The DSS DESYCO: a decision support system for the regional risk assessment of climate change impacts in coastal zones

Prof. Andrea Critto
Centro Euro-Mediterraneo sui Cambiamenti Climatici
Cà Foscari University

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

**DSS** is an interactive computer-based information provider (Loucks, 1995)

**DSS** is an integrated, interactive computer system, consisting of analytical tools and information management capabilities, designed to aid decision makers in solving relatively large, unstructured problems. (Watkins & McKinney, 2001)

**DSS** can be defined as a computer-based tool used to support complex decision-making and problem solving (Shim et al., 2002)
Decision Support Systems couple the intellectual resources of individuals with the capabilities of computers to improve the quality of decisions. It is a computer-based support for management decision makers who deal with semi-structured problems.

Keen and Scott-Morton, 1978
What is a decision support system?

Decision Support Systems are computer-based systems used to assist and aid decision makers in their decision making processes.

They **AID** and **ASSIST** decision makers, but they **DO NOT REPLACE** them.
A Decision Support System (DSS) can be defined as a computer-based tool used to support complex decision-making and problem solving (Shim et al., 2002).

Computerized system that help decision-makers in:

- Structuring and evaluating decisions.
- Gathering and integrating information.
- Selecting and applying analytical procedures.
- Defining management options.

**DSS users**

**Decision-makers:** a person or group responsible for making the decision; they “own the problem”.
(French and Geldermann, 2005)

**Stakeholders:** those with a legitimate stake in the outcome of the decision.
(Bardos et al., 2001)

**Experts:** provide economic, engineering, scientific, environmental and other professional advice used to model and assess the likelihood of the impacts.
(French and Geldermann, 2005)
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 components

Database management system, which allows organization of basic spatial and thematic data and facilitate their efficient use.

Model management system, which includes quantitative and qualitative models to support the resource analysis.

Knowledge base, which provides information on data and models to identify problem, to generate solutions, evaluate their performances, and to communicate the results.

User-friendly interface, which allows communication with the system and visualization of results.
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)
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)
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.

(Woods et al, 1999)
DSS properties and characteristics

To be effective in user involvement, the DSS should be:

- Flexible;
- Adaptable to changes in the decision making process and user requirements;
- User friendly;
- Interactive;
- Providing quantitative and qualitative analyses.
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.
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**.
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**.
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.
Regional Risk Assessment (RRA): prioritization of impacts, targets and affected areas at the regional scale

RRA is a methodology that enables to evaluate all the components contributing to the computation of risk in different sub-areas of the same region, to prioritise the importance of these zones and finally combine the information for estimating the relative risk in the individual sub-areas of the region and rank the individual risk factors.

- Useful in situations where multiple stressors are of concern and for assessments covering broad geographic areas;
- Allow the identification and ranking of the sources, habitats and impacts in the region;
- Based on a Relative Risk Model: a system of numerical ranks and weights factors developed in order to combine and assess different kinds of risks.

Maps of the prioritized risk regions and of the spatial distribution of the analyzed stressors and targets.
The regional risk assessment methodologies allow to evaluate:

- a wide range of **different** types of **sources** releasing a **variety** of **stressors** which can impact a **multiplicity** of assessment endpoints.

- many **environmental hazards** which impact large geographical areas (increased global CO$_2$, ozone depletion, global climate change, biodiversity loss,…).

Regional risk assessment becomes important when:

- **policymakers** are called to face problems caused by a multiplicity of sources of hazards, widely spread over a large area, which impact a multiplicity of endpoint of regional interest;

- the limited **economical resources** don’t allow to plan remediation strategies to reduce all the identified risk to health, safety and environment;

- it is necessary to **classify risks** in terms of their magnitude and to select those to be investigated more thoroughly or to prioritize the remediation actions.
**RRA characteristics**

- Large area of interest (region).
- The presence of multiple sources, stressors, impact and receptors.
- The huge amount input data.
- The need of regional fate and transport models for stressors.
- The need of setting spatial relations between sources and receptors.
- The use of relative risk assessment models (to prioritize the risk).
RRA spatial information

- Landscape **morphology**.
- Spatial distribution of the **sources**.
- Spatial distribution of the **receptors**.
- Identification of the **spatial relations** between sources and receptors.
- Spatial distribution of the **variables** influencing **exposure**.

The development of the RRA depends on the availability of **regional data** and **spatial data**.

Methods to manage and analyse the data (i.e. GIS).
RRA approach (Landis and Wiegers, 1997):

- Identification of the different sources, habitats and possible impacts and their locations in the region.
- Ranking the importance of the different components of the risk assessment (sources, habitats and impacts).
- Spatial visualisation of the different components of the risk assessment to verify if they overlap.
- Division of the region in sub-regions.
- Relative risk estimation.

Based on a Relative Risk Model: a system of numerical ranks and weights factors developed in order to combine and assess different kinds of risks.
Each **combination** among the three components of regional risk assessment establishes a possible pathway to a hazard.

**Fig.** Possible combinations characterizing risk from two sources, two habitats and two potential impacts to assessment endpoints. (Landis, 1997)
• Impacts can be due to a variety of **combinations** of stressors and habitats.

• To result in an environmental impact the risk components must **overlap**.

• Risk is **proportional** to the overlap of source, habitat and impact.

(Landis, 1997)
If a source generates stressors that affect habitats important to the investigated target, the risk is **HIGH**.

A minimal interaction between the components results in **LOW** risk.

If one component does not interact with one of the other two components, there is **NO** risk.

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**Diagram:**

- **a. High Risk**
  - Source overlaps with habitat

- **b. Low Risk**
  - Minimal interaction

- **c. No Risk**
  - No overlap with habitat
  - No overlap with source

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*(Landis, 1997)*
• **Maps of the risk** regions with the associated sources, land-uses, habitats and the spatial distribution of the assessment endpoints.

• Regional *comparison* of the *relative risk*, their causes, the patterns of impacts to assessment endpoints and the associated uncertainty.

• A model of source-habitat-impact that can be used to ask what-if questions about different scenarios that are potential options in environmental management.
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.
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**.
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**.
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.
DESYCO Software architecture

**Graphical User Interfaces**
- **Web-based**
  - New interfaces
  - Integration in existing application
- **Desktop**
  - New interfaces
  - Integration in existing application

**DESYCO PROTOTYPE**
- CMCC software
- Open source software

**C# command line classes**

**Python functions**

**OGR / GDAL modules**

**Data tier**
- Models
  - txt
- Raster
- Shapefile
- Postgres

**Logic tier**

**Presentation tier**
Regional Risk Assessment (RRA) conceptual framework

CLIMATE CHANGE HAZARD ANALYSIS
(identification of Hazard Metrics)

GHG emissions scenarios
(e.g. A1, A1B)

climate models
(e.g. global, subcontinental scale)

high resolution numerical models
(e.g. hydrodynamic, hydrological, biogeochemical)

EXPOSURE SCENARIOS
(exposure functions)

observations

time series and extreme events analysis

RRA model
ranking of impacts, targets, areas at risk and damage evaluation

ATTENUATION FACTORS
(physical or anthropic factors)

SUSCEPTIBILITY FACTORS
(geophysical, ecological or anthropic)

VALUE FACTORS
(environmental or socio-economic resources)

VULNERABILITY ASSESSMENT
(non climatic factors)

GIS

PATHWAY FACTORS
(physical factors determining the impact area)

MCDA functions
Climate change impacts in coastal zones

- Flooding-Inundation
- Storm surge
- Sea water quality
- Establishment of low-drainage sectors
- Surface water stagnation
- Saltwater intrusion into groundwater
- Coastal erosion
- Sedimentation offshore
- Change in carrying Capacity for shore birds
- Terrestrial habitat change/loss (Wetland, Dunes, Hard rock)
- Change in hydraulics of estuaries
- Sea water quality
- Impacts on aquatic biodiversity
- Altered productivity in estuarine ecosystem
- Invasion by exotic/pest species
- Aquatic habitat change/loss (Sea grass bank, Altered productivity)
- Impacts on fisheries and aquaculture
- Change in carrying Capacity for shore birds
- Terrestrial habitat change/loss (Wetland, Dunes, Hard rock)
RRA methodology: steps

1. **Hazard matrix**
2. **Hazard scenario assessment**
   - Weighting
   - Normalization
   - Scoring
3. **Exposure assessment**
4. **Susceptibility assessment**
5. **Risk assessment**
6. **Damage assessment**

**Vulnerability matrix**
- Pathway factors
- Attenuation factors
- Susceptibility factors
- Value factors

**Normalization**
- Weighting
- Scoring
### HAZARD MATRIX

<table>
<thead>
<tr>
<th>BOTTOM STRESS</th>
<th>EXTREME STORMS SURGE</th>
<th>SEA LEVEL RISE</th>
<th>TIDE</th>
<th>WAVE</th>
<th>CLIMATE CHANGE IMPACTS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>HYDRODYNAMIC IMPACTS</td>
</tr>
<tr>
<td></td>
<td>Projected water level</td>
<td></td>
<td></td>
<td></td>
<td>SLR Inundation</td>
</tr>
<tr>
<td></td>
<td>Projected water level</td>
<td></td>
<td></td>
<td></td>
<td>Hydrodynamic impacts</td>
</tr>
<tr>
<td>Water levels associated to extreme events with different return periods</td>
<td>Projected water level</td>
<td>Storm surge flooding</td>
<td></td>
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</tr>
</tbody>
</table>

**HAZARD METRICS**

- Bottom stress
- Projected water levels
- Height
- Coastal erosion

- Storm surge flooding
- Projected water levels
- Distance from coastline
- Artificial protections
- Vegetation cover
- Coastal slope
- Protection level

### VULNERABILITY FACTORS:

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

### VULNERABILITY MATRIX

<table>
<thead>
<tr>
<th>RIVER MOUTHS</th>
<th>WETLANDS</th>
<th>HYDROLOGICAL SYSTEMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Elevation</td>
<td>- Elevation</td>
<td>- Elevation</td>
</tr>
<tr>
<td>- Protection level</td>
<td>- Protection level</td>
<td>- Protection level</td>
</tr>
<tr>
<td>- Extinction of</td>
<td>- Water body configuration</td>
<td>- Water body configuration</td>
</tr>
</tbody>
</table>

### VULNERABILITY METRICS:

- Hazard metrics
- Susceptibility factors
- Pathway factors
- Value factors
- Attenuation factors

### INPUT DATA

- Projected water levels
- Distance from coastline
- Artificial protections
- Vegetation cover
- Coastal slope
- Protection level

### HYDROLOGICAL SYSTEMS

- Water body configuration
- Water body configuration
- Water body configuration

### EXTREME STORMS SURGE

- Extreme storms surge
- Extreme storms surge
- Extreme storms surge

### SEA LEVEL RISE

- Sea level rise
- Sea level rise
- Sea level rise

### TIDE

- Tide
- Tide
- Tide

### WAVE

- Wave
- Wave
- Wave

### CLIMATE CHANGE IMPACTS

- Climate change impacts
- Climate change impacts
- Climate change impacts

### PROJECTED WATER LEVELS

- Projected water levels
- Projected water levels
- Projected water levels

### SLR INUNDATION

- SLR inundation
- SLR inundation
- SLR inundation

### STORM SURGE FLOODING

- Storm surge flooding
- Storm surge flooding
- Storm surge flooding
1) Hazard scenario assessment

Characterization of **climate change hazards** that impact on a system.

Information useful to construct climate change hazard scenarios can be provided by:

- **Global** and **regional climate models** forced by **emission scenarios** (e.g. IPCC SRES A1B);
- **Downscaling** of climate results in order to force **high resolution “impact” models** at the regional scale (e.g. hydrodynamic, hydrological, biogeochemical).

- Analysis of **historical records** by means statistical techniques, trend analysis, model-derived output based on observed data.

Select representative statistics to summarize the huge amount of information into the **hazard metrics** \((h_k,s)\).
Information for hazard scenarios construction

Examples of **statistics** associated with **metrics** for climate change risk assessment are (UKCIP, 2003):

- **mean** or average, **mode** or **median** of values determined over a particular period;
- **cumulative** (time-integrated) **value**;
- the **frequency** or **probability** of particular values or events including **percentiles**,  
- the frequency or probability that values of variables will fall between **particular bounds**, or **exceed** a particular (often extreme) value;
- absolute **maximum** or **minimum values** that may be recorded, usually over a particular interval of time;
- measures of **variance**, **standard deviation** or standard error, or more complete descriptions in terms of probability distributions or functions.

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**choosing** and **using** suitable statistics to represent hazard metrics in hazard scenario assessments is not always a simple task.
2) Exposure assessment

Identify and classify areas where the hazard can be in contact with the target.

\[ E_{k,s} = F(h_{k,s}, P_k, At_k) \]

- **Hazard metrics** \( (h_{k,s}) \)
- **Pathway factors** \( (P_k) \)
  (e.g. distance from coastline, elevation).
- **Attenuation factors** \( (At_k) \)
  (i.e. current or planned adaptation options, e.g. seawalls, natural dunes).

- Exposure functions are defined according to the specific impact;
- The hazard metrics can be normalized with the assignation of scores and weights, if it is specifically required in the Exposure function.
Scenarios Definition in DESYCO

The user can define several scenarios within each application and can import the maps to be used for each specific impact.
Exposure function for the Sea Level Rise inundation impact

The **risk function** for the sea level rise inundation impact aggregates **data** provided by regional **hydrodynamic models** forced with climate change scenarios and **topographical data** coming from Digital Elevation Models in order to calculate coastal areas and targets at risk from inundation.

\[
E_{\text{slr},s} = \min \left( \max \left( \frac{h_{\text{slr},s} - pf_1}{s_1}, 0 \right), 1 \right)
\]

- \(E_{\text{slr},s}\) = exposure score in a scenario \(s\);
- \(h_{\text{slr},s}\) = height of sea level rise according to scenario \(s\);
- \(pf_1\) = height of a cell;
- \(s_1\) = threshold representing the amount of water above a cell which generate the maximum impact.

**North Adriatic data sources:**

**SHYFEM hydrodynamic model.**

**Digital Elevation Model (DEM) 25 m.**
Exposure function for the storm surge impact

The exposure function for the storm surge impact is composed of 3 main components:

- **Hazard (H)** → based on water level return period, projected water level, tidal range, waves height and direction;
- **Attenuation (A)** → artificial/natural protections;
- **Pathway (P)** → distance from the coastline.

\[
E_{ssf,s} = \begin{cases} 
0 & \text{if } pf_3 \geq b \\
\min \left[ \max \left( \frac{((h_{ssf,s}(1- Af_2)) - pf_1) d_1}{s_1}, 0 \right), 1 \right] & \text{otherwise}
\end{cases}
\]

- \(E_{ssf,s}\) = exposure score;
- \(h_{ssf,s}\) = projection of the height of a storm surge water level (cm);
- \(Af_2\) = attenuation factor related to protections from storm surge;
- \(pf_3\) = distance of the center of the cell from the sea (always \(\geq 1\) m);
- \(pf_1\) = elevation of the cell (cm);
- \(d_1\) = distance factor related to distance of the cell from the sea (cm). It is calculated through an hyperbolic distance function;
- \(s_1\) = threshold given by the decision-maker. It represents the amount of water above a cell which generates the maximum impact (cm);
- \(b\) = it represents the distance from the sea over which the probability that a cell may be inundated by storm surge flooding is minimum (i.e. 0).
The **exposure function** for the coastal erosion impact is composed by 3 main components:
- **Hazard** component → to aggregate the hazard metrics with the “probabilistic or” function;
- **Attenuation** component → to define the role of the attenuation factors (i.e. artificial protections) in decreasing the magnitude of the coastal erosion impact;
- **Pathway** component → to consider the distance from the coastline in the definition of the exposure.

\[
E_{ce,s} = \begin{cases} 
0 & \text{if } pf_3 \geq s_2 \\
(\bigotimes_{i=1}^{n} [h'_{ce,i,s}]) (1 - At_{ce}) \cdot d_2 & \text{otherwise}
\end{cases}
\]

- \(E_{ce,s}\) = exposure score related to coastal erosion impact;
- \(pf_3\) = distance of the center of the cell from the sea;
- \(s_2\) = 1 km (i.e. the radius of influence of coastal erosion);
- \(h'_{ce,i,s}\) = hazard metrics classified and weighted in \((0,1)\);
- \(\bigotimes\) = “probabilistic or” function;
- \(At_{ce}\) = attenuation factor related to protections from erosion;
- \(d_2\) = distance factor related to distance from the shoreline.
“Probabilistic or” function

\[ \bigotimes_{i=1}^{4}[f_i] = f_1 \bigotimes f_2 \bigotimes f_3 \bigotimes f_4 \]

where:

\[ f_i = \text{i-th generic factor } f \]

The “probabilistic or” operator can be evaluated as follow, due to the associative and commutative proprieties:

\[ f_1 \bigotimes f_2 = f_1 + f_2 - f_1 f_2 = F_1 \]

\[ F_1 \bigotimes f_3 = F_1 + f_3 - F_1 f_3 = F_2 \]

\[ F_2 \bigotimes f_4 = F_2 + f_4 - F_2 f_4 = \bigotimes_{i=1}^{4}[f_i] \]

The process can be repeated until evaluating all operands.
If just a factor (f) assumes the maximum value (i.e. 1) then the result of the “probabilistic or” will be 1. On the other side, factor with low scores contribute in increasing the final “probabilistic or” score: the more is the number of low factor scores, the greater is the final score.

Susceptibility assessment

Evaluate the degree to which a receptor could be affected by a given climate change impact based on **site-specific territorial information**.

\[ S_k = \bigotimes_{i}^n [sf'_{i,k}] \]

- **Normalization** is provided by expert judgment;
- If just a susceptibility factor assumes the maximum value (i.e. 1) then the susceptibility score will be 1;
- \( sf'_{i,k} \) with low scores contribute in increasing the final susceptibility score: the more is the number of low susceptibility scores, the greater is the final susceptibility.
Classification and definition of scores and weights

The classification and definition of scores and weights is assisted by a specific menu which guide the user through the different possibilities.

Assignation of scores to susceptibility and value factors

Assignation of weights to susceptibility and value factors
Risk assessment

Integrate information about the exposure to a given climate change scenario and the territorial susceptibility in order to identify and prioritize coastal receptors and areas at risk from different impacts in the case study area.

\[ R_{k,s} = E_{k,s} \cdot S_k \]

- Risk score varies from 0 (i.e. no risk) to 1 (i.e. higher risk for the considered area);
- It provides relative classifications about areas and targets that are likely to be affected by climate change impacts more severely than others in the same region;
- It allows to evaluate statistics (e.g. percentage of the territory associated to each risk class, percentage and surface of receptors at risk to a specific impact for each municipality) useful to support the DM in the definition of adaptation measures.
Damage assessment

Provide a relative estimation of the potential social, economic and environmental losses associated to targets and areas at risk in the case study area.

\[ D_{j,k,s} = R_{k,s} \cdot V_j \]

- \( D_{j,k,s} \) = damage score related to an impact \( (k) \) and a receptor \( (j) \) in the scenario \( (s) \);
- \( R_{k,s} \) = risk score related to impact \( k \) in scenario \( s \);
- \( V_j \) = value score of receptor \( j \) .

\[ V_j = \frac{\sum_{i=1}^{n}[fV'_{ij}]}{n} \]

- \( V_j \) = value score of receptor \( j \);
- \( fV'_{i,j} = i^{th} \) value factor related to the receptor \( j \) (normalized in \([0,1]\));
- \( n \) = number of value factors.
A project allows to connect the different elements involved in the implementation of the RRA procedure.
Creation of project

Final interface that allows to perform each single step of the RRA methodology in order to produce the output maps.
decision support tools useful to guide the impact/risk management phase.

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

• DESYCO can be a useful tool to investigate the impacts associated to different climate change scenarios in sensitive targets (e.g. river deltas, beaches and wetlands) and to support the development of sustainable adaptation strategies.

• Regional risk/damage classifications should not attempt to provide absolute predictions about the impacts of climate change. Rather, they should be relative indices which provide information about the areas/targets within a region likely to be affected more severely than others.

• DESYCO is an open configuration (users can add their receptors and factors) and it can be used in different contexts and case studies.

• DESYCO and its RRA methodology is adapted and applied in several European projects: PEGASO (FP7, 2010-2013); CLIM-RUN (FP7, 2011-2013); CANTICO (ERANET, 2008-2011); TRUST (Life+, 2009-2011); SALT (Life+, 2009-2011); KULTURisk (FP7, 2011-2013); ORIENTGATE (2013-2015).
Thanks for your attention!

Prof. Andrea Critto
critto@unive.it

For more information:
Environmental Risk Assessment Unit, Ca’ Foscari University, Venice: http://venus.unive.it/eraunit/

Euro-Mediterranean Center on Climate Change (CMCC), RAAS - Risk assessment and adaptation strategies, Venice: www.cmcc.it/it/divisions/raas