Natural Hazards, Landscapes and Civilizations[☆]

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1 Introduction

This article shows, through a series of recent, historical, archaeological, and palaeoenvironmental case studies, the relationship between natural hazards, rapid landscape change, and disasters. The evolution of societies is inscribed in geomorphology, as a close relationship exists between landscapes and humans (Beach et al., 2008). The role of landscape was paramount in the initial development of civilizations, with a clear influence on the emergence of agriculture and of cities. Ancient cities are closely inscribed in a landscape. Indeed their locations had often been chosen close to (1) a source of freshwater for drinking or irrigation, (2) areas producing food such as fertile soils in floodplains and volcanic areas, (3) waterways for transport and communication (a river or a safe harbor), or (4) strategic locations for safety, e.g., blocking canyon entrances, protecting mountains passes, surrounding hills with strategic viewpoints. These environments are highly dynamic (LaPoint, 2007). Any change, beyond what these societies can adapt to, may become detrimental to their good functioning. Indeed civilizations have often collapsed due to environmental change, but some others have developed for the same reason. Recent natural hazards and their ensuing disasters have highlighted that modern societies remain closely connected to their environment, whether close or distant. This is well illustrated by the 2010 eruption of an Icelandic volcano beneath the Eyjafjallajokull glacier and the closure of the European air space for 8 days, followed by intermittent closures in the succeeding weeks as the ash cloud moved southward and eastward.

The following definitions of natural hazards, disasters, and catastrophes are used here. Natural hazards are relatively rare at any locality, unexpected, uncontrollable, and have a high level of consequence on the environment, although not necessarily directly to humans, at regional and global scales. Disasters are hazards that include impacts on humans. A catastrophe is a disaster on a large scale and, in many cases, is irreversible. Very few global catastrophes have occurred (Leroy et al., 2010).

Disasters are hard to quantify. No linear relationship exists between a hazard and a disaster (Leroy et al., 2010). For example, a large hazard may lead to a small disaster. The relationship is thus, in most cases, not predictable. Measuring a disaster is often done by a metric, commonly number of deaths or economic losses. However this is not satisfactory, as one cannot compare a dollar in the United States, which may have little relative worth, with a dollar in poor countries, which could represent a day's worth of work. Better indicators remain to be developed.

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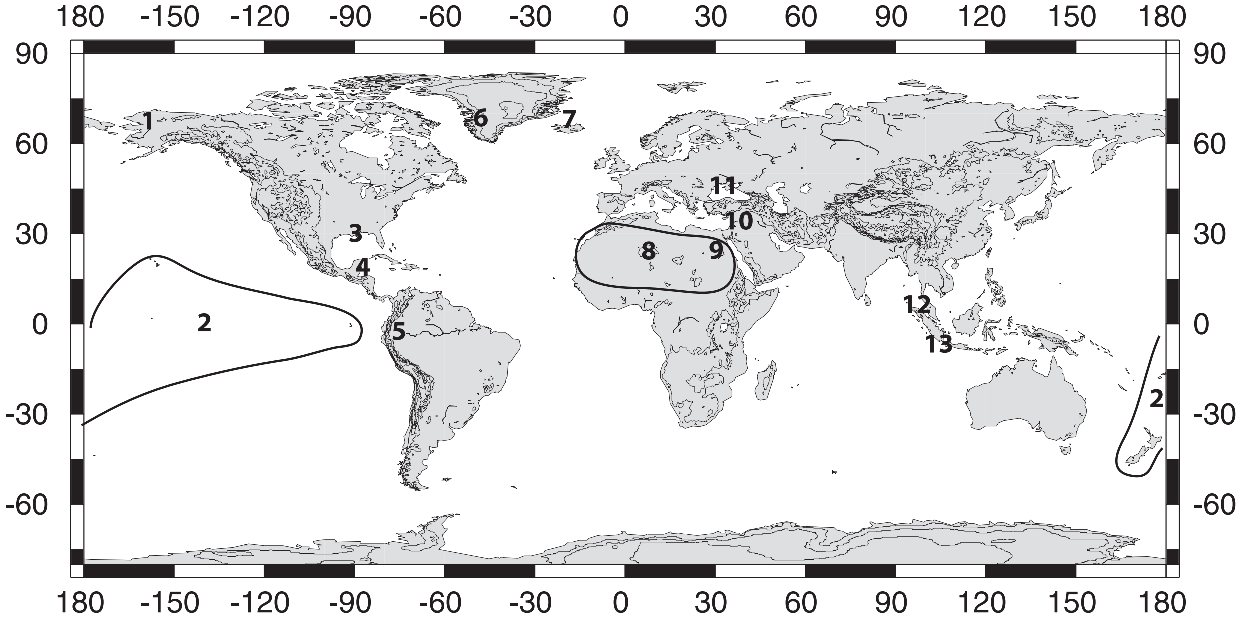

Fig. 1 Location map. 1: NW Alaska, 2: Remote Oceania, 3: New Orleans 4: Maya, 5: Moche, 6: Norse settlements in Greenland, 7: Laki, 8: Sahara, 9: Egypt, 10: Middle East, 11: Black Sea, 12: Aceh, 13: Krakatau.

Disasters and catastrophes are considered in this article, but some slower phenomena that have had huge geomorphic and environmental impacts with long-lasting effects on civilization are also addressed. The 12 case studies presented in this article are derived from archaeology, historical data, and recent events and are taken from the past 13,000 years. They are spread over North and South America, the North Atlantic, southeast Europe and southwest Asia, North Africa, Oceania, and the Indian Ocean (Fig. 1). Although most of the examples are accepted by the scientific community, some continue to be debated, for example the Black Sea flood. Past natural hazards and their consequences remain nevertheless sources of valuable lessons, even if the fine details cannot be confirmed.

2 Slow change or a series of disasters

In this section, two examples of large-scale environmental changes are examined. They appear to take place over several centuries, but actually are the cumulative effect of small disasters. The two examples illustrate the concept of catastrophe, as no return to the previous state of conditions is possible.

2.1 The Younger Dryas period and the initiation of agriculture

Plant cultivation was first practiced during the Younger Dryas, a brief period from ~11,500 to 9800 years before Christ (BC), or 12,900–11,600 years ago (Brauer et al., 2008). This period corresponds to a brief return of the ice ages, i.e., an unexpected global worsening of climatic conditions. Global temperature suddenly dropped by several degrees Celsius (Alley, 2007). The changes at the beginning and at the end of the Younger Dryas took place stepwise over several decades. However recent research suggests that stepped changes in climate happened within years only (Brauer et al., 2008; Steffensen et al., 2008).

Drying in the Middle East (Fig. 1) during the latter part of the Younger Dryas coincide with the Late Epipalaeolithic period and the Late Natufian culture (Meadows, 2005). The archaeology of the Middle East indicates that, prior to the beginning of the Younger Dryas, dense populations of hunter-gatherers had some year-round settlements (Fuller, 2007). Primitive forms of barley and wheat were gathered and eaten by these people before the advent of cultivation. During the Younger Dryas, most of the permanent sites were abandoned, but some groups maintained sedentary lifestyles in order to tend cereal crops. This progressively induced a selection towards non-brittle rachis (flower stalk) essential for domestication, which allows easier harvest owing to the absence of the natural and unfavorable property of seed shattering (Purugganan and Fuller, 2009). After the Younger Dryas, villages reappeared and many of these groups were cultivators. Finds of domesticated plants then became generally widespread in the Neolithic (Purugganan and Fuller, 2009).

Plant domestication has been attributed to a decrease of annual yields of wild cereal stands caused by climatic stress, which created the need and the motivation for cultivation. It seems likely that climatic change before and during the Younger Dryas played an essential role (Byrd, 2005; Willcox et al., 2009; Blockley and Pinhasi, 2011). Concomitant cultural and social changes (Mithen, 2007) led to a dramatic change in lifestyles and laid the foundations for the early civilizations of Mesopotamia and Egypt.

2.2 The mid-Holocene end of the Green Sahara

Many large lakes formed in the Sahara at the beginning of the Holocene (11,600 years ago) (Fig. 1) (de Menocal et al., 2000; Hoelzmann et al., 2001). This period of desert greening is referred to as the African Humid Period (AHP). Precipitation was perhaps as much as 10 times higher than today (Petit-Maire, 2002; Renssen et al., 2006). The monsoon summer rain played a key role in the greening of the Sahara. More summer radiation at the beginning of the Holocene, due to a Milankovitch-driven insolation maximum, warmed the continent, producing more monsoon rain (Ruddiman, 2005). An important megafauna, including giraffes, hippopotami, elephants, zebras, cattle, and horses, lived in what is now a desert (Fig. 2). They were supported by grassland now typical of the Sahel, which at that time extended several hundreds of kilometers farther north. During the early Holocene, this region was occupied by pastoral societies that practiced some agriculture (Hoelzmann et al., 2001; Kuper and Kroepelin, 2006).

After the mid-Holocene, less solar radiation caused the winter monsoon to strengthen, keeping potential rains away from the continent (Ruddiman, 2005). The modeled mid-Holocene transition in the western Sahara from wet to dry is highly non-linear, with centennial-scale climatic fluctuations due to the biogeophysical feedback between precipitation and vegetation cover (Renssen et al., 2006). Therefore, climate oscillated sharply at the AHP termination (Renssen et al., 2006). The Saharan-Sahelian population around 6000–5000 years ago lived in a rapidly changing environment and experienced a succession of increasingly stressful periods of lower precipitation.

As North Africa dried, the pastoral lifestyle became too uncertain because of unpredictable summer rainfall. Thus pastoral societies of the Sahara migrated to refugia such as the Nile Valley, the Sahel, and the Saharan highlands, where they made a vital contribution to many subsequent African cultures, including Pharaonic Egypt (Brooks et al., 2005; Kuper and Kroepelin, 2006). Permanent settlements and agriculture in the Nile Valley were preferably adopted with the support of irrigation (Brooks, 2006).

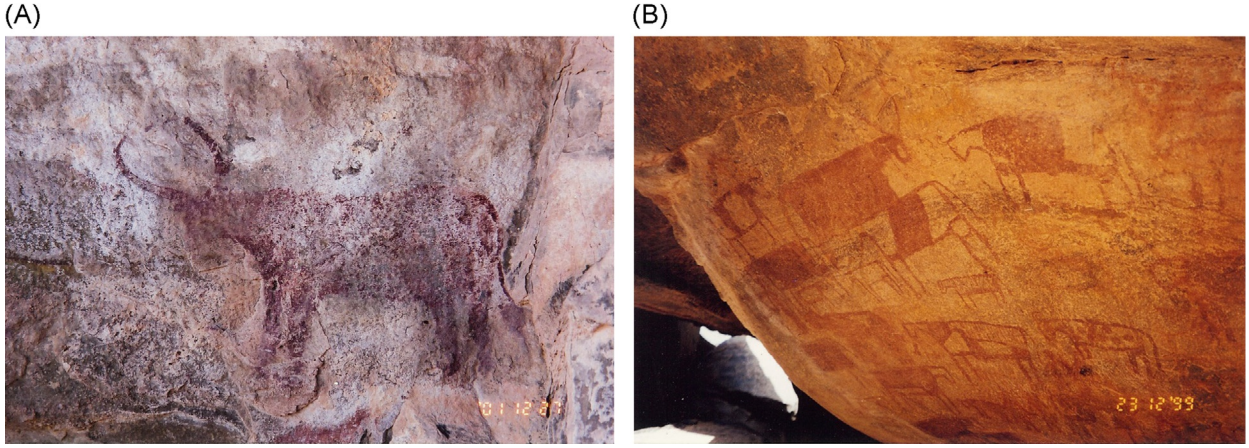

Fig. 2 Mauritanian Neolithic rock paintings of cattle. (A) Hamdoun (December 2001; S. Leroy). (B) Near Chinguetti (December 1999; S. Leroy).

3 Past great disasters

Water deficits and excesses have played a large and often decisive role in the development of ancient civilizations, especially when the crisis lasted longer than the society's resilience capacity. Rapid changes in coastline position and in lake levels are the foundation of many ancient myths and religions; examples include the Gilgamesh flood and Noah flood. Droughts have been invoked to explain the collapse of many civilizations such as the ancient Egyptian dynasties, the Akkadian empire in ancient Mesopotamia, and the Harappans in northwestern India and Pakistan.

The Americas have seen many native Indian societies develop and decline, to be reborn elsewhere in different forms. True collapse did not take place; rather there were expansions and retractions, such as for the ancestral Puebloans in the southwestern United States, the Central American Maya, and the South American Moche.

Delicately balanced nature-human interactions occur when pre-industrial societies settled in pristine environments. These societies modified, and sometimes greatly damaged, these environments with the possibility of negative returns. These environmental disasters may have additionally coincided with climatic changes and contributed, for example, to the abandonment of the Norse settlements in Greenland and to the cultural and environmental collapse on islands in Oceania.

3.1 The Black Sea flood and the spread of Indo-European people

At the end of the Pleistocene, large amounts of meltwater from the Eurasian ice sheet were carried southward into the Black Sea (Fig. 1) by rivers such as the Don, Dnieper, and Volga, and also from the Caspian Sea and lakes farther east and northeast. This inflow maintained the Black Sea at a level much higher than the Mediterranean Sea and produced a strong outflow into the Mediterranean Sea via the Marmara Sea. During the Early Holocene, meltwater discharge into the Black Sea ceased, and the climate became drier; this phase is recognized in southeastern Europe and farther east in central Asia (Wright et al., 2003). The level of the Black Sea dropped below the Bosphorus sill, perhaps by as much as 150 m. Ryan et al. (1997) and Ryan and Pitman (1998) argued that the Black Sea, which was then a slightly brackish lake, was suddenly flooded by Mediterranean waters around 8900 years ago. This catastrophic event, which has been called the Black Sea flood or even Noah flood, is marked by a change in sedimentation as well as a faunal turnover in the Black Sea due to the change of salinity. Water levels would have risen by up to 15 cm per day, causing a rapid inundation of low-gradient surfaces. All economic activities around the Black Sea were directly impacted. People migrated away from the coast and river estuaries, now submerged canyons, where it is thought most of the settlements were located.

The impact of this flood on people has been hotly debated; some have suggested that it was the impetus for the expansion of Neolithic farming into Europe, perhaps even linked to the synchronous spread of the Indo-European language (Ryan and Pitman, 1998). However, arguments persist about the date of the flood and the level of the Black Sea before it was reconnected to the Mediterranean Sea, and thus the speed of water-level rise (Ryan, 2007; Yanko-Hombach et al., 2007).

One interesting scenario that links all aspects of this event is the bursting of Glacial Lake Agassiz in northern North America about 8200–8500 years ago. This outburst flood sent a massive amount of meltwater into the world’s oceans, raising sea level by 1.4 m (Clarke et al., 2004; Turney and Brown, 2007). As the Mediterranean Sea rose, it would have breached the Bosphorus sill, initiating the flooding of the Black Sea, and the subsequent spread of Neolithic farmers and Indo-European culture (Turney and Brown, 2007).

3.2 The First Intermediate period in the Pharaoh dynasties and the 4.2 ka global event

Within the span of two millennia following the adoption of an agricultural mode of life in Egypt (Fig. 1), communities began to coalesce in progressively larger social groups (Hassan, 1997). By 3300 years BC, Egypt was unified in a single state ruled by kings who launched pyramid-building programs that were indicative of a strongly centralized government and of general prosperity. This period coincided with bountiful Nile River floods (Hassan, 1997) and therefore abundant grain harvests. The Pharaohs claimed authority based on their supposed ability to intercede with the gods to supply the annual Nile River floods (Fagan, 2000). When harvests failed for several decades, the power of the Pharaoh declined and the Old Kingdom collapsed.

The Old Kingdom, the Middle Kingdom, the New Kingdom, and the Late Period are separated by intermediate periods of political and social chaos that may have been caused by drought produced by failed rainfall upstream in the Nile River watershed. This link is particularly evident for the First Intermediate period (c. 2181–2034 years BC). A 60-year period of drought began around 2184 BC as an El-Niño drought struck the Ethiopian headwaters of the Nile. In fact the river flow became so low that people in Egypt could walk across it. In the face of grain shortages, the central government of Egypt fell apart, local warlords seized control, and people suffered from severe famine. It took 100 years for Egypt to reunify and subsequent Pharaohs invested massively in irrigation and grain storage to avoid the fate of their improvident predecessors (Hassan, 1997; Fagan, 2004).

Hassan (1986) correlated low water levels of Lake Fayium, a large Nile-fed lake southwest of the Nile River delta, with this Intermediate Period. Stanley et al. (2003) analyzed sediments obtained from drilling at the center of the Nile Delta and identified a thin layer of reddish-brown silt dating to between 2250 and 2050 years BC, coincident with the time of the collapse of the Old Kingdom. They attributed this layer to weathering of the delta plain during a long period of drought.

The crisis in Egypt in 2200 years BC, or 4200 years ago, coincides with other civilization collapses from Egypt to China. Drought affected the Harappan and Akkadian civilizations in Mesopotamia and the Indus River basin, respectively, and exceptionally cold weather affected the Longshan culture in China (Weiss and Bradley, 2001; Gao et al., 2007). A regional advance of alpine glaciers in western North America has been observed at 4.2 ka (Menounos et al., 2008). The 4.2 ka event is recognized as one of the few global events (Staubwasser and Weiss, 2006); therefore its impact corresponds well to that of a catastrophe rather than a disaster.

3.3 The Moche collapse in Peru in about AD 600

Pre-Columbian coastal and highland Peruvian civilizations (Fig. 1) offer exceptional insight into past linkages between culture and climate change because they sustained densely populated and complex agrarian cultures in challenging environments (de Menocal, 2001). The Moche civilization developed in valleys draining west to the Pacific Ocean in northern Peru, between about 100 and 800 after Christ (anno domini or AD). These valleys had no upstream glaciers; therefore the Moche were dependent on local precipitation. The Moche had a hierarchical society consisting of warrior priests, doctors, artisans, and the mass of the agricultural population. The leaders sacrificed their prisoners of war in an attempt to control the weather. The Moche developed sophisticated irrigation systems linking numerous valleys, metallurgy, urban centers, and monumental adobe brick structures. They controlled the entire northern Peruvian coastline south of the Sechura Desert (Chapdelaine, 2011).

Although the western slopes of the Andes are among the driest places on Earth, the adjacent Pacific Ocean is a rich fishery. The sea provided sufficient resources to support large sedentary populations. Agriculture in the lowlands demanded large irrigation canals to control runoff from the Andes. In the highlands, agriculture and pastoralism became increasingly important, in part to supplement the local lowland coastal resources such as salt, fish, and seaweed. The formation and growth of states in both lowlands and highlands may have been fostered by continuous interchange between the coast and interior (Mann, 2005). Moreover the climate strongly linked the lowlands to the highlands. For example, strong El Niño events in Peru are manifested as teleconnections, for example flooding on the north coast coincident with drought in the southern highlands (Moseley, 1987).

The Moche civilization existed at the mercy of droughts, earthquakes, and floods (Fagan, 2000). It seems that a period of collapse in the valleys, known as the Moche IV-V transition, occurred rather abruptly at around AD 600. The main irrigation channels became covered by sand dunes at the time of abandonment (de Menocal, 2001; Moseley et al., 2008). The subsequent Moche V culture was re-established inland between AD 600 and 750, near the confluence of highland rivers draining the Andean foothills where the water supply was more reliable (de Menocal, 2001). For earlier periods in the same region, successive earthquakes, El-Niño flooding, beach ridge formation nourished by sediment eroded during earthquakes and floods, and sand dune incursion caused a series of natural disasters that contributed to the demise of local coastal settlements (Keefer et al., 2003; Sandweiss et al., 2009).

The collapse of the Moche coincided with a megadrought, followed by large El-Niño floods, which have been inferred from a study of the annually layered ice cored in the Quelccaya ice cap in the Cordillera Occidental of the southern Peruvian highlands (Thompson, 1993). This area lies in the same zone of seasonal rainfall as the mountains above the Moche country. The accumulation rate of ice shows a dry period from AD 563 to 594, followed by a wet period between AD 602 and 635. During the three-decade drought, the Moche capital was moved inland and northward and people settled at valley necks, where they could have better control on water resources (Shimada et al., 1991). The data strongly suggest that highland cultures flourished when the mountains were wetter than normal and that coastal cultures flourished when the mountains were drier than normal (de Menocal, 2001).

Drought and the Moche leaders' inability to alleviate it led to unrest and fighting among communities. The strife, together with limited food and productive agricultural land, led to a slow deterioration and, ultimately, to the destruction of the Moche civilization in the following centuries (Dillehay et al., 2004). The decline was presaged by an earlier 17-year-long drought that began in AD 524. In summary, the Moche IV-V transition and the shift of their activities from the coast to the highlands resulted from stresses caused by a succession of natural disasters (Moseley et al., 2008).

3.4 The Classical Maya decline about AD 900 in Central America

The Maya Indian civilization flourished in Central America (Fig. 1) from AD 250 to 900, with roots in the preceding millennia (Wahl et al., 2006). The empire collapsed around AD 900 at the heyday of its intellectual and cultural development.

The Maya had by then developed a sophisticated hierarchical society with a writing system and astronomical knowledge. They left behind impressive cities dominated by large temples. They, however, lived in a fragile ecosystem that ranged from tropical forest in Guatemala and southeastern Yucatan to desert in northwestern Yucatan. Their agriculture was based on slash-and-burn practices, terraced hill slopes, drained fields and irrigation channels. The farmers had many means of intensifying agriculture. However, a relatively large numbers of workers depended on others for food production. Productivity was low and a Maya peasant could produce only twice the needs of himself and his family (Diamond, 2005).

This type of agriculture caused significant erosion. Today many lakes, canals and reservoirs (Fig. 3) contain what is called the "Maya clay," a thick inorganic layer that started to form after about 3000 years ago (Brenner et al., 2002). The deposit reflects severe soil erosion that resulted from widespread, human-mediated deforestation. Erosion decreased progressively towards the Late Classic period due to soil conservation measures (Beach et al., 2009). The end of this deposition corresponds to the Maya collapse and natural reforestation of the landscape (Brenner et al., 2002).

When drought became more common near the end of the first millennium AD, the Maya attempted to adapt to the changing environment through spiritual means. They built more temples and held more ceremonies. Warfare became chronic, and limited food supply made it impossible for any Maya principality to maintain control over the whole region (Diamond, 2005). Population decreased in the late ninth century due to a combination of natural factors, such as erosion and drought, and social ones such as overpopulation, social upheaval, and warfare. No buildings show glyphs with dates after AD 909, although some construction continued (Diamond, 2005; Douglas et al., 2016).

Lake sediments in Yucatán provided the first evidence that climatic change may have been implicated in this decline. Sediments recovered from closed lake basins reveal the onset of much drier conditions between AD 800 and 1000 (Hodell et al., 1995). Oxygen isotope data from cores collected at Lake Punta Laguna, in the Yucatán lowlands, show a period of higher evaporation from AD 280 to 1080 (Curtis et al., 1996). The peak in ∂^{18}O, representing the highest evaporation, is at AD 585, which coincides with the Maya Hiatus, an Early/Late Classic boundary in Mayan culture. Another ∂^{18}O peak at AD 862 concurs with the time of the collapse of the Classic Maya Civilization between AD 800 and 900. A third peak at AD 1391 may correlate with Postclassical abandonment of sites on the northern Yucatán Peninsula (Curtis et al., 1996). Other lake records have since confirmed this period of greater aridity, with peak periods of droughts at times of major Mayan cultural change (e.g., Lake Salpetén in the Petén lowland in northern Guatemala; Anselmetti et al., 2007; Douglas et al., 2015). Other proxies corroborating changes in erosion and agriculture, respectively, are sediment accumulation rates and agricultural indicators in pollen assemblages, such as the pollen of corn or *Zea mays* (Wahl et al., 2006).

Varved sediments in a core taken in the Cariaco Basin, off Venezuela, have yielded similar high-resolution records. A major drought lasting 160 years has been identified at the time of the collapse of the Classic Maya civilization (Haug et al., 2003). The

Fig. 3 Springs near Momostenango, Guatemala (summer 1984; S. Leroy).

cause of this drought is thought to be a southward displacement of the Intertropical Convergence Zone. Likewise, recent work on the Greater Antilles has shown a period of droughts and societal change (Lane et al., 2014). However in this case, it led to intensified agricultural practices and population increase.

3.5 The Norse Greenland demise at the beginning of the Little Ice Age

The Norse people who lived in Greenland (Fig. 1) between about AD 985 and 1450 were not one ethnic group, but rather a spectrum of peoples with many different languages. The main groups, however, were Norwegians and Danes. They arrived from Iceland, which they had colonized in AD 871. The causes for moving to Greenland are diverse: ideology, climatic change, overpopulation, scarcity of land and floods, technological development, and internal political conflict (Diamond, 2005). They arrived on cargo ships, the knorrs, using prevailing currents in the ice-free waters of the North Atlantic. They found in Greenland an uninhabited, virgin landscape, because the Inuit of the Thule tradition only came later. The Norse soon established a herding economy supported by hunting and, initially, barley. At its peak, the Norse population was about 4000, with about 300 farms, 12 churches, a cathedral, and a monastery. The economy, however, depended on trade with the homelands. In exchange for whale, walrus and seal skins, whale bones and ivory, they received silver, gold, silk, spices, salt, and wheat. After about AD 1200, the settlers started trading also with the Inuit, who were very well adapted to this harsh environment. The Inuit used skin kayaks for ocean hunting, sledges, recurved bow with a sinew backing, and the toggle harpoon to hunt through ice year round. They also produced skin clothes. The Norse life was precarious, as they relied on a short summer season to produce much of what they needed for the winter, for example hay (Barlow et al., 1997). They especially feared the exhaustion of stored meat and dairy products before the beginnings of spring sealing.

A study of insects found in the floor layers inside collapsed houses has provided information on the final days of the Norse settlements (Panagiotakopulu et al., 2007). The fly fauna in one of the excavated farms changes from species requiring warmth indicating fire in the hearth, to cold-adapted species indicating a lack of burning wood and finally to outdoor species caused by roof collapse. These changes are accompanied by a change from insects that thrive in a relatively clean environment, although one with human parasites such as fleas and lice, to one rich in carrion. It appears from a study of bones in kitchen middens that, in the final years, the Norse were reduced to eating their dogs, even though they were essential for hunting (Panagiotakopulu et al., 2007).

Greenland ice cores show that climate cooled slowly from AD 1000 to a low at about AD 1500 (Dahl-Jensen et al., 1998). Stock rearing became unreliable toward the end of this period; crops failed often; and the settlements were cut off from the outside world by sea ice for several years at a time. Unlike the Inuit, the Norse settlers were unable to adapt to living off the sea, where fish and seals remained plentiful year round, even as climate changed. The last recorded contact was in AD 1410, although archaeological evidence suggests that one settlement persisted until about AD 1500. The crew of a ship that visited the Norse settlement in AD 1540 noted only abandoned farms.

Another factor that contributed to the decline of the settlements is erosion. When the Norse arrived, they found a sparse Arctic scrub of dwarf birches, willows, heathers, and junipers, which they cleared for agriculture. Land clearing, together with grazing, destroyed the soil and limited the economic activities of the Norse (Edwards et al., 2008).

Diamond (2005) attributes the end of the Norse settlements to a combination of five factors: the Little Ice Age reduction in temperatures and increase in sea ice; damage to the environment by overgrazing and land clearance for agriculture; conflict with the Inuit; reduction of trade with Iceland and Europe; and the unwillingness of the Norse to learn from the Inuit who were considered inferior (McGovern, 1991).

3.6 The colonization of Pacific islands

Polynesians came from Melanesia (Fig. 1) only within the past 2000 years at most (Hurles et al., 2003). Maoris arrived in New Zealand 1000 years ago, and other Polynesians reached Easter Island only about 800 years ago (Hunt and Lipo, 2006). Early human activity is easier to identify in remote Oceania than in the rest of the world, because of the relatively short time of human occupation. Moreover, biodiversity decreases eastward across the Pacific; thus human disturbances are more obvious and identifiable on remote islands far from continents. Human-associated activities such as burning, hunting, and the introduction of new species are apparent in the archaeological record (Hurles et al., 2003). The settlers were farmers, who used slash-and-burn methods to clear land. They rapidly destroyed the natural subtropical forests. Moreover, they brought rats that suppressed coastal and lowland plants and a variety of animals (Towns et al., 2006). Archaeological sites commonly contain seeds with traces of rat gnawing (Prebble and Wilmshurst, 2009).

The recent human colonization of Easter, Necker and Nihoa Islands led to massive deforestation and extensive modification of the landscape (Rolett and Diamond, 2004). In the case of Easter Island, a nearly total destruction of its forest caused the progressive or sudden collapse of a primitive society (Cañellas-Boltà et al., 2013). The collapse coincided with the building of impressive statues to gods who, the residents hoped, would bring a solution to their problems (Rolett and Diamond, 2004; Diamond, 2005).

In New Zealand, the arrival of Europeans in the mid-18th century brought renewed deforestation, this time with far stronger erosion, than had occurred during the Maori occupation. Europeans settled not only the flat plains but also the steep slopes (McGlone, 1989), and, more importantly, they introduced millions of sheep that further reduced plant cover. These activities eroded slopes and triggered large landslides (McGlone, 1989; Glade, 2003). Page and Trustrum (1997) studied sediment cores from several New Zealand lakes and reported an increase in erosion associated with the arrival of the Polynesians, followed by a further, even more dramatic, increase with the arrival of Europeans. A similar close relation between forest cover, soil erosion, and the two fluxes of immigrant populations has been noted for the Cook Islands (Kirch, 2006).

4 Recent disasters

No catastrophes leading to the collapse of a civilization have occurred in the past several centuries. Nevertheless, the number of disasters is increasing. Today, natural hazards affect a larger number of people, due to population growth and increased settlement of risky environments. Two of the following examples deal with localized geomorphic changes (Laki and Krakatau eruptions) with a quasi-worldwide impact. The two other examples (the Indian Ocean tsunami of 2004 and Hurricane Katrina in 2005) illustrate socio-political impacts of natural disasters.

4.1 The volcanic eruption of Laki in AD 1783–84

The Laki eruption (Iceland; Fig. 1) in AD 1783–84 produced the largest lava flow in recorded history. During the 8-month-long eruption, a 27-km-long fissure formed, and huge amounts of sulfur dioxide were released into the atmosphere (Jacoby et al., 1999; Thordarson and Self, 2003). Sulfuric acid and volatiles emitted by the eruption damaged vegetation from the Arctic Ocean to the Mediterranean region (Grattan, 2006). Poor weather, acid rain, and fog in Iceland led to the death of up to a quarter of the population and three-quarters of the livestock (Grattan, 2006). The eruption also cooled climate in Europe and the Middle East for 2–3 years (Stothers, 1999). Europe was affected by a dry fog for 6 months; and the fog reached as far as China, northern North America, and Brazil (Trigo et al., 2009). Air pollution was so bad that human health was affected: the death rate increased dramatically in both England and France (Grattan et al., 1995; Grattan, 2005). Oman et al. (2006) reconstructed lower low Nile floods and suggested that lower rainfalls on the Nile headwaters was caused by cooling of the atmosphere that led to a strong weakening of the African and Indian monsoon circulations. The fog in France came at a time of famine that possibly was exacerbated by other meteorological factors (Thordarson and Self, 2003). Some researchers have seen these events as contributors to social strife that led to the French Revolution in AD 1789 (Grove, 2007). Grattan et al. (2007) emphasize that populations that suffered most were already fragile before the eruption due to other factors, for example overpopulation in Japan and the failed monsoon in India.

Jacoby et al. (1999) inferred the impact of the Laki eruption by studying ring patterns of white spruce (*Picea glauca*) in northern Alaska (Fig. 1). The maximum latewood density of boreal conifer rings differs from year to year, mainly as a function of summer temperatures. Jacoby et al. (1999) found anomalously low maximum-latewood densities for AD 1783, the lowest for a period of over 400 years. They reconstructed a lowering of May-August mean temperatures of more than a 4 °C from the mean. The cooling was spatially variable, interior and northern Alaska being one of the regions most severely affected. An analysis of the written and oral history of Alaska (Jacoby et al., 1999) indicates that the cooling caused famine among the Inuit population. The diaries of Russian and European explorers in the region speak of deserted villages and a notable decline in the native population (Jacoby et al., 1999). The impacts of the eruption were also recorded in oral traditions of a normal spring and early summer that turned suddenly frigid, snowy, and barren. A book written by William Oquilluk provides a record of the oral history of his people, the Kauwerak from northwest Alaska. The book describes several great disasters, each one causing the death of most of the people living in northwest Alaska. One of them was a very cold summer that caused the death of all but a few people in widely scattered communities on the mainland coast; this event is called "The Time Summer Time Did Not Come" (Jacoby et al., 1999).

4.2 The AD 1883 Krakatau eruption and Indonesia Independence

Before 27 August 1883, Krakatau was a volcanic island between Sumatra and Java in Indonesia (Fig. 1). A cataclysmic eruption that day destroyed most of the island (Whittaker et al., 1989) and triggered a tsunami that killed more than 36,000 people (Dörries, 2003). Giant sea waves reached the height of up to 40 m (Fig. 4) and propagated through the Indian Ocean and the South Atlantic Ocean. The explosion was heard as far away as Australia and India, and threw so much ash and gas into the atmosphere that it cooled temperature around the world for years. Krakatau's ash led to stunning sunsets in Europe and the United States that captivated artists. Of the volcanic island itself, only fragments were left surrounding a large underwater caldera. In AD 1927, a new smaller volcanic cone, Anak Krakatau, emerged from its center.

Winchester (2003) has suggested that the eruption of Krakatau sparked a revolution. In AD 1883, no sound scientific explanations were available for this disaster, thus people turned to religion for an answer, especially so in Indonesia. The Muslim prelates of Java concluded that the eruption was punishment from God for the evil acts of men and women (Winchester, 2003). Allah was irritated because so many people were passively allowing themselves to be ruled by the white infidels, the Dutch. To appease Allah, the mullahs declared the Dutch had to be killed and their influence expunged. This exhortation culminated, 5 years later, in an organized rebellion, i.e., the Banten Peasant's revolt in AD 1888 that killed dozens of Dutch and hundreds of Indonesians (Winchester, 2003). Kartodirdjo (1966) attributed the Banten Peasants' revolt to cumulative factors, including a cattle plague in 1879, an epidemic in 1880, the Krakatau eruption in 1883, and years of famine following the eruption.

Volcanic eruptions, especially combined with other disasters, can be catalysts of social change. They provide a "clean break" from which to start anew (Dove, 2008).

4.3 The Indian Ocean tsunami of 2004 and the separatist movement in Aceh

The province of Aceh is one of the closest places to the epicenter of the giant Sumatra earthquake in 2004. The earthquake triggered a tsunami that devastated much of the west coast of the island of Sumatra, including part of the capital of Aceh, Banda Aceh (Fig. 1). About 230,000 people in 14 countries were killed in the disaster. In Indonesia ~500,000 were left homeless; about 167,000 of the

Fig. 4 Large reef block displaced by the Krakatau tsunami and moved 75 m from the coastline to the garden of the Telkomsel guesthouse; on the west coast of Java between Anyer and Carita (August 2007; S. Leroy).

deaths were in Aceh (Hyndmann, 2009). The coastal geomorphology of Aceh was profoundly modified by the earthquake and the tsunami (Paris et al., 2009). In the area of Lhok Nga, west of Bandah Aceh, the erosional imprint extended 500 m on shore and 2 km along riverbeds. Beaches lost an average of about 30 m^3 m^{-1} of sediment and locally more 80 m^3 m^{-1}; however, more than 75% of the sediments deposited inland came from offshore. A year after the tsunami, geomorphic processes were still active. Comparisons of satellite photos before the tsunami, just after it, and up to 4 years later indicate that the recovery of the beaches along the Aceh coast occurs generally within 3 years (Liew et al., 2010).

Aceh has substantial natural resources, including oil and gas (World Bank, 2009, 2012). Islam may have been introduced to Southeast Asia from Saudi Arabia through Aceh. The province is religiously conservative relative to the rest of the country, which was settled by less conservative Muslims from India. Aceh has a history of struggle and resistance to control by outsiders, including the former Dutch colonists and the Indonesian government. In AD 1959, the Indonesian government gave Aceh a "special territory" status, i.e., a territory that has more autonomy than most other regions of Indonesia. For example, the Aceh regional government has the power to construct a legal system independent of that of the national government. In spite of these concessions, a rebellion began in Aceh in 1976, resurfaced in 1989, and gained strength in 1999. In 2003, the rebel group, the Free Aceh Movement (GAM), began an offensive and a state of emergency was proclaimed in the province (World Bank, 2009, 2012). The province was at war when the earthquake and tsunami occurred in 2004.

The local population thought that the tsunami was punishment for insufficient piety. As a consequence, religion gained even more importance after the tsunami, reflected in part in further implementation of sharia law (World Bank, 2009, 2012). The tsunami drew a lot of international attention to the conflict, wiped out many supplies, and killed many persons from both sides of the conflict. Fortunately the earthquake and tsunami helped Indonesia and the GAM to reach a peace agreement that was signed by both parties in August 2005 (Hyndmann, 2009). Earlier efforts to reach an agreement had failed, but the tsunami and other factors brought peace. Under the agreement, Aceh received further autonomy and government troops were withdrawn from the province in exchange for GAM's disarmament. Former GAM members were freely elected to provincial and many district administrative bodies. This outcome is remarkable and inspiring given that only a few years earlier, the region was at war and cut off from the outside world (World Bank, 2009, 2012).

Beardsley and McQuinn (2009) compared the failure of the rebel movement in Sri Lanka (the Liberation Tigers of Tamil Eelam or LTTE) and the contemporaneous relative success of the GAM in Indonesia, both of which were regions severely impacted by the tsunami. They showed that the difference probably was due to the greater need for the GAM to receive support from the local population and therefore a greater desire to reach peace. On the contrary, the LTTE was more dependent on the Tamil diaspora and external resource support and was therefore less amenable to compromise.

4.4 AD 2005 Hurricane Katrina and ethnicity changes in New Orleans

New Orleans, Louisiana, located on the delta of the Mississippi River (Fig. 1), was founded around AD 1718 on a riverbank levee. Already from its beginnings, it was subjected to flooding and hurricanes (Turner, 2007). The area of New Orleans is subsiding at a current rate of about 5 mm $year^{-1}$. The geological setting, subsidence, and a variety of human activities are responsible for a spatially complex geomorphic landscape that was impacted by Hurricane Katrina in 2005. This landscape resulted from Holocene sea level rise, lateral changes in depositional environments, development of Mississippi River delta lobes, and the distributary channels associated with delta development (Dunbar and Britsch, 2008).

In August 2005, Hurricane Katrina made landfall as a Category 3 hurricane between two of the largest cities on the United States. Gulf, New Orleans to the west and Mobile (Alabama) to the east. It packed winds up to 209 km h^{-1}, a storm surge up to 9.1 m high, and rainfall of up to 305 mm. Hurricane Katrina was one of the most catastrophic hurricanes in United States history; nearly 2000 people were killed or went missing, and hundreds of thousands of families were affected (Leroy et al., 2010). Much of the devastation was caused by breaches of New Orleans levees and floodwalls, which left about 80% of the city under several meters of water.

Storms and hurricanes affect coastlines in a dynamic and complex way (Cahoon, 2006), with often large areas of land area loss. However, in a study of two subsiding marshlands along in the Mississippi River delta, it has been shown that Hurricanes Katrina and Rita introduced sediment and facilitated vegetation recovery (seed and propagule dispersion), thus counteracting sediment loss (McKee and Cherry, 2009).

The flooding of New Orleans mainly affected the low-income Afro-American population. The loss of houses, reduced employment, and the rising cost of insurance made it impossible for families to return after the disaster. According to a 2008 report from the Greater New Orleans Community Data Center, 16 of 50 New Orleans neighborhoods that were flooded during Hurricane Katrina have less than half the households that were present in June 2005.

Among these permanently displaced families are musicians, artists, and other groups representing the last vestige of Louisiana's Cajun/Creole French heritage (Leroy et al., 2010). The failure of many displaced citizens to return to New Orleans poses new problems for the future of the city (Falk et al., 2006). It was a local black population that, in the past, provided much of the semi-skilled labor for New Orleans' heavily service-driven labor market. Questions have arisen as to who will perform the countless menial, but necessary, tasks that are the foundation of a service-based economy. One possibility is that people in southern Louisiana and nearby western Mississippi whose lives were disrupted by Katrina will migrate to New Orleans in search of employment opportunities. More likely, Hispanics will move from Texas to Louisiana to help with the rebuilding effort, adding a new ethno-racial element to the historically diverse city. Falk et al. (2006) have forecasted that the city will be smaller, more White and

Hispanic, more affluent, and with an economy based more on tourism and entertainment than was the case prior to Hurricane Katrina (Falk et al., 2006).

An earlier series of hurricanes in neighboring Texas, beginning with the "Great Storm" of AD 1900, caused the economic decline of Galveston and the rise of Houston. The latter city is in a more sheltered position inland of the barrier island where Galveston is situated (Leroy et al., 2010). Category 4 landfalling hurricane Harvey caused in August 2017 unprecedented flooding and damage in Texas. It poured more than 1300 mm of precipitation across the heavily populated Houston area (Zhang et al., 2018). This seems to have been exacerbated by the fast runoff and poor infiltration of the town as well as by the mesoscale convective systems typical of built areas. A study of sediment transport and bathymetry on coastal bays south of Houston at Port Aransas indicates a significant seaward displacement of sand with removal from barrier islands and deposition on the inner shelf (Goff et al., 2019). This is contrary to the usual concept of storm-driven, landward migration of barrier islands through wave-driven erosion of the shoreface and wash-over deposition on the bay (Goff et al., 2019).

5 Discussion

5.1 Factors leading to disaster

Four factors, i.e., time, space, people, and type of hazards, combine in a variety of ways to cause a disaster or even a catastrophe (Fig. 5; Leroy, 2006; Leroy et al., 2010).

The first factor is the speed of onset and duration of the event. Preparation is not possible for a rapid-onset event. A destructive event that lasts several days, for example a flood, quickly exhausts emergency food and water supplies. The second factor is the size of area affected or the proportion of settlement affected. People will not hesitate to move away when no other possibility turns up. In many cases, however, the affected area is so large that there is nowhere to go. The third factor is the type of society that is impacted. A society may be very adaptable, mobile (e.g., nomads), or rigid with a strong hierarchy or a strong attachment to some geographical features. This is what Diamond (2005) calls dropping core societal values. For example, moving New Orleans farther up the Mississippi River would appear to be scientifically sound, but federal and state authorities will not suggest a move, because the present location of the city is perceived to be good for economic reasons, for example a harbor that supports the oil industry. A lack of flexibility is well illustrated by the Norse in Greenland. They chose not to change their way of life and refused to learn from the Inuit. The fourth factor is the type of hazard and its recurrence and the accumulation of diverse types of hazards. Repeated hurricanes like Hurricane Katrina followed by Hurricane Rita will test the resilience of a society. In other cases, successive hazards of different types will have the same cumulative impact, described as a ratchet effect by Chambers (1989) and Ford et al. (2006). The Moche collapse illustrates this point because it appeared to be caused, in part, by a succession of droughts, floods, and earthquakes. In 2010 the devastating earthquake that struck Port-au-Prince, the capital of Haiti, closely followed the disasters caused by Hurricanes Gustave and Ike in 2008, leaving the country with very little coping capacity. Moreover, in this case, the disasters affected a poor country with weak institutions. During the earthquake, government officials essential for the organization of the rescue operation were killed. Moreover, aid workers caused a deadly cholera epidemic, bringing the death count from 90,000 to 100,000 people.

A catastrophe tends to develop when many of the negative aspects of the four factors coincide.

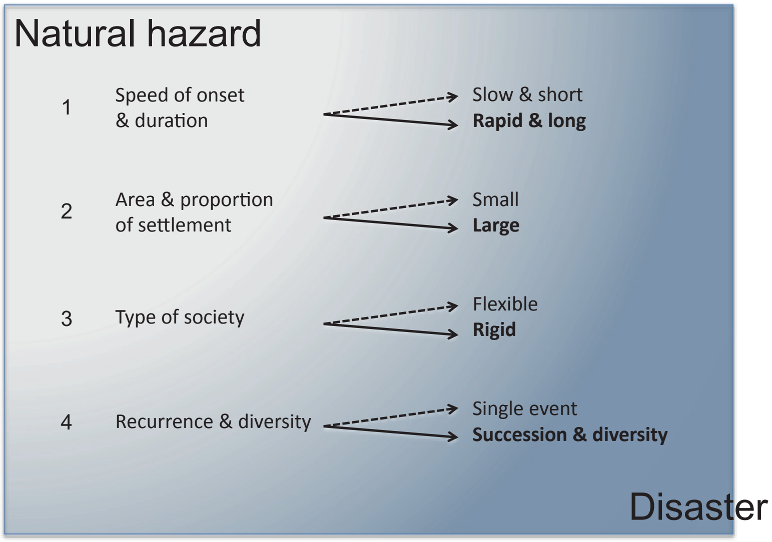

Fig. 5 The four actors leading to disasters and catastrophes.

5.2 Positive effects of sudden environmental changes

Environmental changes commonly are associated with geomorphic changes, which may negatively impact people because adaptation is expensive and time-consuming. Changes have clearly led to various types of dark ages in archaeology. Examples of negative impacts of environmental changes include the aridification at the end of the eastern Roman Empire (Issar and Zohar, 2004) and the global dust veil of AD 536 that resulted from a comet impact or a cluster of large volcanic eruptions (Baillie, 1999, 2008; Büntgen et al., 2016).

Environmental change, however, can also have positive impacts that improve the human condition and increase societal complexity. Brooks (2006) has argued that the earliest complex, highly organized, state-level societies emerged throughout the global monsoon belt caused by an orbitally-driven decrease of insolation leading to an increasing aridity. One of his examples is the aridification of the Sahara (shrinking of large lakes at the end of the AHP) and development of the Pharaonic civilizations. The seemingly deleterious environmental effects of the Younger Dryas (aridification of the Middle East) led to an important innovation that facilitated the subsequent development of civilization, i.e., the domestication of cereals (Brooks, 2006). Rapid landscape changes seem to create conditions from which innovation may emerge.

5.3 Is modern society vulnerable to rapid environmental change?

The argument that technological sophistication protects modern society from natural disasters is a grave misconception. Our modern technological world remains fragile and vulnerable to disasters. This is well illustrated by COVID-19 that caused a worldwide lockdown in 2020 to limit disease propagation and loss of life. This pandemic had long-term economic impacts. Modern medicine remained powerless for months on.

Technology has created a global interconnectedness; metaphorically we are now one island. Our interdependence is illustrated by the fact that, of the five largest power failures in the world in terms of number of people affected (Anonymous, 2020), four have resulted from the cascading effects of localized outages due to poor weather in a rather small area: southern Brazil in 1999 (>75 million people affected) due to a lightning strike; Brazil-Paraguay in 2009 (60 million people) due to heavy rain and strong winds; Italy and southern Switzerland in 2003 (56 million people) due to storms; in northeastern United States and southeastern Canada in 2003 (>50 million people) due to a hot day. Although those power outages lasted only a few hours, the outage caused by the North American Ice Storm of 1998 left some areas without power for several weeks and millions of trees were damaged or fell from the heavy ice. If such events happened during a period of political upheaval or war, or in combination with another disaster such as an earthquake, power could not be restored so quickly.

Another illustration of our interconnection is our reliance on meteorological satellites. The satellite network could be disrupted by a large volcanic eruption or an unprecedented magnetic storm. Data provided by satellites are critical for daily weather forecasts, and any disruption in the network would reduce the accuracy of forecasts, especially in the Southern Hemisphere where fewer ground-based observations are available. The Mount Pinatubo eruption in the Philippines in June 1991 decreased the quality of the satellite-derived sea surface temperature measurements. Negative biases of >1 °C for August and September 1991 was observed in the tropics, sufficient to mask an El-Niño event that was unfolding (Reynolds, 1993).

Another aspect of interconnectedness that is of concern is global food supplies. In order to understand the impact of a global natural hazard such as cometary impact or supereruptions and the ensuing cooling of the weather, the analogy of a nuclear war can be used. Such a model shows its impact on weather and food production, especially grain (Rampino, 2002). It is chilling to note that global food reserves are extremely low. Estimates range from slightly less than 50 days and falling (Helfand, 2007) to 175 days (Laio et al., 2016). Any global hazards would immediately lead to a global famine. Many countries suffer famine even when surpluses exist in nearby countries. Problems of food distribution and differences in wealth hinder relief. Guatemala is a country exporting food, yet half of the children suffer from chronic undernutrition (Loewenberg, 2009).

Because of population growth, increasingly marginal or hazardous environments become inhabited, for example the flanks of volcanoes (Chester et al., 2001), landslide-prone areas (e.g., in the Caucasus; Gracheva and Golyeva, 2010), floodplains (e.g., the Ganges-Brahmaputra Delta), low-lying or even subsiding coasts (New Orleans and parts of the Netherlands), and areas of uncertain rainfall (Sahel).

The concept of “climatic refugee” is a fairly new one, but may soon apply to large numbers of people. Refugees move to two types of places. Firstly, they may move to unoccupied or sparsely populated environments with fragile ecosystems. For example, people are settling natural areas near the great lakes in eastern Africa; these areas are being rapidly deforested causing erosion and ecological damage. Secondly, refugees may migrate to cities. For instance, migrants concentrate in the megacity of Dhaka, which is itself in danger, as it is only 4 m above sea level, in the path of cyclone, and has no infrastructure to accommodate more poor people.

5.4 Towards solutions

Warning systems are one strategy for reducing risk from natural hazards. A complete and effective warning system comprises four inter-related elements: knowledge of hazards and vulnerability, monitoring and warning services, communication, and the capacity to respond (UN ESCAP, 2009). Tsunami warning systems were installed in the Indian Ocean after the 2004 tsunami. They range from beach sirens to deep-ocean monitoring systems. The government of Indonesia provides information and training courses for evacuation in the event of a tsunami (Fig. 6). The September 2007 tsunami in Sumatra illustrated the progress that has been made,

Fig. 6 Evacuation route for tsunami in Anyer, northwestern Java (August 2007; S. Leroy).

but also highlighted remaining weaknesses (UN ESCAP, 2009). No warning was issued during the 2018 eruption of the Anak Krakatau and people were taken by surprise, leading to much loss of life (Syamsidik et al., 2020).

Understanding natural hazards, disasters, and human responses to them requires a multidisciplinary approach, involving both physical and social sciences. This approach is supported by an increasing number of collaborative and conference programs funded by international organizations such as UNESCO, the International Union of Geological Sciences (IUGS), and the International Union for Quaternary Research (INQUA). Communication of science is increasingly being recognized as an important part of student training at the university level. IUGS and the Geological Survey of Canada, for example, have programs to sensitize earth scientists to the importance of communicating geosciences, with a strong emphasis on the role of rapid landscape changes (Liverman, 2010). Populations, however, may be reticent to learn from scientists, because they may be perceived as distant advisers unaware of the local situation. An example of the successful transfer of relevant geosciences information is the case of the recent rise of many lakes in the Argentine pampas. The geologist involved in a study of the problem came from the affected community, Mar Chiquita, and was able to establish a sense of trust with the residents that facilitated the transfer of knowledge and led to successful mitigation measures (Leroy et al., 2010).

Natural parks or limited-use zones should be created in areas of repeated natural disasters (Leroy, 2006). For example Rothaus et al. (2004) has suggested strict rebuilding guidelines and limitations on land use in the area struck by the 1999 Izmit-Düzce earthquake in northwest Turkey, instead of the usual rebuilding programs.

Governments today are unable to move people away from dangerous areas. Unemployment and increased insurance premiums are the two modern forces in the western world that can provide impetus for people to relocate.

Adaptation and mitigation are key to survival, but they should not involve recovery to the same levels that existed before a disaster occurred. Rather, adaptation and mitigation should take society to a higher level based on lessons learned from the disaster (Leroy, 2006). Pressure arises after a disaster to rapidly rebuild and usually in the same place. It may be better to reconstruct elsewhere. With rapid sea-level rise such as the 20th century cases of the Caspian Sea and the Pampean lakes in Argentina (Leroy et al., 2010) or faced with the danger of tsunami such as in Sri Lanka after the 2004 tsunami, it is tempting to prevent building along coasts. This strategy, however, is not feasible because of the economic and societal values of the coastal zone. Moreover land ownership and space availability are often additional problems. In Iran along the Caspian coast, the government finds that, in practice, it can only have limited influence, mostly on state constructions and large hotels (Leroy et al., 2010).

6 Conclusions

The evolution of societies is inscribed in geomorphology: either societies change in response to changing landscapes; or landscapes evolve under human pressure. Humans and nature have never been more closely inter-related, although more than half the world population now lives in cities seemingly disconnected from nature. Increasingly humans tend to forget that the Earth does not belong to them, rather they belong to the Earth.

Disasters and catastrophes typically have an element of surprise. It is impossible to forecast all possible disaster scenarios, thus surprises are unavoidable. Whatever technology and education are applied to preparedness, a disaster will rarely be properly forecast and mitigation will never be satisfactory. Four factors are involved in a disaster, i.e., time, space, society, and the type of events. Recurrence of events causing the ratchet effect and the succession of different hazards in an area can limit long-term recovery and, in extreme cases, lead to societal collapse.

The relationships among hazard, disaster, and political and social change are not always clear. Hazards must be seen in the context of many other factors when considering the cause of a disaster such as Hurricane Katrina. Considering the many problems that will arise from global warming or population growth, one could argue that a major catastrophe is in the offing.

Adaptation is the key to the survival of our civilization as our natural world is in constant flux. We have seen in this article that catastrophes have changed our world, both negatively and positively. What will be the future?

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