INDRA model: for a better assessment of coastal events disruptions

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ABSTRACT

Natural hazards such as extreme coastal events can generate indirect impacts extending far beyond the exposed areas and the direct aftermath of the event. The recognition of such impacts in risk assessment is essential for preparing, mitigating against such events and for increasing the resilience of coastal communities. However the assessment is often limited to the direct impacts. This paper proposes new methodologies for assessing the indirect impacts of coastal storm events. Eight impacts are considered in the approach: household displacement, a financial recovery of households and businesses, business supply chain disruption, ecosystem recovery, risk to life, utility and transport disruptions. These methodologies are incorporated in the open-source INDRA model (INtegrated DisRuption Assessment) to compare and identify hotspots at a regional using a multi-criteria analysis.

Keywords

Risk Analysis, resilience, vulnerability, business continuity, infrastructure

INTRODUCTION

The direct consequences of natural hazards are the loss of assets (built environment), human life and natural habitats. These quantitative losses (e.g. total damages, total injured and total fatalities) are used to report events that have occurred and to assess the potential losses of future events for informing risk management decisions. These numerical estimates might provide a good indication of the scale of the hazard, yet are insufficient to totally value the losses. The estimates are limited to the consideration of the shock of the event, and, as such, they poorly reflect long-term impacts and the lack of resilience of the impacted area. Indeed the loss of certain assets may lead to long and large disruptive effects including the disruption of essential services such as transport and utilities services (electricity and water). Transport might be temporally disrupted during and in the aftermath of a flood but longer periods of disruption due to the loss of essential structural assets such as bridges or a rail lines as was recently observed in major European flood events (EEA, 2014). Another example would be the displacement of a population (Few et al., 2004) where, following very extreme events such as Hurricane Katrina, thousands of households are displaced, many for several years and some have never returned to the same area (Merdjanoff, 2013). The financial recovery of these populations and businesses is another long-term effect which should not be neglected considering the often considerable gap between insured and uninsured losses (CEBR, 2012). The impact on businesses and the supply chain may also have severe consequences in the short and long term for the local economy but also on the global market as was illustrated by the Thailand flood on the automobile and electronic product supply chain (Haraguchi and Lall, 2014).

A traditional and common approach employed in the field of economic loss assessment when applied to natural hazards follows the Source-Pathway-Receptor model (Gouldby et al., 2005). The SPR approach focuses on assessing direct losses and attempts to measure the first order of losses (e.g. business disruption for flooded business). The approach neglects higher order of losses, also called indirect losses or induced losses (Messner et al., 2007; Penning-Rowsell et al., 2013) and is challenged in this regard (Turner et al., 2003; Rose, 2010). This paper describes a new approach developed for assessing various disruptions following a coastal event and how this knowledge contributes to the improved the management of extreme event. The approach has been integrated in the open-source INDRA model (INtegrated DisRuption Assessment model), with the NetLogo software (https://ccl.northwestern.edu/netlogo/) available on the EU RISC-KIT project website (http://www.risckit.eu/) (Viavattene et al., 2015b). This model aims to assess and compare the risk at a regional scale using a multi-criteria assessment approach. The resulting disruption indicators provide a measure of resilience, resilience being defined as “the amount of change a given system can undergo and still remain within the set of natural or desirable states” (Turner et al., 2003).

METHODOLOGY

Any assessment is developed to fulfill specific purposes. These purposes have to be recognized to understand certain methodological choices. The INDRA model has been developed as part of a Coastal Risk Assessment Framework (CRAF), which assess coastal areas at a regional case and identifies hotspots for more detailed assessment. The CRAF is one of the components of a suite of innovative and EU-coherent open-source and open-access methods, tools and management approaches (the RISC-KIT) (Van Dongeren et al., 2014). The main objective is to develop an impact assessment tool able to compare and rank different hotspots along the coast of various European settings using a Multi-Criteria Approach. An MCA imposes a standardisation of several independent criteria. In INDRA, each criterion represents an indirect impact indicator scored from 0 to 1 (0 indicating no disruption and 1 a full disruption at regional scale). An extensive range of impacts might be considered in flood loss assessment (Merz et al., 2010; Meyer et al., 2013). From these eight indicators relating to the different categories of receptors were selected as the key relevant ones, by considering existing methodologies and data for their assessment (Viavattene et al., 2015) (Figure 1):

- Population: three indicators, i.e. the potential risk to the population during an event, the displacement time and the financial recovery;
- Business: two indicators, i.e. financial recovery and the business disruption of supply chains;
- Ecosystems: an ecosystem recovery indicator;
- Transport: regional service transport disruption;
- Utilities: regional utilities service disruption (water plants, power grids or substations).

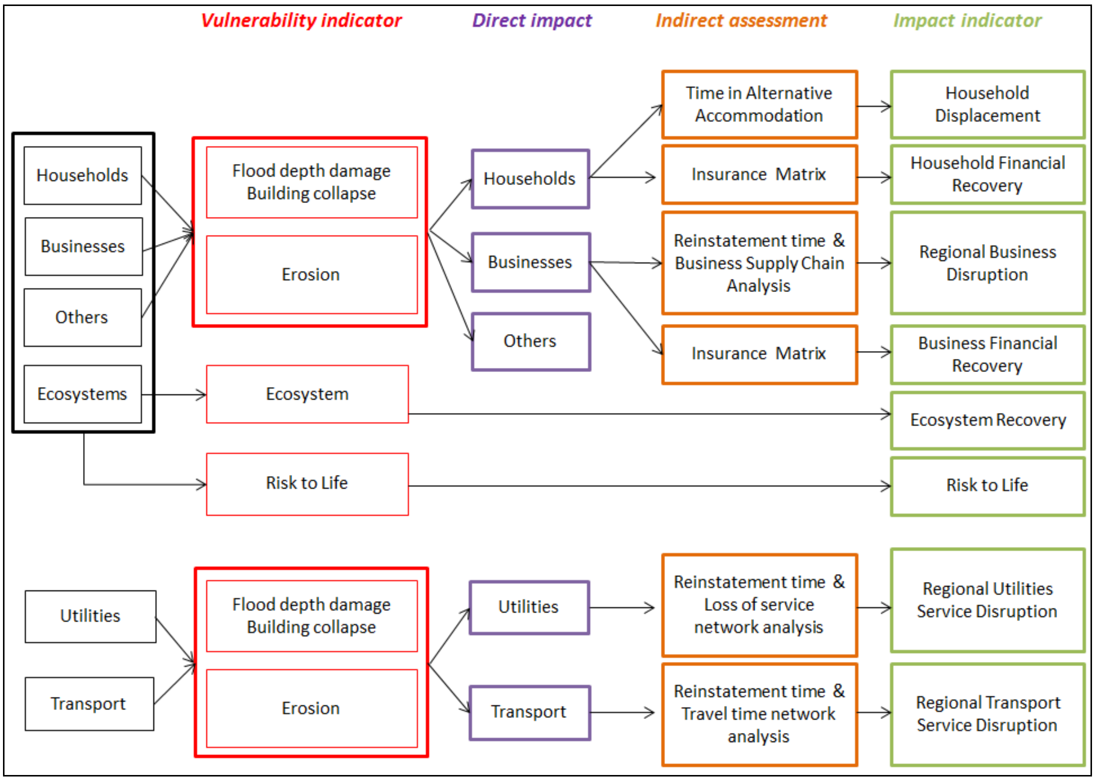


Figure 1: Impact assessment process

Direct impact and reinstatement time

In order to utilise such regional indirect indicators, it remains necessary to calculate the direct impact (purple boxes on Fig.1) at the receptor level (black boxes on Fig.1). This requires combining information on hazards, receptor location and their characteristics, and vulnerability information (red boxes on Fig.1). Yet the availability of data on land use or for different vulnerability components is variable and a key source of uncertainty (Viavattene et al., 2014). These significant issues of data collection and availability are recognized and the approach is developed so that it is:

- Applicable for various types of receptor;
- Applicable for multiple types of impact;
- Not data demanding;
- Sufficient to highlight major differences in impacts;
- Comparative rather than quantitative;
- Easy to use;
- Flexible (from less to more detailed approach).

Therefore, a common five-point scale (None, Low, Medium, High and Very High) is used to assess the direct impact for all receptors (Figure 2). The four thresholds are defined based on those receptors considered and the key hazard intensities resulting in the impact. Table 1 provides an overview of the existing coastal vulnerability indicators considered in the model. For Risk to Life and Ecosystem Recovery, the indicators can be already obtained using existing vulnerability assessment techniques: the Risk to Life model (Priest et al., 2007) and the Ecosystem Vulnerability Indicators (Zanuttigh et al., 2014). For the other indicators new methodologies have been developed and are presented below. It should be noted, here, that the direct impacts will not be considered in the multi-criteria analysis in order to avoid double-counting. However the users have the possibility to export the direct impacts results for further analysis.

The following sections describe the approaches (orange boxes in Fig. 1) developed to convert these direct impacts into the indirect indicators.

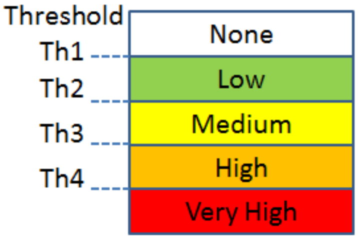


Figure 2: Direct Impact scales and thresholds

Category	Direct impacts	Hazard intensities (main)	Vulnerability indicators
Built Environment	Inundation damages	Flood depth, Duration	Depth-damage curves
	Collapse	Flood depth-velocity	Risk matrix
	Evacuation and collapse	Erosion distance shoreline	Distance-based approach
Population	Risk to life	Flood depth-velocity	Risk matrix
Ecosystems	Change in habitats	Duration, depth, sedimentation	Impact scale

Table 1: Direct impacts, hazard and vulnerability for different categories

Reinstatement time

One key factor required to transform direct impact to indirect impact assessment is reinstatement time. For each impact level the approach considers an associated reinstatement time, i.e. the time required for receptors to return to their original state. The reinstatement time can, in some cases, simply be associated with the repair time. In other cases, various factors influence the recovery process and are difficult to disentangle.

As such, for households, the reinstatement time of a residential property can be considered as the displacement time, i.e. the number of households that are required to move away from their permanent residences and into alternative accommodation. The duration of household displacement may relate to event characteristics (e.g. the severity of the damage sustained), the characteristics of the household (e.g. capacity to pay to repair/rebuild, insured/uninsured) as well as other causes which are event or receptor independent (e.g. the availability of materials or builders to repair/rebuild or the availability of alternative accommodation). Therefore a household displacement indicator cannot be directly and simply associated with the impact level. The methodology proposed in the model consists of a matrix indicating for each impact level the proportion of households being displaced for different period of times, scaled to reflect the potential disruption of the household (the worst case being a permanent displacement). The information required to populate the matrix may be derived from empirical evidence of past events.

Financial recovery

A key factor linked to the resilience of coastal societies from extreme events is the ability of individual households and business to recover financially. Not all households and businesses will need to recover independently of any assistance, there are a diverse set of financial recovery mechanisms (including government compensation, government and private-market insurance, tax relief, charitable assistance, welfare relief). Although considered important to societal resilience, methodologies for the inclusion of this variable are lacking. A semi-qualitative, matrix-based approach (Table 2) has been developed to identify and assign the various potential states of financial recovery likely to be achieved by domestic households and businesses. The matrix has two different inputs, the characteristics of the receptor which draws on the presence of different types of recovery mechanism and the direct impact level. The four levels of financial damage have to be defined using existing vulnerability indicators such as depth-damages curves. The low scale indicates minor depth losses (e.g. drying and cleaning costs and superficial damage). The medium scale relates to depth where the main inventory items are lost, whereas the high scale relates to flood undermining major building components. The very high scale is reserved for building collapse situations. The financial recovery is scored from 1 to 5, 1 indicating a full financial recovery (e.g. recovery with no/few adverse impacts) and 5 a very low financial recovery is possible (e.g. major and permanent changes to their way of life).

			Direct impact on property			
			Low	**Medium**	**High**	**Very High**
	Characteristics of receptor related to financial recovery		**Low financial damages sustained**	**Medium financial damages sustained**	**High financial damages sustained**	**Very high financial damages are sustained**
Receptor types and their characteristics	**Household with no insurance**	**NoI**	2	3	4	5
	Household with no insurance, but resident has self-insured	**NoIself**	1	2	3	4
	Household with no insurance, but which are able to access a small/medium amount of government compensation	**NoIScomp**	1	2	3	4
	Household with no insurance, but which are able to access a large amount of government compensation	**NoILcomp**	1	1	2	3
	Partly insured household	**PartI**	1	2	3	4
	Household with full coverage for buildings and contents insurance	**FullI**	1	1	1	2

Table 2: Insurance Matrix for scoring the financial recovery

Systemic Impacts

Business supply chains, transport and utilities services categories commonly have a systemic vulnerability associated with their networks, which are considered to be an ensemble of nodes and links exchanging flows. The systemic vulnerability is a combination of various factors such as the function and importance of each node, the flows and capacity of the links, the typology of the network, the existence of dependencies and interdependencies, or the degree of uniqueness. The chain of interrelationships that exist between those nodes and links that are directly impacted by the hazard and the rest of the network determines the capacity of a given system to continue functioning. The three indicators associated with each category aim to score such levels of disruption. Modelling the propagation of the impacts through the networks is required. Overall modelling techniques to assess impacts on networks are: empirical analysis based on survey and expert input, statistical analysis, network analysis, flow modelling or agent-based modelling. Network analysis, which is faster and less data-demanding, was selected as the best technique to address the constraints stated previously. In Graph Theory, from which network analysis derived, a network is represented by a set of nodes and by a set of links between the nodes. This technique analyses the network's structural properties based on node and link characteristics such as the connectivity between two nodes (shortest pathways, level of connection, maximum flow) or the centrality of a node in a network (degree, closeness, "betweenness") (Tanenbaum, 1981). In INDRA the assessment consists then at comparing the disrupted network with the network in normal condition producing as such an indicator of disruption scaled between 0 and 1 (0 indicating no disruption). After the flood the disruption varies over time as the damaged assets reach their reinstatement time and become functional again. This dimension is considered in the approach by integrating the daily disruption indicator for each category. However the specificity of the services categories remains to be considered in the assessment. Figure 3 provides possible schematic of the three considered network categories.

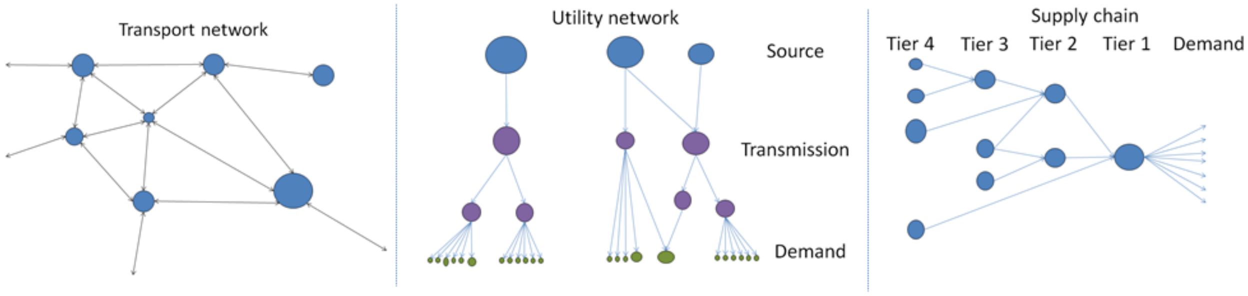


Figure 3: Example of network configurations

For the transport category, the network is represented by a road junction, a railway station associated with an importance value (blue nodes of various size in Fig.3) and by roads and railway lines associated with a speed of circulation (links). The approach estimates the extra journeys between any locations following the temporal loss of one of the nodes or lines due to flooding (direct impact) based on the Dijkstra's Algorithm which is usually employed to perform the calculations of the shortest distance between two nodes of a network. The indicator developed to assess the disruption on the transport network has been called the Weighted Disconnection and Time Lengthening Indicator (WDTL). It combines a Connectivity Ratio and a Time Ratio. The Connectivity Ratio gives information on the loss of connectivity to the places with more or less importance. The Time Ratio aims to represent the scale of increased travel time from one node to another. Hence, the ratio only takes into account the travel times between the nodes that remain accessible after the occurrence of the disruptive event.

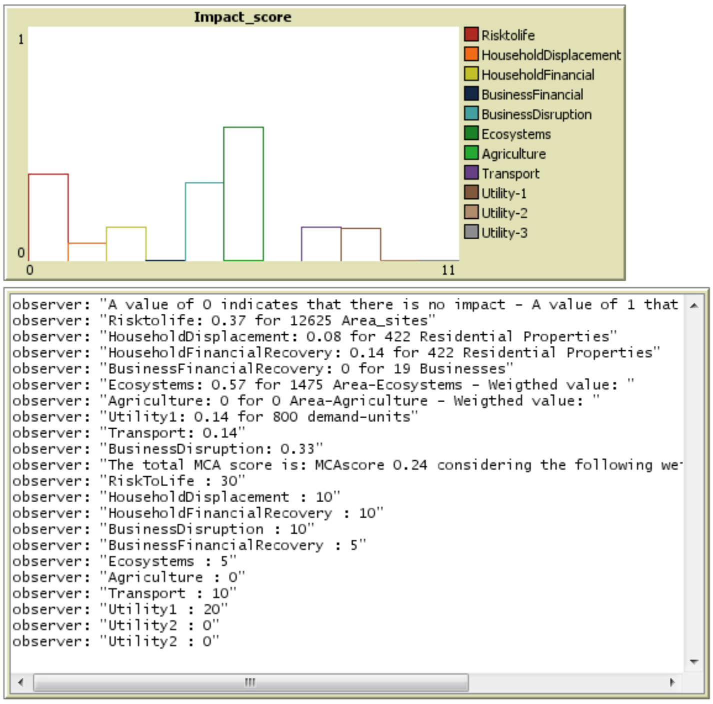
For utilities, a network represents all those assets required to provide a service (e.g. water or power supply): the type of assets vary from one supply system to another but overall can be represented by source (blue nodes In Fig.3) and demand nodes (green nodes in Fig. 3) associated with a capacity and connected by transmission assets (nodes or links). The adopted approach is simplified so that it can be performed with low data input limited to the network topology and source and demand volume. The network topology is modified accordingly over time considering the loss of assets (direct impacts) and their recovery (reinstatement time) to estimate the potential extent of the disruption beyond the impacted areas. The indicator combines a connectivity loss ratio and an imbalance value. The connectivity loss ratio (percentage loss of connection) is defined by assessing if a source remains connected to each supply node and therefore a service is still provided. The imbalance value measures whether the demand exceeds the supply and therefore if there is a risk of services not being delivered (i.e. over demand and potential blackout).

For business disruption a network represents a supply chain, which is a group of businesses exchanging goods following the concept of tiers of suppliers within supply chains (Stadtler & Kilger, 2008). Yet assessing all business supply chains and their interaction remains ambitious. Therefore a helicopter view is recommended.

For coastal impact assessment the focus should be upon the principal coastal infrastructure assets, the principal clusters of businesses (e.g. hotels, food and drinks suppliers, restaurants etc.) and the lines of conveyance (arcs) between these which may be disrupted by an event (Figure 3). The indicator is calculated as the sum of the reduction in the supply capacity of each of its nodes weighted by their relative economic importance. To do so, in the model each business property can be associated with a supply node and, as such contribute, to calculate the overall capacity of the specified node. The temporal loss of each business property (direct impact and reinstatement time) can then be associated with a reduction of the overall capacity of a node at a certain time. The capacity of each node is then calculated considering change in the supply from tier n to tier 0, change in the demand resulting from a lack of attractiveness induced by the loss of other receptors, change in the supply from tier 0 to tier n. The potential spare capacity of the business property is also considered in the approach as mitigating the loss of other business supply capacity.

Multi-Criteria Analysis

For a given storm and hotspot, the obtained indicators can be analyzed as such or combined to obtain an overall indicator. To do so, a multi-criteria assessment by weighted summation can be performed by the end users (Figure 4). A tailored interface allows weighting the indicators between 0 and 100. The sum is constrained to equal 100. Each hotspot can then be compared to the others for a selected return-period or by calculating an overall risk value.



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observer: "A value of 0 indicates that there is no impact - A value of 1 that
observer: "Risktolife: 0.37 for 12625 Area_sites"
observer: "HouseholdDisplacement: 0.08 for 422 Residential Properties"
observer: "HouseholdFinancialRecovery: 0.14 for 422 Residential Properties"
observer: "BusinessFinancialRecovery: 0 for 19 Businesses"
observer: "Ecosystems: 0.57 for 1475 Area-Ecosystems - Weigthed value: "
observer: "Agriculture: 0 for 0 Area-Agriculture - Weigthed value: "
observer: "Utility1: 0.14 for 800 demand-units"
observer: "Transport: 0.14"
observer: "BusinessDisruption: 0.33"
observer: "The total MCA score is: MCAscore 0.24 considering the following we
observer: "RiskToLife : 30"
observer: "HouseholdDisplacement : 10"
observer: "HouseholdFinancialRecovery : 10"
observer: "BusinessDisruption : 10"
observer: "BusinessFinancialRecovery : 5"
observer: "Ecosystems : 5"
observer: "Agriculture : 0"
observer: "Transport : 10"
observer: "Utility1 : 20"
observer: "Utility2 : 0"
observer: "Utility2 : 0"
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Figure 4: Snapshot of the INDRA model MCA Interface

CONCLUSION

The approach proposed and developed within the INDRA model supports decider-makers' assessment of disruption resulting from extreme coastal events. To do so, new methodologies have been developed to better consider indirect impacts within the decision process, including the use of network analysis techniques in loss assessment. The primary objective of the approach is the comparison of risk at the regional scale to identify key hotspots for improved coastal management and the better allocation of resources. The model also allows the identification of the weak points in essential networks and of those communities and businesses which may face a longer and more difficult recovery process. Such identification is essential in the preparedness of an event to mitigate hazard impacts and improve the resilience of coastal cities. However it should be recognized that bringing innovative assessment approach exacerbates the problem of validation already dominant in risk assessment. Depending on the case study, the results will be validated by experts and local stakeholder's consultation, using empirical data on previous events and existing risk assessment. A qualitative and descriptive assessment of the data representativeness used as input in the model is also produced to highlight limitation in the assessment and provides guidance for future improvement to the stakeholders. The model is currently applied to various European regions and the lessons learned from its application will be published by the end of the project.

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