Storm-induced risk assessment: evaluation of two tools at the regional and hotspot scale

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Abstract

Coastal zones are under increasing risk as coastal hazards increase due to climate change and the consequences of these also increase due to on-going economic development. To effectively deal with this increased risk requires the development of validated tools to identify coastal areas of higher risk and to evaluate the effectiveness of disaster risk reduction (DRR) measures. This paper analyses the performance in the application of two tools which have been developed in the RISC-KIT project: the regional Coastal Risk Assessment Framework (CRAF) and a hotspot early warning system coupled with a decision support system (EWS/DSS). The paper discusses the main achievements of the tools as well as improvements needed to support their further use by the coastal community. The CRAF, a tool to identify and rank hotspots of coastal risk at the regional scale, provides useful results for coastal managers and stakeholders. A change over time of the hotspots location and ranking can be analysed as a function of changes on coastal occupation or climate change. This tool is highly dependent on the quality of available information and a major constraint to its application is the relatively poor availability and accessibility of high-quality data, particularly in respect to social-economic indicators, and to lesser extent the physical environment. The EWS/DSS can be used as a warning system to predict potential impacts or to test the effectiveness of risk reduction measures at a given hotspot. This tool provides high resolution results, but needs validation against impact data, which are still scarce. The EWS/DSS tool can be improved by enhancing the vulnerability relationships and detailing the receptors in each area (increasing the detail, but also model simulations). The developed EWS/DSS can be adapted and extended to include a greater range of conditions (including climate change), receptors, hazards and impacts, enhancing disaster preparedness for effective risk reduction for further events or morphological conditions. Despite these concerns, the tools assessed in this paper proved to be valuable instruments for coastal management and risk reduction that can be adopted in a wide range of coastal areas.

Keywords: Coastal risk; Risk assessment tools; Storm impacts.

1. Introduction

Storms impacting coastal areas are responsible for severe hazards (e.g., overwash, inundation, erosion) that can lead to the destruction of goods and loss of life in occupied areas. Recent examples of the above include the severe coastal erosion caused by Storm Hercules on the coasts of France and England (Castelle et al., 2015; Masselink et al., 2016a,b) and the associated destruction of assets; the inundation and loss of life in association with Storm Xynthia in France (e.g., Garnier and Surville, 2011; Bertin et al., 2012; Vinet et al., 2012); the vast destruction due to Superstorm Sandy in the Caribbean and USA (Bennington and Farmer, 2015; Clay et al., 2016), to Hurricane Katrina in the USA (Link, 2010; Kantha, 2013), and to Typhoon Haiyan in the Philippines. Those events highlight how coastal hazards pose a significant risk worldwide and can impact large cities or regions. Potential damages and risks are expected to increase in the near future not only in association with climate change and sea level rise, but also due to the increasing human occupation and economic development in coastal areas (IPCC, 2014; Neumann et al., 2015). The development of methods for detailed assessment of the risk in coastal regions and the evaluation of the effectiveness of disaster risk reduction (DRR) measures is, therefore, required. The development of such tools is important to prevent, or mitigate disasters; promote early warnings to stakeholders; and decide the best management options with the limited resources available to coastal managers. This topic has been of particular concern at the European level and funding has been awarded to projects devoted to mitigating risks at coastal areas, such as the RISC-KIT project (Resilience Increasing Strategies for Coasts – Toolkit; www.RISCKIT.eu).

The main goal of the RISC-KIT project was to provide such tools to the coastal community (scientists, technicians, managers), at different levels (for details see Van Dongeren et al., this issue). These tools include a Storm Impact Database (Ciavola, 2017; this issue) which stores information on storm event impacts; a web-based management guide which documents the available DRR measures (Stelljes et al., this issue); and a multi-criteria assessment to help choosing the best management solutions using a participatory approach (Barquet and Cumiskey, this issue). Among the developed tools two are devoted to identify the areas of highest storm-induced risk and to evaluate the effectiveness of DRR measures:

A) The CRAF (Coastal Risk Assessment Framework; see Viavattene et al, this issue) with two goals: i) hotspot identification at the regional scale (order of ~100 km); and ii) risk evaluation and ranking within selected hotspots. In this paper hotspots (HS) are defined as locations where risk due to extreme hydro-meteo events (e.g., storms) is highest along the coast and high-resolution modelling is recommended to further assess the coastal risk.

B) An early warning system coupled with a decision support system (EWS/DSS) with two main uses: i) as an Early Warning System just prior to a storm event; and ii) as an assessment tool to evaluate potential hazards and the effectiveness of DRR measures well before an event.

The main goal of this paper is to critically review the performance and experience in application of these two tools; to provide insights on how they should be applied; and to discuss their potential, limitations and need for further improvements, based on their application in ten case studies covering the European regional seas. After a summary of the case studies and of the risk assessment tools, the paper presents an evaluation of the tools and ends with a summary of the main application potential and restrictions to their use. For specific details on the application of the tools in each case study, we refer the reader to the set of case study papers in this special issue (see Van Dongeren et al., this issue).

2. Case Studies

The RISC-KIT case studies (Figure 1) include sites on every European regional sea, with diverse characteristics in terms of geomorphic setting, land use, forcing and hazard type, as well as distinct socio-economic, cultural and environmental aspects. The sites considered are located on: the Atlantic Ocean (La Faute-sur-Mer – France and Ria Formosa – Portugal); the Mediterranean Sea (Tordera Delta – Spain, Bocca di Magra and Porto Garibaldi-Bellochio – Italy); the Black Sea (Varna – Bulgaria); the Baltic Sea (Kristianstad – Sweden and Kiel Fjord – Germany); and the North Sea (North Norfolk – United Kingdom and Zeebrugge – Belgium).

Figure 1. RISC-KIT case study sites location (from Van Dongeren et al., this issue).

The diversity of the sites can be summarized as follows:

a) *Hydro-meteo forcing*, as relatively low wave energy in small or enclosed seas (Mediterranean, Adriatic, Baltic and Black Sea) when compared to more exposed coasts (Atlantic and North Sea), different tidal ranges (from macro- to microtidal), influence/absence of fluvial/estuarine interaction, and high (e.g., Adriatic and North Sea coasts) to low (e.g., Black Sea and South Atlantic coast) influence of storm surges.

b) *Geomorphic (and protection) settings*, including the barrier islands of Ria Formosa, the salt marshes of North Norfolk, the estuarine interaction in La Faute-sur-Mer, the fjord at Kiel, the delta plain at Tordera, the highly protected coast of Zeebrugge, the open and urbanized beaches of Porto Garibaldi-Bellochio and Varna, the narrow and relatively sheltered beaches of Kristianstad and the embayed beaches of Bocca di Magra.

c) *Hazard type*, such as coastal erosion, coastal inundation by surges or waves, overwash and breaching.

d) *Land use*, as the deep-sea port of Zeebrugge, the port and town in Varna and Kristianstad, the campsites in Tordera Delta, the large touristic occupation at Porto Garibaldi-Bellochio and at Bocca di Magra, the natural park of Ria Formosa, the small low-lying villages of La Faute-sur-Mer and North Norfolk and the marina in Kiel Fjord.

e) *Socio-economic, cultural and environmental aspects*, as the port of Zeebrugge (crucial for facilitating trade and bringing significant economic benefits for the entire Belgium), the North Norfolk Coast Special Area of Conservation (a Special Protection Area under the Ramsar Convention), the touristic areas of Porto Garibaldi-Bellochio, Varna, Tordera and Bocca di Magra (highly relevant for the regional economy), the relatively local character of the Wendtorf (Kiel Fjord) marina and Praia de Faro occupation (local fisherman and residents), the national relevance of a well-known liquor factory and Port of Ahus exposed at Kristianstad and the unquestionable disruptive effect at La Faute-sur-Mer as proved by Xynthia storm in 2010, which caused several fatalities.

The diversity of coastal types (and behaviours) expressed above makes the use of uniform tools challenging. Only tools designed to be of broad use and with a high degree of applicability are able to assess the risk in such a variety of environments. The RISC-KIT tools have been designed in this way, with the realization that different strategies would be required for some coastal areas.

3. RISC-KIT assessment tools

The Coastal Risk Assessment Framework (CRAF) is the first element of the RISC-KIT risk assessment suite and is applied at a regional scale of about 100 km of coastal length. CRAF is a systematic method to undertake risk assessment using simplified approaches based on simple models and on a screening process to identify and rank hotspots, which may be a useful and accessible instrument for most coastal managers. The CRAF provides two levels of analysis (2 phases).

Phase 1 (CRAF 1) is a coastal-index (CI) approach to identify potential hotspots (Figure 2, upper panel). The coastal index is calculated for a uniform hazard pathway per sector of about one kilometre along the coast (eq. 1 and 2).

$$CI = (i_h * i_{exp})^{1/2} \qquad (1)$$

$$i_{exp} = (i_{exp\text{-}LU} * i_{exp\text{-}POP} * i_{exp\text{-}TS} * i_{exp\text{-}UT} * i_{exp\text{-}BS})^{1/5} \qquad (2)$$

The hazard indicator (i_h) is ranked from 0 to 5 (none, very low, low, medium, high, and very high) with the null value referring to the absence of hazard. The exposure indicator (i_{exp}) embraces 5 types of exposure representative of the potential direct and indirect impacts: Land Use ($i_{exp\text{-}LU}$), Population ($i_{exp\text{-}POP}$), Transport ($i_{exp\text{-}TS}$), Critical Infrastructure ($i_{exp\text{-}UT}$), and Business ($i_{exp\text{-}BS}$). Each is ranked from 1 to 5 (non-existent or very low, low, medium, high, and very high). The overall exposure indicator (iexp) is ranked similarly from 1 to 5. The coastal index is calculated separately for every hazard and return period of interest.

Phase 2 (CRAF 2) utilises a suite of more complex modelling techniques to rank the identified hotspots (Figure 2, lower panel) to select the most-at-risk hotspot. Details on the CRAF methodologies are given in Viavattene et al. (this issue), while this paper provides an evaluation of lessons learned with the application of the tool.

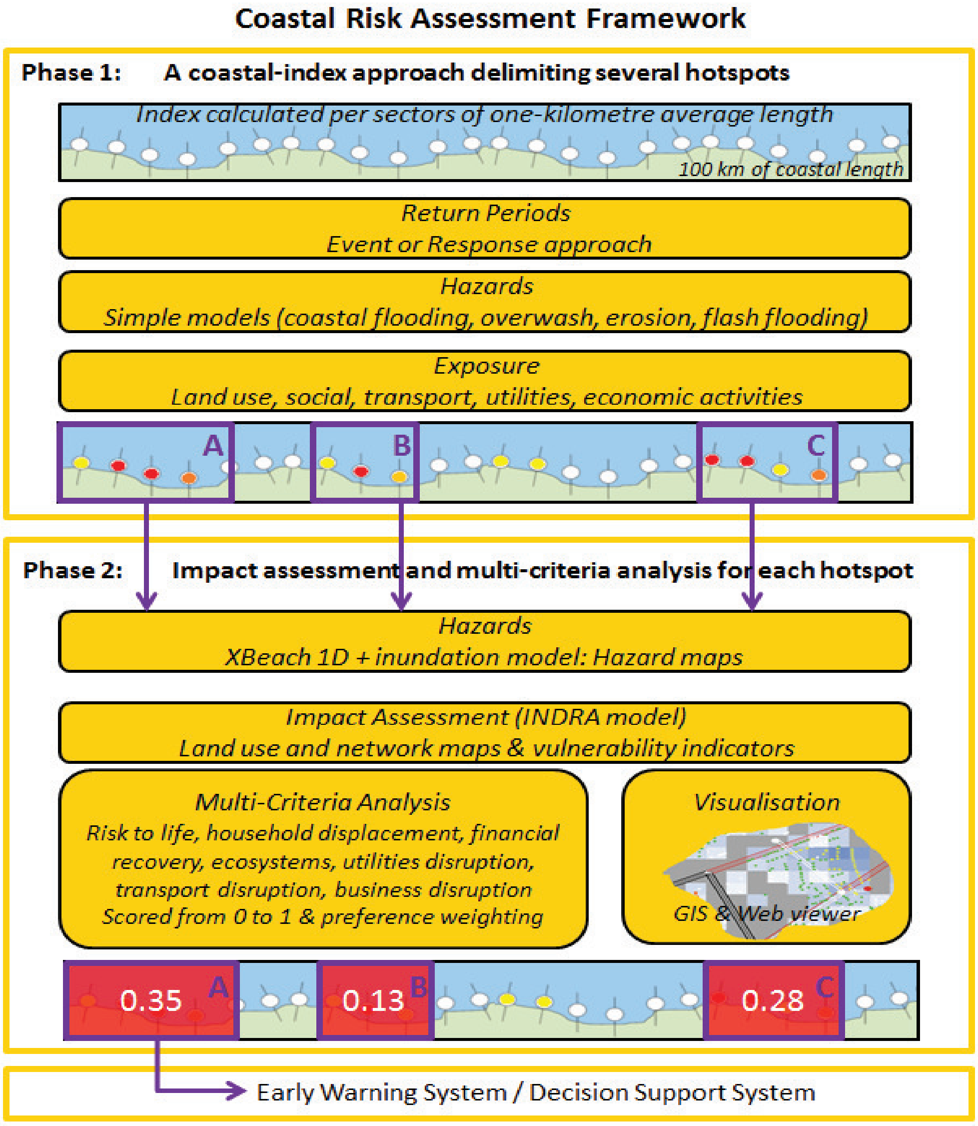

Figure 2. CRAF overview and required steps, as a vertical top-down sequence of analysis, resulting in hotspot identification (A, B and C in the upper panel) and ranking (A > C > B, in the lower panel).

The Early Warning System and Decision Support System (EWS/DSS) makes use of complex-modelling techniques (2DH – two-dimensional horizontal process-based, multi-hazard morphodynamic model, Bayesian Network (BN) analysis) and the demand in terms of data, time and resources is subsequently greater than that for the CRAF. The EWS/DSS (Bogaard et al., 2016; Jäger et al., this issue) is built using the Delft-FEWS software environment (Werner et al., 2013; De Kleermaeker et al., 2015). The philosophy of the system is to provide an open shell for managing data handling and forecasting processes. This system can be organized using the following structure (see Figure 3): data import from external sources (i.e., NOAA GFS, local meteorology, measurement stations); data processing; model runs (WaveWatchIII, Delft3D, Telemac, XBeach); data post-processing; and export to external processes (BN and web viewer). The Bayesian Network is in essence a probabilistic graphical model, which consists of random variables (e.g., wave characteristics, water level, hazard intensity, exposed elements) and conditional dependencies (obtained from modelling approaches or observations) between those variables (Poelhekke et al., 2016). The Bayesian-based Decision Support System integrates hazards and socio -economic, cultural and environmental consequences. These systems can be built as stand-alone applications, run manually by a user, or they can be transformed into fully automated systems.

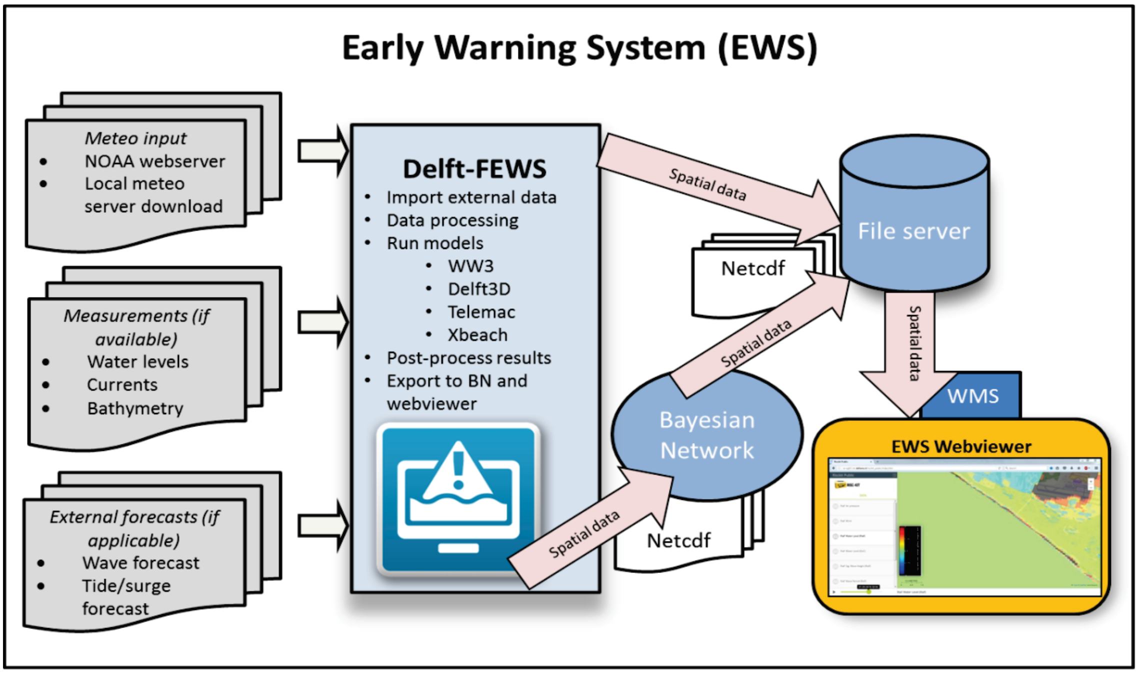

Figure 3. Schematic of the Delft-FEWS concept applied to the RISC-KIT EWS framework. The demanding computational part is performed within the Delft-FEWS system. A visualisation interface is then required (e.g., FEWS controller, or web viewer). WMS – Web Map Service.

In addition to providing forecasts of storm impacts, the EWS/DSS tool can be used to assess the effectiveness of potential DRR measures. In the RISC-KIT project these were chosen by expert judgment in consultation with end-users and stakeholders, and by using information from existing management plans. The impact of predicted future climates scenarios (e.g., sea level rise and extreme storm surge levels), based on available projections at the regional scale under the Representative Concentration Pathway 8.5 or other adequate estimate, were incorporated in the performed tests and afterwards in the EWS/DSS systems to assist in the assessment of the future effectiveness of DRR measures.

4. Coastal Risk assessment Framework (CRAF)

4.1 CRAF 1

CRAF 1 is a coastal-index approach to identify potential hotspots (Figure 2, upper panel) subject to hazards such as: Flooding/Inundation (see as examples Armaroli and Duo, this issue; Christie et al., this issue; Jiménez et al., this issue), Erosion (see as examples Armaroli and Duo, this issue; De Angeli et al., this issue; Jiménez et al., this issue), Overwash (see as examples Ferreira et al., 2016; Valchev et al., 2016) and Breaching (see Plomaritis et al., this issue(b)).

4.1.1 Hazard assessment

Event *versus* Response approach

Because storm-induced coastal hazards usually depend on more than one variable (e.g., water level, wave height or storm duration), which are not necessarily correlated, we recommend to adopt the response approach (Divory and McDougal, 2006; Bosom and Jiménez, 2011; Garrity et al., 2012) to assess those hazards. The response approach uses the forcing (wave and water level) time series to derive a time record of the onshore hazard parameter (e.g., wave run-up, total water level, overtopping, eroded volume), which is then fitted to an extreme value probability distribution. This allows the hazard magnitude associated with a given probability of occurrence to be obtained without assuming relationships between driving variables, thereby reducing uncertainty in the analysis. The application of such an approach requires access to the forcing data (wave characteristics and water levels) and to have long-term data sets of those variables to perform a reliable analysis of extremes. If such datasets do not exist or are not available, the event approach can be used. In this case, the probability of occurrence of the event can be computed by using: i) a single variable (e.g., wave height); ii) a joint probability of variables; or, as often is used iii) empirical relationships between different variables (e.g., period and/or storm duration versus wave height). The obtained value(s) are then used to compute the hazard magnitude for a given return period, assuming that the hazard probability of occurrence is equal to the hazard probability of the event. However, due to the multiple inter-dependences, it is likely that more than one event can produce the same hazard magnitude and, thus, this approach constitutes a simplification that may lead to underestimation (e.g., if only the annual maximum event is considered for the return period definition) or overestimation (e.g., if the interdependencies between variables are not accounted for in the statistical analysis).

Suggested formulations/methods

One of the advantages of the method developed in the CRAF is that, at the regional level, the assessment can be done by using simple formulations/equations (e.g., run-up formulations, simple storm driven erosion models) and approaches (e.g., bathtub, overwash extent and depth, flood depth) which are easy to implement (Table 1). Moreover, the CRAF 1 is flexible enough and can be adapted to incorporate different assessments and methods that are already in use at some locations (cf., Armaroli and Duo, this issue; De Angeli et al., this issue). In cases where the local characteristics do not allow a proper definition of the hazard magnitude by using simple approaches, the proposed methods need to be adapted prior to their application (e.g., Ferreira et al., 2016; Christie et al., this issue). One example is the analysis of flooding in extensive low-lying areas (e.g., Belgian Coast; Ferreira et al., 2016), where the bathtub approach would substantially overpredict the flood prone area. In such cases, a simple flood model should be used instead, or some low hinterland areas must be excluded prior to the flood analysis. In areas with large alongshore tidal range variations, or with extensive saltmarshes (e.g., North Norfolk; Christie et al., this issue) adaptations to the proposed methodology (e.g., alongshore variation of sea levels and hazard reduction by salt marshes) should also be implemented. Overall, the methodology is efficient to properly assess storm-induced hazards at the regional scale for most sedimentary coasts. Moreover, it is flexible enough to be adapted (and modifiable), when local coastal characteristics make the application of simple tools an impractical exercise.

Table 1: Proposed methods for assessing hazard intensities and extent.

Hazard	**Methods**	**Outputs**
Overwash	Holman (1986), Stockdon et al. (2006)[(a)]	Run-up level
Overwash extent	Simplified Donnelly (2008), XBeach 1D (Roelvink et al., 2009)	Water depth, velocity and/or extent
Overtopping	Hedges and Reis (1998), EurOtop (Pullen et al., 2007)	Run-up level and/or discharge
Inundation	Bathtub approach, fast 2D flood solver (e.g., LISFLOOD-FP; Bates and De Roo, 2000)	Flood depth, velocity
Storm Erosion	Kriebel and Dean (1993), Mendoza and Jiménez (2006), XBeach 1D (Roelvink et al., 2009)	Eroded volume, shoreline retreat and/or depth

[(a)] For the wave run-up calculation

Hazard extent

The definition of the hazard extent, the inland area influenced by the hazard per sector for a given return period, is the basis of the impact assessment. The exposure indicators are applied to a given hazard extent and, depending on the elements exposed to the hazard within that extent, the final coastal-index value can be different. The following hazard extents can be considered:

i) Flooding/Inundation (sometimes including overwash)

It is recommended to use a method in CRAF 1 that derives a flood-prone area based on physical principles. A simple method to define the extent is the bathtub, or a tilted bathtub, approach applied to the total water level or to the overwash level. A simple 2D model can also be used to define the hazard extent (cf. Ferreira et al., 2016). Alternative methods include an arbitrary extent of X m (buffer zone), based on local evidences, or the surface area of the municipality to be flooded.

ii) Erosion

The recommended hazard extent to be used is a buffer zone with a given distance from the shoreline/dune line, derived from the maximum computed shoreline retreat. In some cases this buffer zone can be replaced by a representative extent based on expert judgment and historical analysis (variable from place to place).

iii) Overwash

Where possible, it is recommended to use the overwash extent developed by Plomaritis et al (this issue(b)), an adaptation of Donnelly's formulation (Donnelly, 2008; Donnelly et al., 2009). In the absence of sufficient data for this method, the spit width or an arbitrary inland extent (based on expert judgment) can be used.

iv) Breaching

The methodology developed by Plomaritis et al (this issue(b)) is recommended for use to assess breaching and the associated extent (related to the flood delta width).

Hazard Indicators

Application of the CRAF during the RISC-KIT project has shown that various indicators exist for similar hazards, that the appropriateness of indicators depends on the specificities of the coastal region, and that it is not simple to find universal indicators that can be easily applied at coastal areas with different morphologies. A synthesis of suggested indicators per hazard is provided below.

Flooding/Inundation

Indicators to assess this hazard include: Flood depth; Percentage of overtopping flooded area; Total water level; Overtopping discharge; and Flood extension. Some just represent the hazard process (overtopping discharge or total water level) while others relate the hazard to the affected area (flood depth, percentage of flooded area, flood extent). The use of an impact-related indicator is recommended since it integrates the hazard and the coastal morphology while one that only incorporates changes on the hazard may not be useful along coasts with high morphological variability. Simple indicators like flood depth are, therefore, recommended.

Overwash

Overwash depth (Od) (see Donnelly et al., 2009) and Overwash potential (Op) (see Matias et al., 2012) are conceptually similar indicators that express a vertical difference between the overwash level over the dune crest (Od) or the maximum potential run-up level (Op) against the dune/barrier crest. Op is used for its simplicity of computation while Od is more accurate in terms of the actual process. Both indicators are recommended for further use.

Erosion

Erosion assessment was related with episodic storm driven erosion and not structural erosion. Commonly used indicators include: Shoreline retreat; Dune retreat; Berm retreat; and Remaining beach width. These indicators can be reduced to two (shoreline/berm retreat and dune retreat). The use of dune retreat *versus* berm retreat depends on the exposure to be assessed. For coastal sites with infrastructures located on the beach berm (e.g., bars, amenities), the berm or the shoreline retreat should be used. This can then be transformed (or not) into a remaining beach width or a distance to occupation. For coastal areas where infrastructure is located on the dune or in the hinterland, the dune retreat should be used. This can also be transformed into a remaining distance to occupation.

Breaching

Available breaching information is largely qualitative (Kraus, 2003) and there are only few methods devoted to determine or rank breaching vulnerability. Kraus et al. (2002) proposed a breaching susceptibility index based on the ratio between the 10 year surge return period and the tidal range, but this method does not include any morphological characteristics. Basco and Shin (1999) proposed the use of a series of numerical models to separately evaluate overwash and erosion processes. Plomaritis et al. (this issue(b)) developed a new indicator (Breaching Potential) which integrates parameters such as overwash, structural erosion, storm erosion, subaerial barrier volume, back barrier depth and morphology, and washover width to barrier width ratio. This parameter is recommended for further use.

4.1.2 Exposure Assessment

The hazard indicators described above are combined with exposure indicators to obtain a final coastal index to identify potential hotspots.

Land Use

For this indicator CORINE Land Cover (CLC; http://www.eea.europa.eu/publications/COR0-landcover) data can be used as the source to characterise land use data. CLC can, however, be replaced if a better and more detailed cartography is available, allowing a more detailed evaluation of the land use indicator per sector. CLC is also not very useful for some hazards, namely overwash and erosion, since the extent is too narrow (tens of metres) to be captured by the CLC resolution. Overall, it is recommended to use the most detailed land use cartography provided by national, regional or local authorities, or to produce one when not available. That is particularly relevant for small hazard extents bordering the coastline (e.g., erosion or overwash). Stakeholder involvement is recommended for valuing land use. Alternatively existing valuations or user judgment can also be applied.

Population and social vulnerability

An SVI (Social Vulnerability Indicator) is applied to characterise the potential non-tangible impacts to the population. Two main options are recommended: The first uses an existing SVI for the region. The second one consists on developing a specific SVI for the area following the CRAF 1 methodology guidance (see Viavattene et al., this issue) using census data. The “age of the population” characteristic and the financial deprivation are fundamental parameters to calculate the SVI for most regions. A third main important characteristic is education. Health can also be included when relevant. In general, it is relatively simple to build a specific SVI when needed, allowing the method to be applicable to a broad range of conditions.

Transport systems

National or local transport maps should be used to define the transport network, in absence of which OpenStreetMap data can also be used as a source of information. The valuation (see

Viavattene et al., this issue) is straightforward since it is based on the classification system of the roads obtained from the map, matching the descriptive scale proposed in the CRAF methodology (from local to national and highway roads). Information on other transports (trains, ports, and airports) or relevant local knowledge on the importance of local roads can also be used in the valuation. In most coastal areas moderate values are expected to dominate the assessment except for the widely urbanised coasts (cf. Ferreira et al., 2016; Jiménez et al., this issue).

Utilities

The CRAF assessment method is simple and uses a ranking table for utilities. The approach is limited by the availability of information on the location of receptors, and the valuation is therefore often based on expert judgment. In most coastal areas, very low to moderate values are expected to dominate the assessment except for widely urbanised coasts.

Business Settings

The business settings indicator consists of a simple table with criteria to distinguish between different types of businesses and how to rank them. The table can be adapted in order to better relate to the specific business type/setting of each considered coastal area. In highly touristic areas (e.g., the Emilia-Romagna coast discussed in Armaroli and Duo, this issue; and the Catalan coast in Jiménez et al., this issue) the indicator can be adapted to a tourist-based index (as a proxy for existing facilities). Even when case-specific adjustments are required, the method is simple to implement. The involvement of stakeholders is essential to validate the valuation.

4.1.3 Coastal Index (CI)

The CI is a measure for the combined hazard and exposure in a given sector (see Ferreira et al., 2016 and Viavattene et al., this issue), and is used to identify potential HS. An example of the final application of a CI along a coastal zone using sectors of about 1 km is presented in Figure 4.

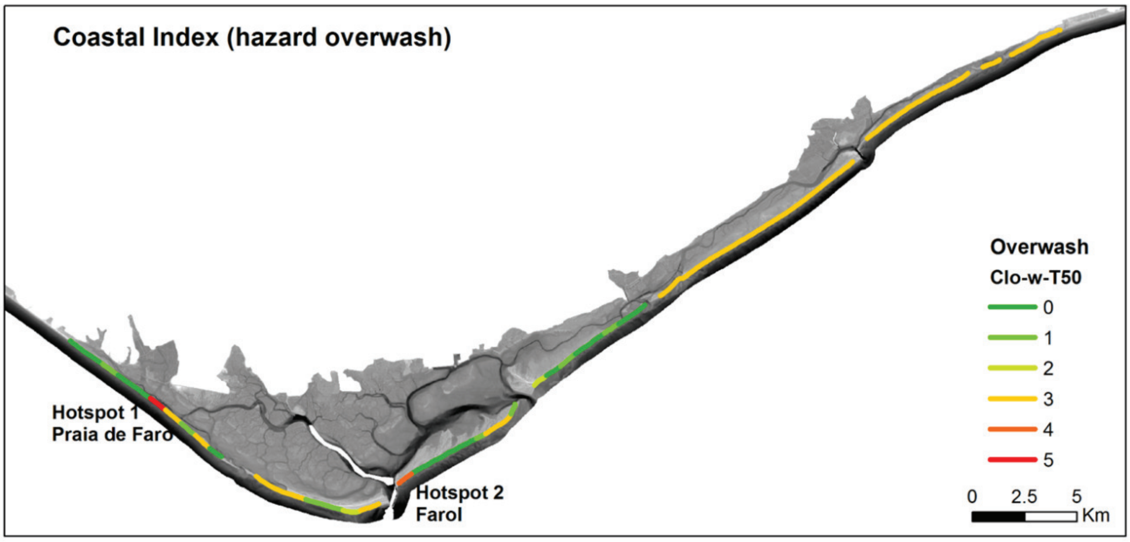

Figure 4. CI applied to the Ria Formosa (Southern Portugal) for overwash and a return period of 50 years, with the identification of 2 main hotspots.

Return period

When defining the storm-induced hotspot, a relevant issue is the definition of its “severity”. This is done through the selection of a return period for the analysis. More than one return period can be (and should be) computed for the same coastal area. This allows an evaluation of possible HS changes according to the return period used within each coastal area. The chosen return periods will vary from site to site, depending on the return periods already in use for coastal management, and their selection should be agreed with local stakeholders. While in some countries (e.g., Portugal) return periods of 100 years are not yet (or rarely) considered, on highly protected coasts (e.g., Belgium) return periods greater than 1000 years are increasingly common in coastal management and safety plans. The selection of return periods in the CRAF 1 should be discussed with stakeholders and reflect their needs or recommendations. The relatively limited number of years (few decades) of available measured or hindcast data reduces the ability to produce results with a high degree of accuracy for large return periods (hundreds to thousands of years), which is still a drawback of the CRAF methodology, as for any other. On the other hand, this method permits results with a high degree of confidence for lower return periods (<100 years), which are most commonly used by the majority of coastal managers and end-users.

Potential Hotspot identification

The number of potential HS determined in CRAF 1 depends not only on the models and scoring applied in the analysis, but also on the chosen return periods, since both the hazard and the exposure will change with the return period. Using a very small return period (e.g., in the order of one to a few years) will probably lead to a small number of HS (due to no or very restricted hazard), while using a very large return period (>1000 years) can lead (mainly at unprotected coasts) to numerous HS, with a difficulty in selecting or ranking among them. This reinforces the need to analyse several return periods for each coastal area in order to better choose the most relevant one, in consultation with the relevant stakeholder (e.g., coastal manager). To reduce the possibility of having false negatives, it is advised to consider a worst case geometry (i.e., a profile with a lower dune/elevation) as a representative coastal profile rather than an alongshore-average profile. In some cases, coastal sectors may require a higher resolution (< 1 km), since they may include (within the 1 km) different morphologies (e.g., relevant differences in dune height or berm width). Changes in coastal morphology, occupation and management will lead to relevant shifts in risk over time requiring a reapplication of the method.

Hotspot validation

A validation of the obtained CI should be performed after CRAF 1 application (as an example of application see Armaroli and Duo, this issue; Figure 5). The sources to be used for validation include historical information on damages, comparison of results against existing evaluation methods, field measurements of storm damages and hazards, and stakeholder information. The use of historical records as a source of validation must be performed with care since past events/consequences may not be representative of present day conditions. For instance, the improvement of coastal protection works taking into consideration longer return periods and tighter safety conditions (e.g., the Belgian coast) disable the use of historical analysis for current conditions. The same applies when relevant land use changes (e.g., house removal, restoration of saltmarshes) have been implemented. Potential deviations between observations and CRAF 1 results can be associated to the following factors:

i) The available data and the analysis do not consider recent coastal management protection in place and therefore the HS highlighted do not completely represent current conditions;

ii) A limitation of the CRAF 1 methodology in not capturing the bi-dimensional hazard pathways (e.g., hydraulic interconnectivity);

iii) CRAF 1 simplification of complex coastal morphologies by just using one profile per sector (average or worst case), which does not completely represent the behaviour of the sector.

CRAF 1 permits the identification of HS existing at a high variety of coastal zones with different morphologies and degrees/types of occupation (cf. Armaroli and Duo, this issue; Christie et al., this issue; De Angeli et al., this issue; Ferreira et al., 2016; Jiménez et al., this issue; Plomaritis et al., this issue(b); Valchev et al., 2016). The CI for a given region can be recalculated by incorporating new data or regional DRR actions, defining in what way (and by what amount) the HS will be affected. This allows the assessment of the evolution of the HS as a function of coastal evolution, but also of coastal management interventions. CRAF 1 has inherent limitations since it uses simple approaches, formulations, databases, and indicators to assess complex coastal problems for a high diversity of coastal types, including areas with important morphological complexity. Therefore, for some cases (e.g., extensive interconnected low-lying areas or complex alongshore morphologies) the method is too simple and the formulations may not apply. The assumptions used in the CRAF 1 methodology can then result in over- or underestimation of the coastal risk. In such case it is recommended to increase the number of hotspots to be analysed in Phase 2, where more complex and robust models are used.

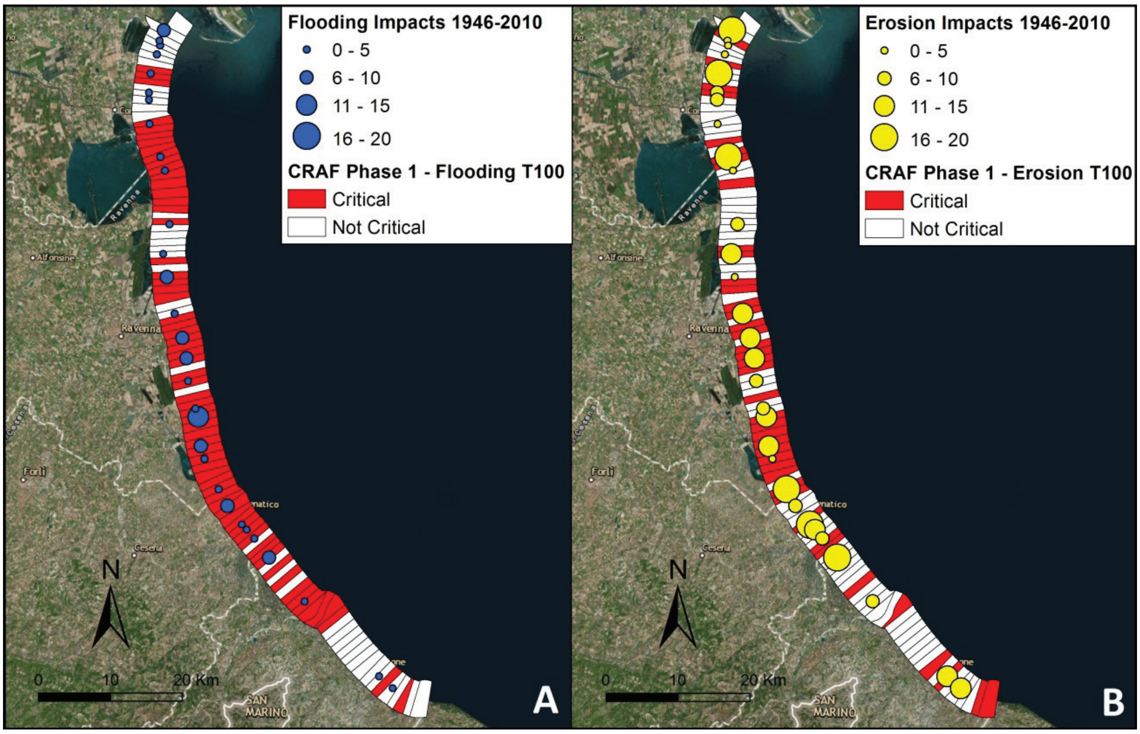

Figure 5. Example of validation of the critical sectors at Emilia-Romagna (from Armaroli and Duo, this issue) against historical data for flooding (left panel, A) and erosion (right panel, B).

4.2 CRAF 2

Once potential HS are identified with CRAF 1, the next step (CRAF 2) consists of an in-depth analysis to discriminate the potential HS in terms of potential impacts by using advanced modelling. This section discusses the applicability of CRAF 2, including results achieved, difficulties identified, and adaptations made, as well as constraints to its application and usage. It also presents recommendations for the application and improvement of the tool. The analysis is split in three sub-sections regarding Hazard and Impact assessments, and hotspot ranking.

4.2.1 Hazard assessment

As for CRAF 1, we recommend the use of the response approach in CRAF 2 to compute return periods of local hazards (flooding and erosion). The recommended models to determine the hazard associated with episodic erosion and/or flooding are the open-source process-based nearshore storm impact model XBeach (Roelvink et al, 2009; for erosion) or XBeach coupled with the overland flood model LISFLOOD-FP (Bates and De Roo, 2000; for marine flooding), with XBeach providing the discharges at the top of the dune/breakwater and LISFLOOD-FP distributing the amount of water along a given area (Viavattene et al., this issue). In both cases XBeach is run in simplified 1D cross-shore profile mode to reduce computational requirements and allow for large sections of the coast to be analysed. Note that other models and approaches can be used, and these can be tailored to the specific geomorphological and hydrodynamic setting. The methodology to assess the hazard discussed in this paper (1D XBeach coupled with LISFLOOD-FP) is relatively easy to apply on a vast number of diverse coastal areas, and has the benefit of relying on models with an extensive user and validation base, providing some confidence in their application in cases with limited validation data. The spatial distribution of the hazard is simulated by using topographic grids, normally of high resolution. Grids on the order of 1x1 m to 10x10 m seem to be able to fully represent the properties of the hazard. Some of the modelling limitations include the lack of high-quality quantitative validation for both XBeach and LISFLOOD-FP models due to lack of data, particularly relating to water discharge, water velocities and inundation extent.

4.2.2 Impact assessment

The INDRA (Integrated Disruption Assessment Model; see Viavattene et al., 2017; this issue) is capable of assessing eight receptor-related impact indicators: household displacement, household financial recovery, regional business disruption, business financial recovery, ecosystem recovery, risk to life, regional utilities service disruption and regional transport service disruption. This section reviews the potential for INDRA application and proposes recommendations for future use.

Data quality

The potential problem of lack of data was foreseen and the CRAF 2 was set up to allow for assessments in data-poor or data-rich contexts, as well as to help identify and report data limitations and provide recommendations on improving data collection. To better assess data limitation a Data Quality Score DQS (Table 2) is recommended to be applied to all coastal areas as a self-evaluation of data quality and required improvements.

Risk to life, household displacement and both household and business financial recovery are the most relevant indicators for impact assessment. Other indicators may or may not be considered if they are significantly (or not) exposed to the hazard. Data of sufficient quality are often lacking (see Viavattene, this issue), and even at the European case-study sites of the RISC-KIT project DQS of 2 or 3 are most common. Data quality will then be site-specific and often dependent on the availability of research surveys. Data availability and data quality are therefore pressing problems and require an improvement either promoted specifically for the needs of the local and regional authorities, or developed as standardized data by national and European authorities.

Table 2. Data Quality Score

1	Data available and of sufficient quality for CRAF 2.
2	Data available but with known deficiencies. Improvements required in the future
3	No data available/poor data use of generic data but representative enough. New data will be required.
4	No data available/poor data, use of generic data but likely not representative. New data will be required.
5	No data available, based on multiple assumptions

Land use data and vulnerability indicator

Information on the geographic location of receptors and their type is essential to calculate direct impact. Land use data are often available (national, regional or municipal dataset) allowing an exact representation of the geographic location of receptors. However, information on the type of receptors (buildings type and associated activity) is limited, requiring additional survey (local, satellite, online). The vulnerability indicator to assess the direct impacts in INDRA can be derived from country-specific datasets or generic datasets. National vulnerability indicators for depth-damages curves are only available in a few countries (e.g., France, Belgium, UK). Where this information is not available, generic data or peer-reviewed papers should be used to generate vulnerability indicators, but confidence in the quality of these indicators is limited. Research is therefore still needed at national and European level to better determine representative vulnerability indicators.

Household displacement

The displacement of, and subsequent disruption to, households is linked in the model to the direct impacts to residential buildings due to flooding and erosion. The approach requires the user to reflect on different displacement durations experienced by households for different hazard intensities using ex-ante or post surveys. The information to assess household displacements is, however, very scarce, and generic data or limited post-event information are then used. Confidence in using the poorly-available post-event data is limited since these are generally not found in peer-reviewed publications or official reports, but in media reports.

Financial recovery (household and business)

The assessment of the financial recovery requires distributing the number of properties across different recovery mechanisms: no insurance, self-insured, small government compensation, large government compensation, partly insured, fully insured, for households; and no insurance, self-insured as large corporate business, self-insured with access to resources, state-owned, partly insured, fully insured, for businesses. Values for financial recovery can be based on national policies, however a differentiation in sub-regions is recommended. There is currently a clear lack of data to distinguish local and regional differences. Access to insurance data and interviews may provide such information – preferentially including a geographic differentiation of the financial recovery distribution within the region.

Transport and utility disruption

The assessment of transport disruption requires the mapping of the regional transport network and the importance of locations within the network. Mapping road networks is often simple. Categorizing road transport capacity (associated with the speed limit) could be achieved using road typology. The importance of junctions can be included, mainly based on the type of road (flow and service associated with importance) and on the presence of specific services identified near the junction (e.g., hospitals, commercial areas). In contrast, mapping and categorizing utility networks is often hampered by limited public data availability and assessment of impacts to these networks often require a direct input from stakeholders in the utilities sector.

Business disruption

Business supply chain disruption considers the potential impacts on the economy, including the tourism economy. For the later, the assessment can be driven by the potential loss of attractiveness (beach) and the loss of accommodation, seasonality being an important factor to address (time laps between storm impacts and start of the tourist season). The impacts on harbour activities (e.g., loss of warehousing facilities) and the transport of goods are other examples to be evaluated under this indicator. Two components are key to assessing the business disruption: the reinstatement time and the business supply chain. If there is no information on business recovery for a given coastal area, generic data can be used as default values. The use of generic data can be considered a critical problem, as it has serious implications in the supply chain calculation, in particular when seasonality has to be considered. The lack of data can result in very simplified supply chains limited to two or three tiers. Engagement with business-related stakeholders, surveys and the involvement of experts in market or economic research will be beneficial for future assessments of this kind.

4.2.3 Hotspot ranking

A MCA (multi criteria analysis) is applied in CRAF 2 to weight the different indicators in each coastal area, allowing a comparison between selected HS (see Viavattene et al., this issue). The weighting for the MCA is either based on experts' or stakeholders' inputs. Multiple MCA weights can be tested, to represent different perspectives. It is advisable to have a good involvement with stakeholders to better define the weights of each indicator (cf. Christie et al., this issue; and Table 3).

Confidence in the impact assessment varies as a function of data quality. However, the approach combining simplified indicators and generic data allows the user to perform a first impact assessment and, in discussion with their stakeholders, to investigate which elements need essential improvement and consider options for improving their dataset as well as agreeing on the HS. It may be noted that in some cases an agreement on the selected hotspot may not be achieved. This may happen if differences in stakeholder perspective lead to strongly different results during the MCA. The contribution of the various indicators to the total score may also vary between HS. If similar impacts are analysed at all HS, then limitations in data quality, and differences in the indicator assessment and MCA weighting are similar across the HS and therefore have less influence in their comparative assessment.

Table 3. Example of MCA (multi criteria analysis) application and final CRAF 2 scores for two hotspots from the North Norfolk coast (UK). Method A - neutral approach; Method B - expert judgement where people, households and business are highlighted; Method C - expert judgement where people and ecosystems are highlighted (for details see Christie et al., this issue). Higher values represent potentially higher consequences, for the same considered hazard. It is relevant to note that the most important hotspot can change as a function of the chosen indicators weight.

Indicators	MCA weights (%) per method		
	A	B	C
Risk To Life	12.5	30	35
Household Financial Recovery	12.5	10	5

Household Displacement	12.5	15	5
Business Financial Recovery	12.5	15	5
Business Disruption	12.5	10	5
Natural Ecosystem	12.5	5	20
Agriculture	12.5	5	5
Transport disruption	12.5	10	20
Wells-next-the-Sea Score	0.1243	**0.1053**	0.1594
Brancaster Score	**0.1880**	0.0790	**0.2825**

5. Early-Warning System/Decision Support System (EWS/DSS)

The EWS/DSS is a tool to be used at the hotspot that is selected using the CRAF method. The EWS/DSS can be used both to provide forecasts of storm impacts as well as to assess the effectiveness of the DRR measures in the planning stage. The main types of hazards to be considered are marine flooding, overwash, and episodic (storm induced) erosion. The results of the high-resolution hazard models are translated into impact using damage curves or any other relationship that relates hazard into damage of the receptors. The associated hazard and impact information is stored in a self-learning Bayesian Network (BN).

5.1 The model train

The coastal Delft-FEWS system (Bogaard et al., 2016) is recommended to be used as a common platform for model input/output. However, for each coastal area a dedicated model train must be developed, starting from the incorporation of available data from other operational systems in FEWS and downscaling storm conditions to local hazards. The different EWS/DSS can, therefore, cover a wide spectrum of downscaling approaches adapted to different coastal areas (see Figure 6 as an example of a model train). The main factors that contribute to the need of having different EWS designs can be summarized in the following:

i. the availability of a suitable regional forecast systems;
ii. the dominant physical, geographical and morphological conditions that control the storm processes;
iii. the selected onshore hazards;
iv. the selected receptors and the expected impact;

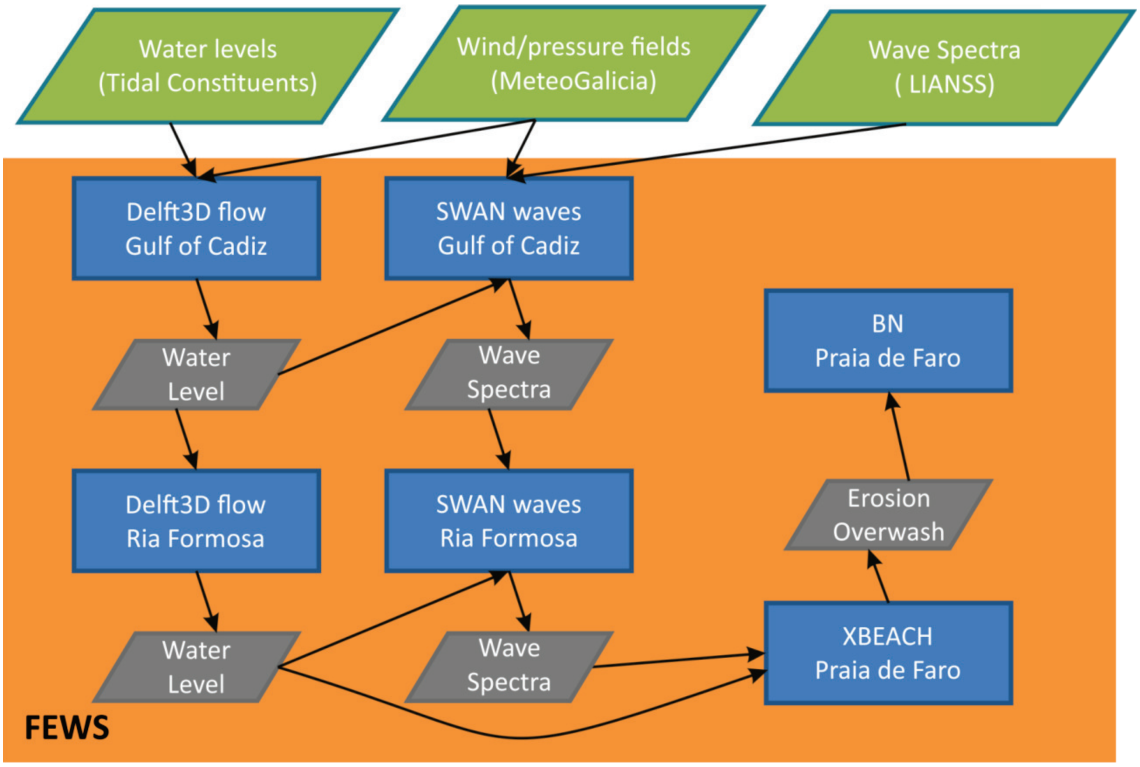

Figure 6. Example of model train used for Ria Formosa (Southern Portugal), with the integration of all models outputs/inputs under FEWS, and the results being exported to a Bayesian Network.

The EWS should integrate models to downscale storm surge and waves to the HS area. Approaches to this downscaling include:

- models that resolve wave propagation in a single domain of few kilometres surrounding the HS (cf. Bolle et al., this issue);
- a two-step approach where the wave propagation and generation is resolved regionally and locally (see Figure 6);
- a three-step approach for HS areas that require high resolution data or where forecast systems do not exist (cf. Jäger et al, this issue; Valchev et al., this issue);
- a single unstructured grid domain with varying grid resolution, including high resolution output in the HS area.

5.2 Bayesian Network set up

In the EWS/DSS the BN describes probabilistic relations between offshore forcing conditions (e.g., wave height), local hazard intensity (e.g., erosion and inundation; see Gutierrez et al., 2011) and impact at the receptors (cf. Poelhekke et al., 2016). The BN must be trained in order to produce correct final results. Details on BN training and examples of application can be found in Jäger et al. (this issue), Poelhekke et al. (2016) and Plomaritis et al. (this issue (a)). Once well trained, the BN is furthermore used to replace the computationally-expensive high-resolution hazard models at the HS in an operational EWS with an instantaneous probabilistic prediction of local hazards and impacts. Training is achieved by providing the BN with data from many pre-simulated storm events using the models in the EWS model train.

As part of a DSS, the BN should be set up using a defined structure (see Jäger et al, this issue). The BN include five categories of variables: Boundary Conditions, Receptors, Hazards, Impacts, and DRR measures. A number of nodes (e.g., peak water level and significant wave height as Hazard Boundary Conditions, or the maximum inundation depth as Local Hazards) is included within each category in the BN. However, due to local differences in the geomorphic and socio-cultural-economic setting, every BN can have different sets of variable nodes.

Spatial variation of local hazard intensity and receptors is accounted for in the BN by means of division of the HS area into sub-domains (i.e., smaller geographical units). The BN provides summary results at the defined sub-domain level (and not necessarily at the individual receptor level). In the definition of the sub-domains, it is not only relevant to account for the spatial distribution of receptors, but also to make an expert judgement or analysis of the hazard intensity patterns for multiple storms, as differences in the expected hazard intensity within units should be minimized. The differentiation of the sub-domains can vary, but is generally based on the following considerations:

- The type of receptors: ranging from people and saltmarshes, to residential, commercial, and industrial buildings, boats and other receptors.
- The hazard pathway: ranging from receptors being exposed from one direction with the hazard intensity decreasing with distance from the coast (e.g., cases where erosion is the main hazard) to being exposed from two or more sides (e.g., flooding at one receptor but from different sources).

The minimum number of pre-simulated storm events required to adequately train the BN is determined by the number of hazard boundary conditions nodes, the discretization of each node into individual bins (or states), the joint probability distribution of the hydraulic boundary conditions, and the number of DRR measures included in the EWS/DSS that modify the local hazard (Jäger et al., 2015; Plomaritis et al., this issue (a)). The number of storm events used to train the BN can therefore vary from about 100–1000, depending on the coastal area, number of hazards included, DRR in place. Although only one run is required to train each state (discretization interval or condition of each considered variable), a larger amount of runs should be used and a minimum of 5 runs per state is recommended for a good BN training.

The maximum hazard over the duration of the event is extracted from the model, for each event. For these a hazard indicator should be selected (similar to the CRAF 1 approach). Using a damage function the hazard is subsequently transformed into impact. Damage functions can be of a quantitative type (see Plomaritis et al., this issue(a)), including for example high resolution percentage functions with monetary outputs. In terms of DRR, three types of measures can be incorporated according to their influence on the pathway, exposure or vulnerability. For the incorporation of each type of DRR a different methodology is followed (for details see Jäger et al., 2015, Cumiskey et al., this issue). Pathway DRR measures are mainly related with alteration of the coastal environment (e.g., seawalls, nourishments) while exposure measures are related with changes of the receptors (e.g., house removal). Finally, the vulnerability DRRs are introduced through changes in the vulnerability relations of the receptors and uptake/operation/effectiveness values that are determined following the definitions of Cumiskey et al. (this issue).

5.3 EWS/DSS Applicability

The evaluation of the applicability of the EWS/DSS is focused on its various uses:

1. As an EWS for the current situation (without DRR measures implemented).
   The BN is able to translate the relevant hydraulic boundary conditions into hazard intensities and impacts at specific receptors, which provide coastal managers, decision-makers and policy makers with systematic information to detect, monitor and forecast potentially hazardous events, and analyse the risks involved. The system can be adapted and extended to more boundary conditions, receptors, local hazards and impacts, to enhance disaster preparedness and effective risk reduction of future events or morphological conditions. The system is also suitable for raising stakeholder awareness of local hazards/risk, although this also requires a friendly graphical user interface. Such stakeholder awareness can be done in association with the implementation of the Multi Criteria Assessment tool, as detailed by Barquet and Cumiskey (this issue). When a coastal zone is exposed to more than one local hazard, the EWS, if correctly developed, is able to assess and make comparisons about their relative importance in terms of hazard intensities and impacts.
2. As an evaluator of the effectiveness of DRR measures.
   The EWS/DSS can be used to compare the effectiveness of DRR measures (see Figure 7), or a combination of measures, in reducing impact in coastal areas (cf. Jäger et al., this issue; Plomaritis et al., this issue(a)). This can be performed by changing the model set-up, re-simulating local hazards or changing receptor and vulnerability information in the impact assessment, and including new nodes and bins in the BN. Difficulties are mainly related with the assumptions needed for the implementation of non-primary DRR measures (see Cumiskey et al., this issue).

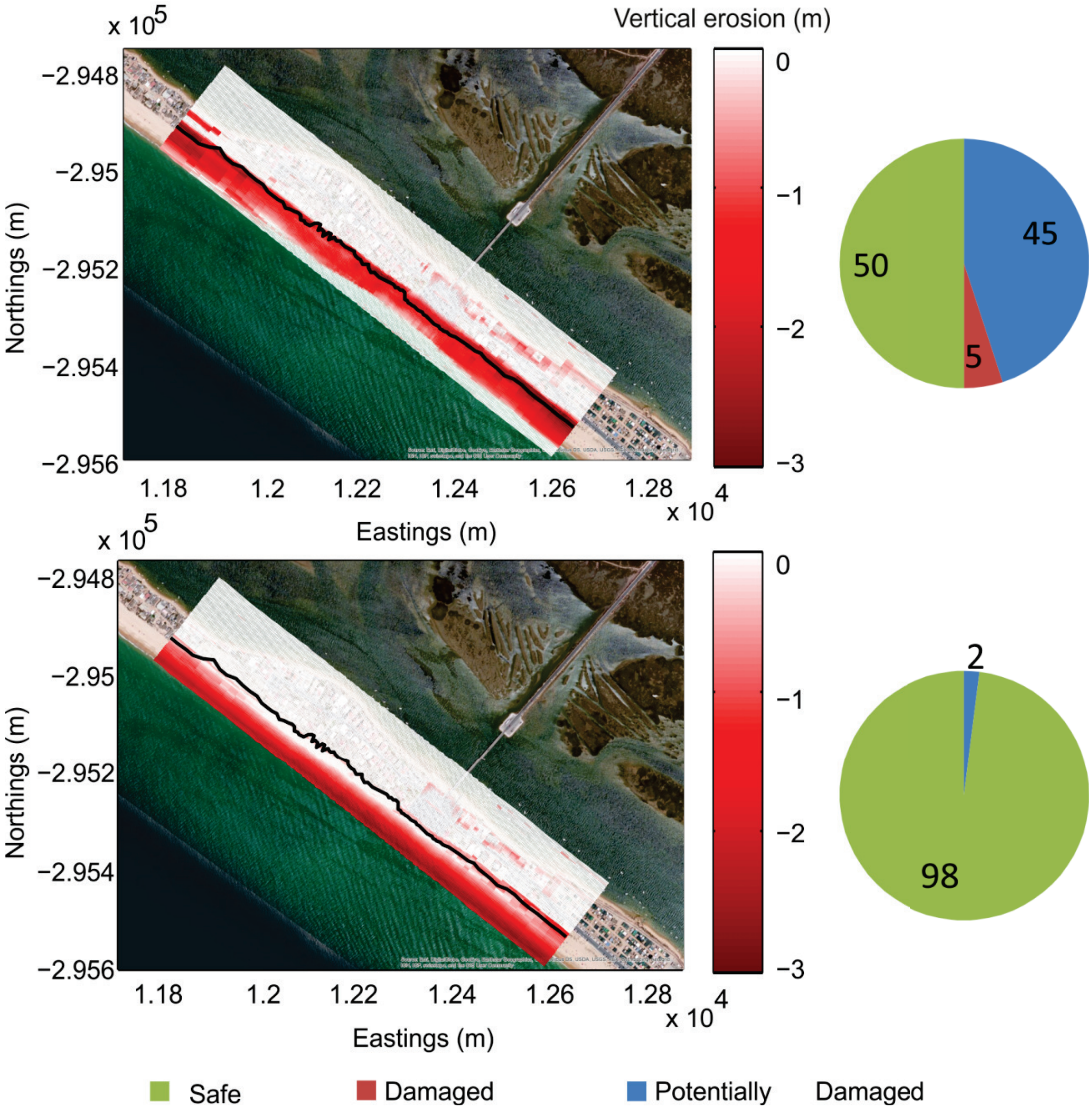

Figure 7. Example of application of the BN and DSS to evaluate the potential effect of a DRR measure (nourishment) at Praia de Faro, for erosion induced by a 50 year return period storm. The black line represents the limit between the beach and the dune or human occupation. Vertical erosion (pink to red) to the inland of the black line means potential damage or damage to the existing occupation. The upper panel represents the evaluation of potential damage, including the percentage of the occupied area to be affected (see the pie chart), for the current situation, while the bottom panel represents the same after a nourishment measure. While the left images are a representation of the performed runs, the results in the pie charts came directly from the BN, after integrating modelling results, human occupation, damage criteria and (for the lower panel) a risk reduction measure (nourishment).

Despite the flexibility and utility of the EWS/DSS, improvements to the EWS/DSS can be achieved over time in the following aspects:

(i) Quality and accuracy of the underlying numerical model trains, namely by increasing validation against further field data of low frequency impacts;

(ii) Vulnerability relationships and detailed receptors, by increasing the number of geographical subdivisions of the HS and increasing the number of bins and model runs;

(iii) Uptake/operation/effectiveness factors of the vulnerability and/or exposure influencing measures, by determination of these factors for each coastal area by historical analysis of other (observed) hazards/events.

(iv) Extended analysis of the effectiveness of DRR measures, by including more aspects linked to the probability of occurrence of events, economic value, and socio-cultural characteristics of the local stakeholders.

(v) Inclusion of regional-scale systemic and indirect impacts of storm events at the HS, following a similar method to that of CRAF 2.

6. Findings and conclusions

Two novel coastal risk assessment tools were developed within the RISC-KIT project. This paper analysed the applicability of the tools, including the difficulties identified, constraints to their application, and recommendations for future use.

The Coastal Risk Assessment Framework Phase 1 (CRAF 1) is applied to identify hotspots caused by storm events in coastal areas on a regional scale of 10–100 km. The CRAF 1 identifies potential HS by assessing different hazards and the associated potential exposure for every coastal sector (typically with an alongshore size of ~1 km). Although still requiring extended databases and information, the CRAF 1 is relatively simple and quick to apply at the regional scale. The hazard indicator is based on a probabilistic description of the considered hazards, which implies the use of long-term datasets to characterize the forcing and, as a consequence, the induced hazards. In cases where instrumental records do not exist and/or are too short to support a reliable extreme value analysis, they can be replaced by simulated (hindcast) data. The CRAF 1 has inherent limitations (simple approaches, formulations, databases, and indicators) related to its use as a relatively fast scanning tool. However, the CRAF 1 is useful to highlight hotspots in regional coastal areas for further exploration in the second phase of the CRAF. The CRAF 1 is robust and can contribute to the optimisation of resources in coastal management plans, namely those related with event-driven risk reduction.

The CRAF 2 is applied to assess and rank HS identified in the CRAF 1 on a large variety of coastal areas and exposed elements. The CRAF 2 HS risk analysis is done by jointly performing a hazard assessment using multi-hazard process-based models, and an impact evaluation using INDRA. The HS ranking is obtained through the use of a multi criteria analysis to weigh varying impact parameters (household displacement, household financial recovery, regional business disruption, business financial recovery, ecosystem recovery, risk to life, regional utilities service disruption, and regional transport service disruption). The CRAF 2 hazard analysis is relatively simple to apply at the HS level, while still achieving useful results. The main uncertainty in the application of the INDRA model is related to the lack of data to input in the model. That difficulty will be particularly relevant in countries where databases describing the required elements for the INDRA model are not accessible or do not exist. As a consequence, it becomes difficult to perform an integrated regional assessment of the business disruption including potential cascade effects. Business supply chain models will probably be very simplified and limited to two or three tiers if there are not enough data available. Further assessment of this impact at hotspots requires the joint participation of experts in the socio-economic sciences. Overall, the method seems to be robust in a wide range of applications, and can contribute to optimizing resources for coastal risk reduction measures towards areas of higher risk to extreme events. The CRAF 2 also provides insights and approaches on how to include indirect effects in the risk assessment, with a high potential to be further developed.

The EWS/DSS is meant to be used in selected HS to assess the effectiveness of disaster risk reduction (DRR) measures in the planning phase, or as an Early Warning System (EWS) in the event phase. The system requires the application of a suite of complex-modelling techniques (2DH process-based, multi-hazard models) integrated into an operational forecasting platform (Delft-FEWS). The individual models should be calibrated and validated with measured data. The boundary condition data for the start of the model train are imported from regional operational forecast systems. Depending on the oceanographic and geographical conditions of the study area, several steps of downscaling can be used. Each EWS/DSS contains a Bayesian Network (BN) that is used to relate the impact of storms to offshore forcing and local hazard intensity. In this role, the BN can replace the computationally-expensive high-resolution hazard models at the HS in an operational EWS with an instantaneous and probabilistic prediction of onshore hazards and impacts. This is achieved by training the BN with data from approximately 100–1000 pre-simulated storm events using the models in the EWS model train. The EWS/DSS can also be used to evaluate how effective a DRR measure or a combination of measures will be in reducing the impact of storm events. One of the main limitations for a more extensive and accurate assessment of the method is the lack of high quality hazard and impact measurements to validate the EWS/DSS for low frequency, high-impact events.

The scale and objectives of the CRAF and EWS/DSS tools varies from large-scale hotspot identification, to the determination of impact at individual receptors. Both tools involve the combined evaluation of hazards and impact assessment, including physical and socio-economic aspects. The tools are applicable, with some modifications, to a large set of coastal areas. A lack of high-quality and high-resolution socio-economic and impact data was observed during the RISC-KIT project. The tools are, however, effective in selecting and ranking HS, at assessing impact at the HS, and testing and evaluating the effectiveness of DRR measures. They are therefore valuable instruments for coastal management and risk reduction. These methods should nevertheless be further exploited, validated, and applied at new case study sites in the future to increase their robustness and to test their limitations.

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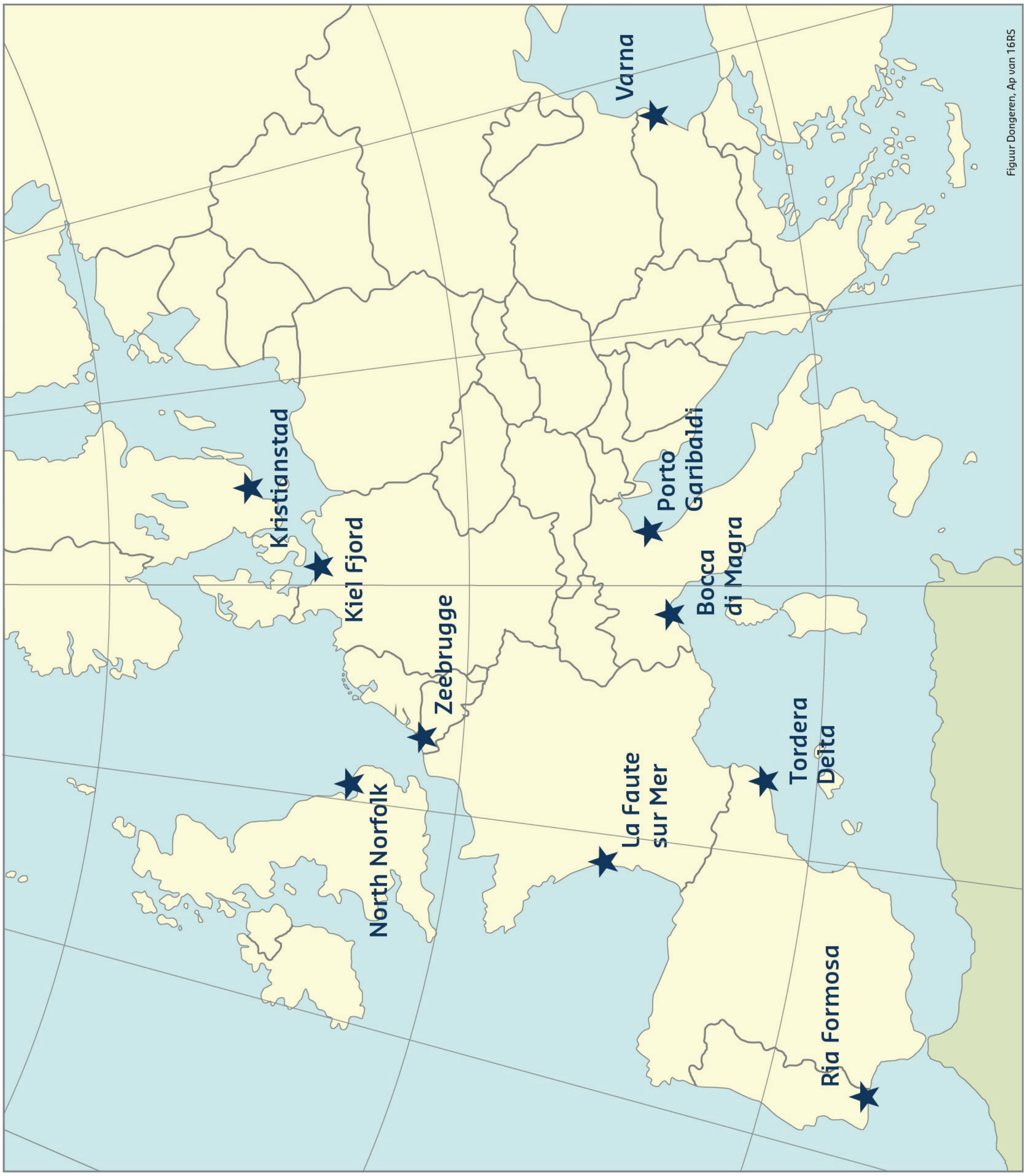
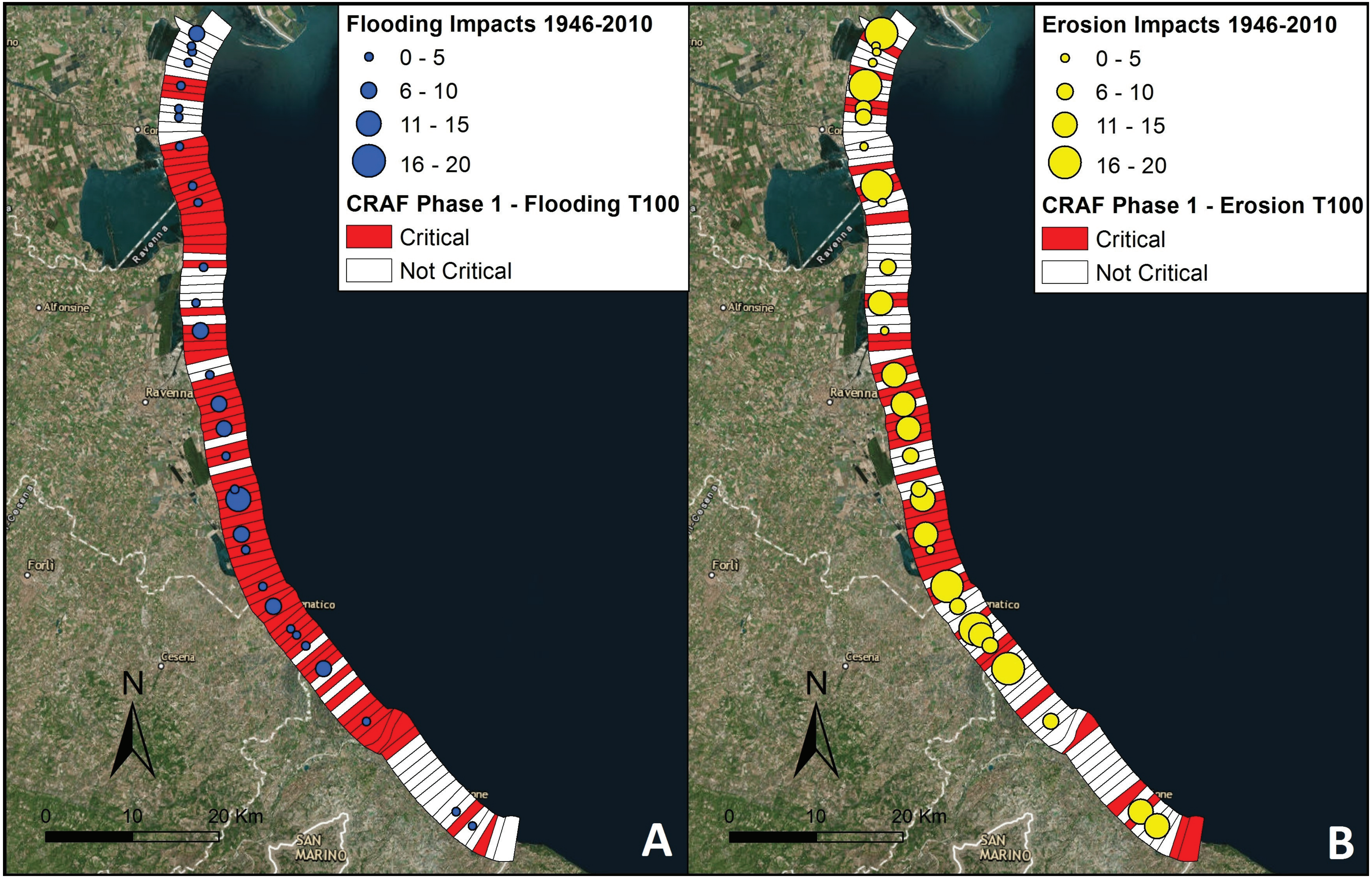


Figuur Dongeren, Ap van 16RS


Flooding Impacts 1946-2010
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CRAF Phase 1 - Flooding T100
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Erosion Impacts 1946-2010
0 - 5
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11 - 15
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CRAF Phase 1 - Erosion T100
Critical
Not Critical
Alfonsine
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