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THESEUS decision support system for coastal risk management

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ABSTRACT

While planning coastal risk management strategies, coastal managers need to assess risk across a range of spatial and temporal scales. GIS-based tools are one efficient way to support them in the decision making process through a scenarios analysis starting from social, economic and environmental information integrated into a common platform. However, this integration process requires a significant effort from a team of scientists in terms of a) identifying the appropriate scales and data resolution for analysing social, environmental and economic issues; b) selecting and linking an appropriate set of tools to build a coupled model; c) representing key emerging (and hence challenging) research issues, such as risk perception and social resilience in the model; d) developing multi-criteria analysis to integrate social, environmental, economic impacts; and e) accounting for the expectations of the stakeholders and therefore optimizing the opportunity for them to interact with the tool development and with the final tool itself.

In this spirit, this paper presents an open-source Spatial Decision Support System developed within the THESEUS Project to help decision makers to scopeg optimal strategies to minimise coastal risks. The exploratory tool allows the users to perform an integrated coastal risk assessment, to analyse the effects of different combinations of engineering, social, economic and ecologically based mitigation options, across short (2020s), medium (2050s) and long-term (2080s) scenarios, taking into account physical and non-physical drivers, such as climate change, subsidence, population and economic growth.

1. Introduction

Improving the adaptive capacity of individuals, groups or organizations requires communicating present and possible trends in risk, building awareness of potential impacts and their implications, and understanding the available mitigation options.

And yet one of the biggest criticisms of much research is that it is not accessible, including policymakers whose decisions help to shape our future world. This is especially true for multi-dimensional problems where a system view is most effective at capturing the key issues and behaviour. However, this necessitates multi-disciplinary working and usually requires engagement with the relevant stakeholders.

A good example issue is coastal flooding and erosion risk management where multiple and interacting factors embracing, human safety, the environment and society must be considered, requiring a system perspective (Narayan et al., 2014; Thorne et al., 2007).

A spatial Decision Support System (DSS) is a computer-based software tool that can assist decision makers in their decision process. Such a DSS is an exploratory tool that allows to assess the conditions of a system under a variety of scenarios and the consequences of different adaptation and mitigation measures. A DSS will generally integrate the relevant environmental models, database and assessment tools – coupled within a Graphic User Interface (GUI), Spatial problems such as flood and erosion risk requires a Geographical Information System (GIS) approach. GIS is a set of computer tools that can capture, manipulate, process and display spatial or geo-referenced data facilitating spatial data integration, analysis and visualization (Burrough and McDonnell, 1998). These functionalities make GIS-tools useful for efficient development and effective implementation of DSS within the management process. For this purpose GIS tools are used either as data managers (i.e. as a spatial geo-database tool) or as an end in itself (i.e. media to communicate information to decision makers). The use of GIS for coastal zone management has expanded rapidly during the past decade (Bartlett and Smith, 2004; Sheppard, 2012; Wright and Bartlett, 2000; Wright et al., 2011).

Based on a review of a range of existing DSSs which deal with coastal areas (Table 1), the main objectives of these tools are the analysis of vulnerability, impacts and risks, and the identification and evaluation of related management options, in order to support robust decisions for sustainable management. Specifically, the objectives of the examined

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Table 1
Review of existing exploratory tools that can be used for supporting decisions applied to coastal areas. These GIS-based tools perform scenario construction and analysis. To be continued.

Name	Year	Ref	Processes	Functionalities
COSMO	1992	Feenstra et al. (1998)	Sea-level rise	Problem characterization (e.g. water quality, coastal erosion,) Impact evaluation of different development and protection plans Multi-criteria decision analysis Ecosystem-based
Coastal Simulator	2000–	Mokrech et al. (2009) Dawson et al. (2009)	Storm surge Flooding Coastal erosion Sea-level rise Socio-economic scenarios	Environmental status evaluation Risk analysis Management strategies identification and evaluation Uncertainty analysis Integrated risk assessment
CVAT	1999–	Flax et al. (2002)	Multi-hazard Extreme events Storm surge	Hazard analysis Social, economic and environmental vulnerability indicators Mitigation options analysis Risk analysis at regional scale
DESYCO	2005–2010	Torresan et al. (2010)	Sea-level rise Storm surge Flooding Coastal erosion Water quality	Impacts and vulnerability analysis Adaptation options definition Multi-criteria decision analysis Regional risk assessment
DIVA	1999–	Vafeidis et al. (2008) Hinkel and Klein (2009)	Sea-level rise Coastal erosion Storm surge Flooding Wetland loss and change Salinisation	Environmental status evaluation Impact analysis Adaptation options evaluation Cost–benefit analysis
KRIM	2001–2004	Schirmer et al. (2003)	Sea-level rise Extreme events Coastal erosion	Environmental status evaluation. Adaptation measures evaluation Information for nontechnical users Risk analysis
RegIS	2003–2010	Holman et al. (2008)	Coastal and river flooding Wetland loss and change Sea-level rise Emission scenarios Socio-economic scenarios	Implementation of DPSIR conceptual model Management measures evaluation Impact analysis. Integrated risk assessment Information for nontechnical users
RAMCO	1996–1999	De Kok et al. (2001) http://www.riks.nl/resources/papers/RamCo2.pdf	Socio-economic scenarios Coastal and river flooding Policy options Impact of human activities Integrated management	Environmental status evaluation Management measures evaluation.
SimCLIM	2005–	Warrick (2009)	Sea-level rise Coastal flooding Coastal erosion	Environmental status evaluation Impact and vulnerability evaluation Adaptation strategies evaluation Cost/benefit analysis
WADBOS	1996–2002	Van Buuren et al. (2002)	Socio-economic scenarios Policy options Impact of human activities Integrated management	Socio-economic, hydrological, environmental, ecological data Socio-economic, ecological, landscape models Management measures identification and evaluation
CLIMSAVE	2010–2013	Harrison et al. (2013)	Emission scenarios Agriculture Forests Water Resources Coastal and river flooding Urban development	Implementation of DPSIR conceptual model Impact analysis Adaptation strategies
THESEUS	2010–2013	(this paper)	Sea-level rise Coastal flooding Coastal erosion Socio-economic scenarios	Hydraulic, social, economic, ecological vulnerability Combination of engineering, social, economic and ecologically based mitigation options Multi-criteria analysis High resolution risk assessment

DSS tools are concerned with three major issues (with examples in brackets from Table 1):

1. The assessment of vulnerability to natural hazards and climate change (DIVA, RegIS, CVAT, DESYCO, KRIM, Coastal Simulator);
2. The evaluation of present and potential climate change impacts and risks on coastal zones and linked ecosystems, in order to predict how coastal regions will respond to climate change (RegIS, CVAT, Coastal Simulator);
3. The evaluation or analysis of management options for the optimal use of coastal resources and ecosystems through the identification of feasible measures and adequate coordination of all relevant users/stakeholders (COSMO, WADBOS, SIMCLIM, RAMCO).

The THESEUS project (www.theseusproject.eu) builds on this experience by developing a comprehensive GIS-based DSS whose design, development and application is described in this paper.

Some example questions which this DSS can address include:

- How will flood risk change if I do nothing?
- Should I use soft or hard management approaches?
- Can enhancing habitats benefit human safety?
- Can the risk-sharing embodied in insurance benefit community resilience?

The THESEUS DSS is intended as a vehicle for communication, training, forecasting and experimentation. It fills a gap among the existing tools, based on the following pillars.

- It provides seamless integration across disciplines: physics, engineering, ecology, social sciences and economy.
- It considers intermediate spatial scales (10–100 km) and short-, medium- and long-term time spans (1–10–100 years).
- It allows diverse portfolios of mitigation options such as engineering defences (i.e. barriers, wave farms), ecologically-based solutions (i.e. biogenic reefs, sea-grasses) and socio-economic mitigations (i.e. insurance, change of land use);
- It supports decision-making based on a balance between deterministic models and expert, discussion-based assumptions.
- It uses an open source approach – based on a specific request from the European Commission – to maximise the availability and uptake of the tool.

This paper first describes in Section 2 the conceptual model framework around which THESEUS DSS was built, and the main modelling challenges when describing physical, ecological, and human (social/economic) processes and assessing the system status. Section 3 summarises the goal of the DSS and the intended application at the Science and Policy interface (SPI), including the stakeholder-informed design measures adopted for promoting its exploitation. Section 4 details the technical structure of the DSS, including scenarios and mitigation options, and the most significant results using Cesenatico, Italy, as an example. Lastly, Section 5 critically discusses the limitation of THESEUS DSS and the wider lessons of this exercise.

2. The modelling framework

2.1. Conceptual framework

The conceptual model for coastal risk assessment proposed in THESEUS is based on the Source–Pathway–Receptor–Consequence (SPRC) model that is widely used in the fields of waste and pollution management (FLOODsite, 2009; Narayan et al., 2012, 2014; Thorne et al., 2007). The SPRC model is a simple 1D–2D conceptual model for representing flood systems and processes that lead to particular flooding consequences. Effectively, the SPRC represents how the Sources (in this case, waves, tide, storm surge, mean sea level, river discharge, run-off) through the Pathways (including, coastal defence units) affect the Receptors (buildings, infrastructure, habitats, etc.) generating economic, social and environmental Consequences. Scenarios of change will modify the consequences of flooding and, given adverse trends such as sea-level rise and increasing coastal development, will increase them. Mitigation options from a wide menu of engineering, ecological and social options can offset this increase in Consequences, and keep risk at a socially-acceptable level.

Following DINAS-COAST (2004), SafeCoast (2008), and FLOODsite (2009) approach, THESEUS also adopts a scenario framework that considers the present situation (2010), and three future scenarios: short (2020s), medium (2050s) and long-term (2080s). In THESEUS, the coastal risk assessment is performed at a high spatial resolution using a Digital Elevation Model (DEM) to support detailed coastal management analysis of receptors, consequences and their mitigation.

Sources have been distinguished as primary and secondary. The primary sources are the weather-related phenomena which generate water that could cause flooding. The secondary sources are the physical manifestations of the above which may cause flooding, e.g. wave, surge, and changes in river volume and flow. For environmental purposes, Sources are essentially classified into three groups according to duration: short-term processes (storm surge, wind waves, tides, run-off due to downpours); seasonal – river high/low waters; and long-term processes (sea-level rise, subsidence).

Source statistics are defined in the study sites by compiling existing research archives (PRUDENCE3 or HIPOCAS4 from the IPCC AR4) and new data through a number of hindcast and downscaling activities, see Weisse et al. (2014). This approach delivers a comprehensive picture of present and potential future climate changes in the study sites and provides an assessment of the uncertainties associated with these changes. Climate parameters include: extreme sea levels and wave heights; long-term variation of extreme sea level occurrence; annual frequency distribution of extreme sea levels for different return periods; extreme sea levels; statistics of storm surges; sea level pressure fields of major flooding events; and present and extreme river discharges if appropriate (see Monbaliu et al., 2014).

Pathways are the route and processes which are active during a flood event and there must be at least one pathway between the source and receptor otherwise no consequences can occur. Pathways are a relative concept and they include the components of the flood system and management through or over which flood waters flow, such as habitats relevant for coastal protection, hard and soft coastal defences, and infrastructure. It is worth remembering that an individual pathway may lead to multiple receptors and individual receptors may have multiple pathways (Narayan et al., 2014). The DSS model needs to be able to describe multiple sets of flood routings.

Understanding the interaction between socio-economic and biophysical system components is complex and the subject of ongoing research, because terms, methods, and scales of analysis differ between natural and social science and are often not comparable (Adger et al., 2004). These data have to be related to each other in a way that makes sense for analysing vulnerability in a specific region and society on a scale that is useful for delivering outputs that can be transferred into the decision making processes. To operationalise vulnerability and resilience and to create vulnerability profiles the identification and quantification of a variety of indicators on different scales have to be further developed (Brooks et al., 2005).

However, the SPRC includes the physical, ecological (habitat) and socio-economic aspects of the flood system and hence provides an integrated framework which the DSS exploits. The physical, habitat and socio-economic analysis and their influence on Pathways and Receptors are considered separately and detailed in the following sub-Sections.

2.2. Modelling physical processes

In order to be fully integrated in the DSS a flood model must achieve the following requirements:

- Predict and represent spatial (raster maps) and temporal characteristics of the flood required by environmental and socio-economical risk assessment procedures, with a particular emphasis on maximum or worst case values of flood characteristics (mainly water depth, velocity and flood duration);
- Produce runs for several risk assessment scenarios (for instance by changing mitigation measures and climate scenarios) in a short time;
- Simulate flooding due to overtopping, overflow and failure of defence measures, including beach retreat;
- Be easily embedded inside the open-source DSS developed inside a GIS framework (desktop or web-based).

There are numerous hydrodynamic models that can be used to simulate the propagation of flood water across floodplain areas. These models generally solve a form of the 2D shallow water equations and range in complexity from raster-based approaches (Bates and Anderson, 1996; Bates and De Roo, 2000; Bates et al., 2005; Bradbrook et al., 2004; Dottori and Todini, 2011; Horritt and Bates, 2001) – that are based on the Manning equation – to more complex finite volume approaches that solve the full 2D equations (Lane and Richards, 1998).

These models are computationally expensive to run, can suffer from instability problems and are time consuming to set up. For these reasons their application and integration in THESEUS DSS was impractical.

Alternatively, simple GIS-based flood inundation or flood spreading models (Brown, 2006; Poulter and Halpin, 2008) can be easily implemented in a DSS in order to map the extent of the flood. This approach does not use a physically based model but performs flood mapping through the spreading of water levels or volumes in a DEM using a GIS-raster based approach, through several techniques (Chen et al., 2009; Gouldby et al., 2008; Lhomme et al., 2008; Wang et al., 2010; Zerger et al., 2002).

The GIS-based flood inundation model selected and implemented for the THESUS DSS is developed by considering a water overflow method, combined with erosion where appropriate. The method follows the marker controlled watershed segmentation algorithm described by Meyer and Beucher (1990) and Soille and Ansoult (1990). This algorithm floods each pixel that is located on a lower level with respect to the fixed water level and that is spatially "connected" to the flooding sources. Through this algorithm it is possible to produce flood maps for different storm surge levels and with multiple sources of flood. This algorithm has been modified within THESEUS to include finite water volumes which are varying with time: this is a significant improvement with respect to the existing bath-tub approach adopted in many similar existing tools (a.o. DIVA, RegIS, RAMCO).

Firstly, the water overflow of a sea bank (either a seawall or a beach bank/dune) during a flood is evaluated through the following procedure (Martinelli et al., 2010).

Waves are transferred for a given tidal range from offshore to the shore, including wave reduction due to structures where applicable, using an analytical Matlab procedure. The reduction of wave height induced by structures or other kinds of mitigation measures is also considered (see Section 4 for details).

In order to define in a simple and quantitative way the flooding process, the proposed failure mechanism is given by

$$(Z_m + Z_r + \eta + R_{u2\%}) - Z_{bank} >= 0 \tag{1}$$

where Z_m is the storm surge level, Z_r is the sea-level rise induced by climate change effects; η is wave set-up; $R_{u2\%}$ is wave run-up corresponding to the characteristic value of 2% exceeding probability; Z_{bank} is the crest height of the sea bank (equal to the beach height plus the dune height/seawall, if applicable).

Eq. (1) is based on the following simplified assumptions:

- Non-erodible cross-shore beach profile during the storm;
- Absence of defence breaching against wave and tidal loads.

Wave run-up is computed by means of Stockdon et al. (2006):

$$R_{u2\%} = 1.1 \cdot \left\{ 0.35 \cdot \tan\beta (H_s L_0)^{1/2} + 0.5 \cdot \left[H_0 L_0 \left(0.563 \cdot \tan\beta^2 + 0.004 \right) \right]^{1/2} \right\} \tag{2}$$

where Eq. (2) is modified to include as H_s the local transmitted significant wave height and as L_0 is the corresponding local peak wave length; β is the beach slope defined as the average slope over a region of two times the standard deviation of a continuous water-level record (β is about 0.01). Eq. (2) already accounts for wave set-up η on natural beaches.

A random-phase Gaussian process is generated having 2% characteristic value consistent with the value of $R_{u2\%}$ estimated from Eq. (2).

The "off-shore" boundary is thus moved to the "sea bank line" where the boundary condition considers a varying level in time $W(t)$ given by Eq. (2). The flood wave propagation is then simulated as a dam-break, where the wave celerity is indirectly represented by the contribution of $R_{u2\%}$ (i.e. potential wave energy at the shoreline).

The flood level $W(t)$ is integrated on coastal segments in time to provide water volumes as input data for the flood model.

Furthermore most existing coastal flooding tools do not consider the effect of coastal erosion. Within the THESEUS DSS, the erosion process is represented by means of a simple 1-line model based on Miller and Dean (2004). The variation of the shoreline position and therefore of the beach width is reflected in the slope to be included in Eq. (2) for estimating wave run-up.

The erosion model is based on the assumption that the starting shoreline position assumed in the calculations corresponds to the equilibrium position.

The governing differential equation is

$$\frac{dy(t)}{dt} = k \cdot (yeq(t) - y(t)) \tag{3}$$

which hypothesises that the shoreline approaches an equilibrium form at an approximately exponential rate. In Eq. (3), $y(t)$ is the shoreline position at time t; $yeq(t)$ is the equilibrium shoreline position determined by the forcing at time t; k is the constant governing the rate at which the shoreline approaches equilibrium.

The differential equation is solved by utilizing a numerical finite difference approach (Miller and Dean, 2004), resulting in:

$$y^{n+1} = \frac{y^n + A\left[\left(yeq^{n+1} + yeq^n\right) - y^n\right]}{1 + A} \quad \text{where } A = k\frac{\Delta t}{2} \tag{4}$$

In Eq. (4) the equilibrium shoreline change, Δyeq, is based on the equilibrium beach profile theory and a Bruun-type conservation of volume argument (Miller and Dean, 2004):

$$\Delta yeq = -w(t) * \cdot \left(\frac{0.106 \cdot Hs(t) + S}{Bh + 2 \cdot Hs(t)} \right); w*(t) = \left(\frac{db}{ADean} \right)^{1.5}$$

being: Bh the berm height, S the storm surge, Hs i the significant wave height at breaking depth db, and $ADean$ Dean's parameter.

The equilibrium shoreline change expression is slightly modified by introducing the tidal range, CM, as follows:

$$\Delta yeq = -w(t) * \cdot \left(\frac{0.106 \cdot Hs(t) + S}{Bh + 2 \cdot Hs(t) + CM} \right), \text{where } w*(t) = \left(\frac{db + CM}{ADean} \right)^{1.5}; \tag{5}$$

A limitation is that the presence of long-shore interruptions of sediment transport, such as jetties, marinas and groynes, is not considered. Therefore the methodology is suited for open coasts only.

However, in the DSS the end users can interact directly by providing a shape file of the eroded shoreline predictable on the basis of expert judgement and/or historical trends.

2.3. Modelling coastal ecosystems

Coastal ecosystems are of great environmental significance: the ecological communities found in these areas represent a transition from both aquatic to terrestrial environments and marine to freshwater environments and are some of the most productive and valuable aquatic ecosystems (Vasconcelos et al., 2007). Over the past decade changes in coastal ecosystems have predominantly been attributed to humans rather than natural processes (MEA, 2005). Such changes are caused by the necessity to meet the rapidly growing demand for food, water and fuel by the increasing human population. Coastal ecosystems are under considerable additional pressure, due to disproportionally large coastal population growth and development. With changes in climate, coastal ecosystems face an additional threat: increasing sea water levels and changes in the weather patterns which are also likely to increase the vulnerability of coastal ecosystems to human-induced and natural stressors. In Europe, these are especially important as many of these habitats are designated under the Habitats Directives and yet threatened by human-induced changes, such as climate change and sea-level rise. Hence, the vulnerability of coastal ecosystems has been explicitly modelled as part of THESEUS DSS.

The modelling considers the impacts of flooding on coastal ecosystems from both a short term and long term perspective, as explained in the following.

Impacts of floods are evaluated in relation to community and habitat vulnerability and also resilience to flooding, erosion and damage associated with storm events. Vulnerability is considered to arise from the system's inherent properties, which determine resistance and resilience. An ecosystem can be defined as resistant if it has a high ability to withstand disturbance events. Resilience is the time the ecosystem needs to recover to the state before the disturbance event took place: a rapid recovery time leads to a high resilience and vice versa. As such, the most vulnerable ecosystems are the ones in which both resistance and resilience are low; the persistence of such systems is highly unlikely, especially under unfavourable scenarios of climate change.

The ecological modelling carried out in THESEUS has developed an Environmental Vulnerability Index (EVI) for 10 coastal habitats including: terrestrial grasslands, terrestrial broadleaf and pine woodlands, sand dunes, salt marshes, biogenic reefs, rocky shore habitats, sub-tidal rocky habitats, sub-tidal soft sediments and seagrass meadows. These habitats represent key coastal ecosystems across Europe that are also found within the THESEUS study sites and are considered to be at risk from flooding. While these habitats are addressed individually, they are linked in various ways (Vannote et al., 1980). For example there is a continuum from sub-tidal sandy habitats to sand dune habitats (Hanley et al., 2014) and dune systems, seagrass meadows and biogenic reefs are sensitive to sediment dynamics and erosion or rapid accretion can have negative impacts on these ecosystems. For rocky shores, a major vulnerability is the impact of sedimentation on communities, particularly over the short term. Over longer time scales coastal squeeze could also present a major threat to biodiversity, where direct losses due to sea-level rise are reinforced by anthropogenic coastal modifications such as the construction of coastal defence walls.

The types of habitat/features to be mapped in the DSS include:

1. Habitat extent: in the form of a habitat land use map (i.e. habitat shapefile), including both intertidal and terrestrial habitats, and appropriate shallow sub-tidal communities;
2. Protected sites: sites designated for their ecological importance. This should include Special Areas of Conservation (SACs), Special Protection Areas (SPAs), Ramsar sites, nature reserves and other sites with local or national protection designations;
3. Key species: key species to be described/listed including rare species and species protected under the Habitats Directive (European Commission, 1992);
4. Commercially important features: locations where economically important species are harvested/farmed should be outlined along with areas that are designated for fishing (including recreational fishing);
5. Other important features: habitat features such as key breeding sites for birds or distinct habitat/land use related to the study site.

The habitats (and key species) affected by flooding and erosion are considered as Receptors following the SPRC methodology (Narayan et al., 2014). Hence they may change in response to changes in the Sources as follows:

i. *Short-term processes* (storm surge, wind driven waves, tides);
ii. *Long-term processes* (sea-level rise, vertical land movements – uplift/subsidence).

These processes have different effects on habitats. *Short-term processes* are temporary process where after inundation floodwater will subsequently retreat (see Hoggart et al., 2014, for a discussion on the impact of salt water flooding to terrestrial areas). This imposes the need for identification of several possibilities for effects on and the recovery of habitats and species in respect to inundation duration. In contrast, for inundation due to *Long-term processes* (e.g. sea level rise) it is assumed that the water will not retreat. While losing terrestrial habitat areas as a consequence of sea-level rise, it is important to recognise that aquatic habitats may be gained or expand resulting in no overall change in total area, but a change in the relative extent of different habitat types. If habitats have the ability to "retreat" (the affected terrestrial habitats can move landward), these newly occupied territories may be considered as additional coastal habitat. Alternatively where there is no possibility for habitat retreat because of natural or anthropogenic barriers (coastal squeeze), intertidal habitats such as salt marshes are expected to decline.

Seasonal effects are not considered in the present DSS modelling.

To assess the vulnerability of ecosystems to changes in stresses and to disturbances an index is adopted within the THESEUS project. This provides a rapid and standardised method for characterising vulnerability across coastal systems, and identifies issues that may need to be addressed in order to reduce vulnerability. By looking at combinations of factors, ecosystem vulnerability can be assessed. Such factors are the inherent ecosystem characteristics, the natural drivers that act upon the ecosystems, human use of the ecosystem, and the effects of climate change.

Vulnerability of habitats is dependent on:

i. Which part of a particular habitat area will be a subject to the unfavourable impact and which species will be affected;
ii. The degree of sensitivity of habitats/key species to unfavourable impact/hazard.

The proposed Environment Vulnerability Index (*EVI*) is similar to that used in Gornitz et al. (1994) and many subsequent studies (e.g., Boruff et al., 2005; Thieler and Hammar-Klose, 1999) to assess coastal vulnerability. Coastal vulnerability index is calculated as the square root of the product of the ranked variables divided by the total number of variables. The *EVI* ranked variables respond to the secondary Sources for particular habitats:

$$EVI = (A_1 \mathrm{x} A_2 \mathrm{x} \ldots \mathrm{x} A_n)^{0.5} / n \tag{6}$$

where $A_1, A_2, \ldots, A_n$ are different receptor habitats/species, identified for the discrete area in question and n is the number of different receptor habitats/species. Each habitat is given a score of 0, 1, 2 or 3 following Table 2. Thresholds beyond which the index increases to a higher value are determined by the specific *EVI* for each habitat and the attributes of the site.

The assessment of *EVI* uses the following steps.

1. *Define sources*: Different primary/secondary Sources are examined with respect to their potential to cause habitat degradation.
2. *Identify and map habitat types, including*: Terrestrial grasslands, terrestrial broadleaf and pine woodlands, sand dunes, salt marshes, biogenic reefs rocky shore habitats, sub-tidal rocky habitats, sub-tidal soft sediments and seagrass meadows.
3. *Identify consequences of the source on each habitat receptor*. For instance, storm surge (Source) affecting sand dunes will cause erosion and inundation.
4. *Calculate the area affected*. The approach will vary according to the Source and habitat Receptor. Use of a GIS platform permits delineation and calculation of the inundated habitat. Construction of these maps requires both habitat maps and a DEM.
5. *Calculate the EVI*. This is calculated for each habitat following Eq. (6). A categorical score of 0 to 3 is given for each habitat based on the definitions in Table 2. Four categories are proposed for Short-term and seasonal processes (categories 0, 1 and 2); for Long-term processes it is assumed that habitats will be permanently affected (category 3). To establish the thresholds (shown in Table 2), for each habitat

Table 2
Definitions of the Environment Vulnerability Index (*EVI*).

	Negligible	Transient effect (no long term change anticipated)	Moderate effect	Permanent effect/change
EVI Index Habitat/key species	0 Negligible impact to habitats/species	1 Changes within the range of Receptor's natural seasonal variation and full recovery is likely within a season	2 Changes are beyond Receptor's natural seasonal variation. Partial recovery is possible within several seasons, but full recovery is likely to require human intervention	3 changes are so drastic that natural recovery of receptor is very unlikely without human intervention

an *EVI* has been developed based on experimental work carried out within THESEUS and expert judgement.

In the DSS, the estimation of the *EVI* of a given habitat requires in turn the estimation of relevant parameters and this requires effort from both ecologists, who have to identify these parameters and their functional relation with the *EVI*, and coastal engineers, who have to schematise and evaluate these parameters.

Table 3 shows an example of the *EVI* for *Sabellaria Reefs* as it was elaborated within THESEUS by the ecological team. The *EVI* depends on the increased wave action, both in terms of intensity and frequency, and on sediment depth and duration. The maximum value of the *EVI* has to be assumed after computing the values of the *EVI* based on the two separated tables elaborated based on threshold values of sedimentation and wave agitation.

The sedimentation depth is estimated based on the typical annual wave climate and on Nielsen (1992) formula for sediment pick-up rate P:

$$P = 0.007 \cdot w_s \cdot ((t_b - t_e)/(r \cdot (s-1) \cdot g \cdot D_{50}))^{1.5} \tag{7}$$

where: w_s is the constant settling velocity; r is the marine water density; s is the relative density of (sandy) sediments; D_{50} is the median beach grain size; t_e is the critical bottom shear stress for erosion, set to be constant based on literature; t_b is the bottom shear stress due to waves, $t_b = 0.5 \cdot r \cdot f_{2.5} \cdot U_w^2$; $f_{2.5}$ is a friction factor dependent on the grain size and calculated as $2.5 \cdot D_{50}$; U_w is the near bed velocity due to waves, $U_w = (H_s/2\ h) \cdot (gh)^{0.5}$; H_s is the significant wave height; h is the water depth corresponding to breaking conditions for H_s; it is made the approximation of depth limited waves and therefore $h = g_b \cdot H_s$, in m.

Table 3
Example of the EVI table for Sabellaria reefs.

Sedimentation			
Quantity of sedimentation	Light	Medium	Heavy
Duration of sediment	<1cm	1-10cm	>10cm
Daily	+	1	1
Springs	1	2	2
once month	1	2	2
once year	2	2	SB
Every 10 years	SB	SB	SB
every 100 years	SB	SB	SB
Wave action			
Intensity of Storms	Slight	Moderate	Heavy
Frequency of increased wave action	10% increase	50% increase	100% increase
Daily	1	2	3
Springs	1	2	2
once month	0	1	1
once year	0	0	0
Every 10 years	0	0	0
every 100 years	0	0	0

The simplified assumptions are made that sediment re-suspension will be essentially driven by waves and that the whole sediment deposition occurring during a typical average storm is fully re-suspended and drifted by currents within the storm duration S_d. Therefore the typical sediment deposition depth Sed_y and duration Sed_d are respectively given by

$$\text{Sed\_y} = P\ S_d \text{and Sed\_yd} = S_d,$$

where P is calculated based on the typical annual storm wave height.

Sediment suspension and deposition related to the extreme storms are then estimated

- By including in Eq. (7) the H_s corresponding to the significant wave height of the selected scenario;
- By assuming the sediment depth due to the storm as Sed_y = P Nh, where Nh is the duration of the storm and is a parameter of the selected scenario;
- By assuming the corresponding duration of the sedimentation Sed_d due to the storm as provided by a linear relation, where the time necessary for the complete re-suspension of the storm sediment depth Sed_y induced by the storm related to the average re-suspension time in the site corresponding to the average sediment depth induced by the typical annual wave climate.

The wave action is estimated from wave celerity c, and specifically

$$c = \sqrt{(g \cdot Z)} \text{ where } Z = Z_m(Tr) + Z_r(\text{year}) + H_s(Tr)/2 \tag{8}$$

Tr being the return period of the selected extreme events.

The selection of this parameter appears to be particularly suited since it allows taking consideration of

- The specific storm by means of Z_m and H_s, and therefore to represent the change in wave action within the same time slice (short, medium or long term scenarios);
- The time slice (and therefore to sea-level rise) that may be particularly important when dealing with sites where the waves are not expected to increase;
- The direct relation between c and P, see Eq. (7).

The increased wave action intensity is therefore estimated as the variation of wave celerity c considering the corresponding scenarios with the same Tr at the selected year and at present conditions – denoted respectively by 'year' and '2010' in Eq. (9) below

$$[c(Tr, \text{year}) - c(Tr, 2010)]/c(Tr, 2010) \tag{9}$$

The increased frequency in wave action can be estimated if climate scenarios are available in the sites also for the typical annual wave climate. In this case, the frequency of occurrence of the typical (not extreme) storms within the typical year can be compared for the short, medium and long term with respect to present conditions.

2.4. Representing society

Social vulnerability is a complex phenomenon and no single measure comprehensively covers the whole spectrum of such vulnerability (Adger et al., 2004, 2005). Recently, the Social Vulnerability Index

(*SoVI*) has been suggested as a comparative spatial assessment of human-induced vulnerability to environmental hazards (Cutter et al., 2003; Wisner et al., 2004). The *SoVI* is based on a large set of measurable variables that can be grouped into main common factors such as: population structure, gender, income, socio-economic status, and renters (www.csc.noaa.gov/slr). Analysis and mapping of social vulnerability should also consider identifying critical facilities or resources to help prioritize potential hazard mitigation.

In the THESEUS DSS, social vulnerability is modelled considering two main aspects: (1) the damages to Critical Facilities (CFs); and (2) the expected number of fatalities. It is worthy to note that flood damages to society also include psychological consequences that are mainly qualitative in nature and are hard to be translated in linear functions with quantitative outputs for practical and ethical reasons (Tapsell, 2011).

CFs are defined as “the primary physical structures, technical facilities and systems which are socially, economically or operationally essential to the functioning of a society or community, both in routine circumstances and in the extreme circumstances of an emergency” (UNISDR, 2009). On the one hand, the notion has been adopted recently in disaster management, and is related to the creation of GIS maps on Community Vulnerability (a.o. DEFRA, 2005; FEMA, 2007); on the other hand, CFs have been applied in the development of priority lists for the effective reactivation of buildings after disasters and applied emergency management (e.g., Hillsborough County -Florida, 2009).

The impact of the flooding process on CFs is estimated following three steps.

1. Ranking of critical facilities
   In THESEUS, a rank was derived based on the function of buildings in relation to social vulnerability (Hillsborough County -Florida, 2009). Considerations were made both in terms of use in emergency management, function in ordinary activities and community aggregation, and symbolic function. The corresponding Approximated Social Value (ASV) was derived and is reported in Table 4, with values from 1 (low) to 5 (high). The final output is an overall view of possible intangible damages in the range 0 to 100. Even if it maintains high levels of uncertainty, it is one of the first attempts to provide to end users the possible effects of floods on the community and individuals. The ASV also provides a re-activation list in reverse order, as the highest values are supposed to receive priority in emergency interventions for reducing social damages. In the perspective of land use planning, the adoption of such an approach should lead to the relocation of high scoring buildings to safer areas or encourage measures to increase buildings resilience. Similarly, higher scores indicate where efforts for higher education and training of personnel should be concentrated and where emergency measures such as mobile barriers could be deployed with maximum effectiveness.
2. Estimation of physical damage for structures
   The damage scale is estimated based on flood depth and duration. Following the method by Schwarz and Maiwald (2008), the damage grade is related to the flood depth (De) through a non-linear function. Intuitively, the effects on society and structures are inversely proportional to flood Duration (D), if one excludes flash flood phenomena. Long duration floods, even if relatively limited in space, produce greater impacts on social functions: a bridge blocked might be a nuisance for an hour, while it could compromise trade routes or tourism activity for a week. Therefore the following scenarios (corresponding to different scores, see Table 4) should be considered: i) Short D (Hours), ii) Medium D (Day/days), Long D (Week/weeks).
3. Definition of touristic impact
   The geographic features that determine the social vulnerability are related both to the physical structures and to the situation where the action is settled (Cutter, 1996). In many coastal areas, one of the most relevant variables affecting the ordinary social pattern should be considered the presence of tourism. It can be presumed that not all the tourist have previous experiences in flooding, and that if a flood happens with a large number of tourist in place critical infrastructures may suffer higher pressure and warning messages may face more problems in their dissemination. The tourist presence can be represented through a value reflecting seasonality S; this factor will act as a final scale multiplier, where low season ($S = 1$)

Table 4
Ranking values and factors required to estimate the Collateral Social Damages.

	Associated social vulnerability factors
ASV	Definition
5	Critical structures that if involved could compromise the emergency action, the coordination chain, public safety and public health in the long term. For example, hospital and emergency facilities. Depending on local features, main military facilities, power plants and institutions can be included in this category.
4	Facilities that provide significant public services and should be activated within 24 h. For example, there can be included nurseries, major water and sewer facilities, fire and police stations, schools and park facilities used to support critical purposes.
3	Facilities that provide important public services but should be sequent to critical facilities ranked 4 and 5 points. Main centers of aggregation, education or prayer that are important for symbolic belonging to the community. Some particular place that links those features to economics can be included too.
2	Facilities that provide public services but that are less critical for the community. Common storages, sport centres can be included depending on the context. Literature on social capital can be taken also as reference.
1	Places which value are mainly symbolical, but can influence anyway the overall amount of social damages. For example, particular community areas of meditation and prayer.
	Depth induced damage
Factor De	Depth range from Schwarz and Maiwald (2008) —has to be adapted to the site
1	0.1–0.5 m
2	0.6–1.5 m
3	1.6–2.5 m
4	2.6–5 m
5	>5 m
	Duration induced damage
Factor D	Flood duration
1	Hour/s
2	Day/s
3	Week/s
	Seasonality
Factor S	Definition
1	Low seasonality
2	High seasonality
	Collateral social damage scale
Score	Definition
0	No collateral social damage.
1–10	Possible malfunctions in citizen's ordinary life are possible but can be prevented. The damage is limited and could be managed with experimented procedures and stakeholders activation. The situation could require more details about which critical facilities involved, and planning of alternative solutions.
11–20	Malfunctions in citizens' life are expected. The damage is still limited but diffused (or high and very concentrated), and requires higher mobilization for the rehabilitation process.
21–30	Social damages are concrete and visible. A major involvement of local relief and reprise resources is expected. The presence of external help is suitable and should be activated in advance in order to avoid higher losses.
31–50	Massive social damages in ordinary period or medium involvement of critical infrastructure in high touristic period. Massive damages could be managed with timing alert and planning, but the presence of external help is absolutely needed. Long times for reactivation of services and community reprise should be prevented.
51–100	Exceptional damages, calamity. The situation could have terrible social damages and should be mediated with external help and cooperation at the highest level possible. Very long times for reactivation of services and community reprise should be prevented.

denotes ordinary conditions, and high season ($S = 2$) implies that the effects will be exacerbated.

The Collateral Social Damages (CSD) are finally estimated as:

$$\mathrm{CSD} = \mathrm{S_I ASV_i} \cdot \mathrm{De} \cdot \mathrm{D} \cdot \mathrm{S} \tag{10}$$

The value of CSD is related to a common scale to allow exportability to other case studies and comparison of the results. The scale is also reported in Table 4.

For tangible social damages, we derived a function of life losses and injuries (NI) from Penning-Rowsell et al. (2005)

$$\mathrm{NI} = (\mathrm{H} * \mathrm{AV})/(\mathrm{Pa} + \mathrm{ID}) \tag{11}$$

where H is the hazard rate, AV is the Area Vulnerability, Pa is the sensitive population (age $<$ 14 years and $>$65 years) and ID is the number of sick and disabled people.

The value of H is computed in each cell of the domain as

$$\mathrm{H} = \mathrm{NI} \cdot \mathrm{y} \cdot \mathrm{v} \cdot \mathrm{DF} \tag{12}$$

where N is the number of people involved in the flood, y is the flood depth, v is the flood velocity, DF is the debris factor equal to 1 for the Mediterranean and 2 for the Ocean.

The Area Vulnerability AV is derived as:

$$\mathrm{AV} = \mathrm{W} + \mathrm{Fo} + \mathrm{Na} \tag{13}$$

where W denotes the Warning, Fo is the speed of onset of flooding and Na is the Nature of the flooded Area, see Table 5.

The value of Na can be derived from statistical demographic data or can be alternatively schematised based on Penning-Rowsell et al. (2005). If statistical data are available, their main use should be identified and impact levels from 1 (low) to 3 (high) are attributed as shown in Table 5. Since social patterns determine the impact levels of special attributes, three main scenarios were identified: day, night and touristic periods. Higher impact was attributed to residential areas when people are generally at home sleeping (night), while zones identified for schools and education are vulnerable when children are in classes (day). Finally, tourist resorts are most susceptible during holidays (touristic period).

The percentage of the Population Aged (Pa) can be derived from demographic data (ISTAT, 2009) or referred to national middle average. The final value of Pa should be conformed to a common value of 50 as: Npa: $\times 50 = \mathrm{Pa}{:}50$, $\times 100 = \mathrm{nPa} * (100/\mathrm{Pa})$.

The percentage of Infirm/Disabled/long-term sick (ID) can be set based on perception or on the national average.

The values for the ID factors are synthesised in Table 5. In general, this function provides and overall count of people that could be subject to death or injuries. We decided not to distinguish between these two aspects as too many external variables such as local lifestyle, wealth or public health services influence the final output of life losses, and the uncertainties are high.

Table 5
Ranking values and factors required to estimate Life losses and injuries.

W	Not present	Present but not implemented	Present and well working
	3	2	1
So	Slow flooding (many hours)	Gradual flooding (an hour or so)	Rapid flooding
	1	2	3
ID	Low presence	Medium presence	High presence
	10%	25%	50%
Na	Touristic season	Day	Night
Residential area	2	1	3
Tourist area	3	2	1
Manufacturing	2	3	2
Common or religious area	2	3	1
Education area	1	3	1
City centre	3	3	3
Parking and green	1	1	1

2.5. Modelling the economy

In the literature, the Economic Vulnerability Index (EcVI) (Guillaumont, 2009) is derived from the composition of the following seven indicators: 1) population size, 2) remoteness, 3) merchandise export concentration, 4) share of agriculture, forestry and fisheries in gross domestic product, 5) homelessness owing to natural disasters, 6) instability of agricultural production, and 7) instability of exports of goods and services.

However, within a Multi-Criteria Analysis, where social and economic impacts must be distinguished and separately weighted, this index turned out to be inadequate, since it combines social and economic indicators. Instead, since detailed data on economic activities in Gross Domestic Product (GDP) terms were available, a consistent approach based on incomes for each economic land use was adopted: e.g., hotels are evaluated in terms of annual GDP, houses are evaluated in terms of annual rents, beaches are evaluated in terms of annual willingness to pay to preserve them.

The overall Economic Consequences (EC) of flood in terms of flood depth and flood duration are estimated by applying the following formula:

$$\mathrm{EC} = \mathrm{v_{ij}} \cdot \mathrm{b_j} \cdot \mathrm{Fd} + \mathrm{v_{ij}} \cdot \mathrm{a_j} \sqrt{\mathrm{Fy}} \tag{14}$$

where $\mathrm{v_{ij}}$ are the values of land uses in euro/m^2/year from census statistic data; Fd is flood duration and Fy is flood depth; $\mathrm{a_j}$ are proportionality constants as functions of Fy that are normalised for each land use j at the maximum value of Fy in 2050 for a storm return period Tr = 100 years, assuming different reference percentage of damage depending on the use (for instance, 50% damage for buildings/homes/hotels, 25% damage for harbours); $\mathrm{b_j}$ are proportionality constants as functions of Fd that express the expected period to restore economic activities as a factor of duration, depend on the land use (for instance, a value of 30 is set for hotels and of 20 for private services) and are normalised to annual incomes with the days/year. Note that flood velocity is assumed to be irrelevant.

The land use value loss is combined with beach loss due to erosion. The value function was derived from a choice experiment exercise carried out at the Santander site, ES, within THESEUS project distinguishing the Willingness To Pay (WTP) for bio-diversity, health risk and recreation. The instant value of the WTP (€/person/m^2/years) is expressed based on the following empirical relation

$$\begin{aligned}\mathrm{WTP} = {} & (1/529,000)(30.358 + (0.408 - 0.002(-5 + (t - 2010))) \\ & \times (-60 + (t - 2010))\end{aligned} \tag{15}$$

where 529,000 is the Santander beach area and t is the year chosen by the DSS users.

Eq. (15) supposes zero damage in case the beach width equals the initial one, while damages are proportional to the eroded area divided by the total (initial) beach area.

Alternatively, a consistent approach based on market values of infrastructures could have been used. Note that it is theoretically possible to move from an income approach to an infrastructure approach under a standard set of assumptions about market competition.

2.6. Multi-criteria decision making

In the overall vulnerability analysis, multi-disciplinary approaches involve different experts, who come from different areas with distinct knowledge and experience, adopt different judgement and evaluation methods (e.g., qualitative and quantitative forms; certain and uncertain assessments), and tackle various and at least partially conflicting objectives (Li et al., 2010).

Multi-Criteria Multi-Expert Decision Making (MCMEDM) is a methodology to deal with the inherent complexity and uncertainty as well as the vague knowledge arising from the participation of many experts in the decision making process (Yan et al., 2011).

Within THESEUS, issues related to vagueness or qualitative indexes were not examined, since each expert group (i.e. ecologists, sociologists and economists) reached an internal agreement on one or more quantitative indexes to be applied: ecologists suggested an *EVI* index in [0,3], sociologists developed one indicator in [0,∞[for the affected population and one indicator in [0,10] for CF, and economists relied on land use values in euro/m^2 in [0,∞[.

Multi-Criteria Decision Making (MCDM) is a response to the inability of people to analyse multiple streams of unalike information in a structured way: preferential information is modelled by weighting factors (i.e. inter-criteria comparisons) and value functions (i.e. intra-criteria preferences).

This methodology was applied in THESEUS framework, by weighting the three impacts (i.e. ecology, society, economy) according to stakeholders' preferences or other user specified weights and by normalising all values estimated by experts.

3. End user involvement in the DSS

3.1. Fundamentals of THESEUS DSS

The primary objective is to provide an integrated GIS-based methodology for planning sustainable coastal defence strategies, which addresses technical, social, economic and environmental aspects. THESEUS-DSS has been defined as a scoping tool to assess risk conditions and consequences of mitigation options against flooding and erosion at a given coastal site.

The tool supports an assessment of the change in risk due to a range of scenarios and selection of the most appropriate intervention measures from an available portfolio of engineering, ecological and social measures.

The primary end-users are intermediate-level coastal managers who need to make sound evidence-based decisions regarding spatial planning and coastal protection.

The main foundation of this DSS is that it has to be “Open and Parametric”, not only in terms of source code and technology but also in terms of usability. This software is designed to be easily modified and distributed across many sites with many diverse characteristics: this requires adequate flexibility in terms of configuration parameters and input materials.

The DSS should also be “Interactive” so that users can explore a combination of scenarios, while being trained in interdisciplinary risk assessment, including the best (i.e. sustainable) solution or combination of solutions for risk mitigation. Here sustainable means protecting the coast while preserving its socio-economic development and the integrity of the ecosystem services.

Underlying the advice and discussion regarding the development of THESEUS DSS, the limitations on the tool should be noted:

- It provides coastal managers with an overview of the drivers, pressures, impacts and response options in different time slices, but it is not expected to replace detailed design tools;
- It raises awareness of the implications of different policy decisions, but it does not prompt the selection of specific policies;
- It should be a tool for aiding decision making but it cannot provide a straightforward decision since a) it does not overcome the representation of the social perception of risk and the resilience of society; b) it includes a strong uncertainty component in the prediction of both physical processes and consequences.

THESEUS DSS is developed on top of an integrated simulation model suitable for performing ‘What if’ analyses based on scenarios. By means of this kind of analysis the user tries to find out how management strategies and scenario sensitive variables and parameters influence risk at the selected coastal site. The policy analysis mainly focuses on the consequences of changing coastal management options. The different components of this analysis can be seen and changed interactively by means of the user interface (see Section 3.2).

Fig. 1 gives an overview of the structure of the integrated model at the most synthetic level. The integrated model is the actual calculation kernel of THESEUS DSS. It contains relations in the form of mathematical equations, formal rules, or transfer functions representing the real world processes.

3.2. The design of the tool

The inclusion and participation of relevant stakeholders (coastal managers) is essential to test the outcomes of the modelling, to identify the most relevant parameters and related scenarios to be included in the analysis and to evaluate adaptation options (Dessai and Hulme, 2004). To maximise the utility of THESEUS DSS, the stakeholders gave their input on:

- Definition of the site boundaries;
- Identification of critical pathways of the existing management that may lead to failure and are worthy of further investigation;
- Usefulness of output indicators for each of the meta-models;
- Appropriateness of the mitigation measures to be included in future coastal management strategies for a given site;
- Site-specific relevance of the social, economic and environmental components of risk;
- Functionality and user-friendliness of the interface.

Following Holman et al. (2008), the set-up of the tool considered two key points.

1. Intuitive and interactive design of the Guider User Interface and possibility as follows.
    - The physical layout of the tool should closely mirror the conceptual model, i.e.; the SPRC components.
    - The user should be able to vary the input parameters through sliders to analyse the potential changes induced by different scenarios or mitigation strategies.
    - ‘Realistic’ and plausible ranges of values for a given parameter should be used to give guidance on the uncertainty associated with a scenario.
    - The users should be allowed to save and compare the graphical outputs from more than one model or scenario.
2. Balance of simplified modelling assumptions and speed to promote the use of the tool for testing different combinations of mitigation options by:
    - Avoiding extensive or prolonged model set-up has been avoided;
    - Providing rapid outputs.

3.3. Type of outputs

THESEUS DSS operates at high resolution to provide geographic specific outputs. While users should be encouraged to study the detailed maps, this output is not suitable for direct application, nor should it be confused with the policies that would accomplish those outcomes and judged based on the avoided monetary damage only. Therefore while the intermediate maps of specific results (for instance: flood depth, land value loss, life losses, etc.) are shown with their own scale, the results of (hydraulic, social, economic and ecological) vulnerability and the overall risk assessment map are given as normalised-quantitative indicators (see Section 4).

Based on these guiding concepts, on the experience gained from other tool development (and specifically RAMCO and RegIS) and on the feedback from stakeholders, the interface for each site consists of a

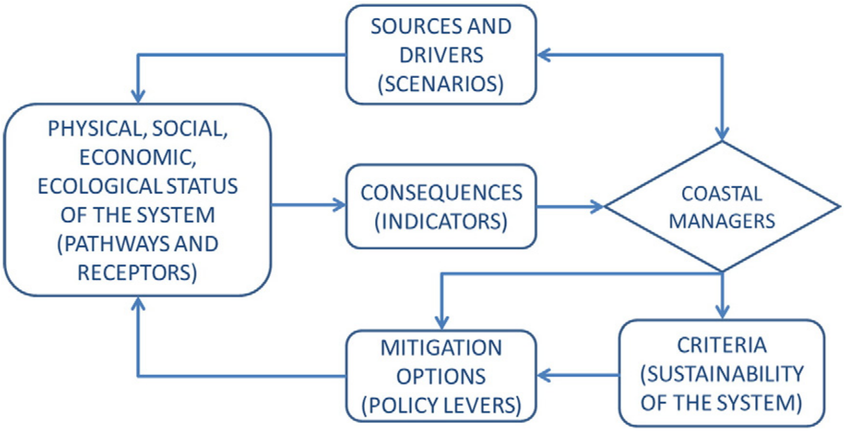
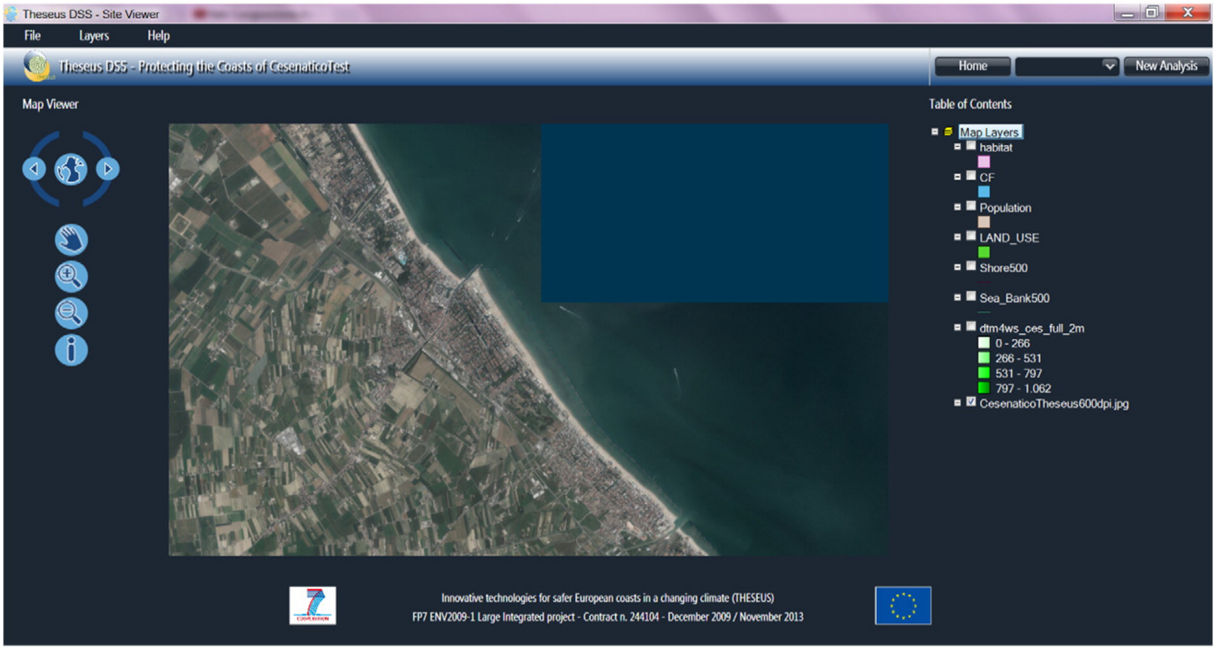


Fig. 1. System diagram view of THESEUS DSS.

viewer at start up (Fig. 2), where the user can visualize the input data (bottom elevation, habitats map, land use map, etc. see Section 4) and evolves to the following four screens, each with a different purpose.

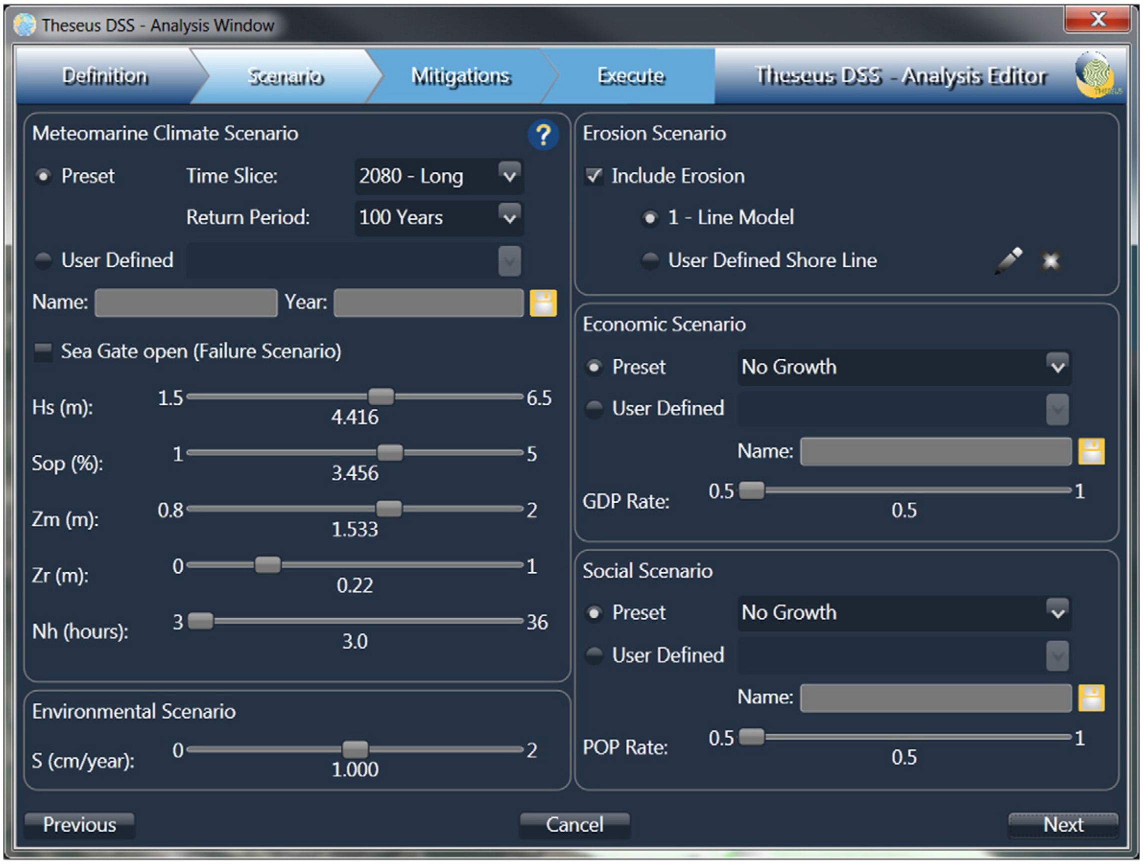
- Definition screen: this allows the user to define the name of the test and write a short description; he/she can also load the settings of a previously performed analysis.
- Scenarios screen (Fig. 3): this allows the user to select among climate, social, environmental and economic scenarios. The user can adopt pre-set scenarios defined by scientists; in this case, the default set of input parameter values for each pre-set scenario allows a rapid model set-up. The user can also create their own scenarios by directly changing the input parameter values used in the models. This enables the user to become familiar with the most significant parameters related to the site-specific scenarios and to explore the effects of uncertainty in any scenario, which cannot be defined by a single set of unique values.
- Mitigations screen (Fig. 4), this allows the user to include:
  - o Engineering mitigations, such as wave farms, barriers, floating breakwaters, sea walls, nourishments;
  - o Ecologically based mitigations, such as management or construction of dunes, reinforcement of salt marshes, creation of biogenic reefs;
  - o Economic and social mitigations such as evacuation plans, land use change and zoning (for instance, managed realignment), insurance scheme.

    When selecting a mitigation option for which size and location have to be defined (for instance: a biogenic reef, a breakwater, a managed realignment), the user can: a) include the shapefile prepared by the scientists with the suggested configuration of the mitigation (position, extension, design parameters); or b) upload a shapefile and enter the design parameters; or c) draw the mitigation directly from the GUI (Fig. 5). For other mitigations, such as insurance schemes or evacuation plans, the user can interact by modifying the insurance premium value, the percentage of evacuated people or the destination of a given area.
- Execution screen (Fig. 6): this guides the user through the analyses to be performed based on the selections made in the previous windows; these analyses include the following steps: (1) modelling of the



Innovative technologies for safer European coasts in a changing climate (THESEUS)
FP7 ENV2009-1 Large Integrated project - Contract n. 244104 - December 2009 / November 2013

Fig. 2. The viewer at the start-up.



Meteomarine Climate Scenario

● Preset Time Slice: 2080 - Long

Return Period: 100 Years

○ User Defined

Name: Year:

☐ Sea Gate open (Failure Scenario)

Hs (m): 1.5 – 6.5: 4.416

Sop (%): 1 – 5: 3.456

Zm (m): 0.8 – 2: 1.533

Zr (m): 0 – 1: 0.22

Nh (hours): 3 – 36: 3.0

Environmental Scenario

S (cm/year): 0 – 2: 1.000

Erosion Scenario

☑ Include Erosion

● 1 - Line Model

○ User Defined Shore Line

Economic Scenario

● Preset No Growth

○ User Defined

Name:

GDP Rate: 0.5 – 1: 0.5

Social Scenario

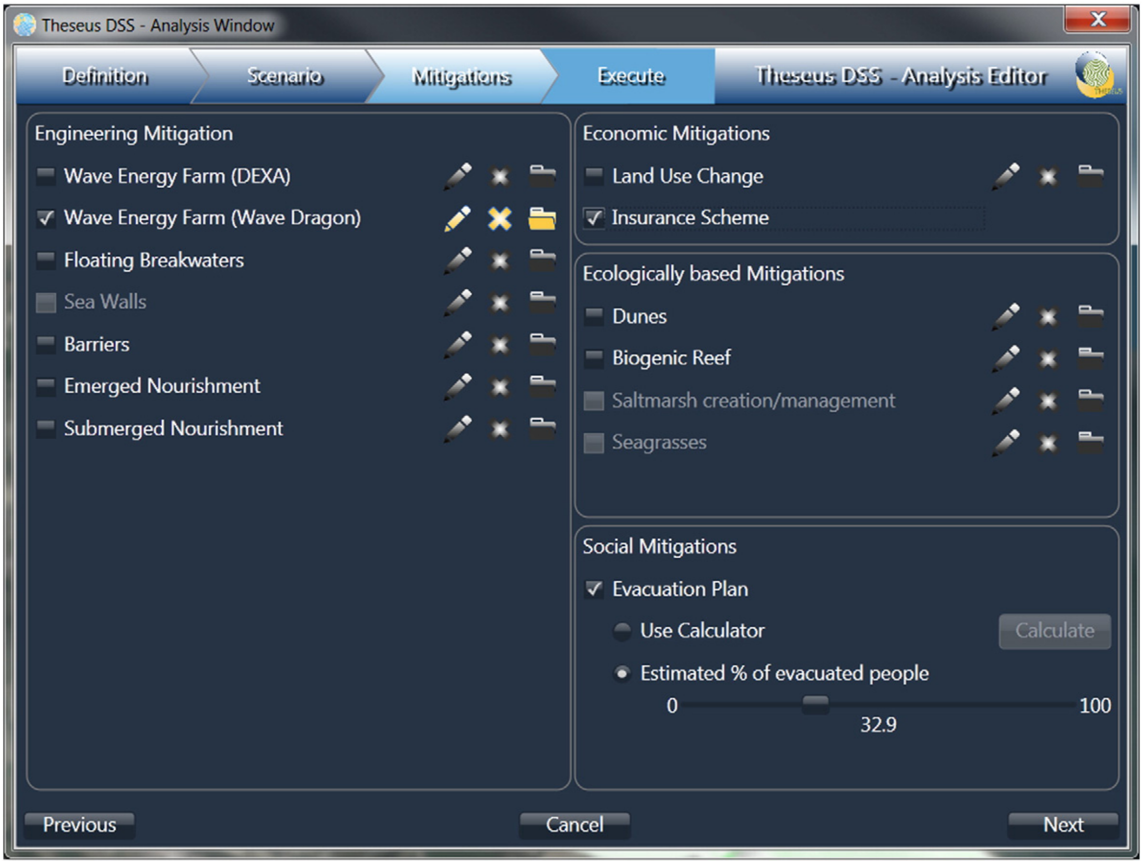
● Preset No Growth

○ User Defined

Name:

POP Rate: 0.5 – 1: 0.5

Fig. 3. Scenarios screen.



Engineering Mitigation

☐ Wave Energy Farm (DEXA)

☑ Wave Energy Farm (Wave Dragon)

☐ Floating Breakwaters

☐ Sea Walls

☐ Barriers

☐ Emerged Nourishment

☐ Submerged Nourishment

Economic Mitigations

☐ Land Use Change

☑ Insurance Scheme

Ecologically based Mitigations

☐ Dunes

☐ Biogenic Reef

☐ Saltmarsh creation/management

☐ Seagrasses

Social Mitigations

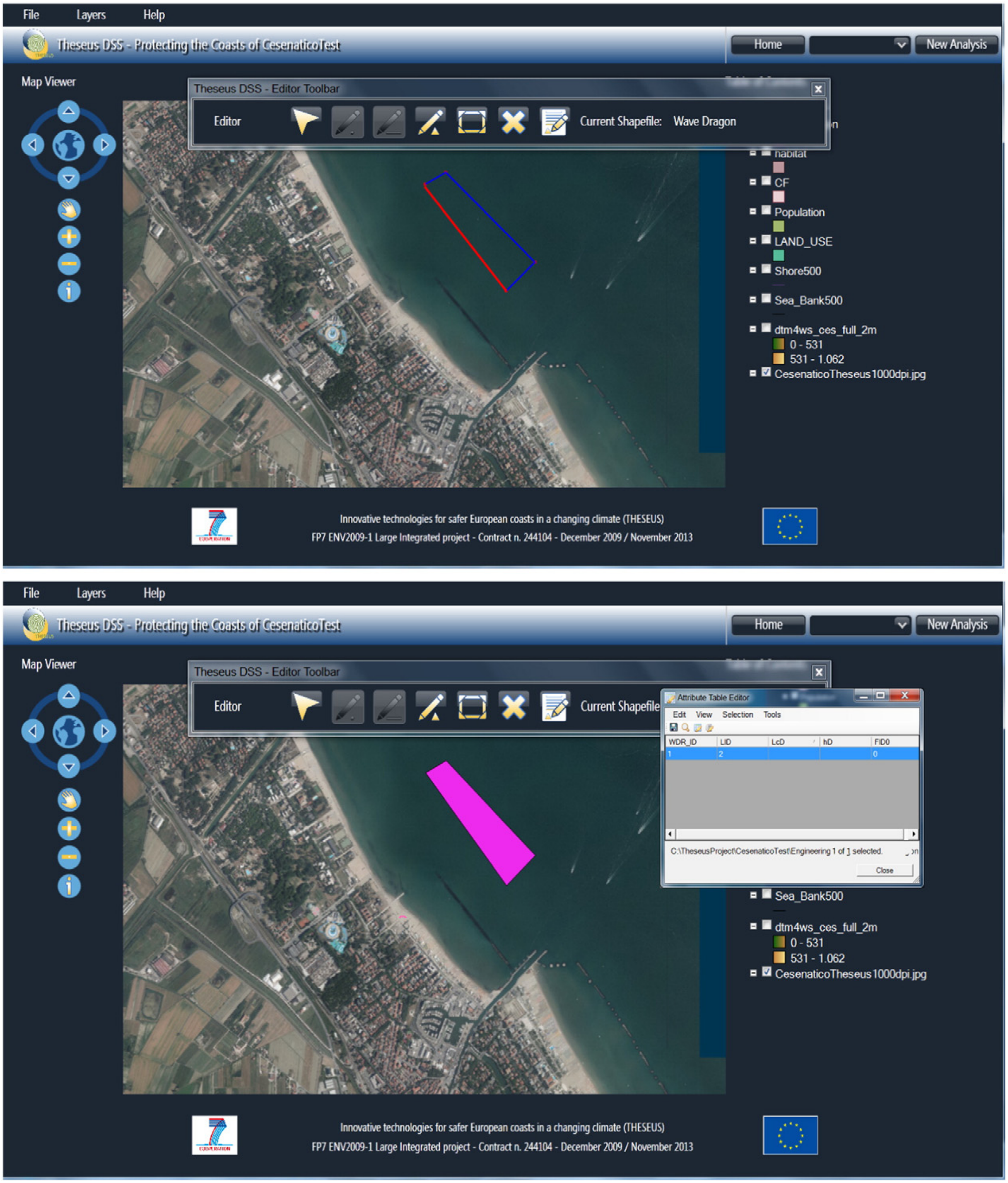
☑ Evacuation Plan

○ Use Calculator

● Estimated % of evacuated people

0 – 100: 32.9

Fig. 4. Mitigation screen.



WDR_ID	LID	LcD	hD	FID0
1	2			0

C:\TheseusProject\CesenaticoTest\Engineering 1 of 1 selected.

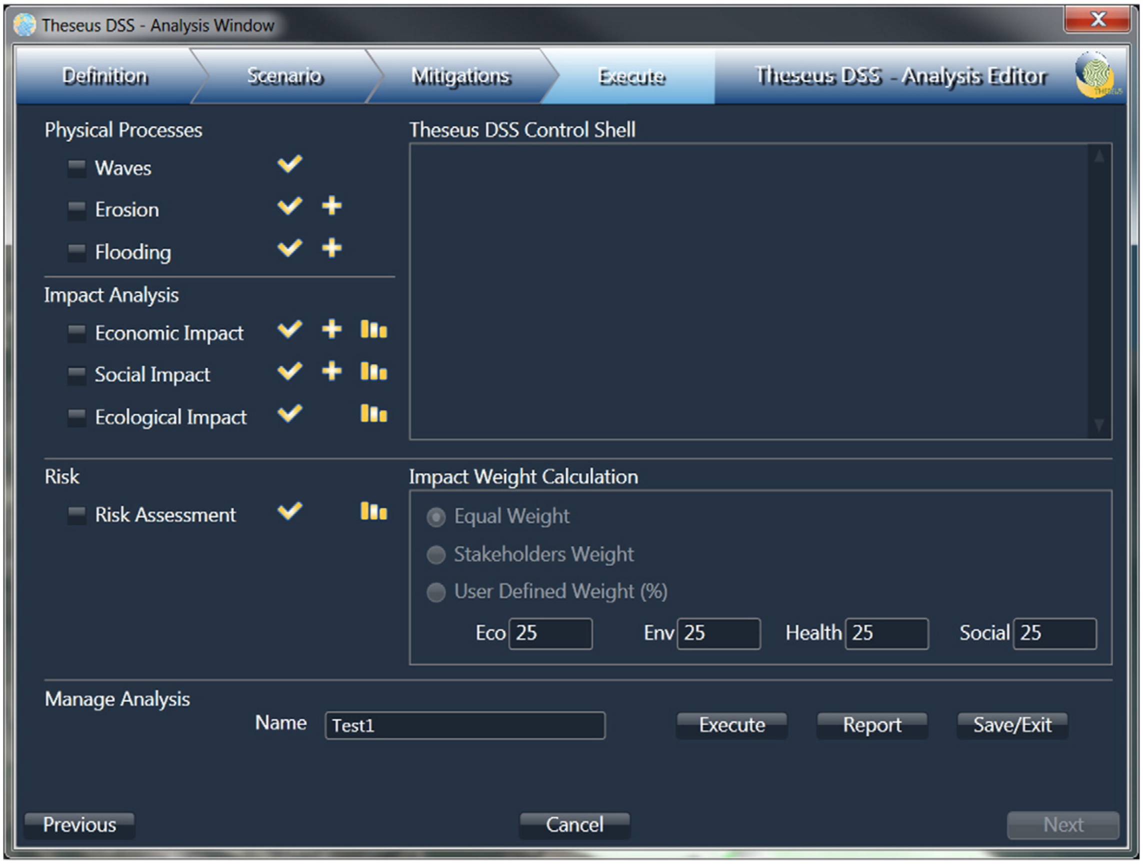
Fig. 5. Editing a mitigation option in front of Cesenatico.

physical processes (erosion, flooding), (2) modelling the impacts on the environment, the society and the economy, (3) assessing the global hydraulic, social and environmental vulnerability and finally (4) assessing the risk. It also imposes constraints on the analysis. For instance, if the user does not include the erosion process in the Scenarios screen, he/she cannot flag the corresponding analysis to be run in the Execution screen. Let us suppose that the user changes the settings of the analysis just performed by including for instance a new mitigation in the Mitigation screen. When back to the Execution screen he/she will be forced to re-run the flooding model if the mitigation is such that it affects the physical processes (for instance, a seawall or a dune) while the flooding model will be hidden if the mitigation does not interfere with the physical processes (for instance, an evacuation plan or a change of land use).

4. The implementation of THESEUS DSS

4.1. Structure

The diagram in Fig. 7 represents the flow of the information within THESEUS DSS. Each component is explained in the following sub-Sections.



● Equal Weight

Eco 25
Env 25
Health 25
Social 25

Name Test1

Fig. 6. Analysis screen.

4.1.1. Input data

The DSS input database for each site has to include the DEM – as detailed as possible; hydraulic structures and infrastructures position, geometry; map of land-use and of critical facilities; list and/or map of geo-referenced social and economic indicators, such as: age, gender, employment, occupation, population health, etc. (Figs. 8 and 9); geo-referenced maps of habitat types and species including: rare species, rare habitats, commercially important marine habitat, habitat relevant for coastal protection.

There are also many significant local parameters required to run the tool such as: typical breaking index, average beach grain size diameter, beach slope, water depth where wave data were obtained, threshold values useful to define low, medium, high and very high vulnerability levels.

4.1.2. Scenarios

THESEUS DSS is based on scenarios analysis and specifically includes:

- Climate and environmental scenarios, which can be a pre-defined set of conditions derived by scientists (wave height, storm surge, sea-level rise, etc.) for short, medium and long term or intervals of these parameters the user can combine based on the kind of scenario he/she wishes to try, ordinary or extreme;
- Economic and social scenarios, essentially based on expected changes or trends of the population and on the gross domestic product; also in this case the user can select the trend value within the range of values suggested by the scientists;
- Environmental scenarios, limitedly for now to subsidence; in future versions scenarios of habitat change based on changes of temperature, social and economic development, etc. may be included.

4.1.3. Interconnecting elements

The DSS needs the definition by the site manager of the following elements (lines, points) that are relevant for modelling the hydraulic processes.

- Waves: the position of the point/s or line/s for off-shore generation has to be identified based on the indication of the water depth where climate scenarios are provided by the scientists; this is the off-shore depth from which waves are transferred to shore.
- Shore line and sea bank line: these lines represent the water/beach boundary relative to which beach retreat is determined, and the water/land boundary where flooding starts, respectively.
- Water sources: one or more punctual sources where flooding will be initiated for each coastal segment depending on the minimal resolution adopted for describing the area.

4.1.4. Mitigation options

Mitigation options are represented both as changes of pathways and of receptors. To illustrate this some examples are given below.

- A farm of wave energy converters locally reduces the landward wave energy and hence acts on the pathway. Reduction of wave energy reduces loadings on coastal structures and coastal erosion during extreme events. Within the DSS this is expressed as a modification of the wave heights landward of the converters.
- Managed realignment fundamentally changes the land use (i.e. it is a change of receptors), but may also change elevation depending on how it is implemented and this needs to be considered. Within the DSS this would be expressed as a change of the land use values and roughness for flood propagation, and any new defences that are constructed as part of the scheme have to be included in an updated version of the DEM.

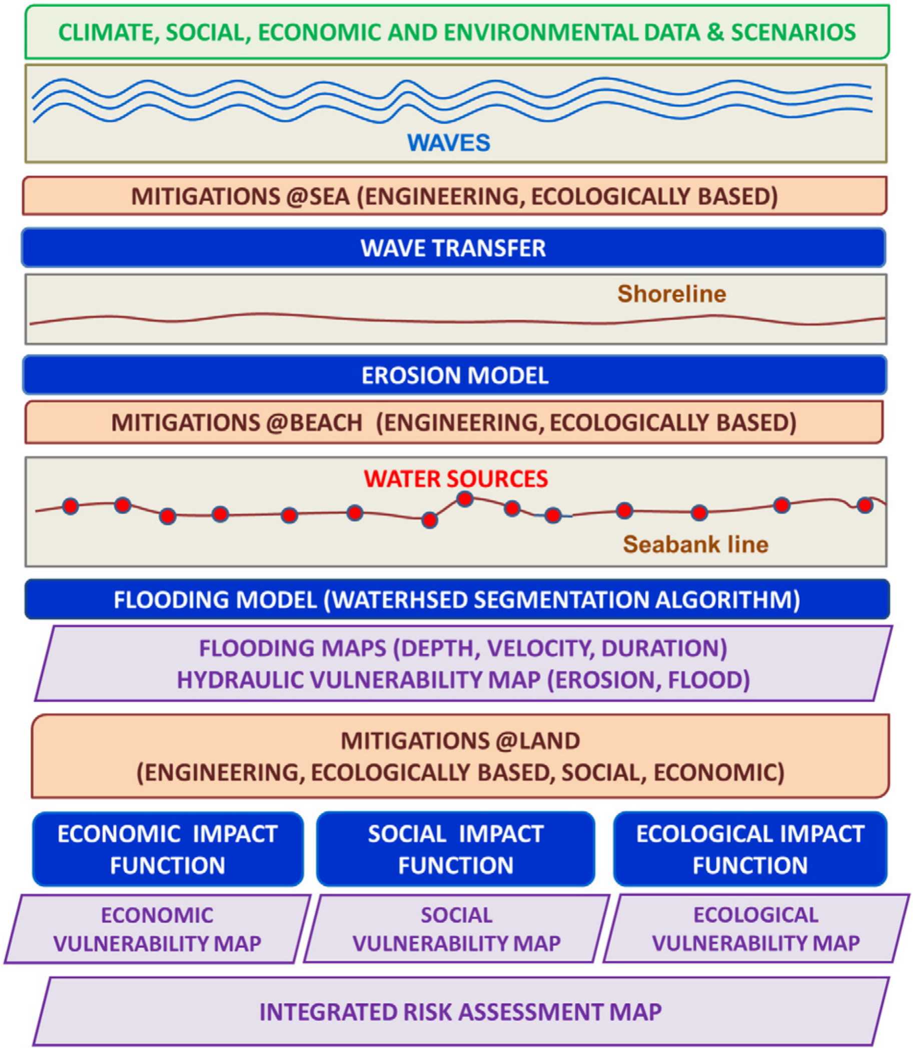


Fig. 7. Key elements and the flow of the information within THESEUS DSS. A sharp rectangle indicates the input data required to run the model; a rectangle with 2 sharp and 2 rounded corners denotes the input data where the users can interact; a rounded rectangle the functions defined by the scientists; with a parallelogram the output of the DSS.

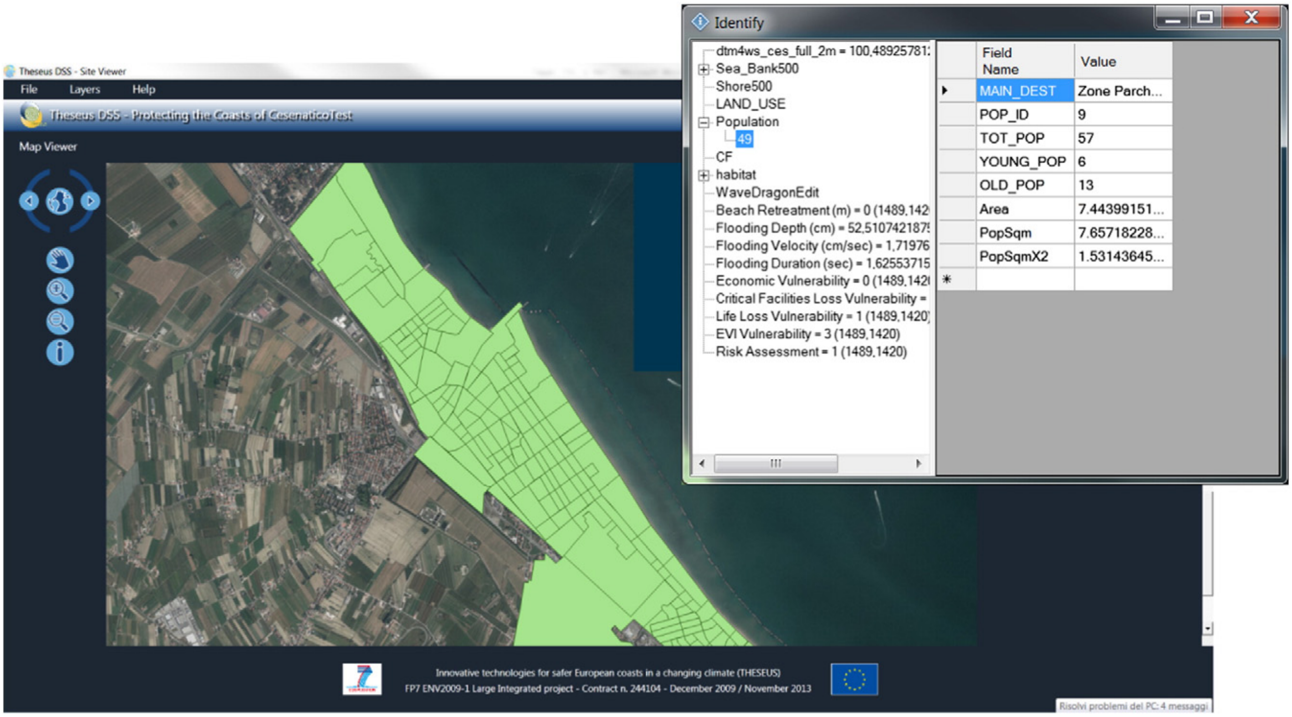
- A new dune raises the DEM and also creates a new habitat that is relevant for coastal protection. Within the DSS this would be expressed as a modification of the digital elevation model and the habitat map. This would make flooding less likely, including allowing for the effects of episodic erosion.
- Insurance plans do not generally modify the flood characteristics of the human receptors, but increase their capacity to rebuild and repair after a coastal flood. Within the DSS this is expressed as an input to the locally affected economy from “outside” the flood-affected area. This input means that any decrease of local GDP due to flooding still occurs, but recovery to the previous status quo is facilitated and/or accelerated due to the insurance-defined funds.

THESEUS DSS includes also the effects that can be obtained by reducing the numbers of people exposed to the hazard using an evacuation calculator developed during the project (Hissel et al., 2014).

4.1.5. Modelling erosion and flooding

These processes include wave transformation from off-shore to the shore-line, beach erosion, wave run-up on the beach and overtopping over the sea-bank, and finally flooding. The propagation of waves from off-shore to the sea-bank, i.e. from the “waves”-line to the “sea-bank” line, follows the procedure described in Section 2:

- Wave transfer from off-shore to the shoreline, following the method by Goda (2000);
- Computation of wave reduction due to engineering and ecologically based mitigations placed between the off-shore line and the shore line by means of specific functions based on new experimental and physical modelling activities carried out within THESEUS or on available literature (THESEUS OD2.7, 2013); the DSS automatically detects the presence of mitigations at sea and operates a segmentation of the coastline at a sufficient resolution to represent the effects induced by single and multiple mitigations, see Fig. 10;
- Estimation of the shoreline change induced by the storm through Eqs. (3)–(5); the user has also the possibility to upload or draw a new shoreline position based on expert judgement and test multiple erosion scenarios (see Fig. 4);
- Estimation of wave run-up on the beach from Eq. (2), where the original formulation is modified to include the transmitted wave height inshore of mitigations and local wavelength; beach slope accounts for the effects of erosion;
- Generation of a Jonswap wave spectrum with amplitude equal to wave-run-up and combination of this water level signal in time with storm surge level and wave set-up. This global water level, i.e. given by the positive terms in Eq. (1), is compared with the bottom elevation along the sea bank, i.e. given by the negative term in Eq. (1): when the water level is higher, flooding occurs. The water volumes to be included at the water sources as input for the flooding model are therefore derived by integrating the exceeding water levels during a given time interval and for the whole storm duration.



dtm4ws_ces_full_2m = 100,48925781
Sea_Bank500
Shore500
LAND_USE
Population
49
CF
habitat
WaveDragonEdit
Beach Retreatment (m) = 0 (1489,142
Flooding Depth (cm) = 52,510742187
Flooding Velocity (cm/sec) = 1,71976
Flooding Duration (sec) = 1,62553715
Economic Vulnerability = 0 (1489,142
Critical Facilities Loss Vulnerability =
Life Loss Vulnerability = 1 (1489,1420)
EVI Vulnerability = 3 (1489,1420)
Risk Assessment = 1 (1489,1420)

Field Name	Value
MAIN_DEST	Zone Parch...
POP_ID	9
TOT_POP	57
YOUNG_POP	6
OLD_POP	13
Area	7.44399151...
PopSqm	7.65718228...
PopSqmX2	1.53143645...

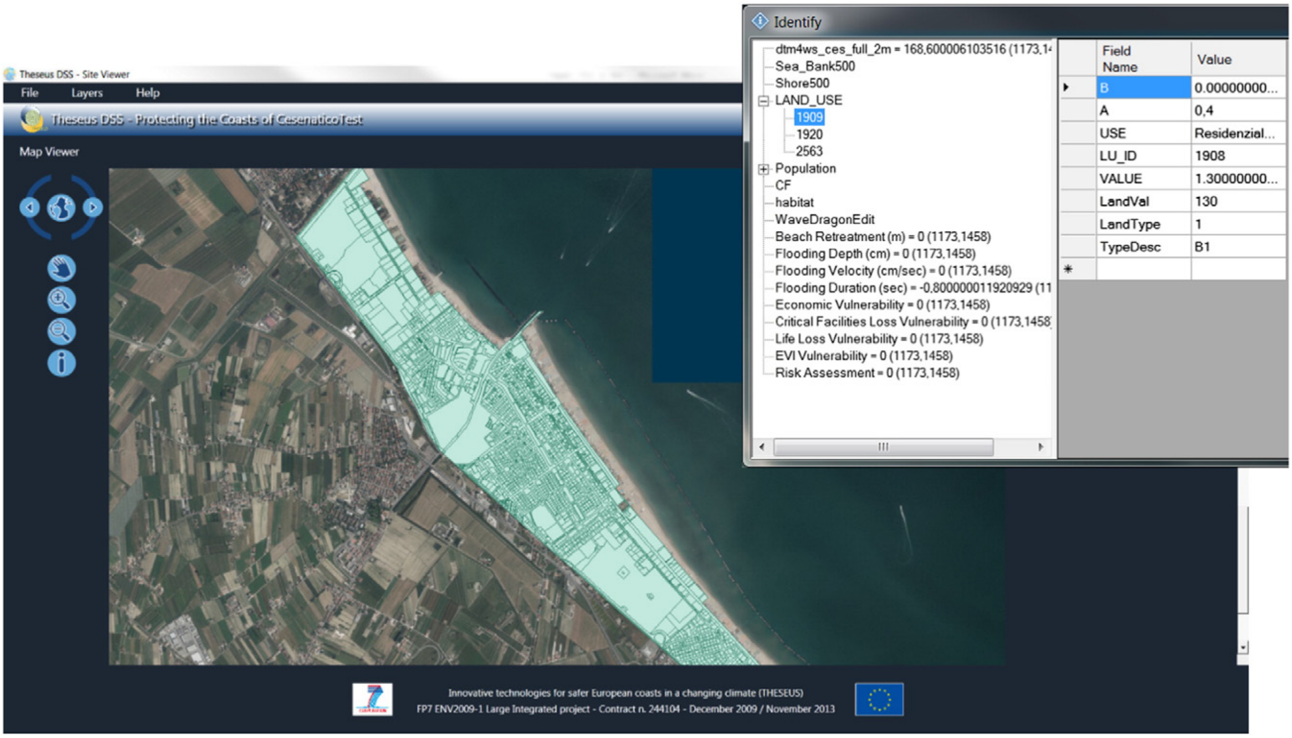
Fig. 8. Example of population data: GIS based map and information about population density and age based on the data resolution available from the stakeholders.

The results of this procedure consist of the shoreline after the storm and the map of flooding depths.

However, to estimate the consequences of flooding on the society, the economy and the ecology, maps of flooding duration and velocity are also needed. Since the flooding model is not a hydrodynamic model, specific procedures have been developed to derive these additional maps from the flooding depths and the characteristics of the terrain.

The map of flood duration is obtained from the combination of the Darcy law and the mass balance, for given soil characteristics (permeability, porosity) under the following simplifying assumptions

- Constant water head at the beach/river/channel boundaries;
- Fully saturated soil (cautious assumption);
- Homogeneous and isotropic medium.



dtm4ws_ces_full_2m = 168,600006103516 (1173,14
Sea_Bank500
Shore500
LAND_USE
1909
1920
2563
Population
CF
habitat
WaveDragonEdit
Beach Retreatment (m) = 0 (1173,1458)
Flooding Depth (cm) = 0 (1173,1458)
Flooding Velocity (cm/sec) = 0 (1173,1458)
Flooding Duration (sec) = -0,800000011920929 (11
Economic Vulnerability = 0 (1173,1458)
Critical Facilities Loss Vulnerability = 0 (1173,1458)
Life Loss Vulnerability = 0 (1173,1458)
EVI Vulnerability = 0 (1173,1458)
Risk Assessment = 0 (1173,1458)

Field Name	Value
B	0.00000000...
A	0,4
USE	Residenzial...
LU_ID	1908
VALUE	1.30000000...
LandVal	130
LandType	1
TypeDesc	B1

Fig. 9. Example of population data: GIS based map and information about population density and age based on the data resolution available from the stakeholders.

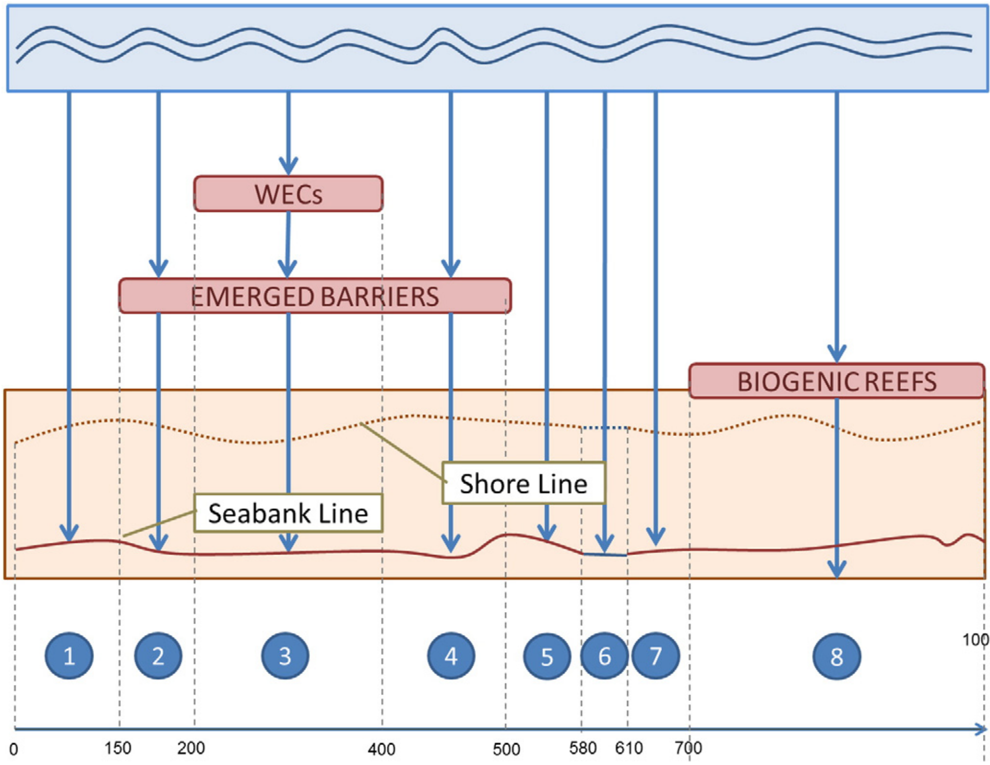


Fig. 10. Example of automatic coastal segmentation performed by the DSS based on the presence of mitigation measures placed between the wave-line and the shore-line.

The map of flood velocity is derived by applying the generalised Bernoulli's theorem between paired points along transects normal to the shoreline (an example is shown in Fig. 11). The computation starts from the points at the shore line, where the velocity is assumed to be a known term, dependent directly on wave celerity and therefore on flooding depth by means of a constant. This hypothesis has been verified for the DSS testing site of Cesenatico, Italy, through 2DH detailed simulations with Mike 21 (Villatoro et al., 2014). The velocity at the inland point is estimated from the balance of the kinetic term at the shoreline, the pressure difference (i.e. flood depth difference) and bottom slope between the two points, and the friction losses estimated following Manning's law where the velocity is assumed to be equal to the known one.

4.1.6. Consequences, vulnerability and risk maps

THESEUS scientists developed appropriate impact functions to link economic, social and ecological data to hydraulic parameters, such as: beach retreat, flood depth, flood duration, flood velocity. These

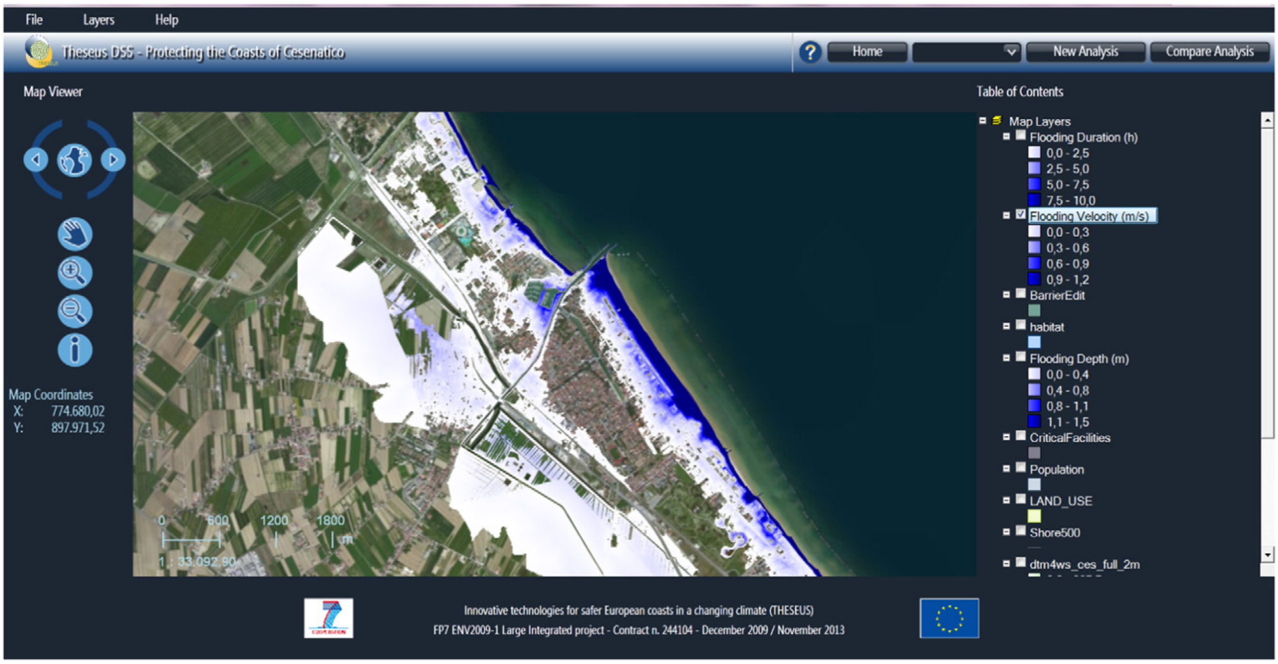


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Fig. 11. Example map of flooding velocities derived from the modified watershed segmentation algorithm. Long term (2080) scenario with return period (combined wave and storm surge statistics) Tr = 100 years.

functions allow to obtain the maps of social, economic and ecological consequences, each one expressed with the typical unit. The economic losses are divided into the losses in the urban area, expressed as euro/m^2, and into the beach losses, expressed as euro/m. The social losses are derived in terms of life losses, expressed as a percentage of the number of expected deaths of the local population in the area, and of CF losses, expressed as a percentage of the functionality loss of each CF (see the example in Fig. 12).

A normalisation procedure of each map of consequences is then carried out in order to obtain a 1 to 4 scale, being 1 = low, 2 = medium, 3 = high and 4 = very high impact. The normalisation is performed by dividing the local values of the consequences by the corresponding site-specific thresholds that are obtained by comparing the consequences of different scenarios with the historical experience and/or data available in the site, i.e. through a process that involves both stakeholders and experts. Site-specific threshold values for low, medium, high and very high impact are defined for each relevant parameter: flood depth, velocity and duration; beach retreatment; beach and land use value losses; life and CF losses. The normalised ecological vulnerability map is directly derived from the calculated values of the *EVI*, by associating the *EVI* 0–3 scale to the 1–4 vulnerability scale.

Hydraulic, social and economic vulnerability maps are generated, being vulnerability assessed as:

$$\text{vulnerability} = \text{exposure} = -\text{resilience}$$

where exposure is the value at risk (De Vries, 2011) and resilience is the damage that will not alter the main functions of human and physical systems in equilibrium in discrete times and at local scale (De Bruijn, 2004).

This set of definitions was adopted as a result of the integration of the different ways THESEUS scientists conceive risk depending on their specific background. Economists and sociologists think in terms of exposure, for instance: “will this railway be damaged by flood?” or “will children suffer from flood”. Ecologists think in terms of resilience, i.e. “will this habitat survive?”, since it would not make sense to consider that the existing habitat is better or worse that the new one that might be induced by the flood event. Engineers tend usually to combine the two concepts, for instance: “will the beach be severely eroded by the storm?” and “will the dyke resist the storm”.

The hydraulic vulnerability map is derived from a weighted average with equal weights of the normalised maps of flood depths, velocities and durations. The economic vulnerability map is obtained by a spatial combination of the normalised beach losses and of the normalised inland value lossed, the two areas being complementary. The social vulnerability map is derived as an equally weighted combination of the normalised maps of life losses and CF losses.

Social, economic and ecological vulnerability maps are then combined through a weighted procedure, in order to obtain the overall risk map (Fig. 13). Within this additive combination, the hydraulic vulnerability is not explicitly considered to avoid duplication, since it is already indirectly included through the social, economic and ecological vulnerabilities that are all estimated on the basis of selected hydraulic parameters (flood depth, velocity and duration).

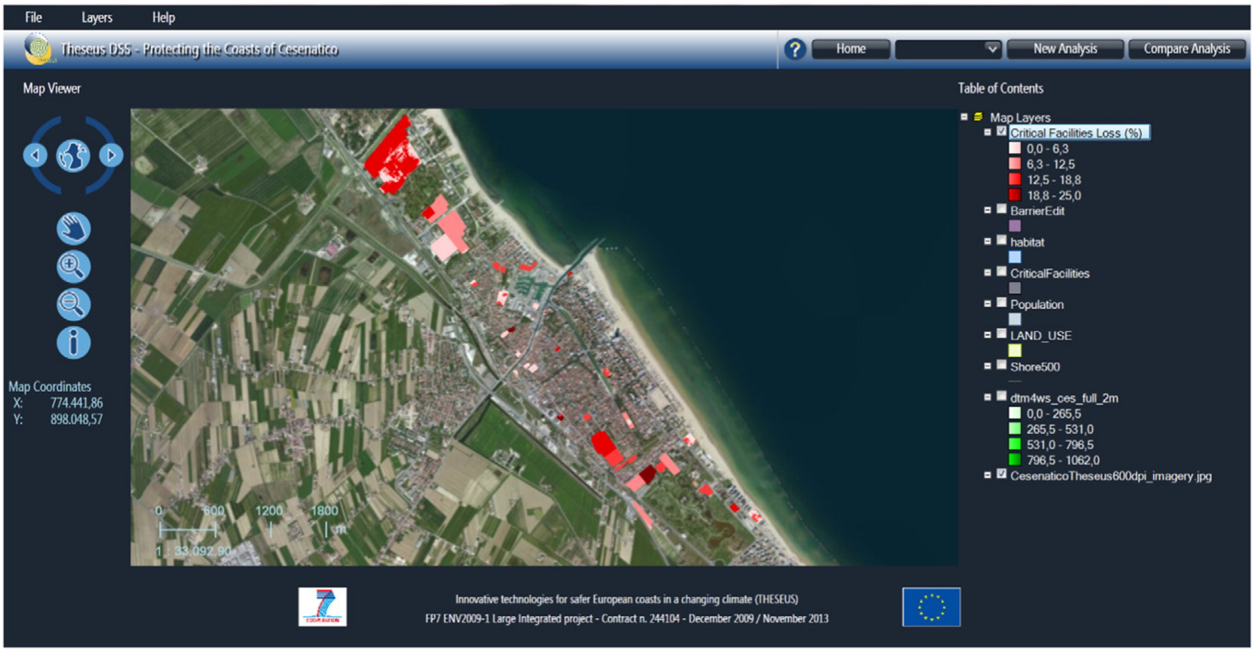
In the generation of the risk map, the users have the chance to select equal weights, their own weights or to use the results of the surveys carried out in the sites (see Fig. 14 for the synthesis of the results in the Italian case study).

Within these surveys, the stakeholders were asked to rank three cards where the three titles referred to the represented main issues (economic, environmental, and social). Some items were clarified with some examples, for instance: the “economic” card shows “houses, tourism, fishery, …”; the environmental card presents “pine forest, biodiversity, animal species, habitats, …”; the social card shows “social cohesion, meeting facilities, sports, psychological distress, fatalities, injuries, …”. Stakeholders were then asked to insert one or more blank cards between the ordered cards, in order to stress relative differences in importance attached to each issue or group of issues.

The normalisation procedure suggested by Kodikara et al. (2010) led to obtain the relative weights for each stakeholder and consequently the weights of each criteria were estimated as the average values.

4.2. Technological framework

The desktop-based architecture of THESEUS DSS (see Fig. 15) consists of three main components: the first tier is a set of windows forms that allows the user to interact with the system (i.e. the GUI already explained in Section 3), secondly a GIS-based tier that provides spatial capabilities to the system and a final tier that allows the integration of models and procedures.



Map Coordinates
X: 774.441,86
Y: 898.048,57

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Fig. 12. Example of impact on critical facilities (%). Long term (2080) scenario with return period (combined wave and storm surge statistics) Tr = 100 years.

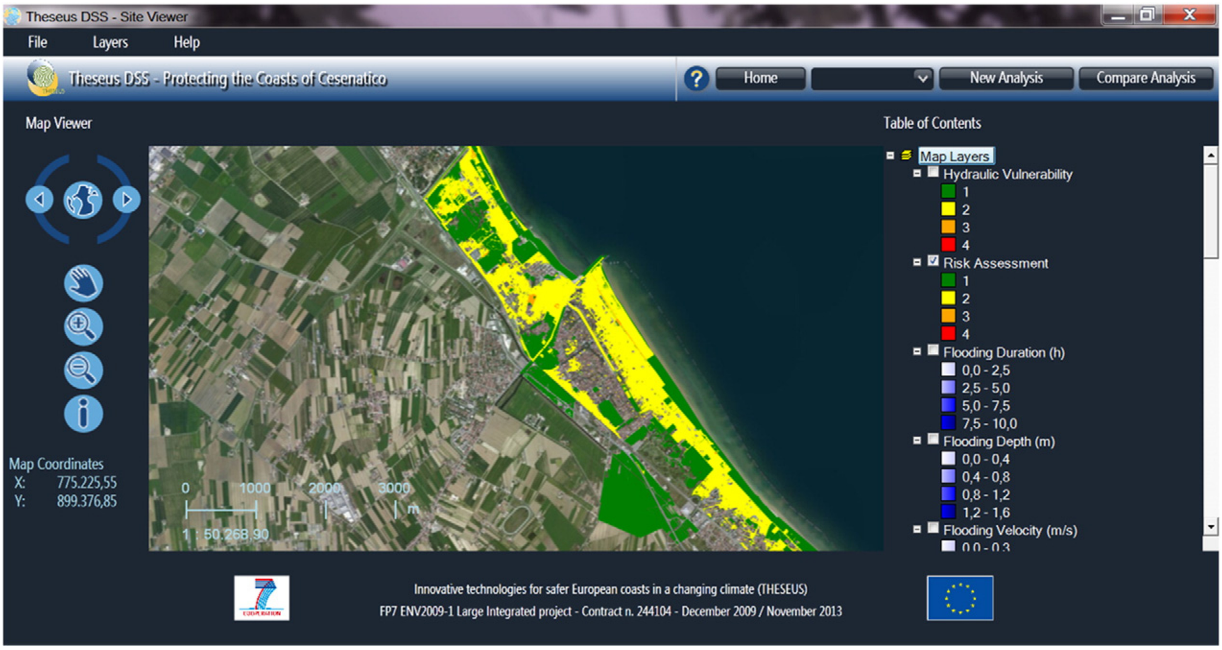

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Fig. 13. Example of integrated risk map, scale from 1 to 4 (from low to very high impact). Medium term (2050) scenario with return period (combined wave and storm surge statistics) Tr = 50 years.

The technological framework selected for the Theseus DSS development is Microsoft.NET 4.0, so the DSS can be run on any Microsoft Windows PC. The software supports the whole user interaction with the system, through a friendly and flexible interface based on maps and standard forms (menus, dropdown lists, etc.). The NET Framework is a solid software platform which includes a wide class library for common tasks such as data access, user interface or network communications that are currently been used by the DSS. It is supported by a Common Language Runtime (CLR) that must be previously installed on the client system. The THESEUS installer package facilitates the installation process, looking for the required dependencies and installing all of them.

DotSpatial, a free, open source set of libraries for.NET, was selected as GIS components of the DSS to easily incorporate spatial data, analysis and mapping into an application. One of the biggest strengths of DotSpatial is its capability to work with common GIS files, such as ESRI Shapefile (.shp), a de facto standard for vector graphic data. This kind of file can be easily generated and maintained by common GIS software.

A Relational Database Management System has been selected to implement a relational model which is able to store the Sites' information; data and configuration. The software selected for this task is SQLite (http://www.sqlite.org/), a software library that implements a self-contained, serverless, transactional SQL database engine.

The graphic and alphanumeric data for each area (environment, socio-economic…) is gathered and configured as packages, so they can be later saved and disseminated on CD/DVD, enclosed to the DSS.

THESEUS DSS is compliant with existing international standards, such as the Open Geospatial Consortium (OGC) standards, since the Dot Spatial framework uses data compatible with the OGC structure. It also respects the approach proposed by OPEN-MI, developed by the HARMON-IT project. However, the standards of OPEN-MI were not fully followed due to its rigid architecture that would have not allowed adopting Dot Spatial, i.e. the only solution to have an open source GIS, and Python, since source codes should be written in c# and java only. THESEUS technological choices had indeed to satisfy the primary requirement of using free-licence software to allow maximum exportability and dissemination.

The model shell is essentially represented by the GUI interface running window. This shell

a) Contains the database including the input data and specific site parameters needed to set-up the scenarios and to run the algorithms and functions at a given site; the data and parameter

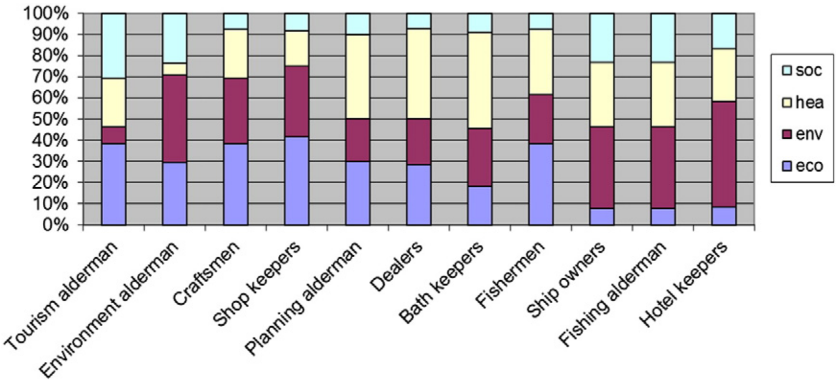

Fig. 14. Weights assigned by stakeholders in Cesenatico, Italy, when considering the flood impact on society, here subdivided as impact on human health (hea) and on infrastructures and activities (soc), environment (env) and economics (eco).

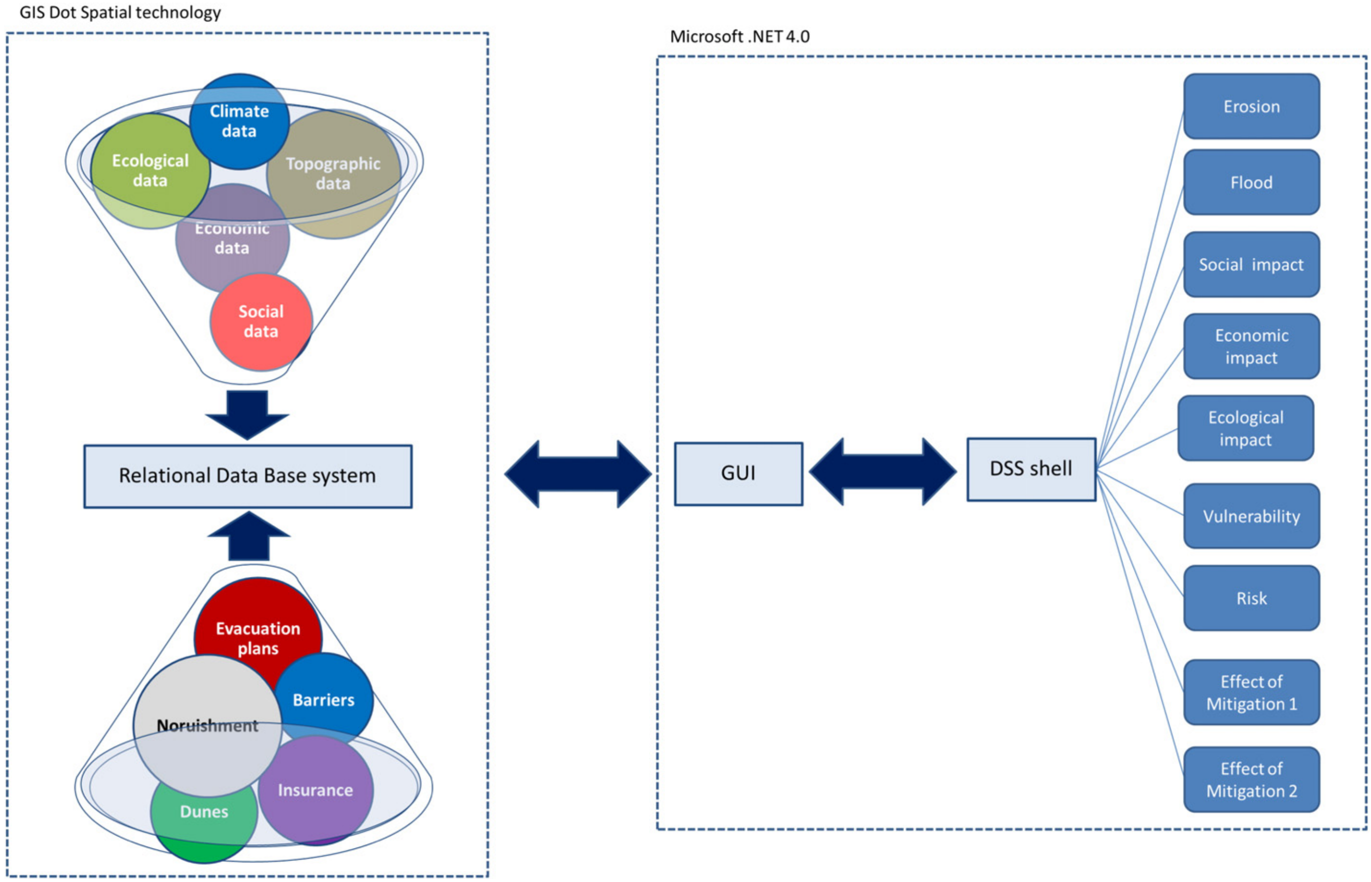

Fig. 15. Architecture of THESEUS DSS.

can be modified by the site manager, i.e. the person with the technical skills responsible for the implementation of the DSS at the selected site, after a password protected log-in as DSS administrator;

b) Calls the different models for the physical processes (wave transformation, shoreline retreat, flood propagation);
c) Calls the functions for estimating the effects of mitigation options and the related impacts, providing also the vulnerability maps;
d) Integrates the results into a risk map.

The user can select which steps have to be run or re-run (points b, c, d); however when a new mitigation is included or a new parameter of a scenarios is selected by the user in the exploratory analysis, the shell automatically suggests which are the algorithms and functions to be re-run for analysing the change.

The algorithms, functions and models recalled by the shell are detailed in the DSS online help and manual; in principle, any of these can be modified and/or substituted by the DSS administrator if the inputs/outputs are the same and the modified and/or new code is provided as an.exe file. Moreover, the application to new sites can be straightforward pursued provided that the users have the required data in the required format, define the required site parameters and identify which kind of habitats/mitigations/scenarios should be added.

These procedures of modification and extension of THESEUS DSS cannot be done directly by the users since they require experience of the DSS. THESEUS scientists also consider that the dissemination of the tool without any contact with the interested users, testing and calibration of the tool in new sites followed by the DSS responsible may led to unreasonable results.

The development of THESEUS DSS had to account for the following main challenges.

1. Heterogeneity. The software has to capture the high heterogeneity of the coastal areas under analysis (e.g. Monbaliu et al., 2014; Villatoro et al., 2014).
2. Robustness. The software has to be able to operate under stress or tolerate unpredictable or invalid input. User modifications must be checked to keep the software in working order, including inputs/outputs from functions and light models. Many different functions or light models (.exe files) that simulate a particular phenomenon (see Fig. 2) are executed in a concatenated way by the DSS shell. THESEUS relational databases have been designed to store maximum and minimum variable values, which are used by a validator method to ensure function robustness. In addition, functions and light models have been fully validated by Theseus partners to provide maximum robustness. The help section of the DSS provides a full description of the functions implemented, including authors mail of contact.
3. Performance. THESEUS DSS is a quick response software (of the order of minutes for one full run from selecting scenarios to risk assessment) based on light models and functions embedded into executable files (.exe). This may allow future implementation of the software at new sites without forcing the developers to write the code in an imposed programming language. The users can run separately the physical processes (waves, erosion, flooding), the impact analyses (social, economic, ecological) and the combination of the analyses into a risk map. This allows to obtain the best DSS performance, i.e. to avoid the penalization of its overall performance, since there are functions running with a lower and a greater level of performance.

4.3. Accessibility

THESEUS DSS was applied to four of the eight case studies examined within the project. These sites were selected since they represent a range of characteristics and diverse environmental, social, economic and ecological issues: Cesenatico, Northern Adriatic Sea, Italy; Teignmouth estuary, South Devon, United Kingdom; Gironde estuary, Atlantic Ocean, France; Santander, Gulf of Biscay, Spain.

From the project website (www.theseusproject.eu) it will be accessible and downloadable after registration the application of the DSS (as an executable code) in these four sites, including the manual and the online help.

5. Discussion of the DSS challenges and limitations

Besides the intrinsic problem of integrating different disciplines with different views and languages, the DSS has to face the following practical and conceptual challenges.

- The conceptual approach and the simplified modelling assumptions that are at the basis of the DSS may be considered too simplistic by the coastal managers and stakeholders to trust the reliability of the results. However, there are at least three key points to answer this problem with the DSS. First, the relatively fast running time allows the user to examine many different scenarios. In this way, the user can identify how and how far the DSS results compare with the historical data and/or the memory in the sites. Second, the inherent uncertainty of the results (that do exist for any type of model) can be overcome if one runs the tool aiming at a sensitivity analysis of the results, i.e. at comparing results of different scenarios considering that all the results are affected by the same simplifying assumptions. Third, it should not be forgotten the clear statement that the DSS is essentially a tool to be used in a preliminary phase for assessing risk and identifying the optimal portfolio of mitigation strategies, but it is not meant as a tool that substitutes for the detailed design process. Hence, the DSS is designed to be part of a stratified analytical approach for coastal risk management.
- In many cases, the topographic, social, economic and ecological high spatial resolution data that are required for running the DSS may be not available. Even when available these data may be owned by different authorities (municipalities, regional governments, ministry) and scattered and hard to obtain, due to miscommunication among the owners and confidentiality issues. This same problem however typically affects all kind of risk assessment for any hazard at any area.
- The non-linear interdependence of the mitigation options is not considered. For instance, the construction of a hard flood defence affects insurance and may also affect public preparedness to evacuate. However the tool separately represents the effects of these three measures on the flood processes, on the land value losses and on the life losses and then these effects are linearly combined.
- Risk perception – and therefore social resilience and its effects in terms of preparedness and social changes in terms of cohesion, livelihoods and opportunities – is not represented.
- A cost–benefit analysis is not included for several reasons. For some mitigation measures (wave energy converters, insurance schemes, biogenic reefs) it is very difficult to assess the costs, especially since a market is not already available. Moreover, as pointed out above, the combination of mitigation measures is actually non-linear and therefore also synergies of the costs and benefits may be achieved, but cannot be easily represented even by more complicated models. The benefits may tackle very different scales, for instance: the relevance of the indirect benefit generated by the reinforcement of a habitat can be judged at national/European scale, the benefit due to the power production of a wave farm requires a regional scale, the benefit induced by an evacuation plan is assessed at the municipality scale.
- Since the users get the results for each computed scenario, they may achieve misleading decision if based on a single DSS run only. It is therefore important to warn the user that the best methodological compromise is running multiple storm scenarios (at least three storms, let's say 10, 50 and 100 years) for each selected time slice (2020s, 2050s or 2080s if one refers to the pre-set ones) and by post-processing the results of these scenarios to get the sources-consequences function. Specifically, the social, economic, hydraulic and ecological vulnerability maps obtained for each storm should be multiplied by the probability of occurrence of the corresponding storm and then added to get the average vulnerability maps. A alternative solution is to define few relevant parameters/indicators and compare their values for different scenarios (i.e. combination of return periods for a given time slice), such as: percentage of flooded area with flow depth greater than a Fixed Threshold Value (FTV), number of CFs whose functionality is damaged for a percentage greater than a FTV, percentage of land or beach values loss greater than a FTV with respect to the total value, and so on.

6. Conclusions

Within the THESEUS project, a new Decision Support System (DSS) was developed aiming at providing coastal managers with information about present and future flood risk assessment and at supporting a sustainable long-term planning of mitigation strategies.

The tool is based on a series of linked simplified models to ensure a rapid run-time and a quick response to the user. Hence, it is most useful in the preliminary risk assessment phase, identifying the most threatened areas, and in the preliminary planning phase, verifying the most promising portfolio of mitigation solutions. Hence its role is to structure the analysis, including selection and use of more sophisticated models for subsequent more detailed analysis.

The DSS is open source and parametric so that it can be applied, in principle, to any coastal area independent of scale issues. However it requires appropriate site data, both to simulate inundation with a sufficient degree of accuracy (needing a high resolution DEM) and to represent social and economic vulnerability and the range of mitigation options.

While the tool can represent hydraulic, social, economic and ecological vulnerability, it is currently limited in terms of the inclusion of the resilience concept. Hence issues such as (1) how far a seabank can resist during a storm?, (2) how much people can recover after the disaster?, and (3) how an increase of risk awareness may affect the rapidity of evacuation? are not currently addressed. This represents an important improvement to be considered in further development.

The tool was designed to allow the user step by step interaction by setting up scenarios, selecting mitigation options, and changing weights within the multi-criteria risk analysis. The possibility to run and compare many different conditions allows the users to explore flood risk and to develop an impact-oriented approach to coastal risk mitigation across multiple criteria. This process of course depends on the technical skills of the user and their local site-specific background.

The monitoring of the use of the DSS in practice and its supporting role – if any – in decision making will allow refinement and further development of the approach.

Acknowledgements

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