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Hurricane Katrina – Observations on a Cyclone that devastated New Orleans and the Mississippi Coast in 2005

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Abstract

Devastating New Orleans and the Mississippi coast in August 2005, Hurricane Katrina became the object of diversified analysis and research of a number of disciplines. After briefly explaining the nature of tropical cyclones, the present paper looks at the vulnerability of New Orleans and the Mississippi delta to cyclonic threats. It tries to bring out some of the factors that contributed to strengthening the hurricane over the Gulf of Mexico. However, adverse meteorological conditions alone are not enough to explain the scale of the disaster. The deterioration of the deltaic environment, the loss of wetlands, and the overemphasis of and dependency on technology versus nature in reclaiming swamps and expanding settlements beyond otherwise viable limits are some of the causal factors. Further the paper discusses some special social aspects of New Orleans and problems of the disaster prevention and management.

Introduction

During the hurricane season 2005 a tropical depression, which had formed near the Bahamas grew into Hurricane Katrina and made its first landfall in southern Florida on the 26th of August 2005. Though weakened over land to a tropical storm, Katrina regained full strength over the Gulf of Mexico and struck with devastating force the coast of Eastern Louisiana, Mississippi and partly Alabama. With more than 1836 registered death and 705 missing persons, over a million displaced persons and more than 200 billion damage, hurricane Katrina is considered the costliest and most destructive natural disaster in the history of the United States.

Devastating disasters are usually not brought about by a single or few inherently damaging events but by the complex interplay of a number of phenomena which contribute, on a nonlinear scale, to drive the imminent disaster to an unforeseen, unimagined, unperceived height of destruction. Hurricane Katrina provides a good example of how many different natural and man-made factors contributed to the final natural and human catastrophe. The present note tries to bring out some of the factors, which added to the devastating impact of hurricane Katrina.

In order to understand the catastrophe, it is necessary to provide first some information on tropical cyclones and to give an

overview of the physical and human environment, both closely linked, of the Mississippi delta and the adjacent eastern Gulf coast.

1. Characteristics of Hurricanes

Tropical cyclones, called hurricanes in the Western Atlantic Ocean and the Caribbean Sea, are depressions of the tropics with very low core pressure and a diameter of several hundred kilometres. Because of the greater pressure difference to the centre, they show high wind speed, often 200 km/h and more. The winds show a strong gustiness. Tropical cyclones originate in tropical seas with seawater temperatures of above 27°C reaching to a depth of at least 50 m. These warm waters constitute the energy source for the developing storms. Thus in summer and early autumn in the northern hemisphere the moist warm air over the water surface forms clouds. Their condensation releases large amount of energy. This energy in turn provides the initial clouds with more intake and uplift of moist air, thus further releasing energy. Latent heat provides the main energy for the formation of cyclones. However, for the circulation to be set into motion a source of convergence is necessary. Such a convergent stream in the lower layers of the atmosphere is frequently provided by the *easterly waves*, a wavelike deflection of the trade winds along the southern limit of the subtropical high-pressure belt. The eastward disturbance wipes out the boundary which normally divides the moister lower air and the drier upper air. Under this condition the cumulus clouds may grow to towering heights of 15000 m. Disturbances in the tropical atmosphere at 10000 m may help to intensify the initial tropical storm, like an anticyclone drifting across an easterly wave (J. S. Malkus, 1957). Cyclones develop at a distance from the equator (at least 6° N or S) as there the latitude becomes sufficiently high for the Coriolis effect to impart a circular movement, the spiral effect, to the air current. Further there should be a pronounced instability in the air column and no vertical wind shear. These above conditions are best met in the inter-tropical convergence zone, 10° or more away from the equator.

In a mature travelling cyclone a sinking air movement produces a dry and relatively calm zone, 10 to 30 km or more across, the *eye* of the storm. This core is surrounded by the *eye wall* formed by deep hanging dense clouds which are the source of the heaviest rainfall that can reach 500 to 1000 mm in a few hours. Below the eye wall the strongest wind occur. The eye wall may undergo periods of shrinking in size and sometimes a double concentric eye wall may form. Structural changes in the eye wall or eye (eye replacement) would be associated with changes in the surface wind speed and may indicate changes in the intensity of the storm. The eye wall is surrounded by *spiral rainbands*. These are clouds and thunderstorms that swirl in counter clockwise rotation towards the storm centre. A cross section through a hurricane (fig. 1) would show: 1. Increased wind speed and rain, 2. violent winds and rain, 3. heaviest rainfall in a zone of 20 to 30 km before the eye, 4. the eye representing a 20 to 45 minutes rainless and relative calm interval, 5. followed by a heaviest rainfall zone (second landfall), and 6. and 7. a slow decrease in wind speed and rainfall. Hurricanes lose their strength only over land or over a very choppy sea because of friction (S. Singh, 2005:243-251).

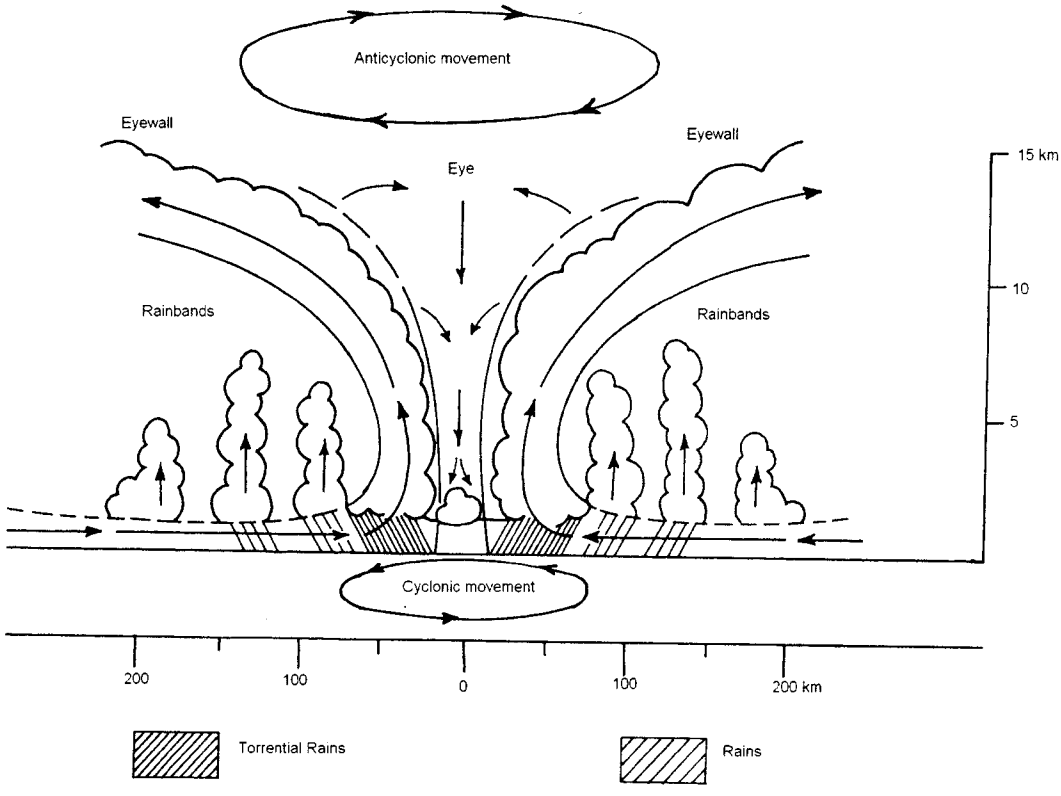

Fig. 1: Development of a Hurricane (adapted from Meyers Lexikonverlag (1989), *Wetter und Klima*: 185)

Table 1: **Saffir-Simpson Hurricane Scale**

Category		**Wind Speed** In km/h	In mph	**Storm surge** In metres	In feet
1	Weak	119-153	74- 95	1.2-1.5	4-5
2	Moderate	154-177	96-110	1.8-2.4	6-8
3	Strong	178-209	111-130	2.7-3.7	9-12
4	Very strong	210-249	131-155	4.0-5.5	13-18
5	Devastating	> = 250	> = 156	> 5.5	> 18

Different phases may be observed in tropical cyclones: **Tropical disturbance**, **Tropical depression**, with wind speed of less than 63 km, **Tropical storm** with surface wind speed of 63 km/h to less than 119 km/h, and **Hurricane**, a tropical cyclone with wind speeds of 119 km/h and above. The Saffir-Simpson Hurricane Scale

recognises different hurricane categories on the strength of the wind speed (table 1). Other criteria of classifying cyclones include minimum pressure, wind direction, rainfall quantity and intensity, point of origin and the characteristics of the track.

Hurricane Season 2005

Most tropical cyclones that are formed in the North Atlantic fall in the period from 1st of June to 30th November, the Atlantic hurricane season. Since 1995 an upward trend in the Atlantic hurricane activity could be observed, were nine out of eleven years had a more than normal share of storms. Though this rise could be part of a general cycle, it could be also attributed to a tropical climatic shift resulting in warmer seawater temperatures and reduced wind shear (T. Hayden, 2006). The 2005 Atlantic hurricane season became the most active season ever recorded. Out of 26 tropical storms, 14 became hurricanes and out of these seven grew into major hurricanes, category 3 or above (Wikipedia 4). Though 2004 had a number of destructive storms, the 2005 hurricane season was by far the most destructive with 100 billion damage (mostly from Katrina) and 2830 deaths (mostly from Katrina and Stan). The hurricane season 2005 was an exceptional season. The season, which usually peaks in September, started that year with several storms and two hurricanes before August and had the highest number of storms in October.

2. The Mississippi Delta and the Gulf of Mexico Coast

The Mississippi Delta

The Central Gulf Coast of the U. S. A. is dominated by the Mississippi delta, which with its bird foot like protrusion extends across the broad and shallow shelf of the Northern Gulf of Mexico till the continental slope and has even given rise to the formation of the Mississippi Cones beyond the slope. The very fine sediments transported by the Mississippi and its tributaries, including the Missouri, have formed the large delta area of 28,490 sq. km where every year the Mississippi piles up 495,000,000 tons of sediments.

A delta environment is a relatively unstable environment and undergoes frequent changes. The evolution of the Mississippi delta shows that during the past 5000 years the active delta has shifted about seven times swinging widely from the westernmost part to the easternmost part of the delta or settling for some time in the centre of the apex. This brought about changes that are still reflected in the present landscape. (Russel, 1959 cited by A. Guilcher, 1963, p. 631). A number of barrier islands trace reworked delta fronts. For example, the semi-circular arrangement of barrier islands, the Chandelier Islands, in the east, indicate the once outer front of an older sub-delta, the St. Bernhard delta (2700 B.P.), though that delta itself has subsided and has been eroded. The present sub-delta is the Balize delta (450 B.P.) and is most actively protruding across the shelf of the Gulf of Mexico thus advancing the delta shoreline 10 km every 100 years (Fig. 2). However, this delta is not active in all its protruding parts, as subsections after channel crevassing show a phase of rapid growth, stabilisation, and later erosion and subsidence in a cycle of about 100 years (J. M. Coleman, H. H. Roberts & G. Stone, 1998).

The coastline in the western section of the apex is characterised by bays, larger is-

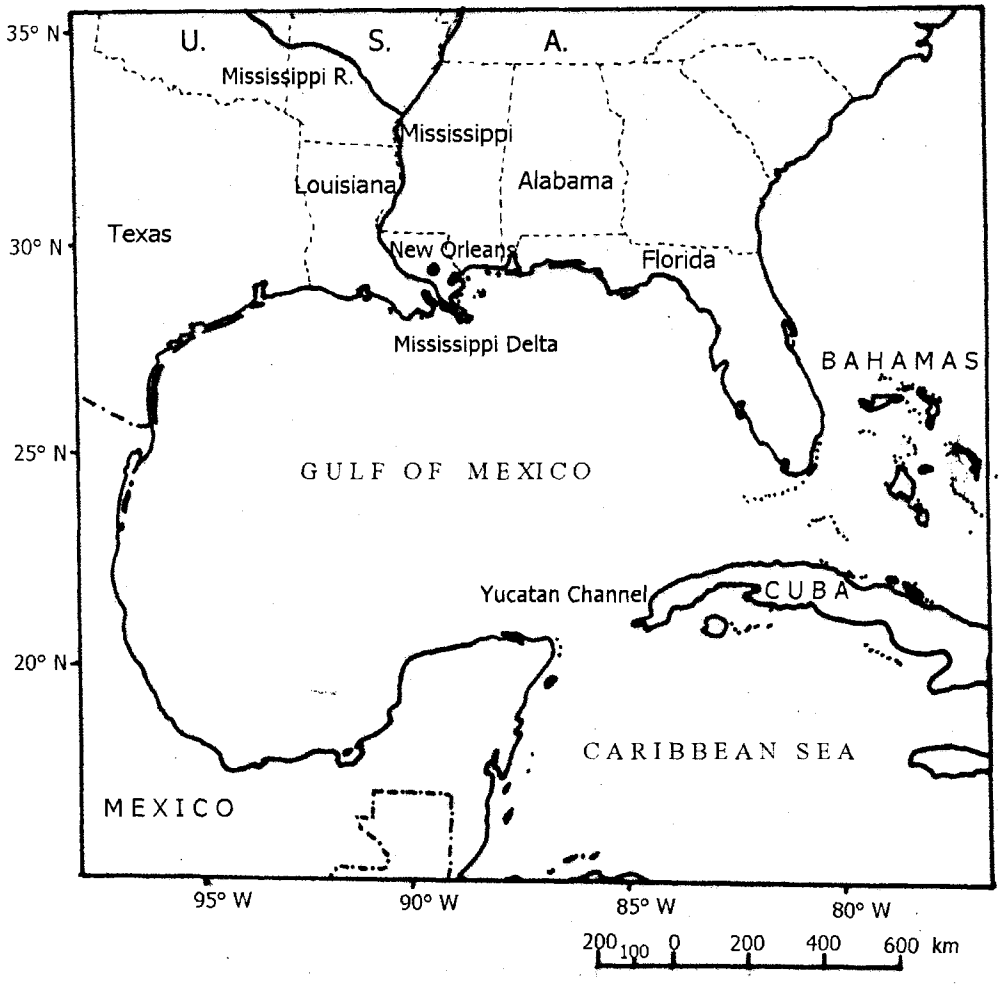

Fig. 2 Location of New Orleans

land and lakes within the wetlands. The central and eastern sections have an extremely irregular coastline brought about by marine erosion and subsidence. The coastal forms of the Mississippi delta indicate that the eastern section is much more vulnerable to erosional stresses of all kinds. The most vulnerable area is the north-eastern section where Lake Borgne and Lake Pontchartrain deeply dent the land inward.

In the delta region, the present Mississippi river shows first a meandering west-east course in the direction of the former St. Bernard delta but adopts east of New Orleans the southeast direction of the present sub-delta. Its levee banks are raised several metres above the surrounding areas and embankments keep the river in its central position. A major distributary of the Mississippi system is the Atchafalaya River, which has a straight North–South course and

builds presently its own delta. The wetlands of the Mississippi delta constitute a special and fragile eco-system with a rich flora and fauna. Marshes, lakes, canals, dead river channels, locally called *bayous*, floating vegetation and barrier islands produce the ever-changing coastal environment. Beaches are absent. However, the Mississippi delta is also rich in oil and gas, and the extraction of these resources has brought about changes in the wetlands. Oilrigs were drilled, canals were dug and pipelines laid in order to transport the crude oil to the refineries and industries in New Orleans. Compaction and subsidence which occur naturally in the thick muddy peaty deposits of the wetlands, increased manifold as a result of the oil and gas mining. Mining, canal and road building, fishing, agriculture, river regulation, all these man-made activities have contributed to the increased erosion of the wetlands and the loss of marshes, at an estimated rate of 65 sq. km a year.

Lake Pontchartrain

Situated north of the Mississippi and New Orleans and slightly south of a Pleistocene terrace with cities like Mandeville, Madisonville and Slidell on its northern shore, this large brackish lake covers an area of 1630 sq. km and has an average depth of 4 m with some dredged deeper channels. The Rigolet Strait links Lake Pontchartrain to Lake Borgne and thus the Gulf of Mexico. The creation of Lake Pontchartrain 4000-2600 years ago is linked to the eastern and southern extension of the alluvial delta deposits and their later decay (Wikipedia 1).

The Gulf Coast of Mississippi and Alabama

The Gulf Coast of the States of Mississipi and Alabama is characterised by sandy soils, some swamps and bayous. This region has some fine sand beaches. The offshore zone is dotted with lines of barrier beaches.

The Gulf of Mexico

The Gulf of Mexico is a mediterranean sea with only two inlets. The Strait of Florida links the Gulf of Mexico to the Atlantic Ocean in the west, and the Yucatan Channel to the Caribbean Sea in the south. The Gulf has a very low tidal range much like the Mediterranean Sea. The continental shelf of the Central Gulf Coast of the States is wide and shallow und thus is likely to have higher seawater temperatures then the neighbouring ocean areas. The Texas Louisiana shelf is rich with major reserves in natural gas and oil and hundreds of offshore platform dot the shelf area. The particular submarine relief and the particular outline of the Gulf of Mexico have given rise to the formation of the **Loop Current** as part of the Gulf Stream. The warm ocean current enters the Gulf of Mexico through the Yucatan Channel and then leaves it by flowing partly around Cuba through the Strait & Florida or travels in clockwise direction along the Gulf coast. A special feature of the Loop Current represents areas of warm water called "eddy" or "loop current ring" which separate in a randomly way from the Loop Current and drift westward. They have higher seawater temperatures (Wikipedia 2). The warm eddies of the Loop Current can intensify hurricanes.

New Orleans – The City that bore the Brunt of Katrina

New Orleans, the major town in the Mississippi delta, was founded in 1717 as a French port town in the sharp bend of the Mississippi river on a relatively higher site. In the north, the town borders on Lake Pontchartrain. The urban settlement on the left bank of the river constitutes the older and more vibrant part of the town. The French Quarter or Vieux Carré at the northern end of the Mississippi meander still bears witness of its earlier history with the St. Louis Cathedral and the typical period houses. 1803 the town became part of the U. S. A. and the first expansion was the Anglophone settlement to the west of the French Quarter both separated by the Canal Street. The growth of the city, first within the crescent shaped meander and along the river, was related to the development of modern port facilities (Fig. 3). From 1910 onwards the reclamation of the marshy lands around the city under A. Baldwin Wood was engineered with the help of a canal system, often called outfall canals, like the Metairie, Orleans or London Outfall Canals, all draining into the Lake Pontchartrain which lies 30 cm above sea level. As a result the town expanded towards Lake Pontchartrain filling the saucer shaped depression between the river and the lake (Fig. 4). Thus most of the urban settlement lies below sea level. Large areas along Lake Pontchartrain but also the modern extension on the right bank of the Mississippi lie between 1.25 m to 4.00 m below sea level. Thus about 80 percent of the total metropolitan area of New Orleans lies below sea level. The site of the city, mostly below sea level, the continuing subsidence combined with a relative high annual rainfall (1425 mm), and occasional cyclones have made a well engineered levee system along the river, the canals and the lake, combined with an effective drainage system supported by 22 major pumps, of vital importance to the town (Encylopaedia Britanica, 1985; Wikipedia 3). Following the Mississippi the distance from New Orleans to the Gulf is about 180 km. The growth of New Orleans as a major port town was linked to the construction of jetties in the South and Southwest Pass of the delta and the deepening of the channel. In the beginning of the 20th century the five and a half mile Industrial Canal linking the Mississippi of central New Orleans to Lake Pontchartrain was built which as we have seen has an outlet to the Gulf. In 1965 the controversial Mississippi River-Gulf Outlet Canal was constructed, thus shortening the passage between the Gulf and the inner harbour of New Orleans to 106 km.

New Orleans has a population of 469.032 and the twin town Metairie 146.136 inhabitants (Encyclopaedia Britanica, Year Book 2005), thus the combined population of the two cities are 615,618. This figure would be higher if we include the numerous smaller settlements in the neighbourhood of New Orleans, where the better-situated, mainly white population have migrated in order to live in a more prestigious locality (1,319,367 people alone in the Standard Metropolitan Statistical Area or SMSA, U. S. Census 2000). Less than 50 % of New Orleans's population are of Anglo-Saxon origin. Many of the Afro-Americans (about 27 %) belong to the very low-income group (Bill Quigley, p. 2). Noteworthy are also the coastal settlements east of the Mississippi delta like Gulfport (39,676 population in 1980), Biloxi (43,311 in 1980), Pascagoula, Mobile (193,646). Besides being industrial

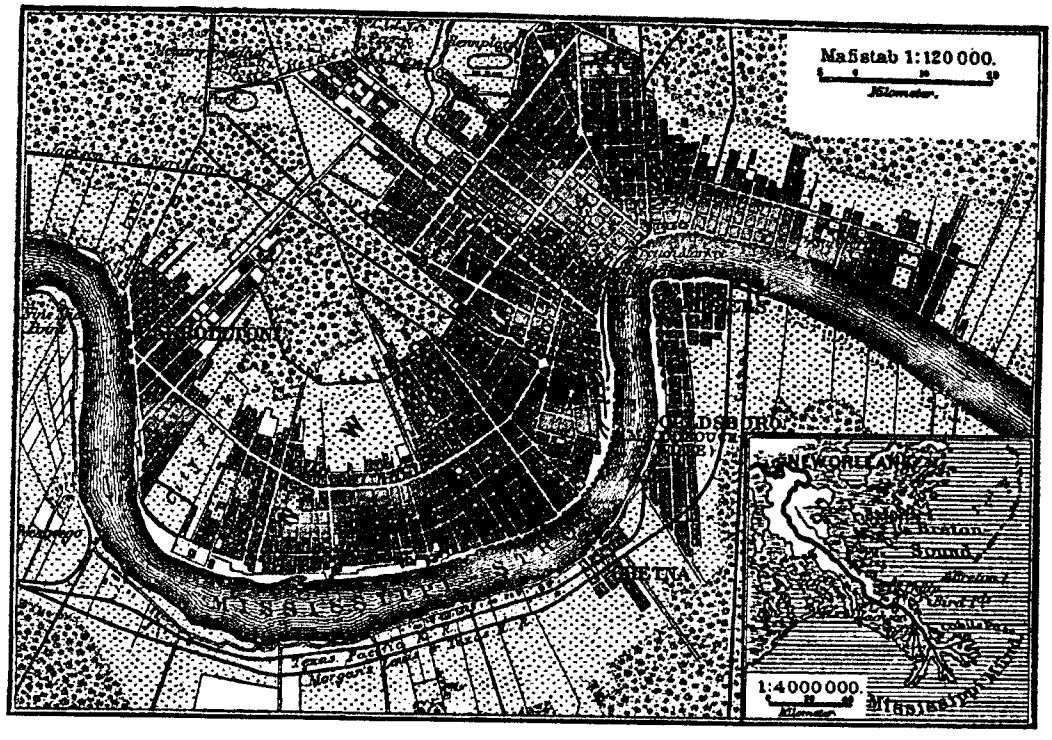

Fig. 3 Map of New Orleans 1880 (population 216,090). The town is nestled along the left bank bend of the Mississippi river, large areas are still woodland swamps to be reclaimed only in the beginning of the 20th century. (Meyers Koversationslexikon 1885-90, 4th Ed., Karte. New Orleans MKL1888.png-Wikipedia)

towns, they are seaside resorts with the longest man-made sand beaches of 45 km from Pass Christian through Gulfport to Biloxi.

3. The Impact of Hurricane Katrina

Huricane Katrina

On 23rd August 2005, hurricane Katrina started as a tropical depression in the Bahamas and gathered the strength of a tropical storm the next day. During its westward movement the storm increased to a Category 1 hurricane on the Saffir-Simpson Hurricane Scale with wind speeds of 119 km/h and gusts of 145 km/h. After having caused substantial damage on its way over the southern tip of Florida (25th-26th August) the cyclone slightly lost its strength. Over the Gulf of Mexico, Katrina first moved westward and then gradually turned towards northwest and then north (fig. 5). Both, the warm sea surface temperature of the Gulf and an upper level anticyclone, provided favourable conditions for the cyclone to rapidly intensify within two days into a major hurricane (Category 3 to 5). Tropical sea surface temperatures are highly correlated with the destructive power of storms (K. Emmanuel, 2005). On 28th August the sea surface temperature near the Mississippi delta was over

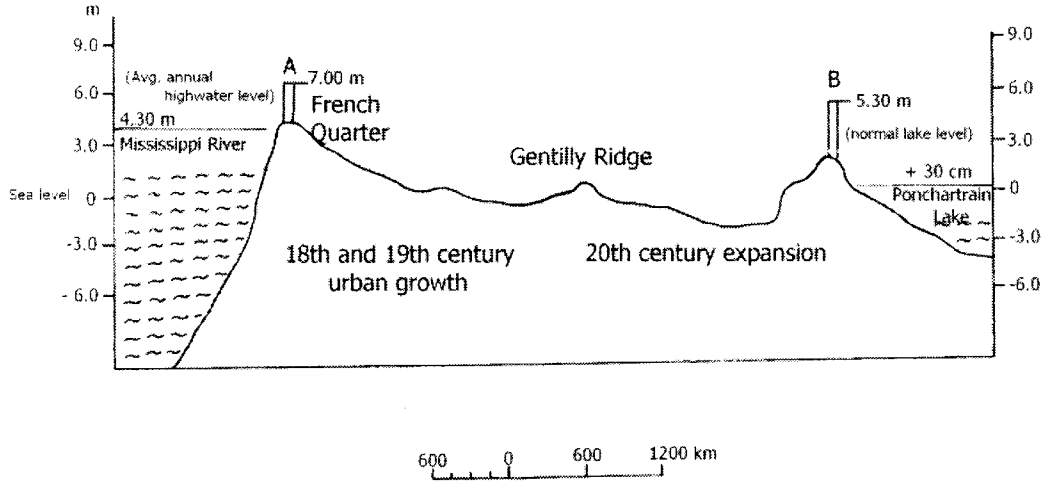

Fig. 4 New Orleans, cross-section from South to North showing most of the town is situated below sea level. Note that the first settlement, the French Quarter, was established on the safest location (for location ref. to fig. 6), (adapted from New_Orleans_Levee_System.gif, based on http://www.usace.army.mil/pao/response/NGVD.asp).

2°C higher than in the southern part of the Gulf. It was also noticed that the warm water temperatures extended to a considerable depth. Crossing the warm waters of the offshoots of the Loop Current further reinforced Katrina to Category 5 strength (E. Graumann et al. 2005, p. 11). Loop current eddies did not only influence the track of hurricane Katrina but also seemed to have influenced the tracks followed by Hurricane Rita and Hurricane Wilma later in the same season. The Loop Current can increase the intensity of a hurricane by 5 to 15 %; Rita had also reached Category 5 strength while passing over this current (T. Hayden, 2006:75).

While approaching the coast, Katrina reached wind speeds of 280 km/h and gusts of 344km/h. On the early morning of 29th August Katrina made landfall in the Plaquemines Parish, close to the mouth of the Mississippi with wind speeds of 204 km/h (127mph) and a central pressure of 920 mb. At 10:00 CDT, Katrina made a second landfall near the Louisiana – Mississippi border with wind speeds of 195 km/h (121 mph). During the day Katrina moved north-northeast ward, still having hurricane strength 100 miles inland. The enormous wind strength, the high waves created by this force and the high rainfall intensity fuelled the all round destruction by Katrina. Though Katrina had weakened before landfall, several factors have contributed to the extreme storm surge: a) the massive size of the storm, where high waves once created on its path over the Gulf are not likely to subside near the coast, b) the strength of the system (Category 5) before landfall, c) the central pressure of 920 mb at landfall, and d) the shal-

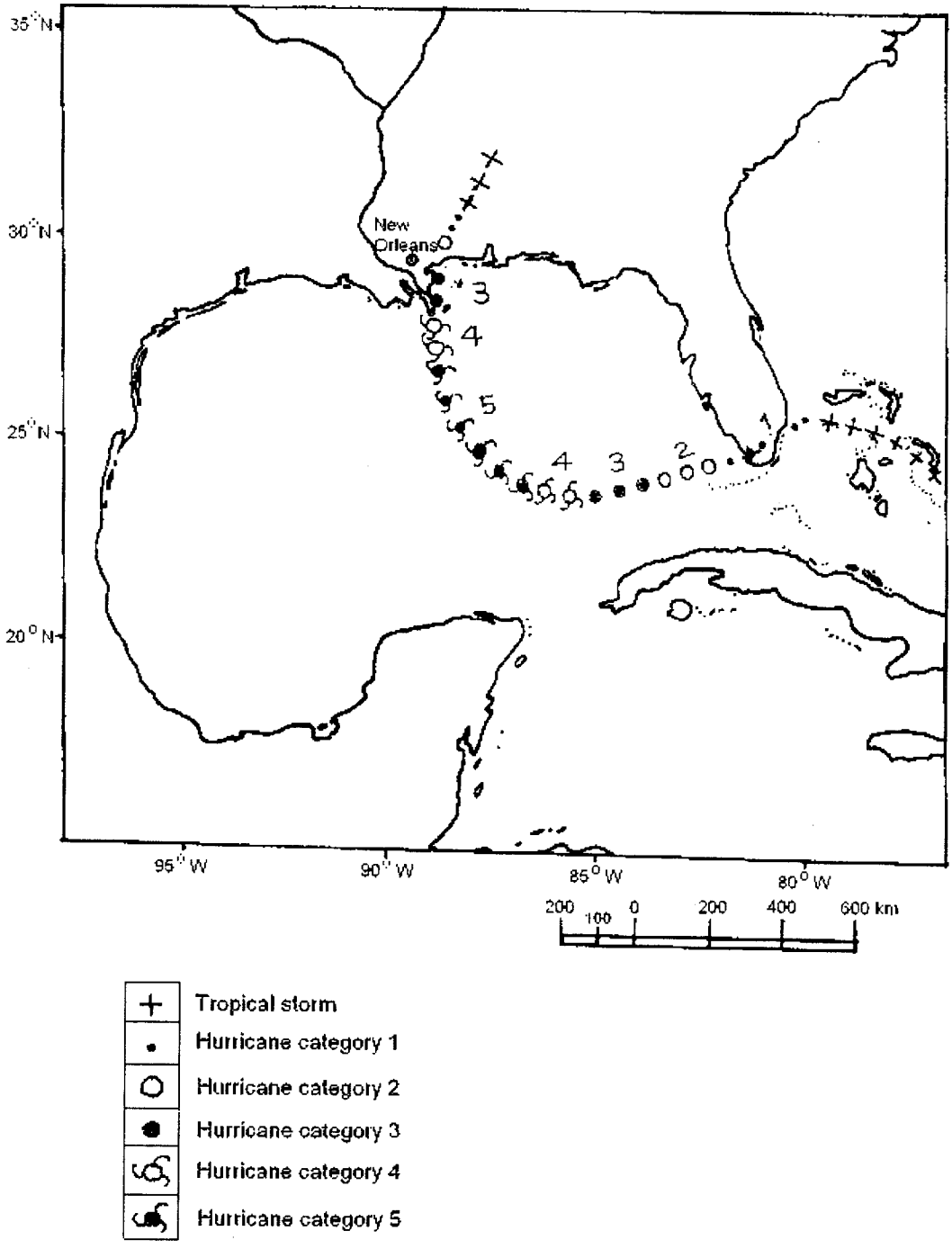

Fig. 5 Track of Hurricane Katrina, Development from a tropical storm to a devastating cyclone. (adapted from http: /en.wikipedia.org/wiki Image:Katrina_2005_track.png)

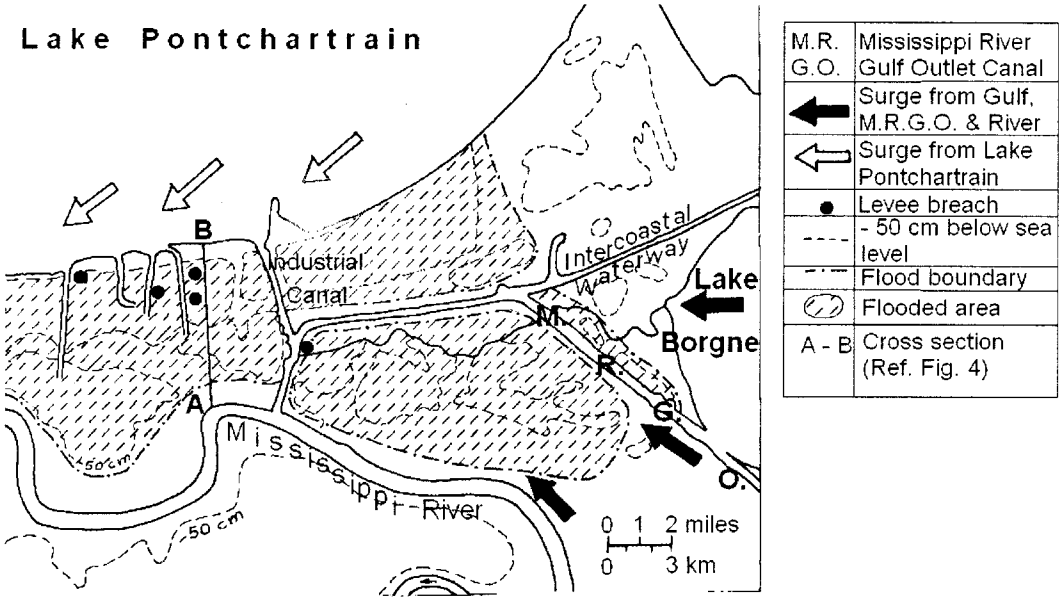

Fig. 6 Flooded Areas of New Orleans. Note the Levees of the Mississippi itself did not breach saving the right bank area of the town from major flooding. (adapted from www.gnocdc.org/maps/elevation.html; www. Stern.de/politik/panorama/545059.html?nv=sb)

low offshore waters (E. Graumann et al., 2005, pp.1-5). The weakening of Katrina to Category 3 strength before landfall has saved the coast from a still greater catastrophe. This weakening has been attributed to the replacement and reorganisation of the eye of the storm, as observed in the satellite images (T. Hayden, 2006).

The Areas that experienced Destruction

The storm surge devastated the settlements southwest of New Orleans, i.e. Plaquemines and St. Bernhard Parishes, then sweeping through Lake Borgne, it backed up the Mississippi several metres. The surge pushed up the level of Lake Pontchartrain thus blocking the outlets of the drainage system into the lake. The rising water level of the lake and other strains on the levee system caused a breach in the levees of Industrial Canal and at several other places (A. Graumann et al.). The water rushed in and flooded 80% of New Orleans up to a depth of 6 m, creating a ghost landscape of vast water expanse with isolated roof and treetops, over bridges disappearing in the water etc. The high-rise buildings of the CBD remained but were severely battered, the Superdome survived, the French Quarter was partly submerged. Besides the twin town of New Orleans and Metairie, the Parishes of Plaquemines and St. Bernard were severely flooded, partly due to a number of breaches in the Mississippi River Outlet Canal (fig.6 and 7).

Slidell on the eastern side of Lake Pontchartrain was largely ruined. Barrier islands, like the Chandelier Islands were destroyed or severely eroded by the storm

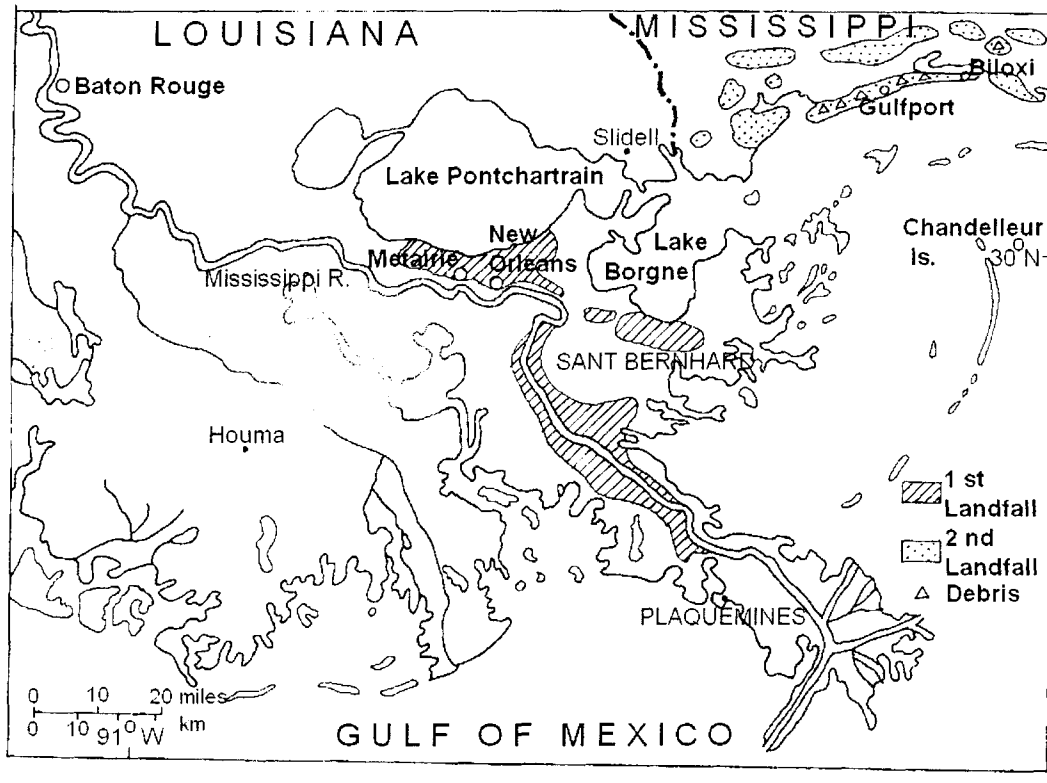

Fig. 7 Areas devastated by Katrina, during the first landfall destruction by wind, heavy rain and storm surges, during the second landfall major destruction was also by storm waves, reducing every thing to debris, ruins, scrap (based on wiki/Image:La-ms-al_pop_090305001.png)

waves. On the Mississippi and Alabama coast surges up to 9 m wiped out most of the coastal settlements. Six to nine metre high waves tossed ships, cars and houses, anything in their way around as the normal swash does with pebbles on the beach. The surge reached 6 km and in some places even 12 km inland especially in bays like Mobile Bay, estuaries and river mouths. Biloxi and Gulfport at the Mississippi coast suffered most (E. Graumann *et al.*).

The strong winds were accompanied by very heavy rainfall, over 25 mm/h for three hours or more. A total rainfall of 200-250 mm fell during the path of the hurricane. Under more normal conditions, it would have already been a challenge for the drainage system of New Orleans to pump out the rainwater. After the flood everything collapsed including the electric supply.

4. Facing the Disaster - Human Response to the Imminent Disaster

Monitoring the development of Katrina after its transit through Florida, the National Hurricane Center (NHC) considered the possibility of a devastating flood of New Orleans. Thus on 26th of August 2005 the

Governor of Louisiana declared a state of emergency for the state agencies. Two days before Katrina made landfall (on 27th Aug.), the President of the United States declared a state of emergency for the States of Louisiana, Mississippi and Alabama. On 28th August, the Mayor of New Orleans ordered the first ever made mandatory evacuation of the city and surrounding areas, the evacuation of over a million people (Wikipedia 5). At the same time other orders followed. As a pre-cautionary measure the railways stopped operating and so did the Greyhound and Amtrak services. Roads were closed to incoming traffic in order to allow more people to leave. The Waterfront Nuclear Power Station was shut down.

Though the state evacuation plan foresaw the evacuation of all including the sick and those who needed assistance by whatever means available, a large number of people were left behind. Those without access to a car (27% of the population, mostly poor Afro-Americans), more than half of the hospital patients and about 75% of the elderly and disabled and their caretakers could not be evacuated. Among those who could not be evacuated were a large number of children. The Superdome gave shelter to about 40,000 people and the Convention Center to 20-30,000 people, both not equipped to provide the minimum relief and medical care needed to take care of such a crowd (Quigley, p.2-3).

Not all people may have taken the warning seriously or they did not have the time or the means to leave. They did not anticipate the extent of the catastrophe, the breaching of the levees, the total collapse of the electricity and water supply, the destruction of the rail and road network and above all the rising water level chasing them on to the rooftops and making them hope for a timely rescue. It is reported that the Coast Guard, the National Guard and the Louisiana Homeland and Security rescued about 120,000 people from rooftops or out of water (Quigley, p. 3).

Though a lot of assistance to the marooned people, including transport and shelter, was provided by the state agencies, in retrospect, serious flaws in the emergency management system of the United States have been recognised. Some of them are the short time for the evacuation, stopping the bus transport, not using the fleet of school buses lying idle, not taking into account the needs of the vulnerable population, and the delay in the relief work after the disaster.

The Aftermath of Katrina

The loss of life and the human tragedy are no doubt the worst effect of Katrina. This is followed by the loss of property, destruction of houses and means of income, thus forcing a number of people, most living in shelters in distant places or make shift homes, to look for a new way to start their life. The poor and disadvantaged population suffered most. They lacked the means of transport, their houses were of poor quality and they lived in the lowest lying and thus deepest flooded areas like the Ninth Ward. In fact, as a result of hurricanes Katrina and later Rita, the population of New Orleans has shrunk by about 64% from 469,000 to 158.000 and along the Gulf Coast of Mississippi State by about 17% (FAZ, 7-6-06). At the same time, a social reorganisation seems to have taken place. While in New Orleans the social fabric changed in favour of an older, richer and Anglo-American population (from 59 to 73%), along the Gulf

coast the Afro-American population increased from 17 to 28%.

A great health risk to humans, animals and marine life alike was posed by the highly polluted and toxic floodwater loaded with petrochemical effluents. This water either pumped back into Lake Pontchartrain or carried by the Mississippi river far out into the Gulf of Mexico posed a serious danger to the fragile ecology of the swamps and the fish grounds, and had severe repercussions on the fish industry. A sizeable number of offshore platforms were severely damaged by Katrina and so was the infrastructure of the petrochemical industry of New Orleans. The disruption of the oil industry had a major economic impact.

One of the far-reaching negative outcomes of Katrina has been the destruction caused to the already stressed wetlands of the Mississippi delta. The damage caused by Katrina is supposed to equal twenty years of normal erosion of the delta. Especially severe had been the erosion of the protective barrier islands like the Chandeliers Islands and the dissolution of the coastline into irregular marsh islands, leaving the coast more vulnerable to future cyclonic impacts (Mrasek, V. 2005).

5. The Perception of Hurricane Threat

Past Experiences

The question one may ask is, did people in the past perceive a possible hurricane threat unleashing a force as destructive as Katrina on New Orleans? The answer would be positive for New Orleans had a history of earlier flooding. In 1965 (9-9-65), the storm surges produced by **Betsy**, a Category 3 hurricane, overtopped the water of the Industrial Canal and flooded the neighbouring areas (Wikipedia 6). That time 76 people lost their life, 164,000 houses were flooded and the damage amounted to 1.42 billion USD. After the flood, taller and stronger levees were built, designed to resist fast moving hurricanes of the strength of Betsy. However the storm models did not take into account extreme, never recorded events. The increased rate of subsidence below the levees and the nature of the substratum were not sufficiently taken note of (Kleine-Brockhoff, T. 2006). Also the levee system, which was to be completed within 13 years at a cost of 85 million USD, was still not completed at the time of Katrina after spending 738 million USD.

On 17th August 1969, **Hurricane Camille,** a Category 5 hurricane, made landfall near the mouth of the Mississippi with a sustained wind speed of 305 km/h and a lowest pressure of 909 m/bar and produced a peak storm surge of 7.3 m. The worst hit was the Gulf coast of Mississippi State, the same coast which later severely suffered under Katrina. Places like Waveland, Bay St. Louis, Pass Christian, Long Beach, Gulfport, Biloxi were flattened or greatly damaged, however New Orleans was spared. 143 people lost their life, 5662 homes were destroyed and 13915 homes severely damaged (Wikipedia 7). Though Camille was the strongest land falling tropical cyclone recorded worldwide, future levee modelling did not include Camille in its calculations.

New Orleans has also suffered from river floods; here one may mention the **Great River Flood** of 1927, the result of several months of continued rain over the Mississippi basin. After New Orleans received 356 mm (14 inches) of rain, surmounting the capacity of the pumping system, major parts of the town were under 1,80

m of water, the French Quarter under 60 cm. The Caernavon levee was blown up to protect the higher income areas of the town thus flooding the east bank of Plaquemines Parish and parts of St. Bernhard Parish, a debatable decision.

Reasons for anticipating a Future Hurricane Disaster

As discussed above, hurricanes and floods have earlier devastated the Louisiana and Mississippi coast and were known to be a disaster in waiting. Among those who tried to raise awareness about the fragile environment and the flood threat, we would like to mention the *Hurricane Camille Project Report* (Roger A. Pielke et al., 1999) and by Joel K. Bourne *Gone with the Water* (2004).

The Pielke Report "*Thirty Years after Hurricane Camille, Lessons Learned, Lesson Lost*" emphasises that future hurricanes of the strength of Camille would be much more devastating, for since then both the number of people living in the coastal areas and the economic wealth of the region have increased. The Report stressed that an improved forecasting system and emergency management would be required to compensate for the much larger evacuation time needed to evacuate the larger number of people living these areas.

J.K. Bourne (Oct. 2004) had already painted the following doomsday picture of a devastating hurricane destroying New Orleans a year before Katrina actually hit the coast:

"As the whirling maelstrom approached the coast, more than a million people evacuated to a higher ground. Some 200,000 remained, however – the car-less, the homeless, the aged, the infirm, and those die-hard New Orleanians who look for any excuse to throw a party.

The storm hit Breton Sound with the fury of a nuclear warhead, pushing a deadly storm surge into Lake Pontchartrain. The water crept over the top of the massive berm that holds back the lake and then spilled over. Nearly 80 % of New Orleans lies below sea level - more than eight feet below in places – so the water poured in.... As it reached 25 feet (eight metres) over parts of the city, people climbed on the roofs to escape it....

Thousand drowned in the murky brew that soon contaminated by sewage and industrial waste. Thousands more who survived the flood later perished from dehydration and disease as they waited to be rescued. It took two months to pump the city dry, and by then Big Easy was buried under a blanket of putrid sediment, a million were homeless, and 50,000 were dead. It was the worst natural disaster in the history of the United States."

Though Bourne's scenario describing a drowned New Orleans after a possible hurricane strike came close to the actual disaster, the anticipated loss of life in 50,000 human lives, thankfully did not occur. What were the observations on which this scenario was built? First the author mentions the drastically changed coastal environment after raising the height of the levees along the river and lining its bed with concrete following the Great Flood of 1927. Consequently the marshes, prone to subsidence were starved of a supply of fresh sediments that were now carried into the Gulf. Only the Atchafalya River to which 10 percent of the Mississippi water is allowed to flow

shows some growth in parts of its delta. Under natural conditions more water would flow into the Atchafalya, but that would interfere with the harbour conditions on the Mississippi, and thus with the economy of the region Secondly the oil exploration and the ship traffic required a large network of canals (13 000 km long), pipes and roads to crisscross the marshes. This not only increased the erosion within the delta, but also allowed the saltwater intrusion into the otherwise brackish or freshwater marshes with severe consequences to wild life, fishing and wetland vegetation of bald cypresses, tupelo gum etc. The destruction of the stabilising woodland swamps, followed by the invasion of more salt tolerant species left the coast unprotected. The Mississippi River-Gulf Outlet Canal (MRGO) was considered as specially damaging for the environment. Though the canal did not fulfil the purpose for which it was built with only few freighters using it, these ships have carved deep indents into the shoreline. In forty years the canal of 150 m width had widened to 500 to 600 m in places. Thirdly the withdrawal of gas and oil has increased the subsidence rate in the wetlands and is likely to do so in future with the increased gas exploitation making the coast more vulnerable.

While the Pielke Report stressed the study of hurricane problems in constant adaptation to changes in the society by fine-tuning of emergency management, and the improvement of hurricane forecasting, Bourne emphasised the dangers of rapidly eroding, protective wetland. But both, among others, had clearly stated the warning signs of a possible hurricane disaster.

Bourne has been only one voice of many pleadings for the preservation of the wetlands in the interest of all. Since the 1980s plans have been there to replenish the marshes with sediments and reducing the salinity by allowing the Mississippi river to spill its water through sluices into the wetlands. Hundred hectares have been regenerated through the Caernavon Spill Canal since 1995 on an experimental base (Fischetti 2005, Bourne 2004).

Other observations focussed on the problems of subsidence of New Orleans (Fischetti 2005). Subsidence is a natural phenomenon in marshes, however, the subsidence rate in New Orleans has increased due to the artificial drainage of the swamps. Permitting the expansion of urban settlements has lead to a constant lowering of the groundwater level. The upper layers of the highly organic soils, which would be wet under normal conditions, dry out, get compressed and thus the rate of subsidence increases. In fact the areas with the highest density of drains and drainage canals in the city are the lowest lying areas. Using space based synthetic-aperture measurements Dixon et al. (2006) have calculated a mean subsidence rate of 6.4 mm/yr and a maximum subsidence rate of 33 mm/yr for New Orleans, the highest subsidence rate in Louisiana. High rates are found in the lowest lying areas including St. Bernhard and New Orleans Parishes to the west of Lake Borgne (20 mm/yr) and along the levee system of the Mississippi River Outlet Canal with a subsidence rate of more than a metre in the last forty years since its construction. Both the straight jacking of the Mississippi by preventing its natural flow, or occasional overflow, and the sophisticated, highly technical drainage system promoting subsidence had made New Orleans so vulnerable to the hurricane impact.

Conclusions

The natural and human catastrophe unleashed by Katrina was the result of the complex interplay of number of factors, such as:

I. Natural Factors

1. The particular weather situation, including the near absence of vertical wind shears.
2. The abnormally high surface water temperature along the Gulf Coast.
3. The presence of the Loop Current which seemed to have had some control over the track of Katrina, while its warm water temperature fuelled it to a Category 5 hurricane.
4. The shallow offshore relief of the Gulf shelf area.
5. The vulnerable delta environment with a highly irregular coastline of dissected wetlands and intruding water bodies.

II. Combined Natural and Human Factors

1. The regulation of the Mississippi river by a complete levee system.
1. The presence of large areas below sea level, especially the location of New Orleans itself, squeezed between the higher Mississippi and Lake Pontchartrain.
2. Natural subsidence and human promoted subsidence through oil and gas exploitation and draining of wetlands
3. The human transformation and exploitation of the delta, which lead to the loss of woodland swamps and the rapid shrinking of wetlands. Otherwise the wetlands could have acted as a buffer zone reducing the hurricane impact, as its strength is rapidly lost over land.
4. The levee and dyke system not designed to withstand such rare hurricane force. Faults in the foundations of the levees, absence of floodgates, which could have prevented the flooding of Lake Pontchartrain into the outlet canals and thus the town.
5. The negative impact of Mississippi River Gulf Outlet Canal.
6. The shortcomings of a never experienced evacuation of such a large population in such a short time, especially the evacuation of large section of sick, invalid or deprived people with no means of transport.

As shown above a large number of factors have contributed to the natural disaster and human tragedy, resulting in the loss of wetlands (equalling 20 years of normal erosion) and protecting barrier islands, in the great loss of life, displacement of a large number of people, in the enormous loss of property and infrastructure, in the temporary shutdown of oil exploitation with global repercussions etc. The study of the impact of Katrina on New Orleans, the Louisiana, Mississippi and Alabama Coast may be by itself rewarding. However, India too is a country frequently visited by cyclones with shrinking or unprotected coastal wetlands, coastal inlets, and vulnerable delta environments on one side and an ever-increasing coastal population and consequently great problems of disaster management on the other. It might be worthwhile to consider some of the experiences learnt after Katrina with reference to the Indian context.

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