Feature

The flooding of New Orleans

With its man-made defences, New Orleans is at best only a marginally stable city, and it was destined to suffer as more powerful natural processes evolved. The aftermath of the August 2005 hurricane was the disaster that had been waiting to happen.

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The delta of a major river is an active geological environment where ground subsidence is an inevitable process. Unfortunately a river mouth is also an attractive location for a city, but any such urban development is therefore fraught with more than its share of geohazards. Add to these the consequences of the weather in the planet's major hurricane belt, and New Orleans could be seen as a classic case of unsustainable development; its flooding was almost inevitable (Fig. 1).

The Mississippi delta

Carrying drainage from nearly half the USA, the Mississippi ends in the classic example of a bird's foot delta. The great river has built out a succession of massive lobes of sand and silt at the ends of distributory channels that develop anew when they slip sideways off the previous lobe of sediment. This all happens on almost imperceptible gradients, and the end result is the huge deltaic plain on which stands southern Louisiana. Sands and silts form the bulk of the great fluvial lobes and deltaic fans.

The surface of the deltaic plain is a complex mixture of channels and inter-distributory backwater swamps. Along the channels, natural levees are formed on the river banks by sediment deposition when floodwaters overflow and lose velocity as they leave the main channel, and point bars are formed inside migrating meanders; both are mainly sand and silt. But the only sediment input to the wetlands away from the channels is fine clay, and this is overwhelmed by plant growth in the swamps and marshes. The result is peat that is generally 80 per cent organic material, and may be many metres thick.

Fig. 1. Flooded northern suburbs of New Orleans two days after the 17th Street canal levee failed. (Photo by Sipa Press, Rex Features)

Within the last 500 years, the Mississippi has built seven major deltaic lobes (Fig. 2). Crucial among these was the St Bernard lobe, active 2800–1000 years ago; this reached to the east and virtually created the basin behind it that now holds Lake Pontchartrain, a huge brackish pond whose surface normally stands less than 300 mm above sea level.

New Orleans, the city

The settlement of New Orleans was established by the French in 1718 on the narrow strip of high ground

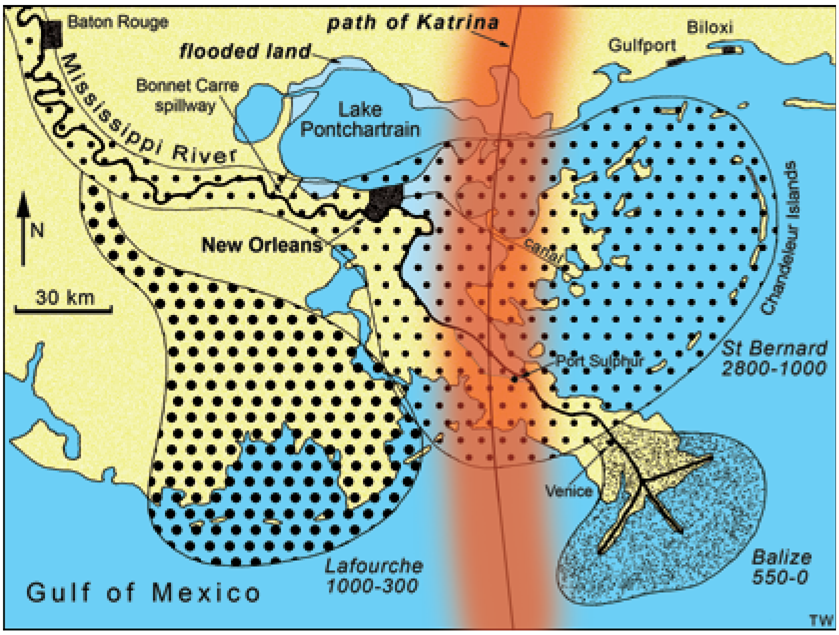

Fig. 2. Features of the Mississippi delta, including just three of the major Holocene lobes with the dates of their activity (in years before present); Katrina's path is shown by the route of its eye; the area of Katrina's flooding is generalised, and is not defined on the outer delta.

on the natural levee along the Mississippi bank where it was closest to Lake Pontchartrain. This was the ideal site, on the river transport artery to the interior, but also with access to the sea via the lake that was easier than the long river channel through the delta.

The original town stood entirely on the natural levee, which was little more than 500 m wide along the left (north) bank of the Mississippi, and the crest of this high ground stood less than 4 m above sea level. It is now known as the French Quarter, although it was rebuilt by the Spanish after a great fire in 1788, before becoming part of the United States in the Louisiana Purchase of 1803. Away from the river, the back side of the natural levee sloped very gently down until it merged into the rather unhealthy swamps. Only around 1900 did the introduction of large pumps make drainage of this wetland possible; water was pumped up into canals, which were built with banks high enough that they could drain freely into Lake Pontchartrain. By 1920 the newly drained land was ready for houses and commercial buildings; by 1950, all the adjacent swamps had been reclaimed to create today's city site.

More than half the city now stands on ground that was once wetland, but now forms drained basins encircled by artificial levees. Within these basins, buildings have to be founded on piles through the soft peat soils and into the clay and sand below. The now-infamous Superdome stands on 2266 concrete piles (each square in section with sides of 410 mm) driven 50 m deep to reach stable Pleistocene sands. The natural levees offer the benefit of stronger sandy soils, besides being higher than most potential floods.

Levees and flood walls

Natural levees are not enough to protect a city site from flooding. They are features of the river system that are inherently over-topped by the highest floods, when excess water is dumped onto the flood plain. A city on the levees and the flood plain would be flooded many times if left in its natural state. So higher artificial levees are built, both on top of and beside the natural levees, in order to protect cities.

By 1727 a bulwark a metre high stretched more than a kilometre along the New Orleans waterfront, on top of the natural levee. It was the start of a system of flood defences that grew apace with the expansion of the city. Much of the current levee system was built in the 1940s and 1950s, and the shipping canal flood walls were completed in the mid-1960s. After Hurricane Betsy caused major flooding in Louisiana in 1965, the US Congress made a historic decision to appropriate federal funds to build a system of levees to protect the city from a similar storm in the future. Overall project completion was scheduled for 2015, and has a total of nearly 2000 km of built levees and walls.

Fig. 3. A typical artificial levee along the Mississippi, with concrete erosion protection on the river face of the silt bank.

A levee is made of clay and silt to create a massive bank with a low profile (commonly with its base ten times as wide as its height). An artificial levee is therefore fairly similar to a natural levee, except that some are built with a facing of armour stone or concrete to prevent erosion on exposed aspects (Fig. 3). The name is the French word for elevated, so it is correctly pronounced as *levay*, though it is often said as *levy* to rhyme with *chevy* in Don McLean's 'American Pie'. As an alternative, a floodwall is built of concrete about 700 mm thick generally where space is insufficient for a levee's broad base, or atop a levee to increase its height. Some floodwalls include gates that can open for access during low water, but can be closed onto rubber seals when a flood is predicted (Fig. 4).

Fig. 4. Floodwall on top of the Mississippi levee in central New Orleans, with its gate open to allow access to a car park that is not used in flood times.

Today, the core of New Orleans rests within a

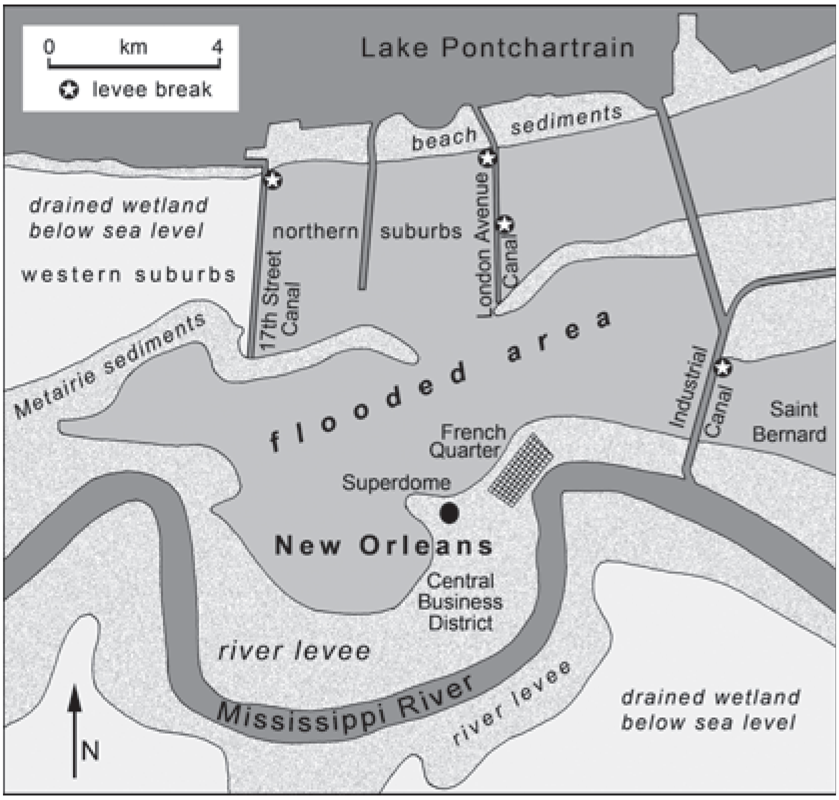

Fig. 5. Flooding in New Orleans, August 2005 (the map covers the main urban area); ground on the natural Mississippi levees, the old Pontchartrain beaches and the Metairie sediments lies above sea level and largely stayed dry, as did the low areas west and south of the town that were protected by unbroken levees; flood walls add height to the natural features along all river and lake frontages and along the canals.

bowl ringed by levees and floodwalls (Figs 5 & 6). It is inextricably sandwiched between the threat of rainwater flooding from the Mississippi River and the threat of seawater surges from Lake Pontchartrain.

The Mississippi River is controlled by its own massive system of levees that reach upstream for nearly 1000 km. It also has various protected outlet spillways into which floodwater can be diverted by simply opening massive sets of sluice gates. These are mainly west of the main channel and well upstream of New Orleans, but include the short Bonnet Carre spillway that can release river water into Lake Pontchartrain before it threatens New Orleans (Fig. 2). Through the city, the artificial Mississippi levees are built on top of the river's natural levees, and are themselves topped by floodwalls (Fig. 4). They crest unbroken at a height of 7.6 m above normal river level. Much of the height was added after the disastrous 1927 river flood, and work on them has, for the moment, been completed. They proved adequate when the 1993 flood peaked at 5.2 m (though nearly a metre was taken off this flood peak by diverting water through the Bonnet Carre spillway), and they stood far above the flood levels generated by Hurricane Katrina.

The Lake Pontchartrain levees stand on top of the raised strip of land formed partly by shell deposits of old beaches. These levees were designed to withstand a storm surge of 3.5 m plus a wave allowance of 300–1700 mm (lower where marshland lies between the levee and the sea; or higher when the levee is not armoured). Most now crest at around 4.3 m, and had already withstood storm surges of 2 m on the lake, but work was ongoing, with project completion only scheduled for 2010. The design of these levees was based on a Standard Project Hurricane equivalent to a fast-moving Category 3 hurricane. This is on the scale of 1 to 5, where a 3 means wind speeds up to 210 km/h creating a surge of 2.7 m to 3.7 m. Up until 2005, it had been accepted that a direct hit by a lingering storm of Category 3, or by any stronger storm of Category 4 or 5 (with storm surges of over 4.0 or 5.5 m respectively), would leave much of New Orleans under 6 m of water.

Ground subsidence

The depth of flooding – as anticipated and as happened – was greater than the height of the storm surge. This is because much of New Orleans is now below sea level due to ground subsidence that has widely reached about 2 m. When the suburbs of New Orleans were built, they were just about at sea level, and most of the subsidence has come later, as a new and artificially induced process.

The major problem with the drained lands of the Mississippi delta is that they are all subsiding – and taking New Orleans down with them. Almost every delta is an environment of subsidence, and the Mississippi ground movement is typical in that it has a host of causes, some natural and some induced by man. Subsidence rates vary enormously across the delta, from a 2 m of lowering in the last 80 years in some places, to an order of magnitude less. Unfortunately, the maximum ground lowering is across the northern and eastern suburbs of New Orleans, and this is largely due to peat subsidence.

Peat is extremely unstable organic soil, with negligible strength unless significantly compressed. It forms in low lying marsh and swamp where vegetation grows in or falls into semi-stagnant water so that it is prevented from oxidizing (and hence disappearing as a suite of gases). Between the distributory river levees and channels, the Mississippi delta top wetlands are an ideal peat environment. In some areas, peat has accumulated to depths of tens of metres within the last 3000 years, and is around 5 m thick under much of New Orleans away from the silt

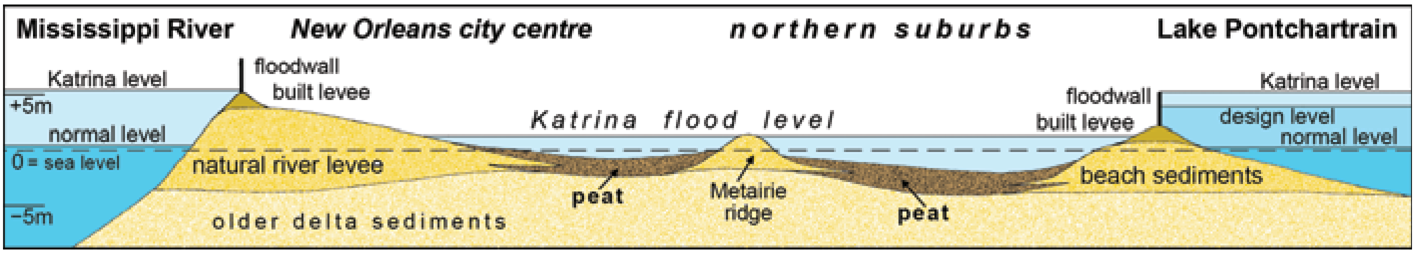

Fig. 6. Relative levels of land and water on a diagrammatic profile through New Orleans; the areas of peat have subsided from their original wetland that was little above sea level.

levees.

There are three processes behind ground subsidence on peat:

1. Consolidation due to loss of water, when the peat loses volume in response to the loss of support offered by internal water pressure;
2. Compaction under load, both self-loading and imposed by other sediments or built structures, when the highly porous peat restructures into a denser material; and
3. Wastage on exposure to air, when the peat simply oxidises and disappears where loss of water leaves it above the water table.

The first and third processes are dominant, and both are largely created by artificial drainage of the land. Swamp peat loses 40–70 per cent of its volume as it dries out, and will eventually lose even more while it is left above the water table. All the volume loss takes place in the top few metres of the peat, while compressed and saturated material at greater depth is relatively stable; there is also less movement where silt is mixed into a peaty soil.

Peat subsidence is the story across the old wetlands of New Orleans, which have been progressively drained since the 1920s. Each phase of drainage induces a phase of consolidation and wastage. This therefore lowers the ground surface towards the new water table - and thus requires a new phase of drainage to keep it habitable; and this induces a new phase of subsidence (Fig. 7). And so it goes on, until all the peat has gone. Many zones of the New Orleans suburbs were on peat 5 m thick, and subsidence has already reached 2 m. Currently, most ground is subsiding by less than 10 mm/year, but this will accelerate if renewed drainage further desiccates the peat. Parts of the city will probably subside by another metre within the next 75 years. Except for structures built on piles that reach stable ground below the peat, everything subsides, and this includes some parts of the interior levees that had subsided by a metre even before Hurricane Katrina struck. Much of New Orleans already lies in a deep bowl below sea level (Fig. 6), and its subsidence can only be halted by keeping the peat ground saturated – clearly impossible in a normal city.

There are other causes of ground subsidence in the Mississippi delta that are natural and unstoppable. Compaction of the clastic sediments, notably the clays, is normal in an active delta, but this is occurring mainly around the front of the Lafourche lobe that formed from 1000 to 300 years ago; subsidence there is over 20 mm/year, though it

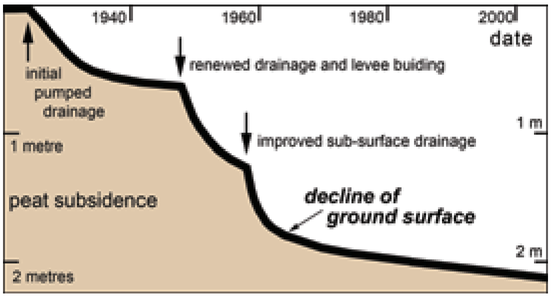

Fig. 7. Successive phases of subsidence in a western suburb of New Orleans that was built on the old peat wetlands. (After Snowden, 1986.)

is well away from the city. However, the loss of the coastal marshlands (also due to rising sea levels) reduces the buffer that they offer to inbound hurricanes (which lose their power over land) and thereby increases the future hurricane hazard for New Orleans. New survey data shows that there is almost no crustal sag (tectonic warping) under the increasing load of the delta sediments, but there is active faulting that increases subsidence in some areas, well away from the city. Subsidence due to

Fig. 8. Massive wind damage in Gulfport. (Photo by FEMA)

hydrocarbon extraction is another artificially induced process that is very significant in some areas, but not around New Orleans.

Hurricane Katrina

On Sunday 28 August 2005, one of the most powerful hurricanes ever seen swirled northwards across the Gulf of Mexico towards New Orleans. Fed by unusually warm sea waters, Katrina grew to a Category 5, with wind speeds of over 250 km/h. Its central barometric pressure of 902 millibars made it the fourth most powerful hurricane on record. Furthermore, Katrina was moving at only about 20 km/h, giving it time to build up a massive storm surge as it approached the coast.

By sheer good fortune, a stream of dry air from the American land mass weakened the storm a little before hitting land early on Monday, and also pushed it slightly to the east. Katrina therefore reduced to a Category 4 hurricane, and its eye passed just east of New Orleans (Fig. 2) at dawn on Monday 30 August. Small towns on the outer delta were the first to be wrecked by wind and water. Then the storm waves eroded away half the area of the Chandeleur barrier islands, which also lost their lighthouse when it was undermined by the sea.

Along the coast east of the delta, the anti-clockwise winds that distinguish a hurricane were onshore and unabated. Sustained wind speeds of well over 200 km/h caused massive damage in the towns of Biloxi and Gulfport (Fig. 8), and a coastal storm surge 6 m high further devastated shoreline structures. Wooden houses were totally wrecked, and many concrete buildings had their ground floors washed out between surviving columns that supported the upper floors. Destruction in the two cities reached about 90 per cent. But on the other side of the storm, there was almost no wind damage to thousands of houses in New Orleans – which were subsequently flooded to their eaves.

The storm surge then swept from the open sea into Lake Ponchartrian, causing it to overflow onto much of its hinterland (Fig. 2). The water piled up against the levees on the northern side of New Orleans, also driven by winds that were here from the north. In the open sea, the surge had peaked at 8.5 m, but reduced to a maximum of 6.7 m on the coastline. The time lag to fill the lake meant that the surge was further reduced to about 5.2 m against New Orleans' northern levees.

This peak just overtopped some of the levees – and caused the disastrous flooding. Even while water was pouring into the city, the surge fell back. But the damage was already done.

Fig. 9. Floodwater pouring through the broken levee beside the Industrial Canal. (Photo by FEMA)

Broken levees and massive floods

The outer delta suffered the first flooding before dawn on Monday 29th August, when levees around the small delta towns were soon over-topped. Venice was totally flooded, timber houses in Port Sulphur were swept on top of cars, and land east of the Mississippi was largely reclaimed by the river. Then at 11 a.m., a levee broke alongside the Industrial Canal on New Orleans' eastern edge, even though it was nominally 4 m high (Fig. 9). These early failures were probably initiated by underseepage through the levee silt, which reached such a scale that silt was washed out to create cavities in the levee; these then grew larger, until the structure collapsed. This is a classic piping failure, which is how most levee collapses develop. As a result, the St Bernard district was described as having 'gone'.

Worse was to come, when the levee failed alongside the 17th Street Canal at 1.30 a.m. on the Tuesday, and this was soon followed by a failure on the London Avenue Canal just to the east (Fig. 5). Both these failures were on canals that were designed to let water, pumped up out of the city's ground, flow away into Lake Pontchartrain; but they now let the lake water flow into the city. The massive inflow only ceased 36 hours later when the level of water in the city equalled that in the lake, where the surge was already declining.

The catastrophic failure at the 17th Street Canal occurred when the storm surge over-topped a slightly lower section of the concrete floodwall on top of the levee. Water cascading over the wall easily undermined its base by scouring away the silt on which it stood. The wall then collapsed outwards as the 8 m long concrete slabs slumped out of line to leave a breach nearly 200 m wide (Fig. 10). This allowed the water of Lake Pontchartrain to flow downward into northern New Orleans, which lies between 1 and 3 m below sea level, until it stabilized at 2 m above sea level.

By then, 80 per cent of the city was inundated. The flood zone stretched north to south between the high ground of the Pontchartrain beach ridges and the natural levee of the Mississippi River. Towards the south-west, flooding was constrained by the low natural levee of the abandoned Metairie distributory channel (Fig. 5). Beyond the western suburbs, a large area outside the levees was under water. There was more flooding to the east from the Industrial Canal breach, and four out of the city's thirteen levee zones were eventually flooded.

Attempts to plug the levee breaches failed while water was still pouring through; sandbags weighing 1.3 tonnes were just washed away. A few days later, the mouth of the 17th Street Canal was plugged at the lakeshore, but water flow had then ceased. The London Avenue levee break was left open so that water could drain out of the city into the lake whose level was continuing to fall. And two levees further south were intentionally breached to let floodwaters drain out. This was only short-term to take the top off the flood, because most of the flooded city lies below sea level.

Consequently, the bulk of the floodwater was only removed by massive pumping operations that lifted it over the intact levees. The permanent pumps that had been inundated by the floods were returned to service, and were augmented by many temporary pumps on the levees. Estimates of how long it would take to pump the city dry fell repeatedly as more machinery was brought into use; water levels were down by over a metre within 10 days of Katrina's intervention. Predictions of 90 days declined to 40 days, suggested a dry city by mid-October. But the problems did not end there, as the legacy of contamination and rotted timber was due to last far longer.

In retrospect, New Orleans had been lucky. A hurricane just slightly stronger or tracking just a little further east would have created even higher flood levels, across even larger areas, after the inevitable levee breaks. It was known that the levees could only withstand a hurricane of Category 3; that's why a total evacuation of the city had been ordered while Katrina was approaching from the sea – when a considerable scale of flooding became inevitable.

Fig. 10. Vertical air photograph of the 17th Street Canal, with its failed eastern levee (on the right) releasing the major flood flow into the city; at the top of the picture floating debris is trapped behind the bridge over the inflow from Lake Pontchartrain, while the urban area west of the canal remains dry. (Photo by NOAA)

Aftermath

The main story after the flood was the fate of the many thousands of people trapped in the city by the rising waters. Most of these had been too poor to have their own cars, which in true American style had been the key element to the Sunday evacuation. About 25 000 of them had gone to the Superdome football stadium, which stood on high ground almost surrounded by floodwater. But there they stayed, without food, water, services or support. It was five days later, on the Friday, before a relief convoy of trucks rolled into town (even though there had been plenty of press and camera crews in and out of New Orleans from the Tuesday onwards). The total chaos was down to bureaucratic incompetence, notably the conflict and lack of cooperation between federal, state and local agencies; there were clear signs of the modern civic culture of 'let someone else do it, so I cannot be blamed'. It was not helped by the Federal Emergency Management Agency having been subsumed into the Department of Homeland Security, where its number one concern was terrorism.

Around 1000 people lost their lives in Hurricane Katrina. And many tens of thousands of people had lost their homes and all or most of their possessions. The floodwater is only temporary, but its effects last longer. Environmental contamination was massive. A week after the hurricane, all sewage was flowing untreated into the Mississippi River. Compulsory evacuation of the many people who had elected to

Fig. 11. New Orleans 2005 - a consequence of urban development on a subsided flood plain. (Photo by US Navy)

stay in their partially flooded homes was enforced because of the health hazard in a city with little working infrastructure. But a week after that, the Mayor was encouraging residents to return home to start the clean-up – though other officials then challenged the wisdom of that.

Besides the sewage, there was major pollution from leaking oil and chemicals facilities. These posed toxic and chemical threats not only to people's homes and the whole urban environment, but also to the Gulf of Mexico, its entire wildlife and its inshore fisheries. It is likely that most of the chemical and biological contaminants will disperse naturally over a period of months, although persistent pollutants may remain for several years, especially on textiles such as carpets and seating that readily absorb them. Complete decontamination will be a massive task, in which waste disposal will present major logistical problems that will determine the pace of redevelopment.

There is also massive structural damage. Most of the suburban houses are built wholly or largely of timber, which rots very quickly in unplanned floodwater. Houses that have been submerged for much more than a week are likely to require demolition, and entire neighbourhoods are going to be razed to the ground (Fig. 11). Federal agencies estimate that rebuilding can not start until the summer of 2006, but there the key question remains of how much to rebuild in a terrain proven to be flood-prone.

There was initial debate over the entire future of New Orleans. Some claimed that the site is unviable, and that federal funds should not go to a wasteful rebuild (at a cost currently estimated as $200bn). On the other hand, mankind has a track record of rebuilding cities that have been all but destroyed by natural events; San Francisco, Lisbon and Tokyo come to mind. New Orleans is a major commercial and industrial centre, is one of America's largest ports, lies at the heart of the country's petrochemical industry, and has huge cultural value. Calls that the site should be abandoned soon faded. The city centre stands high and dry on the natural Mississippi levees (Fig. 5), but it makes sense that some of the lowest of the northern suburban areas, in the deepest and most active subsidence bowls could be returned to wetland.

On top of rebuilding costs, New Orleans is going to need higher and higher levees. Its subsidence is ongoing, and storm surges are going to rise in ever-larger hurricanes that will be generated over warmer waters in a warmer world. In practical terms, neither the subsidence nor the hurricanes can be stopped. Higher levees that will protect the city from a storm of Category 4 or 5 will probably take 30 years to complete; statistically, much of the city will be flooded by another hurricane before they are finished. An early foretaste came less than a month later, when a smaller storm surge created by Hurricane Rita broke the Industrial Canal levee again, and re-flooded the eastern district of New Orleans that had just been drained of its Katrina floodwater.

A novel concept, introduced by the professor of geology at Louisiana State University, is to eliminate or at least diminish the flood threat from Lake Pontchartrain. By diverting the Mississippi through the Bonnet Carre spillway and into the lake, the river's huge sediment load could build a new delta lobe that could fill the lake along the north shore of the city. Bold engineering, but it may compare well with the available short-term remedies.

That New Orleans will be rebuilt, albeit with a rather different pattern of suburbs, is certain. What is uncertain is how long it will be before it is flooded again – on ground that has subsided further, and by more massive storms (on top of higher sea-levels) that result from a warming planet.

Suggestions for further reading

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