Review Article

A typology of marine and estuarine hazards and risks as vectors of change: a review for vulnerable coasts and their management

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Abstract

This paper illustrates a typology of 14 natural and anthropogenic hazards, the evidence for their causes and consequences for society and their role as vectors of change in estuaries, vulnerable coasts and marine areas. It uses hazard as the potential that there will be damage to the natural or human system and so is the product of an event which could occur and the probability of it occurring whereas the degree of risk then relates to the amount of assets, natural or societal, which may be affected. We give long and short-term and large and small-scale perspectives showing that the hazards leading to disasters for society will include flooding, erosion and tsunamis. Global examples include the effects of wetland loss and the exacerbation of problems by building on vulnerable coasts. Hence we emphasise the importance of considering hazard and risk on such coasts and consider the tools for assessing and managing the impacts of risk and hazard. These allow policy-makers to determine the consequences for natural and human systems. We separate locally-derived problems from large-scale effects (e.g. climate change, sea level rise and isostatic rebound); we emphasise that the latter unmanaged exogenic pressures require a response to the consequences rather than the causes whereas within a management area there are endogenic managed pressures in which we address both to causes and consequences. The problems are put into context by assessing hazards and the conflicts between different uses and users and hence the management responses needed. We emphasise that integrated and sustainable management of the hazards and risk requires 10-tenets to be fulfilled.

Keywords: endogenic managed pressures, exogenic unmanaged pressures, pollution, erosion, coasts, estuaries, 10-tenets, ecosystem services, ICZM.

1. Introduction

Many hazards occur in coastal and coastal wetland areas, all of which have causes and consequences (Kennish and Elliott, 2011). *Hazard* is the cause leading to *risk* as the probability of effect (likely consequences) causing a disaster (as human consequences). The severity of the risk is proportional to the number of people or the value of the assets affected and so the concept of disaster is the interaction between social and natural systems. The responses to hazards and the willingness to act depend on the perception and evidence of risk and natural risk can be defined as the damage expected from an actual or hypothetical scenario triggered by natural phenomena or events. This paper aims to refine and explain concepts and examples by presenting a typology for risk and hazard; it builds on Elliott et al. (2010) and the excellent text by Smith & Petley (2009).

Coastal hazards can be divided into those over which individuals or communities have some control, for example by agreeing not to inhabit hazard-vulnerable areas, and those where they have no control, for example tectonic failure or extreme landslip. It is therefore necessary understand how such hazards can most effectively be tackled using technological, governance and economic approaches, for example whether we have the methods, laws and funding to modify and protect coastal landscapes against the influence of hazards or whether we need the capacity to mitigate the effects of hazards by financially supporting those affected by the hazards. At the same time, coastal management, and global agreements such as the Convention for Biological Diversity, aim to protect biodiversity using sustainable, long-term goals. In particular, there are technologies, albeit expensive, to reduce the vulnerability and thus risk due to the effects of change, for example climate change, such as building coastal defences. Underlying this is the need to produce ecosystem services which deliver societal benefits such as infrastructure and urban areas, while protecting the natural functioning (Atkins, et al., 2011; Elliott, 2011). Hence while we have the capacity to engineer the coastline to protect it from hazards, this may result in a non-natural system, thus contravening nature conservation laws.

Natural hazards leading to risks can be divided into two main categories depending on the causes: *endogenous* and *exogenous* phenomena depending on whether they originate within or on the Earth's surface. Endogenous phenomena include those, for example, releasing huge amounts of energy from seismic or tectonic events, manifest as earthquakes and volcanic eruptions and the resulting tsunamis. Exogenous phenomena, such as landslides, floods and accelerated erosion (of beaches and river beds) are often, but not necessarily, linked to extreme meteorological events and act on the Earth's surface, tending to modify the landscape. Of course, the landscape cannot accommodate such forces without change, for example flat landscapes will exhibit greater change by flooding than elevated and complex terrain. Such phenomena clearly indicate the internal and external geophysical dynamics of natural evolutionary processes. However, by interacting with society (population, settlements, infrastructure, etc.) they frequently determine risk conditions (ISPRA, 2007). Hence while natural systems have the capacity to adjust to such natural changes, it is only when the natural and societal aspects conflict that we see hazard and risk terms used in relation to the human uses of the geographical space.

Floods, landslides, the instability of the coastline, abrupt subsidence and substratum failure are all either the cause or result of natural events which are generally grouped together as *hydrogeological phenomena.* They result from interactions between meteorological events and the hydrogeomorphological system, in which humans either exacerbate the problems by making the landscape more susceptible to change or are greatly affected. Thus, natural phenomena can cause disasters but more often human actions make them more severe. For example, in assessing the causes and consequences from Hurricane Katrina in August 2005, Austin (2009) showed that the situation was exacerbated in Southern Louisiana because of its history and features (see also Fritz et al., 2007). These included its often financially poor human population being less able to withstand the changes, a long history of coastal modification by natural and man-made dykes/levees and other modifications through canal construction and the oil exploration and extraction industries. In essence, the loss of coastal wetlands reduced the capacity of the system to cope with natural events such as hurricanes, a financially poor and poorly-prepared population could not cope with the after-effects and the large infrastructure then increased the repercussions of the hurricane (see also Gedan et al., 2011).

The language of hazard and risk includes emotive terms and hyperbole more suited to popular journalism than scientific articles. However, as hazard and risk relate to the societal use of the landscape then such terms have to be used here. For example, a ‘disaster’ can become a ‘catastrophe’ because of anthropogenic factors and/or inadequate risk management and a lack of preparation. An area’s geology, for example, can be considered the underlying cause of hydrogeological risk and serious damage although added to this, however, should be factors linked to human activities. These include human settlement on flood plains or unstable terrain, reduced ground porosity through development cover, the failure to maintain slopes and cliffs through drainage works and the intense exploitation of the coasts for tourism and industry including damage to sand-dunes to create vacation resorts and marinas for pleasure craft.

Against this background, environmental ‘disorder’ resulting from increasing coastal exploitation is exacerbated by adverse meteorological events. For example, heavy rains, rivers in spate and marine surges (either by tsunamis or tidally), all degrade not only of the coastal strip but also inland. Events that the mass media often portray as natural catastrophes – unpredictable because of their “exceptional” nature – are indeed catastrophic in societal terms, but not exactly ‘unpredictable’ as they will certainly occur but with an unpredictable frequency. For example, since the mid-1900s, these phenomena have become increasingly frequent in the Dutch Delta areas or the Po river plain – the North Sea Tidal surge of 1953, the Polesine flood of 1951, the destruction of the Venetian “murazzi” (sea defences) in 1966, the exceptional ‘high waters’ in Venice throughout the 1960s - a set of notable events in a long period of generally variable weather. In turn these destabilised the coastal strip, which was influenced by variable climatic conditions but also by the ever-more intense anthropogenic impact on the natural environment.

The globally exponentially increasing coastal populations and urbanisation in estuarine, wetland and coastal areas in turn increases the potential for risk, the vulnerability of areas and thus the potential for disaster (Wang, et al, in press). Hence the hazard has an actual and/or perceived magnitude and intensity with a spatial extent and duration and its perception by society may be greater than the actual, measured effect. Hence there is the need to determine this magnitude and intensity to people and to the natural and built environment (Smith & Petley 2009). In turn, the hazard and its consequences may be acute, hence being intense over a very short time, or chronic, occurring perhaps at a lower intensity over a long period. We take the view that these define the hazard typology of value to managers (see Table 1).

All coastal societies have adapted to hazards and thus either have accommodated risks or tried to minimise them because of the benefits of living in coastal areas. Technologies can include and enhance adaptation although society needs to be made aware of their vulnerability (Klein et al., 2001), for example for populations living on low lying and threatened coasts such as around the North Sea or in Bangladesh. Coastal managers then need to design and implement adaptation strategies, even if these are not societally desirable. For example, the UK has a strategy of protecting large urban areas and industry in the national interest but not protecting farmland where there is no economic justification for protection (French 2004) - while this may not be desirable by small and isolated residences or farms, it is a pragmatic and economically justifiable approach. The cost of protecting coasts may be £2M (at 2012 prices) per 100m and possibly considerably more expensive than moderate quality coastal farmland (Environment Agency, unpubl.). This requires an adaptation strategy of relying on soft engineering, the use of better information and awareness systems, and site-specific and local decisions (Klein et al., 2001; Gedan et al., 2011).

Hazards and the risk from them can be categorised along a set of gradients from natural to man-made and from the spatial dimension of their impact and intensity, ranging from widespread and diffuse to point-source (Figure 1). They can also be ranked according to whether society has any control over them - in the figure ‘*Voluntary*’ relates to the degree of human control and therefore causation whereas ‘*involuntary*’ indicates that society has no control and must only attempt to respond to the consequences of the event/activity. These are analogous to the separation between *exogenic unmanaged pressures* and *endogenic managed pressures* (Elliott 2011) in which the former originate from outside the system being managed and so management has to respond to the consequences rather than the causes; in contrast endogenic managed pressures occur within the managed area and management can influence the causes as well as the consequences. The axis *Intense*, *diffuse* and *point-source* relates to the extent of the hazard. The figure places climate change at various points depending on whether or not it is accepted as an anthropogenic change and whether it consequently affects other hazards such as the introduction and spread of biohazards.

2. Types of Coastal Hazard

Estuarine, coastal and marine knowledge (e.g. McLusky & Elliott, 2004; Gray & Elliott 2009) lead us to propose 14 types of hazards in these areas (Table 1). Here we describe, explain and give examples of these and also indicate solutions in relation to hazards which are natural or anthropogenic, acute or chronic, short or long-term, and with large or small extent, severity and duration (Figure 1). We use the term ‘anthropogenic’ to imply a societally-caused hazard where in-situ responses may be sufficient to minimise, mitigate or control the hazard or to compensate for any adverse effects.

(A) Surface hydrological hazards

The most frequent and often widespread hazards on coasts and adjacent lands are caused by surface flooding from regular high tidal events, albeit often around spring tides and equinoxes. The low lying areas most at risk are in macrotidal estuaries, flat coastal areas, deltas and natural floodplains. They will be in open coastal areas away from non- or micro-tidal enclosed or semi-enclosed seas and away from amphidromal points and they will have catchments liable to flash-floods and thus high energy run-off. This affects infrastructure, for example the bridge failure at Ponte de Ferro in March 2001 in the Douro River near Porto in Northern Portugal killing 59 people (Sousa and Bastos, 2013). This type of hazard then requires a coordinated response such as the Thames Coast Project, covering London and adjacent area including a multi-agency catchment management plan, flood risk plan and hazard mapping, provision of new ‘sustainable’ infrastructure and a policy of removing the use of property in high risk areas. The surface flooding may be related to changes in global weather systems such as the NAO (North Atlantic Oscillation) - ENSO (El Niño Southern Oscillation) events (Collins, 2009).

(B, C) Surface physiographic removal respectively by natural and anthropogenic processes - chronic, long-term

Surface and shallow geomorphological features may be the cause and suffer the consequences of continuous, long-term and thus chronic removal. Erosion of soft rock or clay/till material or of regular cliff failure may be caused by wave undercutting or, for soft sediments, rotational slumping due to waterlogged sediments. While the failure of soft or hard rock cliffs may be more spectacular, the constant and continual removal of soft sediment leads to a greater impact on coastlines. For example, 70% of the Sicilian coastline is eroding and parts of the island's coasts have retreated by an average 60m since the mid-20thC (Martínez del Pozo and Anfuso, 2008).

The Holderness coastline in eastern England is arguably the fastest-eroding coastline in Europe being composed of glacial tills and clay with occasional moraine areas (Metheringham 2008). The resultant erosion of 1-2m.yr^{-1}, together with occasional rotational slumping in short reaches of perhaps 10m-100m leading to sudden losses of >10m.yr^{-1}, has been occurring since the last ice-age and consequently historically approx. 40 villages have been lost (HCC, 1994). Adaptation and voluntary 'roll-back' is now part of the present management response and building is discouraged within a 100 yr erosion safety limit. Consequently, the local population perceives risk through hazard to their buildings even if lives are not threatened although this has not stopped the development demand. A technological response is possible, e.g. groyne building to create beaches but this is expensive and creates concerns due to repercussions of interfering with natural processes such as the restriction of longshore sediment supply to the adjacent estuarine areas which in turn would increase the risk of flooding there and hence risk to large urban areas. Furthermore, hazards from sea level rise and storm surges could increase due to interference with the sediment supply hence showing the importance of management according to sediment and hydrographical systems - in the UK this is through the use of Shoreline Management Plans (Winn et al., 2003).

Coastal infrastructure (wharves, ports, sea walls, emergent breakwaters) that disrupts longshore drift may starve adjacent beach areas of sediment and thus increase the hazards and risk in those areas through erosion. Similarly, human activities have reduced the flow of sediments from watercourses through building dams, creating diversions, dredging of the river beds, structures to counteract soil erosion and the creation of hard-standing areas. Urbanisation has removed natural defence structures such as *Posidonia* and other seagrass meadows, sand dunes and coastal vegetation which in turn has reduced the resilience of habitats to erosion. The high and increasing demand for coastal space has accentuated the periodical or seasonal retreat of the coastline thus paradoxically increasing risk to the communities creating the problem.

(D) Surface physiographic feature removal - acute/short-term

Intermittent, irregular and thus unexpected cliff failure either along fault lines or other types of substratum may present a greater risk and thus an unforeseen hazard for which it is difficult to prepare. This usually occurs on rock, especially chalk cliffs but can occur on soft cliffs such as in 1993 at the site of the Holbeck Hall Hotel on South Cliff, Scarborough, Yorkshire, Eastern England, 65m above sea-level. It was built in the late 1800s on glacial till (boulder clay with some sand horizons) which in 1993 had suffered small-scale historical movement. A period of heavy rain produced cracks in a cliff-side footpath and around 6 weeks later (by June) a large area of fronting garden slumped down the cliff with subsequent landslides following over the next 24 hours leading to the immediate hotel collapse (Lee, 2009). The cliff failure by rotational slumps was exacerbated in this area by several dry summers (allowing cracks in the clay to develop), followed by a period of heavy rain and modifications to slope drainage, leading to a catastrophic increase in pore pressure. The authorities then had to use Emergency Works Orders to stabilise the cliff and prevent further damage to surrounding properties otherwise the properties would have become uninsurable.

(E) Climatological hazards - acute/short-term

Acute, erratic and short-term hazards may result from climatological conditions in which several phenomena coincide. For example, storm surges linked to tidal conditions and the physiography of the area, and cyclones, hurricanes and tropical storms produce hazards and thus risk to infrastructure and society. These may result from fluctuations in sea surface temperature, wind patterns and the influence of NAO/ENSO events on weather patterns. They influence riverine run-off and saline intrusion and the retention of freshwaters due to tidal pumping which further damages estuarine and wetland systems. For example, the Sundarbans mangrove area of Bangladesh is subject to tidal, fluvial and pluvial flooding and with an increased hazard during the tropical storm and monsoon season. The low-lying area experiences natural hazards but also has rich fishing and other resources supporting a large population (Haque & Elliott 2005). Accordingly this large area is exposed to a high risk as the consequences of the hazards (Smith & Petley 2009; Brammer 2000). Despite this, societies in countries such as Bangladesh have long tolerated and adapted to these natural events.

Shallow macrotidal, semi-enclosed areas are subject to the hazard of storm surges. A combination of a period of high spring or equinoctial tides, sufficient fetch and wind direction, low air pressure (producing higher water levels) and basin shape all combine to produce hazardous and potentially catastrophic conditions (Baxter 2005). In January 31st/February 1st 1953, south-westerly winds in the north Atlantic pushed water into the northern North Sea, a high spring tide, a low pressure system over the southern North Sea, the shape of the North Sea which funnels the water mass into a shallow and narrow area, and the underlying anticlockwise gyre in the North Sea, in itself the result of Coriolis force, all combined to produce a storm surge. This moved down the western edge of the North Sea, giving the English and Scottish east coast a surge height of approx. 3.0m, and then up the eastern continental coasts of Belgium and the Netherlands where the surge was >3.3m, hence overtopping or breaching the defences on low-lying coastal areas. This led to 307 deaths in the UK and 1,835 deaths in the Netherlands and the flooding of approx. 3000 km^2. The sea defences in the immediate post-war period were not designed for such events. The surge led to the construction of higher and more effective defences including the barriers across the Thames estuary and in particular the Rhine-Meuse Delta works (Nienhuis & Smaal 1994), a system of closed estuaries and storm-surge barriers greatly changing the large-scale geomorphology of the southern Netherlands. Baxter (2005) concluded there was no personal fault for the unpreparedness of the flooded areas but that the austerity following WWII exacerbated the problem. Despite flood defence improvements, there remains a potential surge risk in this region, as relative sea-level rise is a problem in south-east England and the low countries, with increased storminess also predicted due to climate change as well as isostatic rebound (see below) exacerbating the effects of such a surge. The frequency of such events (a 1-in-250 year occurrence in the 1950s), could be more than 10 times likely by the 2080s. Indeed, a similar-sized storm surge in December 2013 did not have the same result because of the heightened defences and preparedness since the 1950s (http://www.bbc.co.uk/news/uk-25253080). It is suggested here that if the population is aware of the hazard and risk then funding is agreed but if there is no 'societal memory' or funding is diverted and areas are not prepared.

(F) Climatological hazards - chronic/long-term

While the above indicates acute and severe change, a gradual loss of coastline and thus a hazard to those living on the coast results from global warming and sea-level rise. While the local populations can adapt to the risk or even migrate, there will be large-scale coastal changes especially in countries too poor to respond with hard engineering, for example the Maldives and Bangladesh where only a modest sea-level rise such as that predicted to be 1m by 2100, will remove much land. This will be accompanied by the ingress of seawater and thus saline incursion in the mangrove areas, estuaries and deltas creating problems exacerbated by freshwater abstraction and dam building in the catchments. In Bangladesh the resulting seawater incursion will impact the Sundarbans mangroves (Haque and Elliott, 2005), itself an extensive wetland giving protection against typhoons, tsunamis and storm surges, and be exacerbated by dam building in India, again showing the geopolitical interlinked nature of the hazards.

This shows the need to consider this interlinking which increases coastal hazards. For example, Thornton et al. (2006) concluded that in Monterey Bay, California, the episodic erosion events which occurred when storm waves and high tides coincided, by eroding the sand-dunes, were linked to ENSO events. The dune loss in the Bay during the 1997–98 El Niño winter was 1.82 Mm^3, seven times the long-term annual dune erosion rate.

Climate change is regarded here as an 'exogenic unmanaged pressure'; in managing local areas, we are not *managing* climate change but merely managing both the *consequences* of it and our *responses* to it (Atkins et al., 2011; Elliott 2011). Climate change has accepted consequences - from relative sea-level rise and increased storminess to the responses by organisms in adapting to new temperature regimes or even changing distributions (Nicholls and Cazenave, 2010). Sea-level rise modifies the coastline and produces coastal-squeeze where the low water line is rising but the high water one is often fixed by sea defences. Erosion may occur if global climate change increases storminess. For example, in the long-term, although increased storminess has not been demonstrated in the North East Atlantic, Storch (1996) found a gradual increase of the significant wave heights in recent decades last 30 years by approx. 2-3 cm pa.

(G) Tectonic hazards – acute/short-term

Many coasts are on or close to seismically active areas such as subduction zones or transform faults which increases the potential hazard from earthquakes and tsunamis. These are acute but short-term hazards and are actually or potentially catastrophic, with long-lasting effects. The tsunami of December 2004 in Indonesia devastated large coastal areas (Thanawood et al., 2006) although the effects were exacerbated by the removal of large mangrove areas which otherwise would have provided protection against the inundation (Alongi, 2008; Gedan, et al., 2011). Similarly, the underlying geology and the seismic activity in the central Atlantic include the potential geological failure of Cumbre Vieja, La Palma (Canary islands) would produce a tsunami travelling to the NE American seaboard (Ward and Day 2001). Given the very low frequency of such events, however, it is not surprising that the population and authorities in the receiving areas are unprotected and often unaware. However, in the case of SE Asia, it is unlikely than any protection could be deployed even though the 2004 Indonesian tsunami led to an early warning system for the Pacific Ocean being implemented (Thanawood et al., 2006). The most recent example of this type of hazard was shown with damage to the Fukushima nuclear power plant following the 2011 Tohoku earthquake and tsunami in Japan where unpreparedness and inadequate sea-defences compounded problems with an ageing technology.

(H) Tectonic hazards - chronic/long-term

Coastal tectonic hazards may also be chronic, developing over a long period through geological history rather than being acute, catastrophic events. For example, sea level rise has a greater effect on the low-lying southern North Sea coastlines (especially SE England, and parts of the Netherlands and Germany) that are sinking because of isostatic rebound following the last glaciation (Ducrotoy & Elliott 2008). The removal of the ice sheet has allowed the crust to rise in the Baltic and northern British Isles (Flint 1971). Consequently, the North Sea may experience a relative sea-level rise of 50cm by 2100 (IPCC, 2013) but the spatial variability depends on the eustatic tilt of the European landmass, leading to weaker or even negative trends in sea-level rise in the north (Scotland, Sweden) hence where SLR is less of a hazard (Ducrotoy & Elliott 2008). This type of hazard increases risk caused by the removal of sediments or the interference with sediment processes through barriers and dredging.

The remaining hazards in the typology all relate to materials, whether solid or liquid or biological, physical or chemical which are added to or removed from marine areas by human activities. ‘Contamination’ is the addition of materials which may or may not be hazardous whereas any resulting biological effect is regarded as ‘pollution’ (McLusky & Elliott, 2004; Kennish and Elliott, 2011). Hazard is thus the potential for biological harm (as an adverse effect on organisms including humans) whether at cell, individual, population, community or ecosystem level. Contamination is thus considered an anthropogenic increase in the level of a compound/element in the organisms or system which does not necessarily change its functioning. In the case of hazards, however, pollution (i) is regarded as an anthropogenic adverse impact on the natural system, or (ii) has occurred if it reduces the fitness to survive of an individual/population/species/community. It includes the anthropogenic introduction, directly or indirectly, of biological, chemical or physical materials or energy into the marine environment (including estuaries) resulting in such deleterious effects as to harm living resources, and produce hazards to human health, hinder marine activities including fishing, impair quality of seawater for use and reduce amenities (McLusky & Elliott 2004).

(I) Anthropogenic Microbial Biohazards

The latter definitions can be extended to biological entities, i.e. biohazards; hence *biocontamination* is the introduction of species without noticeable effects (e.g. microbes which are killed immediately by natural conditions). *Biopollution* is thus the effects of introduced, invasive species sufficient to disturb an individual (such as internal biological pollution by parasites or pathogens), a population (by genetical change) or a community or ecosystem (by increasing or decreasing the species complement) (Elliott 2003). This type of hazard can then lead to adverse economic consequences, for example by sewage contamination of bathing and recreational waters.

The coastal practice of microbial biohazard introduction via sewage thus leading to disease is biological pollution which then requires control by ozone or chlorination disinfection of waste waters. The long-established practice of discharging sewage into the sea, even modified since the 1970s through long-sea pipelines, uses the sea’s assimilative capacity through its characteristics of being saline, cold and with high UV levels to kill sewage pathogens. While this controls and acts as treatment for sewage pathogenic bacteria, it is less effective for viruses (e.g. Efstratiou 2001).

(J) Anthropogenic Macrobial Biohazards

Biological pollution (e.g. Elliott 2003), whereby introduced or invasive species create ecological and societal hazards, applies to macro- as well as micro-organisms and includes introducing genetically-modified or other species as escapees from aquaculture. Increased seaborne traffic and the movement of ballast-water increases the likelihood of organism transfer which in turn creates hazards such as the introduction into Europe a century ago, of the Chinese Mitten Crab, *Eriocheir sinensis.* This has now spread to estuaries and rivers from Portugal to Scandinavia (Herborg et al., 2003) where its burrows increase the risk of dyke failure causing flooding. Climate change also changes or expands organism distributions with warm-tolerant species migrating to higher latitudes, again increasing the risk of adverse effects. These changes can affect human health such as the increased incidence of Paralytic Shellfish Poisoning due to introduced red-tide forming organisms or merely reduced amenity through recreation beaches being populated by non-native oysters such as *Crassostrea gigas* in NW Europe (Troost, 2010).

Coastal or channel engineering also increases the risk of invasive species, for example the opening of the Suez Canal in 1869 or linked canals from the Caspian to Baltic Seas have respectively increased Red Sea species in the Mediterranean or Ponto-Caspian species in the Baltic (Occhipinti-Ambrogi, 2007). Again such changes are regarded here as exogenic unmanaged pressures in that marine management has to respond to the consequences and cannot control the causes. Management of the Mediterranean has recently suggested that for the implementation of the European Union Marine Strategy Framework Directive (MSFD), alien species from the Suez Canal should be exempt from management measures (UNEP 2013). This decision may be due to the fact that a member state cannot be legally challenged for breaking the MSFD for factors outside its control.

The threat of aquatic alien invasive species (AIS, e.g. Occhipinti-Ambrogi & Galil, 2004; Galil, 2007) has led to proposals for quantifying the hazard (Olenin et al., 2007; 2011) and risks to ecosystem health (Panov, et al., 2009; Rapport et al., 1998; Boudouresque & Vaerlaque, 2002). Ruiz et al. (1997) firstly identified the degree of hazard but whereas the vulnerability of and risk to ecological systems are known (e.g. Zaiko et al., 2007), there are fewer studies of the consequent risks to human systems. Despite this, countries require mechanisms to deal with the increasing hazard of biosecurity (Olenin et al., 2011). The Central Science Laboratory (2008), Genovesi & Shine (2004), Reise et al. (2006) and Hewitt & Campbell (2007) respectively give the national strategies for identifying and controlling biosecurity hazard in the UK, Europe and Australia/New Zealand although it is axiomatic that in open marine systems it is almost not possible to eradicate AIS once they are established (Olenin et al., 2011).

Panov et al. (2009) gave 4 steps for risk analysis for AIS: 1) identifying the problem, 2) assessing the probability of introduction, establishment, dispersal and impact, 3) managing the problem, and 4) communicating the problem. To this we add the need for actions to deal with the problem. Hewitt & Campbell (2007) concluded, as expected for their area (Australasia) with a unique and formerly isolated fauna and flora, that any policy of minimising risk and thus reducing the hazard relies on prevention by (i) developing Import Health Standards and deciding on the acceptability of intentional introduction; (ii) determining the next likely problem species and the high risk entry locations, such as international ports; (iii) monitoring and rapid response efforts aimed at eradication, and (iv) determining the vectors of greatest concern. However, we suggest that the last of these should be the first in determining the risk and thus the control mechanism. For example, ballast water treatment or discharge prevention are advocated via the International Maritime Organisation to reduce risk from introduced species although these still require ratification by maritime nations (Bax et al., 2003).

(K) Anthropogenic introduced technological hazards

As pollution is defined as materials added resulting in biological harm, then logically this includes large structures placed in the sea which both have an adverse impact and increase the hazard potential. Increased coastal infrastructure and possible failure, such as with coastline protection, thus increases hazards and risk, as indicated above with the Fukushima nuclear power plant in 2011. Similarly, Leavitt and Kiefer (2006) and Fritz et al. (2007) linked the severity of the effects of Hurricane Katrina in New Orleans in 2005 to the city infrastructure. This both exacerbated the consequences by removing natural defences; hence the determination of risk and vulnerability and the response requires a flexible approach including '*coordination, cooperation and communication'*.

(L) Anthropogenic extractive technological hazards

Extracting physical materials can cause hazards, increase risk and exacerbate the effects of other hazards. For example, extracting nearshore sand and gravel for building materials removes the natural defences such as berms, subtidal sandbanks, beach or sand dunes and thus makes storm-surges potentially more damaging. Thornton et al. (2006), showed that in Monterey Bay, California, mining removed an average 128000 $m^3.yr^{-1}$, estimated as half of the sand dune loss over most of the 20^{th}C.; this produced coastal erosion rates of 0.5-1-5 $m.yr^{-1}$ which then stopped after the mining ceased. Similarly, hydromorphological change due to surface and subsurface extraction, for example in NE England, of coal over many decades caused subsidence which then exacerbated wave-mediated shore erosion (Humphries 2001). Similarly, extracting aquifer waters under Venice increased subsidence and thus flooding in the city while upstream abstraction of rivers entering Bangladesh increases saline intrusion and exacerbates the effects of storm surges. Each of these extractive processes has in turn led to rapid coastal destabilisation.

(M) Anthropogenic acute chemical hazards

Chemical inputs can be accidental and thus may be intense and acute but short-lived, for example shipping accidents leading to oil spills, burst petrochemical pipes and humanincompetence. The large-scale and/or the point-source nature of these may be single spillages but may involve amounts likely to cause damage depending on the hydrodynamic regime leading to the dispersion or concentration of the material (McLusky and Elliott, 2004). While most countries have legislation to control the adverse effects of chemical discharges, fewer have legislation requiring companies to have environmental management systems which both reduce the chances of chemical hazards and require a contingency plan for a response to hazards once they do occur. Of course shipping lanes or port estuaries with a high volume of shipping transport increase the risk of hazards occurring and also, because of the sensitive nature of habitats in those areas, increase the consequences of oil-spills.

(N) Anthropogenic chronic chemical hazards

Chronic chemical inputs are usually planned and thus licensed such as point source discharges, from boats and pipelines, but also diffuse inputs from run-off of land and hard-standing structures which are more difficult to control. Long-established industries such as petrochemical plants will not only discharge materials continuously but also leave a residue in sediments which may degrade more slowly once out of the aerobic environment (Wake, 2005). The biological repercussions of these hazards may occur at all levels of biological organisation from the cell to the ecosystem although the natural system may have an ability to absorb those changes (e.g. see Lawrence & Hemingway, 2004). These aspects have been covered extensively elsewhere (e.g. McLusky & Elliott, 2004; Kennish and Elliott, 2011; Clark 2001).

3. **Environmental and Economic Consequences of Risk and Hazard**

Integrated Coastal Zone Management relies on complex and elaborate measures proposed by stakeholders, and active and local involvement to identify sustainability objectives via information dissemination and consensus (Özhan, 2002). This requires monitoring, regulation and good governance. For example, the coast at Casalabate, north of Lecce, Puglia, has been affected by intense hydrogeological hazards and risk disturbance since the 1950s, where unauthorised development occurs on a flat landscape (Trono, 2009a). The low-lying beaches and remnant dunes and marshes are all affected by erosion or anthropogenic removal partially re-exposing the original karst features and altering the natural geomorphology. The most important geophysical processes affecting the shoreline are subject to high uncoordinated and unplanned anthropogenic pressure which increases risk. Hence a high coastal risk of subsidence is caused by widespread hydrogeological pressures and disturbance due to the interference of watercourses, a poor drainage network, and exacerbated by shore instability and unregulated building. Intense coastal erosion and subsidence in the last two decades have made many buildings unsafe. Although current numerical models are inaccurate and inadequate, there is a good conceptual understanding of the interactions between these features and the coastal system linking the beaches, the dunes and the adjacent area. However, widespread urbanisation has reduced the system capacity and adaptability to the new environmental conditions.

The local physiography is central in determining hazard, for example beaches may create hazards but also help to reduce them. They are economically important for recreation and tourism and support prey for commercial fishes but these socio-economic features increase the effects of hazards (Trono 2009b). Beaches are created by fundamental hydrogeomorphological processes such as the prevailing hydrophysical conditions and erosion and accretion may vary with time, hence they can provide varying protection from marine hazards. They provide economic services and societal benefits including protection by dissipating energy, hence the policy of beach nourishment or groyne building to trap sediment, create a beach and dissipate energy (Nicoletti et al., 2006). Beaches will be in an equilibrium between the hydrodynamics and sediment availability but this equilibrium is particularly sensitive and thus at risk from the constant anthropogenic pressure on the coast and its economic assets.

The examples here emphasise that the causes and thus also the responses to coastal hazards such as erosion, should include economic as well as environmental considerations as local populations will demand to be defended even if this requires expensive engineering solutions (Winn et al., 2003; Wang et al, in press). Despite this, the prevailing wisdom is to work with natural processes rather than against them especially where solutions may be either environmentally or economically unsustainable. For example, the dynamic sand and shingle spit of Spurn Point, NE England, is now managed to ensure that natural processes shape its morphology and alignment, rather than attempts to maintain its current position through hard defences (Winn et al., 2003). A temporary moveable road maintains an infrastructure link along its length to retain communications to the lifeboat, pilotage and vessel traffic facilities at the tip of the landform although recent erosion (December 2013) has questioned whether this is sustainable (pers. obs.).

It is thus necessary to focus on the nature of the hazards and risks and their consequences at spatial scales, both regionally and nationally, as illustrated in Puglia, Italy where erosion affects many coastlines which are retreating due to a lack of material from reduced inputs from the main watercourses. The morphology has been compromised both through an unstable coastline but also intensive exploitation for tourism (Trono, 2005; Refolo, et al., 2007). This has even included developers systematically removing the dunes, reducing their area and leading to the loss of psammophillic vegetation. This in turn reduces coastal protection thus both increasing the risk of further damage by waves and reducing the ability to cope with storm-surges.

As an example of cumulative risk, 20% of the Italian coastline (8,350 km), mostly sandy beaches, undergoes erosion and approx. 1,500km of the 4,600 km of low-lying coasts (including coastal plains) are threatened by rising sea levels, erosion and flooding (Aucelli et al., 2004). Italy is also greatly affected by natural, hydrogeological risk (landslides, floods), which are ranked second to earthquakes in terms of the damage caused (Barberi et al., 2004). This hydrogeological risk and disturbance has been increased by demographic and socio-economic growth. Uncontrolled urbanisation and industrial growth in low-lying regions since the 1950s has produced socio-economic benefits but led to large hard-standing areas and increasingly invasive structures (dykes, dams, canals and drainage systems) which interfere with natural processes. Hence, we contend that once areas are 'managed' then management has to continue otherwise the area attempts to return to a (societally) less-desirable state. Coastal degradation, especially in a tourism-dependent economy, is increasingly reflected in the retreat of the coastline and increasing risk of erosion. Hence this impacts on sea-coast interactions and requires a new dynamic equilibrium different from the natural state. In addressing such an increased risk, the authorities have to be reminded that the coastal environment is a highly complex system, closely linked to river and coastal processes supplying sediment thus compensating for erosion.

4. Solutions and Response for Reducing Risk and Hazards from Erosion

The societal adaptation to hazards, thus minimising risk, may be by engineering, behaviour or by statutory or emergency action. Engineering options include improved coastal defences or building construction and design. Societal behavioural changes may be induced by legislation or economics, for example the policy of 'roll-back', whereby human permanent coastal habitation is discouraged by voluntary agreement or spatial planning. For example, the local planning authority responsible for managing development along the fast-eroding Holderness coast, NE England, has adopted this policy to minimise future safety or economic problems (Winn et al., 2003). Even where this has not been implemented by statutory authorities then it could be effected by insurance companies, i.e. any buildings become uninsurable. Hence, coastal adjustment by erosion only becomes a problem once occupied as the natural features of an eroding coastline will remain the same albeit in a different position.

The short and long-term societal responses for protection/preparedness for a high risk event versus the recovery from it can therefore be separated into:

- mitigation – in the short term by immediate disaster aid;
- compensation – in the longer term for those affected;
- protection - environmental control, design of buildings, sea defences;
- societal adaptation – through education and community preparedness (civil defence);

- infrastructural adaptation – by the process of ‘roll back’, i.e. encouraging relocation of residents to less-vulnerable areas and implementing planning controls on building within vulnerable areas;
- technological adaptation – through advances in forecasting and warning system (e.g. storm-surge or tsunami warning).

The vulnerability to a hazard, and thus the amount of risk or the perception to risk and hence the eventual consequences (even disaster) relate to the nature of the area and the degree of preparedness. Technological approaches can deal with coastal hazards and minimise risk plus reduce societal vulnerability. For example, coastal defences can be engineered, by using either soft or hard engineering (French 1997; Elliott, et al., 2007: Wang et al, in press), to minimise or even remove the risk and so protect the local populations although of course this may be costly. Environmental and economical repercussions require addressing via 3 types of engineering intervention: (i) *high geo-environmental impact* (with barriers and breakwaters perpendicular to the coast; construction of sea walls to deflect waves and coastal currents); (ii) *medium geo-environmental impact* (using beach nourishment by distributing sediments usually obtained offshore); (iii) *low geo-environmental impact* (such as constructing submerged breakwaters as artificial barrier systems, and re-creating typical vegetation to trap sediment and dissipate energy).

Hard and soft engineering approaches differ in their different economic and environmental consequences. Hard engineering includes concrete seawalls and very often the fixing and possibly even advancing the coastline, thus ignoring natural functioning. In contrast, soft engineering such as beach nourishment may be environmentally more sustainable and confers initial protection but eventually it will have to be repeated (thus maintaining the line of the coast) (Hanson et al., 2002). However, increasingly solutions may include realigning and even retreating the coast in order to produce wetland (depolderisation), controlled flooding areas or water storage areas which both afford protection and create (and possibly replace) valuable wetland habitats (Mazik et al., 2007; Edwards and Winn, 2006; Jacobs, et al., 2009; Temmerman, et al., 2013). Such measures also include protection of inner coastal areas by fencing off wetlands, protection of coastal dunes via protected nature areas, planting to form sediment traps or the recovery of ancient dunes.

Beach restoration may reduce the hazards such as occurred with the loss of beaches surrounding the Venice Lagoon which exposed the coastline to high risks, including seawater flooding and damage to the rocky shoreline. Restoration included creating a new, wide beach, more than 9 km long, by nourishment using approx. 5 Mm^3 of sand, which is protected by 18 groynes perpendicular to the coast, connected by a submerged breakwater running parallel to the coast, 300 m from the shore, along the entire beach (e.g. Bezzi, et al., 2009). Other measures include armoured breakwaters, e.g. using ‘tetrapods’ a short distance offshore running parallel to the most frequent wave front, to ensure the dissipation of wave energy. However, traditional hard-engineering, such as using rubble-mound breakwaters and sea walls, is not cost-effective in combating erosion over large scales because of high maintenance costs. It may not be sustainable and in some cases may even accelerate erosion by redirecting wave energy. Hence the policy of roll-back (see above) accompanied by ‘managed realignment’ in which dykes are moved back and wetlands created as a method of soft-engineering to minimise risk through erosion and coastal flooding thus aiming for a ‘*win-win-win*’ situation of benefits for human safety, economy and the ecological system (Elliott et al., 2007; Edwards & Winn 2006). Where managed realignment is not practical, as in areas of high economic or historic value, other methods of soft engineering are often used instead of traditional dykes and breakwaters.

The authorities in Flanders, Belgium, are adapting the management of the highly built-up coastline to its natural dynamics to minimise hazard and risk (e.g. Charlier, 2003). Where possible, erosion is managed more subtly by replacing the protection barriers with, for example, vegetated sand dunes that are able naturally to absorb wave energy. Similarly in the southern Italian Adriatic coast where erosion prevention followed by beach-maintenance involves drainage to lower the water table near the shoreline together with the stabilisation of the sand and a noticeable reduction in swash, thus favouring the deposit of beach sediment. Material for replenishing beaches and coastlines affected by erosion has recently focused on extracting sand from marine deposits (generally ancient beaches) (Ispra, 2009, 2010).

The southern North Sea states, noted for unstable coasts, have used traditional solutions to the problems of coastal change, erosion and sea-level rise including hard engineering solutions such as sea defences and barriers and barrages, e.g. across the Thames and Oosterscheldt estuaries to address tidal storm surges. Despite the increase in soft-engineering to protect areas (Elliott et al., 2007; Edwards & Winn, 2006), some areas need protecting by hard engineering. The UK strategy of protecting large urban areas and industry in the national interest (e.g. coastal gas terminals) gives no protection to low-value agricultural land; however, this may change if land is needed for biofuel. This has led to policies, plans and strategies for dealing with habitat change using not only flood-risk management planning but also habitat planning and managing carrying capacity (Costanza, 1995). Consequently our science and management must relate to how we regain, maintain and/or create ecological and socio-economic carrying capacity. This is especially a challenge for low-lying coastal areas experiencing sea-level rise and isostatic rebound (Elliott et al., 2007).

Prior to management actions and thus possible solutions, assessing and quantifying risk involves defining and quantifying the hazard, determining the elements at risk, and analysing the vulnerability of those elements to change (Smith & Petley 2009; Wang et al, in press). Risks may be deemed *unacceptable*, *tolerable* or *acceptable* thus using the *ALARP* framework where risk is managed to be '*as low as reasonably practicable*' (Melchers 2001). This infers a governance element (the *managed* aspect), the societal demands (the *reasonably* aspect) and technological and economic aspects (the *practicable* aspect). 'Unacceptable' risks have to be addressed almost irrespective of the costs given society's high concern. 'Tolerable' risks require to be tackled using the ALARP principle in that society will take a decision depending on a cost-benefit analysis and may decide not to address 'acceptable' risks especially given an adverse cost-benefit outcome (Smith & Petley 2009).

Risk management in turn requires identifying and quantifying hazards, protecting or removing the elements at risk and therefore reducing vulnerability, i.e. as an action, evaluating social consequences against the probability of occurrence (e.g. see the GIS-based system for the Chinese coast developed by Wang, et al., in press). Determining risk is required by evaluating the likelihood of an event thus increasing preparedness, e.g. for the design of coastal defences according to, for example, a 1-in-250 year wave height. However, a cost-benefit analysis would determine the wisdom of preparing for only a 1-in-100 year event which would be less expensive than the longer event return-period. This may apply, however, to locally-caused changes and acute events but society has to respond to the gradual changes caused by climate change, as emphasised here a hazard considered an exogenic unmanaged pressure in which the cause cannot be addressed locally, i.e. it requires global action, but society has to respond especially locally to consequences to reduce risks. Again it is emphasised that an involuntary risk is imposed externally and where the stakeholder has no influence, such as the presence of a soft sediment, low-lying coastal area which is liable to landslip/coastal erosion (Mai et al., 2008, Barnett & Breakwell, 2001). However this becomes a risk to the stakeholders voluntarily occupying the area. Therefore, an involuntary risk can become a voluntary risk by building and allowing occupation on an eroding coastline. Hence, there is the need to determine at what stage is a risk perceived or when do residents consider they are not vulnerable.

5. Concluding Comments - Challenges and Changes for Sustainable Management of Vulnerable Coasts

We have shown that some hazards relate to many coasts worldwide, both temperate and tropical, such as storm-surges and waves, coastal erosion, flooding, saline intrusion (acute by typhoon tidal waves but also chronic by sea-level rise and water abstraction) and building damage. Tackling these requires multi-disciplinary action and especially the need to engage with all stakeholders rather than imposing actions from outside - success is more likely if society engages in the responses; communities restoring habitats on vulnerable coasts and increasing protection increase both the chances of success and awareness of the problem.

As certain habitats highly protect coastal areas then these should be maintained, for example, offshore coral reefs and coastal mangroves protect against tropical storms and cyclones as well as producing ecosystem services and other societal benefits (Alongi, 2008; Atkins et al., 2011; Wang, et al., in press). Impacts on livelihoods following damage occurs especially when coasts without such habitats are more vulnerable to extreme weather than coasts protected by intact natural areas (in addition to any loss of other resources such as fisheries in degraded habitats). As an example of positive and community-based action, *Wetlands International* (www.wetlands.org) aims to protect and restore these threatened and degraded coastal zone ecosystems in Africa and Asia. It works with local communities, to replant mangroves and other coastal forests and clean up coral reefs.

Here we have emphasised coastal change resulting from both natural and anthropogenic hazards. These aspects are complex in terms of the environment, economics and the law and likely to become more important due to the increasing frequency of floods and storminess and rising sea levels linked to climate change (e.g. Garzia 2007). Hazard removal and risk reduction requires an integrated approach linking environmental sustainability, coastal economic reconstruction and actions on other coastal uses and users, for example tourism and maritime traffic. A complex governance framework is needed to tackle the problems at an international, national and regional level and from the numerous public and private interests affected by and affecting shoreline developments. There needs to be a good understanding of coastal dynamics and greater awareness and realism among the community regarding the environmental impact and what is possible and what is not possible to reduce the coastal hazards. Taken together, we can reduce vulnerability by coastal retreat (both physically and socially) albeit with environmental and economic consequences. However, as the risks occur on many coasts, they require coordinated, comprehensive and long-term intervention strategies to conserve and protect areas increasingly at risk.

Coastal protection and the minimising of hazard and risk are central to Integrated Coastal Zone Management (ICZM) Plans with authorities attempting to address comprehensively the many problems affecting the coastal system. ICZM is required for sustainable coastal and marine activity management and hence concerns not only physical damage such as erosion but also addressing the full range of hazards in this typology – including marine pollution, protection of typical natural marine habitats, infrastructure, residential areas and tourism. Physical change can be addressed by restoring sediment budgets, maintaining coastal dynamics, increasing the science knowledge, restoring resilience and ensuring holistic responses to coastal erosion (e.g. see EUROSION, 2003).

As indicated here, ICZM by definition requires a planned approach based on proven principles rather than piecemeal solutions, by cost-effective responses, increasing the social acceptability of the measures and keeping options open for the future. The above sites further recommend the need to incorporate the costs of coastal change and risk in planning and investment; such enhanced planning and management requires regional strategies including disseminating 'best practice' (including 'what works and what does not'). For example, Italy now requires a Strategic National Plan for ICZM. Of course, coastal disasters usually cause a re-think and perhaps re-prioritisation of measures to protect the coast, even by working with nature rather than trying to 'over-engineer' the coast. Pilkey & Young (2005), for example, emphasise that Hurricane Katrina caused a rethink of the way shoreline management is carried out in the US, increasing concerns about building infrastructure close to or on the coast and the way we have engineered coasts.

We emphasise that the successful and sustainable management of environmental problems has to follow an interlinked set of *10-tenets* which ensure the protection of the natural system and at the same time its exploitation by society (Elliott, 2013). Table 2 explores those tenets according to responses to coastal hazards and risk, to emphasise the increasing roles of engineering (technological) and economics in tackling coastal hazard and risk, with these perhaps given even greater weighting than the environmental and ecological aspects, as human safety may be endangered. Despite this, societal demands (and constraints) account for 9 out of the 10-tenets, including the importance of cultural, ethical and communication issues. In particular, given the various complex and elaborate measures proposed by local experts and politicians, we need active community involvement, to identify sustainability objectives using information and consensus. Hence promoting environmental awareness entails strategies for monitoring and regulation, but also processes of good governance (Trono, 2012).

Here we show the breadth of environmental management and governance (McLusky & Elliott, 2004; Bell & McGillveray, 2008) but we question whether the increasingly difficult economic conditions will reduce the preparedness for tackling coastal hazards. The European Union recently proposed a new Directive for Marine Spatial Planning and Coastal Management (European Union, 2013) which in theory should allow a holistic management of present and future hazards and risks. However, as emphasised here, the size and number and inter-related nature of hazards from the climatological, hydrographical and geomorphological conditions of coasts as well as anthropogenic change of catchment regimes, polluting processes, and urban and industrial development, both make that integrated management necessary while almost unattainable if all stakeholders are to be accommodated. We emphasise the distinction made by Zunica (2001) regarding natural and anthropogenic hazards and hence we indicate those causes over which society may have some control and those which it does not but that where it has to respond to the consequences - the exogenic unmanaged and endogenic managed pressures (Elliott 2011), hence the importance of the 10-tenets in framing our actions. Risks may be reduced by preparedness and planning, by education and by good science to inform decisions but an increasing coastal population increases the effects of the hazards and risk being proportional to the value of the assets or the population at risk. The degree of mitigation or adaptation needs to be determined by a willingness to pay and/or react to the hazard. We emphasise the need for a greater understanding of processes to address the causes of these hazards and thus minimise risk. Again we emphasise that this requires the multidisciplinary approach *a la* the *10-tenets*. Most importantly we need to ensure policy makers are educated act across that multidisciplinary framework.

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Table 1 Typology of Hazards in Coastal and Coastal Wetland Area (adapted and expanded from Elliott et al., 2010)

Hazard	Type	Examples
A) Surface hydrological hazards	Natural but exacerbated by human activities	High tide flooding, spring tide and equinoctial flooding; flash flooding, ENSO/NAO patterns
B) Surface physiographic removal by natural processes - chronic/long-term	Natural but exacerbated by human activities	Erosion of soft cliffs by slumping
C) Surface physiographic removal by human actions - chronic/long-term	Anthropogenic	Land claim, removal of wetlands for urban and agricultural area
D) Surface physiographic removal - acute/short-term	Natural	Cliff failure, undercutting of hard cliffs
E) Climatological hazards - acute/short-term	Natural but exacerbated by human activities	Storm surges, cyclones, tropical storms, hurricanes, offshore surges, fluvial and pluvial flooding
F) Climatological hazards - chronic/long term	Natural but exacerbated by human activities	Ocean acidification, sea level rise, storminess, ingress of seawater/saline intrusion
G) Tectonic hazards - acute/short-term	Natural	Tsunamis, seismic slippages,
H) Tectonic hazards - chronic/ long-term	Natural	Isostatic rebound
I) Anthropogenic microbial biohazards	Anthropogenic	Sewage pathogens
J) Anthropogenic macrobial biohazards	Anthropogenic	Alien, introduced and invasive species, GMOs, bloom-forming species
K) Anthropogenic introduced technological hazards	Anthropogenic	Infrastructure, coastal defences
L) Anthropogenic extractive technological hazards	Anthropogenic	Removal of space, removal of biological populations (fish, shellfish, etc); seabed extraction and oil/gas/coal extraction leading to subsidence
M) Anthropogenic acute chemical hazards	Anthropogenic	Pollution from one-off spillages, oil spills
N) Anthropogenic chronic chemical hazards	Anthropogenic	Diffuse pollution, litter/garbage, nutrients from land run-off, constant land-based discharges, aerial inputs

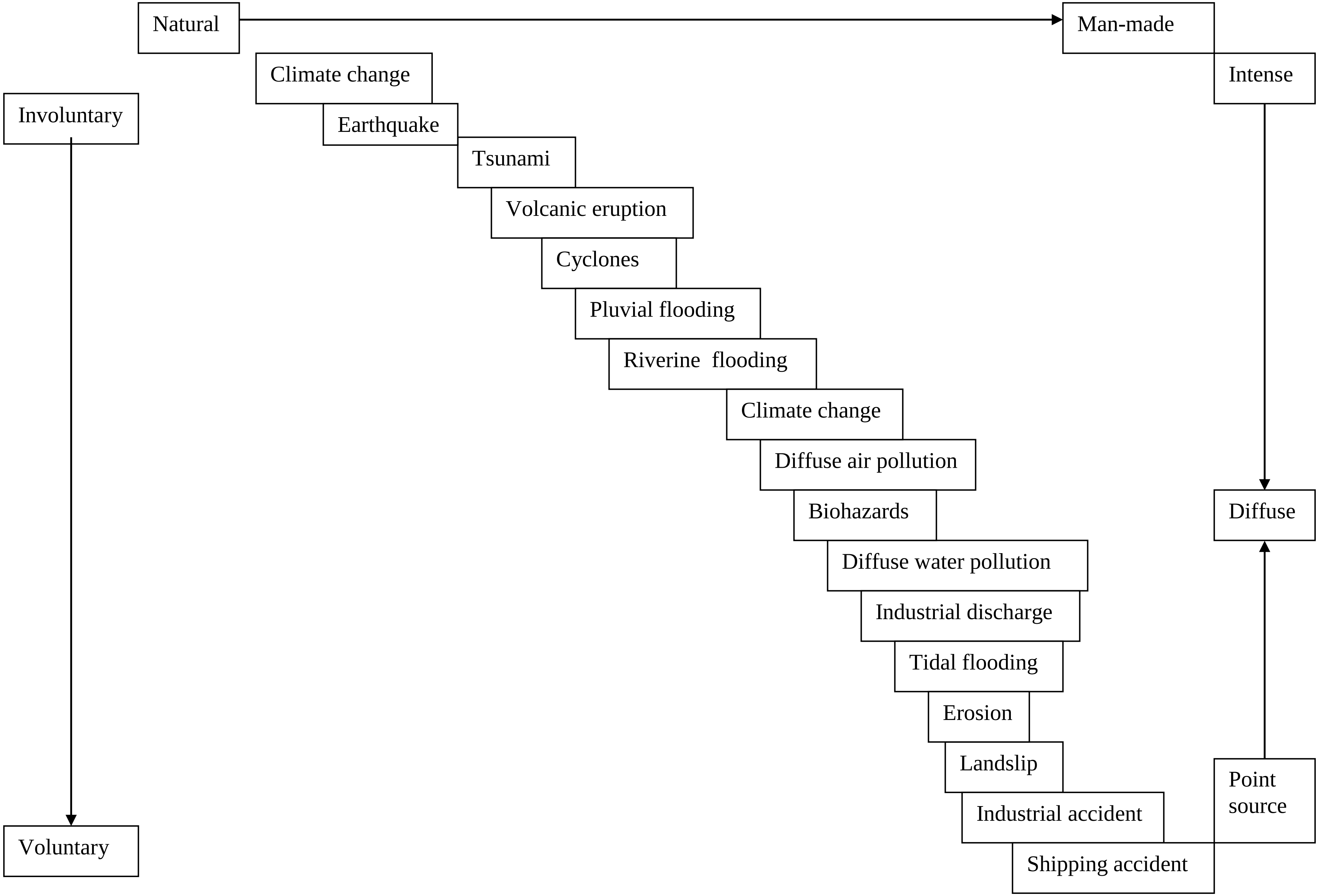
Table 2. The 10 tenets of sustainable environmental management (adapted and expanded from Elliott 2013) as related to coastal hazards and risk

Tenet	Meaning	Examples for Hazards and Risk Prevention and Response
Ecologically sustainable	That the measures will ensure that the ecosystem features, structure and functioning are safeguarded	That the natural ecology is maintained where possible and is sufficient to deliver ecosystem services
Technologically feasible	That the methods and equipment for ecosystem and society/infrastructure protection are available	Flood barriers, shore protection, treatment plants of chemical pollutants, mechanisms to prevent the inflow of biological organisms
Economically viable	That a cost-benefit assessment of the environmental management measures indicates sustainability but that adaptation to hazards is within financial budgets	Compensation schemes for those people and areas affected; that industry in the national interest and large urban areas are protected; that measures for pollution reduction are funded
Socially desirable/ tolerable	That the environmental management measures are as required or at least are understood by society as being required; that society regards the protection as necessary	The society is educated regarding the effects and implications of coastal hazards and thus has a high level of preparedness; that the societal 'memory' of disasters is accommodated
Ethically defensible (morally correct)	That the wishes and practices of current and future individuals are respected in decision-making	Dealings with individuals are at the highest level and that no single sector is favoured unduly; that the costs of present action to be borne by future generations is considered (e.g. economic discounting)
Culturally inclusive	That local customs and practices are protected and respected	That indigenous peoples, habits and customs are incorporated into decision-making; aboriginal (first-nation) rights are defended
Legally permissible	That there are regional, national, governance bloc (e.g. European) or international agreements and/or statutes which will enable the management measures to be performed; that either under regular or emergency statutes the hazard protection can be achieved	International agreements for aid and minimising hazards or the consequences of it; national laws and agreement allowing regional and national bodies to act even in emergencies; governance mechanism are adequate
Administratively achievable	That the statutory bodies such as governmental departments, environmental protection and conservation bodies are in place and functional to enable the successful and sustainable management	Flood management schemes, erosion protection schemes, shoreline management plans etc. have been created; that there are contingency plans showing the command structure to respond to hazards and disasters; that there are bodies to carry out these actions within the governance framework

Effectively communicable	That all horizontal links and vertical hierarchies of governance are accommodated and decision-making is inclusive	That all sectors are aware of the important issues and involved decision making; that all stakeholders have the opportunity to participate in decision-making
Politically expedient	That the management approaches and philosophies are consistent with the prevailing political climate	That there is pressure on politicians to carry out measures; that politicians are aware of the risks and the consequences of either not being prepared nor having suitable responses for the hazards occurring.

Figure Legend

Figure 1 A gradient of natural and anthropogenic environmental hazards covering spatial scales from the global to the local (greatly modified from a concept in Smith & Petley 2009, and adapted from that given in Elliott et al., 2010; see text for explanation).


Natural
Man-made
Climate change
Intense
Involuntary
Earthquake
Tsunami
Volcanic eruption
Cyclones
Pluvial flooding
Riverine flooding
Climate change
Diffuse air pollution
Biohazards
Diffuse
Diffuse water pollution
Industrial discharge
Tidal flooding
Erosion
Landslip
Point source
Industrial accident
Voluntary
Shipping accident