Cause, Assessment & Management of Flood Hazards associated with Landfalling Tropical Cyclones & Heavy Rain

by

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Part 2

Case Assessment of the Failure of ‘New Orleans Flood Protection System’ from Hurricane Katrina -

Outlines

Part 2 – Case Assessment of the Failure of 'New Orleans Flood Protection System' from Hurricane Katrina

- New Orleans Area
- Hurricane Katrina
- Hurricane Protection System
- Failure of Hurricane Protection System
- Direct Physical Causes of the Catastrophe
- Contributing Factors

Acknowledgement

The material presented in this presentation is based primarily on the following report

THE NEW ORLEANS

HURRICANE PROTECTION SYSTEM:

What Went Wrong and Why

American Society of Civil Engineers (ASCE)

Hurricane Katrina External Review Panel, 2007

New Orleans Area

A city built on the east bank of Mississippi with swamps, marshes & bayous flanking to the N&E

New Orleans in 1849

An 1849 map shows New Orleans built adjacent to the Mississippi River, with marshlands and bayous to the north.

Development on the Marshes

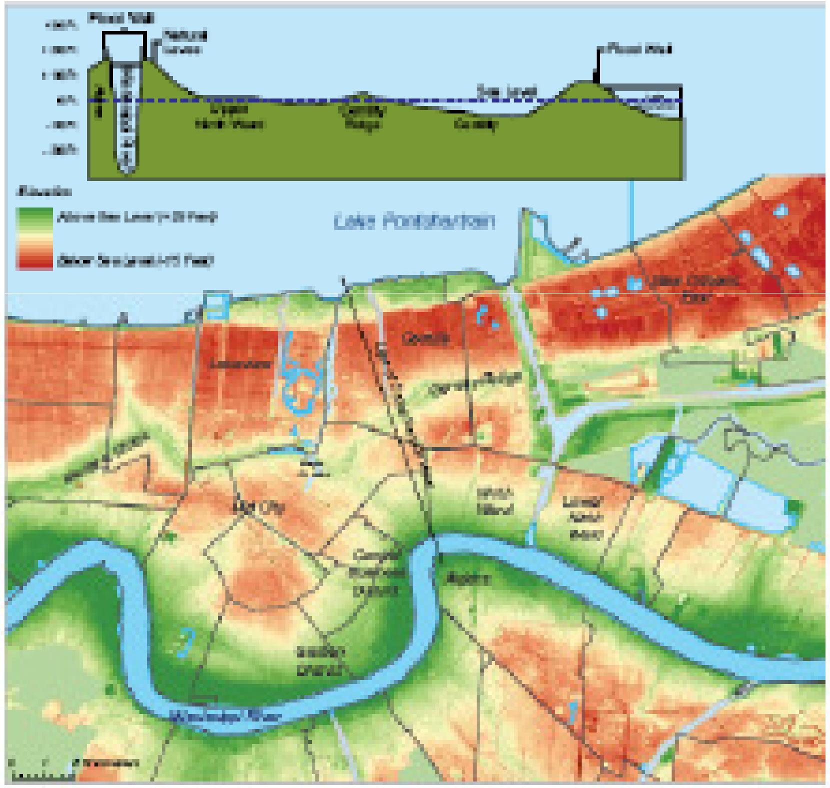
- Levees & floodwalls were built on the banks of several former bayous from N to S
- Key waterways are shown in the map

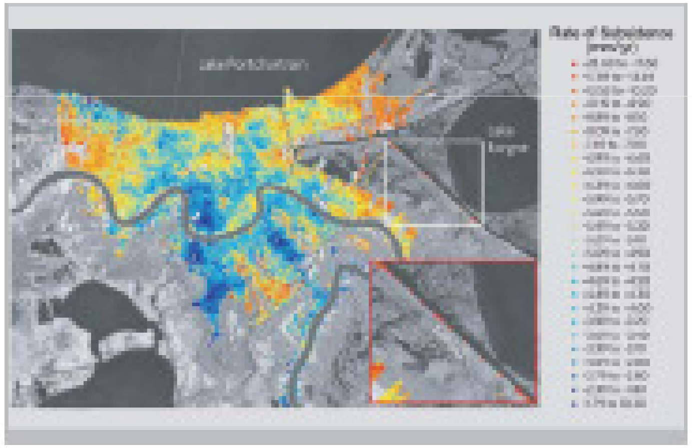
The New Orleans Waterways

New Orleans is surrounded by – and inter-fingered with – water: lakes, rivers, bayous, and canals.

New Orleans Topography/Subsidence

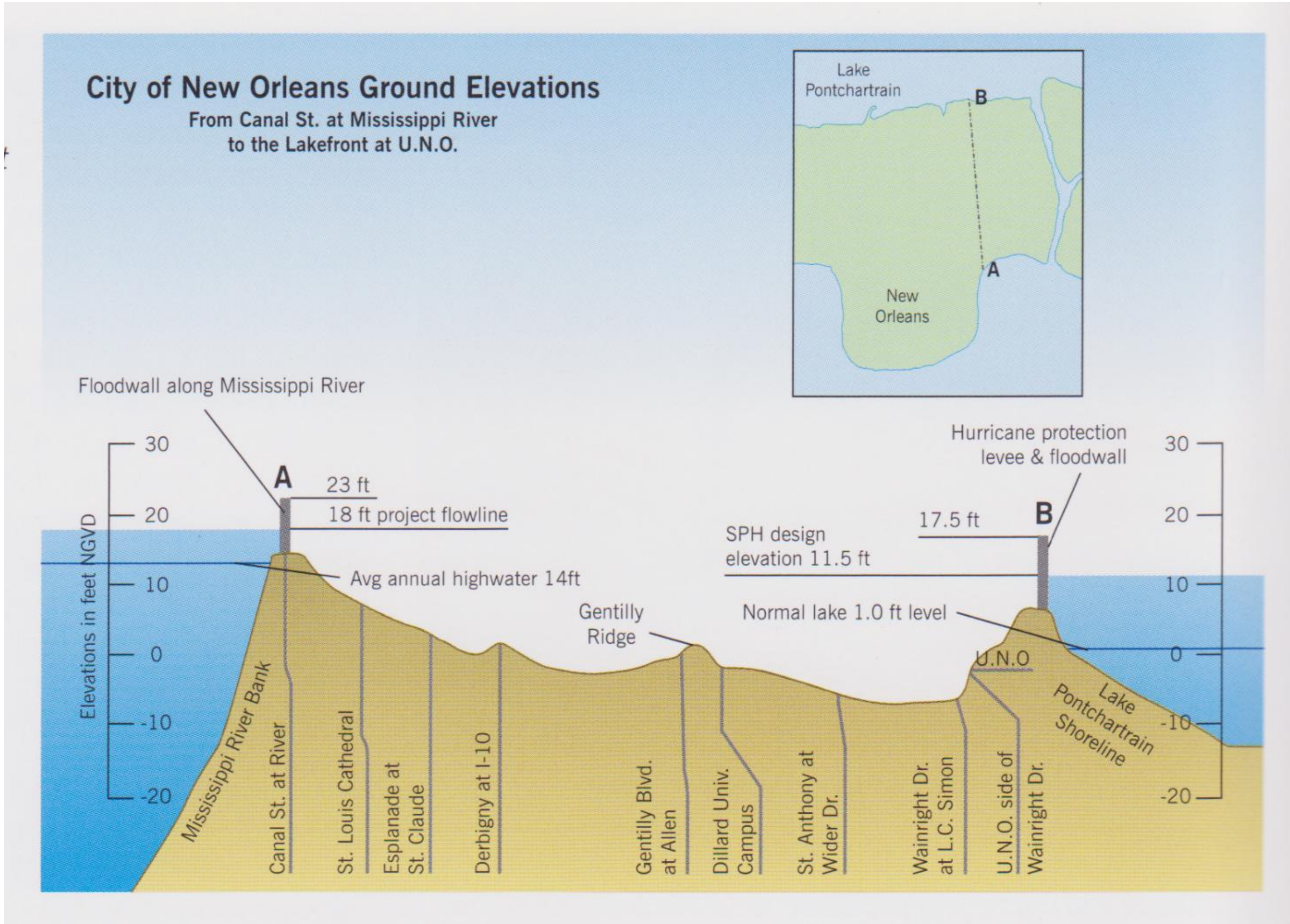
(after Grossi and Muir Wood, 2006, RMS Report)



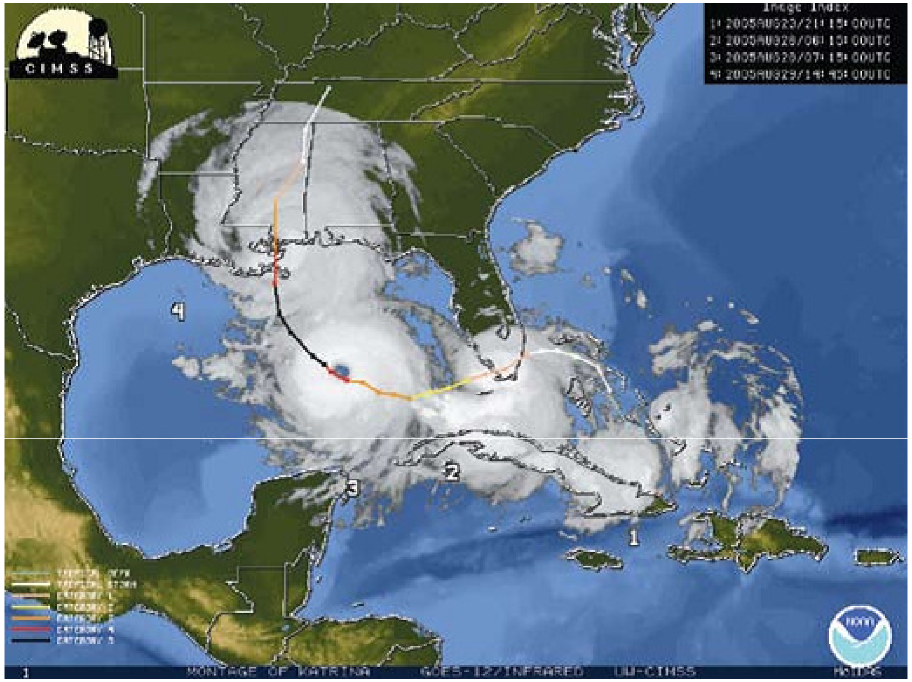


some areas > ~1 in/yr

City below River & Lake Levels



Hurricane Katrina- Category 3 at Landfall



Major Hurricanes to Have Crossed Southeast Louisiana or Vicinity (1851-2004)

HURRICANE	YEAR	CATEGORY AT FIRST LANDFALL	CENTRAL PRESSURE AT FIRST LANDFALL (millibars)
CAMILLE	1969	5	909
KATRINA	2005	3	920
ANDREW	1992	5*	922
LA (NEW ORLEANS)	1915	4	931
LA (LAST ISLAND)	1856	4	934
SE FL/SE LA/MS	1947	4	940
AUDREY	1957	4	945
LA (CHENIER CAMINANDA)	1893	3	948
BETSY (SE FL/SE LA)	1965	3	948
LA/MS	1855	3	950
LA/MS/AL	1860	3	950
LA	1879	3	950
LA (GRAND ISLE)	1909	3	952

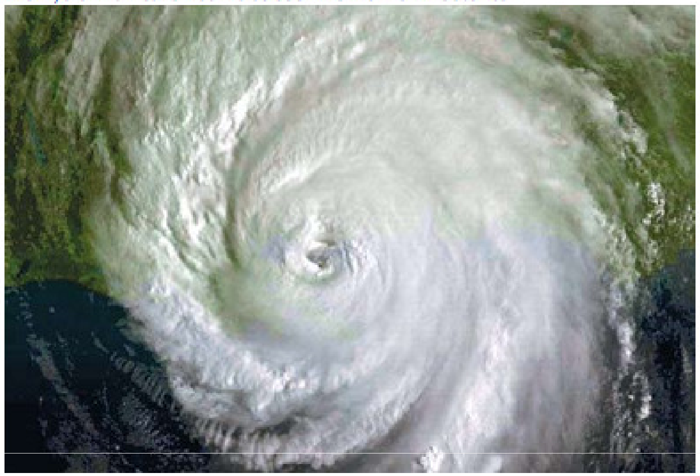
Source: National Oceanic and Atmospheric Administration (NOAA) Technical

The Saffir-Simpson Hurricane Scale

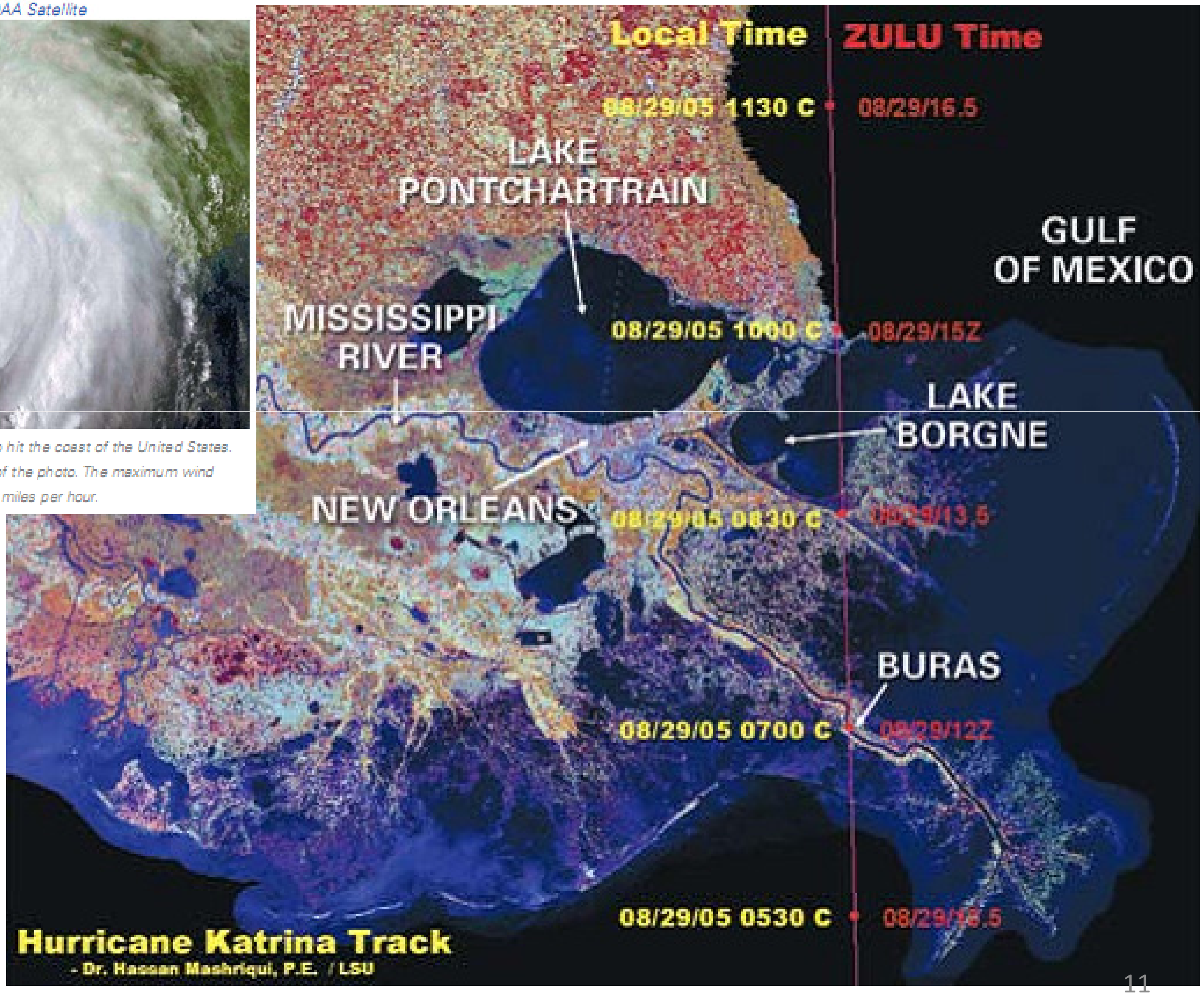
CATEGORY	WIND SPEED (mph)	TYPICAL STORM WATER SURGE (ft)
1	74 - 95	4 - 5
2	96 - 110	6 - 8
3	111 - 130	9 - 12
4	131 - 155	13 - 18
5	> 155	> 18

Hurricane Path through New Orleans

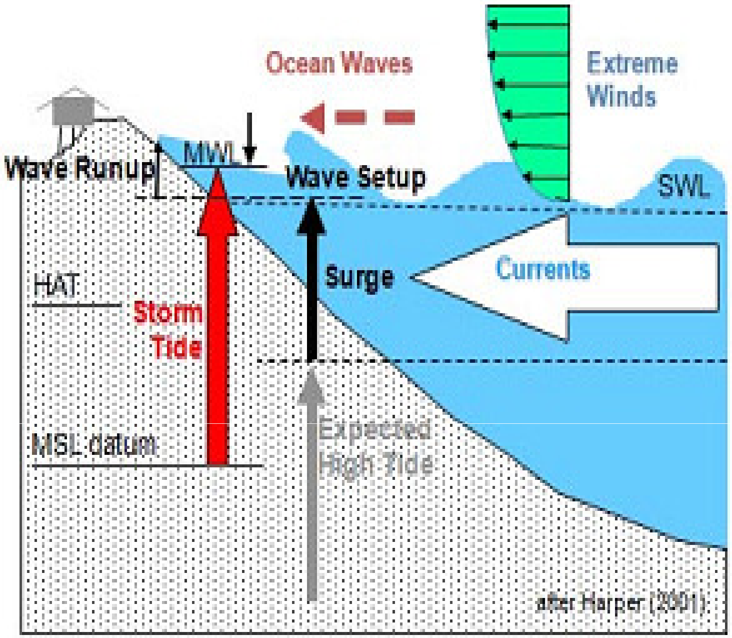
The Eye of Hurricane Katrina as seen from a NOAA Satellite



Hurricane Katrina was one of the strongest storms to hit the coast of the United States. The eye of Hurricane Katrina is shown in the center of the photo. The maximum wind speeds estimated during Hurricane Katrina were 160 miles per hour.



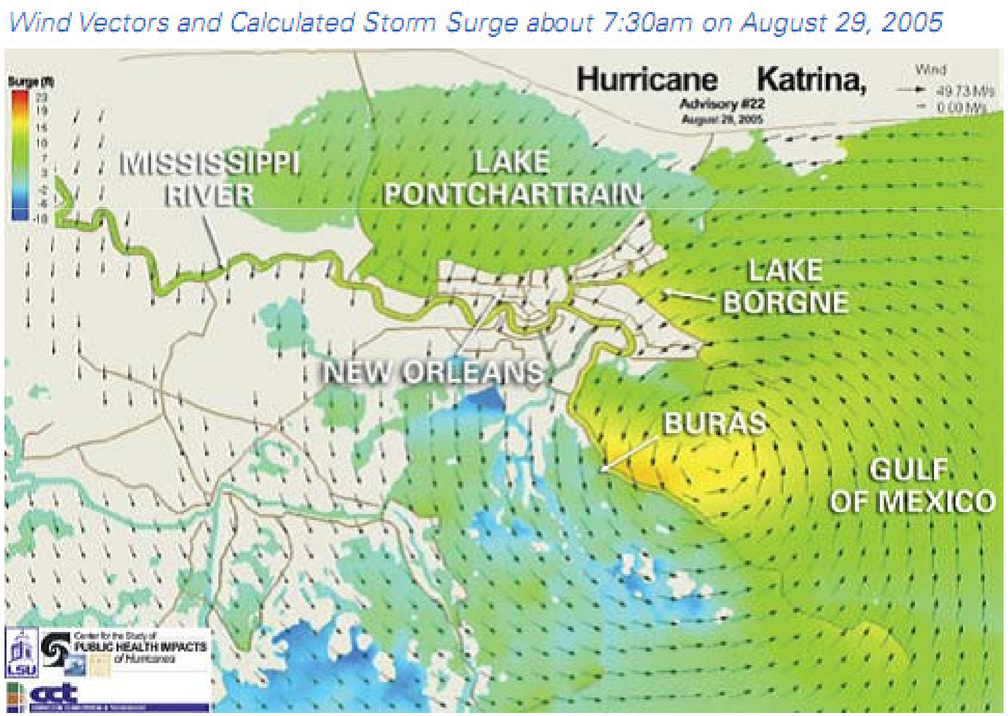
Wind, Surge, and Waves



- Wind-generated waves superimposed on surges
- Central pressure 902 mili-bars or 27 inch of Hg- 3" below atmospheric pressure (causes water level to rise 3 ft above normal)
- Max. wind speed of 160 mph
- Offshore Wave Ht of 100-ft in Gulf of Mexico
- Worst timing that storm surge occurs at high tide

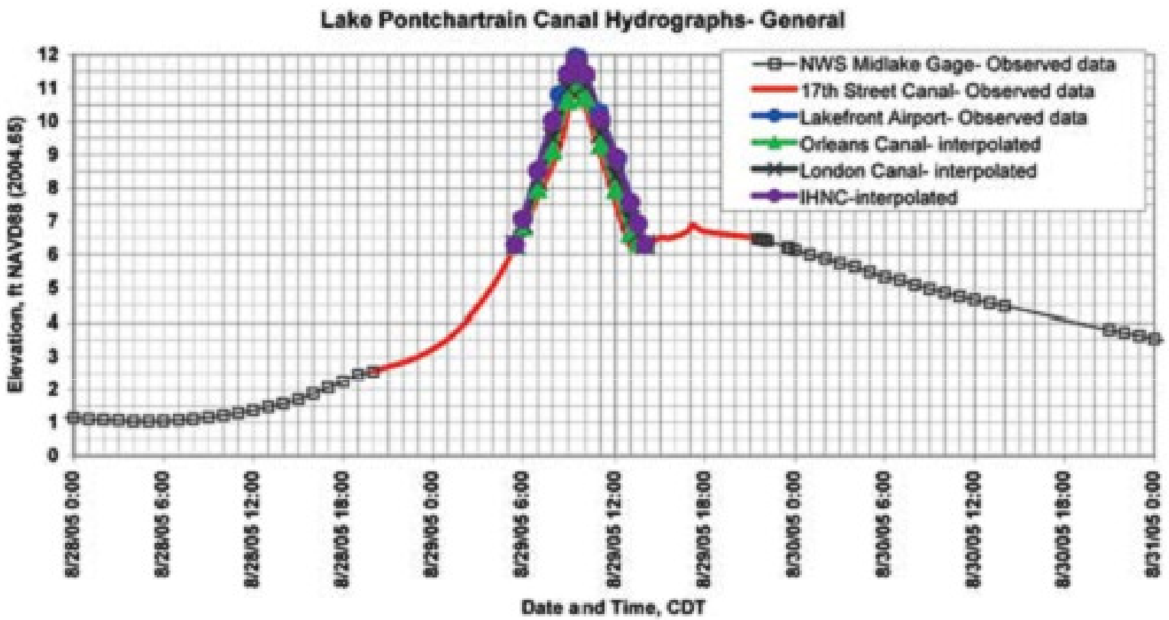
Wind, Surge, and Waves

- Katrina made landfall at Buras, La., at 6:10 am, Aug 29, 2005 with wind speed of 127 mph (Category 3) counter-clockwise rotation
- **Before landfall** at **Category 5** (160 mph)
- Central pressure = 920 mb (3rd lowest in US record)
- Peak water level = 20 ft MSL at S ends, and 12 ft MSL at N ends



Storm surges at canal entrances to Lake Pontchartrain

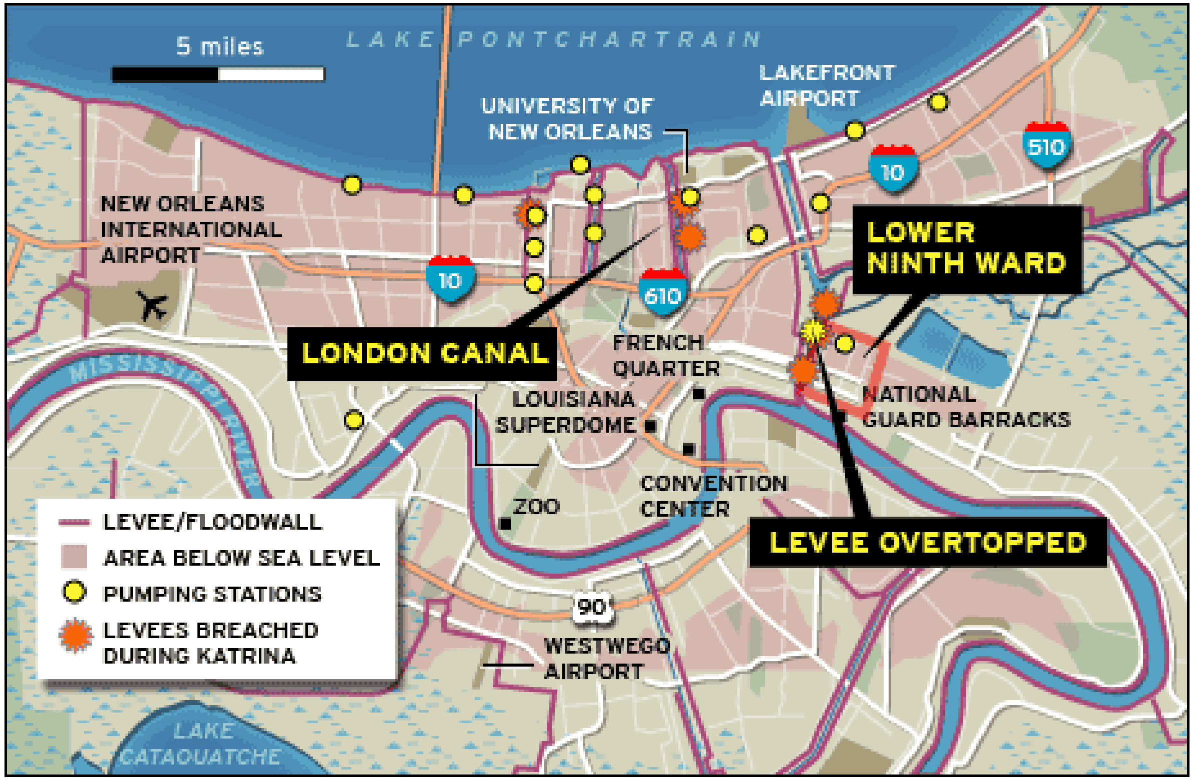
Hydrograph for the Canal Entrances at Lake Pontchartrain



On the lakeshore of New Orleans, water levels from the storm surge built up to a peak at 9:30am By 10:00am, the eye of the hurricane had passed slightly to the northeast of New Orleans, and the water levels began to fall.

In addition to surges, 13.6 inches of rain fell in some area over 24 hrs. The 100-yr rain (24-hr) in New Orleans is 12.6 inches

Hurricane Protection System



SOURCE: U.S. Army Task Force Hope MSNBC

- Levees & flood walls were built by USACE and others
- Interior drainage & pumping stations are by others
- All O&M are by local agencies & levee boards

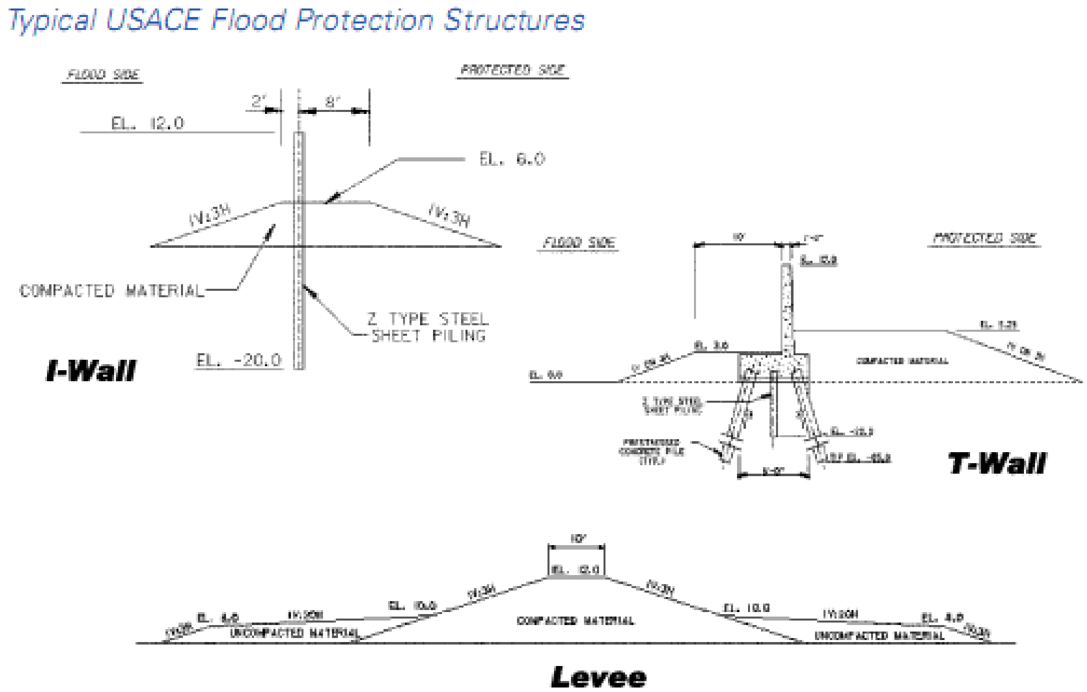
Hurricane Protection System

Standard Project Hurricane (SPH)

“ the most severe combination of meteorological conditions that are considered ‘reasonably characteristic ‘of the region”, comprising :

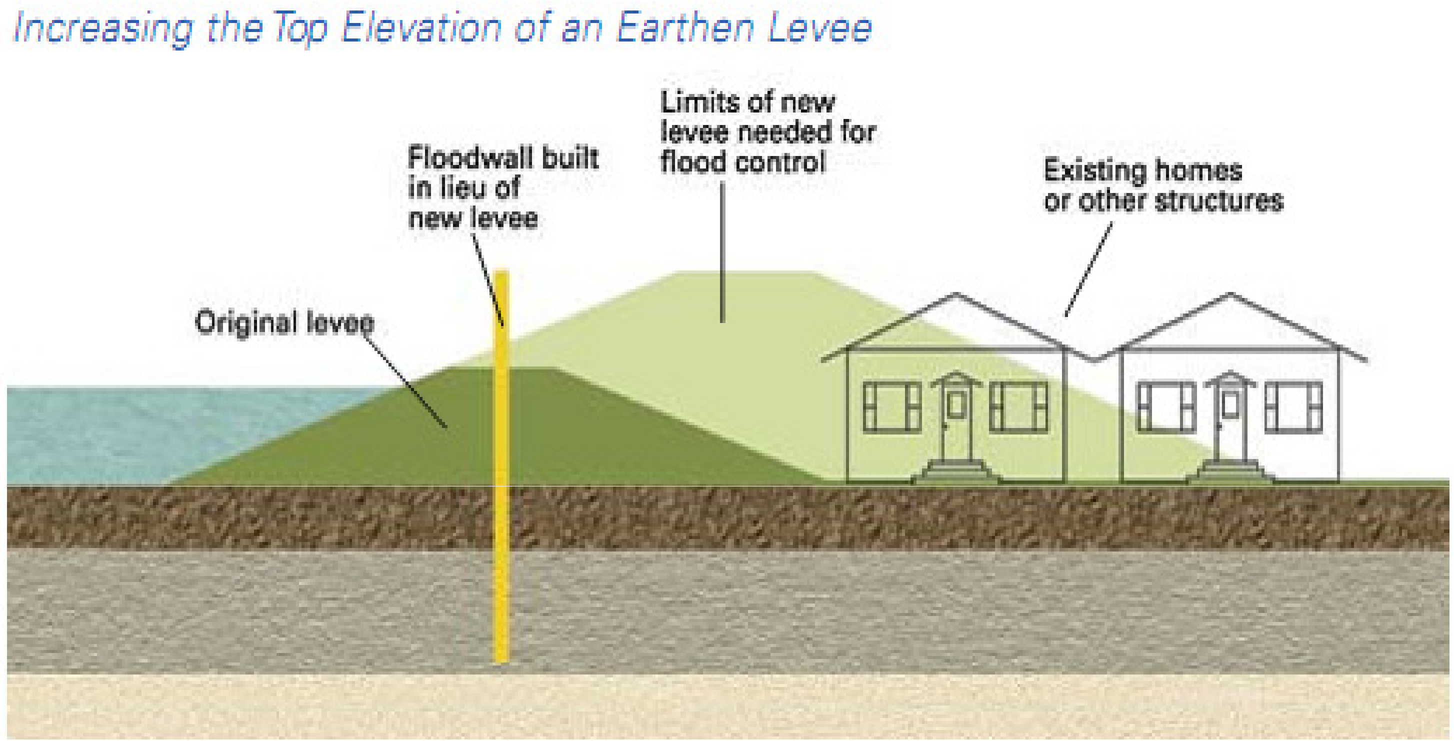
- 1 value of Central pressure index
- 3 values of forward speeds & radius of max winds
- 1 value of gradient wind speed
- 2 values of surface wind speed

Typical Flood Protection Structures- Levees & Floodwalls



- Height of levees & walls **varied** throughout the protection system
- In some places, **hydraulic fill** was used instead of compacted material to construct levees

Raising of Levee Height



- Where existing levee was located adjacent to buildings, canals, or other structures, the USACE often resorted to **using I-walls** to raise the elevation of levee protection
- In certain segments, **T-walls** were constructed.

Datums & Elevations

Several sources of **design/construction errors** :

- Structures were constructed w.r.t. land-based geodetic datum, which was incorrectly assumed as being equivalent to water-level datum (or MSL). This resulted in structures built 1-2 ft below intended elev.
- Segments of levees were not raised to the authorized protection levels due to delay in funding or construction.
- Fallen structural top elevation due to **regional subsidence**. The 'Industrial Canal' structures, for example, are > 2 ft below intended elev. Associated with subsidence over the 35-yr project life.

Interior Drainage & Pump Stations

- Much of New Orleans is below sea level-a series of large 'bowls' surrounded by levees.
- Interior drainage system, including pump (lift) stations, outfall pump stations, and outfall canals, are designed to dispose of rain water , but not to remove water from overtopping or breaches
- Most pump stations are designed for 10-yr, 24-hr storm, or 9 inches of rainfall
- Mixture of new and old (100-yr age) pumps. Some are diesel driven, and others are provided by electric grid with back-up diesel generators.

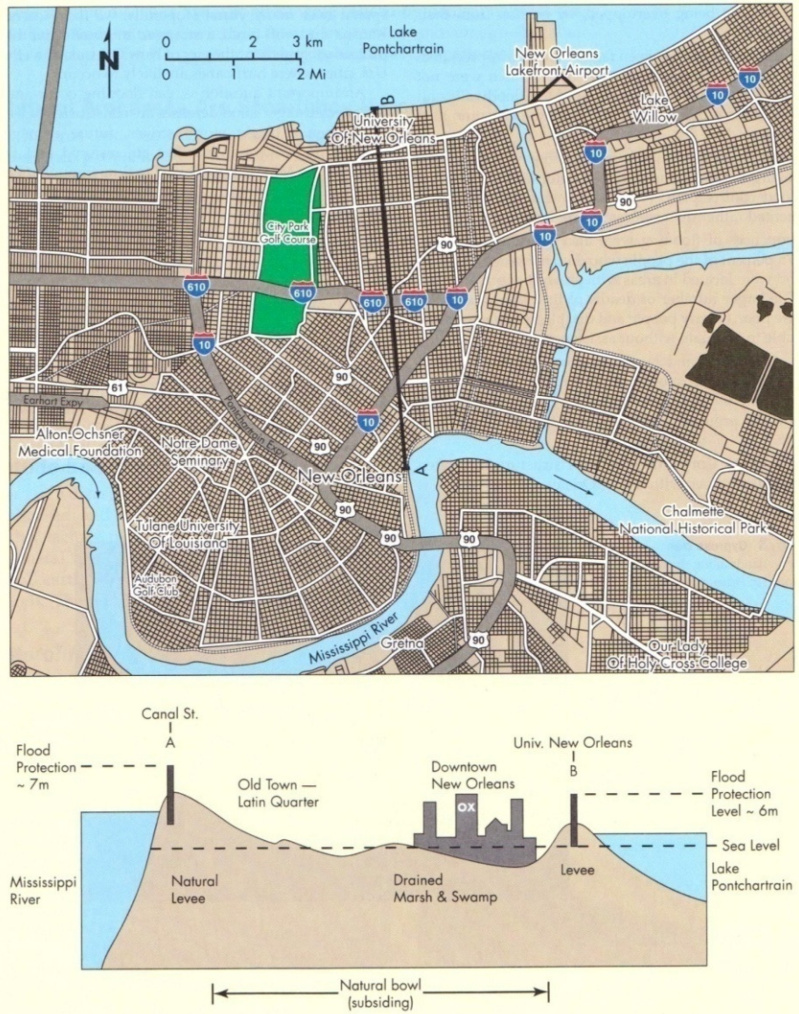


Figure 5.2 Map and cross section of New Orleans Much of the city is below sea level between the Mississippi River and Lake Pontchartrain. *(Edward A. Keller)*

Failure of Flood Protection System

- Ruptures of 50 locations in the system

  169 mi, out of 284 mi, of the federal levees & floodwalls (a total of 350 mi in New Orleans) were damaged by overtopping & breaching
- Storm surge from the east converged along **Gulf Intracoastal Waterway (GIWW) & Mississippi River Gulf Outlet (MRGO) first.**
- High water in **Lake Ponchartrain** burst thru floodwalls on 17th St Canal & London Canal.
- Industrial Canal was battered from both directions.

Storm Surge Damage

- **Before landfall** at 6:10 am on **29th August**, storm surges from Lake Borgne reached Industrial Canal. Waves & surge overtopped & eroded MRGO levees
- 6:10 am: **Storm surge overtopped levees** in Plaquemines Parish
- 6:30 am: levees south side of New Orleans East area were **overtopped**
- On landfall, **waves of 4 ft high caused overtopping** in the the southern section of Industrial Canal

Hurricane Damage in Plaquemines Parish

The storm surge from Hurricane Katrina overtopped levees (seen in this photo adjacent to the water) in Plaquemines Parish and knocked hundreds of homes off their foundations. (This photo was taken after flood waters had receded.)

Cracks in the System

Ruptures (or breaches) in four I-walls developed, all before water levels in the adjacent canals overtopped them.

- **East bank of Industrial Canal I-wall**
- **I-wall at 17th St Canal**
- **London Ave Canal I-wall (south breach)**
- **London Ave Canal (north breach**)

Cracks in the System

5:00 am: breach in east bank of I-wall of **Industrial Canal**

North Breach >

South Breach >

* Photos were taken after flood water began to recede

Cracks in the System

6:30 am: breach of I-wall at **17th St Canal** began

9:00 am : torrents of water from Lake Ponchartrain rushing in thru 450-ft long breach segment

Cracks in the System

7:00 am: breach in a London Ave Canal I-wall (south breach)
8:00 am: 2nd breach at London Ave Canal north breach)   **V**

A City Under Water

- Peak surge levels were over when most of the major I-wall failures occurred.
- Flooding continued until water level in the bowl-shaped landscape equalized with that in Lake Pontchartrain.

New Orleans Flooded

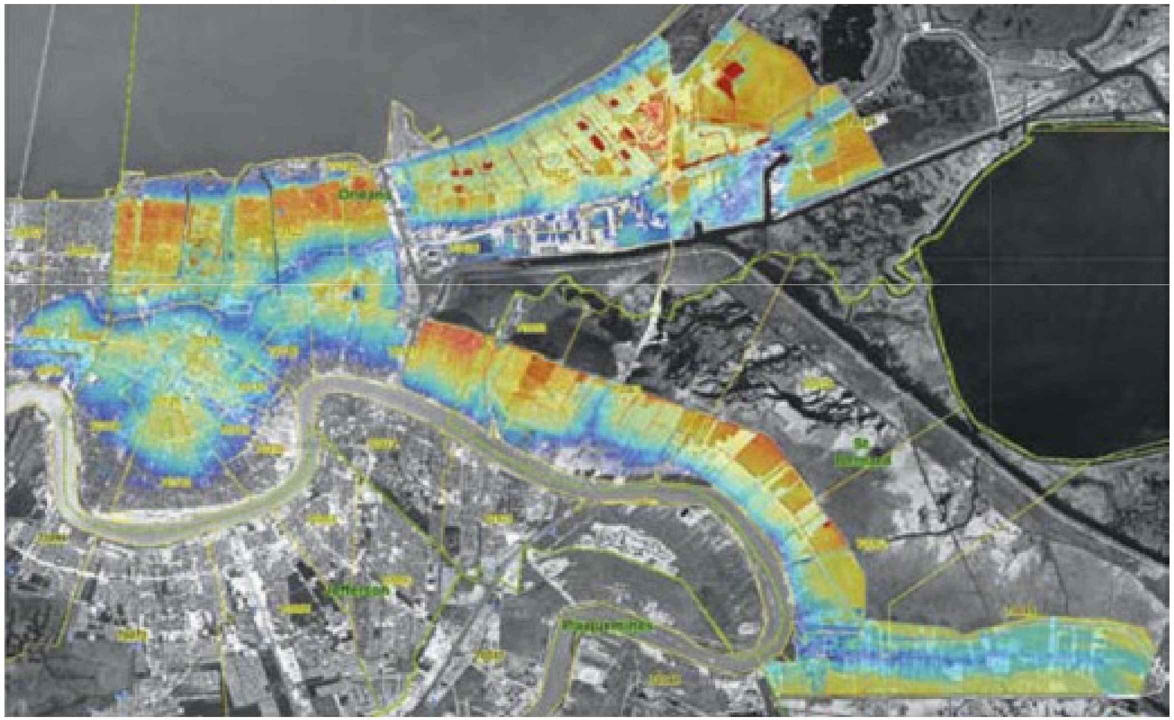
A City Under Water

By Sept. 1st,over 80% of metropolitan New Orleans was flooded (2/3 from breaches and 1/3 thru overtopping & rain)

Orange-red: . 10 ft

Green-aqua: > 6 ft

Maximum Flooding Depth



By September 1, 2005, portions of Lakeview, Gentilly, New Orleans East, and the Lower Ninth Ward were submerged in more than 10 feet of water (orange and red colored areas). Significant portions of the city stood in water more than 6 feet deep (green and aqua colored areas).

Pump Station Shut Down

Pump stations could offer no relief to flooding as they were mostly left inaccessible and inoperable by the failure of the hurricane protection system

Submerged Pump Station No. 6

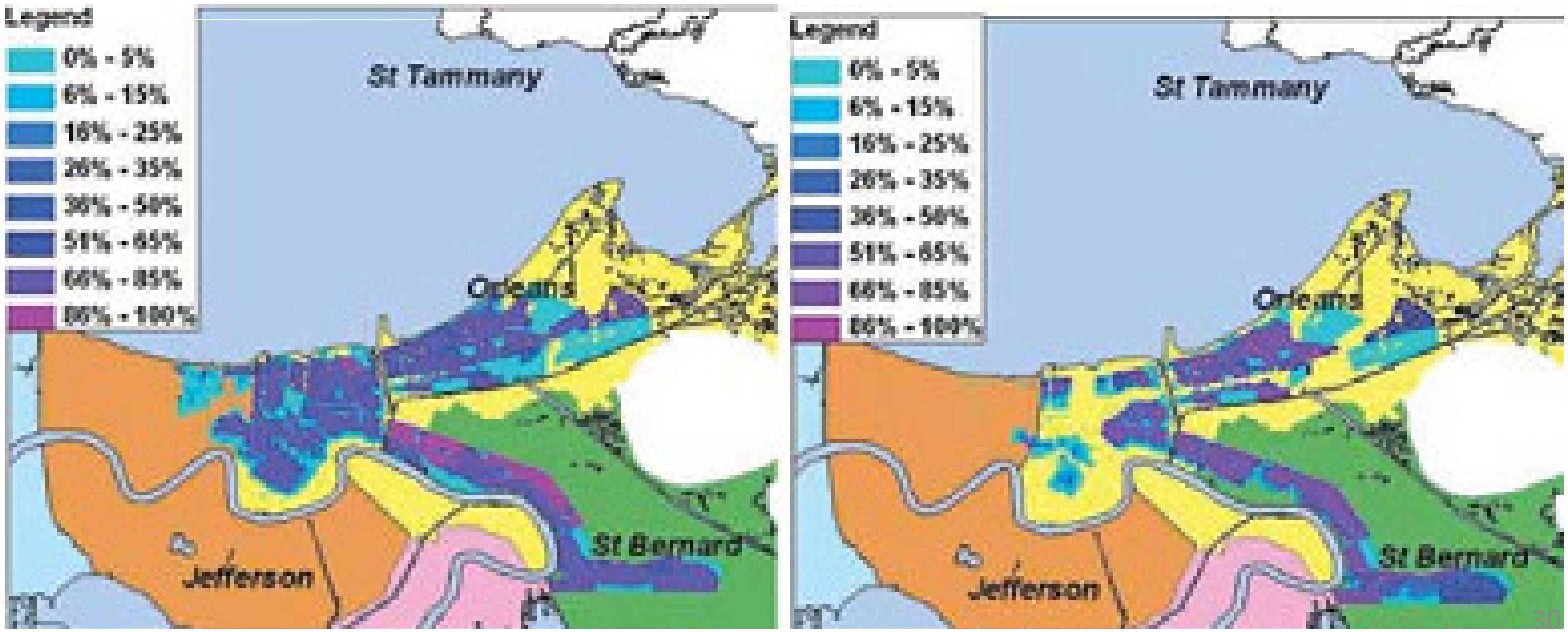
Rapid and far-reaching flooding caused by the hurricane protection system failure left most pump stations, such as Station No. 6 (on the 17th Street Canal), inoperable.

Had the Hurricane Protection System Not Failed

Had the levees, floodwalls & pump stations not failed:

- 2/3 of the deaths (~1,200) would not have occurred
- ½ of the property losses ($10 billion) would be saved
- More savings in damages to infrastructures & utilities would have occurred

Property Damage Modeling Results



Direct Physical Causes of the Catastrophe

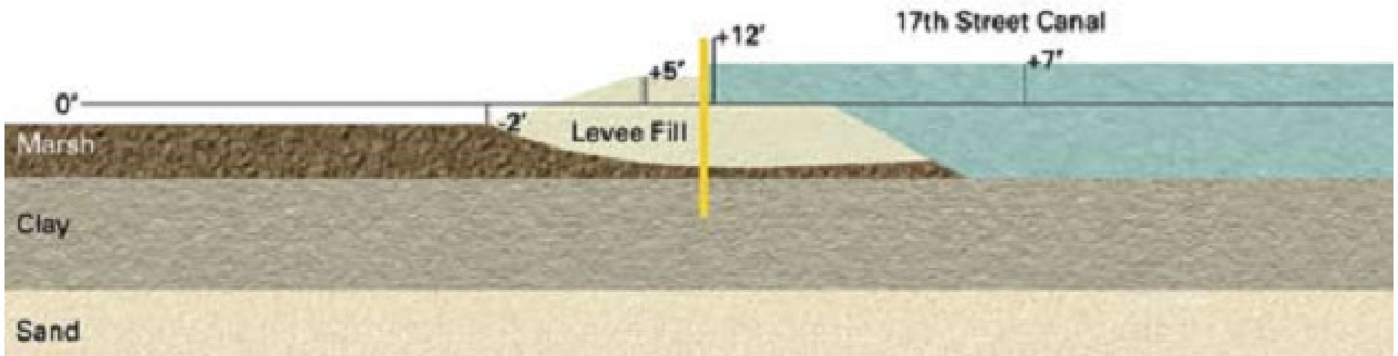
Mush of the destructions was the result of eng. & engineering-related policy failure.

- **Levees** were built to protect against high water, and yet they failed
- **Pump stations** were built to remove rainwater from interior-the New Orleans bowl, but weren't always designed to withstand a hurricane or levee breach, and they failed

17th Street Canal Breach

- At 6:30 am, a 450-ft long section of I-wall along the east side of Canal failed. Water level in the Canal was 5-ft lower than top of the wall, well below designed level.
- Levee & floodwall were built over organic soil or marsh, which overlays a layer of v. soft clay. Levee indeed failed through sliding away from the Canal

Cross-Section of 17th Street Canal Levee and Floodwall



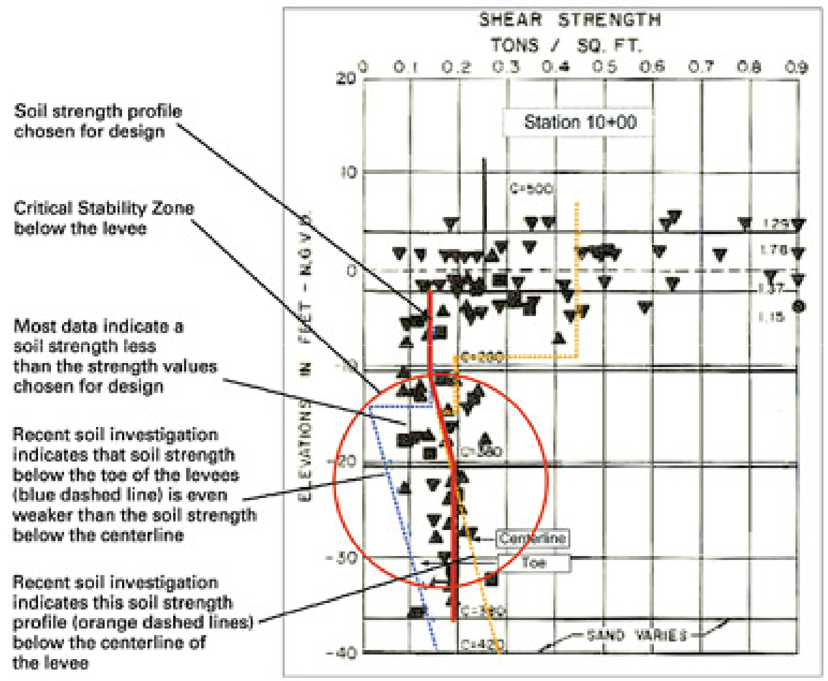
The levee and I-wall failed by sliding away from the canal along a failure surface in the weak soft clay below the levee.

Soil Strength Over-estimated

Critical zone: **El-15 to -30 ft**

- **Un-conservative shear strength** was chosen
- **Misuse of lumped data**: Localized (failure segment of 450 ft) soil strength of 0.13 tsf, is 32% lower than strength from lumped data over 5,000 ft levee distance (0.19 tsf)
- **Misuse of centerline data**: Ave strength beneath and beyond the toe of levee slope is much lower than that below the centerline of the levee.

Plot of Soil Strength beneath the 17th Street Canal Levee



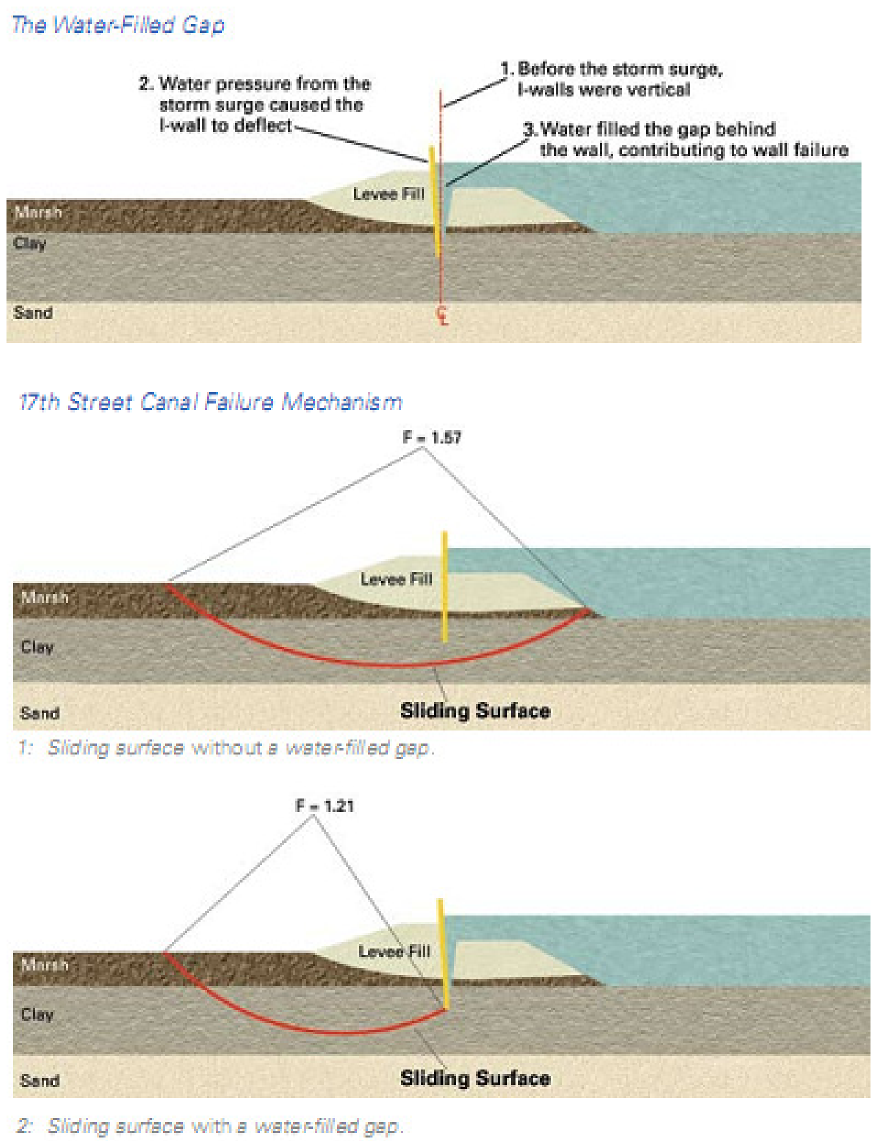
Mis-interpretation of soil data below the 17th Street Canal levee was one of three primary reasons the I-wall failed.

Factor of Safety

- A Factor of Safety (FS) of 1.3 was used which is below the accepted engineering practice- 1.5 or above under long-term condition.
- The **cumulative effect** of **using a low FS** and **over-estimating the soil strength**-a compounding error- was disastrous. It allows little or no room to account for variables or uncertainties

Water-Filled Gap

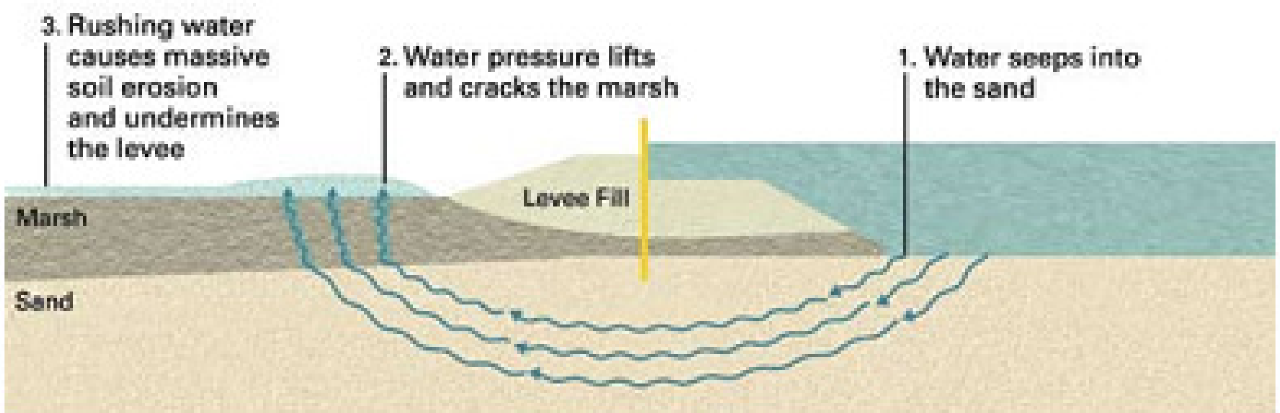
- Water pressure from surge caused I-wall to deflect & formed water gap behind wall
- **Critical sliding surface** starts at the base of water-filled gap with lower FS (from 1.57 to 1.21) which is below the design FS of 1.3- **incipient failure**
- Failure to check existing designs for safety & stability in the light of new info & guidelines ('80s & '90s) on potential of water-filled gap to develop



London Avenue Canal- South Breach

- Water level in Canal was 5 ft below top of wall, at time of failure. Seepage uplift force on land side exceeded wt of overlying marsh layer & topsoil. The marsh layer was lifted up off the sand & cracked open. Cracks widened and scour-holes expanded back under the levee-eventually undermining & destroying it.

Cross-Section of London Avenue Canal Levee and Floodwall



The levee and I-wall failed when pressure from the water seeping through the sand below the levee caused the marsh layer to crack. The sand then flowed out with the water, undermining the levee and I-wall.

Over-simplified Assumptions on Seepage control

Potential uplift of the marsh layer was not accounted for properly, e.g.,

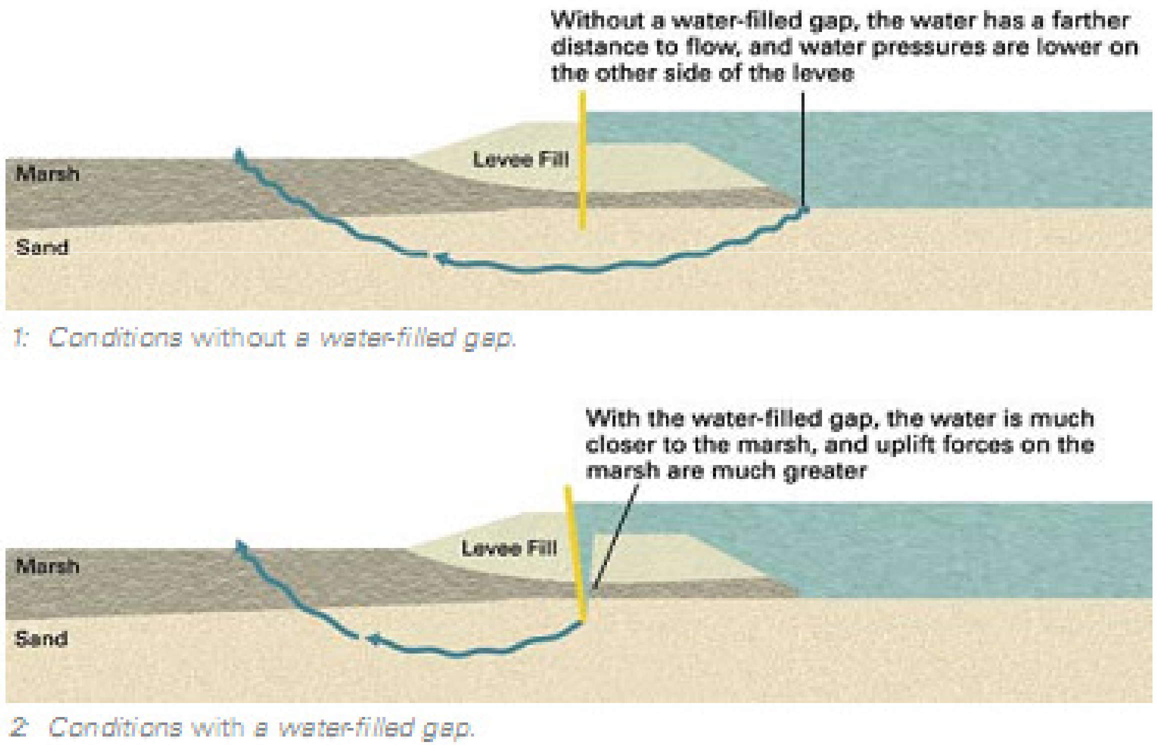
- Flow nets were drawn, but none included marsh layer.
- Uplift potential was assessed, but computations used a critical hydraulic gradient appropriate for soils, not for marsh.

Failures could have been avoided if problems were predicted & corrective actions taken: such as extending depth of sheet pile wall, or installing relief wells .

Water-Filled Gap on Uplift Force

Uplift forces on marsh layer are much greater as the seepage path is shortened by water-filled gap

London Avenue Canal South Breach Failure



Without the water-filled gap (top), there is less pressure on the underside of the marsh layer. The water in the water-filled gap (bottom) exerts significantly higher pressure on the marsh layer because it is closer.

London Avenue Canal North Breach

- Occurred around 7 or 8 am on August 29th. Foundation condition is similar to London Avenue Canal South Breach, except that the sand was much looser & weaker. Failure mechanism is similar to that of 17th St Canal-sliding failure exacerbated by under seepage & associate water pressure.

  FS was about 1.0 due to water-filled gap (Fs would have been 2.0 without crack).

Industrial Canal East Bank North Breach

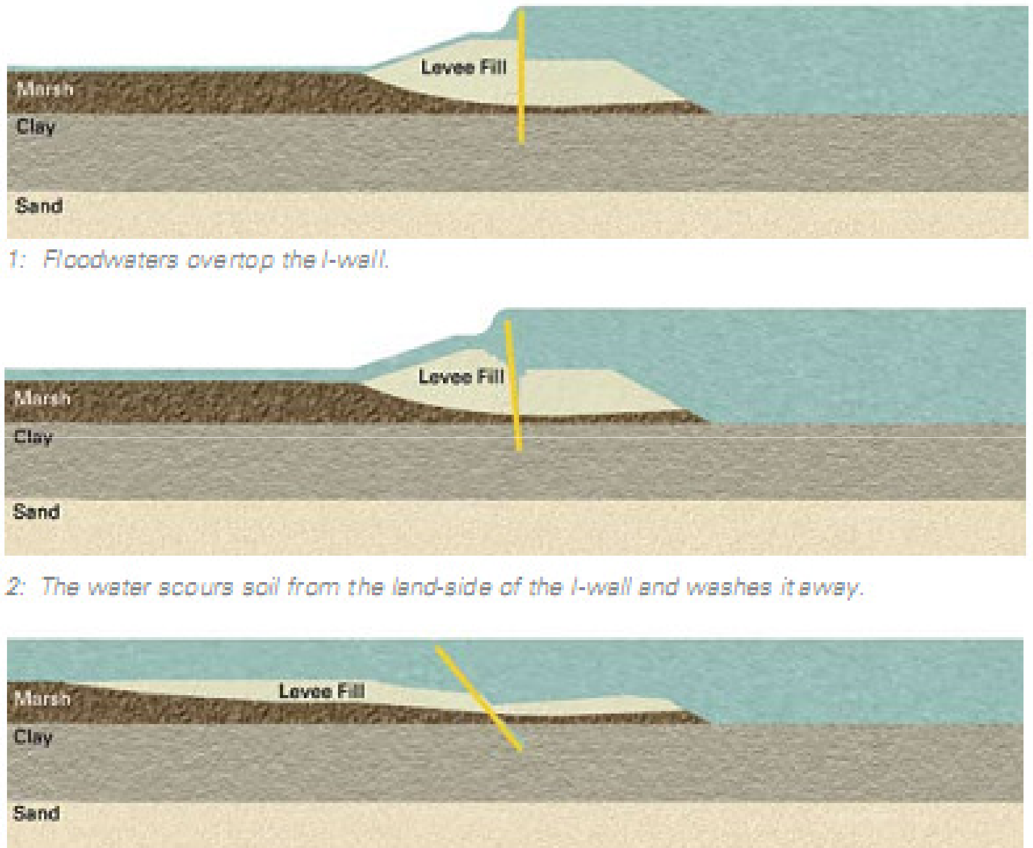
- I-wall failed at 5:00 am in much the same way as 17th St Canal: by slope failure along a sliding surface in the marsh layer. The presence of water-filled gap greatly reduced the FS.

Industrial Canal East Bank South Breach & Industrial Canal West Bank Breach

- Both were overtopped by flood water from Hurricane Katrina.

- Peak water level was about 1.7 ft above top of the flood walls.

Overtopped I-wall Failure Mechanism



1: Floodwaters overtop the I-wall.

2: The water scours soil from the land-side of the I-wall and washes it away.

3: I-wall fails due to lack of foundation support.

Water flowing over the floodwalls scoured and eroded the land-side of the levee at the base of the walls. The sheetpiles that support the I-walls were undermined. In some locations, the sheetpile walls may have lost all of their foundation support, resulting in failure of the wall.

Industrial Canal West Bank South & All Other Levee Breaches

- Levees were overtopped by Hurricane's storm surge.
- Majority of breaches are attributed to overtopping & erosion.

Overtopped Levee Erosion Failure Mechanism

1: Floodwaters overtop the levee.

2: The water scours soil from the crest and land-side of the levee and washes it away.

3: Some levees constructed of sand and silt washed away completely.

Water overtopping the levees caused serious scour and erosion. Some levees were completely washed away.

Levees with properly compacted clay & good grass cover withstood the storm the best.

- Levees with higher silt & sand content, or built with hydraulic fill sustained the worst erosion damage, and in some cases were completely washed away.

Levee Under the Paris Road Bridge in New Orleans East

Even though this earthen levee was overtopped (as was shown in Figure 5.1), it sustained relatively minor damage. (This photo was taken after floodwaters had receded.)

Obliterated Levee along the Mississippi River-Gulf Outlet

Many levees that were constructed with hydraulic fill severely eroded or washed away entirely. (This photo was taken after floodwaters had receded.)

Pumping System: Useless During Hurricane Katrina

- Pump stations were designed to remove storm-water runoff & seepage water from the interior drainage system and pump it into Lake Ponchartrain or other adjacent Canals & water bodies. Only a few stations operated (16% of overall capacity) during & after the hurricane.
- More than 12-in of rain fell on parts of New Orleans.

Causes of pump station failures

1. Operators evacuated and pump stations lay idle
2. Pump stations were flooded by water from levee overtopping & flood wall breaching, causing widespread equipment damage & failure.
3. The buildings housing older pump stations could not withstand the wind and water forces from hurricane.
4. Water in some Canals flowed through some idle pumps back into the city, in the absence of automatic backflow preventers or human operator plus electric power.
5. Pump system won't be inadequate to cope with the huge amount of water through overtopping & breaches, even if it had survived. Further, pump discharge would have been re-circulated back from the breached Canals.

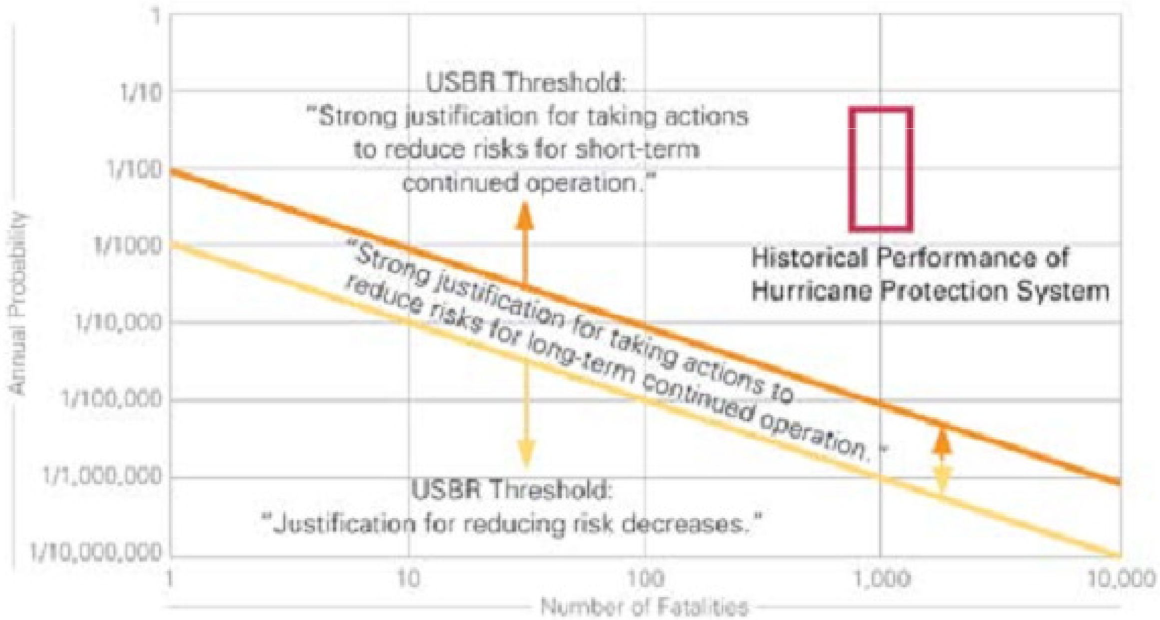
Contributing Factors to System Failure:
Decisions, Management, & Organization

- Lack of Risk Quantification of Potential Failure of Protection System
- Piecemeal Construction of Hurricane Protection System
- Hurricane Protection System under-designed
- Land subsidence plus incorrect use of datum
- No One Entity is in charge of Hurricane Protection
- External Peer Review Lacking
- Funding Process Flawed

Lack of Risk Quantification of Potential Failure of Protection System

The consequences of failure to human safety & the probability of a failure were not incorporated in the design & construction of the system, nor communicated to the public.

Risk Evaluation Chart



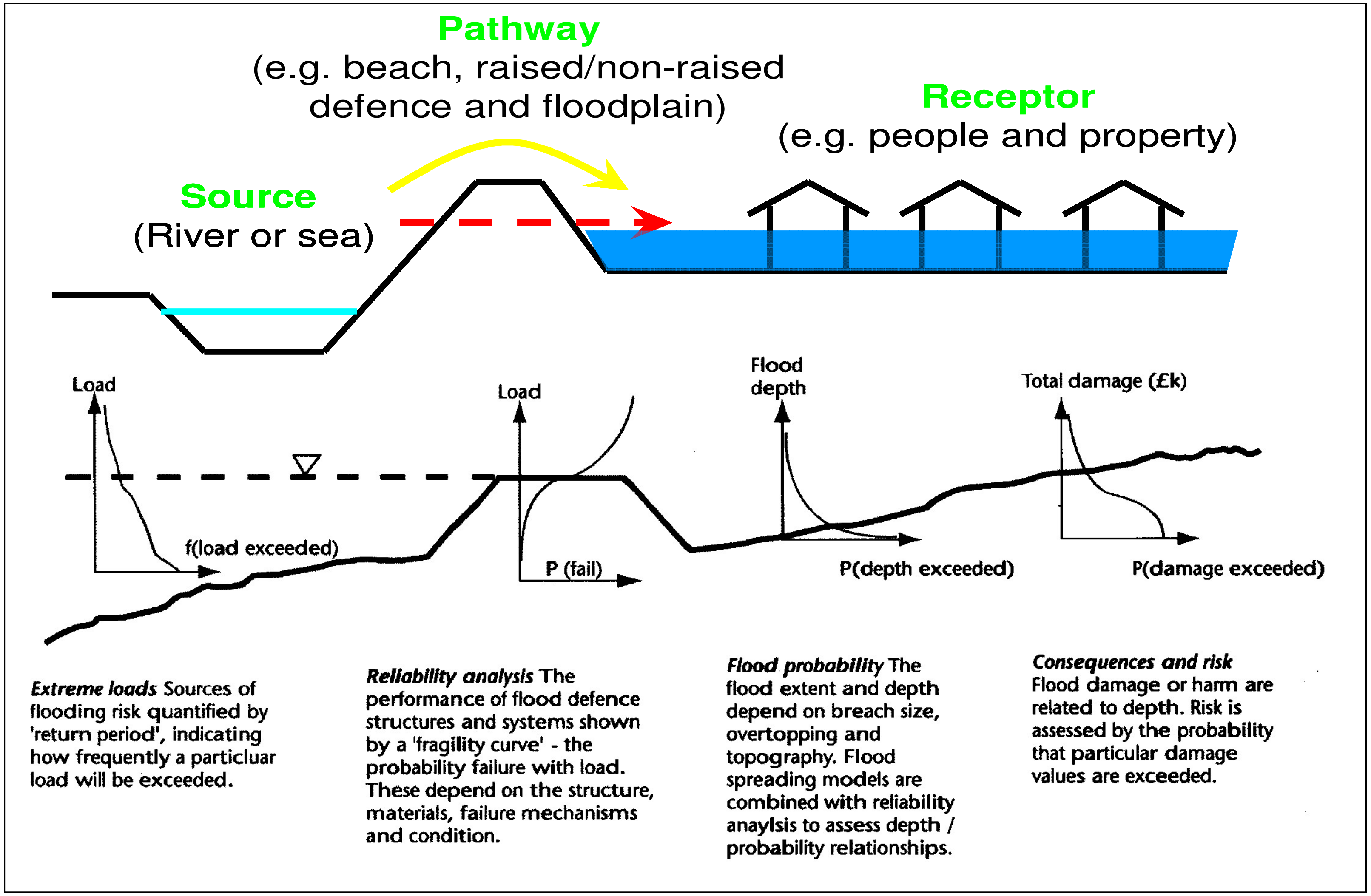
The USBR guidelines for achieving public protection in dam safety are shown in yellow. The risks posed by New Orleans's hurricane protection system (shown in red) were significantly higher than people are generally willing to accept.

Critical risk-related questions on hurricane protection system

- What is risk?
- How much risk is acceptable?
- How can this level of risk be effectively communicated?
- How should the hurricane protection system be designed based on risk?

  **It appears the Hurricane Katrina had a probability-based recurrence interval of 50-500 yrs.*
- What is the probability that the protection system would fail ?

Estimation of Flood Risks



Source : Foresight project on Flooding and Coastal Defence 2004

Colin Thorne, University of Nottingham

Piecemeal Construction of Hurricane Protection System

- Protection system was planned, designed & constructed over four decades
- Construction began in earnest after Hurricane Betsy in 1965 and not scheduled for completion until 2015.
- System comprises many individual projects that were conceived and built in a piecemeal fashion. Levees & I-walls were built with different top elevations & of different materials: earth, steel, and concrete.
- There are numerous penetrations for roadways, rail lines & pipelines throughout the levee system, with closure systems missing or inoperable.

Failed I-wall and levee sections

Failed I-Wall and Levee Sections

The levees and I-walls were constructed piecemeal with different top elevations and of different materials: earth, steel, and concrete. The floodwaters preferentially attacked the lower-elevation erodible earth first, causing major breaches.

Hurricane Protection System Under-designed

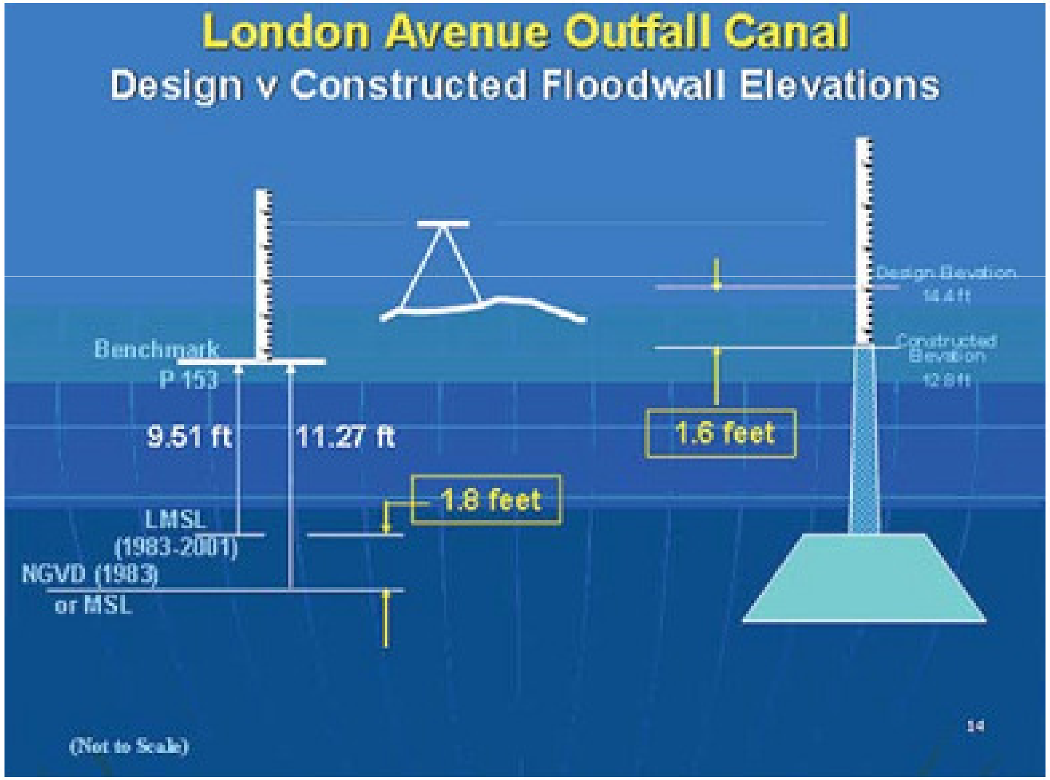
- Adopted **SPH** (**Standard Project Hurricane**) for protection system: the most severe combination of hurricane parameters that is reasonably characteristic of a specified region.
- **PMH** (**Probable Max Hurricane**): a combination of meteorological parameters that will give the highest sustained wind speed that can probably occur at a specified coastal location. The relationships between the meteorological parameters (central pressure index, forward speed, wind direction & speed) are interrelated and complex.

- Had the protection system been evaluated using **PMH**, the consequences of a more severe storm could have been considered in the preventive measures, such as armor protection for levee sections subject to overtopping/erosion, and strengthening of pump stations. More comprehensive evacuation programs could have been installed.

Many Levees Not High Enough

- Use of SPH resulted in protection system being under-designed
- Errors in reference datum caused some top elevations being lower than intended by design

Discrepancies between Design and Construction Elevations



Because of errors in the reference datums, segments of the hurricane protection system were constructed so that the top elevations are lower than intended by the design.

Land subsidence plus incorrect use of datum

- Land subsidence (0.2 in/yr) was not incorporated in the design
- In some older part of the system, subsidence plus incorrect use of datum reduced design ht by 3 ft. Storm surge was only 1-3 ft above

  top of levee/wall

No One Entity is in charge of Hurricane Protection

- Apart from discontinuities in the physical protection system caused by piecemeal construction & incorrect elevations, there were also discontinuities in organizational responsibility. The management of hurricane protection system is chaotic & dysfunctional.
- No single entity is empowered to provide system-wide oversight of the critical **life-safety** issues. No agency ever defined clearly expectations of what the hurricane protection system was really intended to achieve.

Examples of Administrative Problems

- *Flood gates at France Rd were out of service & left open during storm.*
- *Trees were allowed to grow on the levees, and swimming pools & hot tubs had encroached on levee R-O-W.*
- *President of Jefferson Parish ordered the pump station operators to evacuate prior to the storm. Flooding would have been reduced significantly if all 5 pump stations remained operable.*
- *USACE proposal to provide protection along the lakefront of Lake Pontchartrain, instead of along the canals, was dropped because of strong objections from the Sewerage & Water Board and the Orleans Levee District.*

External Peer Review Lacking

- Lack of independent review assessment., or some of the peer review are discretionary, not triggered by sound eng. principles. There is no mechanism to gauge their fidelity, and contains vague processes for selecting reviewers.
- As a result, questionable engineering decisions were made: margins of safety were too low in levee design, and improper datums were used in construction.

Funding Process Flawed

- The ‘push-pull’ mechanism for funding of the critical life-safety system is essentially flawed. It creates a ‘disconnect’ between those responsible for design & construction decisions and those for managing purse-strings.
- The project-by project approach resulted in piecemeal construction with an overall lack of attention to ‘system’ issues, e.g., armoring was not installed because it’s outside the congressional authorization.
- USACE accepted the tight control of budget by the congress without arguing vigorously enough for adequate funding in ensuring public safety.

End of Part 2

Part 3

Management & Mitigation
of
Flood Hazards associated with
Landfalling Tropical Cyclones

Outlines

Management & Mitigation of Flood Hazards associated with Landfalling Tropical Cyclones

- Measures for flood damage reduction
  - Structural Alternatives
  - Non-structural Alternatives
- Emergency Action Plan
- Urbanization
- Encroachment of Flood Plain
- Land Subsidence
- Conclusions

Measures for Flood Damage Reduction

- **Structural Alternatives**
  - Flood-control reservoirs/detention basins
  - Diversion structures
  - Channel modifications or improvements
  - Levees and/or floodwalls
  - Pumping system for interior flooding
  - Operation, Maintenance & Surveillance (OMS) program for all measures and facilities

Measures for Flood Damage Reduction

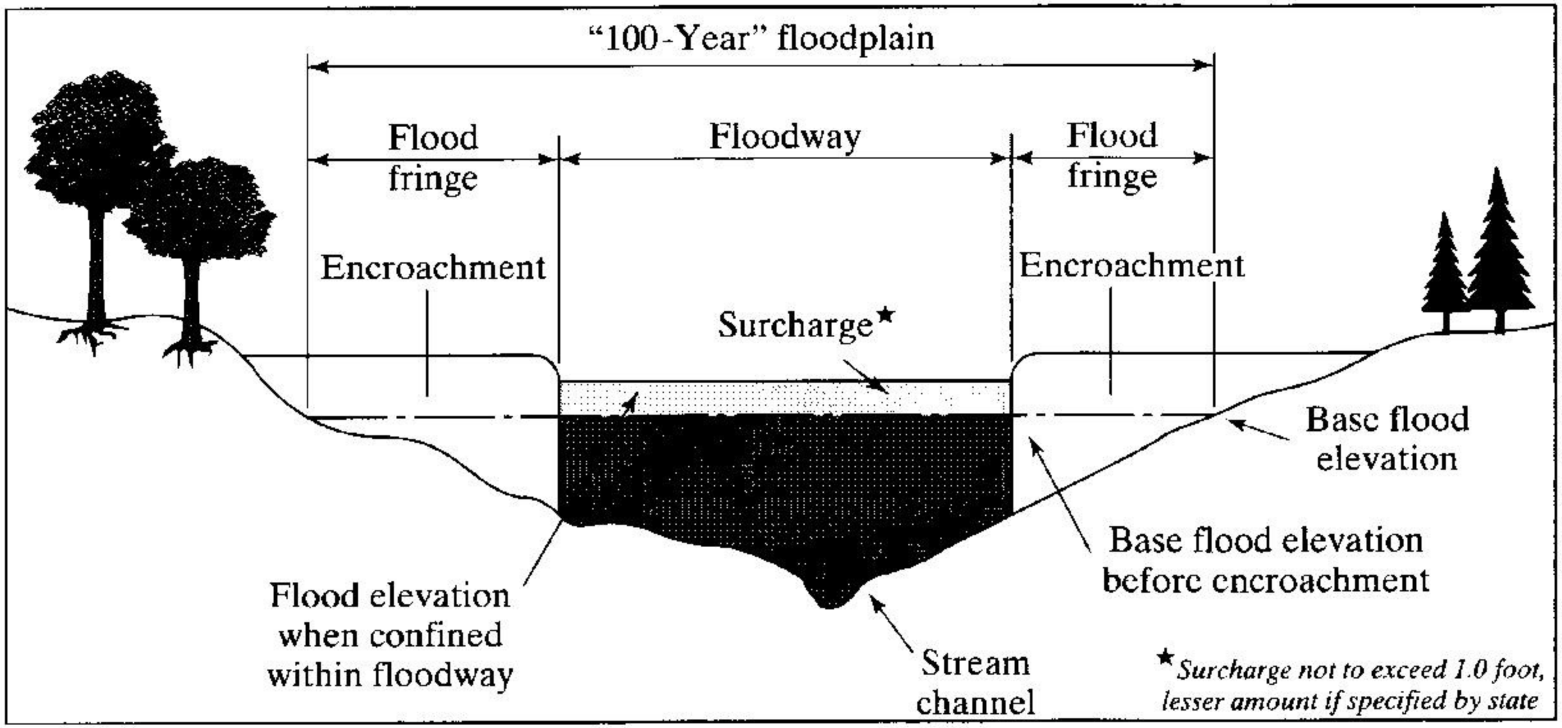
- **Non-Structural Alternatives**
  - **Floodplain management :** floodplain regulations; flood insurance program
  - **Flood proofing-** elevating structures, water proofing walls & closures, and re-arrangement of structural working space.
  - **Land-use & construction regulation**
  - **Catchment Stormwater Management:**

    Low Impact Development **(LID)**

    Best Management Practice **(BMP)**

    as part of land-use planning for new developments and renewal/remedial projects.

Flood plain, Floodway & Flood Fringe



Measures for Flood Damage Reduction

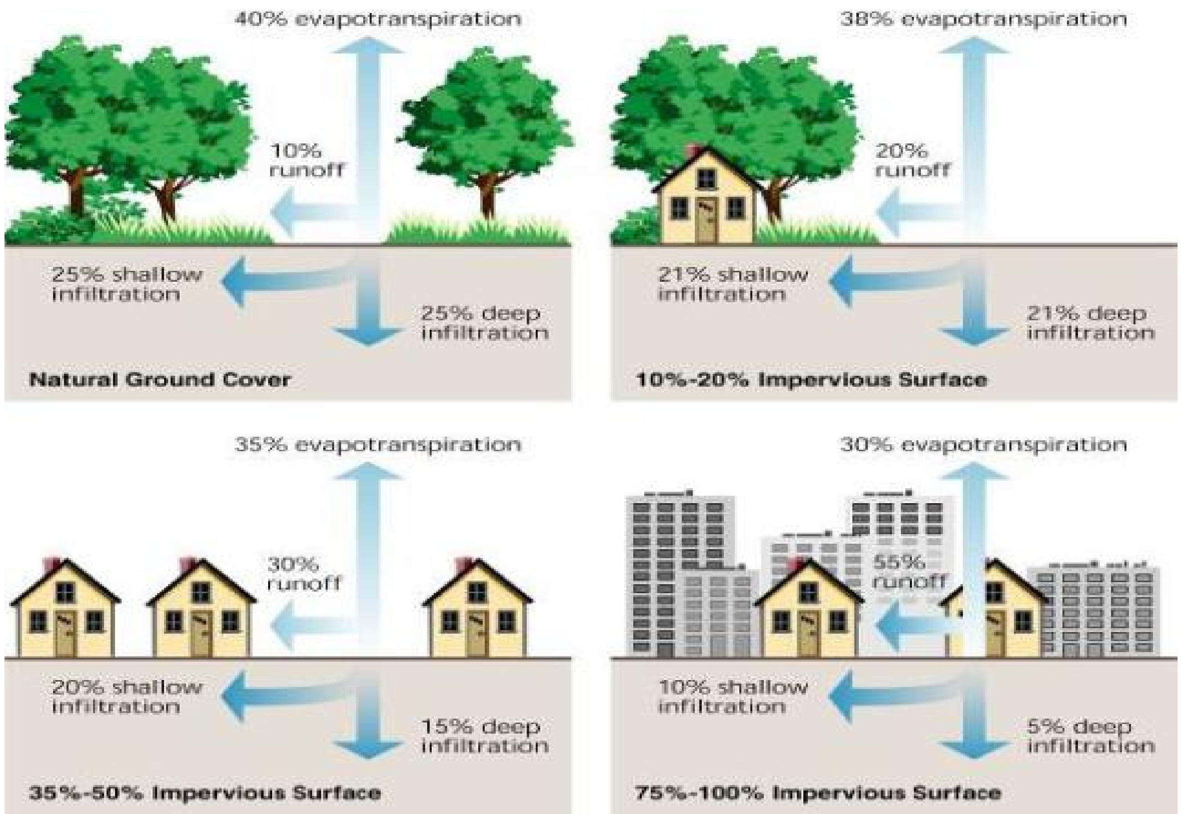
- **Non-Structural Alternatives (cont'd)**
  - **Relocation**
  - **Acquisition**
  - **Flood warning plan & system**
    - Flood-threat recognition subsystem
    - Warning-dissemination subsystem
    - Emergency-response subsystem
    - Post-flood recovery subsystem
    - Continued system management- including OMS
  - **Emergency action plans**

Emergency Action Plans

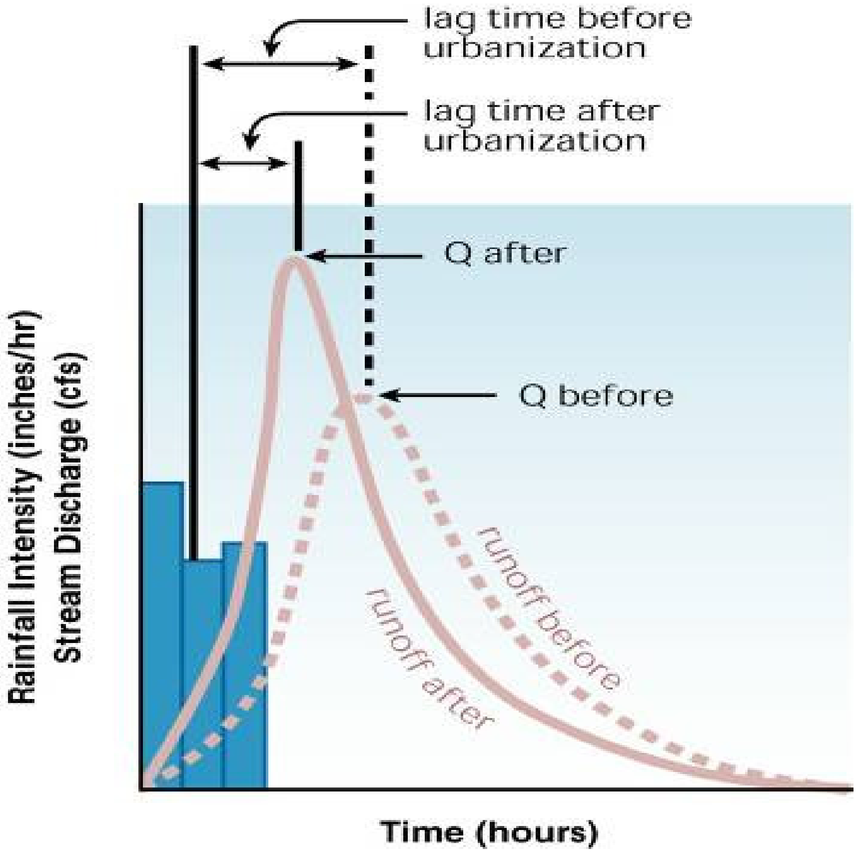
- Operation & Maintenance of flood monitoring and Early Warning System (EWS)
- Staff assignments for acting on emergency calls
- Preparation of detailed action procedures when emergency occurs
- Lists of businesses & residents to be notified/evacuated from potential inundation areas, including contact means & contact information
- The most safe & efficient evacuation routes and rescue organization
- Use GIS for data storage, analysis & utilization; and for interfacing emergency action plans with flood simulation/forecasting/warning models

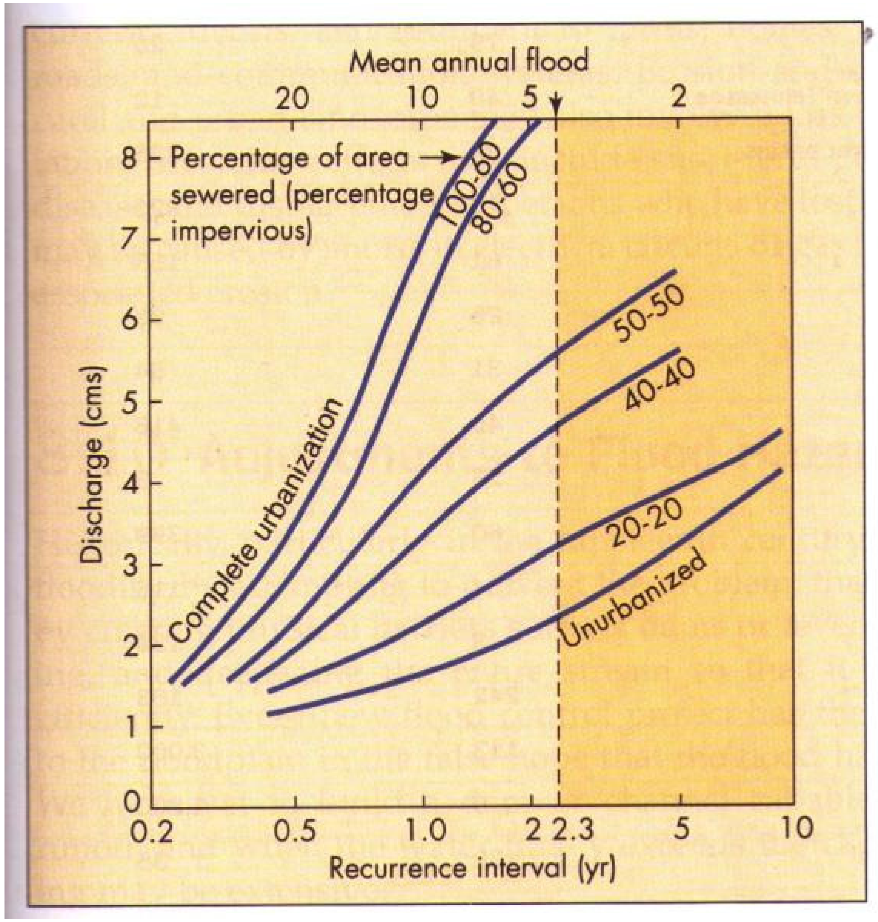
Urbanization on increase of flood peak & volume

Urban development: increase in % of paved and % of storm sewered land areas, resulting in manifold increases in peak flood discharge



Manifold increase in flood peaks

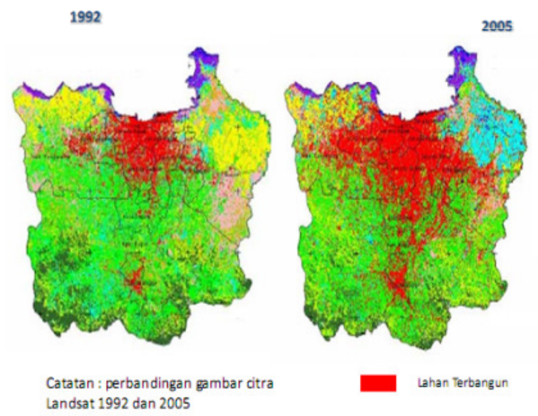


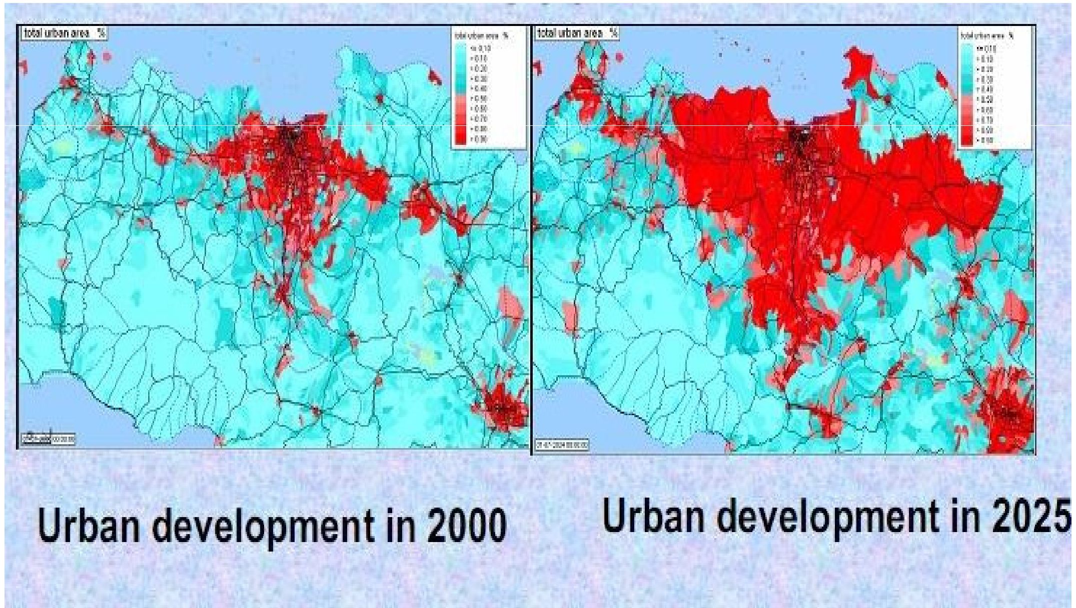


Rapid Pace & Extent of Urban Expansion

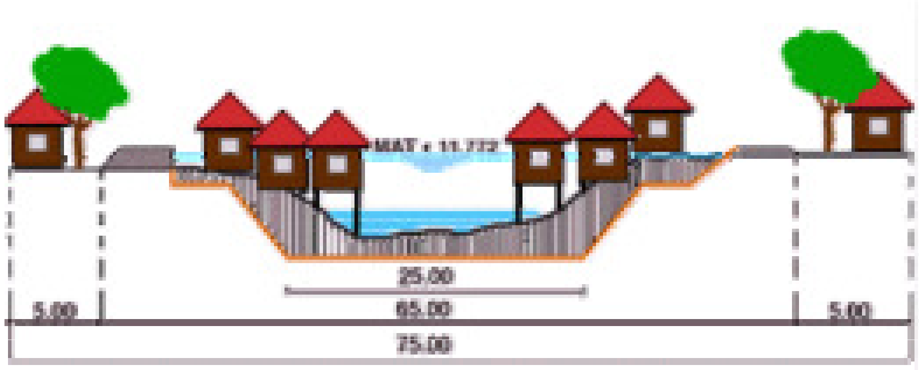
- **Rapid pace of areal expansion of urban, suburban, industrial and commercial lands**
- **Typical urban expansion pattern in Jakarta, Indonesia**

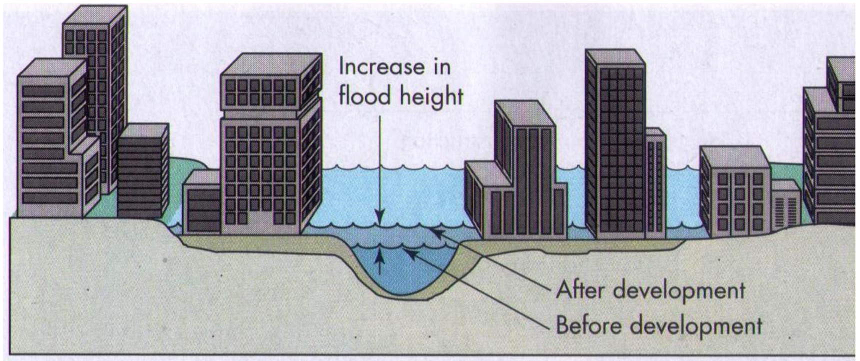
1992 2005

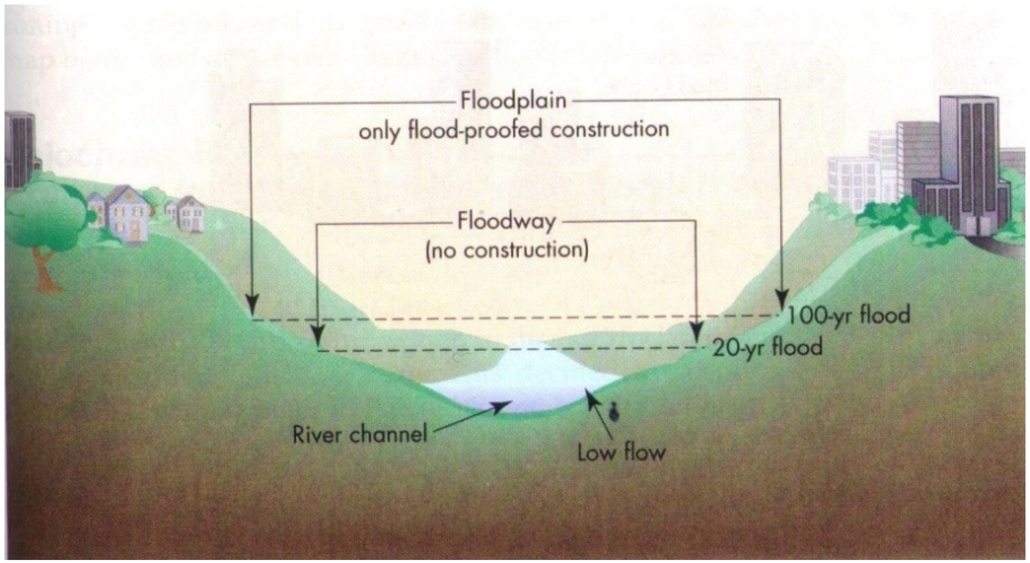




Encroachment of Flood Plains
on reduction of drainage capacity







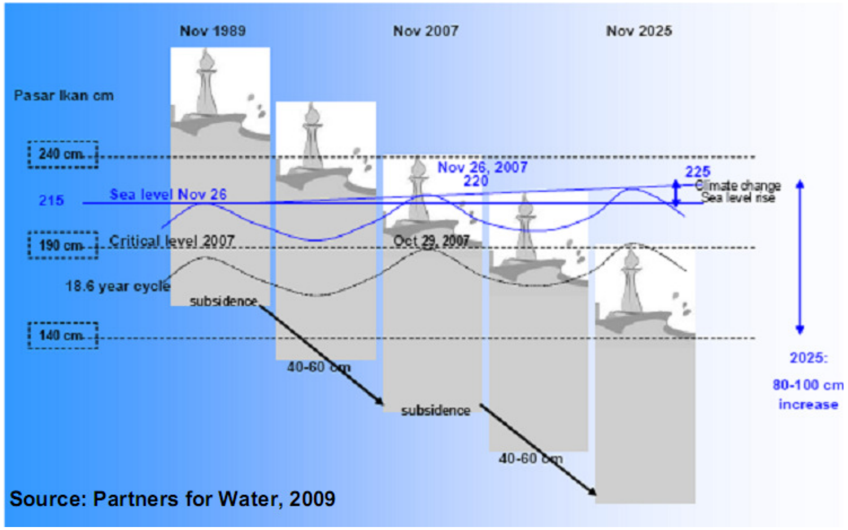
Land Subsidence vs Tides & Sea Level Rise

Jakarta, Indonesia

Land subsidence:
2-3 cm/yr (1989-2007)

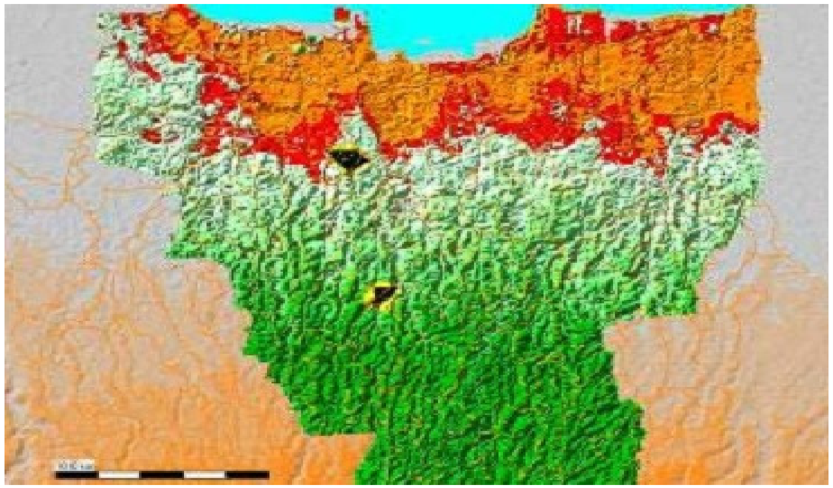
Sea level rise : 0.2-0.3 cm/yr

insignificant tides during 1996, 2002, & 2007 floods



New Orleans, Louisiana, USA

Land subsidence: 0.4-0.5 cm/yr
(USGS data,1951-1995)
due to natural consolidation, groundwater withdrawal, petroleum production, etc.



Bangkok, Shanghai, & others

Conclusions

- Tropical cyclones are powerful natural forces that cause catastrophe hazards to human lives, properties and economy
- The damages are generally associated with coastal surges (with winds, waves, and tides), river floods (high stages and currents), interior flooding (high rain), and debris/mud flows
- They also provide beneficial contributions towards water supply in the region & maintenance of global heat balance

- **Urbanization**, with increases in impervious cover & area served by storm sewers, increases the magnitude & frequency of flood. Effective urban planning, incorporating the BMP & LID practices for stormwater management, would reduce the impact of flooding in urban community.
- **Flood plain encroachment** increases flood hazard locally & upstream of the area. The most effective solution are combination of ‘flood plain regulation’ and appropriate ‘structural flood-control measures’. Other means includes **flood proofing, relocation, and flood insurance**.

- Control of ‘land subsidence’ by limiting withdrawal of water from groundwater source and augmenting the supply from surface water and other sources.
- Periodic review and enhancement of the flood control policy (structural & non-structural) , and rigorous implementation of the Operation, Maintenance & Surveillance (OMS) for the facilities and measures are essential to safeguard the effectiveness of the system.
- warning system, is the key measure to minimize flooding damages associated with tropical cyclones. Development & implementation of ‘Emergency Action Plan’ for flood control, including flood forecasting &

End of Part 3