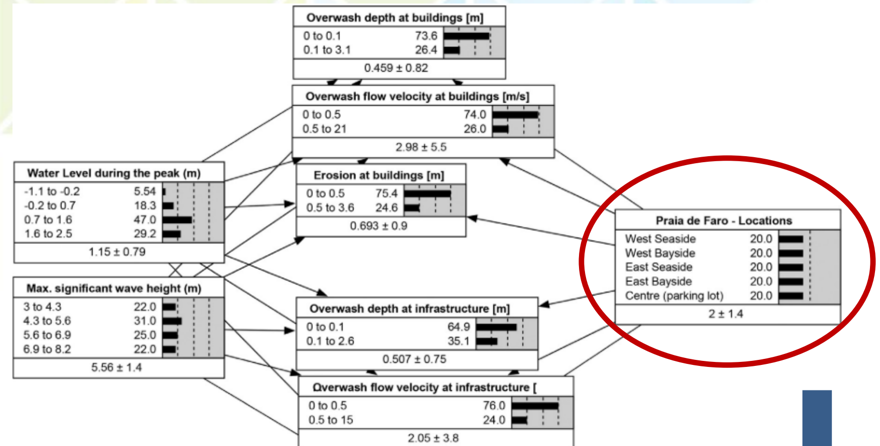
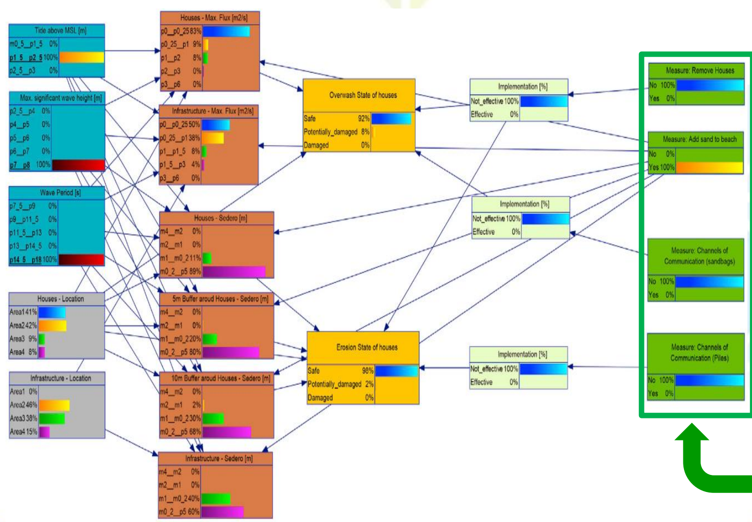
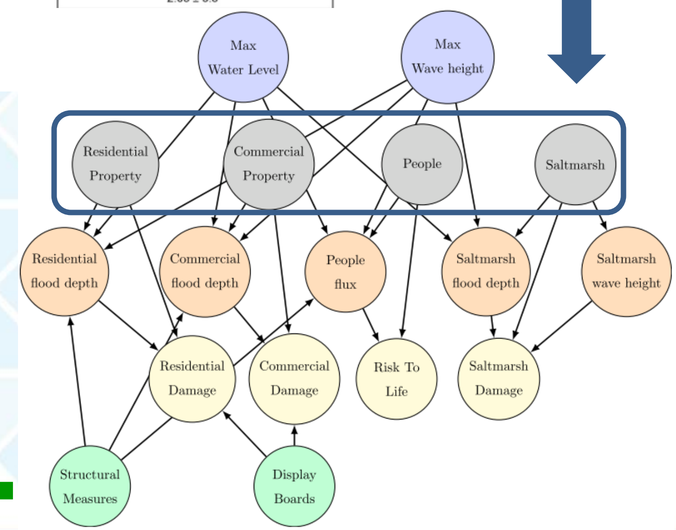
Bayesian Network for coastal erosion risk assessment and management: case studies









References:
Gutierrez et al., 2011
Poelhekke et al., 2016
Jäger et al., 2017
Plomaritis et al., 2017

Bayesian network to predict coastal vulnerability to sea level rise

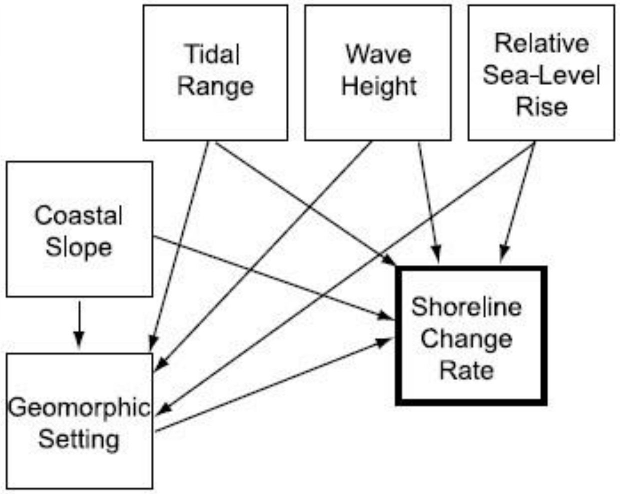
Gutierrez et al., 2011

Climatic threat/issue	Name of tool	Purpose	Scale
Long-term shoreline change/erosion	Bayesian Network	Assessment of long-term prediction uncertainty of shoreline change associated with sea level rise	National, Atlantic coast of the United States

U.S. Atlantic Coast

The 6 variables (nodes) are divided into three categories:

- **Driving forces** (relative sea level rise rate **S**, mean wave height **W**, tidal range **T**)
- **Boundary conditions** (geomorphic settings **G**, coastal slope **β**)
- **Response** or **vulnerability indicator** (long-term shoreline change rate **R**)



Bayesian network to predict coastal vulnerability to sea level rise

Gutierrez et al., 2011

- Each node is sorted by five classes corresponding to risk categories

Variable	1	2	3	4	5
Geomorphology	1 – very low risk rocky, cliffed coasts, fjords	2 – low-risk medium cliffs, indented coasts	3 – moderate risk low cliffs, glacial drift, alluvial plains	4 – high-risk cobble beaches, estuarine and lagoonal coasts	5 – very high risk barrier beaches, sand beaches, salt marsh, mud flats, deltas, mangroves, coral reefs
Shoreline change (m/yr)	>2.0	1.0–2.0	−1.0–1.0	−2.0–−1.0	<−2.0
Coastal slope (%)	>0.2	0.2–0.07	0.07–0.04	0.04–0.025	<0.025
Relative sea level change (mm/yr)	<1.8	1.8–2.5	2.5–2.95	2.95–3.16	>3.16
Mean wave height (m)	<0.55	0.55–0.85	0.85–1.05	1.05–1.25	>1.25
Mean tidal range (m)	>6.0	4.1–6.0	2.0–4.0	1.0–1.9	<1.0

- Data points are sorted by each node and rank

Variable	1	2	3	4	5
Geomorphology	318	54	234	414	1358
Shoreline change (m/yr)	111	76	1169	323	699
Coastal slope (%)	331	515	781	523	228
Relative sea level change (mm/yr)	413	601	584	251	529
Mean wave height (m)	1	34	954	854	535
Mean tidal range (m)	0	59	456	749	1114

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Triton

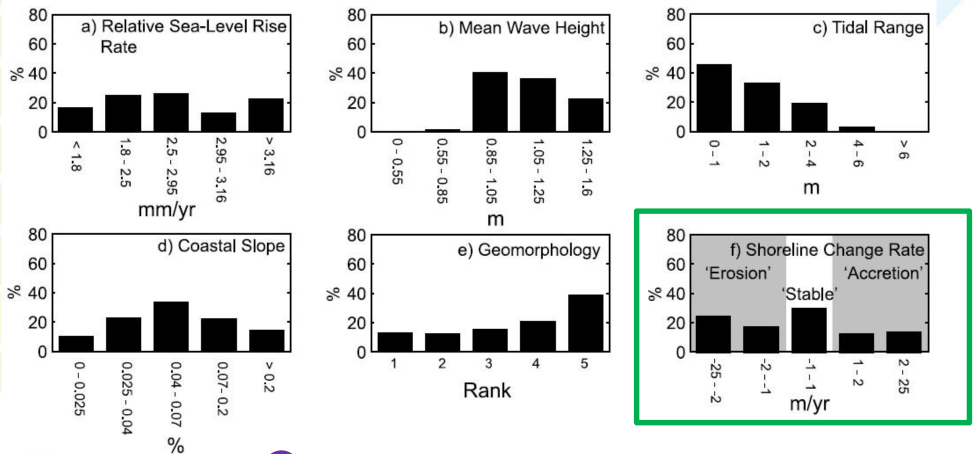
TRITON
Development of management tools and directives for immediate protection of biodiversity in coastal areas affected by sea erosion and establishment of appropriate environmental control systems

Bayesian network to predict coastal vulnerability to sea level rise

Gutierrez et al., 2011

- **Baseline scenario**

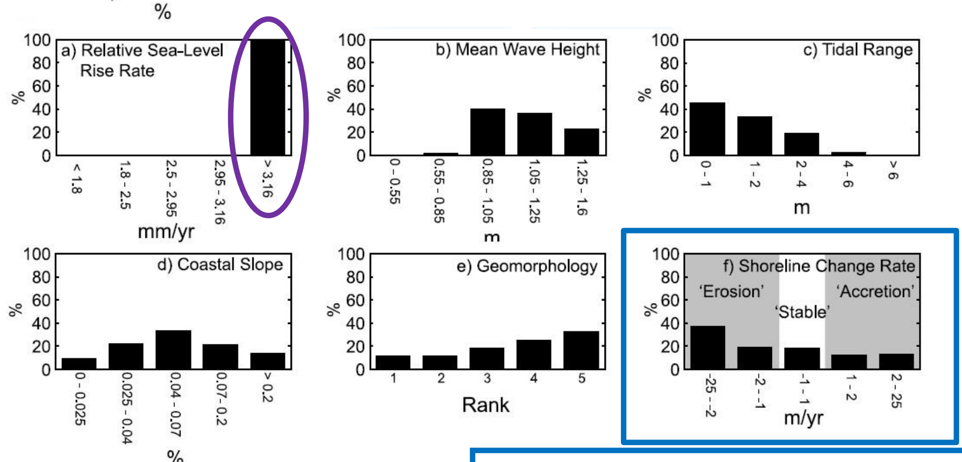
  Erosion: 42.5%
  Stability: 30.5%
  Accretion: 27%



- **Scenario (1)**

100% probability of **SLR > 3.16mm/y**

  Erosion: 57%
  Stability: 18%
  Accretion: 25%



Merging classes on shoreline change rate

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Bayesian network to predict coastal vulnerability to sea level rise

Gutierrez et al., 2011

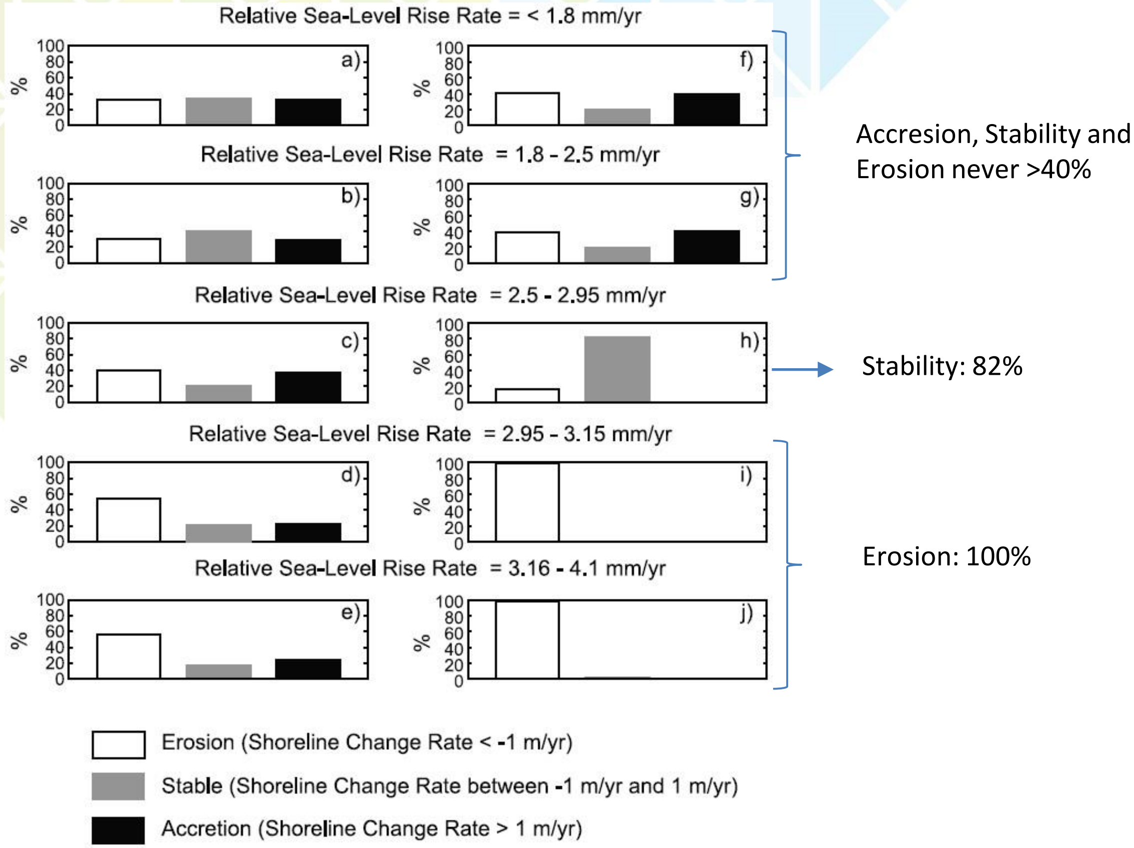
- **Scenario (2)**

100% probability of **Wave height = 0.85 – 1.05 m**

100% probability of **Geomorphology = 4**

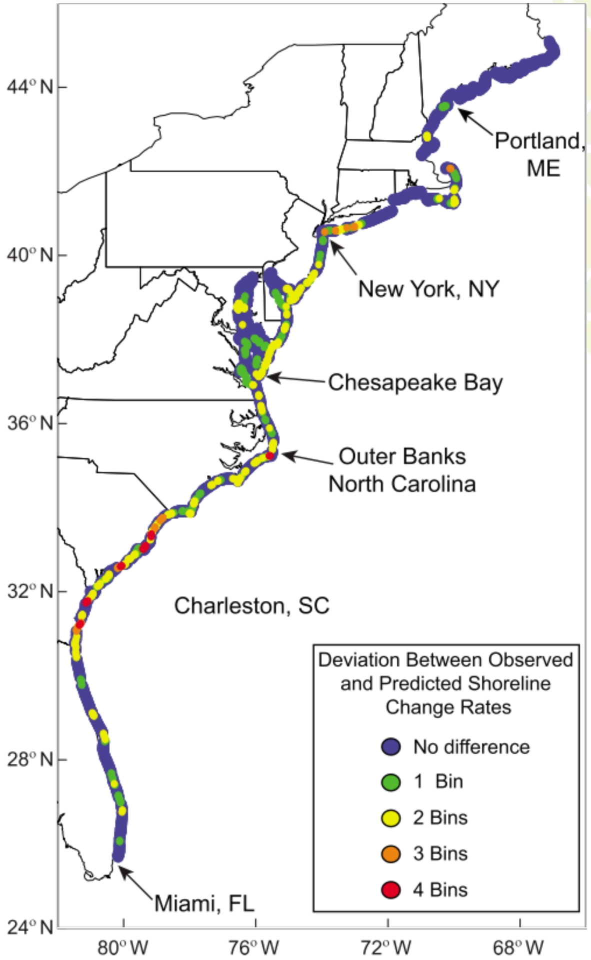
100% probability of **Tidal range = 0 – 1 m**

100% probability of **coastal slope = 0,04 – 0,07 %**



Bayesian network to predict coastal vulnerability to sea level rise

Gutierrez et al., 2011



- **Mapping outcomes**

  (Scenario: Shoreline change <-1 m/year)

Difference (expressed in the number of rate-of-change bins) between observed data and predicted shoreline change rate, computed for each geographic location in the data set:

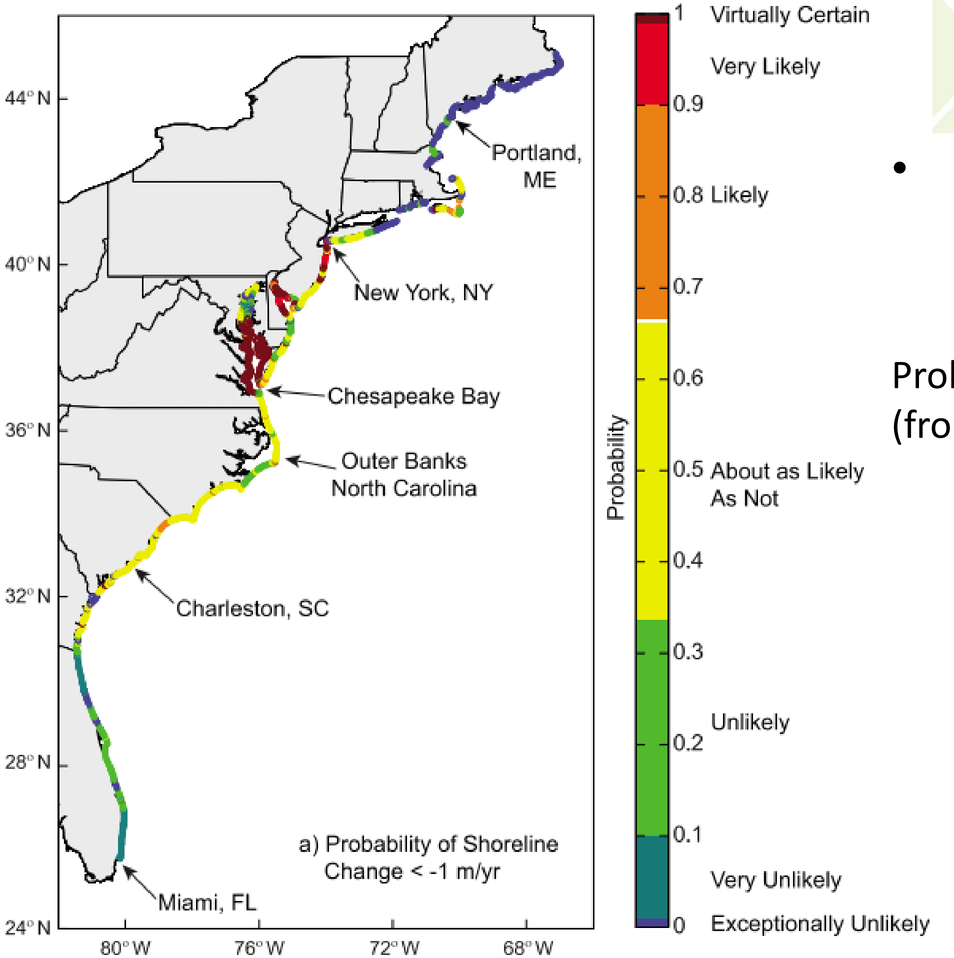
71%: no difference

13%: predictions fall in an adjacent bin

16%: predictions differ by 2 or more bins

Bayesian network to predict coastal vulnerability to sea level rise

Gutierrez et al., 2011



- **Mapping outcomes**

  (Scenario: Shoreline change <-1 m/year)

Probability of shoreline change <-1 m/year at each location (from moderate to severe erosion)

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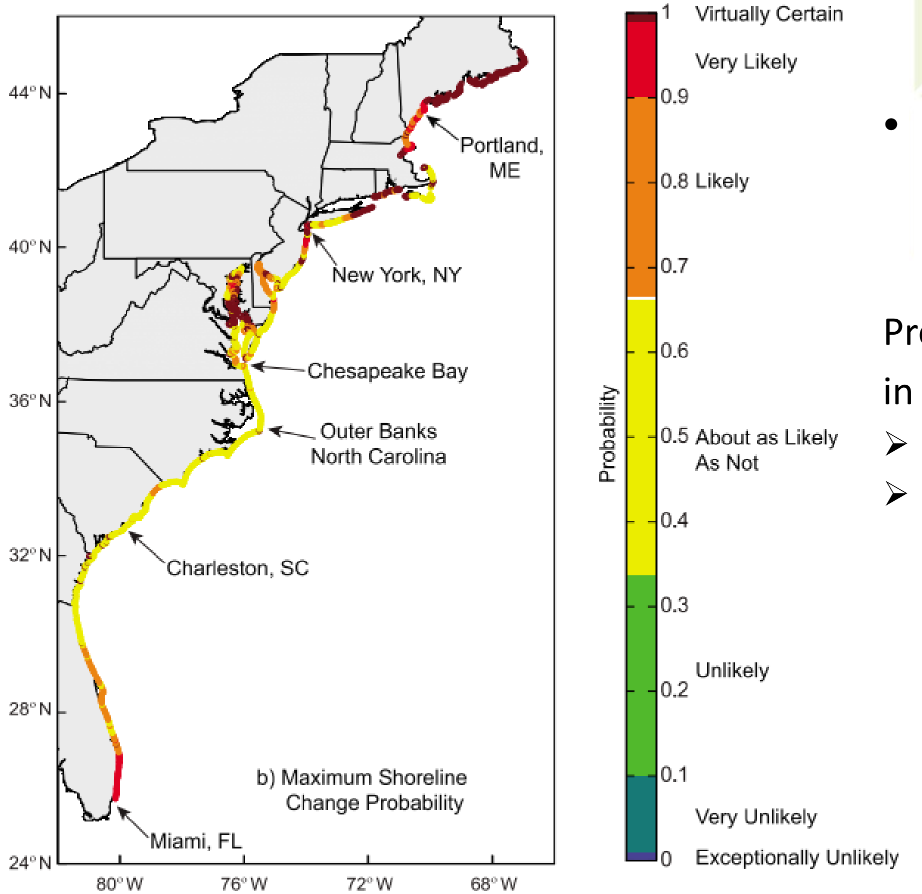
Bayesian network to predict coastal vulnerability to sea level rise

Gutierrez et al., 2011



- **Mapping outcomes**

  (Scenario: Shoreline change <-1 m/year)

Probability of the most likely outcome in order to identify:

- ➢ areas with high degree of confidence in any outcome predictions
- ➢ locations with a greater degree of uncertainty

- Where the BN needs to include more or better information;
- Where scientific understanding needs improvement.

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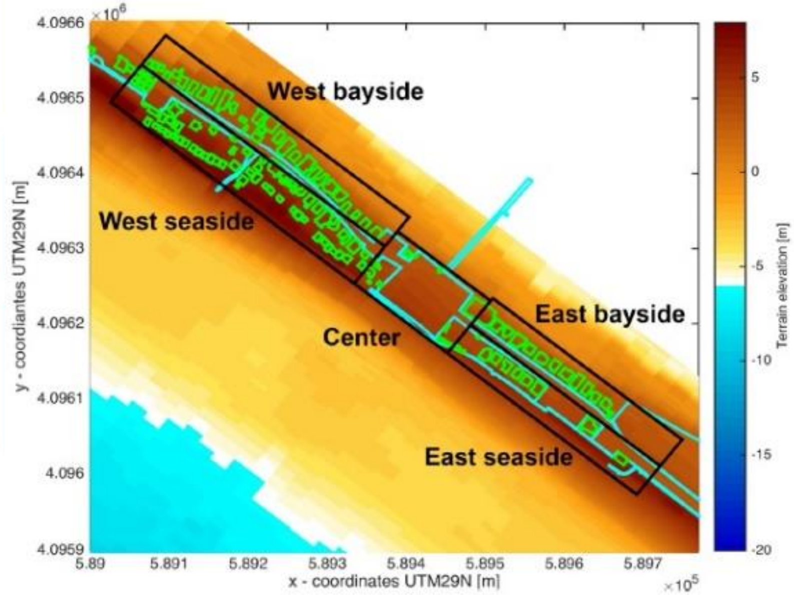
Predicting coastal hazards for sandy coasts with Bayesian Network

Praia de Faro, Portugal

Poelhekke et al., 2016

Climatic threat/issue	Name of tool	Purpose	Scale
Long-term shoreline change/erosion	Bayesian Network	Predicting coastal vulnerability SLR and assessing the interactions between barrier island geomorphic variables	Local, Praia de Faro, Portugal

- The site has been divided into **5 areas** in terms of dune height, barrier island elevation and distance between buildings and infrastructures and the shoreline



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Predicting coastal hazards for sandy coasts with Bayesian Network

Poelhekke et al., 2016

Baseline scenario

CONFIGURATION 1

- 4 boundary conditions
- Nodes discretised in 4 bins
- Erosion will take place? YES or NO

CONFIGURATION 2

- 4 boundary conditions
- Hazards discretised in 2 bins
- Erosion will take place above a certain threshold

CONFIGURATION 3

- 2 boundary conditions
- Hazards discretised in 2 bins
- Erosion will take place above a certain threshold

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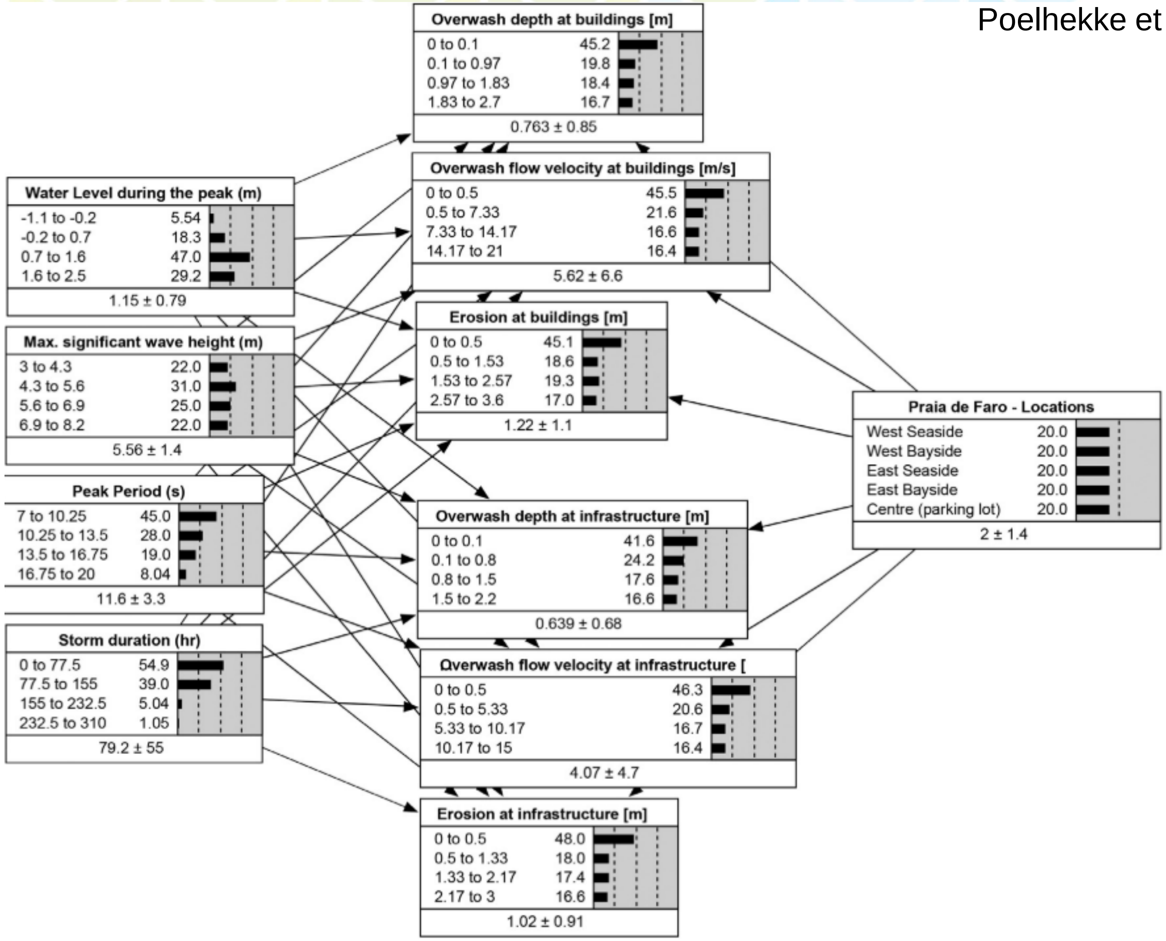
Predicting coastal hazards for sandy coasts with Bayesian Network

Poelhekke et al., 2016

- **Baseline scenario**

CONFIGURATION 1

Each node is discretised in 4 bins



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Predicting coastal hazards for sandy coasts with Bayesian Network

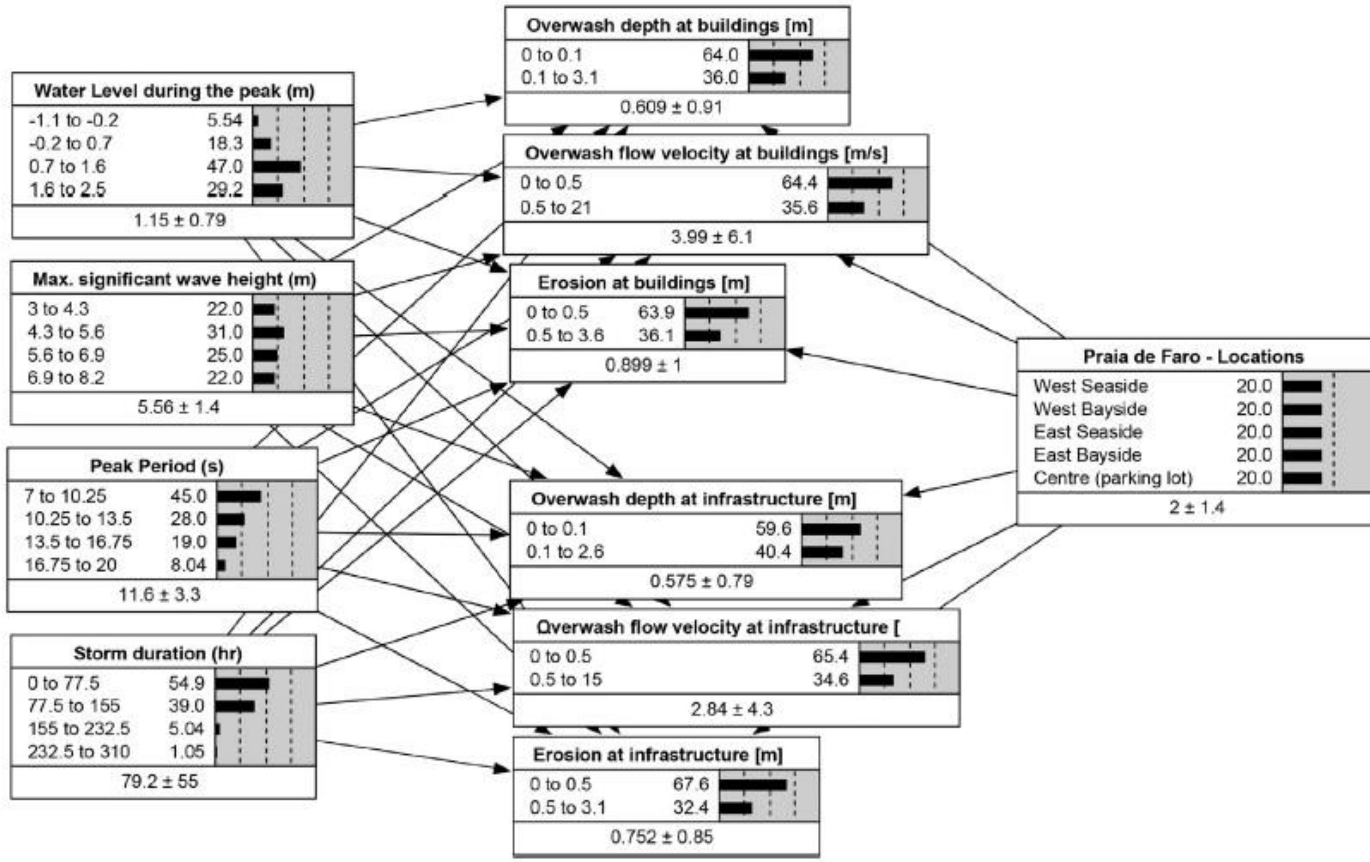
Poelhekke et al., 2016

- **Baseline scenario**

CONFIGURATION 2

Boundary conditions are discretised in 4 bins

Hazards are discretised in 2 bins



Predicting coastal hazards for sandy coasts with Bayesian Network

Poelhekke et al., 2016

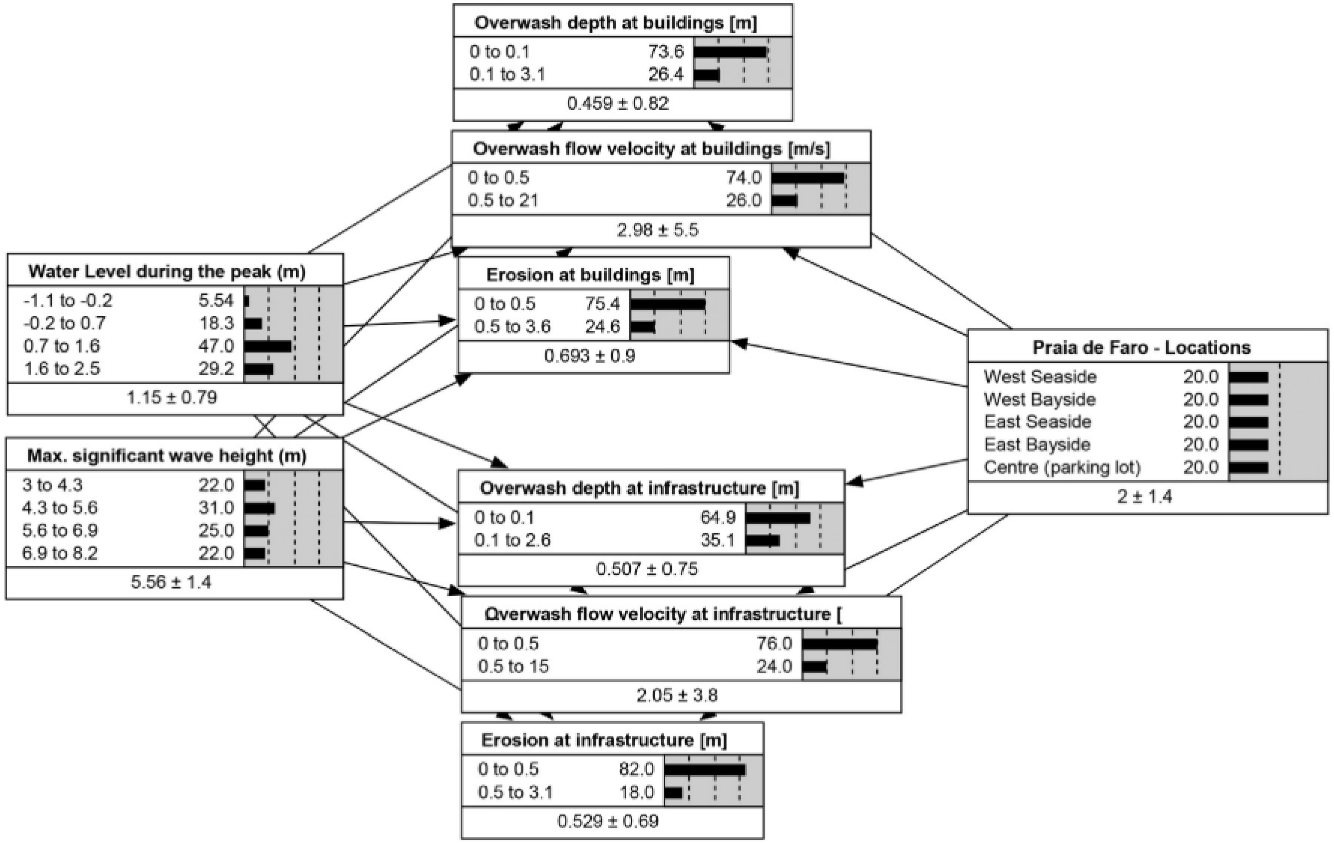
- **Baseline scenario**

CONFIGURATION 3

Only 2 boundary conditions

Boundary conditions are discretised in 4 bins

Hazards are discretised in 2 bins



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Predicting coastal hazards for sandy coasts with Bayesian Network

Poelhekke et al., 2016

The BN configurations have been tested according to the log-likelihood ratio (LLR) method.

LLR > 0, if the likelihood of a prediction increases as compared to the prior probability

LLR < 0 if the predictions likelihood decreases as result of the updated prediction

$$\mathrm{LLR} = \sum_{j=1}^{n} \log\left\{p(\mathrm{F_i}|\mathrm{O_j})_{F_i=O'_j}\right\} - \log\left\{p(\mathrm{F_i})_{F_i=O'_j}\right\}$$

F_i is the forecast variable
O_j is a subset of observations
O'_j is the observation that is withheld from the prediction

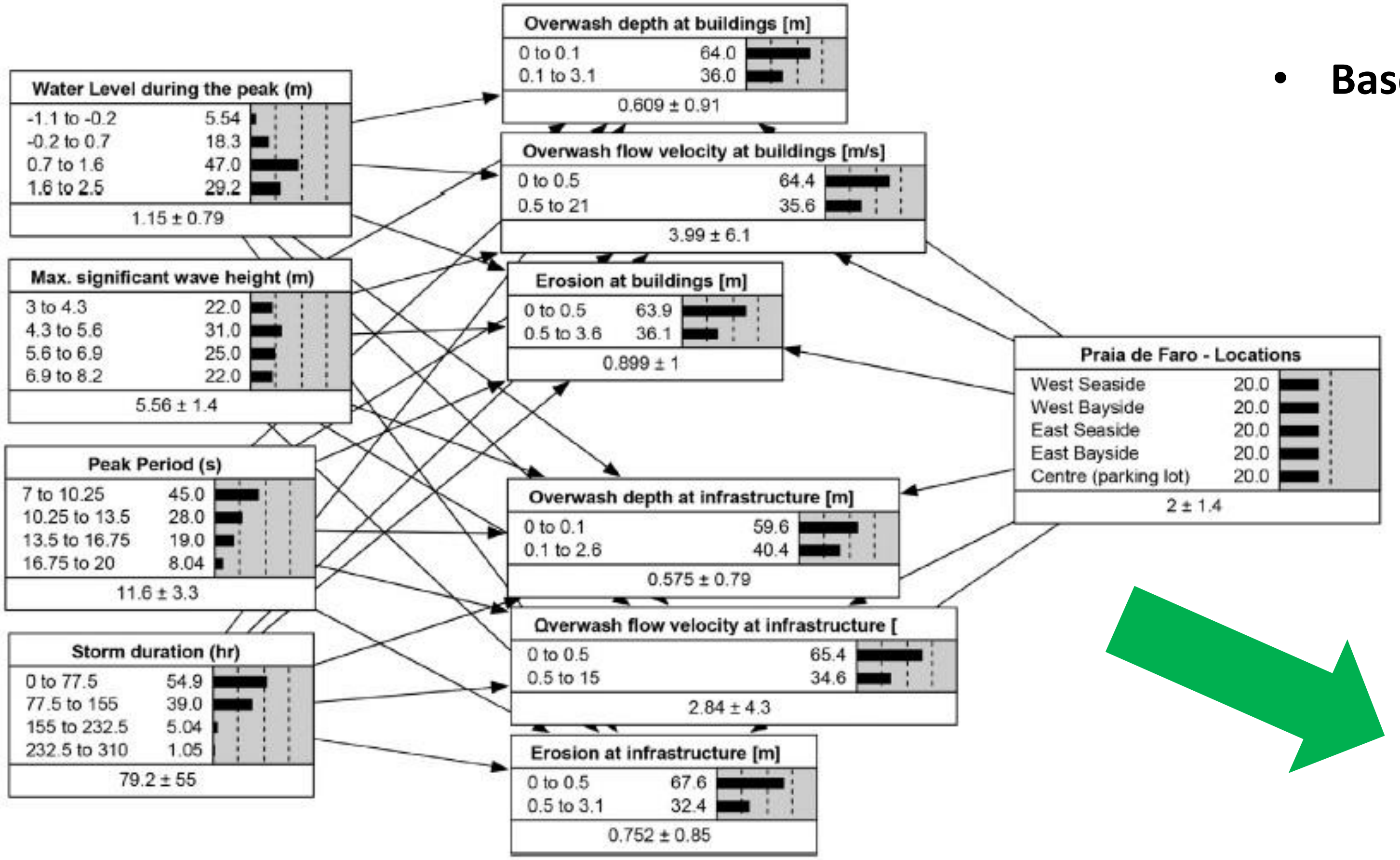
STEP 1: LLR for each configuration

The LLR scores are positive for all three Configurations, indicating predictive skill.

BN Configurations	Overwash depth buildings	Overwash velocity buildings	Erosion buildings	Overwash depth infrastructure	Overwash velocity infrastructure	Erosion Infrastructure
1	38.49	41.56	38.29	40.13	39.57	33.12
2	28.69	27.89	30.03	28.89	27.00	22.54
3	22.27	20.96	25.57	24.67	18.75	17.14

Predicting coastal hazards for sandy coasts with Bayesian Network

Poelhekke et al., 2016



- **Baseline scenario**

Configuration 2 has the best performance

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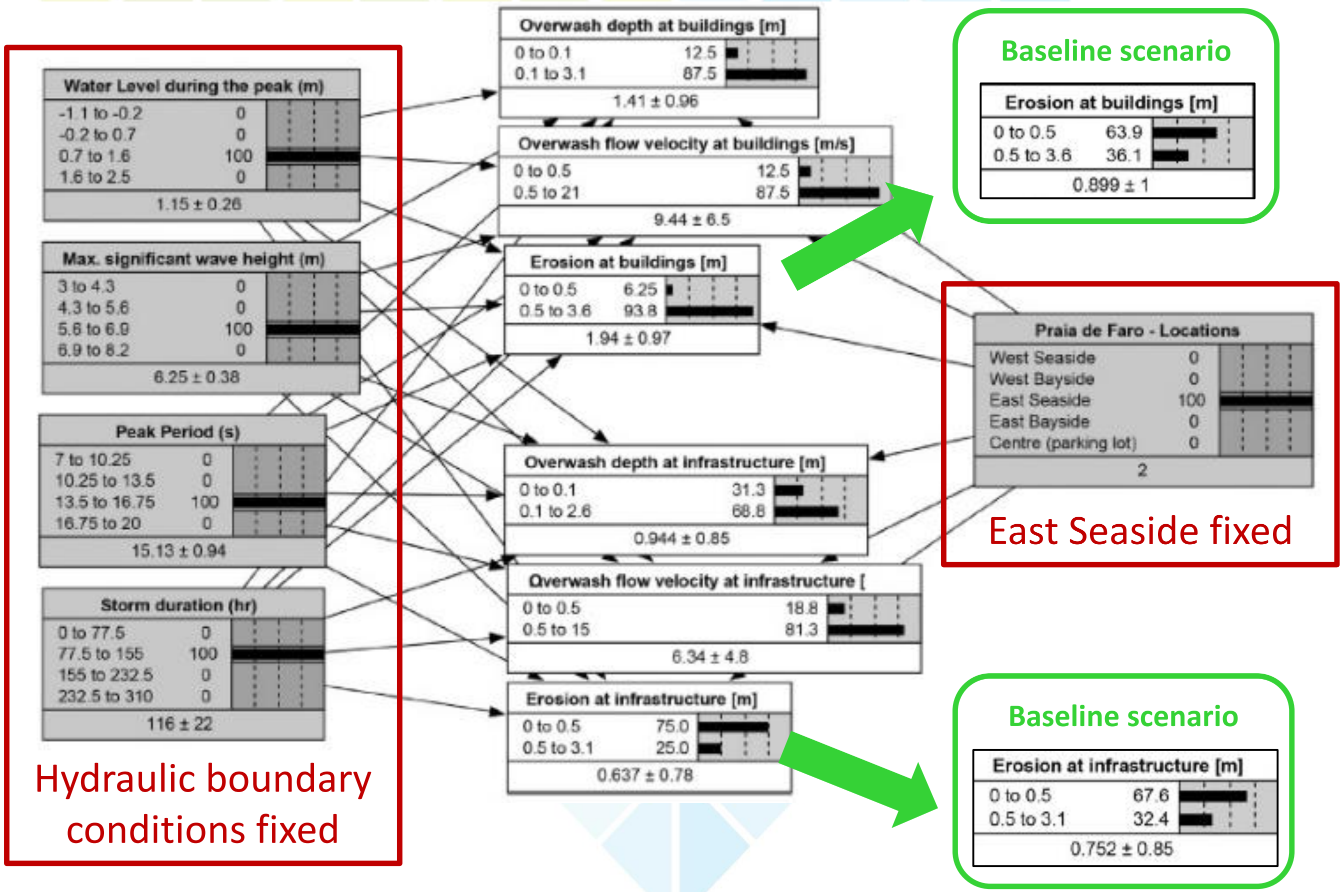
Predicting coastal hazards for sandy coasts with Bayesian Network

Poelhekke et al., 2016

- **Scenario (1)**

Updated probability of the hazards

- ➢ Erosion stays below the threshold
- ➢ Large probability of overwash



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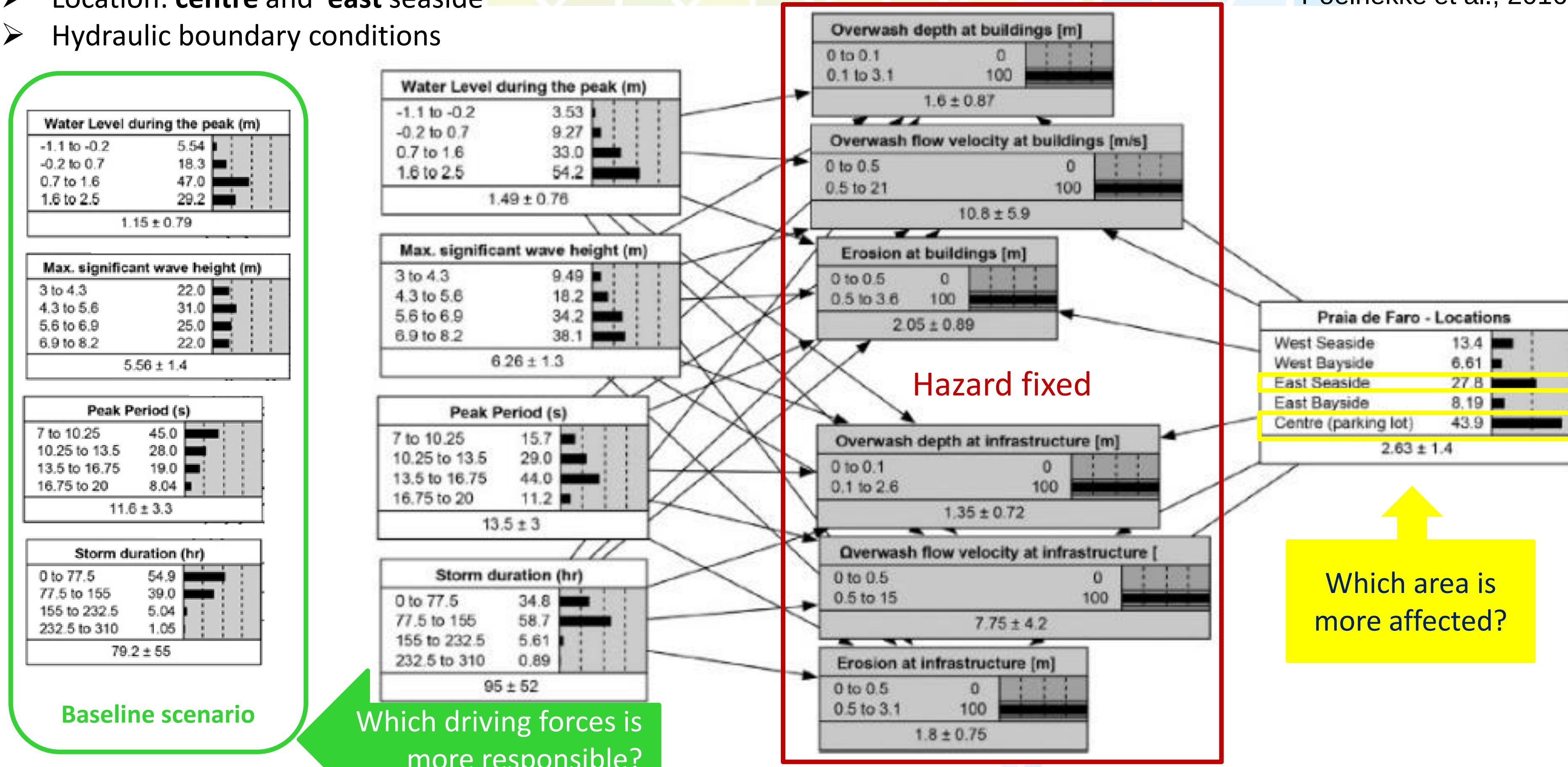
Predicting coastal hazards for sandy coasts with Bayesian Network

- **Scenario (2)**

Updated probability of the hazards

- ➢ Location: **centre** and **east** seaside
- ➢ Hydraulic boundary conditions

Poelhekke et al., 2016



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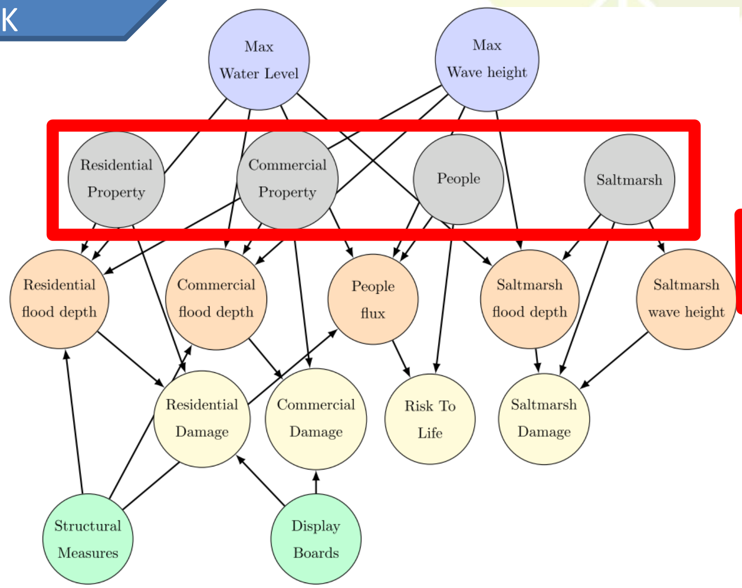
A Bayesian Network approach for coastal risk analysis and decision making

Jäger et al., 2017

Climatic threat/issue	Name of tool	Purpose	Scale
Erosion and flooding	Bayesian Network	Assessing the vulnerability to storm surges causing erosion	Local, North Norfolk – United Kingdom

North Norfolk, UK



- SOURCE: **Boundary conditions** (peak water level, max wave height, peak period, storm duration)
- PATHWAY: **Interaction** of water levels and waves with coastal landforms and ecosystems, coastal infrastructure and low-lying coastal hinterlands
- RECEPTOR: **Entities at risk** (people, built environments or ecosystems,…)

Integration of environmental and human receptors

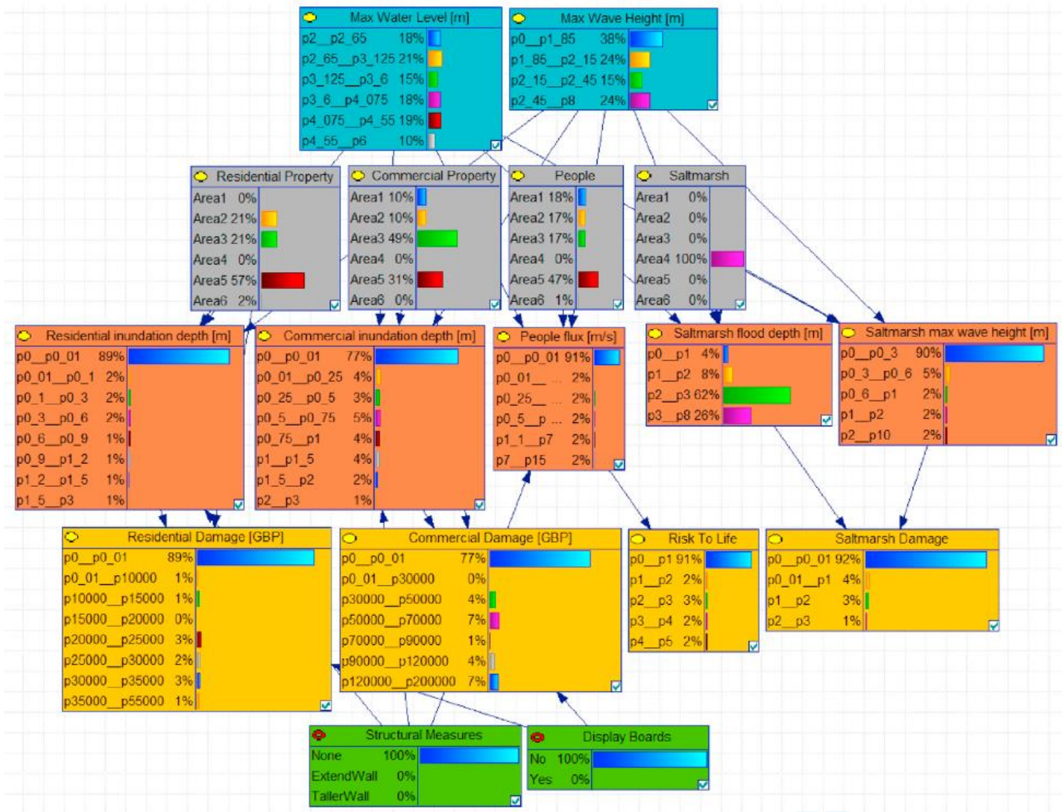
RISC-KIT

Project co-funded by European Union, European Regional Development Funds (E.R.D.F.) and by National Funds of Greece and Italy

A Bayesian Network approach for coastal risk analysis and decision making

Jäger et al., 2017

- **Baseline scenario**



RISC-KIT

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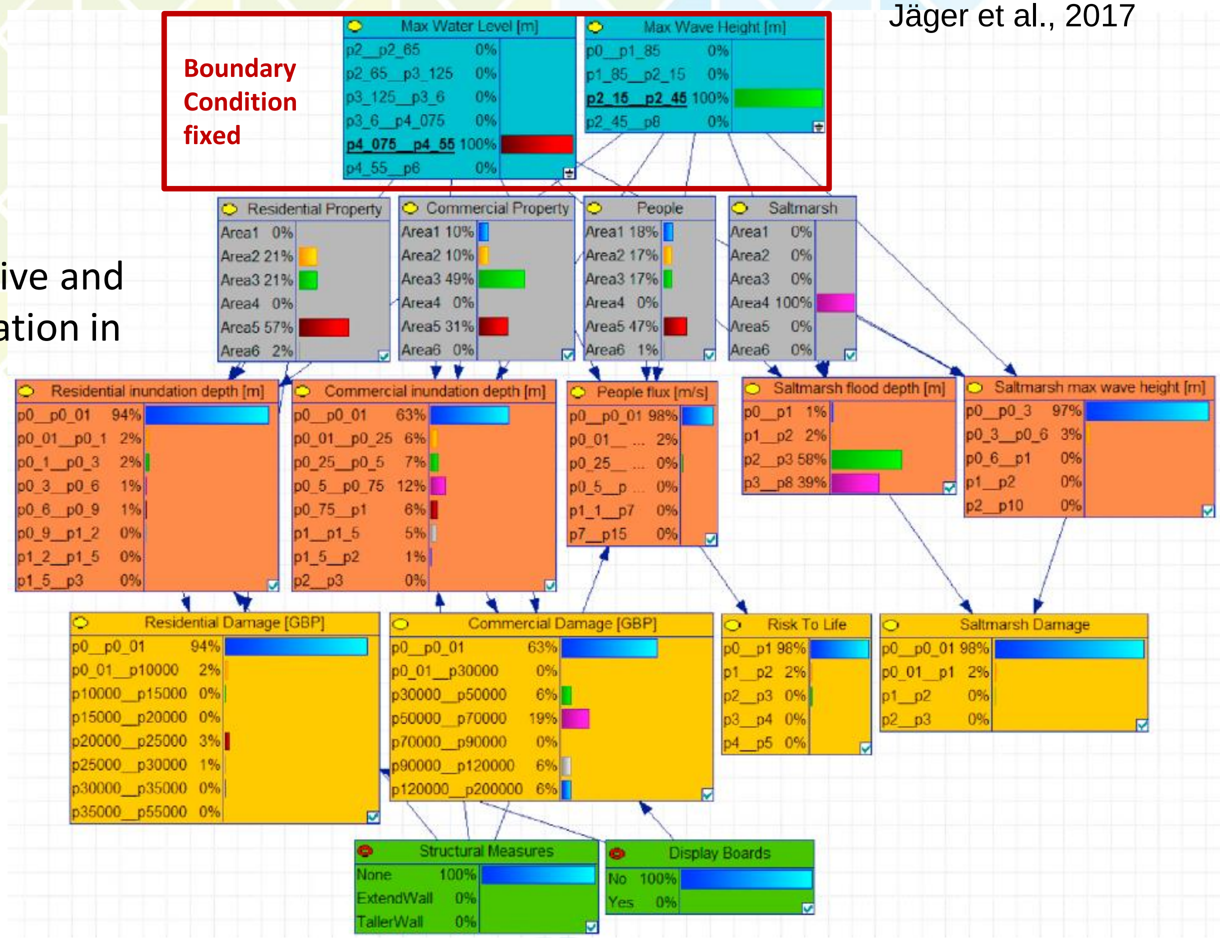
A Bayesian Network approach for coastal risk analysis and decision making

Jäger et al., 2017

- **Scenario 1**

100% probability of water level 4.075-4.55 m
100% probability of wave height 2.15-2.45 m



The resulting BN forms a comprehensive and concise representation of risk propagation in a complex system

- Helpful tool for decision makers
- Understand risks as a result of multiple disciplines

Project co-funded by European Union, European Regional Development Funds (E.R.D.F.) and by National Funds of Greece and Italy

Use of Bayesian Network for coastal hazards, impact and disaster risk reduction at a coastal barrier (Rio Formosa, Portugal)

Plomaritis et al., 2017

Climatic threat/issue	Name of tool	Purpose	Scale
Flooding and Coastal erosion	Bayesian Network	Reproduction of erosion, hazard potential impacts and the effect of the beach nourishment	Local, Ria Formosa coastal lagoon, Portugal

Ria Formosa coastal lagoon, Portugal

- Hazards: **overwash** and **erosion**
- Case study divided into **4 areas**
- 5 classes of BN nodes (variables of interest):
  – Boundary conditions, locations, hazards, impacts, **MEASURES**

- 124 simulations

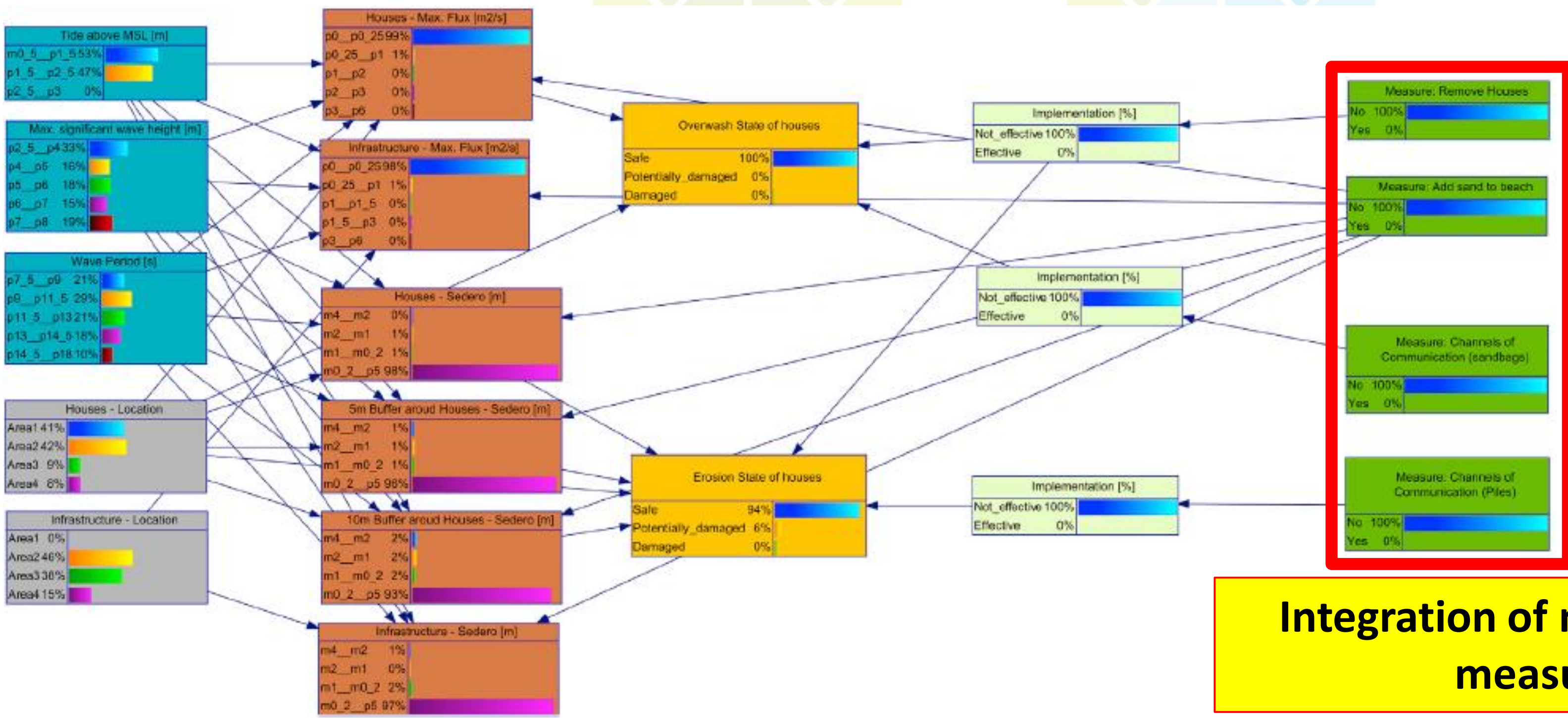
- Three main objectives of BN based tool for Faro Beach :
  - i. Surrogate the computationally expensive morphodynamic simulations within an EWS, transforming the offshore physical parameters to onshore hazard;
  - ii. Transform the hazard into impact for selected receptors;
  - iii. Incorporate into the tool DRR measures so it can be used by coastal managers as a DSS.

Project co-funded by European Union, European Regional Development Funds (E.R.D.F.) and by National Funds of Greece and Italy

Use of Bayesian Network for coastal hazards, impact and disaster risk reduction at a coastal barrier (Rio Formosa, Portugal)

Plomaritis et al., 2017

- **Baseline scenario**

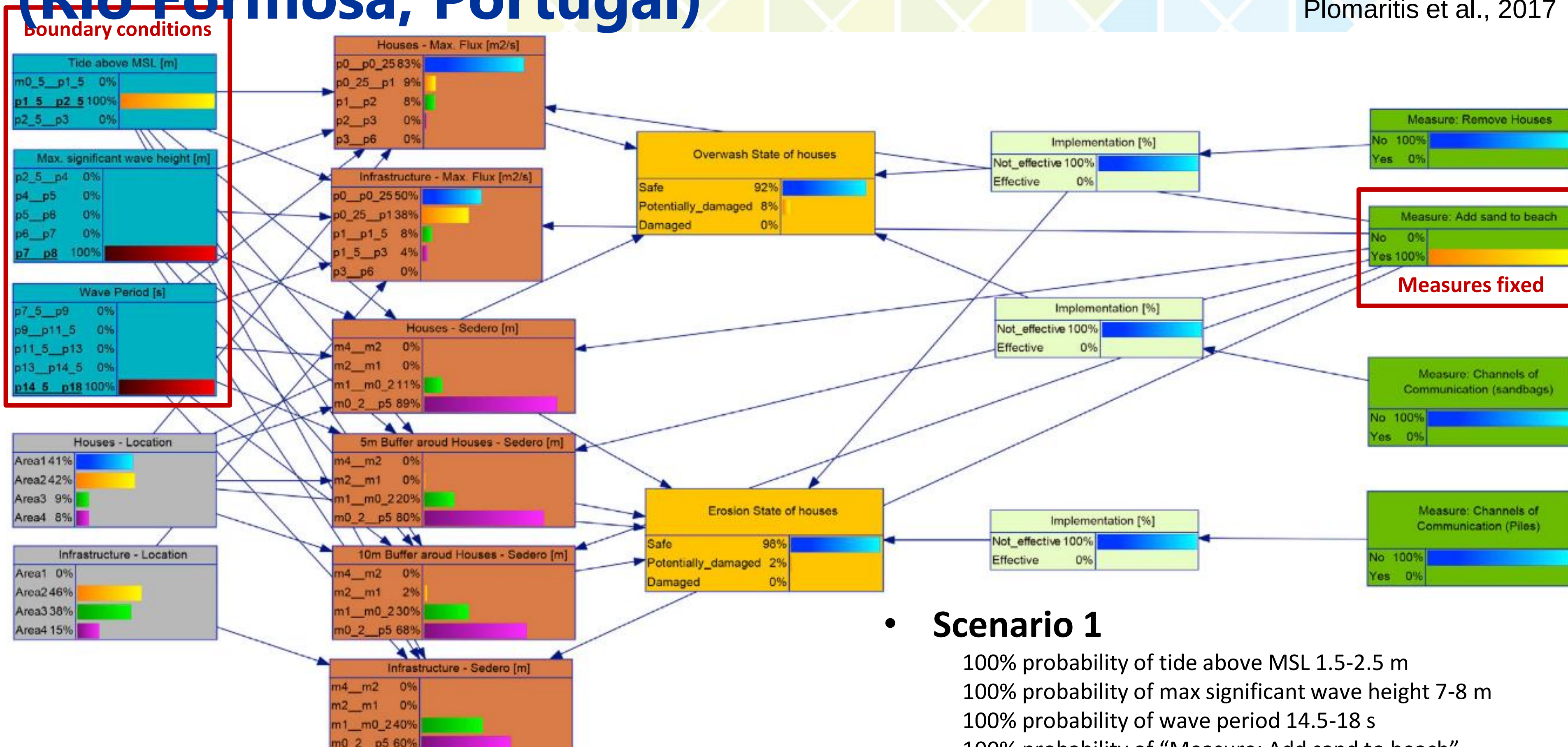


RISC-KIT

Integration of management measures

Use of Bayesian Network for coastal hazards, impact and disaster risk reduction at a coastal barrier (Rio Formosa, Portugal)

Plomaritis et al., 2017



- **Scenario 1**
  - 100% probability of tide above MSL 1.5-2.5 m
  - 100% probability of max significant wave height 7-8 m
  - 100% probability of wave period 14.5-18 s
  - 100% probability of “Measure: Add sand to beach”

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Linking source consequences of coastal storm impacts for climate change and risk reduction scenarios for Mediterranean sandy beaches

Sanuy et al., 2018

Climatic threat/issue	Name of tool	Purpose	Scale
Erosion and flooding	Bayesian Network	Compare strategic alternatives to reduce coastal risk in current and projected future scenarios	Regional, Lido degli Estensi-Spina, Italy and Tordera Delta, Spain

Lido degli Estensi-Spina
Tordera Delta, Spain

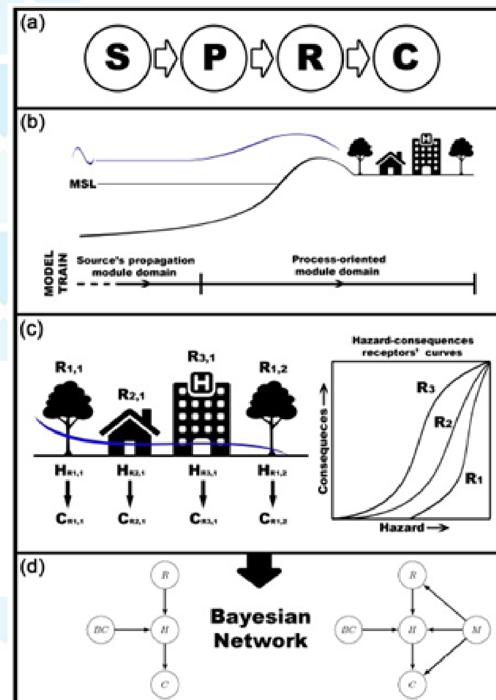
SLR future scenario: **RCP8.5**

- Tordera Delta: 0.73 m by 2100 and shoreline retreat 22 m
- Lido degli Estensi-Spina: 0.30 m by 2050

BN stucture is based on the **SPRC**

BN has 5 components:

- source boundary condition,
- hazard,
- receptor,
- impact/consequence,
- risk reduction measure



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Linking source consequences of coastal storm impacts for climate change and risk reduction scenarios for Mediterranean sandy beaches

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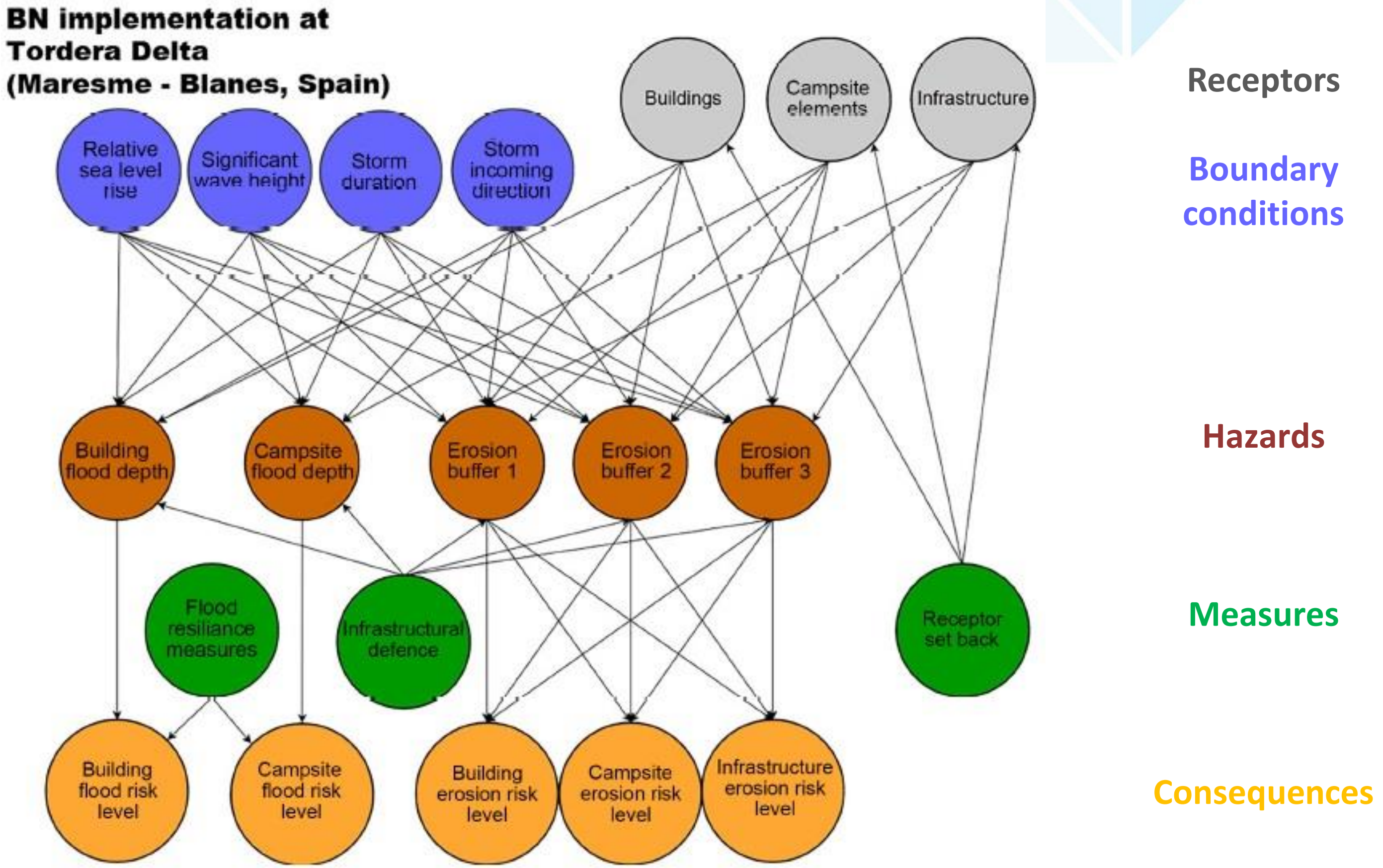

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Linking source consequences of coastal storm impacts for climate change and risk reduction scenarios for Mediterranean sandy beaches

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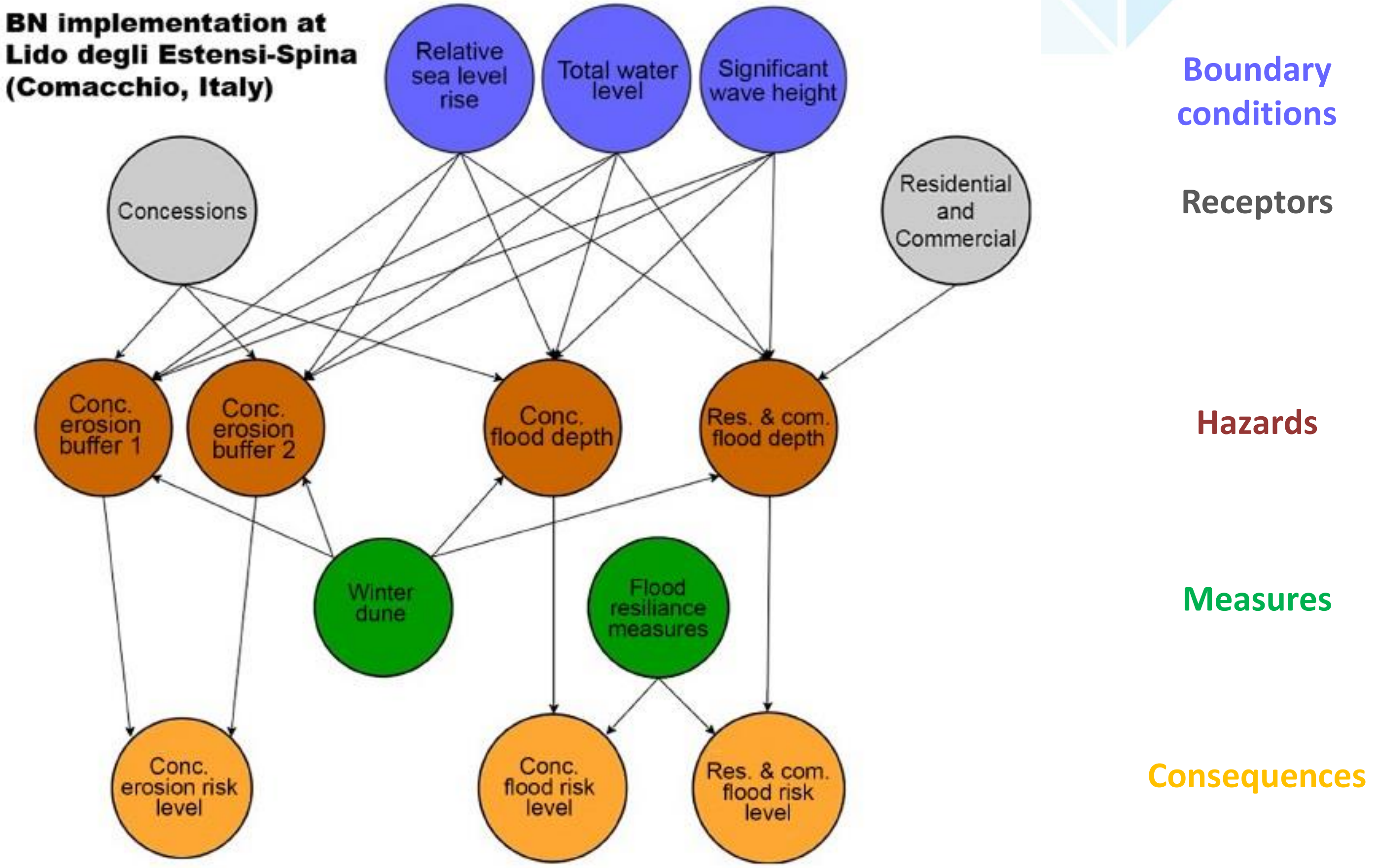
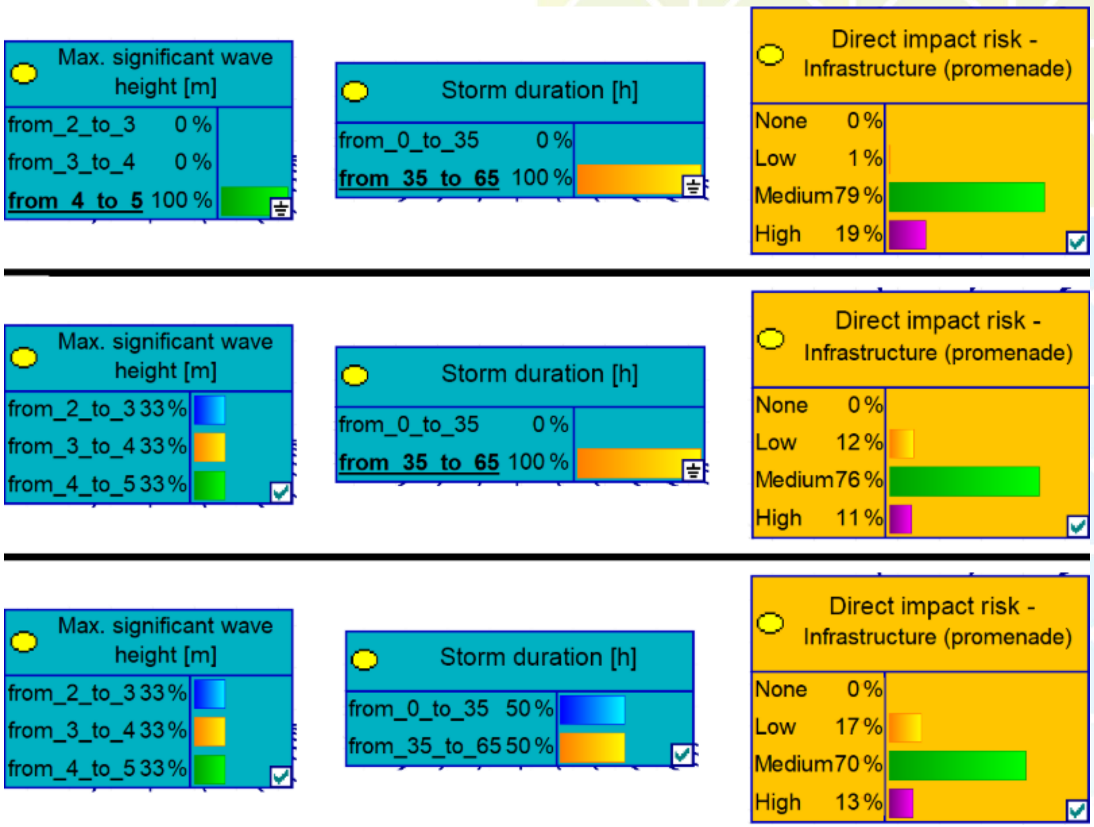


Linking source consequences of coastal storm impacts for climate change and risk reduction scenarios for Mediterranean sandy beaches

Sanuy et al., 2018



Scenario 1 – Tordera Delta
100% probability of
- Max significant wave height 4 – 5 m
- Storm duration 35 – 65 hours

Scenario 2 – Tordera Delta
33% probability of
- Max significant wave height (divided equally in 3 bins)

100% probability of
- Storm duration 35 – 65 hours

Scenario 3 – Tordera Delta
33% probability of
- Max significant wave height (divided equally in 3 bins)

50% probability of
- Storm duration (divided by 2 bins)

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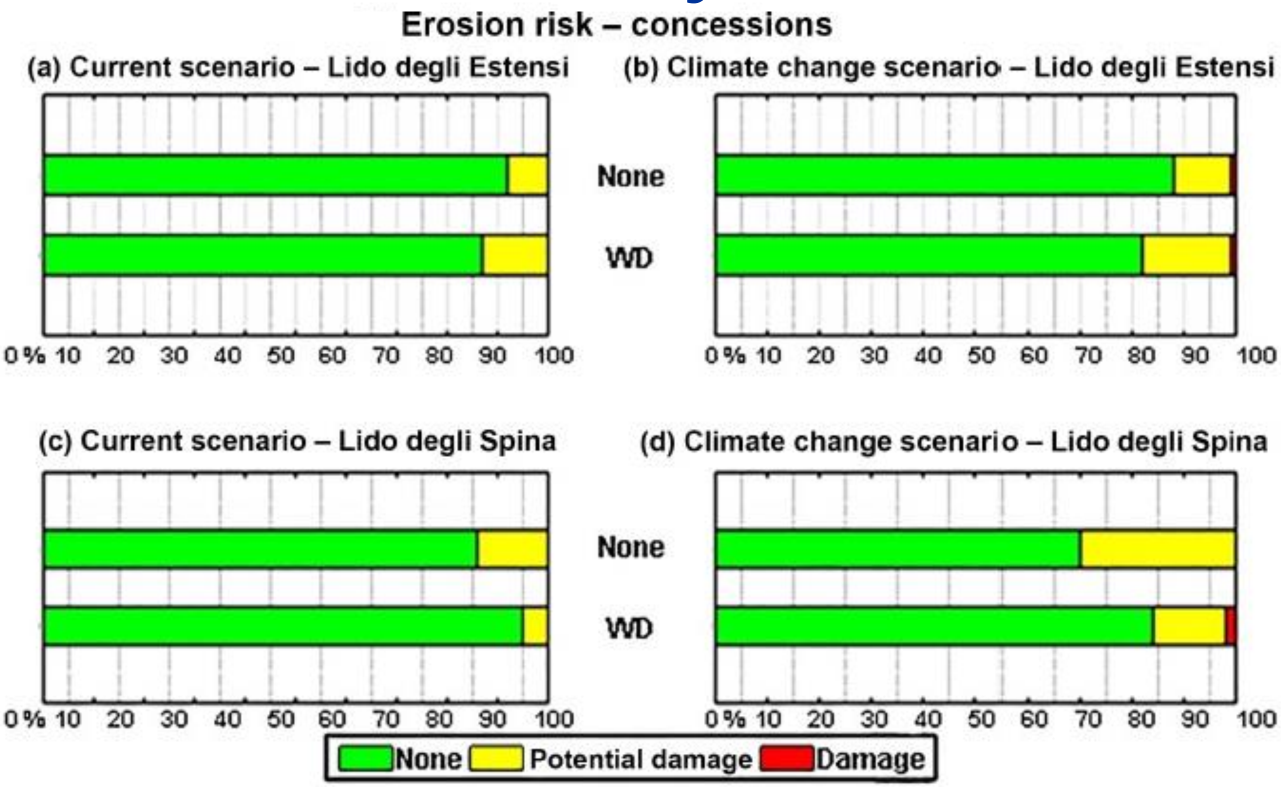
Linking source consequences of coastal storm impacts for climate change and risk reduction scenarios for Mediterranean sandy beaches

Sanuy et al., 2018



Lower risk than for flooding, but with Climate Change Scenario (CCS) the risk level increases up to:

- 11% (Estensi) and 30% (Spina)

AR5 RCP8.5

BN Strengths and Weaknesses

- Allow to consider **multiple stressors** and endpoints in the same framework;
- **Integrate knowledge** from various disciplines permitting very different variables to be assembled in **a systematic manner** using the same unit of measure (i.e. probability distribution);
- **Interactions among stressors** can be quantified using both **quantitative** and **qualitative information**;
- **Provide a stochastic assessment of risk**;
- Directly **account and deal with uncertainty**;
- Allow **stressors comparisons and prioritization against a stated objective**;
- Support **scenarios analysis**;
- **Implement the adaptive management principle**;
- Highly **flexible** to new knowledge integration;
- **Facilitate stakeholders engagement and participation**.

- Scarce representation of temporal and spatial dynamics and feedback loops;
- Limits in perform a strong quantitative validation:
  - Lack of large set of observed data;
  - Quantitative validation limited to portions or single parameters of the network;
  - Use of indirect methods (i.e. expert evaluation, comparison with previous studies, model simulations) of validation.

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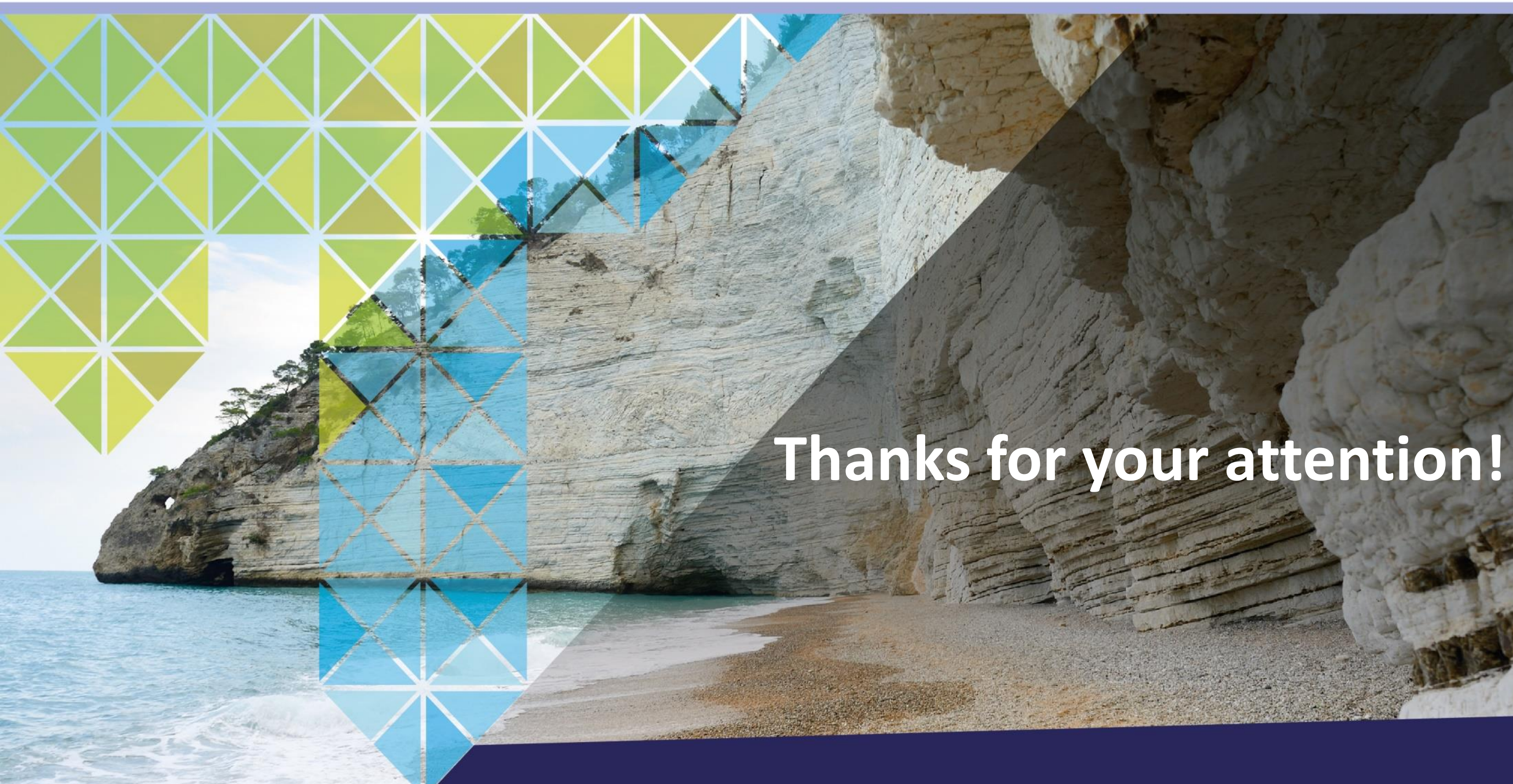

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