

Hotspots of coastal vulnerability: A DPSIR analysis to find societal pathways and responses



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ARTICLE INFO

Article history:

Received 31 October 2012

Accepted 11 October 2013

Available online 22 October 2013

Keywords:

coastal hazards

disaster mitigation

risk governance

vulnerability reduction

coastal zone

global environmental change

social-ecological systems

ABSTRACT

Dramatic loss of life and economic losses in coastal zones have focused attention on natural and man-made hazards. The paper starts with a review of the coastal vulnerability terminology. Coastal zones are then presented as complex, socio-ecological systems. Four main coastal hotspots of vulnerability; namely Arctic coasts, small islands, river-mouth systems and urban coasts (including megacities) are analysed to demonstrate the complexity of coastal vulnerability. A DPSIR framework is used to explore the causes and consequences of coastal vulnerability. The paper then focuses in particular on societal, as well as floods, storm-surges and tsunamis to technological and engineering solutions. These include raising awareness, advancing forecasting, enhancing preparedness and improving governance.

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1. Introduction

The context for the paper is the projected increase in frequency and/or intensity of natural disasters (IPCC, 2012) which, coupled with an increasing population in the coastal zone, potentially increases vulnerability, risks and losses (Munich Re, 2012). The Land-Ocean Interactions in the Coastal Zone (LOICZ) project identified coastal hotspots that include Arctic coasts, small islands, river mouth systems, and urban coasts (Newton et al., 2012).

The paper explores the following research questions: (1) *What are the environmental and societal drivers of coastal vulnerability?* and (2) *How may managers respond to increase the resilience of vulnerable coastal communities?* Thus, the aim of the paper is to clarify what are the environmental and anthropogenic components of coastal vulnerability hotspots and to provide managers with state-of-the-art responses that increase resilience.

The paper considers the coastal zone to be a social-ecological system and therefore uses the DPSIR framework (Atkins et al., 2011) as the approach and method for the analysis of the vulnerability of the coastal hotspots (Newton et al., 2012).

The paper includes a review of the terminology, addresses the coastal vulnerability hotspots and analyses these using a DPSIR framework. The focus is finding solutions, in particular societal pathways, which are responses that are complementary to technological and engineering solutions.

Key terms and a brief review of the relevant terminology: The understanding of coastal vulnerability and how to approach this issue is evolving, together with the definition of the main terms. The 2012 IPCC Special Report “Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation” (IPCC-SREX) has substantially revised the previously adopted glossary of climate change scientists, thereby facilitating interactions with disaster risk reduction (DRR) scientists and thus opening the way for new fruitful collaborations and revisions of past and recent approaches and tools (IPCC, 2012). It is impossible to cover all definitions of key terms in this paper and readers desiring additional information are advised to review the works referenced throughout, in particular the IPCC (2012), however, some key terms are introduced below.

A first key term is **natural hazard**. In general, it is used to refer to “natural processes or phenomena occurring in the biosphere that may constitute a damaging event and that in turn may be modified by human activities, such as environmental degradation and urbanisation” (UNDP, 2004, p. 11). Characterised by its location, frequency and intensity, the occurrence of a natural hazard event may have physical, environmental, social and economic impacts in a given

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area and over a certain period of time. For Turner et al. (2003, p. 8074), hazards are threats to a system, comprised of perturbations and stress (and the sources of stress, i.e., stressors). Perturbations are major spikes in pressure beyond the normal range of variability in which the system operates, and commonly originate beyond the system or location in question. Examples of perturbations that are coastal hazards include tropical cyclones and tsunamis.

Another important term is **disaster risk**. In general, it refers to “the probability of future damage and loss associated with the occurrence of natural hazards, where levels and types of loss are determined by the levels of exposure and vulnerability of society” (UNISDR, 2004). From this perspective, disaster risk is the result of the interactions in time and space of probable physical events with exposed vulnerable elements of social systems. This view was taken up by the authors of the IPCC-SREX who defined disaster risk as “the likelihood over a specified time period of severe alterations in the normal functioning of a community or a society due to hazardous physical events interacting with vulnerable social conditions, leading to widespread adverse human, material, economic, or environmental effects that require immediate emergency response to satisfy critical human needs and that may require external support for recovery” (IPCC, 2012, p. 5). Consequently, a disaster itself is the product of a complex relationship between the physical world, the natural and built environment, and society, its behaviour, functioning, organisation, and development (Quarantelli, 1998). It is commonly defined as a social condition whereby the normal functioning of a community or a society has been severely disrupted by the levels of loss, damage and impact suffered. From a social perspective, disasters may also be seen as a forced and rapid social change, reflecting unmanaged risks and unresolved development problems. This is the reason that social networks and bodies emerge to respond to the distinctive demands generated by frequent disasters.

Although the term of **vulnerability** is widely used in different research traditions – e.g., in the field of risk, hazard, and disaster management, in global environmental change research and development studies – there is no common definition or conceptualisation, but diverse views, different foci and meanings (Tapsell et al., 2010). At present, the term vulnerability has a range of meanings from disaster risk management, for example the physical resistance of engineered structures. Vulnerability has been proposed as the key to understanding a novel conceptualisation of risk that includes broader societal causes and processes of disaster risk and disasters as well as the more causal, mechanistic attitudes that have characterised the relationship between human societies and their environments over past centuries (Bankoff, 2003, p. 6f.).

To be vulnerable to hazards refers to the propensity or predisposition to be adversely affected by the impacts of hazards (IPCC, 2012). Vulnerability is a dynamic coincidence of places and people with an *external* side due to the sources of the stress (Chambers, 1989). However, vulnerability also has an *internal* side that refers to the lack of means to cope with stress of individuals or communities. The degree to which a system is modified or affected by an internal or external disturbance or set of disturbances, as defined by Gallopin (2006, p. 295), is called **sensitivity**. Conceptually, it can be measured as the amount of transformation of the system per unit of change in the disturbance. Long-term social processes and power relations operative in society are often the root causes that result in dynamic pressures and unsafe conditions (Blaikie et al., 1994; Lewis, 1999; Bankoff et al., 2004). Thus, the social system generates unequal exposure to risk, making some people more prone to disaster than others. Within the context of the present paper, vulnerability refers to “the propensity of exposed human beings and their livelihoods and assets to suffer damage and loss when impacted by hazard events” (Weichselgartner, 2001).

The term **resilience** became prominent within ecology as “a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables” (Holling, 1973, p. 14). The more resilient a system, the larger the stress it can absorb without shifting into an alternate regime or collapsing. However, the relationship between vulnerability and resilience is not linear. Lowering vulnerability may or may not increase resilience, or may even create other forms of vulnerability (Oliver-Smith, 2009, p. 15). Furthermore, regimes that are considered undesirable can also be very resilient. Resilience does not only support and maintain a system in a desirable state, but may also maintain a system in an undesirable state, making recovery difficult. Likewise, some system regimes may be considered desirable by some parts of a community and undesirable by others. Although resilience is now applied in various disciplines and different fields and contexts, it is not a universally accepted term. IPCC (2012) defines resilience as “the ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration, or improvement of its essential basic structures and functions” (IPCC, 2012, p. 563). According to Walker et al. (2006), resilience rests on three abilities: (1) to anticipate and deal with the impacts of natural hazards; (2) to adapt to change; and (3) to be proactive and self-determining, rather than just reactive and outside-determined. The term resilience is used in this paper as the “ability of coastal social–ecological systems (SES) to cope with the impacts of a hazard event and reorganise while undergoing change so as to still retain essentially the basic structures and functions”.

2. Coastal vulnerability and hotspots

Coastal zones are subject to both hazards from land (e.g., river flooding) and from the sea (e.g., storm surge, tsunami). In addition, population and urban settlement patterns result in vulnerability hotspots (Newton et al., 2012) that are located disproportionately in coastal zones (Pelling and Blackburn, 2013).

McGranahan et al. (2007) calculated that the Low Elevation Coastal Zone (LECZ), defined as the contiguous area along the coast that is less than 10 m above sea level, covers only 2% of the world's land area but contains 10% of the world's population and 13% of the world's urban population. This area is one of the most vulnerable to sea level rise, one of the consequences of climate change (IPCC, 2013). There are variations and uncertainties with regard to the exact number of vulnerable coastal population, depending on the quality of input datasets and differences in methods used to construct spatial population datasets (Mondal and Tatem, 2012). However, it is obvious that many of the recent (2004–2011) costliest disasters occurred in coastal zones (Table 1), not only in terms of financial losses but also in terms of fatalities. In the 30 years between 1980 and 2009, there were 416 significant flood events (not all coastal) in Europe which are classified as ‘significant’. Nearly 9 million people were affected, there were 2546 fatalities and economic damages are estimated to be greater than €75 billion (<http://www.cred.be/>). For coastal flooding, Ciscar et al. (2011) used IPCC scenarios to model the increase (with respect to 1995) in number of people affected annually. The 2.5 °C increase coupled with 49 cm sea level rise affected 775,000 people, whereas the 5.4 °C increase and 88 cm sea level rise affected 5.5 million. These estimates will now have to be revised in view of the latest figures for Sea Level Rise and temperature increase (IPCC, 2013). The ranges of loss in household welfare was 0.16–0.46% and the drop in GDP was 19–0.24%. The potential economic impact of coastal flooding was \$13 trillion (€9.97 trillion) or \$8 trillion (€6.14 trillion) in 2010, with increases since 1970 (Jongman et al., 2012).

Table 1

The costliest natural disasters in coastal zones (since 2004). Fatalities are not given as they are not the focus of this paper.

Rank	Year	Geo-event	Convective event	Winter storm	Flood	Region/Country	Total losses ^a	Insured losses ^a	% Of loss insured
1	2011	Tohoku Earthquake, tsunami				East coast/Japan	210	35–40	17–19
2	2005		Katrina			Gulf coast/USA	125	61.6	49
3	2004	Two earthquakes				Honshu/Japan	28	0.8	3
4	2004		Ivan			Caribbean, USA	23	13.8	60
5	2008			Winter damage		China	21	1.6	8
6	2005		Wilma			Caribbean, Mexico, USA	20	12.4	62
7	2004		Charley			Florida/USA	18	8	44
8	2005		Rita			Gulf coast/USA	16	12	75
9	2007	Earthquake				Niigata/Japan	12.5	0.3	2
10	2004		Frances			Caribbean	12	5.5	46
11	2004	Earthquake, tsunami				Indian Ocean	10	1	10
12	2007			Kyrill		Western Europe	10	5.8	58
13	2008				Floods	Midwest/USA	10	0.5	5
14	2004		Jeanne			Caribbean	9.2	5	54
15	2004		Songda			Japan, South Korea	9	4.7	52
Number	5		8	2	1				
Total loss	260.5		232.2	31	10		533.7		
% Total loss	48		44	6	2				Mean 36

^a In US\$ billion.

Source: modified after Kron (2008, p. 5)

Table 1 shows that earthquakes and tsunamis are extremely destructive and costly, accounting for about 48% of the total losses since 2004. However, meteorological events such as hurricanes, cyclones and typhoons are almost as costly (44% of total). The financial costs do not reflect the loss of life, for example the deadly 2004 earthquake–tsunami (Banda Aceh) is ranked 11th in comparison to the earthquake–tsunami (Tōhoku), which claimed fewer victims but ranked first for financial losses. It is interesting to note that on average (mean) only 36% of the losses were insured. This also varies considerably, for example the Caribbean and Gulf coast seems to be well covered by insurance for losses from its frequent storms (mean 56% cover over seven major storms). In contrast, there was only 5% of insurance cover for the Midwest floods. In Asia, the percentage of insurance cover is also much lower, with only 15% average insurance cover for the six largest events (earthquakes, tsunamis, and storms, including Songda). However, if Songda is not included in the calculation of the mean, this figure drops to only 8% for the five largest disasters in Asia.

The IPCC-SREX reveals that, in many regions, the main drivers of future increases in economic losses due to some climate extremes will be socio-economic in nature (IPCC, 2012, p. 273), “medium confidence, based on medium agreement and limited evidence”. This highlights that robust studies are still needed, especially ones that are capable of identifying and addressing the underlying causes and key drivers of vulnerability. An example is a study that links climate risk and the economics of real estate (McNamara and Keeler, 2013) and the resulting responses of those living in flood zones. The multifaceted terrain at the interface between conceptual thinking and practical applications too often remain unexplored. Specific gaps exist with regard to operational methodologies applicable by local practitioners, studies addressing the underlying causes and systemic drivers of vulnerability and thus providing empirical evidence, and a lack of unity between expert and local knowledge (Tribbia and Moser, 2008; Tapsell et al., 2010; Weichselgartner and Kaspersen, 2010; IPCC, 2012).

Hotspots of coastal vulnerability: As a scientific response to the impact of these natural hazards, the Land–Ocean Interactions in the Coastal Zone (LOICZ) project identified four coastal hotspots (Newton et al., 2012) that are particularly vulnerable. They include Arctic coasts, small islands, river–mouth systems, and urban coasts. A brief overview emphasizing the vulnerability of these coastal hotspots is given in the following sections to illustrate the socio-

ecological complexity of coastal vulnerability issues in the context of global environmental change.

2.1. Vulnerability of Arctic coasts

2.1.1. Drivers and pressures

Global environmental change is making oil, gas, and other large scale mineral deposits increasingly accessible as well as opening northern sea routes (Arctic Council, 2009; Smith and Stephenson, 2013). The demand for natural resources from the energy and mining sectors are therefore some of the major drivers of Arctic transformation. This results in increasing opportunities for extraction and shipping activities as well as the influx of new northern residents. The population of the vast Arctic region is only about four million, of which only about ten percent are indigenous (Forbes, 2011). The inhabitants of the Arctic coastal zone are therefore culturally, politically, demographically and economically very diverse, encompassing remote Inuit settlements and increasingly urban cities such as Tromsø. Arctic societies are vulnerable to a combination of rapid changes involving environmental processes, cultural developments, economic changes, industrial developments, and political changes.

2.1.2. State of the environment

Global environmental change may well result in an ice-free Arctic ocean in the next decades (IPCC, 2013). This puts increased emphasis on observing Arctic change, predicting the impacts on the social systems at various scales, as well as exploring the response options for adaptation and possible societal responses. The loss of important ecosystem services, such as reflecting back sunlight, from ice-cover is still poorly understood (Eicken et al., 2009). The changes in the carbon cycle due to climate change in the Arctic is an issue of global concern. Future research is needed to incorporate the understanding gained from observational and process studies across a spectrum of spatial and temporal scales into both uncoupled and fully coupled carbon–climate models (McGuire et al., 2009). It remains a major challenge for the scientific community to study the effects of global warming in the Arctic, which – may be irreversibly – affecting a broad spectrum of social–ecological systems.

2.1.3. Impacts on human welfare

Global environmental change impacts Arctic inhabitants in different ways (ACIA, 2004). Many traditional activities of the

indigenous Arctic communities are increasingly at risk, with major impacts on social identity and lifestyles. Strong social networks that have facilitated adaptability in Inuit communities are being undermined by the dissolution of traditional ways of life (Ford et al., 2006). Changes are also forecast for Arctic fisheries (Forbes, 2011) that will impact fishing communities through changing employment opportunities as well as the distribution of income and wealth. The social impacts are therefore especially felt by local communities that are located in more resource-strategic positions, such as along the Arctic coasts.

2.2. Vulnerability of small islands

2.2.1. Drivers and pressures

Islands are particularly good illustrations of the interdependence of Humans and their environment. This is particularly true of small islands, which have a relatively large coastal zone and a small, exposed interior. Small islands are the quintessential social-ecological system, with a high dependence on local (island) natural resources, often resulting in highly specialised production. In addition, islands have a limited natural resource base with a spatial concentration of productive assets. Increasingly, traditional subsistence farming and fishing are being replaced by commercial agricultural and aquaculture production. Remoteness generates deeper poverty and livelihood vulnerability – but paradoxically, this can be turned into a comparative advantage (FAO, 2006).

Small islands present singular demographic factors, such as a limited human resource base, a relatively small population, rapid population changes, often a single urban centre and a population concentrated in the coastal zone. There is intense land-use and high competition for it. The small economies are not competitive and global market liberalisation and economic globalisation can threaten the economic security of small islands (Pelling and Uitto, 2001).

Remoteness is another consequence of insularity that results in high transport costs and time delays, dis-economies of scale leading to high per capita costs for infrastructure, such as bridges, and services, such as electrical supply. Kelman and Khan (2012) illustrate the complicated migration-vulnerability links of small islands. The emigration of the skilled population can result in a situation of brain drain. Social-economic factors, such as poverty, age, health problems, marginalisation, and lack of access to information, discourage migration of certain segments of the island population. Moreover, poor people often move to coastal areas to gain access to common coastal and marine resources. Thus, vulnerability to hazards and manifestations of that vulnerability is both a reason for migration and a major factor preventing migration. While vulnerability may be an incentive for migration from the coast the options may be very limited or non-existent on a small, low-lying island.

2.2.2. State of the environment

Small islands and coral reefs are vulnerable to multi-stressors, such as climate change, ocean acidification, bleaching and extreme events, migration, multiple resource use, contaminants, pollution, dynamite fishing, invasive non-native species, eutrophication and turbidity (Hughes and Connell, 1999; Pelling and Uitto, 2001). According to the IPCC (2012, p. 15), the very likely contribution of mean sea level rise (SLR) to increased extreme coastal high water levels, coupled with the likely increase in tropical cyclone maximum wind speed, is a specific issue for tropical small island states. Global environmental change therefore places Caribbean, Indian Ocean and Pacific Ocean low-lying islands in the front line of vulnerability. These islands may experience the largest relative increase in flood risk due to sea level rise (Nicholls et al., 1999; Woodroffe, 2008).

Global environmental change also affects the physical vulnerability of islands through changes to fresh water and geomorphology. Reefs perform valuable ecosystem services, including coastal defence, and their loss will impact human well-being. In tropical regions, the change of state of reef island ecosystems, as a consequence of SLR, are still poorly understood.

2.2.3. Impacts on human welfare

Natural disasters, such as cyclone Evan in December 2012 in Samoa, can affect the biodiversity and impact livelihoods on small islands. These result in salt intrusion (Mimura, 1999) and coastal erosion (Zhang et al., 2004) and subsequent loss of ecosystem services that impact Human welfare. Thus, island vulnerability arises from spatially variable combinations of these physical, biological, and socio-economic factors.

2.2.4. Response

The unique characteristics of islands and the narrow spatial scale require the development of appropriate economic, social and environmental vulnerability indices and related indicators as tools for the achievement of the sustainable development of Small Island Developing States (UN, 2005). Since vulnerability is heightened in a small island situation, it is important to combat complacency, boost disaster mitigation capability, improve hazard forecasting, and extend insurance cover. Nevertheless, recovery on a small island hit by a disaster can be difficult (Bunce et al., 2009). It is necessary to improve island social-ecological systems response and adaptation capacities system change and other sudden shocks by increasing cross-scale connectivity (flows of people, goods, information, money, power).

Island communities are characterised by social resilience and adaptive capacities, including traditional and acquired skills, economic and social capital endowments, and institutional networks. A study in Sagar Island, India, examined how different occupational groups perceive environmental hazards from their respective occupational standpoints, underpinning the importance to amalgamate diverse occupational groups and to actively involve them in hazards management (Mondal, 2013).

The political economy and island governance contexts affect resource entitlements and adaptation options, eroding resilience of coastal societies and increasing their vulnerability. Governance is highly context-dependent and island-specific rules may apply (Glaser et al., 2010).

It is important that coastal policy-makers and managers adopt holistic views that integrate science-based understanding of coastal dynamics with local communities' perceptions of change and management responses. For example, on the Caymans and other Caribbean islands hit by hurricanes in 2004, repair materials became scarce and shortages of labour became problematic. Some repairs were carried out by workers with little or no training, thus leaving the buildings even more vulnerable to subsequent storms (Munich Re, 2006, p. 25). Coastal vulnerability can be mitigated by strengthening key resilience elements. Ecosystem-based approaches are one promising type of management response (Grantham et al., 2011).

2.3. River-Mouth systems

2.3.1. Drivers and pressures

River-mouth systems (RMS) occupy a unique space in the Earth system where land, sea, and atmosphere all meet. This makes RMS particularly vulnerable to hydro-meteorological events, since they can be subjected to storm surges from the sea and floods down the catchment. Many of the river basin syndromes listed by Meybeck (2003) have parallel consequences on coastal systems (Newton

et al., 2012), which makes RMS particularly susceptible to fluxes of water, sediment, fertilisers, and contaminants. Surface and ground water from rivers and aquifers is extracted to support agriculture, industry, and domestic consumption.

2.3.2. Environmental state

There are numerous indices applied to various aspects of vulnerability of RMS. These usually focus on a particular issue, such as eutrophication, and many have been widely tested and applied (Gordon et al., 1996; Bricker et al., 2003; Swaney and Giordani, 2011). Nevertheless, an integrated tool that considers both physical and social vulnerability of RMS to multiple pressures, threats and hazards is still lacking. One example is the over-extraction of ground water that contributes to subsidence, so that many of the major deltas are sinking (Syvitski et al., 2009) and pumping can even trigger earthquakes (Gonzalez et al., 2012). This is particularly problematic in view of climate change scenarios (Nicholls et al., 2008a).

2.3.3. Impact on human welfare

River-mouth systems have long provided multiple ecosystem services to mankind, in particular to the urban population. Floodplains in low-lying coastal zones, especially deltas, offer both benefits and risks and it is society and its governance system that determines which, and to whom. Some of the largest cities in the world are associated to RMS and this presents special problems described in the following section.

2.4. Physical and social vulnerability of urban coasts and megacities in the coastal zone

2.4.1. Drivers and pressures

Population, urbanisation and property values in the coastal zone are increasing (McGranahan et al., 2007; Sekovski et al., 2012; Mee, 2012). There is a parallel escalation in exposure and vulnerability, particularly along the Gulf and Atlantic coasts of the United States (IPCC, 2012, p. 19). Many features of large coastal cities contribute to both their physical and social vulnerability. For example, intense demand for land for urban development is a driver for wetland reclamation, draining, and subsequent construction on unconsolidated sediments that are vulnerable to liquefaction during earthquakes.

2.4.2. State of the environment

The degradation and reclamation of wetlands and the loss of their multiple ecosystem services are serious concern (Gedan et al., 2011; Shepard et al., 2011). Now that humans have drained large areas of wetland to develop coastal cities, the benefits and ecosystem services are starting to be recognised. Ironically, humans are now constructing wetlands for storm water (Moore and Hunt, 2012).

2.4.3. Impact on human welfare

The concentration of crucial physical assets, productive industries, and energy installations, and city infrastructure (tunnels, bridges), increase existing vulnerabilities. Rodriguez-Vidal et al. (2012) mapped the world's geographic zones that are at risk of large tsunamis. This highlighted 23 nuclear power plants with 74 reactors in high risk areas, mostly located on shorelines in South and Southeast Asia. City inhabitants are very dependent on dense and complex systems of interconnected services and infrastructure for core services (water, electricity, and transport), and this vulnerability extends from the urban core into the hinterland. Spatial concentration brings both benefits (e.g., economies of scale) and risks, often cascading into domino effects that pose a great challenge for spatial planning. Cities concentrate populations and therefore are vibrant with social-cultural diversity. But coastal

cities also have large vulnerable populations of migrants who are marginalised by poverty, limited entitlements, and absent social safety nets. Coastal cities are centres of political power, economic activity, global trade and finance. Their strategic importance results in a capacity to trigger economic contagion at national, regional and global scales after a natural disaster, such as New York after hurricane Sandy and Tokyo after the Tōhoku earthquake.

3. Environmental and anthropogenic drivers and pressures of coastal vulnerability

In this section, the DPSIR (Driver-Pressure-State-Impact-Response) framework is used to examine the environmental and anthropogenic drivers and pressures that contribute to coastal vulnerability.

Coastal systems are dynamic, undergoing modifications and adjustments of form and process at different spatial and temporal scales in response to geomorphological and oceanographic factors. Hence, vulnerability to coastal hazards is multi-causal, multi-dimensional, and nested in multiple scales. However, the potential capacities counteracting vulnerability also are multi-level. Thus, it would be inappropriate and not very effective to use a conventional “one-cause/one-effect” approach to address coastal vulnerability, because the natural variability of coasts hinders the exact identification of the drivers and quantification of pressures of coastal vulnerability.

Environmental **drivers** of vulnerability are diverse. They include natural hazards such as windstorms, storm surges, and tsunamis. While these are natural events, their frequency and intensity is being affected by human activities. Examples include (1) increases in sea surface temperature (SST) affecting storm formation; and (2) intensity and subsidence from over-extraction contributing to SLR. Anthropogenic **drivers** and **pressures** act in synergy with environmental drivers and pressures contributing to coastal vulnerability. The combination of natural and anthropogenic drivers, operating at difference scales, and the interacting drivers and pressures are presented in Table 2. Some of these drivers are also not independent of each other, illustrating the complex web of diverse social and economic drivers and pressures. These include demography, health, education, governance, wealth, social needs, social networks, degradation of social-ecological systems, as well as development, urban, economic and technological.

Some global processes are significant drivers of risk and are particularly related to vulnerability creation (IPCC, 2012, p. 70ff.). There is high confidence that these include anthropogenic drivers and pressures such as population growth, rapid and inappropriate urban development, international financial pressures, increases in socio-economic inequalities, trends and failures in governance (e.g., corruption, mismanagement), and environmental degradation. Development for industry, shipping, transport, aquaculture, and tourism needs to be adequately adjusted to potential hazards, especially in coastal zones at risk.

Table 3 illustrate the diversity of drivers and pressures interacting in a complex way, resulting in a multiplicity of causal structures and societal responsibilities. It follows from a coding system-based meta-analysis (Zou and Thomalla, 2008) that examined the scientific literature on social vulnerability to coastal hazards in South and Southeast Asia to determine the relationships between the drivers and pressures contributing to hazard vulnerability in order to review recommendations made for reducing vulnerability to coastal hazards. The selected documents – 120 scientific articles published in academic journals and 8 journal editorials or communications, all published in English between 1970 and 2006 – were characterised in terms of the disciplinary and geographical affiliations of the authors, their epistemological

Table 2
Dynamic drivers, stresses and pressures affecting coastal zones.

Drivers (Earth system: environmental and anthropogenic)	Stresses and pressures
Plate tectonics	Damage from earthquakes and tsunamis
Climate change	Sea-level rise, sea surface temperature
	Damage from windstorms and storm surges
	Ocean acidification
Energy needs	Oil spills (contamination)
	Changes to seabed (e.g., wind farms)
Demographic changes	Coastal defences
Urbanisation of the coast	Draining of wetlands
	Impermeabilisation of surfaces
	Flooding
	Increased effluents and sewage
Technological developments (e.g., damming by energy and agricultural sectors)	Erosion from disrupted sediment fluxes (e.g., sediment retention by dams)
Exploitation of natural resources (e.g., fisheries)	Loss of ecosystem services
	Degradation of social-ecological systems (e.g., overfishing)
Shipping and maritime activities	Port structures
	Dredging
	Antifoulants
	Ballast water introduces NIS
	Marine litter
Changes in global economy (e.g., price of petrol)	Oil exploration
	Off shore platforms and wind farms
Changing societal needs and lifestyles (e.g., increase animal protein consumption)	Pressures from shipping (see above)
Changing belief and value systems (e.g., gentrification of the coast, recycling)	Eutrophication from disrupted nutrient fluxes (e.g., Harmful Algal blooms)
Tourist resorts	Increase in urban pressures such as sewage
Marinas	

Table 3
Most frequently mentioned individual drivers contributing to vulnerability to coastal hazards.

Environmental drivers and pressures	Rank and	Number of times mentioned	Human dimension drivers and pressures
Climate change	1	44	Population growth
	2	34	
Change in the level of rainfall	3	33	
	4	30	Development and land use change
	5	28	Individual poverty
Low-lying coastal land	6	27	
	7	26	High population density
Sea-level rise	7	26	
Deforestation	9	25	
High wind during monsoon season	10	24	
	11	23	Habitation of high-risk marginal areas
	11	23	Contaminated fresh water
	13	22	Lack of access to assets and entitlements
	14	18	Poorly planned industrial development
Timing of disaster	14	18	
	14	18	Post-disaster disease incidence
	17	17	Migration
	18	16	National poverty
	18	16	Resource dependency
	18	16	Social inequality

Source: modified after Zou and Thomalla (2008, p. 52)

billion, it far exceeded 2005, previously the costliest year on record. Insured losses also came to a record US\$ 105 billion. Munich Re's Geo Risks Research, recording all natural hazard events that give rise to property damage or personal injury, registered 820 loss-related events in 2011, which corresponds to the average number of events for the past ten years. Depending on the monetary and humanitarian impact of these events, they are divided into six categories, ranging from minor losses to great natural catastrophes (i.e., thousands of fatalities and/or hundreds of thousands left homeless and/or substantial economic/insured losses). Fig. 1 illustrates 50 selected major events (small circles) and the five great natural catastrophes (big circles) for 2011. The predominant contribution has been the Tōhoku earthquake in Japan, the most costly natural catastrophe in history. Preliminary U.S. damage estimates are near US\$50 billion, making Sandy the second-costliest cyclone to hit the United States since 1900. There were at least 147 direct deaths recorded across the Atlantic basin due to Sandy, the greatest number of U.S. direct fatalities related to a tropical cyclone outside of the southern states since Hurricane Agnes in 1972 (Blake et al., 2013).

The list of natural disasters is endless, especially those with a focus on the coastal zone. They include historical events such as the widespread destruction caused by the Lisbon earthquake and tsunami (1755). The enduring cultural importance of such events is reflected in the myths and legends of the destruction of the Minoan civilisation as well as religious texts from different religions describing great floods. In the last decades, there are many examples of extraordinary natural hazard events that caused great disasters (Fig. 2), either in terms of scale, number of fatalities, or financial losses, many of which are in the increasingly crowded coastal zone (Mee, 2012).

The observed upward trend in the frequencies of loss events from natural disasters is predominantly down to weather-related events (Munich Re, 2012). When comparing regions in the trends of frequencies of weather-related natural catastrophes, the largest increase happens in North America followed by Asia – both continents with long, intensively populated coast lines. Moreover, the long-term trend visible on the so-called convective event losses from big thunderstorms is critical for many coastal areas.

approaches and methodologies, and the focus of their work within the disaster risk reduction cycle. In 128 selected articles, a total of 336 vulnerability factors and 227 recommendations were identified and analysed. The 20 most frequently mentioned individual factors contributing to vulnerability to coastal hazards (Table 3) illustrate the diversity of factors interacting in a complex way, resulting in a multiplicity of causal structures and societal responsibilities. Surprisingly, there was no local case study among the large number examined that employed a conceptual or theoretical framework to guide the analysis: *“There are very few links in the literature between theoretical thinking and the context-specific richness of experience and knowledge derived from local case studies”* (Zou and Thomalla, 2008, p. 5). Moreover, the authors identified existing mismatches between causal factors producing social vulnerability and the recommendations for its reduction and management, with most of the recommendations failing to target the underlying factors while focussing on short-term relief.

Apparently, the gap between conceptual work on vulnerability and empirical case studies largely contributes to our incomplete understanding of drivers and pressures of coastal vulnerability and their interconnectivity (Thomalla et al., 2008; Wallendorf et al., 2008). Good examples of this are the multi-stressors on the Great Barrier Reef system (Butler et al., 2011) as well as on sea-ice in both the Arctic and Antarctic (Eicken et al., 2009).

4. Impacts on human welfare: social-economic costs in the coastal zone

The year 2011 was the most expensive natural catastrophe year ever in economic terms (Munich Re, 2012, p. 50f.). At US\$ 380

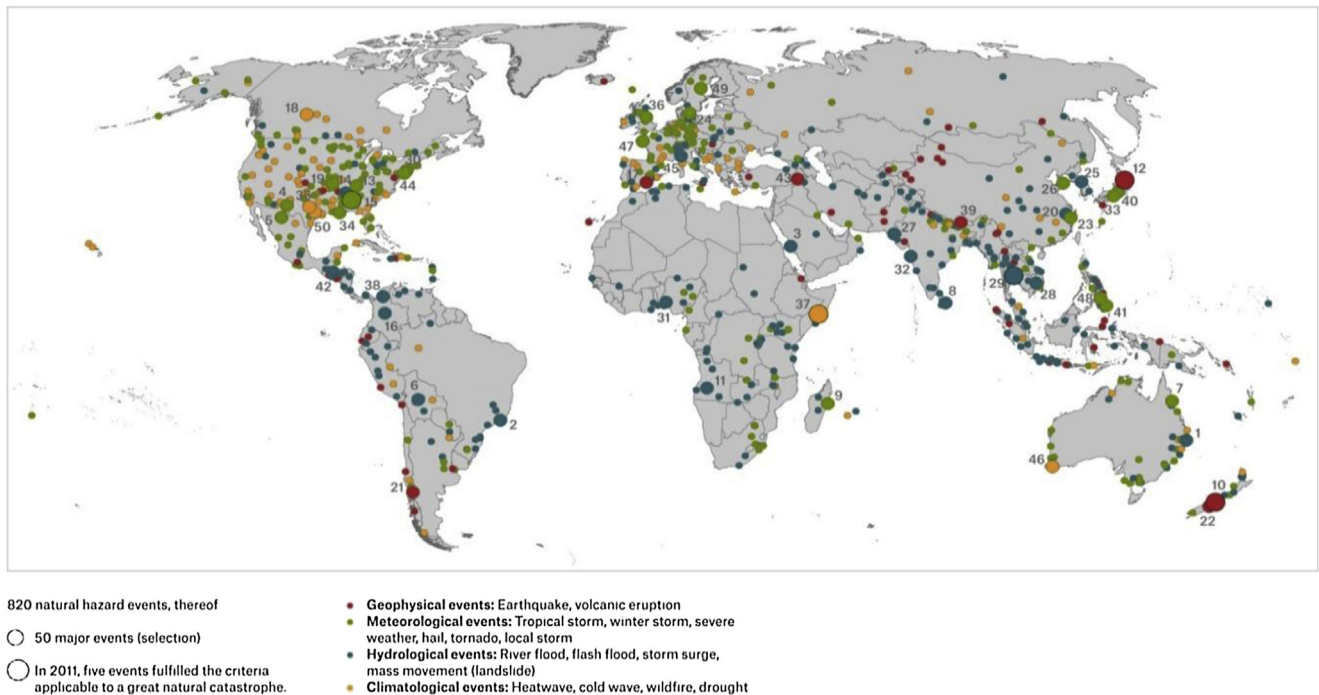


Fig. 1. World map of natural catastrophes 2011.

Source: [Munich Re \(2012, p. 59\)](#)

Hydrological and meteorological events can be very destructive, expensive, and cause mortalities. In 2010, storm Xynthia caused widespread destruction in western Europe. Particularly at the French Atlantic coast, the storm resulted in a significant amount of flooded land, more than forty fatalities, and considerable financial costs. Just in France, total public expenditure amounted to € 467 million; insurance payouts came to € 690 million to cover damaged infrastructure ([Cour des comptes, 2012](#)). In 2008, Myanmar was hit by tropical cyclones that left thousands dead and vast landscapes destroyed by wind and flooding. In 2007, it was Bangladesh that was battered by storms as was Australia, where the east coast suffered four consecutive storms. In January 2007, winter storm Kyrill cost US\$ 10 billion in Europe, whilst losses due to flooding in the United Kingdom amounted to US\$ 8 billion. In 2005, hurricane Katrina passed six other hurricanes and climbed on top of the most expensive natural disasters for the insurance industry in the USA. In 2011, the losses caused by large thunder storm related events in the US are at a record high, about 50 percent higher compared with 2010 ([Munich Re, 2012](#)). Likewise, geophysical events (e.g., earthquake, tsunami) can have severe impacts on the coastal zone. On 26

December 2004, a disastrous tsunami killed more than 220,000 people in 13 countries around the Indian Ocean ([Kron, 2008](#)). Almost one decade later, it is still visible that livelihoods and local economies have been impacted by the loss of mangrove and aquaculture farms ([Griffin et al., 2013](#)). In March 2011, the tsunami triggered by the Tōhoku earthquake not only devastated several hundred kilometres of Japanese coastline but also led to the nuclear disaster at Fukushima.

5. Societal response: pathways to resilience

During the last decades, scientific understanding of the dynamic, complex and interacting processes contributing to vulnerability has improved considerably ([Kasperson et al., 2005](#); [IPCC, 2012](#)). Despite these advances, gaps still exist with regard to practical applications of conceptual thinking in vulnerability assessment, operational methodologies relevant for and applicable by local practitioners, concrete measures that address the systemic underlying causes of vulnerability, and assessing the substantial costs of implementing vulnerability reduction strategies ([Tribbia](#)

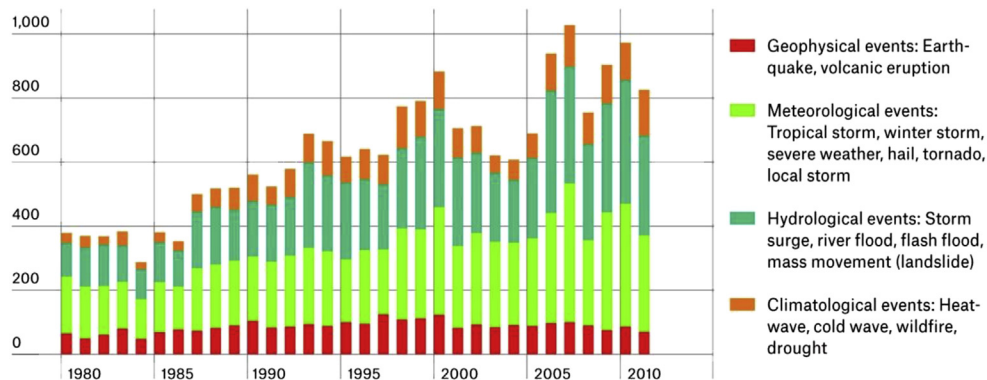


Fig. 2. Number of natural catastrophes 1980–2011.

Source: [Munich Re \(2012, p. 50\)](#)

and Moser, 2008; Weichselgartner and Kaspersen, 2010). Recent efforts to co-design frameworks and co-produce assessments together with inputs of coastal planners, climate change experts, risk practitioners, and development professionals (e.g., Tobey et al., 2009; Camill et al., 2012; Sherrieb et al., 2012), and to quantify coastal vulnerabilities (e.g., Nicholls et al., 2008b; Balica et al., 2012) are constructive pathways to close existing gaps.

More attention should be paid to synthesising existing local knowledge and resources from non-scientific entities, since these are the avenues through which people experience the changes in social–ecological systems (Weichselgartner and Marandino, 2012). This would give a better understanding of how the various factors interact to produce social vulnerability to coastal hazards in different environmental, historical, and social contexts. More comparative studies synthesising the collective experience are also needed, since most study findings are highly context and place specific.

The coastal zone is appropriate to both study GEC processes (because almost all are evident there) and to develop mitigation and adaptation measures (because they are most needed there). The development of appropriate assessment indicators and evaluation criteria could be strengthened if the efforts of science, policy, and practice would jointly concentrate on a specific social–ecological system, such as coastal zones. Focussing on the “social–ecological system coastal zone” has the advantage to combine environmental and anthropogenic aspects to seek empirical evidence regarding the many factors and drivers of coastal vulnerability. Most vulnerability assessments to date have based their evaluation and judgement on a relative comparison of vulnerability levels between different social groups or regions (IPCC, 2012, p. 94). But a gap remains between theoretical concepts and practical applications. This could be overcome by efforts of science, policy, and practice, to jointly design vulnerability reduction measures. We suggest to begin with four components, which are suitable for joint collaboration on defining integrative and consistent goals for vulnerability reduction.

The 4 key components that we consider crucial in order to decrease vulnerability and enhance resilience are: (1) raising awareness, (2) advancing forecasting, (3) enhancing preparedness, and (4) improving risk governance.

5.1. Raising awareness

There has been some excellent research into the environmental and engineering components of coastal vulnerability, but far less on the assessment of the societal aspects of coastal vulnerability. Public risk perception is usually linked to past experiences, so recent residents may underestimate their risk even if they know they are living in a flood-prone area Bradford et al. (2012). This differs from that of flood managers who base their perception on probabilities. In particular, the presence of coastal defence structures may create a sense of false security. Fundamental aspects are the capacity to prepare for, mitigate and adapt to vulnerability and exposure to a natural hazard. Assessment of coastal vulnerability should therefore consider the impact of coastal emerging risks minus the effects of adaptation. Few methodologies have been developed to systematically assess coastal vulnerabilities and societal impacts from environmental risks and stresses. Existing impact assessments focus on large urban centres and coast lines of economic importance.

5.2. Advancing forecasting

Despite the success of systems such as Meteoalarm, “MyWorld-Weather” and the Helsinki Testbed system, there is still a need for

innovation in the forecasting capability of hydro-meteorological hazards and their extremes. This should improve the provision of timely information and warnings to decision makers and the public for saving lives and avoiding economic losses. Innovative methods for assimilation of different types of information used for now-casting and very short range forecasting of severe weather are still to be developed and tested. For long-term forecasting, it is necessary to develop scenarios that forecast the effects of climate change on risk from extreme meso-meteorological events as severe winds, storm surges, squallines, local circulations, coastal and estuarine floods based on IPCC projections using global climate models. While changes in storminess may contribute to changes in extreme coastal high water levels, the limited geographical coverage of studies to date and the uncertainties associated with storminess changes overall mean that a general assessment of the effects of storminess changes on storm surge is not possible at this time (IPCC, 2012, p. 18). Reconciling regional and local scale as well as the medium-term versus short-term forecasts remains a major challenge (Demeritt et al., 2013). For example, the European Flood Alert System part of the EC Global Monitoring for Environment and Security (GMES) Emergency Management Service that focuses on river flooding, has not been fully integrated into Member States flood risk management programmes. Smart phones are an obvious way of delivering targeted information to individuals, but extreme events can shut down core services, including cellular networks, so we should not rely too heavily on these.

5.3. Enhancing preparedness

Among the greatest remaining challenge is the translation of the knowledge gained into operational assessment methodologies for practitioners and tools for decision-makers to develop effective management strategies and policies to reduce vulnerability to natural hazards (White et al., 2001; Weichselgartner and Obersteiner, 2002; Cutter et al., 2012). This includes simple measures, such as the supply of sandbags, to sophisticated evacuation and emergency plans and procedures. These may be linked to triggers, such as water level, that lead to a management action (Lumbroso et al., 2012). A major challenge is the spatial mismatch between zones at risk from flooding and administrative boundaries. Stimulating public participation through better communication is fundamental to enhancing preparedness. Maps, risks and plans should be available to the public through the internet. The roles and responsibilities of different actors involved with flood management need to be more clearly defined.

Flood management tools are in place, but sometimes remain unused and are often poorly understood by local residents and should be adapted to local needs. The existing tools differ in scope, approach, complexity, and application scale, making it difficult for the stakeholders to select the tools appropriate for the local circumstances. The methodologies frequently require data or modelling expertise that is unavailable or too expensive for local decision makers who need them to make informed decisions about mitigation and adaptation. Coastal managers prefer certain types of information and information sources and thus would benefit from various learning opportunities to make better use of available information (Tribbia and Moser, 2008). In addition, they require financial and technical assistance from other agencies at the state and federal level to implement vulnerability reduction and adaptation measures. Knowledge is needed to identify options for intervention and leverage points that can move coastal systems toward transitional and less vulnerable development pathways. An interdisciplinary team of scientists working with local stakeholders can mobilise and empower coastal risk networks to share knowledge and co-design improvements to coastal risk management so

as to reduce the disaster risks from coastal hazard (Schelfaut et al., 2011; Heintz et al., 2012). Campaigns should focus on easy to implement flood mitigation measures for householders and locally tailored information on evacuation (Bradford et al., 2012).

5.4. Improving governance

Improving and integrating risk governance is a vital pathway to reduce coastal vulnerability. Among the many difficulties is the complex and often unclear distribution of responsibilities between various public and private actors, including home owners, insurers, and local and national governments (providing or not providing coastal protection, mitigation, and compensation measures). Constitutional reforms may be required and a more effective environmental governance system may have to be instituted (Biermann et al., 2012). An example of this is in Europe. Losses from floods (not all coastal) prompted the adoption of a legal instrument to improve flood-risk governance. Directive 2007/60/EC on the assessment and management of flood risks that entered into force on 26 November 2007. The Directive now requires Member States to assess if all water courses and coast lines are at risk from flooding, to map the flood extent and assets and humans at risk in these areas and to take adequate and coordinated measures to reduce this flood risk. This Directive also reinforces the rights of the public to access this information and to have a say in the planning process. However, Member States are not applying the Directive in the same way (Klijn et al., 2008).

Indeed, more innovation is needed in governance to re-orientate institutions and responsibilities in disaster risk management. This includes a critical assessment of progress in disaster risk reduction, using the Hyogo Framework for Action 2005–2015 of the United Nations International Strategy for Disaster Reduction as reference (UNISDR, 2005), and concerted efforts in disaster risk education, capacity building, and empowerment of citizens to ultimately put “words into action” (UNISDR, 2007).

6. Concluding remarks

Dramatic loss of life and economic losses in coastal zones in recent years have focused attention on natural and Man-made hazards. It is essential to synthesise and capitalise on the knowledge gathered from past disasters and related research to develop best practice models.

What lessons can we learn from past disasters?

- 1) Lesson number 1, **How to build**: The 1755 earthquake in Lisbon launched the era of earthquake-proof construction, the “*gaiola pombalina*”, named after the Marques de Pombal.
- 2) Lesson number 2, **Where not to build**: Rebuilding was setback from the sea front after repeated tsunamis at Hilo, Hawaii (Newton et al., 2011). After the 2004 Indian Ocean tsunami, the Indian government mapped the whole coastline to establish setback lines. There will be no rebuilding in areas subject to liquefaction after the Christchurch earthquakes. Sites for key infrastructure such as power plants (especially nuclear) should be set well back from the coastal zone.
- 3) Lesson number 3, **No regrets and no false security**: Construction of inadequate coastal defences can create a sense of false security and investment pays off in the long term. Cash-strapped managers are loathe to make expensive long-term “no-regrets” decisions, thus gambling that the disaster will not occur on their watch. The cost of hurricane Katrina was orders of magnitude greater than the cost of strengthening the dykes would have been. When various options are available, a cost-benefit analysis can yield interesting results (Meyer et al., 2012)

- 4) Lesson number 4, **Disaster are improbable but they do happen**: Much to the outrage of the international science community, seven Italian scientists and risk experts were prosecuted and convicted for multiple manslaughter based on “false assurances” before the l'Aquila earthquake of 2009. This highlights the fundamental mis-understandings between the public and the scientific community arising from probability. The IPCC reports now couch every statement with a “probability” statement.
- 5) Lesson number 5, **Coastal ecosystems provide valuable ecosystem services including coastal protection**. The impacts of the 2004 Indian Ocean tsunami in Banda Aceh showed that coastal ecosystems, such as mangroves and coral reefs, perform valuable services protecting the coastal populations from tsunamis. The importance of ecosystem services for coastal protection has been assessed by Lique et al. (2013).
- 6) Lesson number 6, **Collateral damage can also be serious**. Collateral damage is also a serious consequence of coastal disasters, with examples of widespread fire from oil lamps in Lisbon (1755) and a nuclear emergency in Japan (2011).
- 7) Lesson number 7, **Warning systems save lives and forecasting is essential at an ocean scale**: Repeated loss of life from tsunamis resulted in the implementation of a tsunami warning system for the Pacific, but there was no early-warning system in place for the Indian Ocean in 2004.
- 8) Lesson number 8, **Awareness and preparedness saves lives**: The areal video footage of the Tōhoku tsunami showed the magnitude of the event. Although there was tragic loss of life, the number of fatalities was relatively small because of the high level of awareness and preparedness of the Japanese population who followed well established evacuation plans.

As the population of the coastal zone grows, there is an increase in exposure of people and economic assets. Therefore, there is an urgent need to strengthen disaster mitigation and risk governance efforts, as climate change is altering the frequency and magnitude of meteorological and hydrological hazards.

Coastal societies can be vulnerable to multiple threats, so an integrated multi-criterion approach is necessary to determine coastal vulnerability. Realistic scenarios are also needed in order to enhance forecasting capabilities, as well as improving the accuracy of risk assessments to extreme events.

Efforts to reduce vulnerability to coastal hazards will be most successful if they are context-sensitive and co-designed by scientists and decision makers in policy and practice. Addressing the key drivers of vulnerability – changing demographics, urban and economic development, environmental degradation, and governance dimensions – are crucial elements for developing successful adaptation and mitigation strategies. Further international scientific cooperation, governance, and a policy-driven context are also necessary.

Changes in demographics, in settlement patterns, and in socio-economic conditions have influenced past conditions of exposure and vulnerability to natural hazards and continue to modify existing ones. In the next decades, increased numbers of people, infrastructure, and ecosystems will be at risk in the coastal zone. Every year, major cities such as Bangkok (2011) and New York (2012) are affected by floods. The final cost of Hurricane Sandy to New York City has not yet been fully estimated, but it will be considerable, in addition to the tragic loss of life. So, it is essential to view vulnerability as a long-term dynamic process and analyse the underlying conditions and drivers that have led to the observed state. Bankoff (2003, p. 20) has proposed that complexity may be both a source of vulnerability and an answer to risk.

Attempts to control the environment by building seawalls and dikes, need to be complemented by approaches that emphasise ways of dealing with unexpected events, that stress flexibility, adaptability, resilience, and uncertainty. The causes of vulnerability are not compartmentalised by the boundaries of academic disciplines and societal sectors so it is important to determine how the overlap between these conventional boundaries affects vulnerability. The compartmentalisation may effectively lead to an underestimate of total vulnerability as a cumulative function. Likewise, lowering vulnerability at one spatial level may create other forms of vulnerability at another level.

The problem of coastal vulnerability is global, but mostly has to be addressed at the local scale. A transdisciplinary partnership between scientists, engineers, planners, managers, insurers, and civil society can build social resilience through better understanding. Innovative approaches that enhance ecosystem services can complement hard engineering solutions. Solutions include the implementation of “no regrets” measures, such as early-warning systems, ecosystem management that boosts ecosystem services, coastal defence, better access to information about assessment tools and possible solutions, the use of land zoning and building codes, as well as capacity-building activities focussing on risk awareness and education. Capacity building to make state of the art knowledge available to practitioners and the public can raise awareness, advance forecasting, enhance preparedness, and improve risk governance.

Acknowledgements

This work has been supported by the EC 6FP grant agreement 036992 (SPICOSA, www.spicosa.eu); EC 7FP grant agreement 226675 (KnowSeas, www.knowseas.com); EC 7FP grant agreement 228845 (COMET-LA, www.comet-la.eu); and the IGBP/IHDP core project LOICZ (www.loicz.org).

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