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# Storm impacts along European coastlines. Part 2: lessons learned from the MICORE project

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ABSTRACT

This paper describes the MICORE approach to quantify for nine field sites the crucial storm related physical hazards (hydrodynamic as well as morphodynamic) in support of early warning efforts and emergency response.

As a first step historical storms that had a significant morphological impact on a representative number of sensitive European coastal stretches were reviewed and analysed in order to understand storm related morphological changes and how often they occur around Europe. Next, an on-line storm prediction system was set up to enable prediction of storm related hydro- and morphodynamic impacts. The system makes use of existing off-the-shelf models as well as a new open-source morphological model. To validate the models at least one year of fieldwork was done at nine pilot sites. The data was safeguarded and stored for future use in an open database that conforms to the OpenEarth protocols.

To translate quantitative model results to useful information for Civil Protection agencies the Frame of Reference approach (Van Koningsveld et al., 2005, 2007) was used to derive Storm Impact Indicators (SIIs) for relevant decision makers. The acquired knowledge is expected to be directly transferred to the civil society trough partnerships with end-users at the end of the MICORE project.



## 1. Introduction

Recent natural disasters in coastal areas have underlined the potential devastating effects of hazards with a marine origin (tsunami, hurricanes, etc.). These powerful natural events have raised awareness that the coastal areas can be exposed to natural disasters. Although the processes that generate these events are beyond human control, many lives could be saved in the future if adequate mitigation procedures can be developed. Examples of existing procedures include the warning systems for tsunamis and associated vulnerability mapping, and accurate forecasting of major storms and hurricanes via synoptic weather circulation models. Closely linked to this are civil defence and coastal evacuation plans that aim to reduce the risk to human life and minimise damage to property and infrastructure. An increasing scientific and public concern with natural hazards is currently of interest to environmental policy priorities of the European Union and its member states. Of particular relevance to the protection of coastal areas is to understand if there is an increase in the intensity and frequency of powerful storm events characterised by larger peak wind speeds and consequently larger waves.

Engineering or "pro-action and prevention" has been favoured in the past as the best option for disaster mitigation at the coast. However, most engineering works are constrained

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by economics, and a compromise must be sought between the potential threat to lives and property and the resources available for design and construction. Furthermore, the design of structures is based on predicted extreme events which themselves are subject to uncertainty, especially in a rapidly changing global climate.

The huge damage to the city of New Orleans by Hurricane Katrina clearly illustrates what can go wrong when engineering design is subjected to forcing beyond its design limits and when civil evacuation and management plans fail. Hurricane Katrina also illustrates that the experience of past storm events can be quickly forgotten and post-event policies of mitigation rather than defence are the norm. For example, although Hurricane Camille in 1969 had a significant impact on coastal Louisiana, post-storm construction criteria aimed at mitigating future flooding were clearly inadequate as damage inflicted by Katrina followed a similar pattern. The threat of hurricane Gustav only three years after Katrina illustrates the additional effects of consecutive storm impacts.

Due to economic limitations it is simply not possible to design, fund and build schemes to protect vulnerable coastal areas from all anticipated events. Indeed, scenarios of climate change impacts from present models are diverse and cannot at present be relied upon to give accurate forecasts of future extreme events around coastal Europe. Therefore, there is an urgent need to develop new coastal management systems to respond to as yet unforeseen extreme events that fall outside the design limits of existing and future coastal structures. In this context, the development of on-line warning systems providing predictions of storm impacts would support civil protection mitigation strategies with an interesting new source of information.

Ciavola et al. (this issue) have outlined the joint efforts of the MICORE and the ConHaz projects to make steps in handling storm impact along European coastlines. It was observed that specialist knowledge of coastal behaviour under storm conditions could be useful in improving emergency preparedness.

The MICORE project aimed to set up an on-line warning system utilizing as much as possible already existing open data feeds in combination with already available off-the-shelf models and/or the new open source model XBeach (Roelvink et al., 2009). The end result is believed to give a sound basis for emergency response supplying predictions up to 3 days in advance continuously. To notice that this time restriction is due to the reliability of weather forecasts, which are normally issued for a 72-h scenario. The objective of this paper is to discuss the approaches that are followed and to summarize a number of important lessons learned during the setup and execution of the project. After a brief introduction of the MICORE project, a review of the knowledge on historical storms is discussed, trying to find trends in the studied datasets. Finally, lessons learned on data management, model development and warning system development are described.

## 2. The MICORE project

The MICORE project (www.micore.eu), funded under the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement 202798, aims to develop and demonstrate on-line tools for reliable predictions of the morphological impact of marine storm events in support of civil protection mitigation strategies. The project has a budget of 4,597,074 € and receives a contribution by the EU for 3,499,954 €. It started in June 2008 and has duration of 40 months, with a partnership of 16 institutions across Europe. The project specifically focussed on emergency response rather than on strategic preparation. As such it is a clear example of a practice oriented research programme towards coastal management. The main implication on the project's development strategy is that, although MICORE aims to further enhance the state-of-the-art in storm impact modelling, the project is supposed to deliver results that are useful/applicable by end users. The project is being developed accordingly with a strong emphasis on the usability of results, following a philosophy of matching research with end user needs (Van Koningsveld et al., 2003). As such, MICORE is building on previous experience developed during previous projects, among others CoastView project (Davidson et al., 2007; Van Koningsveld et al., 2007) and ConScience (Marchand, 2010).

To facilitate the development of a generic approach and promote practical applicability of its end results, MICORE selected nine case-study sites throughout Europe (Ferreira et al., 2009b). Here monitoring was undertaken for a period of at least one year to collect new data sets of bathymetry and topography using state-of-the-art technology (Lidar, ARGUS, Radar, DGPS). The impacts of the storms on living and non-living resources were assessed using DGPS methods and undertaking post-damage assessments. These impacts were afterwards catalogued on local GIS systems and databases and stored on a single repository accessible for all partners. Numerical models of storm-induced morphological changes were tested and developed, using commercial packages and the new open-source XBeach code. The models were linked to wave and surge forecasting models to set-up a real-time warning system and to implement its usage within Civil Protection agencies. The most important end product of the project was the production of an operational warning system with predefined data processing algorithms. Storm Impact Indicators (SIIs) were used for the prediction of major morphological changes and flooding events in relation to predefined management issues.

The management issues for which SIIs were defined and the uncertainty involved in their use were a sensitive issue that was discussed with decision-makers. The MICORE project employed the Frame of Reference method to assist in the process of defining relevant SIIs for each of the field sites. Just as in CoastView (Van Koningsveld et al., 2005, 2007), the MICORE project found it was necessary to distinguish between variables, that describe physical aspects of the coastal system, and Storm Impact Indicators (SIIs), that provide a quantification of the coastal system in a form suitable for decision making. Given the focus on storm-related impacts, common variables that were calculated for each site included: wave height, run up levels, flow velocities, beach and dune erosion (volume/rate), overwash discharge, extent of inundation area, inundation depth, etc. The notion that maps of flow velocities, for example, would not be seen as adequate information to support decision makers per se, a lesson learned already in the CoastView project, still served as an eye-opener to many of the researchers involved.



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The focus on developing SIIs, the use of the Frame of Reference approach and the associated interaction with end users, revealed another interesting benefit from practice-oriented research: additional inspiration from suggestions by end users.

## 3. Analysis of historic storms

One of the MICORE objectives was to undertake an analysis of changes in storm occurrence and to consider possible future variability in the context of climate change. This analysis included the study of trends in meteorological data (e.g. changes in storminess proxies) and intended to provide guidance for the understanding of the response of coastlines to potential changes in the forcing agents. The analysis presented hereafter is based on the study of existing databases available at national and European level for different forcing agents. The full MICORE report on historical storms (Ferreira et al., 2009b) is publicly available on the project's website. The considered driving factors included storm waves, wave energy, winds and surge levels, depending on data availability and on the specific conditions of exposure of each coastline. Further information can be found in Ciavola et al. (this issue).

The use of 58 proxy analyses for 12 coastal regions of Europe, including modelled and measured data and the most important storminess indicators (surges, winds and waves), could have given indicative values about storminess trends in Europe (cf. Ferreira et al., 2009b). However, it must be stated that there was no general trend of storminess change in Europe, based on the studied coastal regions, used proxies and datasets. For some coastal regions, specific trends were found (Fig. 1). Notice that here only trends that were statistically significant are presented.

At present storminess variability is much higher than the observed trends at the time scale of the performed analysis (records longer than 3 decades). Some analyses (e.g. France – Aquitaine, Spain – Andalusia) indicated a direct relationship between storminess and the NAOI (North Atlantic Oscillation Index). It was however not possible to observe any clear association between storminess changes and global climate change. This does not imply that global climate change consequences (e.g., sea temperature increase, sea level rise) will not have an influence on European storminess and storminess impacts. It mainly means that for the existing and available data sets, those impacts have not been detected or do not have a visible and strong signal at European level.

The inventory of generically applicable thresholds for storm impact showed that each site has its own specific physical features influencing how offshore waves, wind, pressure fields and tides affect the coast. This warrants the setup of a warning system that is based on process models as this is the only way to come up with one generic approach that

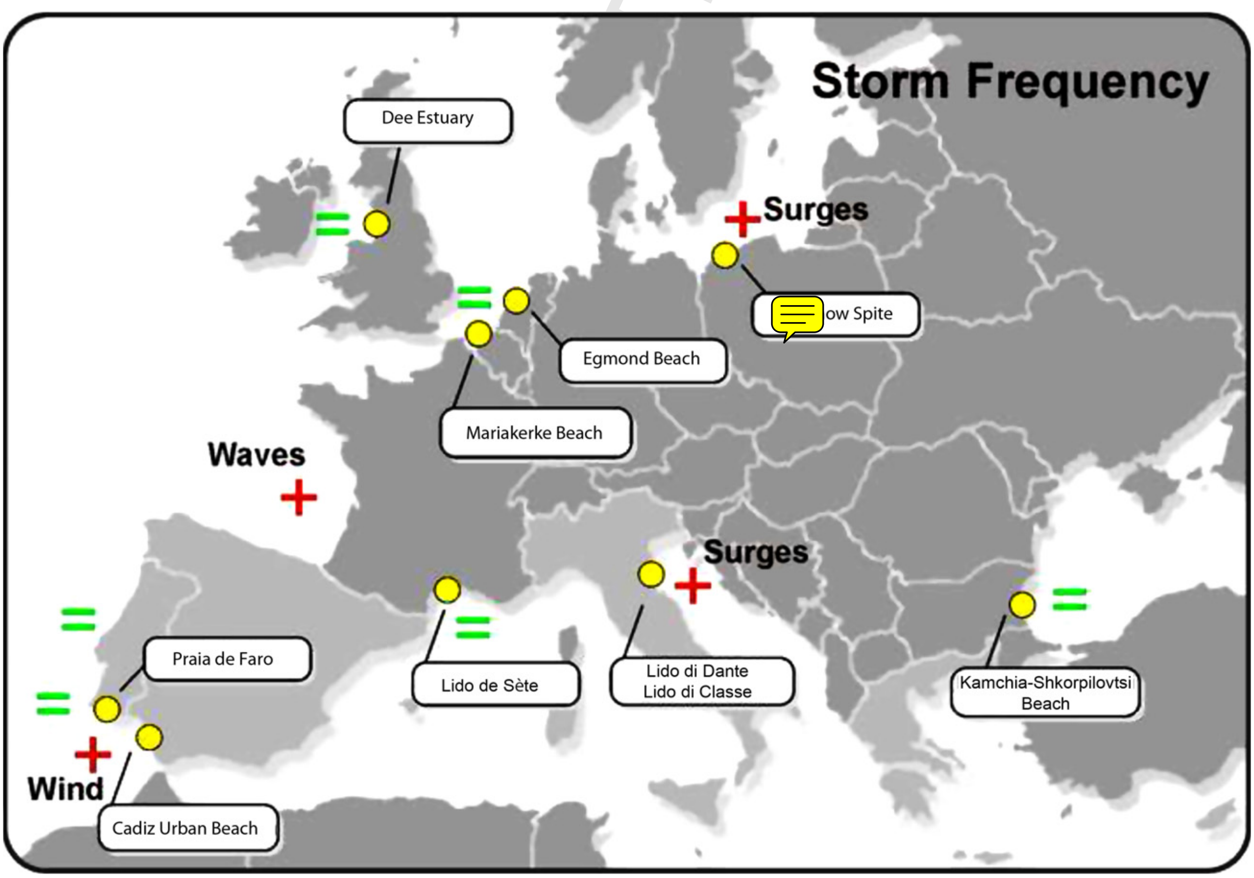


**Fig. 1 – Summary map of the presence of changes in storm frequency identified by the MICORE storm review. Only statistically significant trends are presented here with positive (increase) ~~or negative (decrease)~~ sign. The equal sign means that no trend was present in the data.**

may be applied to various locations with such variability in physical characteristics like European coastlines.

## 4. Open earth data and knowledge management

The MICORE project adopted the OpenEarth approach to data and knowledge management (Van Koningsveld et al., 2010). OpenEarth provides a project superseding approach to handling data, models, tools and information. Traditionally, large R&D programmes with partners from various organisations and countries approach the setup of supporting knowledge management infrastructures one project at a time. While this is apparently attractive from a budget management perspective, it also results in grave inefficiencies in developing and archiving the basic elements that are invariably involved: data, models and tools.

Hardly any project is by itself of sufficient scale to develop easy-accessible and high-quality data archives, state-of-the-art modelling systems and well-tested analysis tools under version control. Research institutions, consultancy as well as major construction projects commonly spend a significant part of their budget to set-up some basic data and knowledge management infrastructure, most of which dissipates again once the project is finished. Institutions generally employ internally intranet services and internal networks to collaborate and exchange information. However, due to increasing complexity, large projects nowadays are regularly executed by consortia. The internal services of individual institutions do not allow for external collaboration due to technical limitations or simply denial of permission for security reasons. As a result, the way data, models and tools are currently managed, while presumably aimed at protecting the knowledge capital of organizations, in fact also inhibits progress (individual as well as collective).

In MICORE the solution to the fragmentation and difficulty of data access, typical of large-scale, multi-partner projects, was solved adopting an open database approach, without having to rely on commercial proprietary packages and/or onto the local approach normally taken by end-users. The view of the Consortium was that the database should not ''die'' with the end of the project but rather be maintained and possibly expanded with internal resources of after bidding for new EU funds.

OpenEarth (www.openearth.eu) was developed as a cloneable, free and open source alternative to the project-by-project and institution-by-institution approaches to deal with data, models and tools. OpenEarth rather transcends the scale of single projects In its most concrete and operational form, OpenEarth facilitates collaboration within its user community by providing an open ICT (Information and Communication Technology) infrastructure, built from the best available open source components, in combination with a well defined workflow, described in open protocols and based as much as possible on widely accepted international standards.

The MICORE project showed that it is possible to store data from various partners residing in various countries in one project superseding database, overcoming problems of data format, data exchange capabilities and management effort by the relevant workpackage leader. As a result, the data from MICORE will be available for easy use in future R&D projects. This is a significant improvement to current approaches, where databases are set up specifically for one project often resulting in accessibility problems after the project has finished. The MICORE project also showed that it is possible to share and collaboratively develop generic tools between project partners from different countries, but also interaction with other projects. The project superseding character of the OpenEarth tools repositories also ensures that those developed by MICORE will be available to other projects for further use and refinement.

Applying the OpenEarth approach reduces the time needed in a project to set up ICT infrastructures as these are made freely available. To make the OpenEarth approach work in practice, the required effort shifts towards providing sufficient support and training to assist researchers in making the unavoidable (usually minor) changes in their normal workflow. The setup selected in MICORE was to arrange sufficient support and training at the beginning of the project, including the identification of one dedicated person from the workpackage leader to provide any required support.

An important lesson learned is that data archives should be made available in an easily usable form as soon as possible in the project, i.e. immediately after data collection rather than at the end of the project only. The former approach makes sure that the efforts put into database setup are immediately of use to the project itself, whereas the latter approach only benefits future projects. The interest to the project expressed by end-users invited to attend local dissemination workshops and the final conference (see project's website for details) greatly enhanced the quality of the data archive stimulating users to possibly add their own data. This is particularly true for National Institutions (e.g. Meteorological and Hydrographical Services) that provided data but could not give authorization for data release outside the project. In this case the information is only present in the database in the form of metadata information but it was used in the review of historical storms discussed in the current paper. To notice that all data in the database follows closely the Inspire Directive (2007/2/EC). The problem of open data access to meteorological and oceanographic information which is far beyond the competence of MICORE but possibly must be taken at EU level and discussed with member states.

## 5. XBeach open source model

In MICORE modelling techniques used for morphological modelling are based on an open source approach using the XBeach model, which has undergone extensive testing at a variety of sites (Roelvink et al., 2009; Van Dongeren et al., 2009). As described in Roelvink et al. (2009), the model solves coupled 2DH equations for wave propagation, flow, sediment transport and bottom changes, for varying (spectral) wave and flow boundary conditions. It resolves the wave-group and infragravity time scales, which are responsible for most of the swash and overwash processes, which thus can be modelled explicitly. The model was further developed inside MICORE adding algorithms for groundwater dynamics inside the beach and 2D hydrodynamics around offshore breakwaters. The code is particularly suited for studying dune erosion, overwashing and breaching as it can represent complex geometries and contains essential physics related to the swash motions during storms. It is open source and freely available at www.xbeach.org, where every change to the code is logged through version control systems.

The MICORE project has demonstrated that a community model can indeed be effectively applied within R&D programmes. All field site modellers set up a dedicated version of the model capturing the specifics of each coastline and producing useful and reasonably accurate results. The application of one generic process model to a vast number of field sites proved to be a great advantage to test the model thoroughly. The fact that the open source model could immediately be improved if any bug or problem would emerge, meant that the model was improved significantly throughout the project.

An automated testbed was set up and each change in the source code was automatically tested on a large number of datasets. The testbed proved to be a great tool in checking the models robustness and their range of applicability. The automated test runs, accompanied with an automated test report that was mailed to all model users weekly, proved to be a great quality assessment tool enhancing the users' confidence to apply the model.

## 6. Indicator based Early Warning System

Building a fully operational regional Early Warning System (EWS) is a very ambitious plan and far beyond the scope of the MICORE project. The set-up of such a system would require at least 5–10 years and the support of end-users on a national and European level. It was found that at present end-users are not ready to develop a EWS on a regional scale, although they are indeed interested in applications that demonstrate the capabilities of an operational tool. MICORE therefore focused on providing end-users with a prototype operational chain of models that could demonstrate the capabilities of an Early Warning System for each test site.

The fact that, with the selected approach, predictions would be available approximately three days in advance only, limited the kind of decisions for which the information could potentially be used. The Frame of Reference approach developed by Van Koningsveld and Mulder (2004) was used to help researchers from different field sites to use one method generically applicable to embed their highly specialized model results in a practical decision context. The SIIs are the base for the EWS as the thresholds of these indicators control if, and at what level, a warning should be issued. Table 1 shows the elaboration of a number of management approaches developed within the MICORE project expressed in terms of the Frame of Reference.

The MICORE project intended to prove that based on a predicted storm and sufficient information about the state of the coastal zone and its infrastructures (e.g. bathymetry, topography of beach and dunes, dyke characteristics), accurate predictions of storm impact in support of civil protection mitigation strategies could be made. Hereto a generic concept of an Early Warning System (EWS) was developed, consisting of five essential modules (illustrated in Fig. 2):

- An observation module, including weather, wave, surge measurements;
- A forecast module, including weather, wave, surge and morphological forecasts (XBeach);
- A decision support module, including Storm Impact Indicators and hazard maps;
- A warning module, including warning at different levels which are site-specific;
- A visualisation module including on-line GIS based maps.

To provide on-line warnings of coastal hazards, the EWS preferably should be able to rely on real time measurements of the driving forces (waves, water levels, wind and currents) and on the receptor characteristics (the coastal area, characterised by the morphological status of the nearshore, the beach characteristics, the presence of infrastructures on the beach and in the hinterland). Some EU members already have an operational monitoring network for offshore oceanographic parameters (e.g. waves and tides) and are willing to integrate their data into a EWS. The morphological status is also frequently measured along the coastal area in different EU member states. What is often missing is the link between all these observations and an operation, robust, forecasting system.

In order to convert predicted weather forecasts (i.e. wind and pressure fields) into a wave field and/or a surge level, a number of numerical models should be combined in the forecast module (cf. Baart et al., 2009). This module should foresee the translation of weather forecasts into a morphological forecast that predicts the morphological status of the coastal area. In the case of areas protected by flood protection structures, the latter provides essential input for the dyke breaching and flood forecast modules. Within the MICORE project the morphological forecast module used the XBeach model and was set-up to translate the physical parameters into Storm Impact Indicators (SIIs). These SIIs relate physical parameters to strategic and operational objectives and to actions, if required (Table 1). For each SII a forecast will be issued by each warning system at each demonstration site, linking the outcome to the decision support module. Based on pre-defined thresholds within the SIIs different levels of warnings can be issued, distinguishing no risk, medium risk and high risk. The warning system concept can be easily visualised using an online web interface based on open source software like Google Fusion Tables and Google MAPS that can be implemented within almost any existing website maintained by end users.

Within the MICORE project, the Dutch (cf. Baart et al., 2009) and Belgian (Fig. 3) test cases were set up at an early stage as examples for other partners within the consortium. In the example of Fig. 3 the wave and water level predictions were provided by the Flemish Government and taken from an ftp-site or equivalent. Together with sediment data and the most recent bathymetric and topographic measurements, the input data for the XBeach model is kept up to date. The collected

**Table 1 – A summary table of some example of the MICORE Frames of Reference. The greyed table row represents the quantitative building block that should be derived from models or measurements. This building block is used in the quantification of the SII. The surrounding table cells provide the practical context in which the SII is relevant. Notice how the structured approach enables cross-comparison between different Frames of Reference.**

| Management issue | Dike and dune monitoring (extreme marine forcing conditions) | Protection of beach property Safeguarding immobile goods (extreme marine forcing conditions) | Protection of beach property Safeguarding mobile goods (moderate marine forcing conditions) | Coastal safety – Conservation of natural areas (EU Council Directive 92/43/CEE) | Swimmer safety (average marine forcing conditions) |
|---|---|---|---|---|---|
| Strategic objective | Guarantee an efficient as well as an effective response to coastal threats during major storms. | Protection of as much property as possible during storm conditions in an economic optimal way. | Sustain recreation entrepreneurs by preventing storm-related damage. | Guarantee sustainable safety of natural heritage. | Prevent injuries or casualties for recreational beach-goers during everyday conditions. |
| Operational objective | Personnel responsible for monitoring the development of natural threats to a coastal resort should be deployed timely to the proper locations. | Allocation of the (limited) last minute protection measures to limit economical damage as much as possible. | Timely warn recreation companies to put movable goods in a safe place in case of run-up events. | Reduce impact of flooding behind the beach and/or dunes. | Prevent the unsupervised presence of swimmers in areas in the surf zone where hazardous currents occur. |
| Quantitative State Concept | Likelihood map with most probable locations for coastal flooding developed to unambiguously identify the location as well as the timing of most threatening High Water events. | Risk maps (time and space) with expected economical damage in the coastal strip (that contains houses, shops, etc.). | Run-up timeseries (e.g. extracted from beach morphodynamic model, e.g. XBeach results). | Run-up and maximum flooding cross-shore and longshore extension (marine water ingression limit). | Space-time map of areas that are unsafe for swimming, covering at least the most used areas. |
| Benchmark desired state | Reference state: Water levels from the model results should not reach beyond a predefined acceptable level. | Reference state: No (minimum) economical damage. | Reference state: Seaward edge of the beach recreation land-use zone as indicated in spatial planning regulation. | Reference state: Safety is guaranteed as long as the sum of run-up+set-up+surge+tide is below the max berm-beach and dune elevation. | Reference state: Define areas that are "deep", "safe", "unsafe" and "dry". |
| Benchmark current state | Current state: Synoptic results from the model on development of water levels in space and time represent the current state. | Current state: Expected economical damage in a coastal strip from inundation maps and socio economical data. | Current state: The first exceedance of the benchmark level as predicted by XBeach. | Current state: Weather, wave and surge forecasts. Warning advice transmitted to local authorities. | Current state: Velocities from the model results, combined with the latest measured water temperature, represent the current (or predicted) state in space and time. |
| Intervention procedure | According to a comparison between computed water levels and the predetermined acceptable level a map with different colours indicating different flooding probabilities can be constructed based on which dike monitoring personnel could be deployed. | Use available protection measures to put up local barriers (sandbags or other) at inundation bottlenecks locations to minimize economical damage. | When the SII indicates impact on private properties then a warning should be issued to the beach property owners (as soon as possible but at least one day ahead of time). | Protection of natural areas if the predicted overtopping discharges are high enough to generate consistent flooding (x $m^3$/s); build up of temporary protections. | Flagging of hazardous conditions and locations and evacuation/rescue of people in hazard zones by life guards. |
| Evaluation procedure | Operational objective: After a major storm evaluation of the operational objective may point out that significant high water events occurred on other places than it was foreseen.<br><br>Strategic objective: Evaluation of the strategic objective may suggest that a combination of inspectors and video monitoring could be more effective and maybe even more efficient. | Operational objective: With emergency response measures the damage to property is likely to be prevented/minimized in the most economical way.<br>Strategic objective: It remains to be seen however if flooding is the only physical parameter of interest to estimate the economical damage. | Operational objective: Related to the operational objective this procedure will assist entrepreneurs to avoid damage to beach beds in case of run-up.<br>Strategic objective: Related to the strategic objective we notice that other storm related hazards (wind) are not covered. | Operational objective: Natural areas are safe below the critical run-up+set-up+surge+tide value and protected with emergency defences when higher overtopping discharges are expected.<br><br>Strategic objective: Set-back strategies may be considered. | Operational objective: Determine if there are actual offshore currents occurring. If not refine the model. Determine if the people are aware of the flagged areas.<br>Strategic objective: Evaluation of the strategic objective may suggest that a combination of inspectors and video monitoring could be more effective and maybe even more efficient. |

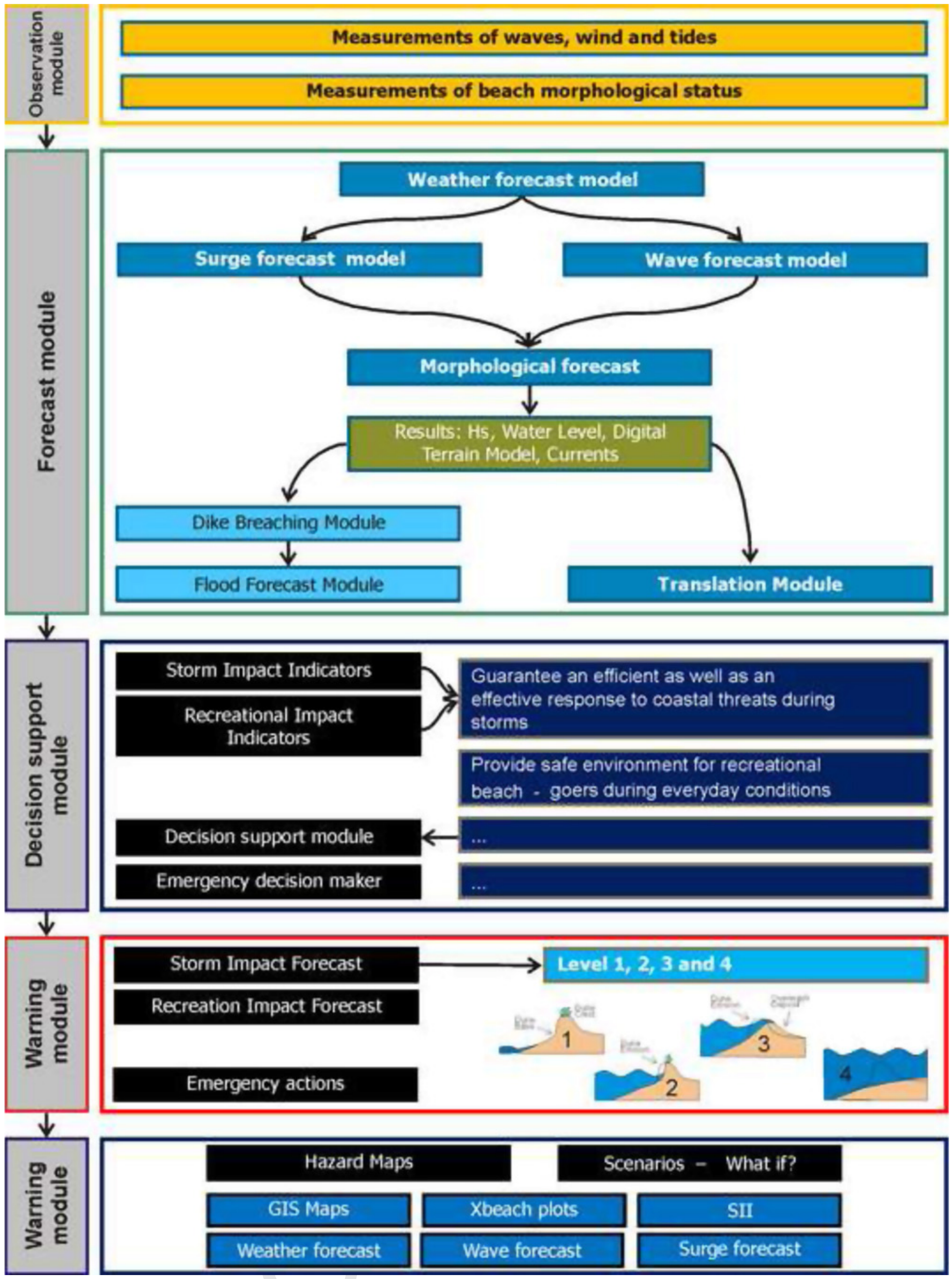


**Fig. 2 – Generic concept of the MICORE Early Warning System prototype. The Storm Impact Level builds on the scale proposed by Sallenger (2000).**

data is automatically transformed into the standard input format for XBeach that calculates the morphologic evolution of the coastal stretch for the given hydrodynamic conditions. The Storm Impact Indicators (SIIs) are derived from the XBeach model results by applying dedicated algorithms. Routines are set-up to automatically determine the most critical locations within a coastal section (Fig. 3A). The SIIs are calculated for each profile, during the entire simulation (Fig. 3B). The test case for the Belgian coastline visualizes (i) the status of all predefined SIIs, (ii) the dry beach width (DBW) of the profiles, merged into a line, (iii) time series of some output parameters of XBeach and (iv) the strategic objectives described in the SIIs.

An important lesson learned in the MICORE project is that once it becomes operational, the EWS should be running all the time with minimal intervention by operators. This is crucial to thoroughly test the systems robustness and ensure its stable operation in the event of an extreme storm. When the EWS predicts the exceedance of a predefined SII related threshold, a warning should be sent automatically to the competent end-user, e.g. the Civil Protection, which would then decide how to act accordingly. Informing the general

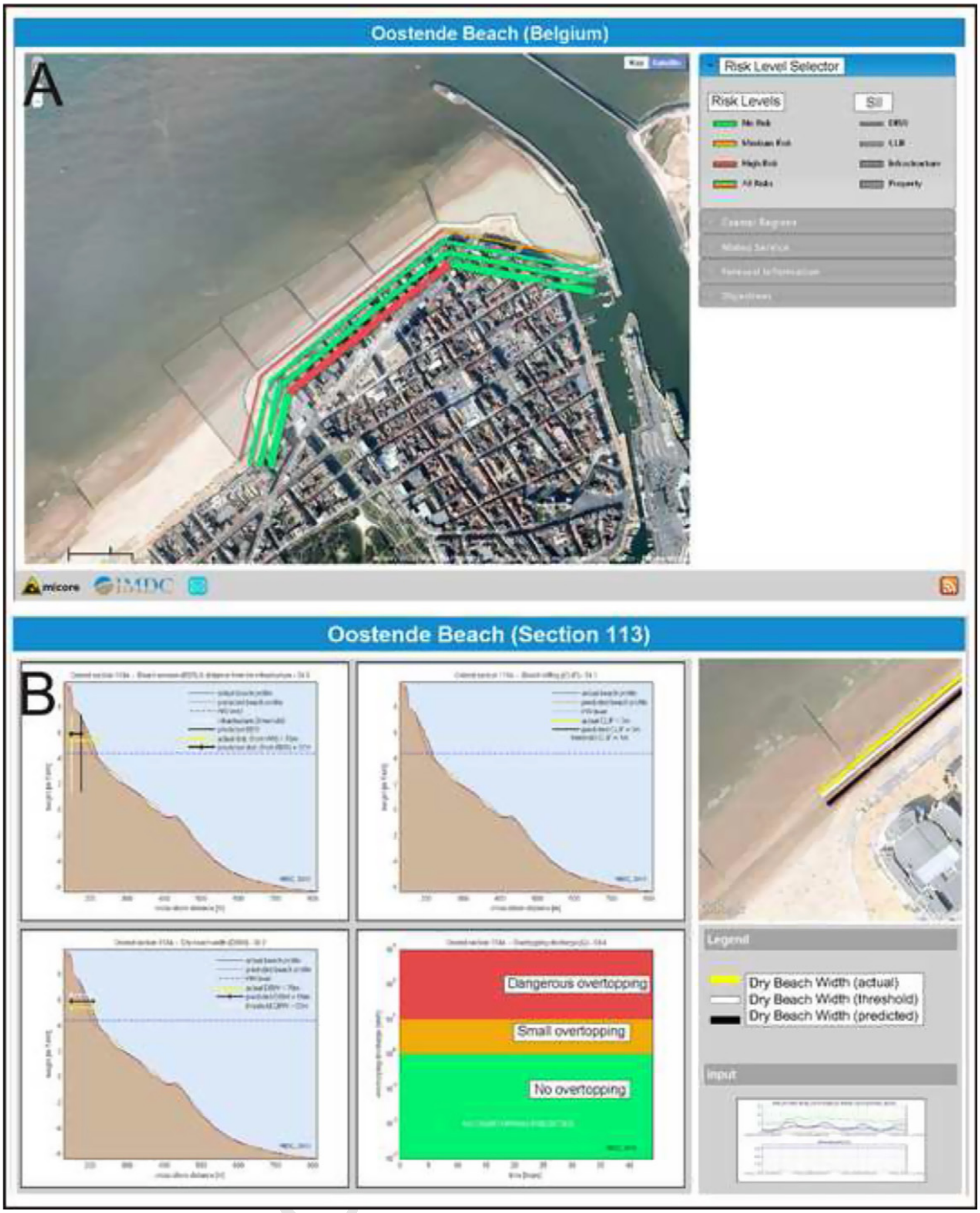


**Fig. 3 – (A) Example of visualization of the Early Warning System in the test case for the Belgian coastline at Oostende Beach; (B) example of details on the Early Warning System visualization on beach profiles. The system is accessible on http://gis.hostoi.com/Micore_Oostende/.**

public could be done by SMS and Internet interfaces but it is important to carefully consider the desired public response. Finally, it could be imagined that the end-users at the bottom scale of the safety chain, e.g. Fire Brigade, dyke inspectors, local police, may use portable GIS systems or even a Smartphone to visualize the areas where erosion and flooding are predicted to occur. One important point that must be always remembered during EWS development is simplicity. Not all users of the EWS may be competent in GIS technology and warning levels must be easy to understand (e.g. clear colour coding).

## 7. Conclusions

Economic limitations mean it is simply not possible to design, fund and build schemes to protect vulnerable coastal areas

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from all anticipated events. Indeed, scenarios of climate change impacts from present models are diverse and cannot at present be relied on to give accurate forecast of future extreme event around coastal Europe. Therefore, there is an urgent need to develop new coastal management systems to deal with as yet unforeseen extreme events that fall outside the design limits of existing and future coastal structures. MICORE addressed this by revisiting historical extreme storm events and evaluated closely their impact on the human occupation of the coastal zone. It was found that an obstacle to database building is the freedom of access to meteorological and marine (waves, tide level) datasets.

It is recommended that a policy of free access is implemented at national and supranational level. It is also recommended that the database on storm impacts should be extended at EU level. The database initially set-up by MICORE should be maintained and continue to use an open-source approach like the OpenEarth one.

MICORE has addressed the problem of predicting morphological storm impacts and provided innovation through the development of a storm Early Warning System based on real-time data acquisition and assimilation into a range of state-of-the-art hydrodynamic and morphological models. This will initially only be available for the case study sites, but will be further exportable to the whole National coastline whether national governments may decide to adopt it. The Early Warning System developed within MICORE is providing the answers to the feedback loop of morphological changes that a beach undergoes during storm events. The outcome of the EWS should be coupled to other models to forecast flood and dyke breaching.

An important point to support the robustness of the Early Warning System is validation, which implies a certain continuity of morphological monitoring programme. It is recommended that EU member states start a national programme of coastal monitoring after high energy events using accurate and rapidly deployable methods like plane based Lidar. Additionally, for specific sites other more localized approaches must be sought (e.g. videomonitoring or X-band radar). Data access to this information must be at no cost for research purposes as this would underpin numerical model calibration.

One of the main reasons to start the MICORE project was to enhance the emergency response effectiveness of Civil Protection authorities in the case of a severe coastal storm; an objective that was thought to become even more relevant in the light of predicted climate change (including sea level rise). With the development of state-of-the-art real-time prediction systems, which would quantify storm impact including the process of erosion, an important new source of information would be available. It is recommended that national and regional government stimulate the setting up of these warning systems as well as support ancillary research development of the codes to make them more stable and reliable.

The MICORE project provided demonstration Early Warning System for rapid visualization of storm impacts. How and if this information will/should be used in actual crisis situations was outside the MICORE scope. It is however recommended that at the level of Civil Protection in member states marine storm risk becomes one of the considered hazards with appropriate safety and response plans. Post-event surveys of economical damages should be undertaken to justify future investment in adaptation strategies.

## Uncited reference

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Ferreira et al. (2009a).

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