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<th>Leroy</th>
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<td>Organization</td>
<td>Institute for the Environment, Brunel University</td>
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<tr>
<td>Address</td>
<td>UB8 3PH, Uxbridge, UK</td>
<td></td>
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<tr>
<td>Email</td>
<td><a href="mailto:suzanne.leroy@brunel.ac.uk">suzanne.leroy@brunel.ac.uk</a></td>
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<td>Louisiana State University</td>
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<tr>
<td>Division</td>
<td>Iranian National Centre for Oceanography</td>
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<td>Address</td>
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<tr>
<td>Division</td>
<td>CICTERRA-CONICET-UNC, Facultad de Ciencias Exactas, Físicas y Naturales, Universidad Nacional de Córdoba</td>
<td></td>
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<tr>
<td>Address</td>
<td>5016, Córdoba, Argentina</td>
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<td>Division</td>
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Geoscientific data combined with historical documents on past natural hazard events and on the disasters that followed are essential to improve mitigation plans. It is only with this method that the full scale of potential rapid changes that are not covered by the instrumental record can be obtained. Therefore, the collection of these past data and their integration into planning should become one of the priorities of the Hyogo Framework of Actions. This paper analyses the following five case studies: global warming impact on the indigenous populations at high latitudes of Canada, hurricane impact on the southern coast of the USA as experienced in New Orleans, rapid level rise in several lakes of the Argentinian Pampas with emphasis on Laguna Mar Chiquita, the rapid sea level rise of the Caspian Sea as seen from Iran and the tsunami risk in a large Alpine lake of Northern Italy, Lake Como. In each area, the main natural hazard is part of a potential series of hazards that, if combined, could lead to a shift from disaster to catastrophe. The most successful cases of transfer of information between geoscientists and end-users are when the hazards and subsequent disasters are visible or when the messengers bearing the information are trusted by the local communities.

**Keywords** (separated by `-`)
- Geosciences
- Natural hazard
- Disaster
- Mitigation
- Canadian Arctic
- New Orleans
- Argentinian Pampas
- Caspian Sea
- Alpine lakes
The Role of Geosciences in the Mitigation of Natural Disasters: Five Case Studies


Abstract Geoscientific data combined with historical documents on past natural hazard events and on the disasters that followed are essential to improve mitigation plans. It is only with this method that the full scale of potential rapid changes that are not covered by the instrumental record can be obtained. Therefore, the collection of these past data and their integration into planning should become one of the priorities of the Hyogo Framework of Actions. This paper analyses the following five case studies: global warming impact on the indigenous populations at high latitudes of Canada, hurricane impact on the southern coast of the USA as experienced in New Orleans, rapid level rise in several lakes of the Argentinian Pampas with emphasis on Laguna Mar Chiquita, the rapid sea level rise of the Caspian Sea as seen from Iran and the tsunami risk in a large Alpine lake of Northern Italy, Lake Como. In each area, the main natural hazard is part of a potential series of hazards that, if combined, could lead to a shift from disaster to catastrophe. The most successful cases of transfer of information between geoscientists and end-users are when the hazards and subsequent disasters are visible or when the messengers bearing the information are trusted by the local communities.

Keywords Geosciences · Natural hazard · Disaster · Mitigation · Canadian Arctic · New Orleans · Argentinian Pampas · Caspian Sea · Alpine lakes

Introduction

The rationale for this paper is to emphasize the role of geosciences in mitigating natural disasters and to highlight the need to bridge the gap from natural hazard study to human and societal responses (leading to mitigation).

A series of recent case studies, i.e. twentieth and twenty-first centuries, of natural hazards are presented and for each of them the link with past hazards, i.e. over the last millennia, is made to provide the full potential of hazard range. The chapter goes on to examine whether any lesson has been learned from the past or could have been learned. Finally, in the light of a positive answer to this question, the mechanisms of transfer of information are analysed.

The case studies and the contributors of this paper have been brought together following two past conference programmes, IGCP 490 on “The role of Holocene environmental catastrophes in human history” from 2003 to 2007 and ICSU Dark Nature on “Rapid Natural Change and Human Responses” in 2004 and 2005. The aims of these two programmes were to (1) refine the record of rapid (<100 years) environmental changes affecting physical environments and ecosystems during the last 11,500 years; (2) examine how past societies and communities reacted in the face of harmful change; and (3) explore the implications of rapid natural change for current environmental and public policies (Dark Nature1). The latter point proved to be very

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challenging and is illustrated amongst the examples chosen for this paper.

What causes a catastrophe? Not all natural hazards (geological and hydro-meteorological) cause a disaster (loss of life and/or damage to environment), and not all disasters lead to a catastrophe. A catastrophe is the result of a combination of negative factors at the spatial, temporal and societal scales (Leroy 2006). The larger the area affected or the larger proportion of the settlement affected, the worse is the impact. Similarly, the sharper the onset and the longer the duration of the hazards, the worse is the impact. A society that is not willing to modify some of its rules (lack of flexibility and adaptability) or a society that is not ready (without mitigation plans), will also suffer from most severe impacts. The examples shown here are not real catastrophes but they may have been near misses, or they could potentially develop into one due to an accumulation of hazards.

Five diverse case studies have been selected throughout the world: two are linked to rising water levels (a lake and a sea), one is a geological hazard and two are linked to climate (global warming trend and a discrete event). Two are in North America (at low and high latitudes), one in South America, one in S-W Asia and one in Europe.

Global Warming at High Latitudes and Rapid Landscape Change in the Arctic

Introduction and Tableaux of Past Changes

“The Earth is faster now.” This is how an aboriginal elder from northern Alaska describes changes she sees around her. Across the Arctic the effects of warming are clear (Furgal and Prowse 2007, Hassol 2004, Krupnik and Jolly 2002). The extent of sea ice is decreasing year by year, surface temperatures are rising, permafrost is melting, tundra soils degassing, and shallow coastlines retreating as waves batter soft sediments. Glaciers and ice sheets are retreating in many places, and ice patches on mountainsides are melting, to the delight of archaeologists who study the artefacts melting out after centuries of icebox preservation. Birds and insects previously unknown are now spotted in unfamiliar places, and some key land and marine species that are essential sources of food are under threat of extirpation. Some communities on shallow coasts are under increased threat of flooding. Roads, airport runways and buildings are subject to differential settlement.

In some places northern landscapes have changed little in thousands of years. Some aboriginal hearths and house sites, for example, have remained undisturbed near present-day beaches for 4–5000 years (McGhee 1996, 2007). However, elsewhere in the Arctic coasts have accreted or eroded, inland rivers have switched channels and migrated, glaciers have surged and retreated, slopes failed, and floods have occurred repeatedly (Pienitz et al. 2004, Overpeck et al. 1997). Studies of ice cores, permafrost ground temperatures, lake and coastal deposits and tree-ring records have shown that substantial landscape changes in the North American Arctic and Subarctic took place long before large-scale human influences on the environment occurred (Brown et al. 2000, Hewitt et al. 2000, Gajewski and Atkinson 2003). Variations in regional temperatures of as much as 10 ºC occurred several times during the Quaternary (NRC 2002, Weart 2008), each leading to a longer period of steady temperatures. For example, Greenland ice cores bear evidence of a rapid warming of 5–10 ºC in a decade or so, bringing to an end the Younger Dryas around 11,500 years ago. Though later climatic events may not have been as marked as this late glacial warming, it demonstrates just how dramatic natural climate change can on occasion be.

Rapid environmental changes also occur during periods of relatively stable climate. Volcanic eruptions, huge floods, destructive earthquakes, and, on a smaller scale, landslides and coastal storms can lead to marked changes in landscape conditions. About 1200 years ago volcanic ash from a vent near the Yukon-Alaska boundary blanketed the southern Yukon and adjacent parts of the Northwest Territories. This appears to have been the largest pyroclastic eruption anywhere in the past 2000 years (Lerbekmo 2008) and may well have had major ecological and human impacts (Workman 1979). Where thicker, the ash would probably have smothered much of the shrubby vegetation on which animals depended, leaving local inhabitants of the time – the Athapaskan people – without their usual source of game. Recent archaeological studies indicate a rapid change in hunting methods with the introduction of bow and arrow technology at the time.
of the eruption (Hare 2008). This sudden landscape change may have forced people to leave their traditional lands, some moving eastwards and others perhaps southwards to settle eventually in the southern USA, as the ancestors of the modern Navajo people (Moodie et al. 1992).

Among some Inuvialuit, the people of the western Arctic, a story is told of a once barren land transformed into one of lakes, rivers and plentiful fish and game. The cause was a sealskin bag full of water that grew and grew until the hunter who found it built a large raft and was able to escape when the bag burst, flooding the land and drowning the other people (Alunik et al. 2003). Reminiscent of the flood stories of other cultures, this suggests actual experience with widespread flooding.

The story of the Arctic peoples of North America – including the Dene, Inuit, Inuvialuit, Inupiat and their forebears - thus took place against a climatic and geological backdrop of varying stability. From time to time they faced major changes in landscape and ice cover, which must have challenged their way of life. Those who study cultural traditions, beliefs, attitudes and practices of northern peoples are working to extend the record of environmental change beyond the memories of those now living, or that of their parents and grandparents (Barber and Barber 2004, Cruikshank 2005, Berger and Liverman 2008).

The extent to which the various waves of migration across the Arctic over the long history of northern peoples (Fig. 1) were driven by environmental and climate changes, or were responses to new opportunities for trade or for hunting is still a matter of debate (Berner et al. 2005). McGhee (2007) suggests that it was the discovery of iron and copper that initiated migration into the eastern Arctic of ancestral Inuit around 1000 years ago, and that a few centuries later, trade opportunities with the prosperous Greenland Norse brought about a further expansion eastward. However, other movements may have been caused by the warmer climate during this period (the Medieval Warm Period), which brought open water near the coastal lands, restricting the sea-ice hunt and opening up maritime habitats. Further south, in northern Newfoundland, a period of warming sea temperatures around 1,100–1,500 years ago appears to have undermined aboriginal seal hunters and encouraged the northward movement of other indigenous people (Bell and Renouf 2008).

Elsewhere in the Arctic, major landscape changes also took place during times of human occupation. Around 8000 years ago early people were living along the margin of the East Siberian Sea. Remains of their wooden houses can still be seen on what is now a remote island some 600 km north of the present mainland (Bauch and Kassens 2005, McGhee 2007).

**Present: Responding to Climate and Landscape Change**

Traditional and subsistence ways of life are becoming more difficult for many Northern peoples, and their long-standing ability to adapt to changing circumstances of weather and climate, is being seriously challenged by rapid climate warming, the effects of which are expected to become ever more severe (Einarsson et al. 2004). The long history of successful human survival in the harsh Arctic environment is witness to the extraordinary resilience of northern peoples, who have managed to keep their culture and traditions more or less intact in the face of environmental change. One important key to survival was their ability to move between sedentary and nomadic livelihoods and to maintain flexibility in where they lived and how they organized themselves socially (Berner et al. 2005). Another key has been their intimate knowledge of one’s landscape based on observations of the seasons, the weather, the soil, and the plant and animal life. Indigenous people and others, who live close to the land, at least beyond towns and cities, possess a special understanding of the natural world around them.

The way in which today’s Arctic inhabitants are themselves tracking and adapting to the challenging climate-induced changes in their environment (Ashford and Castleden 2001, Nunavut Department of the Environment 2005, Ford 2008) may be relevant to other rural societies facing change. Local observations of changing environments have provided knowledge essential to circum-Arctic nations as they press for action on climate change. Typical of the kinds of changes now being seen across the Arctic (Climate Change Impacts and Adaptation Network 20072) are
those noted by the Inuvialuit of Banks Island in the Western Canadian Arctic:

- Multiyear ice no longer comes close to Sachs Harbour in summer, resulting in rougher seas and more dangerous travelling on ice.
- Open water is now closer to land in winter, and it is now harder to predict springtime ice break-up, weather and storms.
- Permafrost is no longer solid in places, and lakes are draining into the sea as permafrost thaws and ground slumps occur (Ashford and Castleden 2001).

**Lessons**

There are two important roles for the earth sciences in this time of profound change: assessing what is taking place now in the northern landscape, and unravelling the geological record of the recent past, even if the IPCC projects future changes of much greater magnitude. Tracking, describing, analyzing and communicating the physical changes taking place in contemporary terrestrial and marine environments is of prime importance, for the landscape provides the background against which ecological and social changes are now taking place. Garneau and Alt (2000) and Furgal and Prowse (2007) provide convenient summaries of these conditions. Of equal importance is the investigation through a wide range of palaeoenvironmental approaches of the geological changes of the past. Unravelling the record of past climates can yield valuable information about the extent and causes of change, whether abrupt or gradual. It also contributes to an understanding of past human development, including the origins of cultural traditions (Cruikshank 2005).

To strengthen communications with the public, the Geological Survey of Canada has produced a series of climate change and “geoscape” posters to illustrate how Canadian landscapes are shaped by geological processes past and present. These are aimed at schools and the general public. For example, the geoscape poster for Whitehorse, the small, subarctic capital city of the Yukon Territory (Turner et al. 2003) illustrates...
clearly how water and energy resources can be conserved, natural hazards and disasters reduced, and natural ecosystems protected. A climate change poster for Nunavut (the Inuit homeland in the eastern Canadian Arctic) explains how glacier fluctuations and sea levels are related, and how changes in the permafrost active layer affect infrastructure (Climate Change Impacts and Adaptation 2001). The north is also covered by a new Canadian earth science programme to promote private and public collaboration on adaptation issues and to develop tools to help in adapting to a changing climate (Adaptation website, Natural Resources Canada3).

In the Arctic, the past century saw one of the most rapid and most successful adaptations to external forces. This took place when many of the northern peoples of Canada and elsewhere were obliged by government policy to abandon their nomadic ways and settle in towns and villages where there are strict controls on resource use and management, land use and ownership, and where market-drive economic activities now dominate. In two or three generations, the way of life of the Inuit and other northern peoples has changed substantially, as they strive to build a new society and exercise more control over their lands.

It might be suggested that the ways in which prehistoric nomads reacted to rapid climate and landscape change could provide helpful insights as to how societies and individuals facing even faster change in the twenty-first century might adapt. However, comparing a contemporary, largely sedentary, technologically advanced society with far smaller numbers of hunters and fishers of past centuries and millennia seems rather far-fetched. In the face of the current changes now coming from climate warming, loss of traditional biodiversity and widespread air-borne pollution from southern sources, the new way of life means that traditional adaptation strategies are no longer possible, and possibilities for flexibility much reduced. Scientific research, especially from the earth sciences, is providing some of the essential understanding of the ecosystem and landscape changes involved. However, it remains to be seen how the peoples of the circum-Arctic will adapt, as access to their hunting and fishing grounds become more difficult, and the social, cultural and economic consequences of changes to their way of life loom ever larger.

Hurricanes in the Tropical Atlantic: New Orleans

Introduction and Past Records of Hurricanes

The Louisiana coast is located on the Gulf of Mexico, between latitudes 29 and 30°N. Because of its location, this region is prone to tropical cyclones that develop in the Atlantic, i.e. hurricanes. Hurricanes are low pressure, intense tropical weather systems connected with strong thunderstorms and have a well-defined counter-clockwise circulation of winds near the earth’s surface, and sustained wind speed of 119 km/h and higher. These complex systems feed on heat released from rising hot and humid air masses. Hurricanes develop each year in the Atlantic Ocean and the Gulf of Mexico from June to November. Although the timing is stable, the intensity of hurricane activity in the Gulf varies, as does the number of hurricanes that make landfall in urban areas. According to the U.S. National Oceanographic and Atmospheric Administration,4 the 2008 Hurricane season set records. For the first time since hurricane monitoring started, six consecutive tropical cyclones made landfall on the U.S. mainland, and this is also the first Atlantic season to have hurricanes in five consecutive months. The majority of hurricanes entering the Gulf of Mexico are Category 3 and lower. One of the threatened geographic areas, the Northern coast of the Gulf of Mexico, hosts unique coastal ecosystems and major U.S. cities. In Louisiana, New Orleans is a metropolitan port city of historical significance with a thriving and colourful tourism industry. To its south, swamps accounting from 40% of the nation’s wetlands create a natural barrier between New Orleans and the

3 Adaptation Website, Natural Resources Canada. Available at http://adaptation.nrcan.gc.ca/index_e.php/ [Accessed 5 November 2008].

Gulf of Mexico. Economically, this region is the heart of Louisiana owing not only to tourism, but also to fisheries and the oil and gas exploration and refining infrastructure. Twenty-five percent of all the oil and gas used in America and 80% of the nation’s offshore oil and gas travel through Louisiana’s wetland; more than 95% of all marine species living in the Gulf of Mexico spend all or part of their life cycle in Louisiana’s wetlands; 30% of the nation’s fisheries catch comes from offshore Louisiana; and 75% of all waterfowl breed exclusively in the wetlands (America’s Wetland Campaign to Save Coastal Louisiana’s website5).

Storms from 1944 till present are recorded in details by the U.S. National Hurricane Center and their impact can be evaluated. Since the 1800s, storms known from historical documents can also be taken into account when analyzing risks. Gulf coast hurricanes have changed the face and economic strength of historic cities for decades. For instance, the “Great Storm” that devastated Galveston, Texas, in 1900 is known from survivors’ memoirs and various books (Greene and Kelly 2000, Bixel and Turner 2000). From these writings, it is evident that at the turn of the century, Galveston was the major port city in the United States. But this storm’s high death toll (over 8,000) led city officials to encourage the transfer of the population and infrastructure inland, in Houston, Texas.

As controversy is fuelling the debate on the relationship between global warming and frequency of hurricanes worldwide, it is urgent to analyze the frequency and intensity of great storms further back in time, by understanding their sedimentary records (Leroy and Niemi 2009) and integrate the findings into future mitigation plans and assess future risks. To document the frequency and intensity of past hurricanes, detailed sedimentary records are now analyzed and compared to that associated with modern storm deposits. For instance, Horton et al. (2009) and Park et al. (2009) analyzed fresh hurricane-induced storm deposits to improve the recognition of older hurricane sedimentary signatures. Horton et al. (2009) collected hurricanes Katrina and Rita storm surge deposits before they were removed or naturally eroded. They estimated the surge to be of 7.5 m in Alabama with inland extents greater than 700 m. They noted that the surge sedimentary unit had a thickness ranging from 7 to 13 cm, was coarser than pre-storm surge units, and had lower organic content and a virtual absence of foraminifera tests. Park et al. (2009) conducted a similar study, but focused on storm surge sediments from a lake in San Salvador Island, Bahamas. They used a multi-proxy approach (e.g. grain sizes and composition, microfossil assemblages and geochemical analyses) to define the geological signature of storm deposits in this region.

These modern deposits can then be compared to the sedimentary records of past storms. Palaeotempestology, the study of the signature left by hurricanes in sedimentary archives, such as sand layers in the fine-grained sedimentary record of lakes or coastal lagoons, is a key step in this direction. For instance, Liu and Fearn (2000) proposed on the basis of coastal lake and marsh sediment studies that, in the past, Category 4 or 5 hurricanes hit the U.S. Gulf coast only about once every 300–600 years on average at any one point. In a similar study, Donnelly and Woodruff (2007) analysed the frequency of hurricanes that affected a Caribbean lagoon within the last 5,000 years and found periods of more intense hurricane activity and periods of quiescence, which they linked to the El Niño-Southern Oscillation and the West African monsoon. McCloskey and Keller (2009) studied a 5,000-year sedimentary record of hurricane strikes on the central coast of Belize and concluded that major hurricanes have struck the Belize coast on average once every decade for the past 500 years, and that two periods of hyperactivity occurred between 4,500 and 2,500 years BP. This type of hurricane hyperactivity might have induced significant stress on the Maya civilization (McCloskey and Keller 2009) just as it does on modern civilization living in the path of frequent hurricanes today.

### A Recent Disaster: Hurricane Katrina

When on 29 August 2005, Hurricane Katrina made landfall between two of the Gulf’s largest cities, New Orleans and Mobile, as a Category 3 hurricane with winds at 209 km/h, storm surge up to 9.1 m, and rainfall up to 30.5 cm, hundreds of thousands of families were affected (Figs 2 and 3). Approximately 5.8 million people in three states experienced hurricane-force...
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Fig. 2 (a) View of the Bart family residence at the corner of Annette St. and Sumpter St., two blocks from the London Avenue Canal (New Orleans), the day following Katrina's landfall. Note the top of the truck in front of the second house. Photograph by Michelle Dejoie Manning. (b) Same view, 2 months later. After waters receded, locals were allowed to return to their home to remove debris such as these refrigerators seen in the background. Note the watermark on the same truck. Photograph by Christine Alexander

Fig. 3 Inside the Bart’s residence, all walls, electrical systems, all belongings, and 50 years of memories have been destroyed by water and mold. Photograph by Christine Alexander

winds (Gabe et al. 2005) and most of the major damage was located in a 160-km radius from the landfall area. But the bulk of the devastation was caused by flooding associated with breaches of New Orleans levees and floodwalls that left most of the city under several metres of water. Because of the extent in geographic impact, intensity, death toll and damages to properties and the environment, Katrina was one of the most catastrophic hurricanes in U.S. history. The Louisiana Recovery Authority\(^6\) assembled a one-year anniversary report. Available at [http://lra.louisiana.gov/index.cfm?md=sitesearch&tmp=home&keyword=hurricane+katrina+anniversary+data](http://lra.louisiana.gov/index.cfm?md=sitesearch&tmp=home&keyword=hurricane+katrina+anniversary+data) [Accessed August 2008].
In addition to the obvious cost in human life, structural and economical losses, the cultural landscape of Louisiana has taken a major hit. The loss of houses or work, and the rising cost of insurance made it impossible for entire families to come back to their hometown. Among these permanently displaced families are musicians, artists, and some of the last stronghold of the Cajun/Creole French heritage. Many Mexican immigrants moved from Texas to Louisiana to help with the rebuilding effort, further enhancing the cultural shift of the region. According to an August 2008 report from the Greater New Orleans Community Data Center, 16 of 50 New Orleans neighbourhoods that flooded following Katrina have less than half the households present in June 2005.

Transfer of Information

To its credit, Louisiana had an excellent evacuation plan in place. It operated in partnership with the National Hurricane Center (NHC). The NHC broadcasts 5-day forecast for all hurricanes on local and national television channels. Hence, the public and officials were aware of the storm approach. But the 3-day forecast zone of hurricane Katrina extended from Texas to Florida, and three days before the storm made landfall, the main evacuation routes were already saturated with persons evacuating four states (Florida, Alabama, Mississippi and Louisiana). On 28 August 2005, hurricane Katrina was upgraded to a Category-5 hurricane. At that time, the mayor of New Orleans ordered the first-ever mandatory evacuation of the city. Numerous smaller cities along the storm’s predicted path were also issued mandatory evacuation orders. Following this announcement, the Louisiana State Police implemented the Contraflow Lane Reversal on three major interstates, i.e. I-10, I-55 and I-59, allowing 1 million persons to evacuate successfully and find refuge in shelters, university dormitories, and with friends and families out of state. Yet, a reported 150,000 persons were unable to evacuate. One of the reasons was that 112,000 households were without private vehicles (Cutter et al. 2006). Others chose to remain because they did not believe the storm constituted a serious threat, while others were too poor or physically unable to evacuate. The high death toll from Katrina can be attributed in part to the fact that hurricanes have been affecting Louisiana for years without long-lasting consequences, and therefore, many families underestimated Katrina’s threat. Today, the state is working on improving its evacuation plans. For instance, evacuation buses have been added to assist families without transportation.

The devastation brought by Katrina also jump-started new collaborations between scientists. For instance, at the LSU Center for Computation and Technology, the tragedy mobilized groups working on high performance computing, sensor networks and visualization, GIS, remote sensing and coastal and atmospheric modelling. One of their missions is to provide data to Public Health governmental agencies to better prepare for storms through visualization and modelling.

The greatest challenge remains storm protection. The region desperately needs better protection for the population living in the low-lying parts of town. Early French settlements in New Orleans in the 1700s were strictly restricted to the high natural levees of the Mississippi River (Fig. 4). After the construction of pumps, rainwater drainage canals and levee systems, many of the marshes and swamp forests (visible in the 1723 map of Fig. 4) were drained and converted to residential areas. Today, these neighbourhoods host the majority of the Greater New Orleans population and most are located below sea level.

The levees were not high or strong enough and some of the failures were linked to the poor integration of known sedimentological data into their design. In some cases, the levees were not armoured; therefore lacking protection against erosion from overflowing water. This problem was addressed by the Corp of Engineers, which used reversed “T” shaped walls in the reconstruction process. Another issue concerns the subsurface sediment on which the levees were built. Nelson and Leclair (2006) reported that some of the levees are anchored in or close to peat deposits. Peat is an unstable sediment that was originally formed in swamp forests that made up the region’s environment before the French settlements. Another puzzling discovery was the several metres of sand deposit at

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7 Greater New Orleans Community Data Center, 2008. New data reveals 16 New Orleans neighborhoods have less than half their pre-Katrina households. Available at http://www.gnoedc.org/ [Accessed November 2008]
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Fig. 4 A particular map of the St. Louis River (now Mississippi River) ten leagues above and below New Orleans, on which are marked the homes and lands granted to some private individuals along the Mississippi (ca. 1723). Note that most of the areas along the rivers are natural swamp. Houses were built only on the high banks of the river. Cartes Marines from the Newberry Library (call number: Ayer ms map 30, no. 80)

...the site of one of the breaches (Fig. 5). An astounding 26,380 m$^3$ of sediment were deposited in the city in the days that followed Hurricane Katrina (Fig. 6). This means a deposition ranging between 0.3 and 1.8 m in two days close to the levee breaches (Nelson and Leclair 2006). Since no sands were used to build the levee, Nelson and Leclair (2006) argue that this sand originated from the underlying Pine Island Trend beach deposits. This unit was deposited some 4,000 years ago as sea level rose (Coleman et al. 1998) and is found beneath all the drainage canals. Nelson and Leclair (2006) point that this raises one of the most significant concerns about the future stability of the New Orleans drainage-canal levee system.

In addition to immediate concern of levee stability, the larger-scale hurricane protection system needs to be revisited. van Heerden and Bryan (2007) proposed a three-layer defense plan. The first layer should be the improvement of existing levees, and construction of new levees or floodwalls in front of all major population centres. A second layer should protect this inner layer. An obvious natural barrier is a healthy swamp; and Louisiana’s wetlands could be replenished by flooding from the Mississippi River. Finally, a third layer should protect the wetlands from erosion by strengthening barrier islands.

When Mechanisms of Economy and Mitigation are Shaping a City

One of the broader implications of hurricanes is the economic impact on hurricane-affected regions. Physical geography influences economic performance (Diamond 1997). The geographical tropics contain the poorest countries in the world showing that geography...
Fig. 5  An impressive sand layer deposited during the few days following the canal breach inside this residence located along the London Avenue Canal raises important concerns about the stability of the entire canal system in New Orleans. Photograph by Renée Hetherington

Fig. 6  Two blocks away from the Bart’s residence, along the London Avenue Canal, sedimentary deposits add to the destruction. In the background, a 1.1-metre thick sedimentary layer was deposited on this porch during the few days following the canal breach. Photograph by Klaus Arpe

is a key factor in the distribution of wealth. Sachs et al. (2001) stated that the geography/wealth relationship is due to three components: tropical countries face higher rates of infectious disease, lower agricultural productivity and have more difficulties transporting foods and goods. One factor that should also be considered when assessing needs of tropical countries such as those in Central America and southern U.S. is the frequency and intensity of hurricanes. The economic impact of hurricanes has been underestimated in the geographical analysis of wealth distribution and considering current prediction on global warming, hurricanes’ economic impact should become increasingly significant. Horowitz\(^8\) predicts that a 1°C temperature increase across all countries would yield a 3.8% decrease in world GDP.

\(^8\) Horowitz, J.K., under review. The Income-Temperature Relationship in a Cross-Section of Countries and its Implications for Predicting the Effects of Global Warming. Environmental and Resource Economics. Available at http://faculty.arec.umd.edu/jhorowitz/ [June 2009].
Katrina’s cost are estimated to be several billion US dollars, but the reconstruction effort is mostly federally funded – a support system that other hurricane-prone countries such as the Dominican Republic, Cuba or Haiti do not have. But even for a large economic powers such as the U.S., hurricanes have some devastating trickling effects, such as the increase of insurance premiums, on each citizen and specifically those in hurricane-affected area. Elsner and Kara (1999) reported that hurricanes accounted for 62% of all catastrophic insurance losses. Since 2004 and the intense Florida and Louisiana hurricane seasons, storm-related payouts almost erased earnings of some of the biggest publicly-traded auto and home insurers. As a consequence, rates of insurance have increased significantly forcing some businesses to relocate out of state. In some of the most vulnerable areas, insurance companies cancelled policies. The only option for many homeowners to find insurance is via the Federal Government. According to officials at the U.S. Department of Homeland Security’s FEMA, financial assistance to state and local governments to help repair or replace infrastructure throughout the Gulf coast damaged by Hurricanes Katrina and by hurricane Rita (a Category 3 hurricane that made landfall in Louisiana just 24 days after Katrina devastated the region) has topped the 10 billion USD mark. Public officials in southern states, have been fighting insurance companies for years over rising rates and companies “non-renewed” policies for hurricane-battered places like Florida and Louisiana. Vitello (2007), the president of the Insurance Information Institute, said “Considering what happened between 2003 and 2005, and considering that the best meteorological minds are telling us that for the next 15–20 years hurricane activity will be heavier than normal, if we didn’t do something to reduce our exposure, we’d be out of business.”

These types of views bring out another issue. As CO2 concentration keeps increasing in the atmosphere, and as temperature responds with a general warming trend (0.6°C in the past 100 years) (Mann and Kump 2008), there are little doubts that sea level will keep rising, threatening Louisiana’s wetland, and increasing flood risks. Because hurricane feeds on warm and moist water, it seems logical to assume that the frequency and strength of hurricanes will increase as well, but current data do not prove this conclusively and there is still no consensus regarding links between hurricane activity and climate change (Arpe and Leroy 2009). Meanwhile, New Orleans’ face has changed forever with demographic data showing a smaller and whiter population (Stewart and Donovan 2008) than pre-Katrina.

Rapid Sea Level Rise: Caspian Sea

Geographical Setting

At the border of Asia and Europe, the Caspian Sea is the world’s largest isolated basin (Fig. 7). Its catchment basin covers an area of 3.5 million km², which is mainly located in five littoral states, namely Iran, Turkmenistan, Kazakhstan, Russia and Azerbaijan. The catchment also covers small sections of Turkey, Armenia and Georgia (Rodionov 1994).

The Caspian Sea is a semi-elliptical basin oriented in a N-S trend with a length of about 1,200 km and a mean width of about 310 km. The sea surface area and water volume (at the level of −27.5 m relative to world sea level) is around 376,400 km² and 78,100 km³ respectively (Terziev 1992). On the basis of its bottom morphology, the Caspian Sea can be divided into three distinct sub-basins, deepening southward to a maximum depth of 1,025 m. The Southern Caspian basin that has the main volume of water is separated from the middle basin by the Apsheron sill at a depth of 150 m (Kosarev 1975). The total length of the Caspian coast is around 4,460 km (Caspian Environmental program 200211).

The general atmospheric circulation over the Caspian Sea and its drainage basin, which comes from the north Atlantic and the Arctic and their interac-

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Fig. 7 Projected inundation area around the Caspian Sea in case of sea level rise up to −22 m that experienced in the late Holocene and historic periods. Compiled and modified after Caspian Environment Program 2002.

Past and the Future

Historical literature and ancient coastal remains have recently contributed to unravel the sea level fluctuations for the past two millennia successfully (Apolov and Fedorova 1956, Kroonenberg et al. 2007, Leroy et al. 2007). Using geological and geomorphological investigations at a quasi-annual resolution, a likely 65 year cycle has been highlighted (Kroonenberg et al. 2000, Giralt et al. 2003). Since instrumental measurements, the sea level has fluctuated with an amplitude of 3.8 m (Voropaev 1996). The rate of the last sea level rise that began in 1979 is hundred times faster than that in the world oceans (Kroonenberg et al. 2000). Rapid sea level changes had different, often deep, impacts on the Caspian shores (Kaplin and Selivanov 1995, Voropaev et al. 1998, Kroonenberg et al. 2000), depending on coastal slope and composition. The gentle slope of the north coast and some parts of east coast are prone to inundation with sea-level rise and emergence with sea level fall.

Atmospheric pressure, wind, wave, riverine influx, temperature-salinity, impulsive energy (such as earth-
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quake, submarine landslide and mud volcano), and the position of the Sun and the Moon, all contribute to changing the Caspian Sea level. Wind waves and wind-induced sea level changes (storm surge) are very important in short-term sea level fluctuations (Terziev 1992, Kazancı et al. 2004). The northerly and southerly winds are prevailing wind patterns that produce corresponding waves, which reach their maximal elevation in the middle and northwest parts of the south basin (Koshinskii 1975). The highest wave is recorded in Azerbaijan coastal waters at a height of 12 m (Terziev 1992). Sea level rise due to storm surge occurs at various scales in the three sub-basins. The maximum wind-induced sea level rise is around 1 m in the middle and south basins, while in the north Caspian with its shallow waters and a gently sloping coastal area, a 4 m rise in water has been recorded in a storm in 1957 (Terziev 1992). In addition to positive storm surge, negative storm surges are also important for the north Caspian coast. They displace coastal waters towards the sea and cause ports to become unusable. The impulsive energy in the Caspian Sea that may have a potential to generate tsunami waves could have three sources: submarine landslides from the south and western shelf of the middle Caspian basin, mud volcano explosion in the south Caspian and earthquake in the middle Caspian Sea. The first two sources are poorly studied, while seismogenic tsunamis have historical records in the Caspian coasts. A possible return period for tsunamis with a height of 3 m is suggested as 60 years (Dotsenko et al. 2002).

Long-term sea level fluctuations depend on the sea-water balance (difference between river influx to the sea and evaporation over the sea surface) and geological processes. Geological processes such as subsidence, uplifting, spreading, and sedimentation, can cause a change in the Caspian Sea water volume over the long term (Fedorov 1996, Rychagov 1997). Geological processes over the Caspian catchment basin can affect the water balance, such as watershed and river course switching to another basin (Varushchenko et al. 1987, Leroy et al. 2006).

Water balance is the determining factor for Caspian Sea level change since isolation from the Paratethys 5 Ma ago. The main input elements of Caspian Sea water are river influx, precipitation over the sea surface and groundwater seepage. The loss of water depends on evaporation from the sea surface and from Kara Bogaz Gol Bay, which acts as an evaporative basin (Giralt et al. 2003). The rate of the last sea level rise since 1979 was around 14 cm/a reaching its maximum value in 1995 (Voropaev 1996). The sea level rise is attributed to an increase in Volga discharge (Frolov 2003). Intense water consumption from the mid twentieth century especially in the Volga basin has dropped the sea level by about one metre (Zonn 1996). Without this human impact, the water level would be 1 m higher than the present stand.

The prediction of Caspian Sea level changes has been the subject of many research projects during the past century. They have attempted to forecast the Caspian Sea level on the basis of stochastic models of water balance, palaeodata of sea level changes, cyclicity of sea level changes, and correlation between sea level change and the factors that can contribute to its water balance (Shiklomanov et al. 1995, Frolov 2003). However long-term forecasting of the Caspian water balance and consequences for its level have remained unsuccessful. None of the studies predicted the sea level rise in 1979 and the fall in 1995. The Caspian Sea, including its closed catchment basin, has an area of around 1% of the earth’s surface. The hydrometeorological cycle in such a huge area is globally affected (Voropaev 1996). The main problem of forecasting is the mechanism by which controlling factors act on the elements of water balance. The transfer of humidity to the Caspian basin and the physical processes in and over the Caspian Sea, which determine the rate of evaporation, are critical points that are not yet clearly understood (Kosarev and Tuzhilkin 1997, Arpe and Leroy 2007).

Some short-term sea level changes have a predictable character. Warning systems for forecasting wind waves and storm surges are relatively successful in coastal states in reducing the risk. For tsunamis, there is no system for early warning and some potential sources are as yet poorly known.

Present: Impact of Sea Level Rise on the Coastal Community

Human activities of circum-Caspian nations are distributed unevenly in the region. Hazardous sea level change in the Caspian region became important from the late nineteenth century with the development of industry, oil exploitation and marine transportation (Komorov 1996, Lahijani 2001). Natural extreme events such as the tsunami in 1895 due to
an earthquake (dotsenko et al. 2002), the storm surge of 1952 and the high wave of 1957 had disastrous effects. During a four-day surge (10–13 November 1952) in the north and north-west Caspian Sea caused by a strong storm, water level in places rose up to 4.2 m, then penetrated 25–35 km inland and flooded 17,000 km² including five islands. The rate of rising water level was 20 cm/h. The return period of this type of surge is estimated around 150–200 years. During the storm of 20–21 November 1957, the Caspian west coast, mainly including Azerbaijan and Dagestanz, was hit by high waves. The waves destroyed oil structures and were associated with loss of human life (terziev 1992). The sea level rise of 1979–1995 inundated 8,300 km² of coastal territory (Zonn 1996). Most economic loss occurred on the western and southern coasts, which are densely populated. Human activities in the coastal area accelerated after the collapse of the Soviet Union in 1991. Petroleum-related industry and transportation are the main branches of economic activity. The Caspian coast, with a mostly arid climate and a smaller area of sub-tropical climate on the southern coast (from Lenkoran in Azerbaijan to Gorgan in Iran) and with its lack of rivers on the east coast, has a limited attraction for development. Therefore human settlements and infrastructure are unevenly distributed along the coast. At present the population settled in the Caspian catchment basin is estimated to be around 80 millions, most of whom live in Russia (73%), Iran (13%) and in Azerbaijan (10%) (lahijani 2001). Around 3.9 million people, or approximately 50% of the Azerbaijan population, live in the coastal zone in the four regions of Lenkoran, Central Aran, Apsheron and Quba-Xacmas. The Iranian regions of Gilan, Mazandaran, and Golestan border the Caspian coast with a population of 6.3 million persons that is 9% of Iran’s population. The population in a narrow, 2 km wide, shore strip zone on the Iranian coast is around 370,000 that increases to 1.63 million within the first 10 km and 3.70 million within 50 km (pak and farajzadeh 2007). The total population in the 13 coastal regions of littoral states is around 15 million (caspian environmental program 200212).

The Iranian Coast with a population density of 235.9 per km² (pak and farajzadeh 2007) has the highest density in the Caspian periphery. The Iranian Caspian coast with sandy to gravelly beaches and a forested landscape with a relative proximity to large cities attracts domestic tourism during the main vacations when the population doubles. Except for the easternmost part of the coast, each metre of coastal area is occupied by homes (fig. 8), towns, agricultural fields, fisheries and resort facilities. The main infrastructure on the Caspian shores consists of ports, railroads and pipelines on the western and northern coasts and of oil fields that are mainly developed on the Azerbaijan and Kazakhstan coasts.

Natural hazards, including long-term sea level change, storm surge, tsunami and wind waves, form a potential threat to the Caspian coast. However, the whole Caspian Sea rarely experiences brief hazardous sea level changes simultaneously. The North Caspian with its shallow waters (on average 5 m deep) does not allow the generation of high waves. In contrast the area is liable to severe surges, both positive and negative. The north sub-basin is frozen in winter, when there is no opportunity for brief sea level changes. The middle Caspian receives wind waves, surges and tsunami waves. The west coast, mainly in the middle sub-basin and the north west of the south sub-basin, is the most hazard-prone coast. The Apsheron sill prevents the development of tsunami waves towards the south basin. The South Caspian coasts are exposed to medium-range storms and surges.

As humans intensively occupied a narrow shore zone during the twentieth century, a sea-level rise now means a disaster for the coastal area. All the coastal countries are in a developing stage of their economies. The three newly formed circum-Caspian states (Azerbaijan, Kazakhstan and Turkmenistan) mainly rely on oil exploitation from the Caspian Sea and its peripheral fields.

A rise of sea level by more than 1 m will inundate the five littoral states to various extents, which is at a minimum in Iran with 300 km², but in Kazakhstan it is up to 6,300 km². This range of sea level

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rise is probable during a storm surge. A rise in sea level to the level that was experienced in late Holocene and historical periods at around 22 m below world sea level (Rychagov 1997, Kroonenberg et al. 2007, Lahijani et al. 2009) would inundate many population centres and infrastructure (Fig. 7). Many coastal structures were designed for extreme events around the mid-twentieth century. Now the sea level is 2 m higher than during that period and therefore the hazard could overwhelm the structures. Long-term sea-level rise remains the main potential threat for the Caspian coast. A population of more than half million in the Astrakhan region including the southern part of Astrakhan city is at high risk. The Azerbaijan coast is more vulnerable to sea level rise. Its economy depends on Caspian resources, 50% of its population including the capital and other large cities are located on coastal areas and their main infrastructure is coast based. Around 140,000 persons in Azerbaijan live in high-risk areas including some parts of the capital Baku and in Lenkoran. A steeply sloping coast prevents deep penetration of flooding into the Iranian coastal zone. Nevertheless, sea level rise could impact on low-lying areas with high-density populations. Anzali (a port in the Guilan province), the east part of Mazandaran and the south of Golestan are facing a high rate of risk with a population of 150,000. The east and northeast coasts with scattered populations would have a lower risk in future sea level rise. Main roads and railways in Astrakhan-Atyrau and some oil structures in Kazakhstan and Turkmenistan are located in a high-risk area. People in these two east littoral states that settled in high-risk areas is however estimated to be less than 20,000 persons (Caspian Environmental Program 2001).

Lessons: Adaptation and Mitigation Measures

The economic loss of the last sea level rise is born partially by the littoral states, as overall measures that could be planned to reduce or restrict vulnerability are

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based on the resilience of people or the reliability of protective devices (Smith 1996). Both approaches are in use in the developing littoral states. Building dams and dikes to protect coastal settlements and infrastructures against inundation and reinforcing ports for new water stand provide a feeling of reliability when applying technology and engineering design. To accept hazardous sea level rise as a part of life demonstrates a lower capacity to face natural extreme events. Adaptive methods could be applied by the littoral states themselves, in that they could avoid, or protect themselves against sea level hazard (Soroos 2000).

At the level of the whole Caspian Sea, mitigation measures are implemented by individual states, as regional cooperation does not work. Stabilizing the Caspian Sea level was of great concern during the Soviet period, when sea level was declining, but due to ecological problems (such as joining the separate basins of Caspian Sea, Aral Sea, Black Sea, west Siberia, Barents Sea and Kara Sea (Voropaev and Ratkovich 1985)), it has been abandoned. As the Caspian problems are shared between coastal states, all the states should promote initiatives about Caspian environment regardless of any legal debate (Olioumine 2003).

The Iranian coastal zone of the Caspian Sea is governed by four laws: (1) The law of “coastal lands and coastal freed lands ratified in 1975.” Under this law, a 60 m wide strip of the Caspian coastal zone from the maximum level in 1962 and the land up to 150 cm of that level, which emerged due to sea level fall, are declared as state-owned territories. Some exceptions and details are mentioned in the Law for private and state activities. Ministry of Agriculture, Department of Forestry and Pasture is authorized for the execution of the Law, but the related executive regulations are still not prepared. Moreover this law is over-ruled by the Caspian Sea rise since 1962, as the land is not under water. (2) The law of “fair distribution of water ratified in 1982.” Under this Law all coastal zones of seas, gulfs, bays, lagoons and river banks are state owned and any construction and land use are permitted only by the Ministry of Energy, Water Department. This Law mainly concentrates on water uses and sand excavating. The two above-mentioned laws are in conflict over some points. (3) The “Code of port and shipping organization ratified in 1969.” Any port construction and maritime activities need the authorization of the Ministry of Road and Transportation, Port and Shipping Organization. (4) A national law of “land and housing” and regulation of each municipality apply to urban construction, including the Caspian coastal zone.

During the past three years, the National Government tried to free 60 m coastal zone for public access. The main part of the Mazandaran coastal zone is occupied by governmental agencies. Some of them prepared a public access agreement to the coastal zone over the past few years. In spite of different Laws for management of the Caspian coastal zone, jurisdictional difficulties remained until now. In practice the two first Laws have been abandoned, because they conflict with each other, no regulations were prepared after their ratification and the limits of governing territories are not clear (Moghimi 1997). Moreover some parts of the coastal zone have been under seawater since the sea level rise of 1979. The two later Laws are in force for construction of buildings in urban areas and ports. Even in Caspian coastal cities, the threat of sea level rise is not considered for urban development. Regulation for construction in rural areas is not rigid. Valued coastal biospheres that are mentioned in the Ramsar Convention14 are however being monitored and preserved by the Department of Environment.

The circum-Caspian nations, which are enjoying its resources, need more awareness of the Caspian environment and the behaviour of its water level. The attention of the international and regional scientific communities to Caspian-related researches has increased during the past two decades. Despite of good progress in research, intensive human activities along the Caspian shores in vulnerable areas show that scientific information is not well received both by local people and decision makers. The transfer of knowledge to policy makers and stakeholders should be focussed on overall ecosystem services, which are more valuable than short-term economic benefits. Different levels of cooperation may be recommended for the Caspian issues, but public demand and awareness is vital for the improvement of the present situations (Pak and Farzadeh 2007).

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Rapid Lake Level Rise in the Pampean Plains of Argentina

General Setting

The present-day South American climate distribution is closely linked to the particularly tapered shape and the topography of the continent as well as to global circulation cells, ocean currents and the proximity of large bodies of water (Cerveny 1998). The Andes Cordillera largely controls the atmospheric circulation of Southern South America fostering a tropical-extratropical air mass exchange especially along their eastern side (Garreaud et al. in press). East of the Andes, a vast lowland area from Colombia and Venezuela to the Argentinian Pampas is an outstanding South American geomorphological feature. In Argentina, the Pampean plain is a flat and low area with altitudes between 80 and 400 m a.s.l. that extends to the south to ca 40°S, characterized by widespread Late Pleistocene-Holocene loess deposits (Zárate 2003).

The twentieth century climate variability shows contrasting hydroclimatic patterns on the Pampean plains. The region was affected by long drought intervals throughout the first three quarters of the twentieth century followed, since the 1970s, by an abrupt hydroclimatic shift to a humid phase. High-resolution palaeoclimatic reconstructions to fully appreciate the climate variability are still scarce across the Pampean plains. Middle latitudes paleoenvironmental reconstructions proposed so far were exclusively based on geomorphic-stratigraphic data (Iriondo 1999, Kröhling and Iriondo 1999) and historical proxies (Cioccale and Piovano et al. in press). However, during the last few years there has been a noticeable increase in high-resolution studies based on palaeolimnological record of Pampean lake systems (Piovano et al. 2002, 2004a, 2004b, 2006a, in press, Córdoba et al. 2006, Palamed). The initiation of the program PALEOPAMPAS15 now provides the opportunity to analyze past climate variability at larger time-windows and from a more regional perspective.

Laguna Mar Chiquita: A Sensor of Past and Present-Day Hydroclimatic Changes in the Pampas

Laguna Mar Chiquita (30° 54’ S – 62° 51’ W) is a highly variable and shallow (10–12 m maximum water depth) hypersaline endorheic lake containing a detailed record of past hydroclimatic changes from Late Glacial times until the Little Ice Age and the late twentieth century (Piovano and Leroy 2005a, Piovano et al. 2006b, Piovano et al. 2006a, Piovano et al. in press). Variability in precipitation and river discharge during the twentieth century has triggered noticeable sharp lake-level fluctuations, across the Argentinian Pampas (Fig. 9), where Laguna Mar Chiquita is a sensitive hydroclimatic indicator for middle latitudes in South America (Piovano et al. 2002, Pasquini et al. 2006, Piovano et al. 2004a). Historical and instrumental data show that during dry intervals (i.e. prior to the 1970s) the lake surface was reduced to ~1,000 km², from an extent up to ~6,000 km² during periods with a positive hydrological balance (Fig. 10). At highstands, like today, it is not only the largest saline lake in South America but also one of the world’s largest. Well-dated short cores provide a calibration of the lake’s sedimentary, isotopic and biological response to the last 100 years of documented lake levels changes, which yield a well-constrained multiproxy model for the basin (Piovano et al. 2002, 2004a, 2004b, Varandas da Silva et al. 2008). A semi-quantitative estimation of palaeolake-levels using the carbon isotope composition of organic matter as a hydrological proxy (Piovano et al. 2004a) shows for the last millennia a pattern of alternating lake highstands and lowstands (Piovano et al. in press). Palaeohydrological reconstruction for the period coeval with the Medieval Climatic Anomaly (Villalba 1994) indicates a wet phase (by 1,060 cal. yr BP) with lake level magnitudes equivalent to the present-day highstand. Conversely, the palaeohydrological proxies for the cold period corresponding to the Little Ice Age indicate very dry conditions with the occurrence of short-lived humid pulses, especially during the second half of the nineteenth century. With the exception of a few short-term lake-level rises, the lowstand recorded after the Medieval Climatic Anomaly is dominated by the conspicuous hydroclimatic shift that took place in South Eastern South American (SESA) during the last quarter of the twentieth century (Fig. 9). The wet spell,
Fig. 9  (a) Satellite image of Southern South America of the area marked with a rectangle in the image of the left upper corner. White arrows indicate Río Paraguay and Paraná gauging stations used in graphs of Fig. 9b; Laguna Mar Chiquita, Laguna Melincué and Lagunas Encadenadas del Oeste de Buenos Aires (LEO system). Pictures on the right illustrate the consequences of water-level increase in the Pampean lakes; 1-2: Laguna Mar Chiquita (Pictures taken in year 2004); 3-4: Laguna Melincué (year 2005) and 5: Laguna Epecuén in LEO system. (b) Lake-level curve for Laguna Mar Chiquita. The interval AD 1890–1967 was reconstructed from historical data dashed line. Instrumental records started in AD 1967. $D$ lake level = 0 is an intermediate lake-level stage that matches the AD 1977 shoreline elevation (66.5 m a.s.l.). Positive values represent highstands (black areas), and negative values indicate lowstands (gray areas). Annual precipitation for the AD 1925–96 interval. Values above average are in black and below average in gray. Standardized runoff of rivers Xanaes (within the Laguna Mar Chiquita basin) and Ríos Paraguay and Paraná from Río de La Plata Basin. Discharges above and below the mean annual runoff are in black and gray respectively.
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Fig. 10 (a) Laguna Mar Chiquita extension and palaeoshorelines mapped in a satellite image of year 1976 (see Fig. 10b). The present-day size of the lake matches with the position of palaeoshorelines. (b) Satellite images showing the lake-surface variations between 1976 and 2001. Satellite images were obtained at http://conae.gov.ar excepting the image of 1976 (taken from Bucher et al. 2006)
since the 1970s, that triggered the present-day highstand has no precedent in the historical (ca. last 400 years) or instrumental (ca last 40 years) sources of the region.

The twentieth century hydroclimatic changes in the Pampean Plains, Impacts and Recovery

The twentieth century hydrological variability in central Argentina was characterized by distinctive fluctuations of lake levels, river discharges and surfaces of flooded low plains (Fig. 9). The most recent hydroclimatic scenario of the region (i.e. last ca 100 years) is represented by two contrasting hydrological situations. Long dry intervals characterized the first 3/4 of the century while a wet phase occurred after the 1970s impacting on traditional socio-economic activities in the region. In addition to the economic damage, the current wet interval in the Argentinian Pampas expanded the area devoted to crops (mainly soya) that in turn deeply affected the quality of non-marketable natural resources and processes (e.g. erosion control, fresh water supply, biodiversity, biogeochemical cycles) (Viglizzo and Frank 2006). Episodes of heavy rainfall are becoming more frequent. For instance the frequency of precipitation events exceeding 100 mm in Central and Eastern Argentina have increased threefold during the last 40 years (Barros 2004) deeply modifying the recurrence of predicted intense rainfalls and thus triggering unusual erosive processes (Argüello et al. 2006).

The most recent hydroclimatic change (i.e. since the 1970s) is also occurring at a sub-continental scale in a wide and very productive region of the SESA between 22 and 40°S, including Uruguay, Paraguay and the subtropical regions of Argentina and Brazil (see river runoff in Fig. 9b). Amongst all sub-continental regions of the world, SESA has shown the largest positive trend in precipitation during the last century (Giorgi 2002). The increase in annual precipitation in the last 40 years has been more than 10% over most of the region, but in some places it has been higher than 30% (Castañeda and Barros 1994, Minetti et al. 2003). Agricultural products from this region provide sustenance for the majority of the population of these countries (>200 millions), and constitute a large fraction of their exports (Magrin et al. 2005). Therefore, understanding the relationship between present-day and past climatic fluctuations and hydrological variability is of great interest to the regional economies that depend heavily on agriculture and hydroelectricity.

The present-day wet phase resulted in a general increase of precipitation and streamflows in the Río de la Plata basin (Genta et al. 1998, Robertson and Mechoso 1998, García and Mechoso 2005, Barros et al. 2006, Pasquini and Depetris 2007), in central Argentina (Piovano et al. 2004a, Pasquini et al. 2006) and central western Argentina (Compagnucci et al. 2002, Pasquini et al. 2006). The lake level variability instrumentally recorded across the Pampas (i.e. Laguna Mar Chiquita, 30°S; Laguna Melincué, 33°S; Lagunas Encadenadas del Oeste de Buenos Aires, 37°S) (Piovano et al. 2002, Piovano et al. 2004a, Piovano et al. 2006b, Córdoba et al. 2006) is synchronous and in phase with the discharge fluctuations of the Paraná and Paraguay Rivers (Piovano et al. 2004a) pointing toward a large-scale climatic phenomenon affecting SESA (Fig. 9a).

The wet spell that started after the 1970s has affected the socio-economic activities of several lakeshore villages across the central plains of Argentina (e.g. Miramar in Laguna Mar Chiquita, Melincué in Laguna Melincué, Carhué and Guaminí in Lagunas Encadenadas del Oeste de Buenos Aires; pictures on the right in Fig. 9a). Although the area was initially occupied by Indians probably since 10,000 years BP, these villages were founded by Europeans immigrants during the end of the nineteenth century or beginning of the twentieth century, a period matching the end of the Little Ice Age. Very low lake levels and extensive droughts forced settlement close to the lakes, usually below the topographic levels of geomorphological evidences of former highstands (Piovano and Leroy 2005b).

Although the hydrological change started in the early 1970s or even before, it was only after 1977 that the Laguna Mar Chiquita extension went beyond the historical record (i.e. year 1976 lake shoreline in Fig. 10a) producing drastic economic and social consequences. For instance, the number of inhabitants in Miramar fell from ca. 5,000 to 1,600 as people were forced to move away from the rising lakeshore during the period 1977–1985. An area of 120,000 m² of buildings (including 90% of hotels) was flooded or destroyed. This new scenario strongly disrupted the
tourism-based local economy that was flourishing during former low lake-levels years due to the therapeutic properties of hypersaline waters (Piovano and Leroy 2005b).

The new hydroclimatic conditions have rendered obsolete a great part of the infrastructure related to water management, since it was designed for a different climate. Most of the infrastructure was, and still is, designed with the implicit assumption of a stationary climate, reflecting the lack of awareness of the technical community about the regional climate trends and their hydrological consequences (Barros et al. 2006). Particularly, the inhabitants of Miramar seem to have recovered from the past traumatic experience and now are adapted to higher, but always fluctuating, lake level scenarios. In fact, the new lake situation is widely considered as a positive factor for improving the regional development based on the tourism industry. This activity is additionally promoted since the lake ecosystem became a protected site by the Ramsar Convention on Wetlands.16

Sublacustrine Landslides and Tsunamis in a Large Alpine Lake

Past Landslides and Tsunamis in Lake Como

Lake Como (198 m a.s.l.) is located in Northern Italy (Fig. 11). It is the deepest lake of the Alps (425 m), and it has a particular lambda shape that allows it to be divided easily into three main branches: the northern Alto Lario, the southwestern Como branch and the southeastern Lecco branch. The deepest sector of the lake is the Como branch, with an extensive area at a depth of 400 m (Fig. 12a, b). This branch has a typical fjord morphology, deep and narrow, a length of 27.8 km, and the peculiarity of being hydrologically closed. In fact the western end of the lake, where Como is located, is surrounded by hills (altitude of 336–469 m a.s.l.). The only effluent of the lake, River Adda, flows out from the eastern branch (Fig. 11). In both the southern lake branches (Como and Lecco), the presence of several turbiditic deposits were defined, mapped and characterized, resulting from the combination of a bathymetric survey (multibeam Simrad 3,000) with a high-resolution seismic reflection study (single-channel 3.5 kHz sub-bottom profiler) and a coring campaign (gravity corer) (Fanetti 2004, Fanetti et al. 2008). In particular two deposits with a significant thickness (> 1.5 m), a volume (10^6 m^3) and with a basin-scale distribution were characterized in the Como branch, the shallower one named Megaturbidite 1 (MT1) and the deeper one Megaturbidite 2 (MT2) (Fig. 12b). The estimated ages of these turbiditic deposits, extrapolated from mean sedimentation rates based on radiocarbon (\(^{14}\)C) and radionuclide (\(^{137}\)Cs) analyses, are around the mid-12th (MT1) and early 6th (MT2) centuries AD.

The multibeam data together with the acoustic-facies distributions and the volumes of these two major sedimentary deposits, MT1 (~ 3 × 10^6 m^3) and MT2 (~10.5 × 10^6 m^3), indicate that they resulted from large slides that occurred at the northern tip of the Como branch, along the steep slopes of a sub-lacustrine plateau. In fact, at the beginning of the western branch, a bathymetric sill exists (Fig. 12a), at 140 m water depth, with two morphological scarps, on both the NW and NE flanks. Moreover the volume of the material deposited in the western branch is comparable with the sediments missing from the NW slope of the sill (Fanetti et al. 2008).

Dangerous tsunami-like waves (seiches) can be generated by large sub-aqueous landslides leading to such megaturbidites in this fjord-like basin. Possible trigger mechanisms leading to these catastrophic events in the Como branch include a combination of steep-slope overloading, with significant lake-level fluctuations related to Holocene climate change and/or earthquake shaking. In particular, the MT1 event may have been caused by an earthquake with an estimated magnitude of 6.2, which occurred in AD 1222 at Brescia (Guidoboni 1986), a city located ~ 90 km from the plateau (Fig. 12a); while for the older event (MT2) historical documents (Fanetti et al. 2008) report a catastrophic alluvial flood event in October AD 585, ravaging northern and central Italy.

Evidence for the repetition of the geohazard is based on the Lake Como sedimentary archive, which is limited to the shallower portion of the sediments (maximum investigation depth ~ 16 m in the Como branch)
where two significant catastrophic events have already been noted. Moreover it has to be highlighted that, in the historical documents of Como town (Fanetti et al. 2008), sudden floods or lake surface movements have also been recorded that for the knowledge of the time were enigmatic and not attributed to a natural event (heavy rains, sub-aerial landslides, ...). Now we can assume that such phenomena could have been the result of past anomalous waves or ancient tsunami, linked to sublacustrine landslides, exactly the same events found in the sedimentary record.

The two main turbiditic deposits in the Como branch that occurred in the mid-12th (MT1) and early 6th (MT2) centuries had a time interval of about six centuries (Fanetti et al. 2008). In the eight centuries since the last catastrophic event, no other large-scale sublacustrine landslide has occurred. Different land practices that have reduced erosion and sedimentary input to the lacustrine basin could be the reason of this longer quiescent period (Fanetti and Vezzoli 2007).

Another type of geohazards that is significant in the Lake Como area, is the subsidence of the town of Como. During the period 1950–1975, because of deep-water withdrawal from wells, the Como area was affected by a human-induced accelerated subsidence with a velocity of 10–20 mm per year, i.e. one order of magnitude higher than the natural rate (2.5 mm/a). Nowadays the subsidence rate has returned to its natural trend (Comerci et al. 2007).

**The Present Geohazards Potential**

Tsunami events are typically characterized by an instantaneous onset, especially in lacustrine environments, given that in such settings also amplification will occur even with a moderate phenomenon. According to the triggering factor the speed could however be slightly different: either earthquakes, which will take people by surprise as they are still unpredictable, or...
Fig. 12 (a) Topographic profile of the Como branch obtained by the longitudinal 3.5 kHz seismic line showing the Bellagio plateau, the deep over 400 m basin and the shallower transect towards Como town. Dotted lines indicate the extension of the four stages of the large slope failures associated with MT1 and MT2 in the deep basin: the large slide scars (s), the ∼2.4-km-long accumulation zone (az), the ∼4.8-km-long debris-flow deposits (df) and the ∼5.5-km-long megaturbidites (mt). (b) Detailed seismic section of the basin fill where are located the large ponded megaturbidites (MT1 and MT2) and the well-stratified hemipelagic sedimentation draping the basin morphologies.

Long rainy periods which can be predicted and could cause progressive alarm in the community. Because the speed of a tsunami on Lake Como, the onset of the hazard would be rapid, while the duration of the phenomenon would be relatively short. Indicatively, similarly documented events in alpine type lakes (e.g. Lake Lucerne; Schnellmann et al. 2006) reach their maximum amplitude within a couple of hours. Following a tsunami disaster, a short bad period is expected that involves both human society and the biosphere: this period would not be longer than the food storage capacity because Lake Como is in a highly developed area (relatively easy to rescue); but significant and persistant damage to the drinkable lacustrine water
is expected (most of the drinking water of the area comes from the lake). Also, the lacustrine fauna (e.g. fish) would suffer because of the sediment displacement. Moreover communication routes would be easily disturbed in a mountain setting due to the consequential flood.

A tsunami wave generated by a sublacustrine collapse on the SW plateau flank will involve all Lake Como’s SW branch (27.8 km long). Since this sector of the lake, as highlighted before, is hydrologically closed, narrow (fjord morphology) and the lake floor becomes gently shallower towards the south, the amplitude of the tsunami’s dangerous waves would be increased towards the end of the branch, right at Como town (Fig. 13). The area and the portion of settlement that would be involved are small, but it is not possible to escape such a rapid phenomenon.

Nowadays Como would recover fast from such a disaster but only at the cost of many lives. Lake Como is located in the Lombardy Region, a densely populated and urbanized area. Two towns are located at the southern tips of the lake (Como town, 83,600 inhabitants, and Lecco town, 45,500 inhabitants) and several villages are set along the shores, right at the lake level (Fig. 12a). An estimate of the average people present in the villages along the western shore plus the Como inhabitants is about 120,000 people (Gruppo di Lavoro Lago di Como 2006). Along the lakeshores, there are several tourist villas, heritage sites, and the dwellings of world-famous people. The lake is navigable and therefore, every day, many commuters use the lake as a way to reach their workplace and also, in the high season, a lot of tourists cruise on the lake.

The population around Lake Como could suffer from a modern disaster because tsunami waves, according with their intensity, could: (1) generate serious damage to the houses near the shore; (2) flood part of Como town, and of the other settlements, close to the lake; (3) induce shore instability due to the rapid change in the water level; (4) remix the lacustrine sediments and therefore compromise both the drinkable water sources and the fishing economy; and (5) interrupt strategic life lines. The tsunami threat would also seriously compromise the ever-growing tourist economy.

The possibility of job loss is real in a tsunami scenario. In fact psychological fear alone could induce a lot of tourists to chose other holiday resorts, as in the case of the Twin Towers act of terrorism (9/11), when most of American tourists skipped Europe in their journeys as reported in the newspapers. This tendency can seriously damage the economy of the area, which nowadays also includes the influx of visitors. Moreover there is worldwide indication that possible or defined geohazards increase the costs of insurance premiums (Beer et al.17), which could induce more interest in the tsunami geohazard in Lake Como by the decision makers and the politicians.

The adaptability of society to such natural phenomena is likely and simple since the people and the administration bodies are already used to living with other geohazards (such as landslides, flood and subsidence) frequent in northern Italy. Therefore it would not be difficult to add mitigation plans for tsunamis.

**Lack of Lessons Learned**

In 2005, on the occasion of the *Dark Nature Final Meeting,* Como’s population was informed for the first time of the new scientific database relating to the lake and of the potential threats. Tsunamis in Lake Como are not freak phenomena as both scientific documentation and historical reports testify to their existence in the recent time. Since any earth process that poses risk to human life can be said to be a geohazard, we can declare that the risk in Lake Como is medium-high. This is because, from the geological point of view, there is still the probability that a sub-lacustrine landslide will happen and the scale of the damage that such an event could induce is high (both in terms of loss of lives and in structural and economical damage). Other Alpine lakes can potentially be affected in the same way.

In truth, the main recognized vulnerabilities of the area do not include the possibility of tsunamis as real hazards. Consequently no mitigation or evacua-
Fig. 13  Satellite image of the lake Como with the failure area, the turbiditic deposits and the location of Como town. On the right a cartoon of the lake to explain the direction (arrows) of an anomalous wave generated by a sublacustrine collapse of the plateau western flank. In the table the physiographic characteristics of the MT1 and MT2, and the Como town inhabitants

<table>
<thead>
<tr>
<th>Failure source</th>
<th>Sublacustrine plateau area (Bellagio)</th>
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| Volume of the deposits  | MT1: 3.5\times10^8 m^3
                         | MT2: 10.5\times10^8 m^3               |
| Landslides estimated age| MT1: 1260±120 AD
                         | MT2: 800±200 AD                       |
| Distance from the source area to Como town | ~27.8 km |
| Como town inhabitants   | 83600                                |

Lessons Learned from the Past: Understanding and Communicating

The main lesson from these five examples is the importance of understanding the record of rapid landscape change and natural hazards. It is after all the palaeoenvironmental record in the sediment of the Caspian Sea, Mar Chiquita, Lake Como, Gulf of Mexico and the Arctic that has shown that such hazards are not one-time affairs, not necessarily human-induced, and that they must be taken into account in development planning and policy. In the case of new world countries, geoscience analyses at high time resolution are critical to complement the short instrumental and written records which started only very recently, such as in Argentina. It is only through earth science that the background rates, trends and cyclicity of natural hazards may be established. Where these cannot be worked out, those responsible for disaster management should at least recognize that bad things have happened in the past, and that their people/societies/cultures have survived through them and in some cases may not have fully recovered from them (Diamond 2005).

The second lesson is that the earth science community needs to work much harder to get the
Table 1  List of actual hazards in the five regions analysed in this chapter

<table>
<thead>
<tr>
<th>Region</th>
<th>Main hazard</th>
<th>Other significant hazards</th>
</tr>
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<tbody>
<tr>
<td>Arctic</td>
<td>Rapid climatic change at high latitude</td>
<td>Loss of sea ice and permafrost, landslides</td>
</tr>
<tr>
<td>Coast of Louisiana</td>
<td>Hurricanes</td>
<td>Delta erosion, delta subsidence, wetland loss, sea-level rise</td>
</tr>
<tr>
<td>Caspian Sea Coast</td>
<td>Rapid sea level rise</td>
<td>Rapid sea level drop, tsunamis, earthquakes, wind surges (and retreat of water by wind)</td>
</tr>
<tr>
<td>Argentinian Pampas</td>
<td>Rapid lake level rise</td>
<td>Rapid lake level drop, soil erosion, hydroclimatic event</td>
</tr>
<tr>
<td>Alpine lakes in Italy</td>
<td>Underwater landslides and tsunamis</td>
<td>Earthquakes without tsunami, floods, on-land landslides</td>
</tr>
</tbody>
</table>

Ratchet Effect of Hazard Accumulation

In each of the five case studies, the main natural hazard was analysed for its extent and its impact. However each region potentially may suffer from a range of natural hazards (Table 1). It is not inconceivable that two or more of the hazards could occur in quick succession (before total societal recovery) or even at the same time. For example, in 2005, the hurricane-damaged city of New Orleans was hit again one month later by hurricane Rita; and in 2008, hurricane Gustav added wind-damage to structures that were being rebuilt. Following an accumulation of disasters, it becomes more difficult or impossible to return to previous conditions: this is known as the ratchet effect (Chambers 1989, Ford et al. 2006). Each time there is a new disaster, the capacity for society to recover decreases and it may reach a point when there is a societal collapse.

After a disaster, there are two ways to recover: (1) return to past conditions, but retain the same susceptibility/vulnerability to hazards, (2) adapt and modify society (sometimes in depth) in order to increase resilience (Leroy 2006). The second situation is of course by far more preferable; though there are situations where the best solution would be for people to move away from a disaster area, such as one buried by ash deposits or lava flows, or inundated by sea-level rise. However our modern world is closely linked to technology and infrastructure that cannot be easily transported, decreasing therefore the likelihood of migration. There was little adaptation after the...
1906 earthquake in San Francisco, at least not until recently – and yet this was rebuilt as one of the most attractive US cities. Many people tend to return to their traditional homelands after an eruption. It may not be preferable from a management viewpoint, but from a cultural standpoint it is perhaps easiest to move back into the threatened area, as people have done from time immemorial (e.g. Berger 2007) and rely on resilience.

**Transfer of Information**

In each of the five case studies, the transfer of information to the local communities from the geoscientists has been done with varying success. In one extreme case there is no interest at all and in another one the local community has integrated the geoscientific data very well. Table 2 summaries the type of recovery and the lessons learned in the five case studies.

**Global Warming at High Latitudes, Yukon**

New scientific research in the Arctic, as elsewhere, underpins moves to influence public policy on climate change and its human drivers. The work of government geological survey departments and of academic researchers is communicated to the public and to policy makers through authoritative reports (e.g. Furgal and Prowse 2008), and a multitude of journal articles (e.g. Berger and Liverman 2008). Indeed, based on observations such as those above, the Manitoba Government recently developed a school guide to help teachers and students understand climate change and its impact on Arctic communities (Manitoba Education and Youth 2003). This shows how collaboration between scientists and aboriginal peoples can help to attain a better understanding of the world around them (see also Ashford and Castleden 2001, Krupnik and Jolly 2002, Berger and Liverman 2008).

**Hurricanes in New Orleans**

Outstanding plans were born from the lesson learned. Hurricane prediction, evacuation and recovery efforts are managed very effectively. Thousands of families were safely evacuated just preceding the landfall of Hurricane Katrina, and procedures were improved to help the population that remained in the city in 2005. All plans were extremely effective during the succeeding hurricane season as seen with the crisis management during Hurricane Gustav and Hurricane Ike in 2008.

With warmer sea-surface temperature and the associated - more than probable - intensification of hurricane seasons, in a region that is losing wetlands, the protection issue is the only key element that still needs improvement. Some of the elements of the three-layer protection system (strengthening of barrier islands,
swamp replenishment, and better levee system) proposed by scientists are in progress and other components are considered, but a full protection system is not yet in place. To implement such a system, it will take continued collaboration between scientists and engineers, several years of new infrastructure construction, and major federal funding. It is clear to politicians, scientists and citizens that basic building laws limiting construction to certain geographic areas or heights in the city will only solve short-term problems and the focus will need to stay on protection now that prediction, evacuation and recovery efforts are adequate.

Rapid Sea Level Rise in the Iranian Coast of the Caspian Sea

Iran’s Caspian coast is facing three major problems: high density population in the coastal zone, inundation of this zone due to sea-level rise, and weakness of the existing laws and lack of much required laws for regulating the relationship among the stakeholders (Pak and Farajzadeh 2007). These problems have increased the governmental level of interest and it has initiated now the integrated coastal zone management (ICZM) program. In this program, basic information has been gathered for establishing a realistic strategy. Moreover, the Caspian Sea has attracted more scholarly attention over the past two decades, with an increase in research contribution at the international level. Before passing the ICZM plan through bureaucratic procedures, the government began to free a 60 metre coastal zone for public access. The enhancement of public awareness and of inter-sectorial cooperation is crucial for management of the coastal zone. The level of scientific knowledge and the quality of institution related to the Caspian Sea are relatively good, but the share of the private sector remains negligible. Moreover, the transfer of scientific knowledge to the wider public requires more effort, which is needed if the laws and managerial procedures are to be respected.

Rapid Lake Level Rise in the Argentinian Pampa

After demolishing that part of the village that was affected by the 1970s lake-level rise (i.e. buildings under lake-water and ruins), new regulations on urban development were established by land-use decision-makers together with local officials. The implementations of the urban regulations are based on the combined knowledge of society, hydrologists and palaeoclimatologists about the short- and long-term changing nature of the lake. Regulations take into account prior lake-level variability and prohibit the building below the maximum possible lake-level. The necessity for constraining urban growth was seen as a crucial task for the whole of society. In this sense, the ICSU conference organized during the year 2005 in Miramar (Piovano and Leroy 2005b) played an important role in confronting not only local officials but also society with the importance of planning actions based on understanding how to diminish “environmental risks,” when a society is vulnerable in face of the environmental unevenness.

Palaeolimnological data point towards the need to reinforce palaeoclimatic research at mid-latitudes in South America to fully appreciate natural climatic variability beyond the instrumental record and to plan future strategies leading to sustainable development.

Underwater Landslides and Tsunamis in Large Alpine Lakes, Italy

Unfortunately the potential recurrence time of the hazard appears to the politicians and to the end-user to be too far-off. All the evidence is below the lake, buried underneath the lacustrine sediments, or lost in ancient historical observations. The absence of evident and clear signals of the possible threat makes it easy to ignore this as a serious geohazard. The time scale is too large: the problems that are urgent for the local political class have a time scale of years and not of centuries.

Therefore no lessons for public policy have been learned from the past tsunami events which occurred in Lake Como in historical time.

In brief, it is clear that the information transfer from the earth scientists to the end-users works best when the hazards are frequent and visible and when the messengers are trusted by the local community. The latter may lead then to a participatory approach to the mitigation of disasters. An analysis of the role of culture in disaster management clearly emphasises the need to give a large role to the most vulnerable groups in the decision–making process relating to them in order to ensure success for the mitigation measures (Hewitt 2008).
The Role of Geosciences in the Mitigation of Natural Disasters

**Geosciences and the Hyogo Framework of Action**

The contribution of geosciences to the list of priorities of Hyogo Framework for Action\(^20\) and to the conclusions of the review of the “Yokohama Strategy for a Safer World”\(^21\) (adopted by the United Nations in 1994) is that good mitigation decisions will be taken only if the full scale of hazards, disasters and risks, which is certainly not covered by instrumental records only, is known. Therefore it is necessary to look at the past millennia and include in any framework of action information on hazards, disasters and catastrophes obtained from historical documents, archaeological, palaeoenvironmental as well as geological data, all at a time scale relevant to society (Leroy 2006).

**Conclusions**

The incorporation of geoscientific data into mitigation plans has been examined in the case of five recent examples of disasters. A first lesson learned is that geosciences are able to provide high-time-resolution information on past hazards that are directly relevant to society.

The second one is the difficulty that many geoscientists meet when they try to communicate to the wider public, as often they are not trained for this and their efforts are not valued by their employers. Amongst the five examples analysed here, in one case there is no interest by the wide public as the hazard is perceived as too improbable because too infrequent. In another case, the local community has fully integrated in their building plans the information provided by the geoscientist owing to their trust in him.

In conclusion, we strongly recommend that any framework of action to mitigate natural hazard disaster integrates geoscientific information on hazards in their plans. It is crucial to be aware of the full range of potential hazards and of their frequency.

**Acknowledgements**

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**References**


The Role of Geosciences in the Mitigation of Natural Disasters


### Chapter 9

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