Innovative technologies for safer European coasts in a changing climate

A GIS-BASED DECISION SUPPORT SYSTEM FOR MULTICRITERIA COASTAL RISK ASSESSMENT AND MANAGEMENT: THE THESUES APPROACH

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7th EUREGEO European Congress on REgional GEOscientific Cartography and Information Systems (EUREGEO)
THESEUS at a glance

- Title: Innovative coastal technologies for safer European coasts in a changing climate
- Instrument: Large Integrated Project - FP7
- Total Cost: 8,519,726 €, EC Contribution: 6,530,000 €
- Duration: 48 months, Start Date: 01/12/2009
- Consortium: 31 partners from 18 countries
- Project Coordinator: Barbara Zanuttigh, Alma Mater Studiorum Università di Bologna (Italy)
- Project Web Site: http://www.theseusproject.eu
- Key Words: coast, flood, erosion, risk, technology, mitigation, adaptation, climate change
THESEUS Aim

- deliver 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.
THESEUS study sites

- Vistula delta plain
- Elbe Estuary
- Scheldt Estuary
- Plymouth Sound to Exe estuary
- Po delta and adjoining coast
- Varna spit
- Santander Spit
- Gironde
Focus on the sites
Cesenatico (FC)

Boundaries
- Northern, Tagliata Channel
- Southern, Valverde
- Western, railway track
WP5 Theseus DSS: Concepts

- Decision Support System (DSS) is a computer based information system that supports decision making activities – typically consisting of underlying databases and mathematical models with a graphical user interface for editing, generating and viewing results.

- Prerequisites:
  - The target DSS users are “coastal managers” - Intermediate level. Stakeholders are administrators with technical skills. Scientifically sound and innovate in particular aspects.
  - Coherent with EU policies and vision.
  - Trying to integrate and make useful most of Theseus findings.

- Core functionality:
  - Evaluate potential risks due to climate change in three distinct dimensions: economic, life losses and environmental.
  - Analyze and compare sets of mitigation measures, both structural and non-structural, to reduce risks.
DSS Flowchart

1) General Requirements:
   - Scope
   - Target User
   - Flexibility
   - IT and Technological

2) Flood Vulnerability/Damage Model
   - Environmental, Socio-Economical Model
   - GIS Based approach: Map Calculation
   - Definition of Damage Function
   - Identification of key flood parameters for damage/vulnerability evaluation
   - Water depth
   - Velocity
   - Turbulence
   - Duration

3) Mitigation Options and Scenario drivers
   - List of mitigation option to be evaluated and modelled by the DSS
   - Costal engineering measures
   - Environmental mitigations
   - Socio economical actions

4) Coastal Mathematical Models
   - Storm surge flood: GIS flood model
   - Erosion
   - Wave overtopping
   - Evaluation of coastal mitigation options
   - Models must be compliant with IT requirements defined previously

5) Multicriteria Risk Assessment
   - Spatial GIS based MCA
     - Overall Risk Map (environment+socio+economic)
     - Economic evaluation

6) Technological Design of DSS
   - Web or Desktop
   - GIS software
   - Programming languages
THESEUS DSS Characteristics

- Target User: Coastal Managers
- Risk Scenarios -
  - Climate Change
  - Subsidence
  - Mitigation Measures
- Hazard: Flooding and Erosion
  - Storm Surge Flooding
  - Wave Overtopping
  - Coastline Erosion
- OUTPUT - Quali-Quantitative coastal risk assessment
  - Map of single coastal risk criteria (enviro, socio, economic)
    - Qualitative ranking (High, Medium, Low)
    - Quantitative ($, loss of life, loss of species)
  - Map of Multicriteria risk (MAUT MAC - Cost-Benefit $$)
- Support in mitigation measure selection
  - Where and Which are the best mitigation measures in order to minimize single
    and multi criteria coastal risk
- User friendly GUI
  - Desktop of Web-based
  - Open Source
THESEUS DSS Ingredients

• Relational Databases
  – Climate and wave data
  – Mitigation Measures
  – Damage Curve

• Geo-Databases
  – GIS Layers
    • Receptor

• Mathematical Models—Linked and embedded
  – Sea Level and wave propagation
  – Storm Surge Flooding
  – Wave Overtopping
  – Coastline Erosion

• Geoprocessing and Map algebra script
  – OGR/GDAL Libraries
  – Damage Function and MCA

• GIS Mapping GIS
  – Desktop GIS
  – Open Source
The SPRC Risk Assessment method
RECEPTOR MODULE

• GEO DB with Layer map useful for receptor identification by the DSS users
  – DTM, SRTM
  – Landuse
  – Urban classification
  – Population and Census data
  – Socio economic data
  – Vegetation map
  – Habitat map

• GEO DB (ESRI or POSTGis DB) with metadata

• GUI: The data are uploaded in the DSS, the user can interact in a mapping framework with the layers

• The user can define and add new receptor layers for risk assessment
Receptors
Bottom elevation
Population density
Sensitive Population Density

Cesenatico
Sensible Pop. Density
14>Age> 60

Legend

pop_sens_mq

0 - 0.0000001
0.000000101 - 0.001235269
0.001235269 - 0.001852904
0.001852904 - 0.002470538
0.002470538 - 0.003088173
0.003088173 - 0.003705808
0.003705808 - 0.004323442
0.004323442 - 0.004941077
0.004941077 - 0.005558711

0 195390 780 1,170 1,560 Meters
Land use
Spatial distribution of GDP

Legend
GDP [euro/m²]
- 50
- 51 - 60
- 61
- 62 - 100
- 101 - 130
- 131 - 152
- 153 - 180
- 181 - 3554
Habitat survey
Habitat survey

Scolelepis squamata

Huge abundance of Lentidium mediterraneum

Interstitial organisms: big nematodes and turbellaria
Habitats

Legend
- Artificial benthic habitat
- Artificial dune
- Artificial river bank
- Channel
- Flooded wetland
- Protected sandy beach
- Protected soft bottom
- Sandy beach
- Soft bottom
- Vegetated habitat
ArcGIS map of other potentially relevant stressors

http://globalmarine.nceas.ucsb.edu
• Database of pre-cooked climate scenarios
  – for flooding purposes: pdf functions
    • Storm Surge including tide
    • Waves statistics
  – For erosion scenarios:
    • Representative typical annual wave climate
    • Time series
• User can interact with Flooding scenario by selecting the time horizon
• GUI: the user play with a time slider defining the time scenario and extracting climate/wave parameters
• The data selected in this module are used as input for Flooding and Erosion model
Sources: storm surge, waves

- 3D model SHYFEM coupled with spectral wave model WWM
- Climate model downscaling S18E5 is introduced.
- Regional downscaling atmospheric dataset, produced by DWD, provided by HZG
- Control period 1960-1990 and tA1B IPCC scenario (2010-2100).
Sources: storm surge, waves

- Flooding scenarios

![Graph showing flooding scenarios over time]
Sources: storm surge, waves

- Flooding scenarios

![Graph showing flooding scenarios over time with different data points for different time periods: 1960-1990, 2040-2070, and 2070-2100.](image)
Flooding scenarios

- Peak storm duration: 12 hours
Climate change and MSL
DRIVERS MODULE - DSS GUI

- Database with subsidence and climate change trend
- The user can define a specific DRIVER scenario interacting through a GUI and selecting the climate change and subsidence characteristics
- The user can modify the pre-loaded climate change and subsidence trend
- GUI: a window with a curve tool (time vs subsidence/climate change)
- Raster GIS based procedure to obtain the new DTM considering the subsidence trend
Subsidence

Model for subsidence
Inclusion of this model to update the dtm

Subsidence rate
mm/year

Existing management
Existing management
Pathway Module

- Sea Level and Wave Wave Propagation Models
  - Wave transmission – Matlab/Python Script
- Overtopping Models
  - Artificial Neural Model for overtopping (Verhaeghe 2008)
- Storm Surge Flooding Models
  - Pre-cooked run of numerical model
    - MIKE 21
  - GIS Based Mathematical models
    - LISFLOOD
    - Watershed segmentation flooding
- Erosion model
  - CERC Formula GIS Python Script
- OUTPUT: Map of flooded area, water depth, velocities and duration
Sea Level and Wave Propagation
Shoreline boundary condition

W(t)

Setup, R2%, Hsi

Runup, setup

Transmission

Wave transformation

Tide, Hso

Y [m]

2.5

2.0

1.5

1.0

0.5

0.0

-0.5

03:00 03:10 03:20 03:30 03:40 03:50 04:00

2010-04-23
Equilibrium flood mapping is based on a comparison of the maximum total water height and ground elevation; land lower than the maximum total water height is assumed to flood.

- Impact of grid size in GIS based flood extent mapping using a 1D flow model. M. G. F. Werner
Watershed Segmentation GIS model

- marker controlled watershed segmentation algorithm operator (Meyer and Beucher, 1990; Soille and Ansoult, 1990)
  - CREDITS Nicolas BEUCHER (nicolas.beucher@ensta.org)
- The terrain model represented by a floating image is flooded preserving the hydraulic connectivity from a specific seed or source (usually the minima) defining a specific water level (storm surge)
DTM pre-processing

- Linear interpolation of river cross section and river bathymetry definition
- LIDAR no data in river bed
- Bank delineation
DTM pre-processing

a) TIN created from LIDAR points results in artificial dams

b) Integrated terrain (TIN) with mesh and LIDAR points

c) TIN created from LIDAR points

d) Integrated terrain (TIN) with mesh and LIDAR point
MIKE 21 Vs WS GIS based model

- Maximum flood extension simulated with MIKE 21 and the GIS model

$Tr=100\text{ years}$
MIKE 21 Vs WS GIS

Tr=100 years
Watershed Segmentation GIS model
Map of Flooded Area

- Possibility to map flood extension and water level in presence of new defense systems (dikes, barriers, etc) or if they deleted or damaged/breached.
Watershed Segmentation Models: Finite Volume

8 Mmc

15 Mmc

25 Mmc

35 Mmc
Watershed Finite Volume Test

- $Q=10000 \text{ mc}$
Watershed Finite Volume Test

• $Q = 100000 \ mc$
Watershed Finite Volume Test

- $Q=1000000 \text{ mc}$
Flood Duration

\[
\frac{dh}{dt} = -\frac{K}{n} \frac{h - h_0}{L} \frac{h_0}{px} \frac{1}{px^2} = -a(hh_0 - h_0^2) = 
\]

where

- \( A \) = soil surface flooded area = \( px \times px \) (m²)
- \( n \) = porosity
- \( px \) = width of flow = pixel size (m)
- \( S \) = medium thickness of hydraulic head (m)
- \( K \) = permeability (m/s)
- \( i \) = hydraulic gradient (-)
- \( h \) = hydraulic head of flooded pixel
- \( h_0 \) = hydraulic head of the nearest drainage system (river, sea, channel)
- \( L \) = distance pixel I from the nearest drainage system (river, sea, channel)
Soil Type

- Sand
- Silt and clay
- Silt and clay
Soil Permeability

<table>
<thead>
<tr>
<th>K</th>
<th></th>
</tr>
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<tr>
<td>0.0000000</td>
<td>0.0000001</td>
</tr>
<tr>
<td>0.000002 - 0.000100</td>
<td></td>
</tr>
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</table>

Meters
Erosion scenarios, GIS simplified model

• Required input:
  – Shoreline survey;
  – Sediment sampling;
  – Selection of the scenario
  – Typical annual wave climate;
  – Time horizon for the simulation.

• Assumptions:
  – average uniform sediment diameter in the area (d50=0.2 mm),
  – reconstruction of a Dean’s beach profile (A=0.09),
  – Triangular distribution of sediment transport (maximum at the breaking line).
EROSION

1 Line Model – Miller and Dean
Erosion scenarios, shoreline change
Flood Duration (h)
CONSEQUENCE/IMPACT MODULE - Vulnerability - Damage Function Approach

Damage module

Land use

Inundation depth

Damage function

Damage

Vulnerability

Damage
CONSEQUENCE/IMPACT MODULE - Vulnerability - Damage Function Approach

- Water Depth WDij,
- Velocity,
- Duration
CONSEQUENCE MODULE - IMPACT

Damage Function Approach

- Vulnerability Map Vij
- Hazard/stressor Map: Water Depth, Velocity, Duration
  - \( WD_{ij} \)
- Damage function \( D_{ij} = f(W_{dij}, V_{ij}) \)
Damage Function: Example

- Kok, 2001

Fig. 4. Scatter plot with the water-volume- and water-depth-damage (Epanechnikov-kernel with bandwidth h) for regular damage. Data source: Amt der NG Landesregierung, Abteilung Landwirtschaftsverbesserungen (2006a).

<table>
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<td>5</td>
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<td>1</td>
</tr>
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</table>

Fig. 6. Accumulated ln-ln-water-volume-damage curve and accumulated ln-ln-water-depth-damage curve (accumulated for all building types). Data source: Amt der NG Landesregierung, Abteilung Landwirtschaftsverbesserungen (2006a).
Consequence Module IMPACT

Height/Velocity Flood Map

Population Map

Landuse Map

Assets Map

DAMAGE Function

Economic Damage Map
Ecological Damage Map
Social Damage Map
Economic impact

damage function $f = a \sqrt{\text{depth}}$

Legend
a Value
High : 0.8
Low : 0

$WT = 1.7$  $Tr = 100 \text{ years}$
Distribution of economic damages

Legend
damage
GDP [euro/mq]
High : 3846.6
Low : 0

Tr=100 years
Environment vulnerability assessment

Sampling, Historical data

Temperature
- Wind
- Currents
- Granulometry
- Sediment transport
- ...

FBEM learning algorithm

Δ Temperature
- Δ Wind
- Δ Currents
- Δ Granulometry
- Δ Sediment transport
- ...

FBEM predictive algorithm

Δ Biological variables + biological autocorrelation

New sampling, Physical model, Online data

WT 1.5

Biological variables
Vulnerability of benthic communities

- Estimates for a surface of 400 cm$^2$
- Start of damage: for flooding scenarios with Tr=20 years
EVI Benthos

cesenatico EVI scenario1

\[ y = 0.0972x - 0.0829 \]

EVI Benthos

cesenatico EVI scenario4
**PINEWOOD EVI matrix**

**Drivers**: sea level rise, elevation, flooding duration

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<tr>
<td><strong>Sea level rise (cm)</strong></td>
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<td>3</td>
<td>3</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
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</table>
Pinewood damage curves

Pinewood damage curve (SLR:22cm)

Flooding duration (h)

EVI (damage)
Social vulnerability: ‘flooded’ people

WT 1.7

Tr=100 years
Vulnerability of Sensitive Population (14\textgreater \text{Age} \textgreater 60)
Risk for Population

Scenario 2050
TR 50

Legend
Calculation 3

Risk for Population

Meters

0 145290 580 870 1,160
Vulnerability - Sensible Pop

Legend

edifici_point_istat
popsens_po

- 0.000000 - 0.157895
- 0.157896 - 0.400000
- 0.400001 - 0.590909
- 0.590910 - 0.750000
- 0.750001 - 0.928571
- 0.928572 - 1.125000
- 1.125001 - 1.625000
- 1.625001 - 2.315789
- 2.315790 - 5.500000

Cesenatico
Sensible Pop
14>Age> 60
0 390 780 1,170 1,560 195
Meters
Hazard – Water Depth

Legend
Y_2020TR_50WLdtm4ws_cessub50.tif
Value
- High : 155
- Low : 0

0 120240 480 720 960 Meters
Hazard
Water Depth cm at Buildings
Scenario 2050
TR 50

Legend
edifici_Y_2020TR_50WL
RASTERVALU
- -9999.000000 - 5.000000
- 5.000001 - 8.800003
- 8.800004 - 25.000000
- 25.000001 - 40.799995
- 40.799996 - 57.222504
- 57.222505 - 74.400002
- 74.400003 - 92.073227
- 92.073228 - 109.904976
- 109.904977 - 129.601944
- 129.601945 - 154.899994

Meters
Social Risk for Sensible Pop = Hazard(WD) * Vulnerability

HAZARD

VULNERABILITY

Legend

Cesenatico
Sensible Pop. Density Age > 60

Legend

Social Risk to Life
Scenario 2050
TR 50

Legend

Social Risk 2 Pop Sns
Value
Low : 0

High : 0.680993
Social Risk Index – Sensible Population (14>Age>60)

Social Risk to Life

Scenario 2050
TR 50

Legend
SocialRisk2PopSens
Value
High : 0.680993
Low : 0
Social Risk to Life
Scenario 2050
TR 50

Legend
SocialRisk2PopSens
<VALUE>

0
1
2
3
4
Vulnerability of social functioning of the places
Risk for social functioning of the places

- Risk\_SF = Vulnerability\_SF * WD(cm)
Single and Multi Criteria Risk assessment

• What kind of method?
  – One-metric or
  – Multiple-metrics and multi-criteria analysis

• Criteria for integrated risk evaluation?
  – Selection of an homogeneous quantification for the impact
  – Risk evaluation in absolute terms so that risk in different study sites can be compared
  – Weights to be included in the final evaluation: selected by software user?
Single Risk Maps Indicator

- The user can define different flood risk map criteria
  - Economic risk
  - Environmental Risk
  - Social Risk
- The risk criteria can be converted in monetary value in order to obtain a single risk map or they can be analyzed in a spatial MCA tool
Multicriteria Risk Assessment

Multicriteria risk mapping: aggregation of the different criteria maps

Two different approaches used:
- Disjunctive approach
- Additive weighting approach
Multicriteria Approach: MAUT vs CB

• Problem Definition:
  – Set of risk mitigation measures (n alternatives)
    • Aj=A1….An
  – Set of risk criteria (environment, social, economic)
    • Ci=C1…….Cm
  – The score aij (raster map) describe the performance (costal risk indicator) of Alternative Aj respect the Criteria Ci
  – Wi(i=1….m) are the weight of importance for each Ci , assigned by stakeholders

• MAUT
  – Aggregation of different Ci risk criteria into a function, which has to be maximized
    • Economic risk
    • Environmental Risk
    • Social Risk

• CB Analysis
  – Evaluate the cost and benefit of each Aj in Monetary Base
The general concept of additive MAUT approaches is to generate a weighted average of the single criterion values for each alternative. Given a set of evaluation criteria (economic, environmental, social) and a set of alternatives (ex. Flood risk scenario, mitigation measures, etc) to be compared as well as scores for each alternative in each criteria and a set of weights for each criterion the procedure for this is the following:

- Standardise the criteria scores to values (or utilities) between 0 and 1.
- Calculate the weighted values for each criterion by multiplying the standardised value with its weight \( w_i \) (pair-wise, ranking, ......)
- Calculate the overall value (utility) for each alternative by summing the weighted values (utilities) of each criterion.
- Rank the alternatives according to their aggregate value (utility).

\[
x_j = \frac{\sum_{i=1}^{m} w_i a_{ij}}{\sum_{i=1}^{m} w_i}, \quad j = 1, \ldots, n
\]

- where \( X_j \) is the overall value or utility of the alternative \( A_j \), \( a_{ij} \) is the value or utility of the alternative \( j \) regarding criterion \( i \) and \( w_i \) is the standardised weight for criterion.
MCA Normalization

- **MAUT:**
- **Normalization of** $a_{ij}$ **score** through a normalization or utility function that transforms the raw performance values of the alternatives against diverse criteria, both factual (objective, quantitative) and judgmental (subjective, qualitative), to a common, dimensionless scale (e.g., [0,1], [0,10], [H,M,L])
- **Weight**
MCA Weighting

- Rank Sum Method

\[ w_j = \frac{n - r_j + 1}{\sum (n - r_k + 1)} \]

- Pairwise Comparison

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<thead>
<tr>
<th>Value</th>
<th>Definition</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Equal importance</td>
</tr>
<tr>
<td>2</td>
<td>Slightly more important</td>
</tr>
<tr>
<td>3</td>
<td>Much more important</td>
</tr>
<tr>
<td>4</td>
<td>Very much more important</td>
</tr>
<tr>
<td>5</td>
<td>Absolutely dominating</td>
</tr>
</tbody>
</table>
Raster MCA

1. STANDARDISING

Risk Maps

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<tr>
<th>Economic Risk</th>
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<th>90</th>
<th>80</th>
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<tr>
<td>0</td>
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2. WEIGHTING

Standardised Risk Maps

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Weighted Standardised Risk Maps

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3. AGGREGATING

Aggregated Risk

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Rank

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<td>2</td>
</tr>
<tr>
<td>6</td>
<td>8</td>
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</table>

Based on Malczewski (1999), own example
MCA MAUT: Cesenatico Case Study

TOTAL RISK

Legend

test.asc

Value

0 1 2 3 4
• The single and multicriteria risk tools are developed using GIS map/raster algebra script (python GDAL).
• The GUI consist in a set of windows where the user can play with the different input for single and MCA (normalization, weighting, aggregation) risk assessment
Thank you for your kind attention