Geologic Factors Promoting Ground Subsidence and Coastal Land Loss in the Mississippi Delta *and the Great Debate About What to Do About It*

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Guest lecture for

Social Science and Engineering

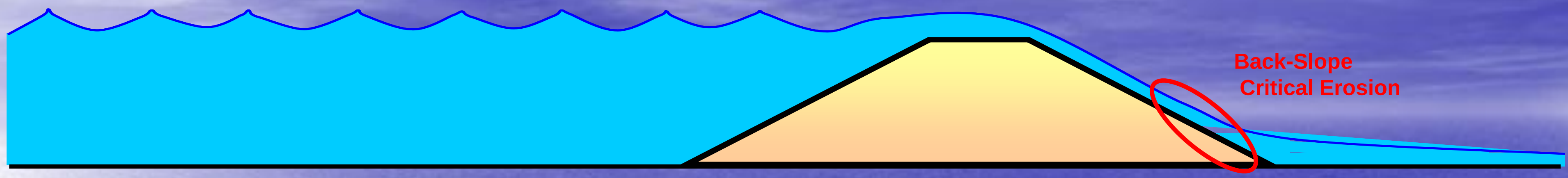
University of New Orleans

Thursday January 22, 2009

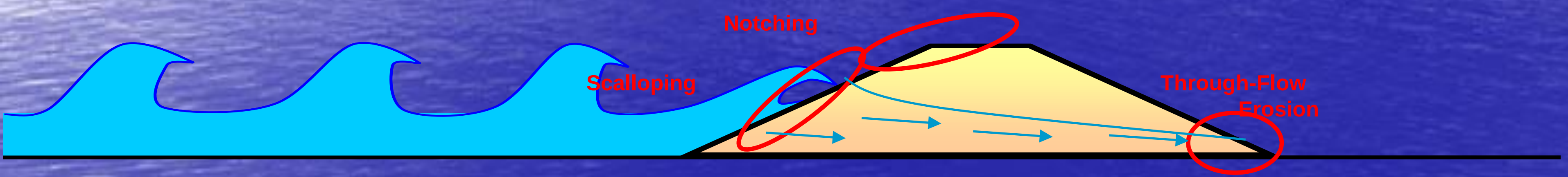
For engineers designing flood protection systems, the core value should be SUSTAINABILITY

Above all else, flood barriers, such as levees, should be constructed to withstand short-term overtopping <u>without catastrophic failure</u>.

Two kinds of overtopping-induced damage



Velocity-induced scour at toe of back slope, at flow transition. Accelerates when vegetation stripped off, depending on cohesion of embankment materials



Scalloping and notching on the fetch side of the levee, due to wave pounding; and hydraulic piping fomented by emergent seepage at the toe of the back slope

Note: damage at back slope toe looks similar for both modes

Cohesionless shell fill is easily eroded by moving water

- Levees comprised of organic-rich materials and bereft of sufficient clay simply disappeared during Hurricane Katrina.


Steel sheetpile cutoff walls along the MRGO
channel were all that remained of the levee
after overtopping erosion from Hurricane
Katrina's storm surge

- **Surficial erosion of the outboard toe of embankment bordering a borrow are along the western side of the reconstructed MRGO channel; this is suggestive of <u>low cohesion fill</u>.**

PROCESS CLASSIFICATION OF COASTAL LAND LOSS BETWEEN 1932 AND 1990 IN THE MISSISSIPPI RIVER DELTA PLAIN, SOUTHEASTERN LOUISIANA

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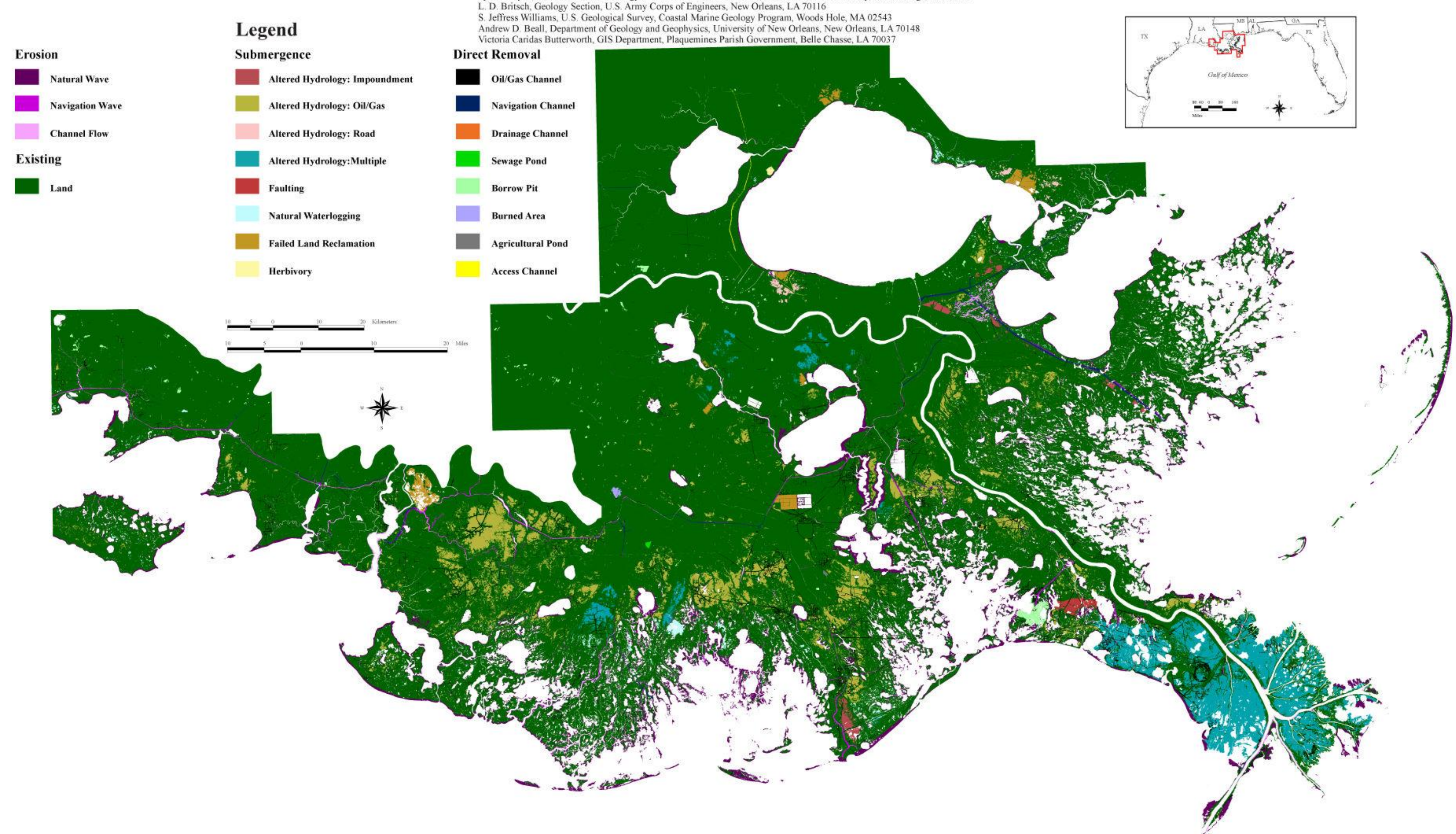
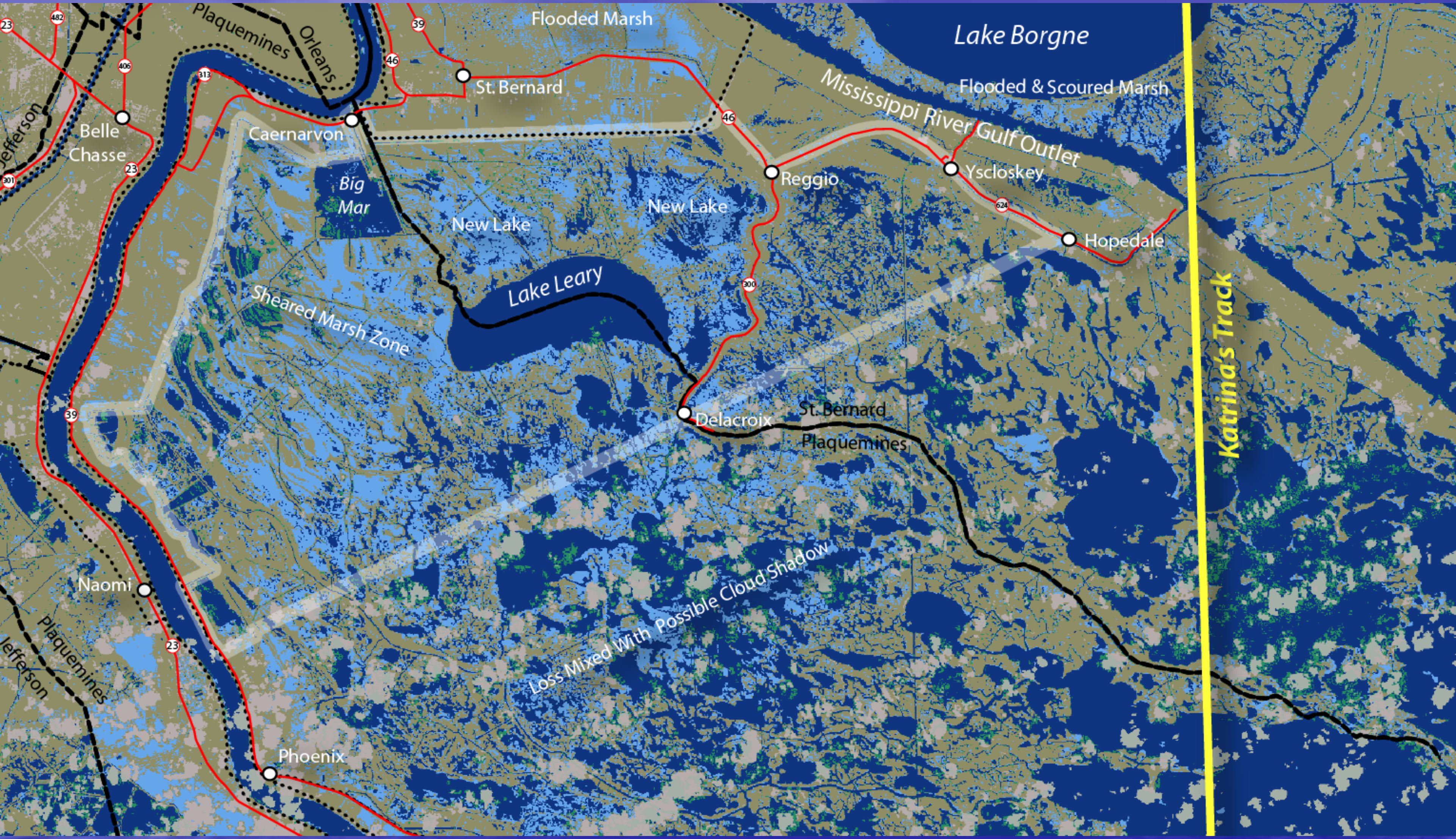


- **Between 1932-1990 an average of 35 square miles of land was being lost to the sea each year in the Mississippi Delta; and an average loss of 44 square miles/year of wetlands.**

- **Acute wind shear from Hurricane Katrina stripped off large tracts of floating marsh across the Mississippi Delta.** ***Can we construct sustainable levees on these kinds of materials?***



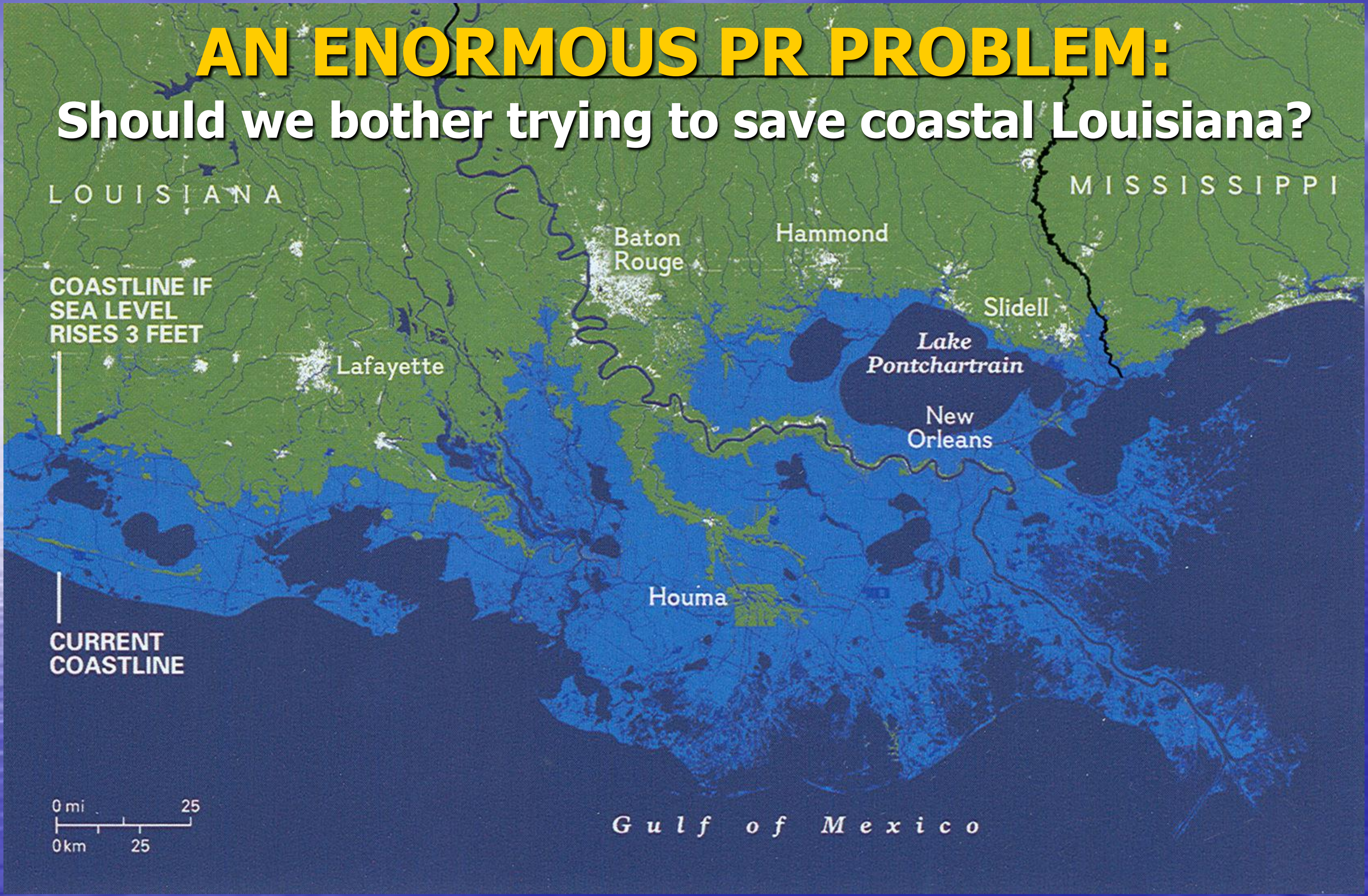
- During Hurricane Katrina, 115 square miles of land area was lost. This shows "land loss" in Breton Sound (in light blue) after the 2005 hurricane season.

A thought fro this evening:
IMAGES can have *fantastic influence* on public, and therefore, political perceptions…..

In the post-Katrina world, few images have had greater negative impact for Louisiana than one predictive map that appeared in the August 2007 issue of *National Geographic*

AN ENORMOUS PR PROBLEM:

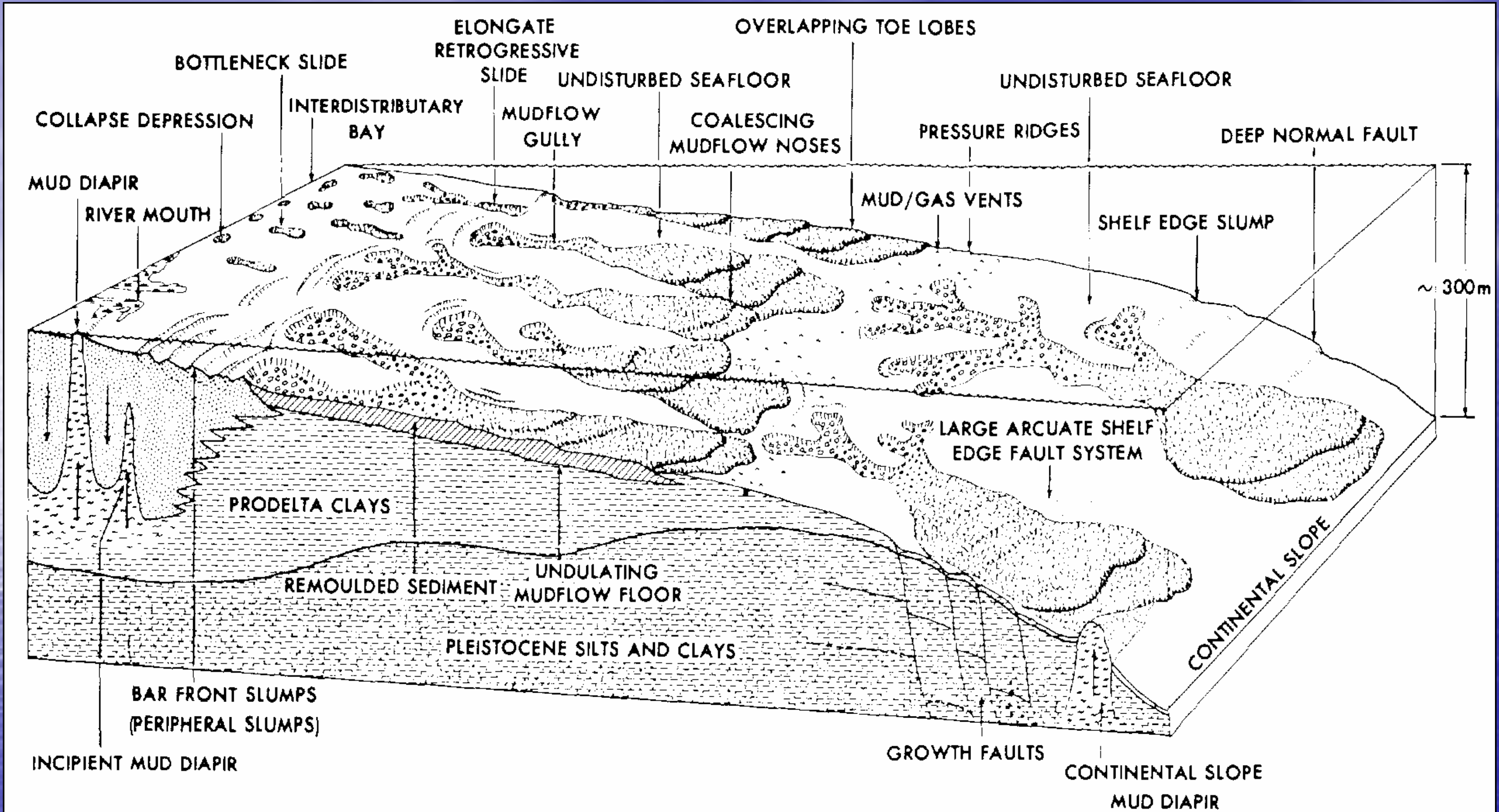
Should we bother trying to save coastal Louisiana?



- Coastal Louisiana is subsiding at an average rate of ~7 mm/yr, while sea level is rising about ~3 mm/yr. Over the next 100 years we can expect a net differential of ~1 m, shown here (image from August 2007 National Geographic).

MECHANISMS DRIVING GROUND SETTLEMENT

- The causes of ground settlement are a contentious issue in coastal Louisiana
- There appear to be many different causes, briefly summarized in the following slides

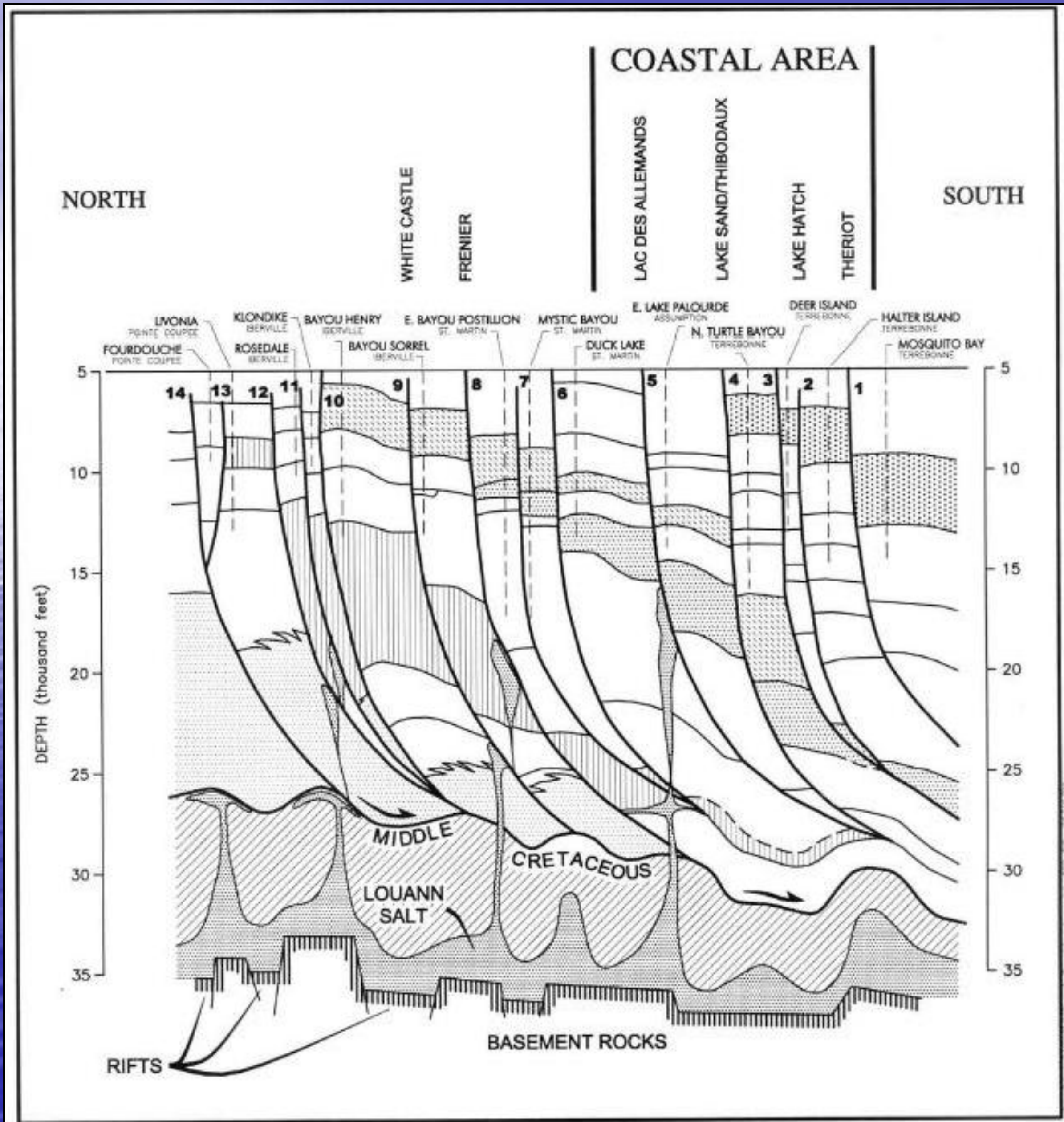


- Block diagram illustrating various types of subaqueous sediment instabilities in the Mississippi River Delta, taken from Coleman (1988).

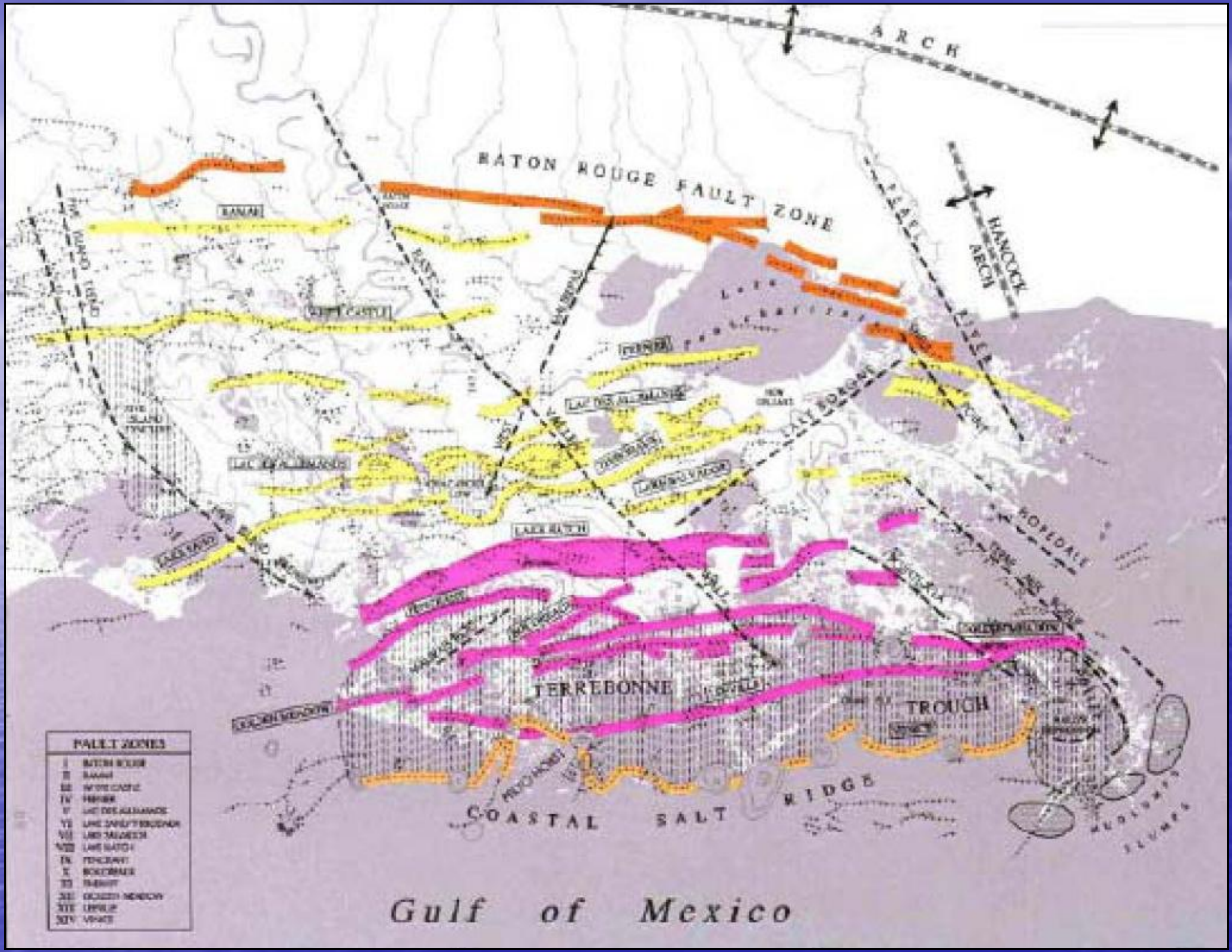
FLUID EXTRACTION OF OIL, GAS, AND WATER

R.A. Morton of the USGS has blamed oil and gas extraction for the subsidence of the Mississippi Delta. Morton has constructed convincing correlations between petroleum withdrawal and settlement rates on the southern fringes of the delta, near the mouth of the Mississippi, but this theory fails to account for marked settlement further north, where little or no deep withdrawal of oil or gas has been carried out.

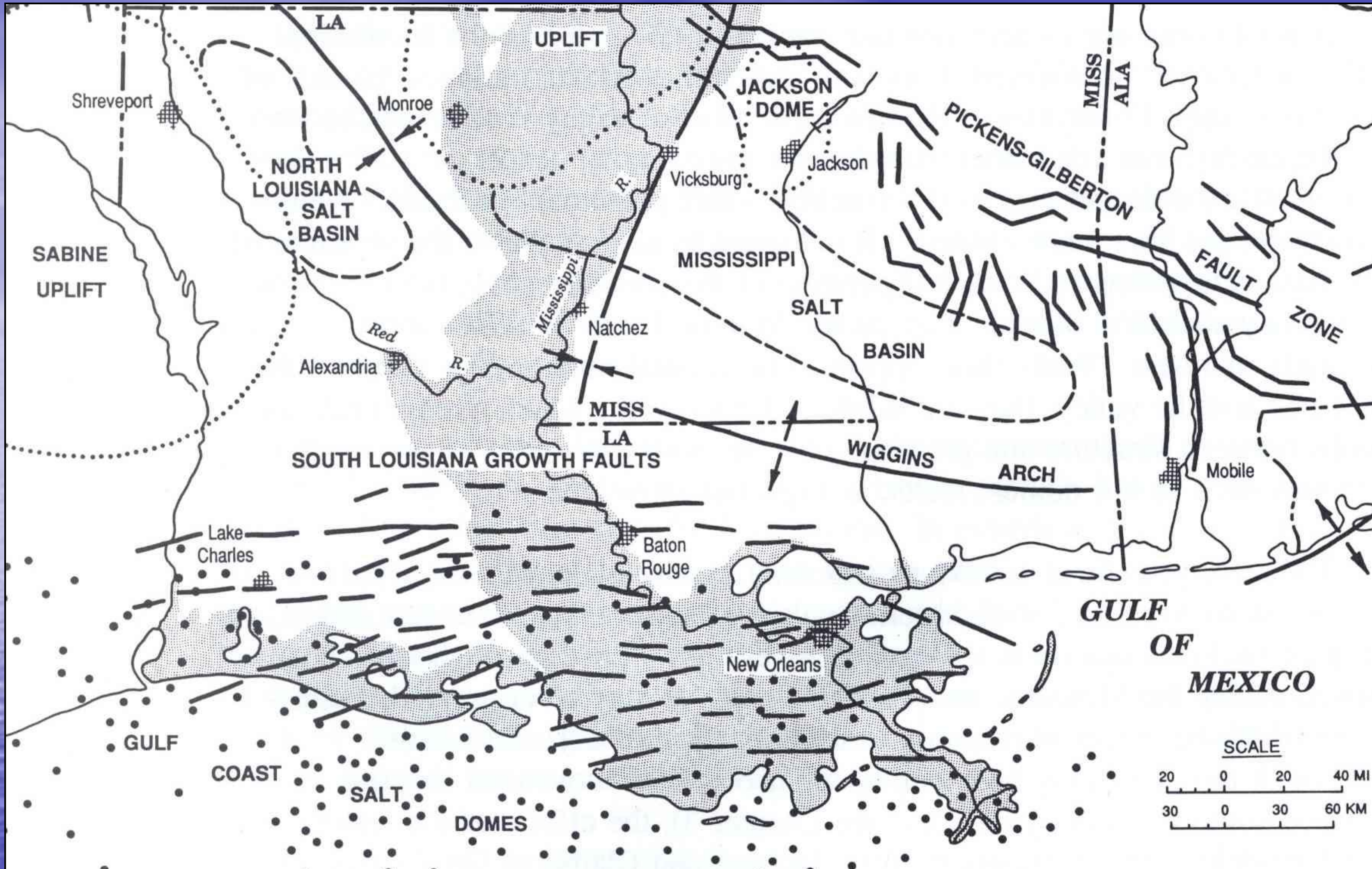
Growth Faults



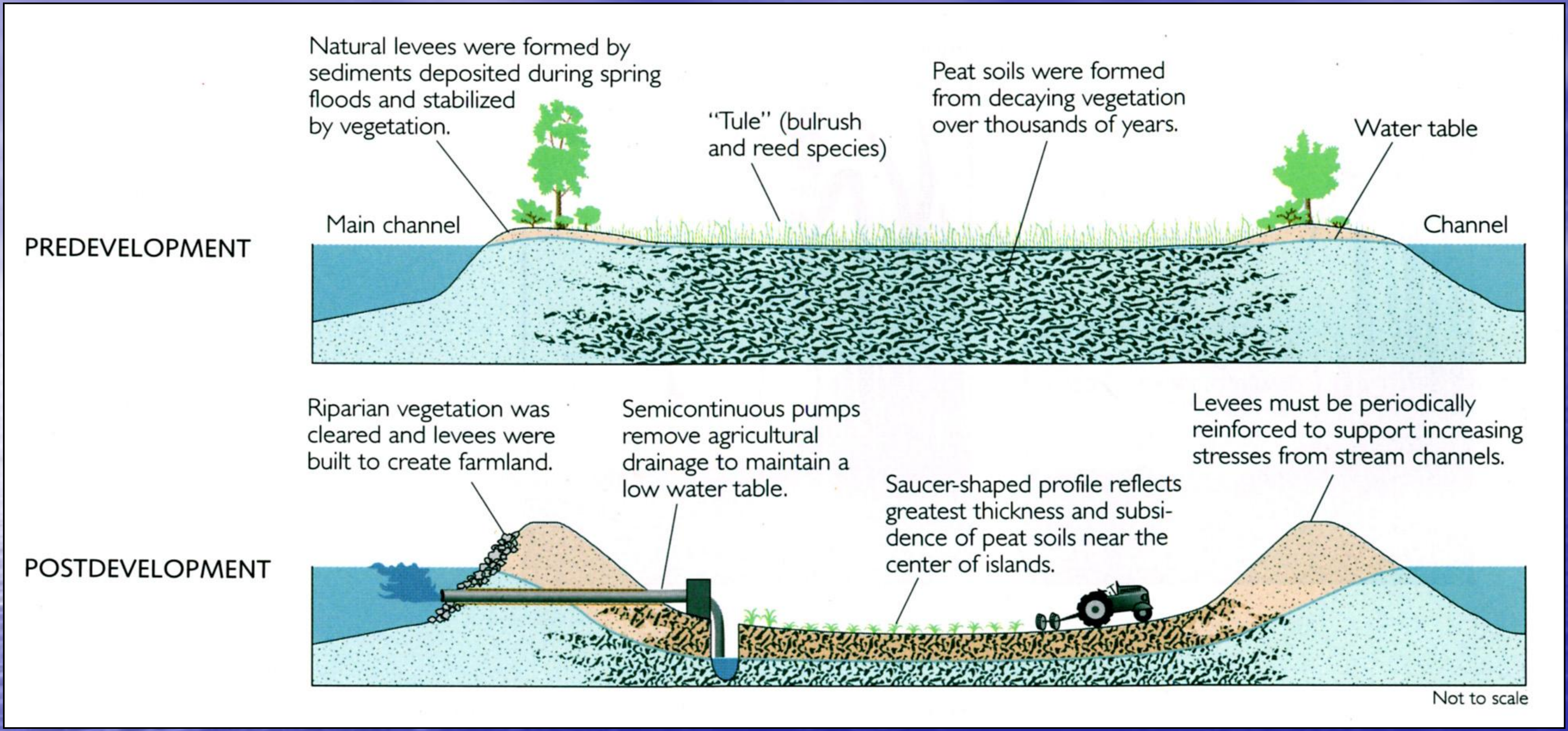
- Geologic cross section through the Gulf Coast Salt Dome Basin, taken from Adams (1997).
- This shows the retrogressive character of *lystric normal faults* cutting coastal Louisiana, from north to south.
- The faults foot in a basement-salt-decollement surface of middle Cretaceous age.



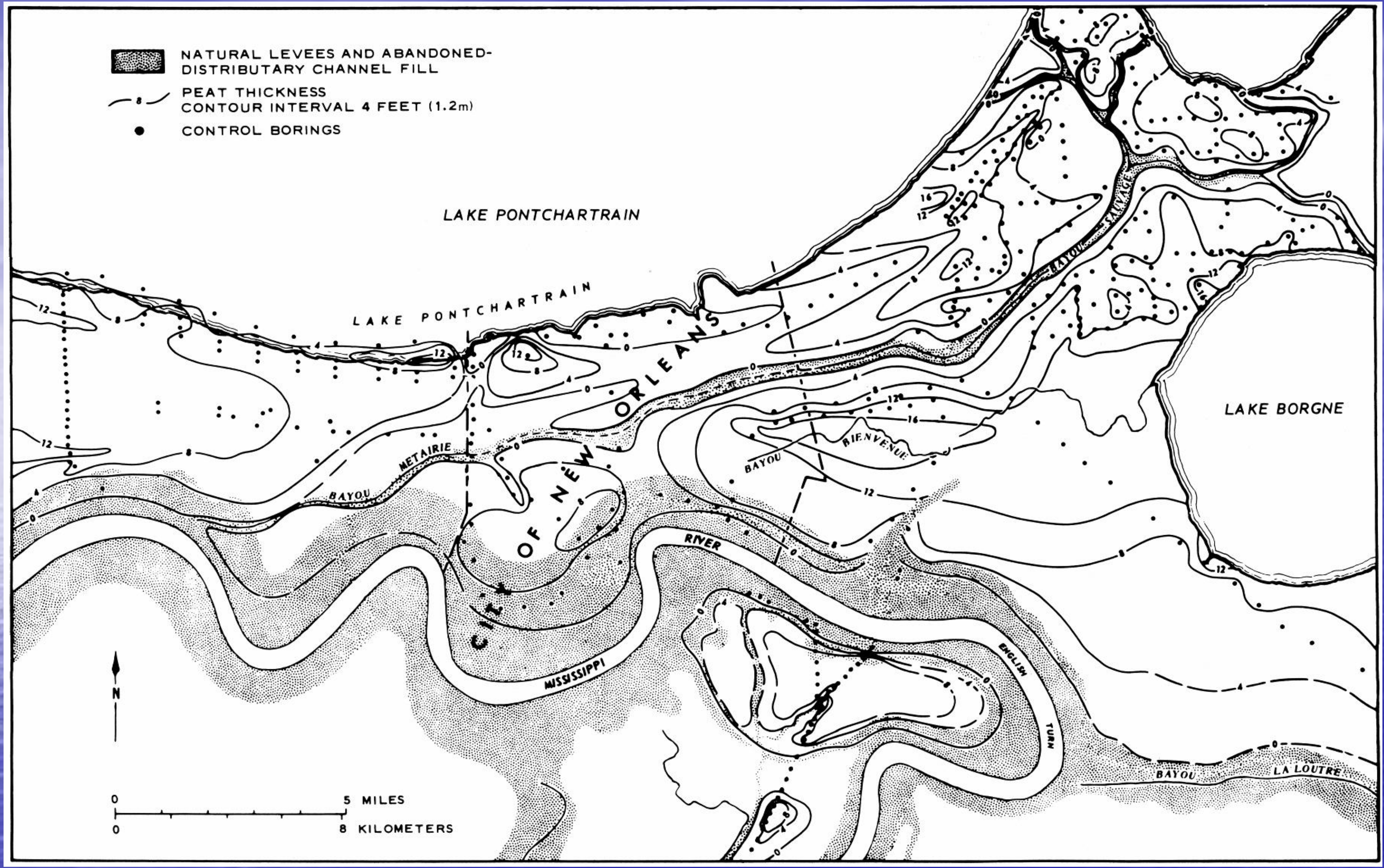
- This plot illustrates the en-echelon belts of growth faults forming more or less parallel to the depressed coastline. The Baton Rouge Fault Zone (shown in orange) has emerged over the past 50 years, north and west of Lake Pontchartrain (data from Woody Gagliano, Coastal Research).



Saucier's 1994 structural geology map of the Mississippi Delta, published by the Corps of Engineers. This shows *salt basins*, *salt domes*, and active *growth faults* that pervade the delta region.



- **Draining lowlands and backswamps** for agricultural or urban development increases the effective stress on underlying sediments and hastens rapid biochemical oxidation of organic materials, causing settlement of these surficial soils.



- New Orleans was built on compressible peaty soils. This isopach map shows the areal distribution of the surficial peaty soils (contour interval = 4 feet). From Gould and Morgan (1962) and Kolb and Saucier (1982).

Compaction of Surficial Sediments

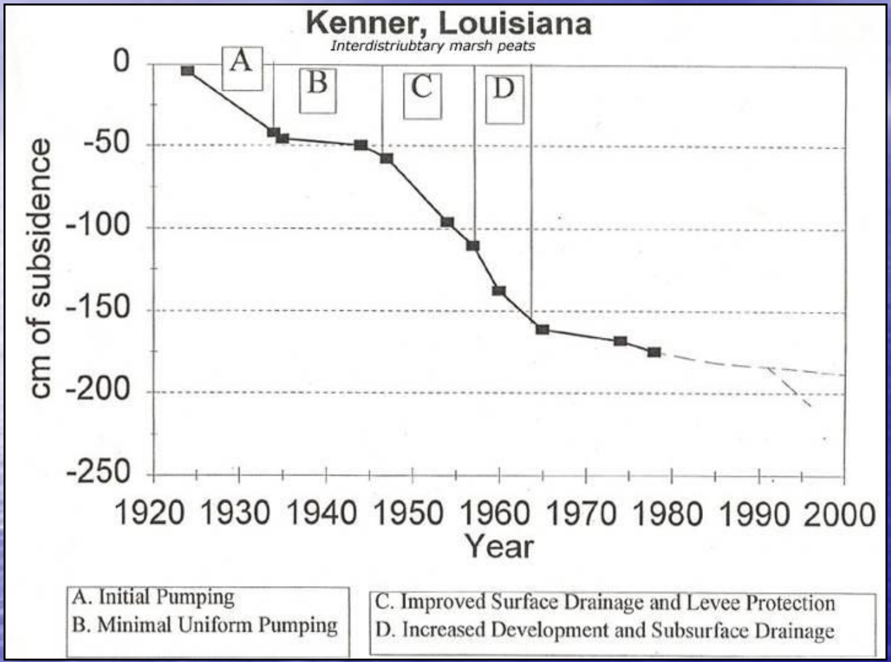
The interdistributary sediment package covering the old back swamps around New Orleans are under consolidated, and they exhibit gross settlements.

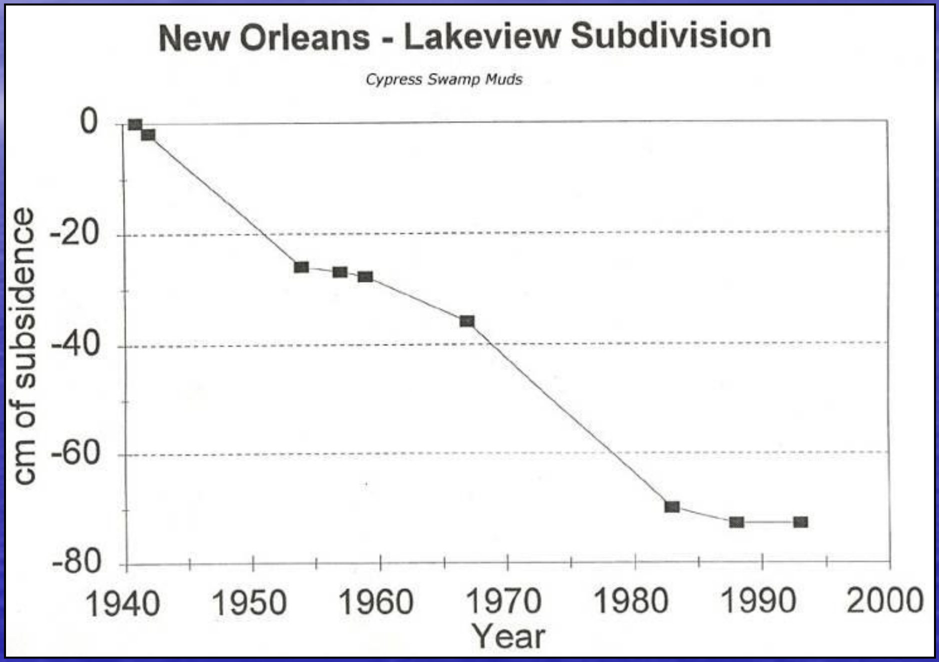
These examples are from the Lakeview area adjacent to the 17th St. Canal failure, where the ground appears to have settled 10 to 16 inches since 1956.

Most residential structures in New Orleans are founded on wood pilings 6 to 8 inches in diameter, driven 30 feet deep. The ground beneath these post-1950 homes has settled 10 to 18 inches.

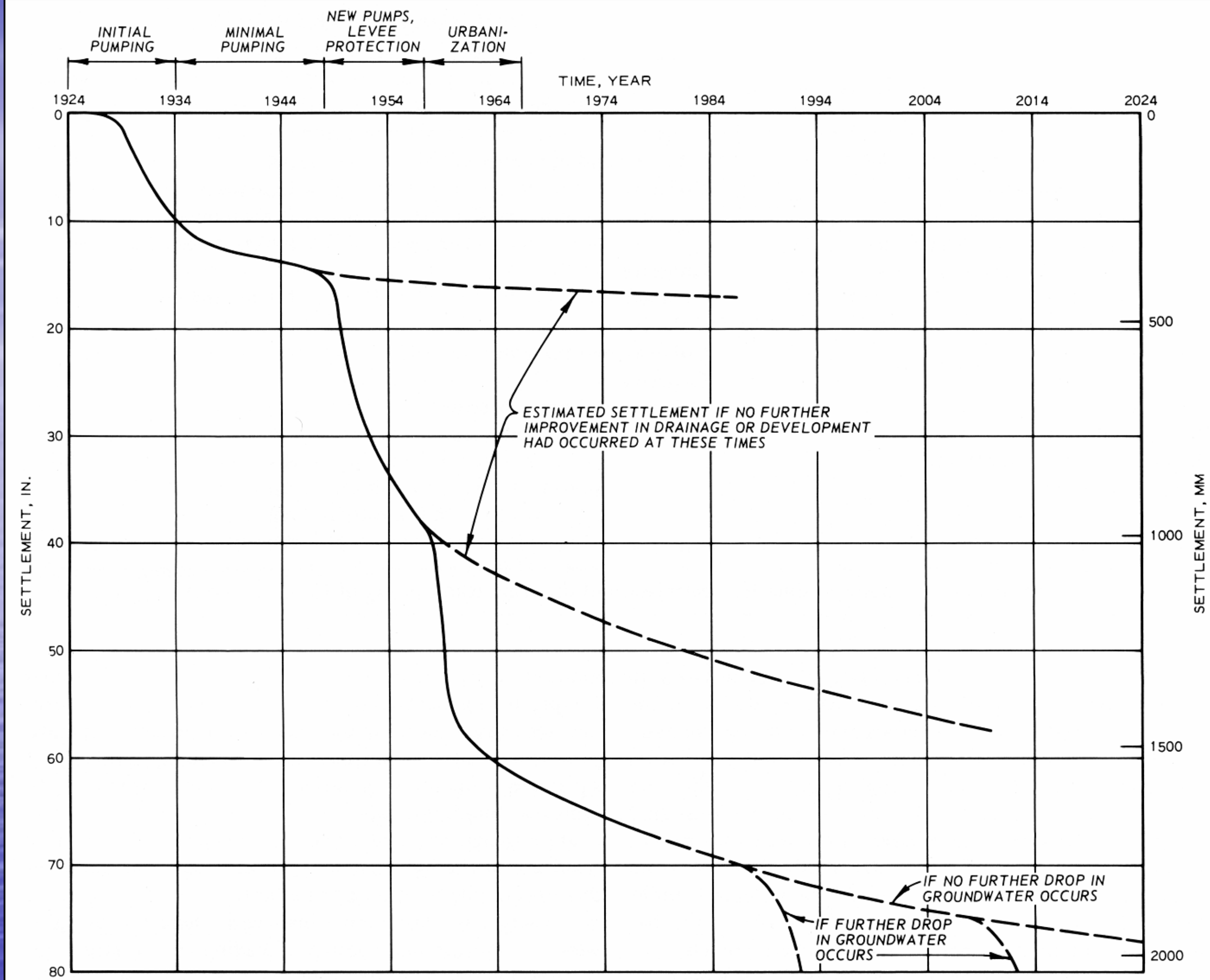
The mechanisms driving this settlement are likely drainage of near-surface soils, by dewatering and interception of storm water runoff, which is collected and conveyed to the city's pump stations.

Industrial and municipal groundwater withdrawal

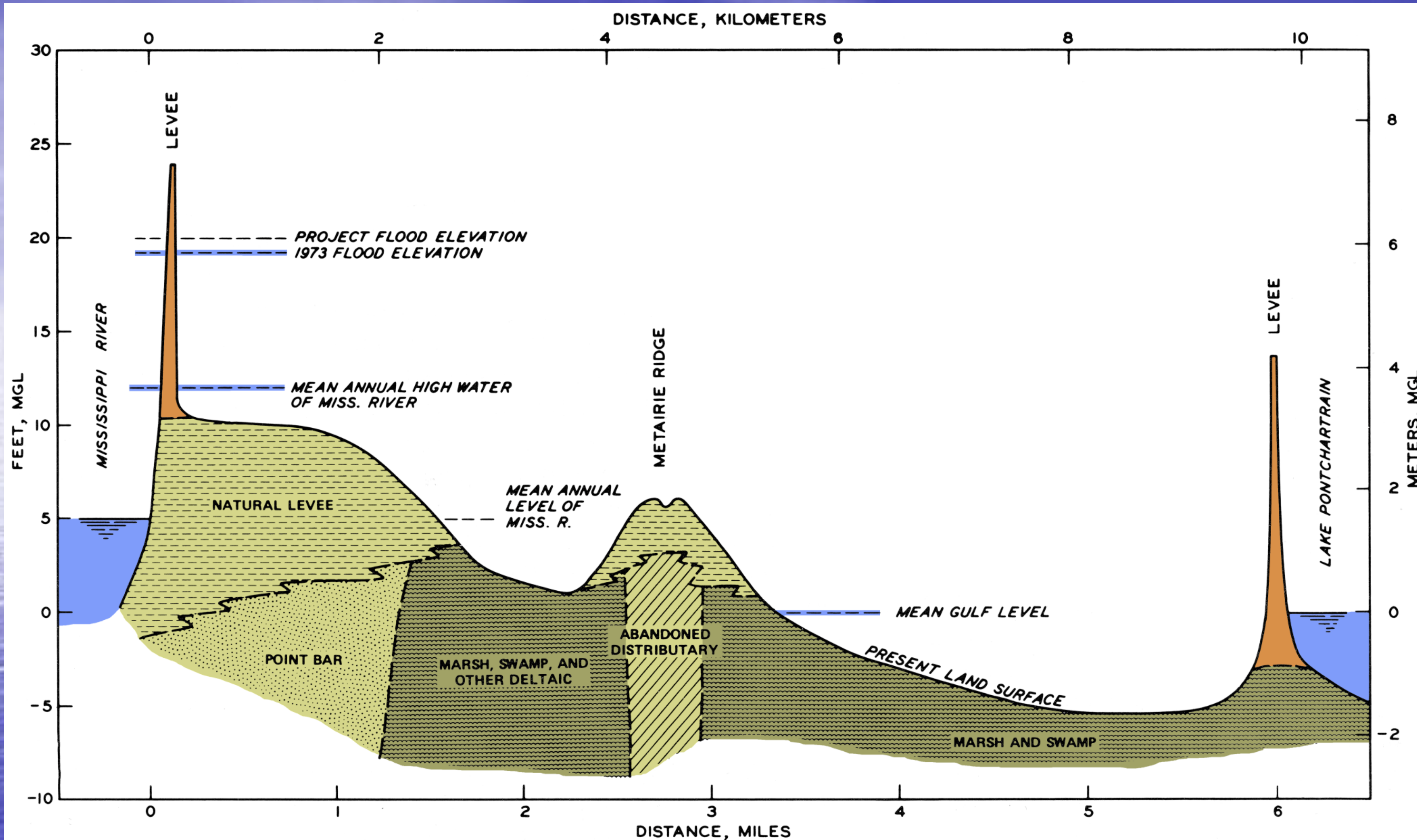




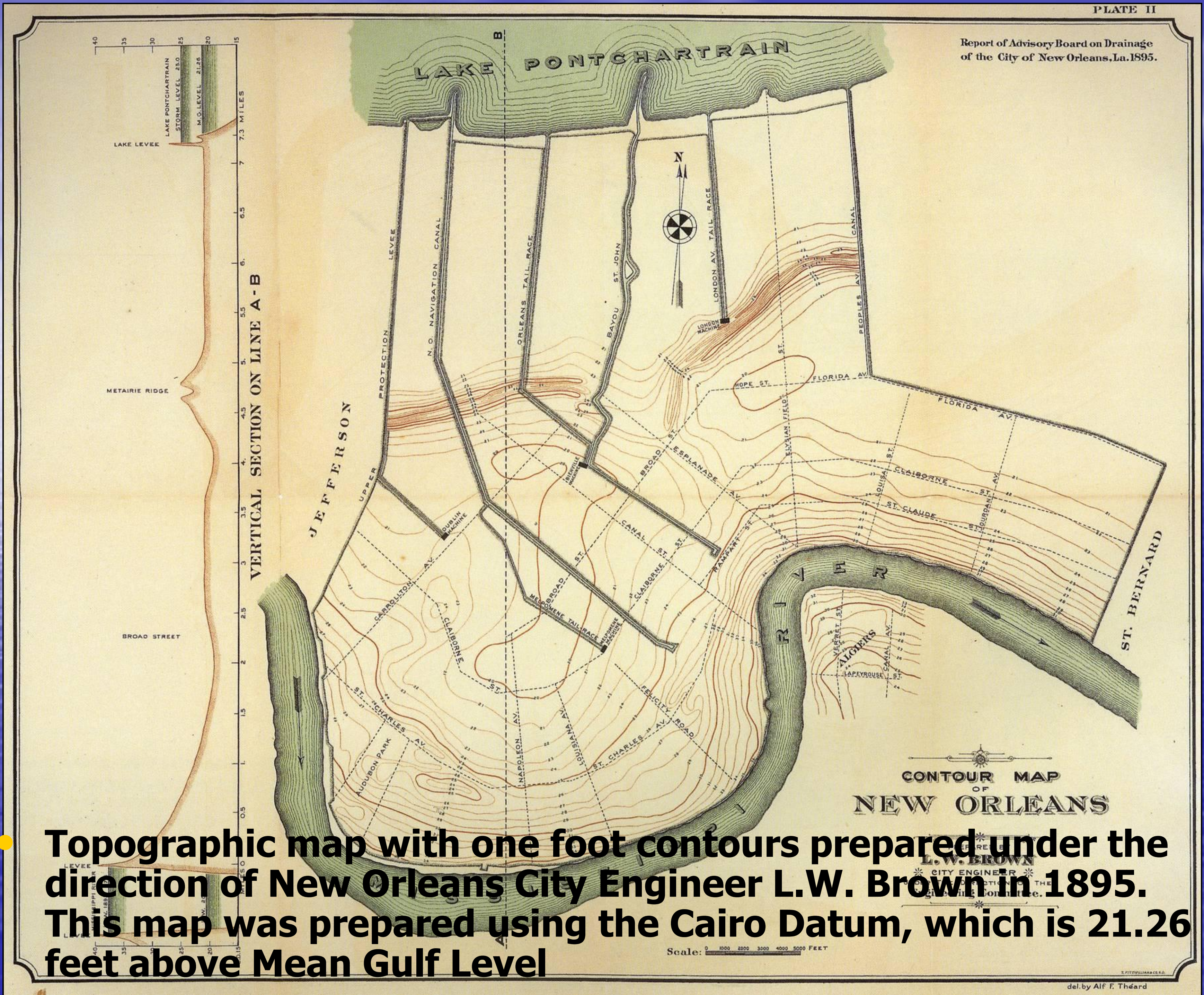
As groundwater levels are depressed by withdrawal of groundwater, organic-rich peaty soils are oxidized, and the ground settles. This settlement creates depressed zones below the grade of adjacent watercourses, which creates challenges for providing flood control.



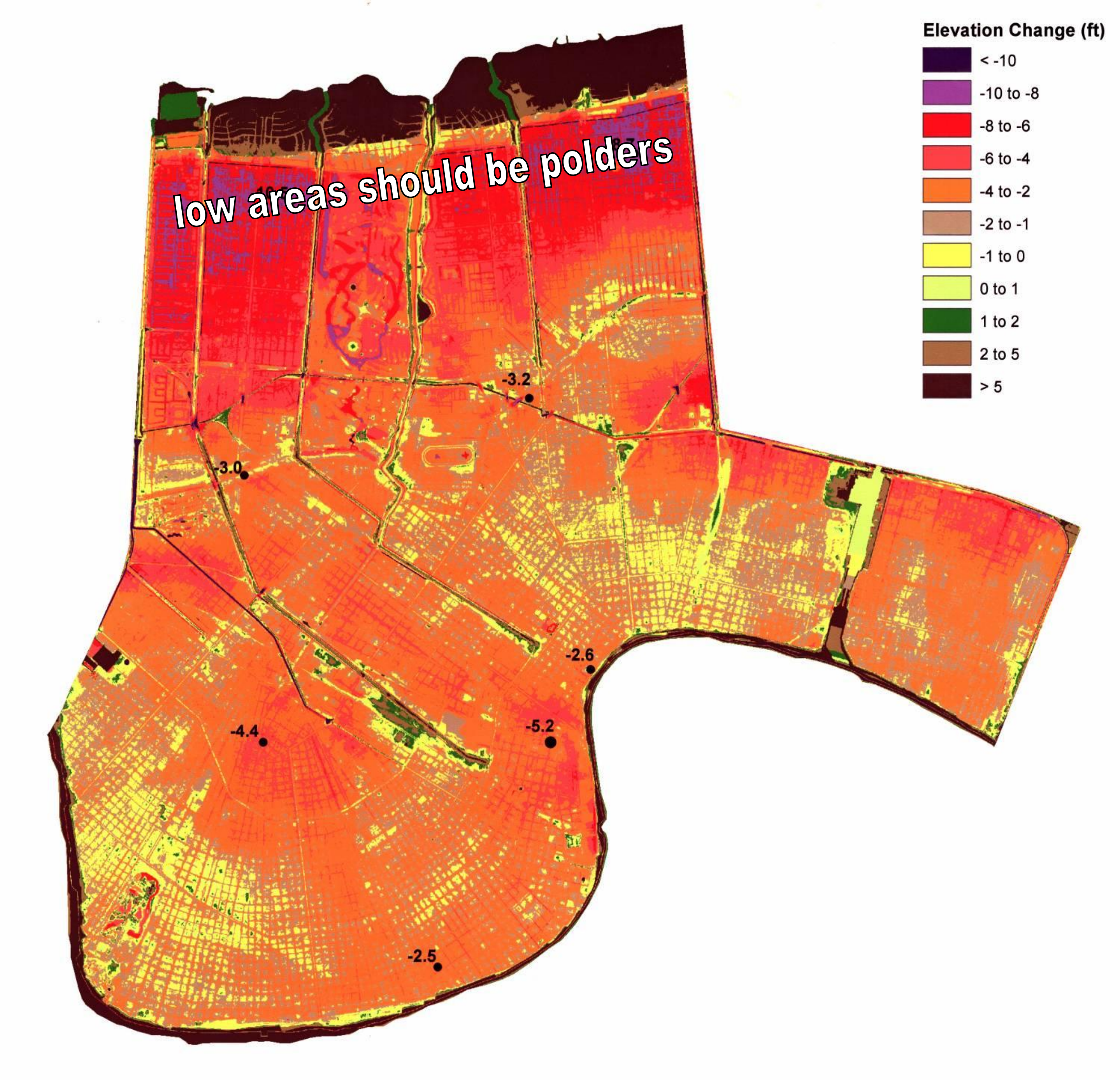
- Record of historic settlement in the town of Kenner, which is underlain by 6.5 to 8 feet of surficial peaty soils.
- The steps in these curves were triggered by groundwater withdrawal for industrial use and urban development. This area was covered by dense cypress swamps prior to development.



Much of New Orleans lies below sea level, Lake Ponchartrain, and the Mississippi River, making it particularly vulnerable to flooding. The Mississippi levee crest is 24.5 feet, while the Pontchartrain levee crest is 13.5 feet,



- **Topographic map with one foot contours prepared under the direction of New Orleans City Engineer L.W. Brown in 1895. This map was prepared using the Cairo Datum, which is 21.26 feet above Mean Gulf Level**



- Map showing **relative elevation change between 1895 and 1999/2002**, from URS (2006).
- The net subsidence was between 2 and 10+ feet, depending on location.

STRUCTURAL SURCHARGING

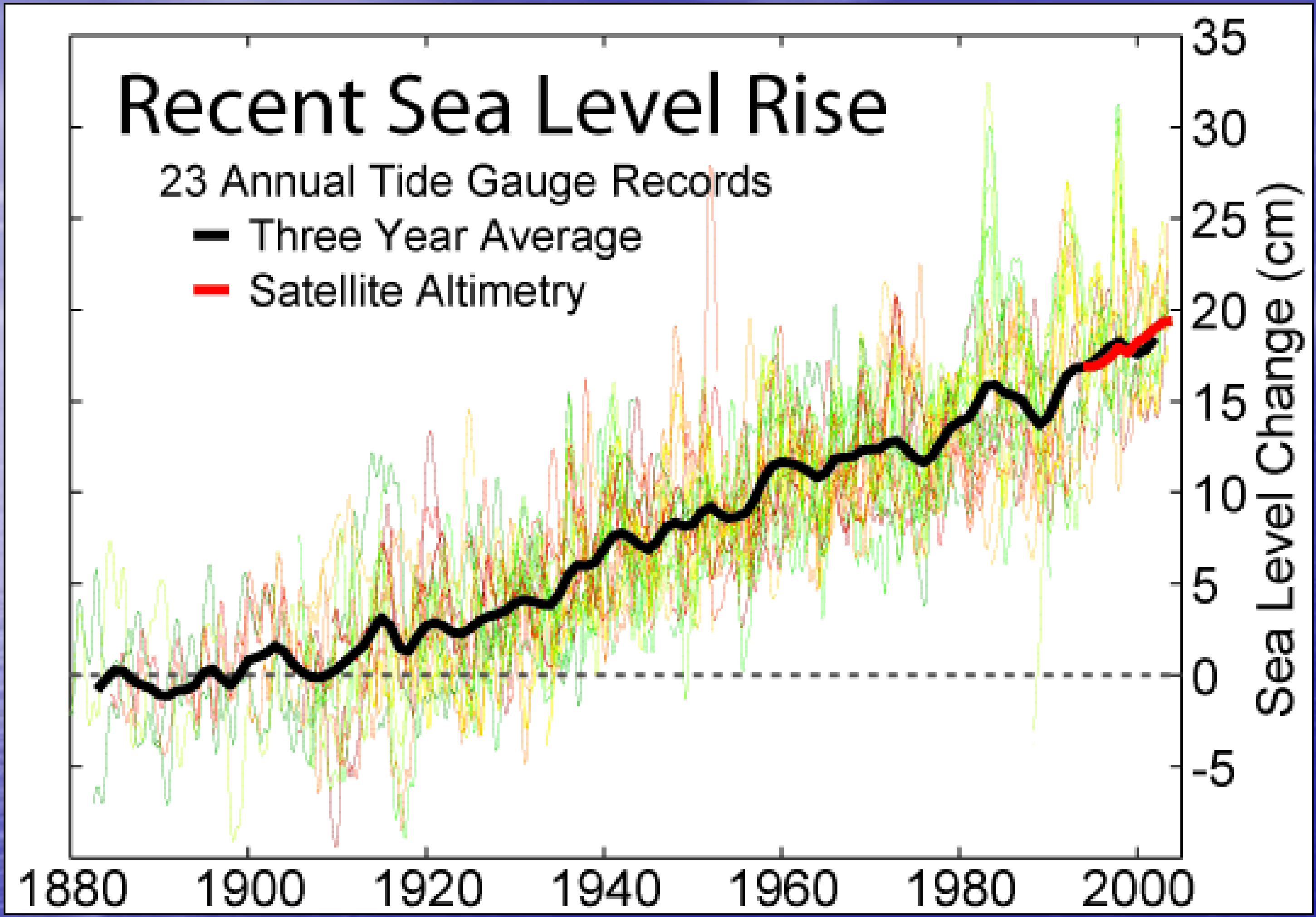
- An interesting aspect of the URS-FEMA settlement study is the marked increase in settlement in the Central Business District, where tall structures are founded on deep piles. This area settled 5 inches in 100 years, but the settlement was much less away from the heavy structures
- *Even the sandy river levees have settled 2 inches*; likely due to surcharging by MR&T levee heightening between 1928-60

Mechanisms of Ground Settlement -1

- 1) Elastic deformation of Mississippi Delta from silt deposition (isostasy)
- 2) Tectonic compaction caused by formation of pressure ridges and folding
- 3) Subsidence on seaward side of lystric growth faults
- 4) Drainage of old swamp and marsh deposits increasing stress on underlying clays
- 5) Biochemical oxidation of peaty soils

Mechanisms of Ground Settlement -2

- **6) Consolidation of compressible soils** caused by surcharging with fill
- **7) Surcharging** by structural improvements
- **8) Reduced groundwater recharge** in developed areas because of impermeable surfaces
- **9) Extraction of oil, gas, and water** causing pressure depletion
- **10) Solutioning** of salt domes and **seaward migration** of low density materials (salt and shale)



Coastal land loss in Louisiana is also exacerbated by **sea level rise**, which averaged about 1 foot during the last 100 years. This value could accelerate during the 21st Century, to as much as 3 feet.

The National Debate that has erupted since Katrina....

- **Can we build levees that won't fail?**
- **Should we, as a society, allow or encourage urban development of lands that are either: 1) below sea level; or, 2) barely above sea level?**
- **People who choose to live in high risk areas should pay greater insurance premiums for the privilege of living in those areas**
- **Should we bother trying to save the Mississippi Delta? Why? *New Orleans ships the greatest volume of exported goods from the USA, mostly wheat, corn, and soy.***

Is it within the grasp of our society to save the Mississippi Delta?

- One modern analog – The Netherlands, following the 1953 floods; but this also involved a substantial investment, almost 30% of their GNP for 20 years.
- Can we apply 21st Century technology to help solve these immense challenges?
- Diverting sediments onto the land will require a much greater investment in operations and maintenance, several orders of magnitude more than we've spent heretofore.

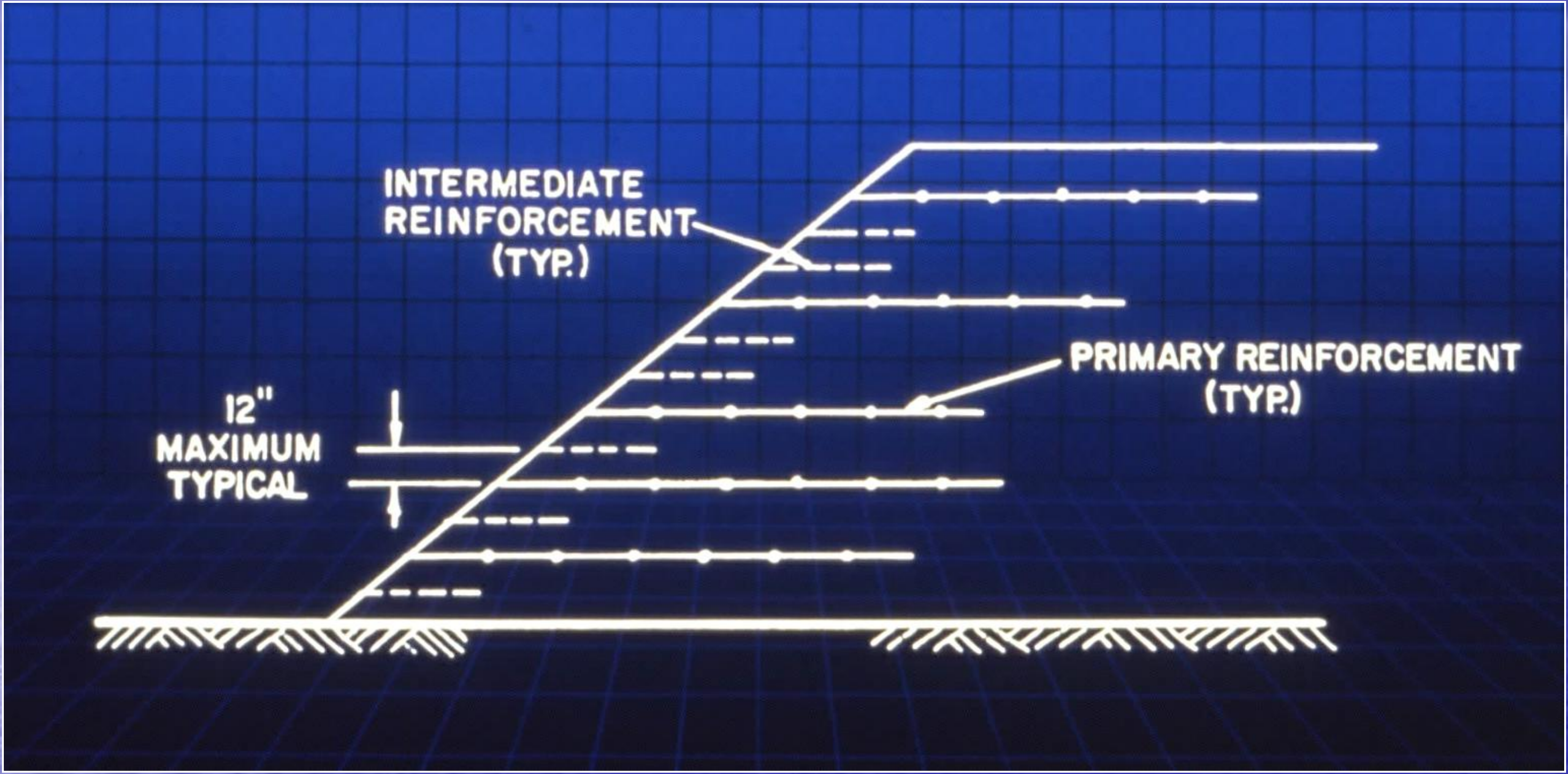
Earthen Levees are old technology

Levees are susceptible to erosion by *overtopping*, by *edified flow*, and by *undercutting*.

Once flood waters overtop an embankment they quickly scour the land-side toe of the embankment, and deep scour holes develop on either side of the "*hydraulic jump*" that forms at the point of overflowage, enlarging the breach, as shown here.

COULD *SOIL REINFORCEMENT* TECHNOLOGIES BE APPLIED TO CREATE MORE ROBUST PROTECTION SYSTEMS ?

- Geogrid-wrapped hay bales or gravel filled HDPE baskets can be used as facing elements for **mechanically-stabilized embankments**.
- These materials do not corrode and plants and trees can take root in them, so they are more "environmentally friendly"

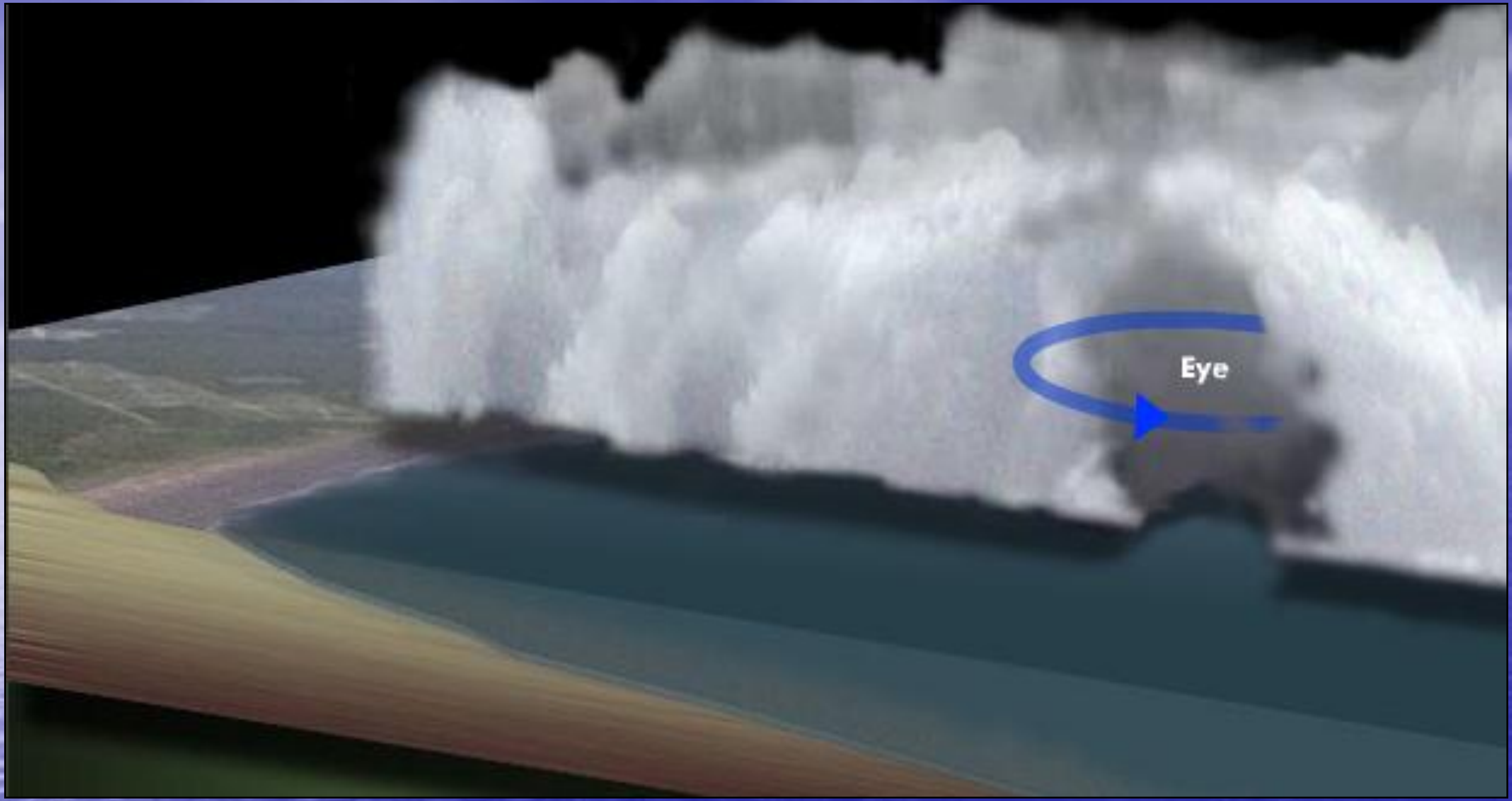


- We can make embankments slopes as steep as we desire by using "false layers," of geotextiles, between primary reinforcement layers of mechanically stabilized embankments (MSE).
- These false layers restrict slope raveling and erosion

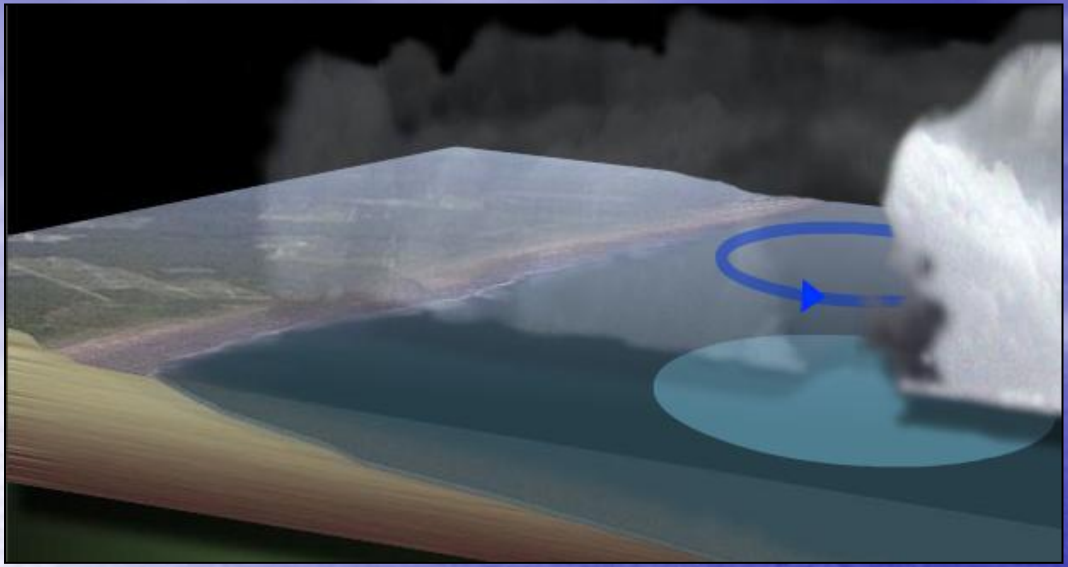
- Example of a 45 degree fill face supporting a shopping center complex adjacent to a line of mature trees. The embankment was constructed using false layers of geotextiles spaced 1 foot apart (from Rogers, 1992)

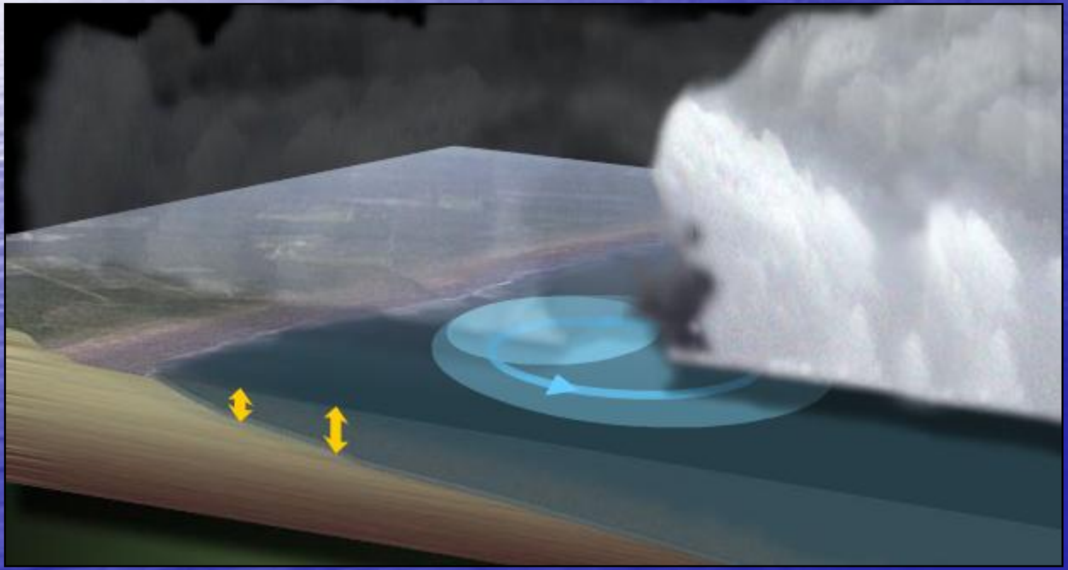
- Same 45 degree fill slope after hydroseeding and sprouting of fescue grass mix (from Rogers, 1992).

STORM SURGE AND WAVE ENERGY



- Storm or tidal surges are caused by lifting of the oceanic surface by abnormal low atmospheric pressure beneath the eye of a hurricane. The faster the winds, the lower the pressure; and the greater the storm surge. At its peak, Hurricane Katrina caused a surge 53 feet high under its eye as it approached the Louisiana coast, triggering a storm surge advisory of 18 to 28 feet in New Orleans (image from USA Today).



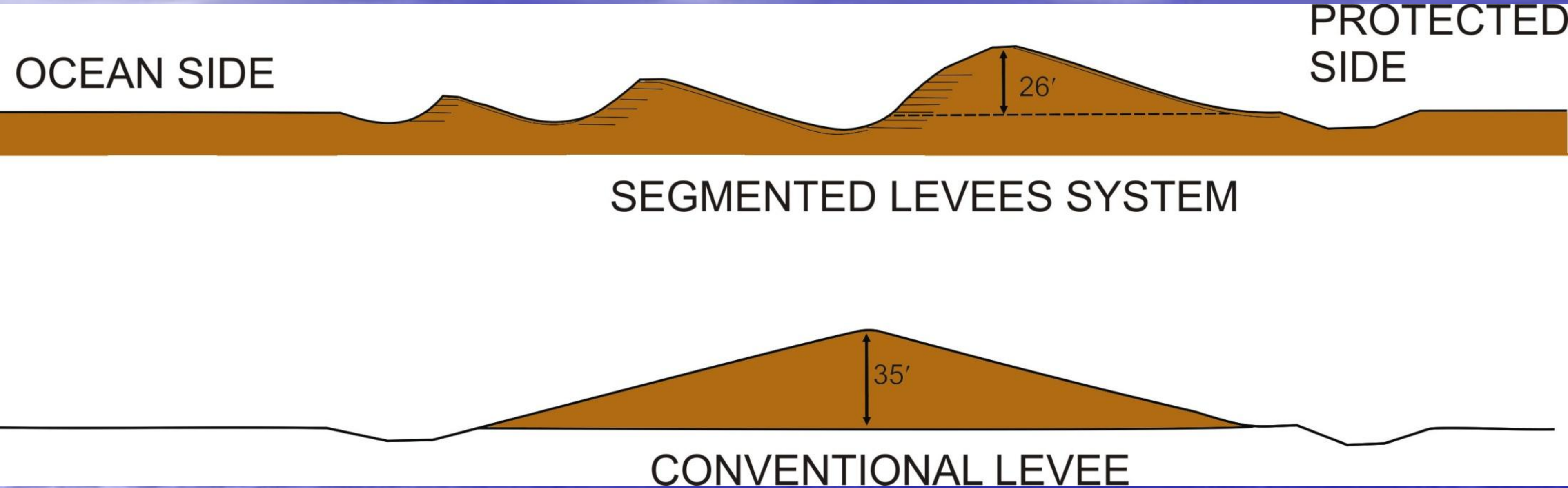


Images from USA Today

Storm Surge

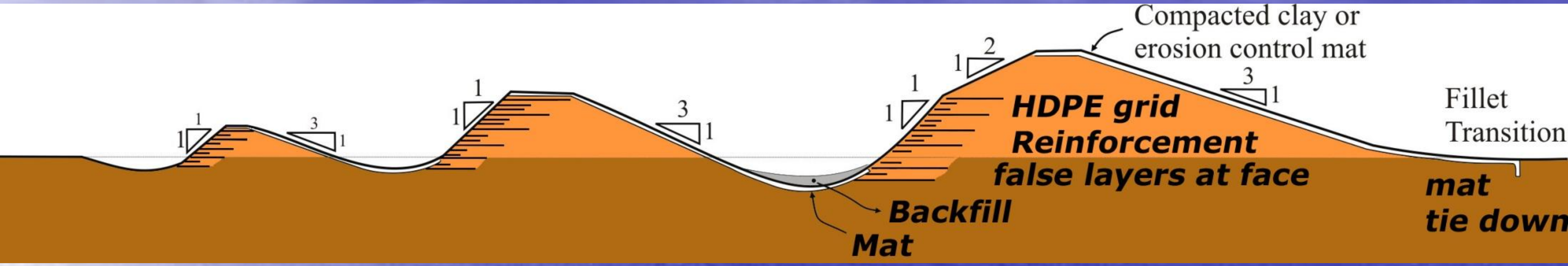
- The surge effect is minimal in the open ocean, because the water falls back on itself
- As the storm makes landfall, water is lifted onto the continent, locally elevating the sea level, much like a tsunami, but with much higher winds

Segmental Levee Systems

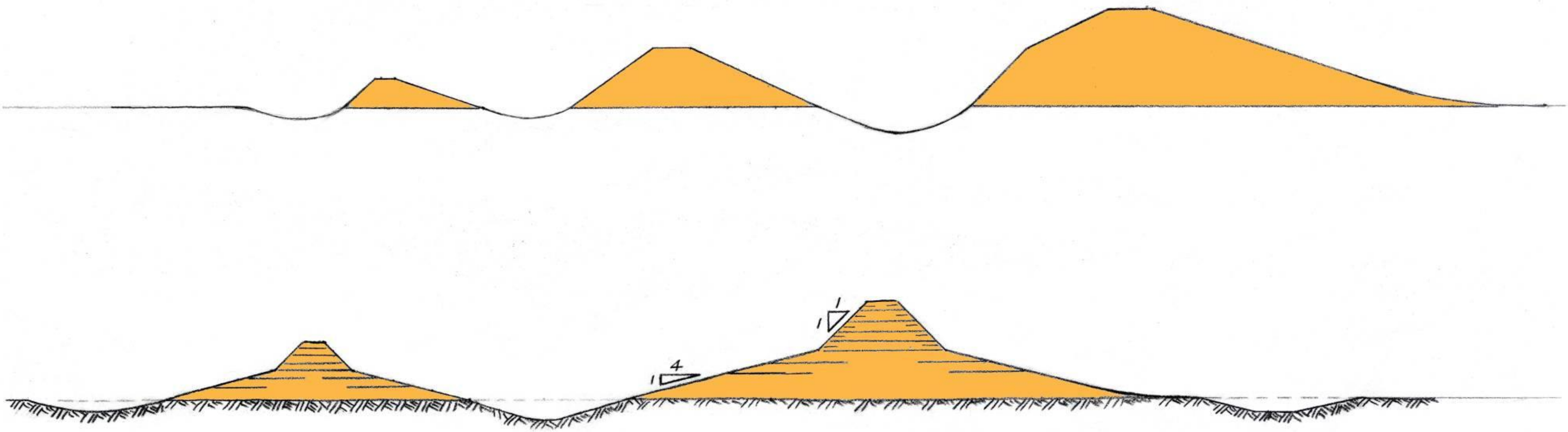


- In areas exposed to storm surge some thought might be given to equipping levees to be more efficient *energy dissipation systems;* and not just simple barriers. *Though more complicated, they might not have to be as high.*

Soil Reinforcement



- Soil reinforcement could be applied to engender greater shear strength, allowing much steeper cross sections
- Steeper side slopes form more efficient barriers to dissipate forward wave energy
- Note curved troughs between the embankments.



- HDPE geogrid soil reinforcement could be also be employed to engender *greater flexibility* in levee profiles, as suggested here.
- Levees could be molded into more efficient barriers to retard and survive storm surge
- The lower sketch shows how bearing loads could be reduced by employing soil reinforcement, allowing a greatly reduced cross sections.

Cypress Swamp die-off

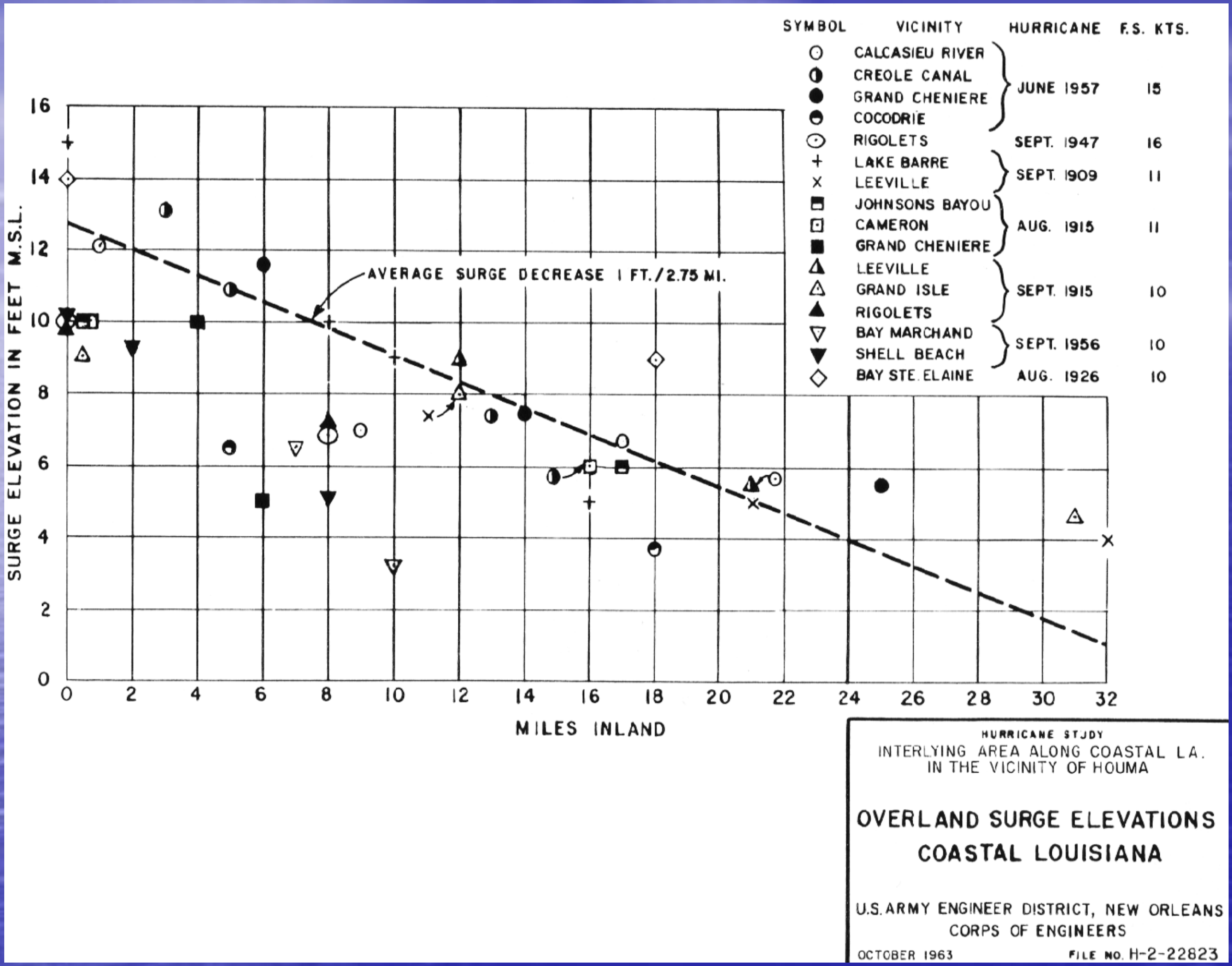
The entire delta is slowly subsiding. If new sources of sediment do not replenish the swamp, the **young cypress shoots cannot germinate in water > 2 feet deep**; and Cypress forests die off all at once, becoming a treeless, grassy marsh, with a forest of dead tree trunks.

Mature Cypress swamps retard storm surges by mechanically dissipating incoming wave energy

Much propaganda has been circulated concerning the potential mollifying effects of cypress forest dispelling wave energy, when hurricanes make landfall along the Louisiana Coast.

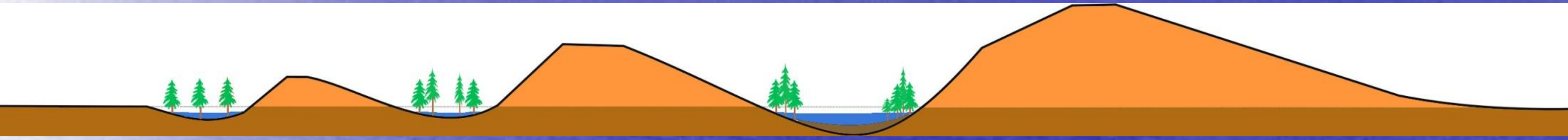
The most common-cited figure is 1 foot of storm surge reduction for every 2.7 miles of mature cypress swamp.

This value is not valid for the entire coastline. The actual impact depends on a number of physical factors.

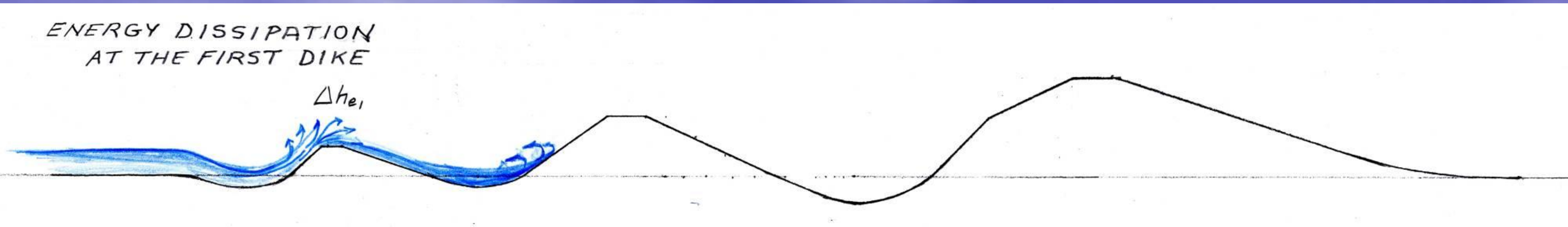


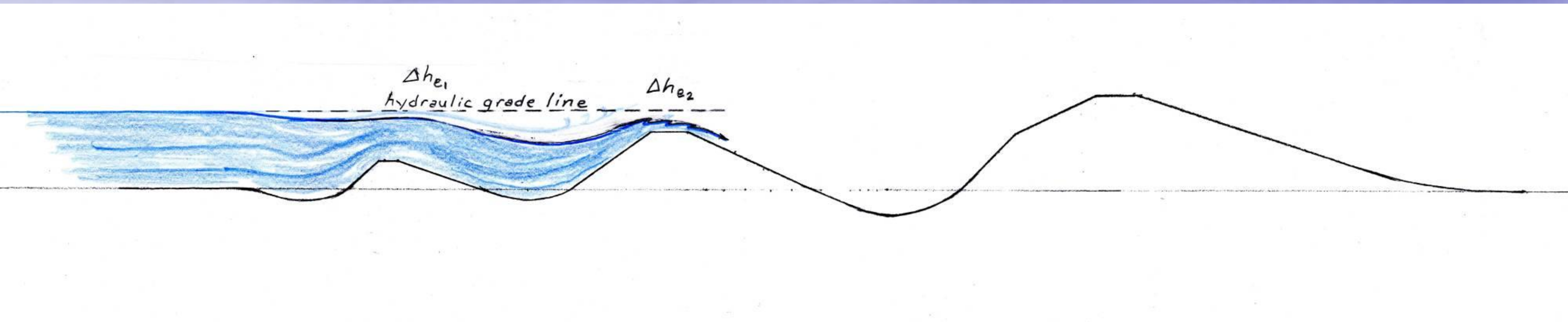
- Impact of coastal wetlands and cypress-gum swamps with storm surge reduction. The average decrease is 1 foot for every 2.75 miles of swamp.

Green Levees: Create troughs to promote growth of cypress trees as mechanical barriers

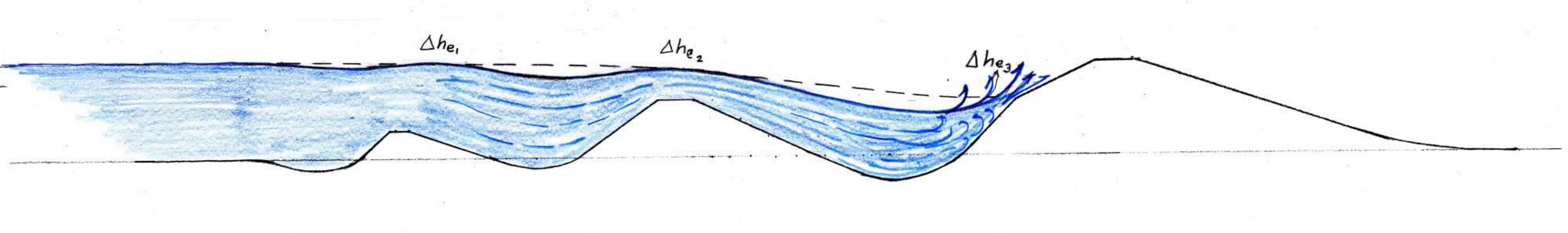


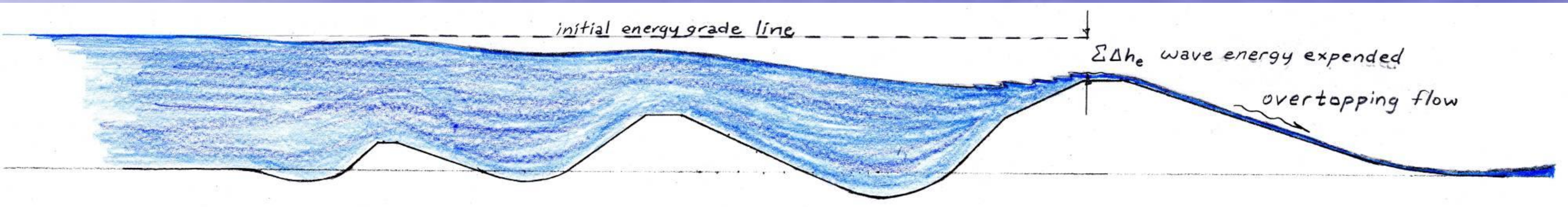
- Segmental levee systems could be crafted into "green" systems, which would employ swamp troughs between the embankments
- As the cypress trees mature, their impact on storm surge dissipation would increase, helping to offset freeboard losses caused by regional settlement





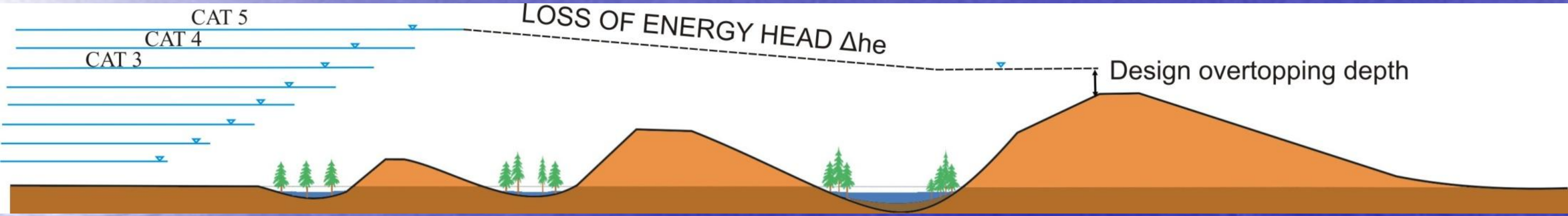
- Each flow obstruction will drain energy head from the advancing storm surge.
- Troughs with steep faces are some of the most efficient energy dissipaters, because the deflect forward energy upward.





- As the obstructions get larger, more and more wave energy is bled off and expended
- This might allow for a LOWER crest elevation for the highest embankment
- <u>The system should be designed to survive short-term overtopping</u> (e.g. 12 hours)

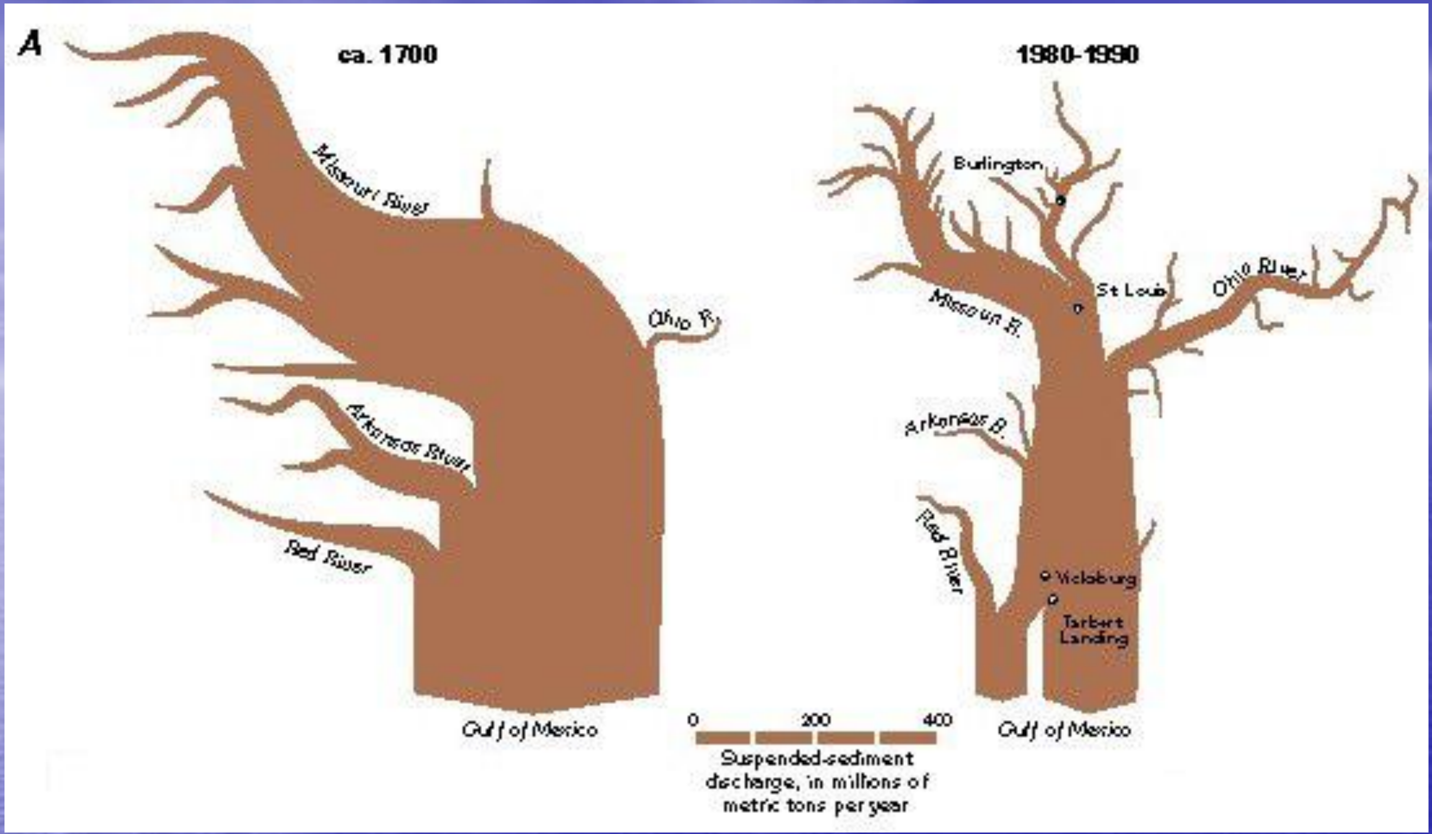
Maximum Flexibility, with Innumerable Design Options



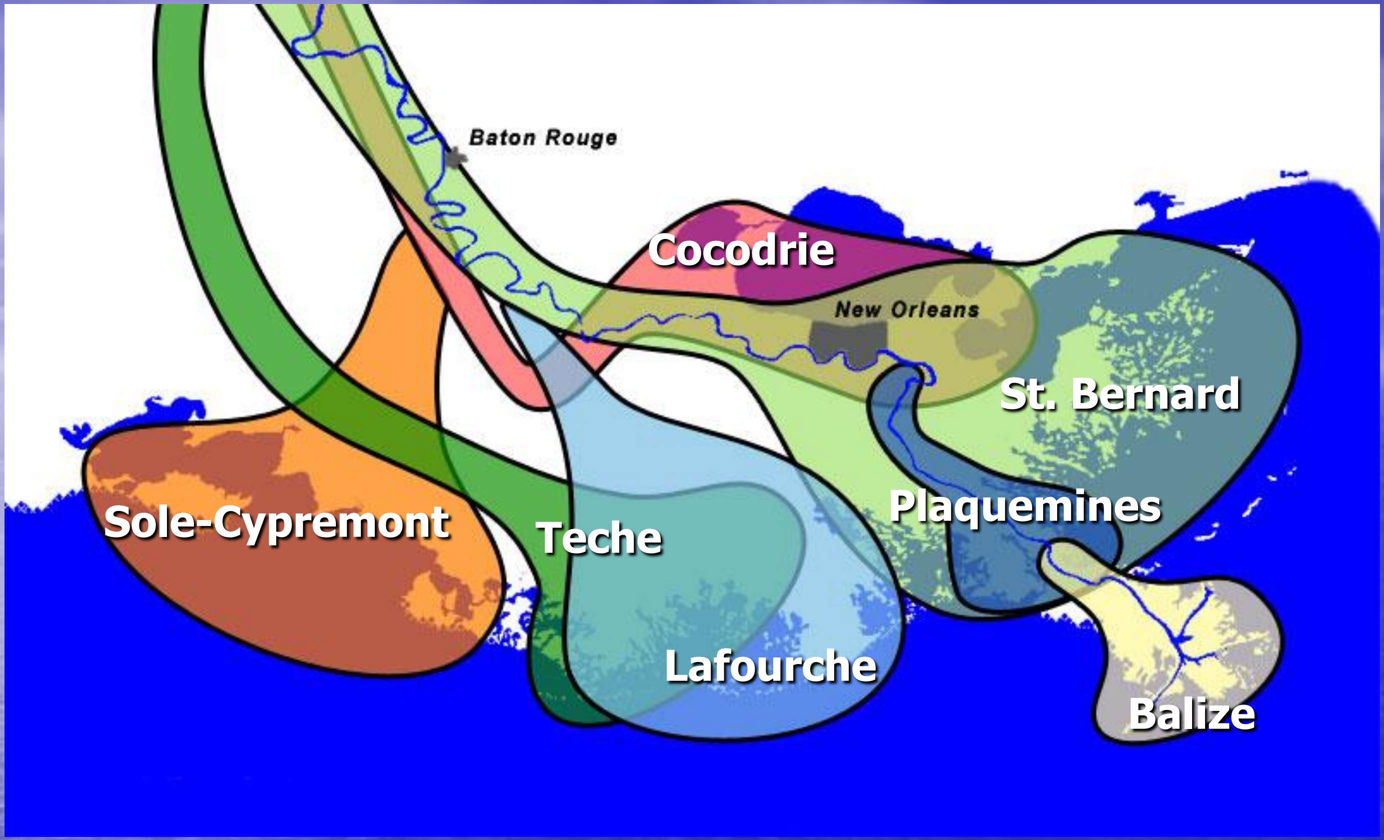
- Green segmented levee protection systems could be tweaked for any number of variables; including a *design overtopping depth* to accommodate low frequency events; without using as much earth fill as conventional embankments.

CAN WE DO A BETTER JOB OF RETARDING LAND LOSS FOSTERED BY DIMINSIHED SILTATION IN THE DELTA?

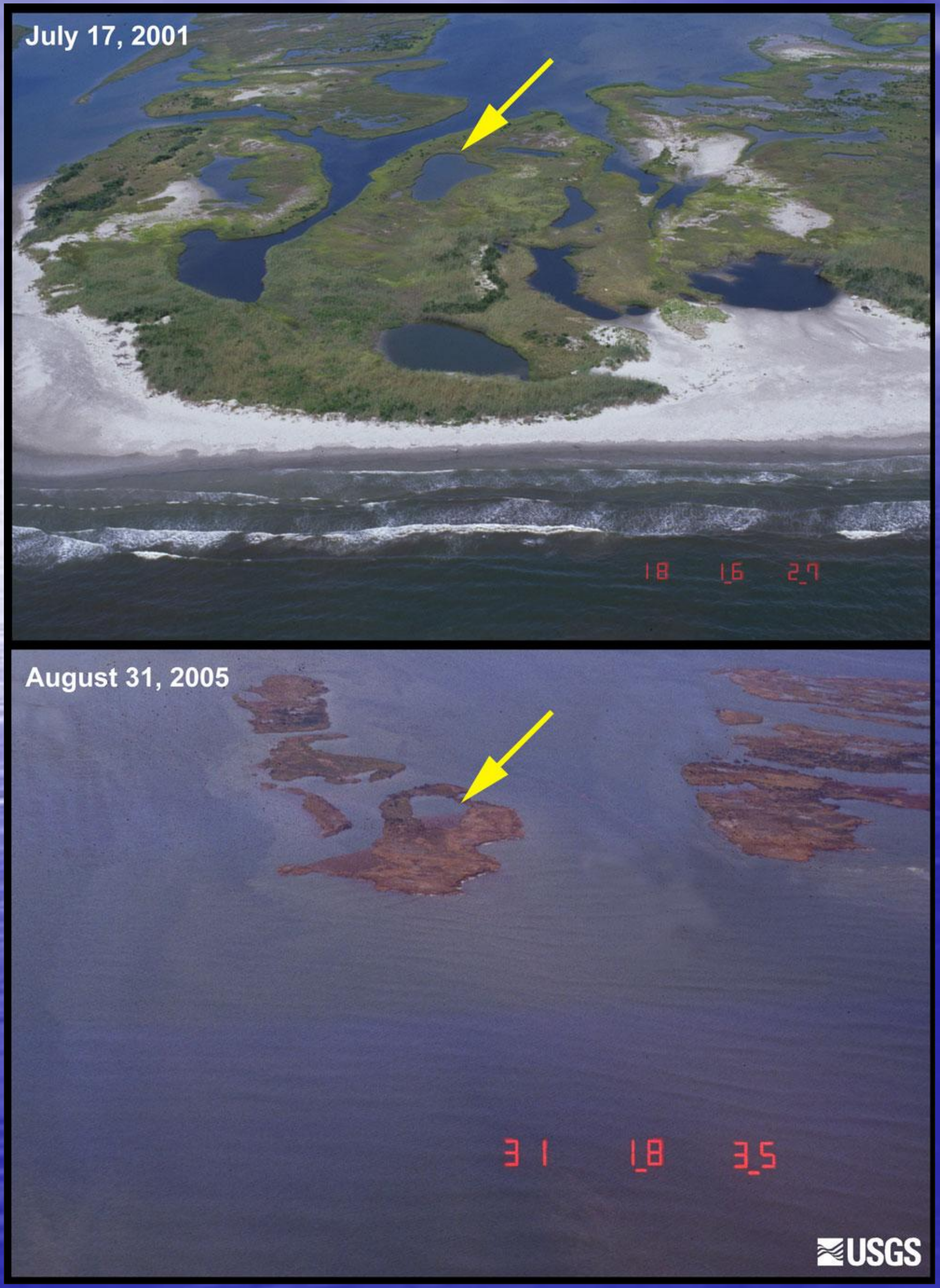
- The Mississippi River drains approximately 41% of the continental United States, discharging about 580 km^3 of water each year (420 billion gpd).
- Almost 50% of the water comes from the Ohio River, which has 1/6th of the watershed.
- The Missouri River encompasses 43% of total watershed area, but only contributes 12% of the discharge.



- Prior to 1700, the average sediment discharge was about 440 million tons/year, mostly from the Missouri River watershed.
- This figure has decreased about 50% since 1950, because of dams constructed on Missouri and Arkansas Rivers.
- This loss somewhat compensated by 5 to 10 fold increase in sediment load carried down the Ohio River, because of row farming and deforestation.

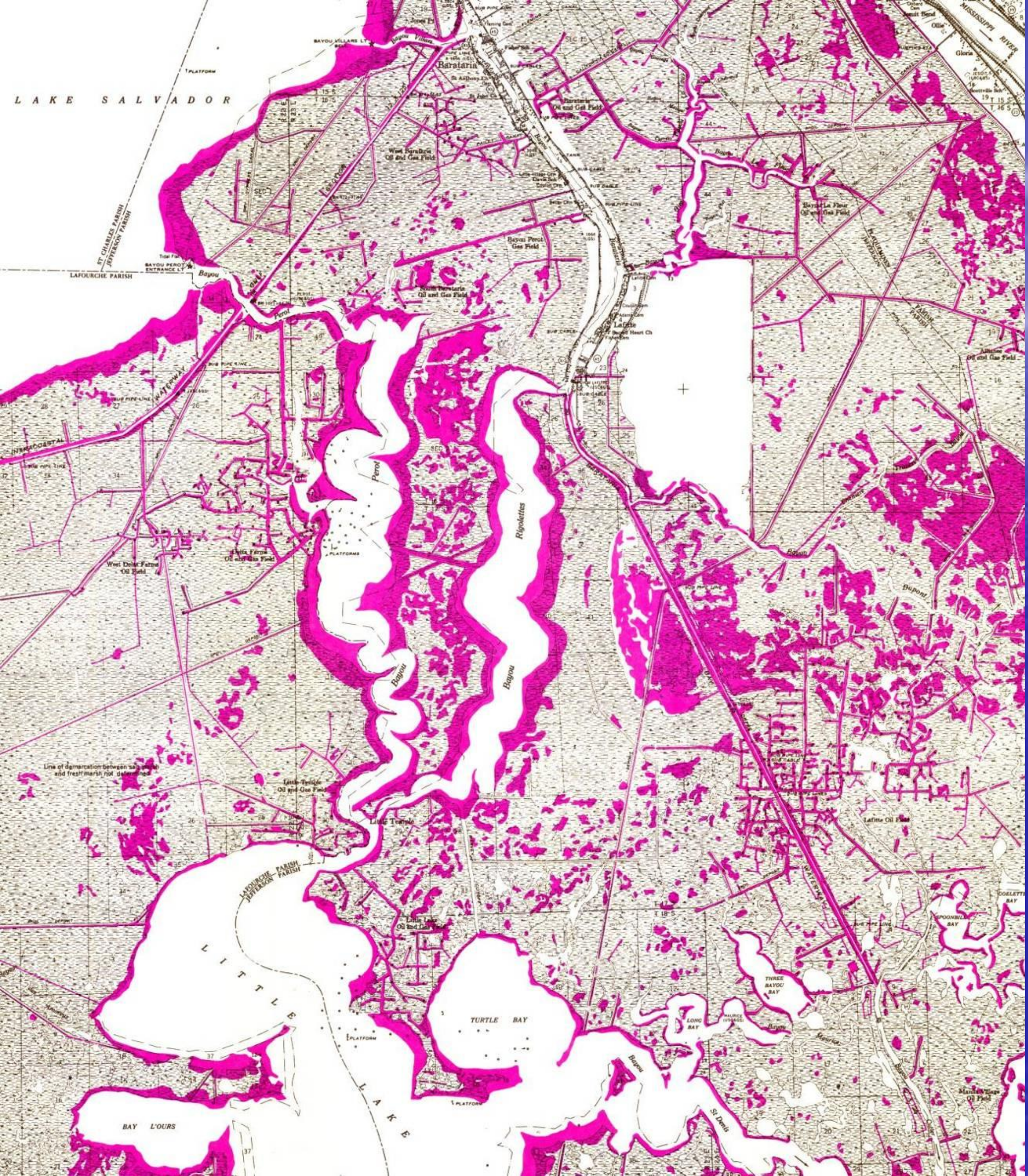


- **The river has deposited enormous deltaic lobes during the late Holocene: Balize (550 yrs); Plaquemines (750-500); Lafourche (1000-3000); St. Bernard (2500-1000); Teche (3500-2800); Cocodrie (4600-3500); and Sole-Cypremont (>4600).**



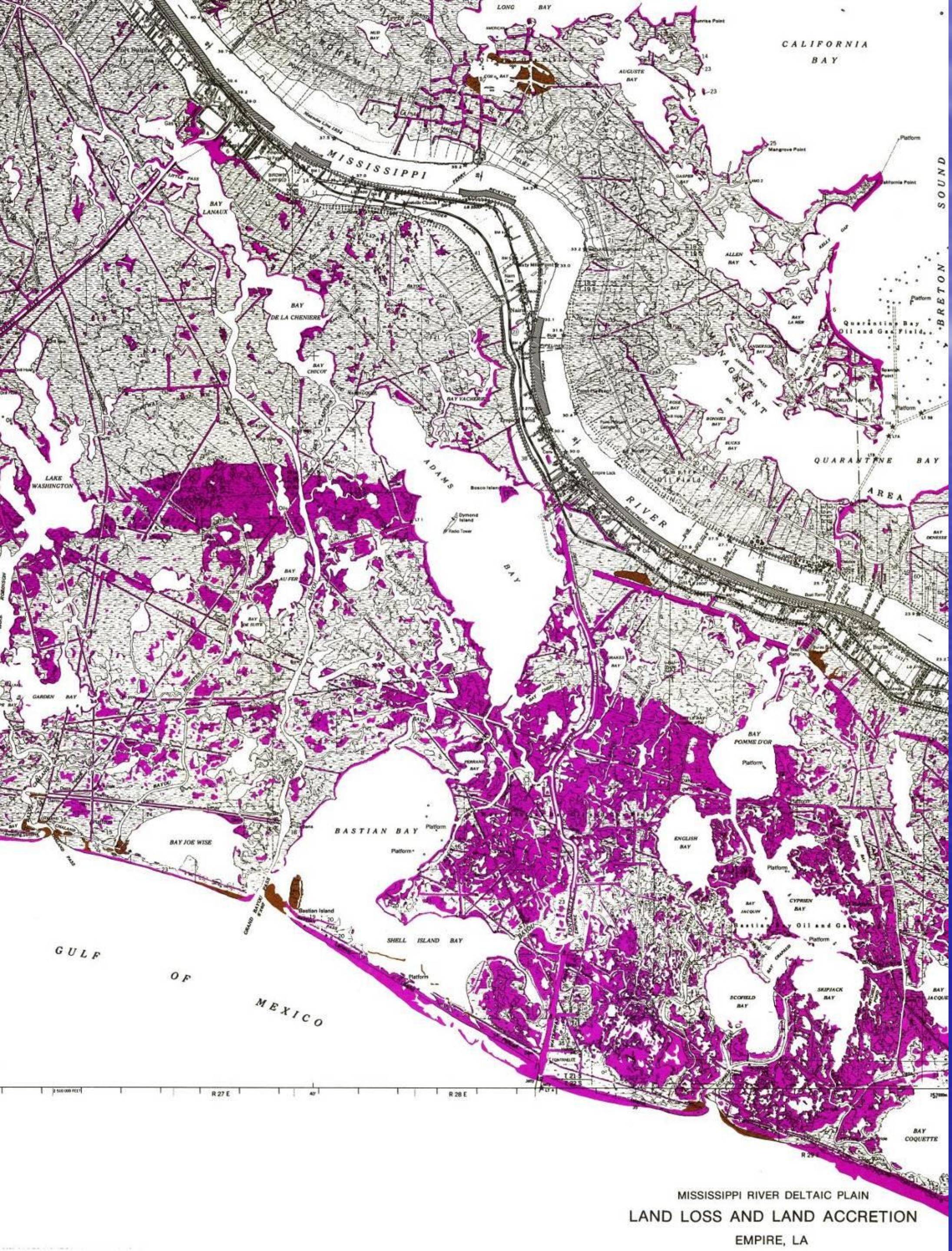
Dynamic Environment: Chandelier Islands; before and after Katrina

- Wave erosion stripped off sandy cohensionless deposits during Hurricane Katrina
- 4000 people were killed in this area in the 1915 hurricane



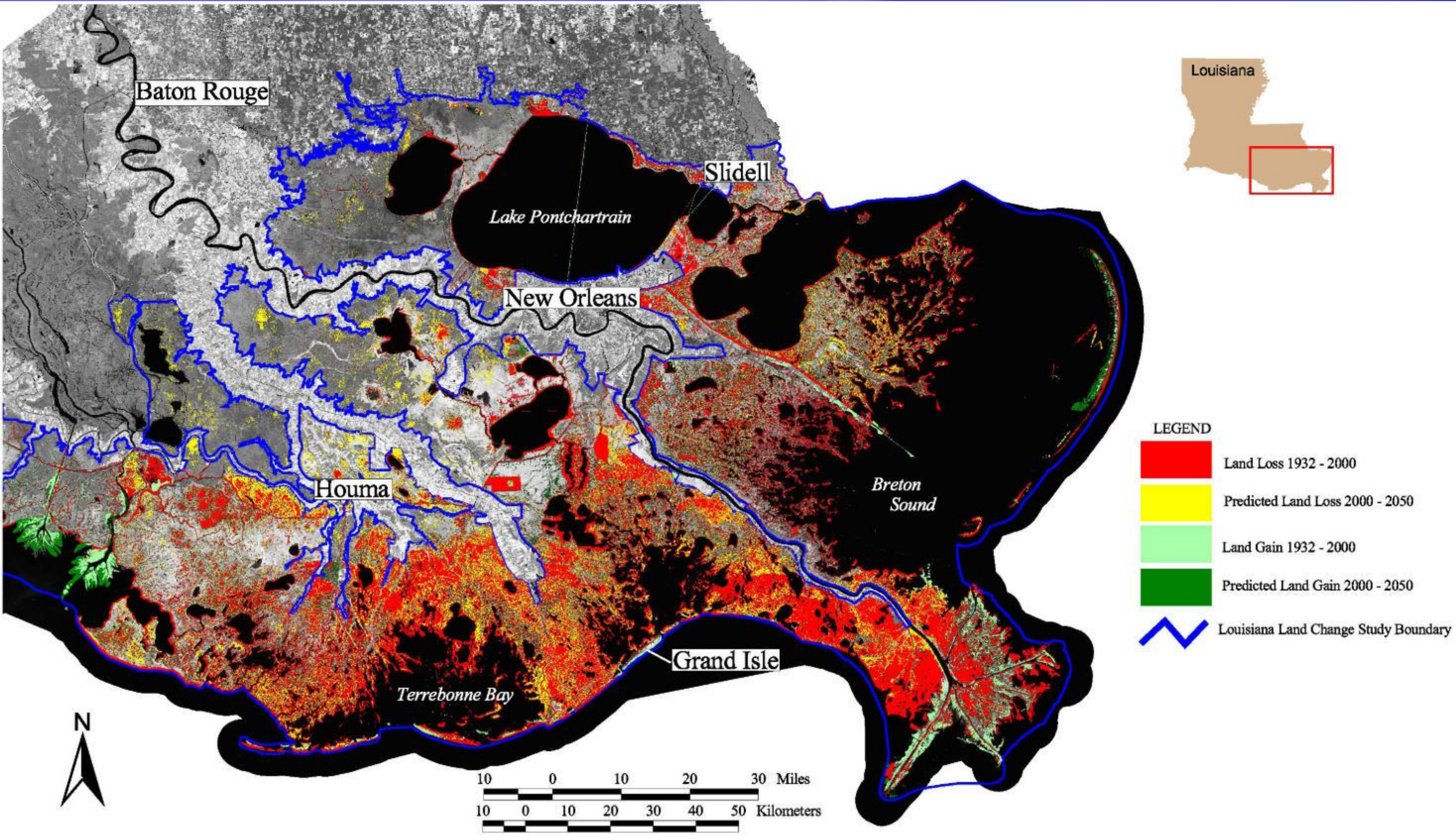
Land Loss Barataria Quadrangle

- Coastal land loss has been accelerating since 1950
- Annual sediment volume about 750 million tons/yr prior to 1950



Coastal land Loss – Empire quadrangle

- **Since 1950, the average sediment load of the Mississippi River has been reduced to about ~215 million tons per year.**
- **But, most of this is lost out the jetties**



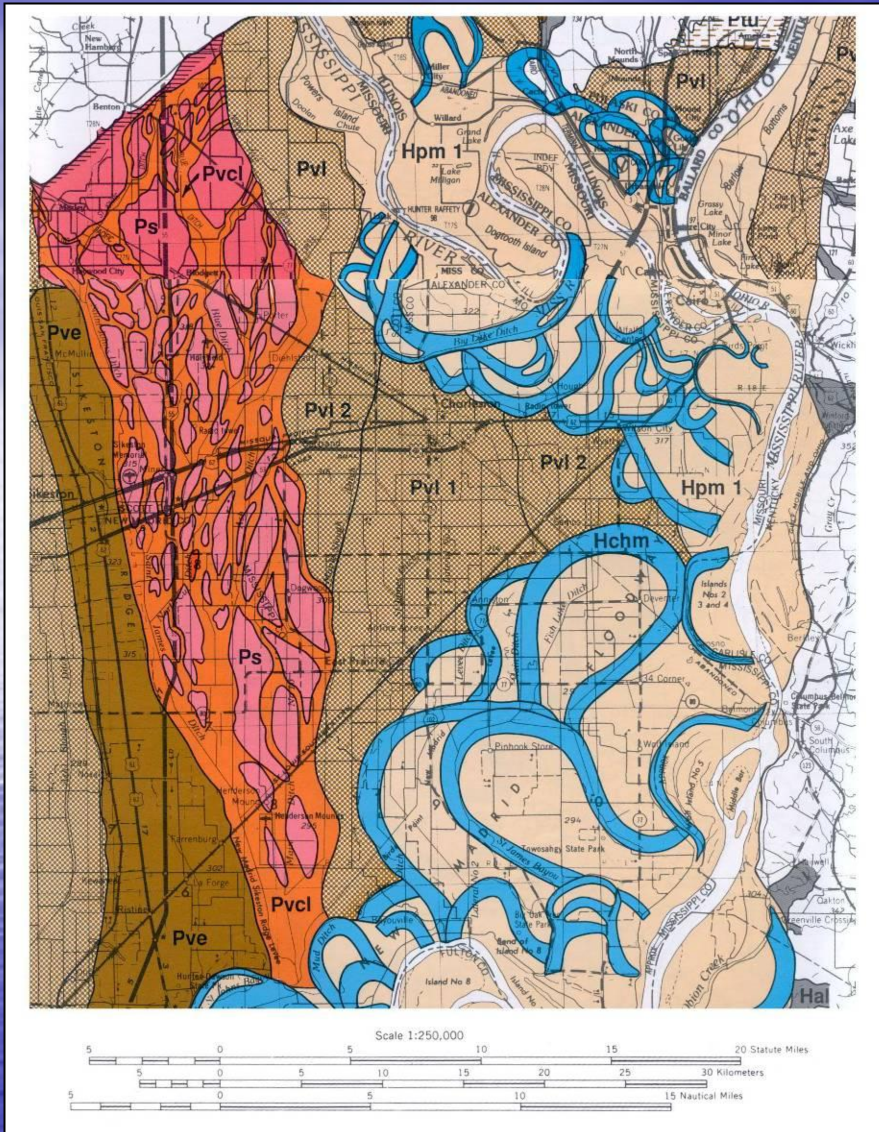
- **Coastal Land Loss since 1932 (red) and land gain (green). We are losing about 50X more land mass than we are saving at present, even with the 2050 plan. (data from Ray Dokka at LSU).**

The physical situation:

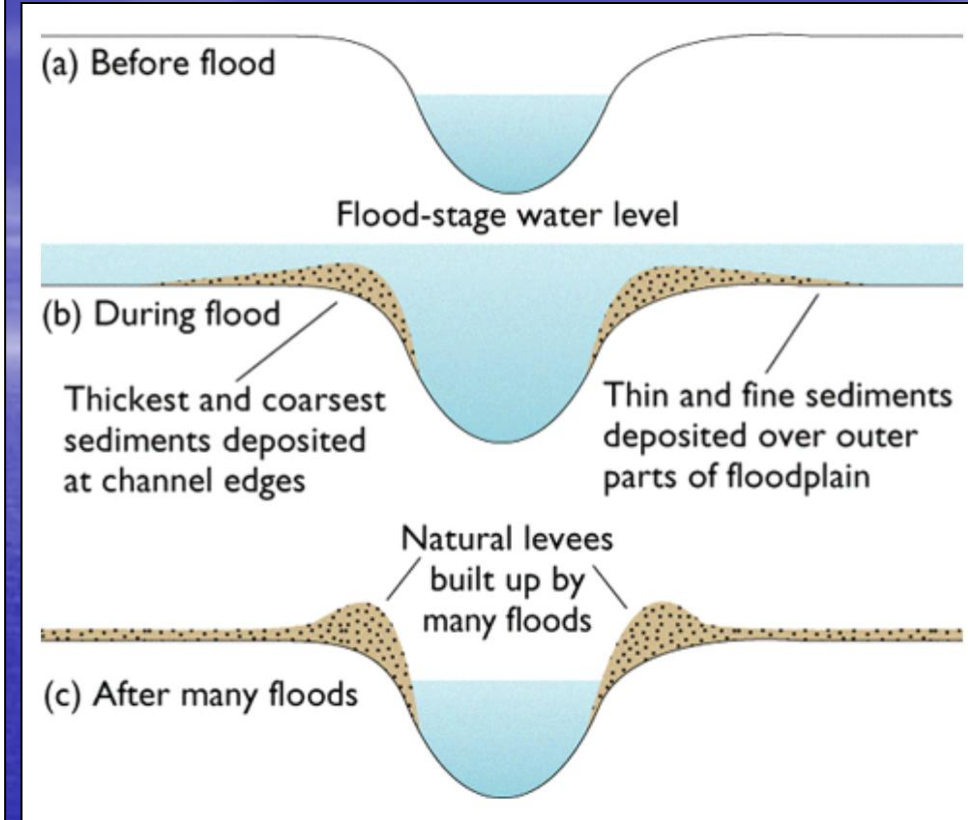
the river runs down in a deep hole…

The design problem:

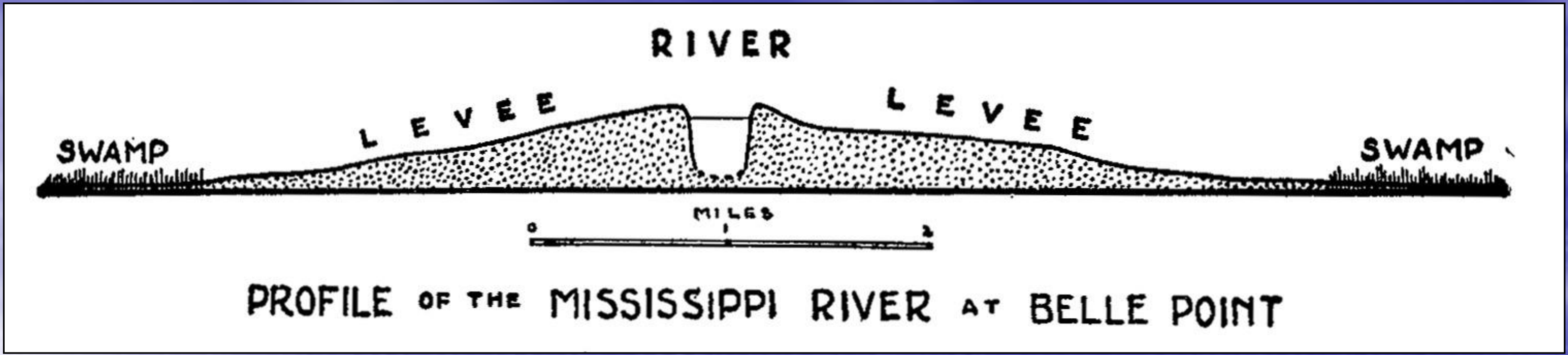
how can we extract its sediment?

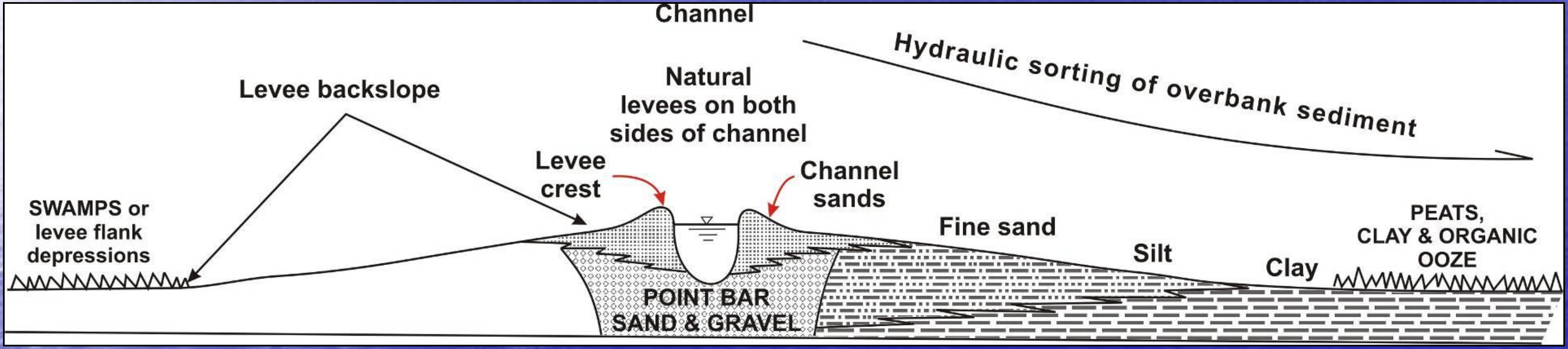


Map of Mississippi River Valley showing abandoned meanders. The active channel is shown in white along right side of map.

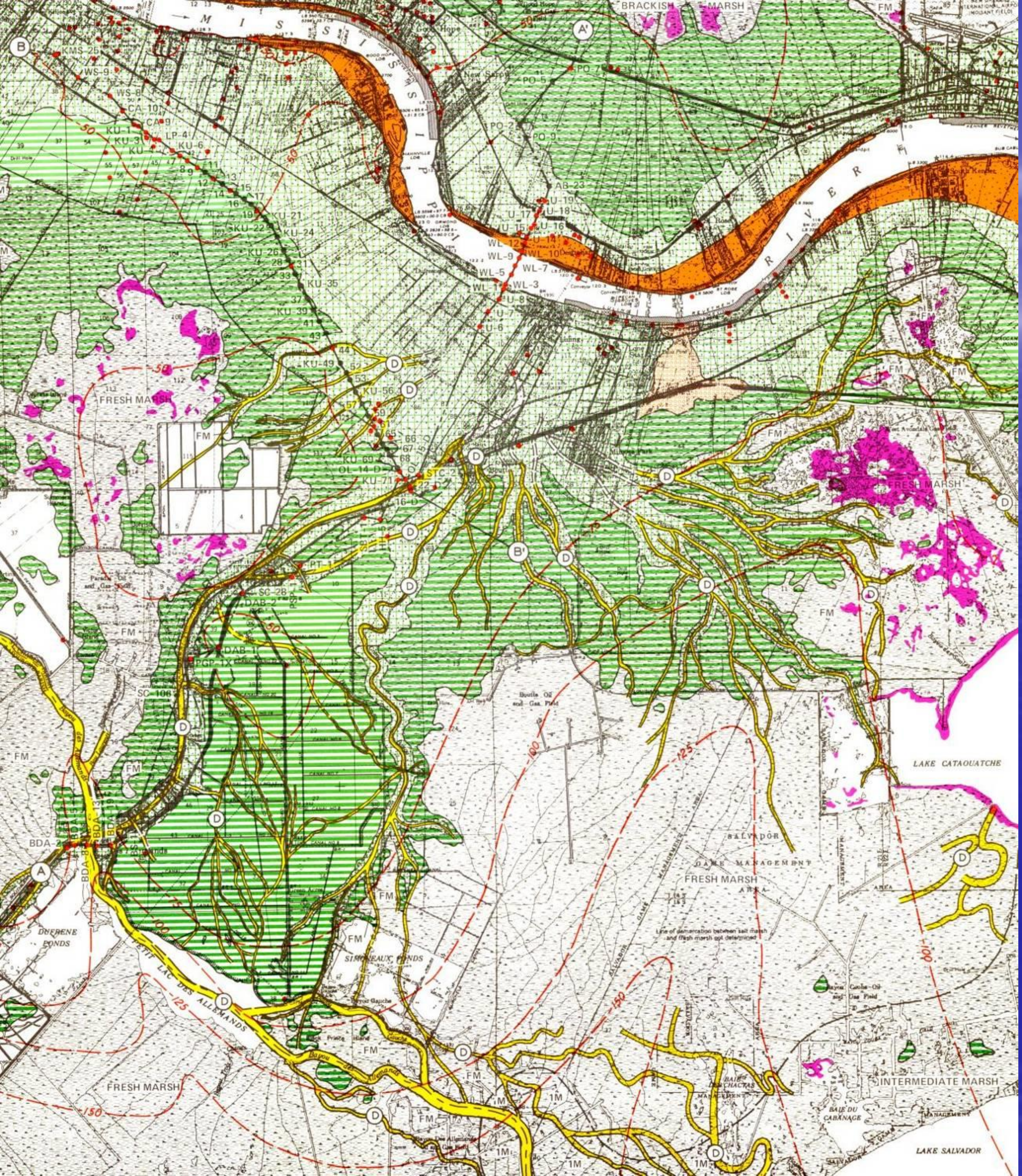


- The Mississippi River has developed some impressive natural levees





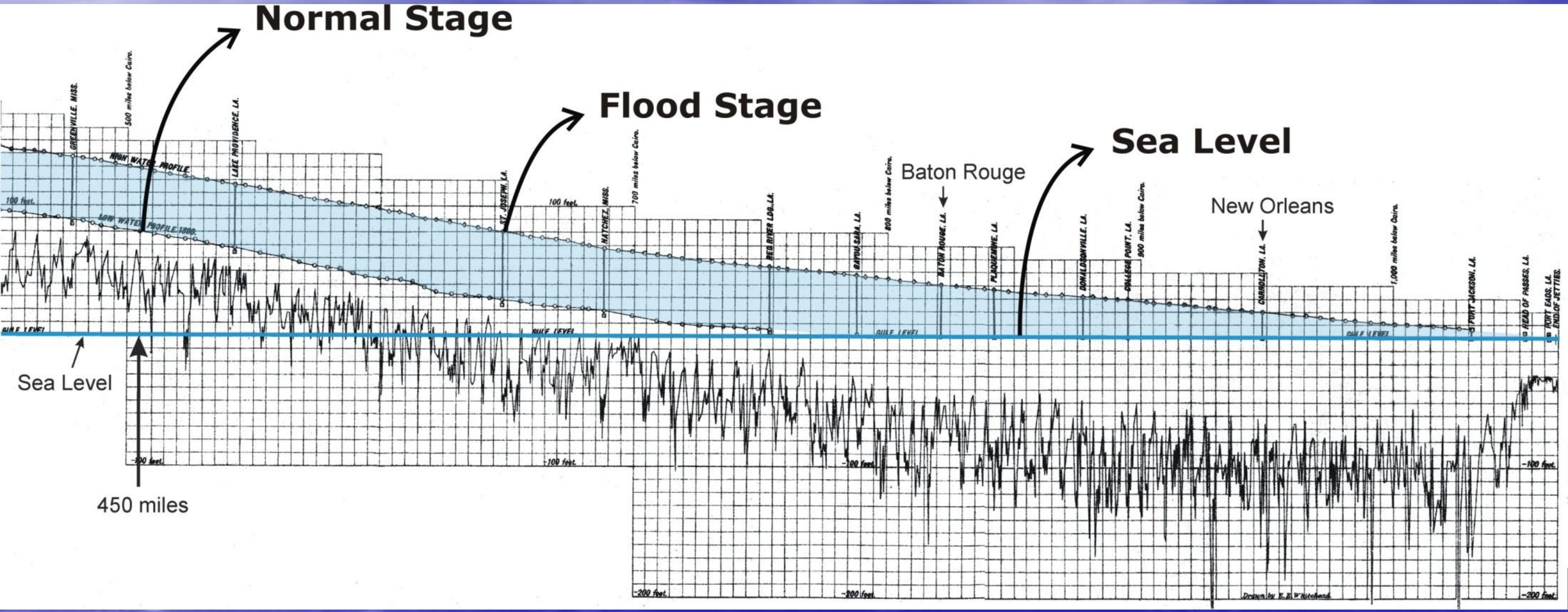
- **Typical cross section through the sandy bank levees of the Mississippi River, illustrating how the river's main channel lies above the surrounding flood plain, which were poorly drained swamp lands prior to reclamation.**
- **There is significant hydraulic sorting of materials deposited on either side of these levees, as sketched below.**



Hahnville is just upstream of New Orleans

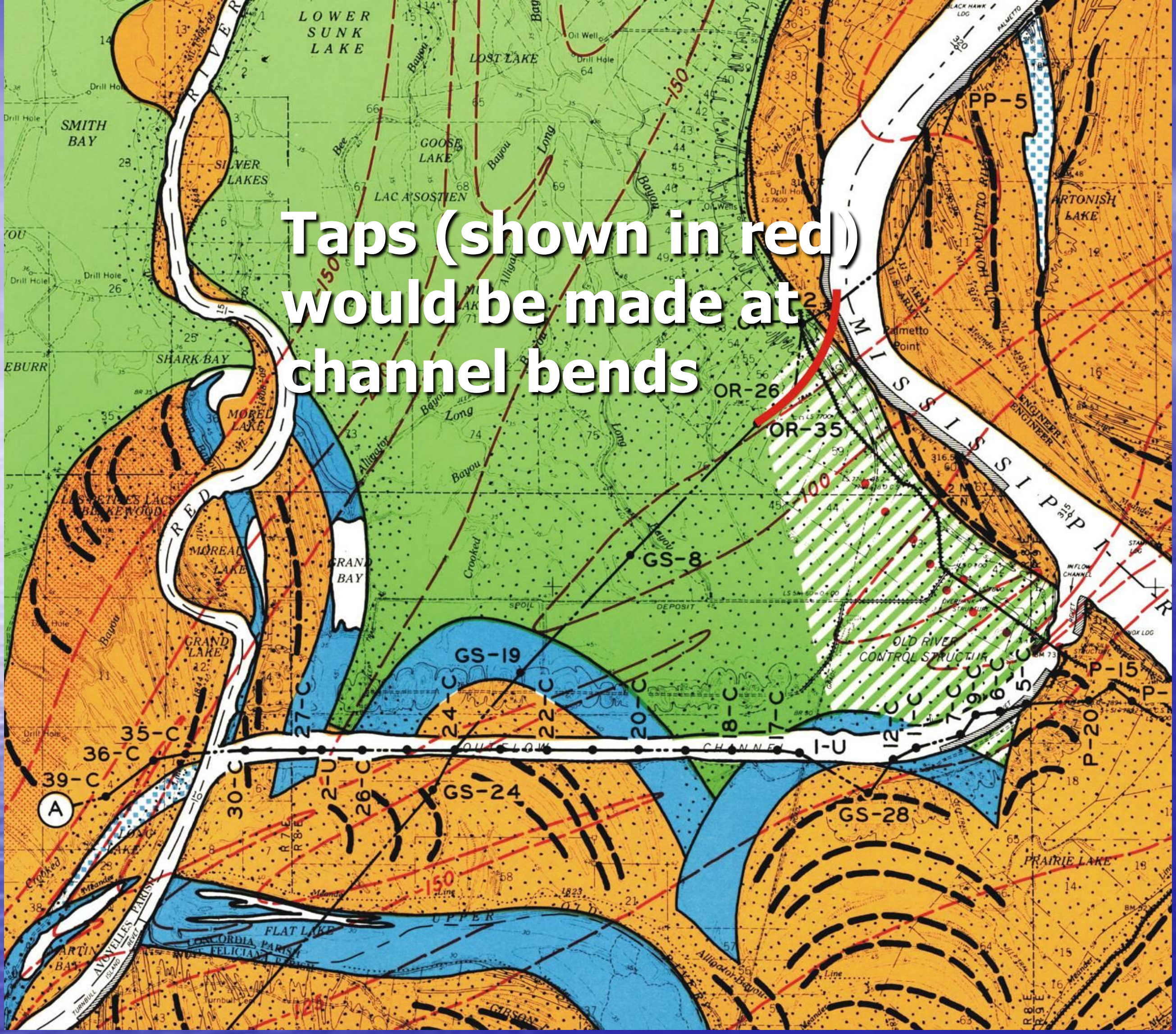
- Note classic birdfoot pattern of sand-filled distributary channels, shown in yellow
- Note development

Profile of the Lower Mississippi



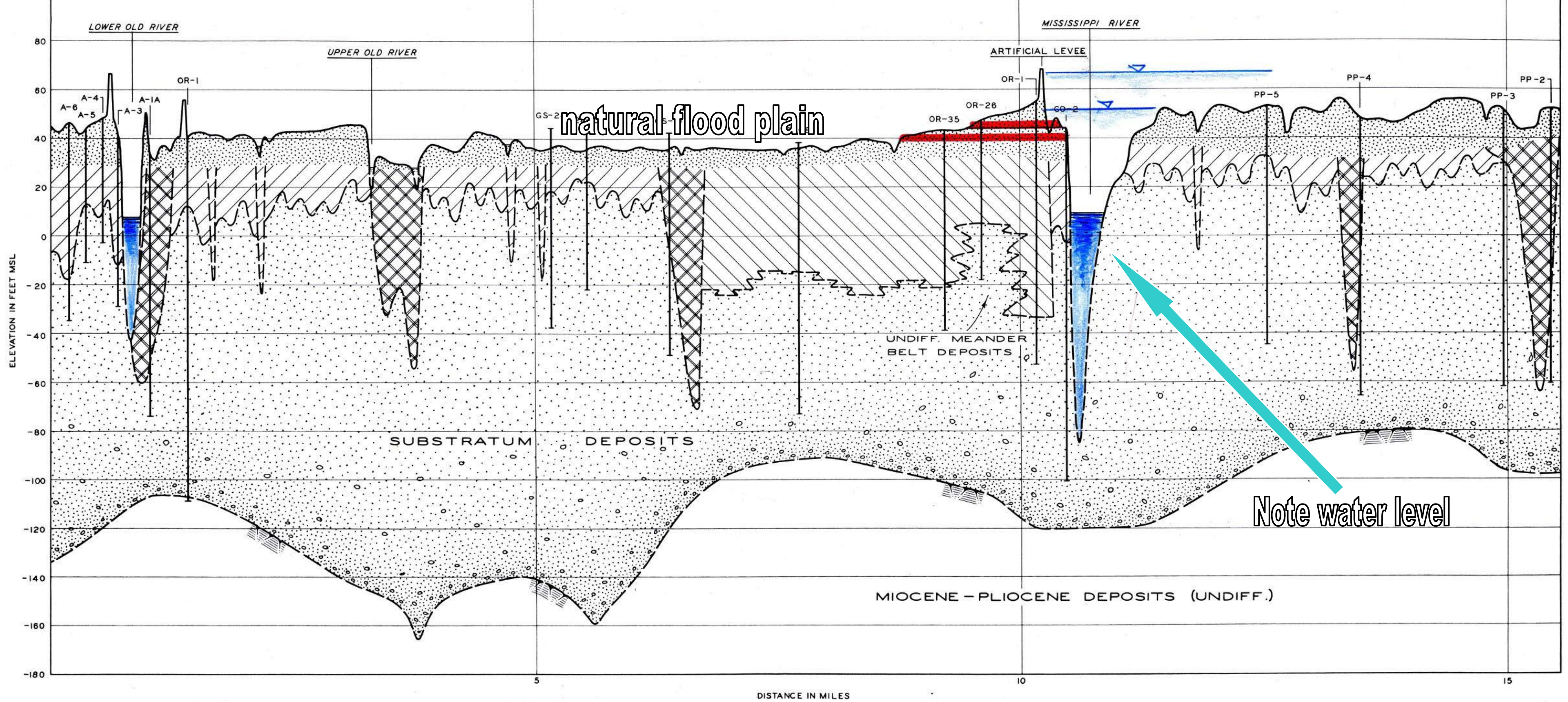
The bed of the Mississippi River is below sea level during the last 450 miles of its course, up to Greenville, Mississippi. We can only extract meaningful amounts of sediment during short-lived periods of high flow.

Can we come up with a viable scheme for diverting silt-laden waters during brief periods of high flow?



One idea is to divert the flow of the river during high flows This map shows Artonish, Louisiana

- Artonish is typical of the Mississippi River's flood plain <u>upstream</u> of Baton Rouge
- Note multiple meander belts

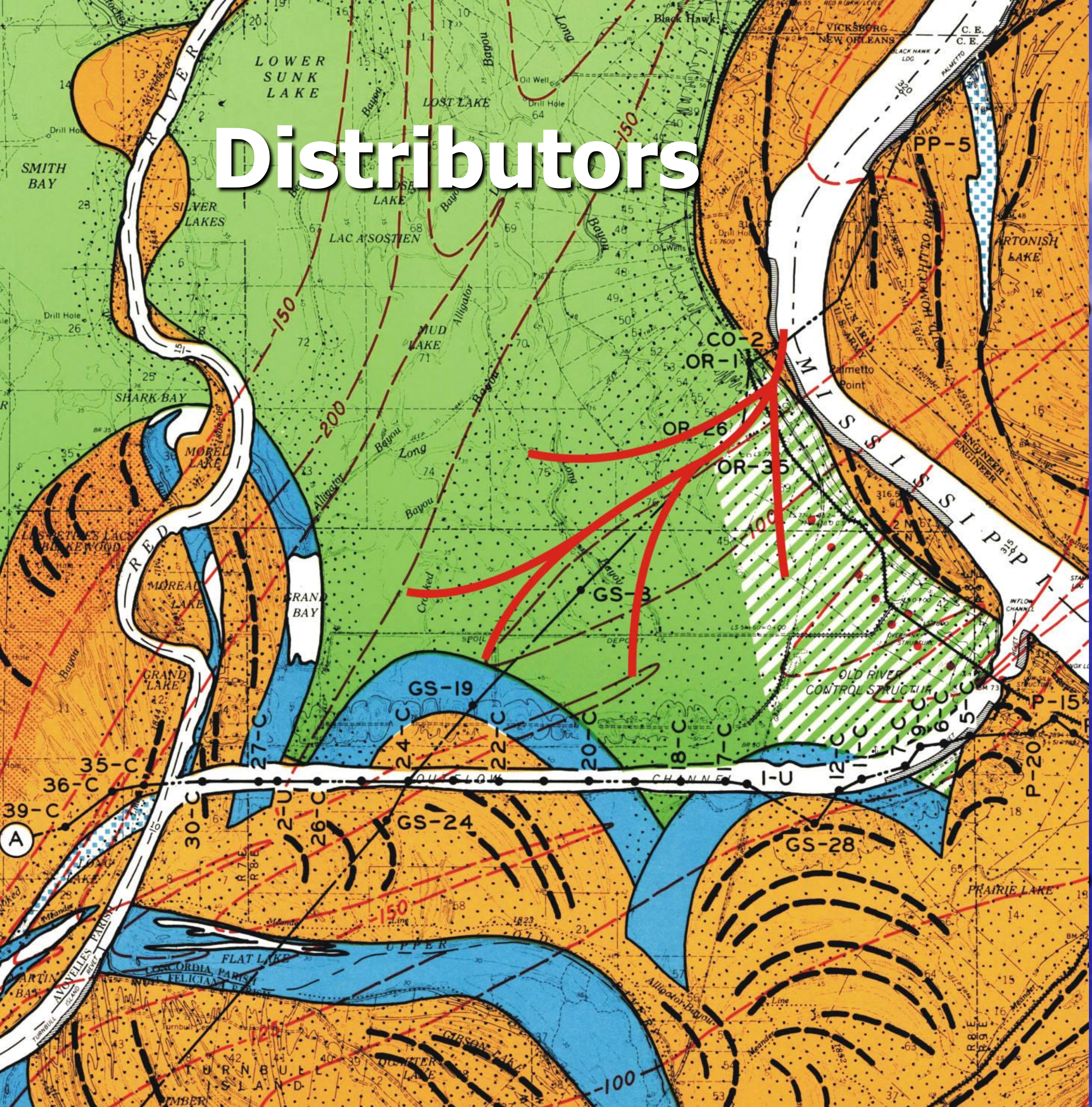


- This section shows a pair of proposed "tunnel taps" (shown in red), 1 and 1.8 miles long
- Precast concrete liners could be jacked through the overbank sediments, beneath the river's levees, similar to the Boston Big Dig.

Jacking of precast concrete tunnel boxes

- During the Boston Big Dig, the world's largest precast concrete box tunnel section, for Interstate 90, was hydraulically jacked into position, beneath existing rail lines and bridges

Distributors



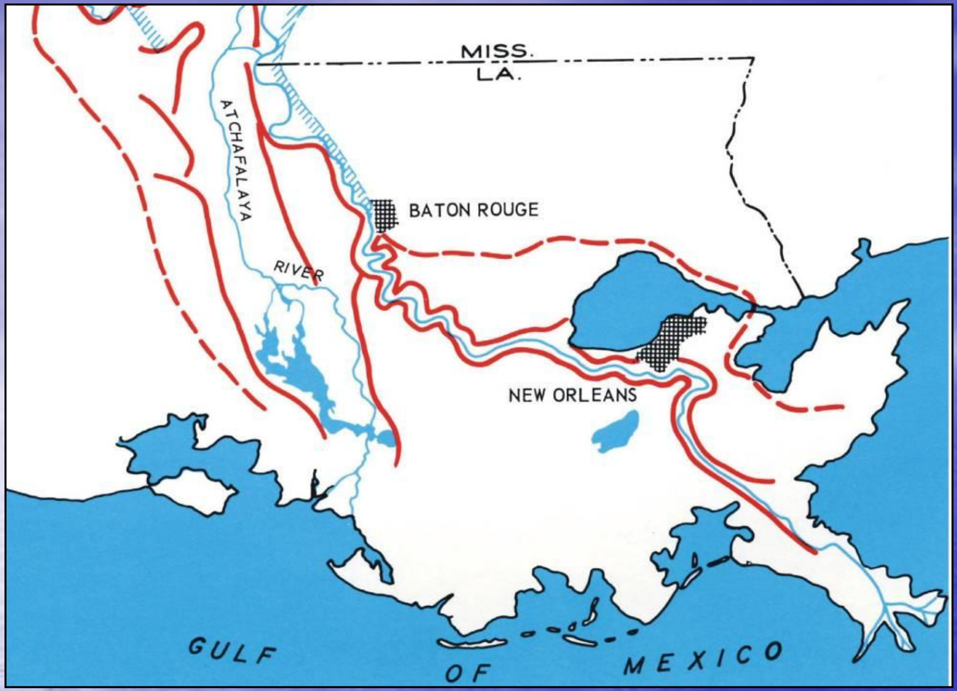
Ability to shift lines

Distributor alignments would need to be flexible, to accommodate distribution of sediment

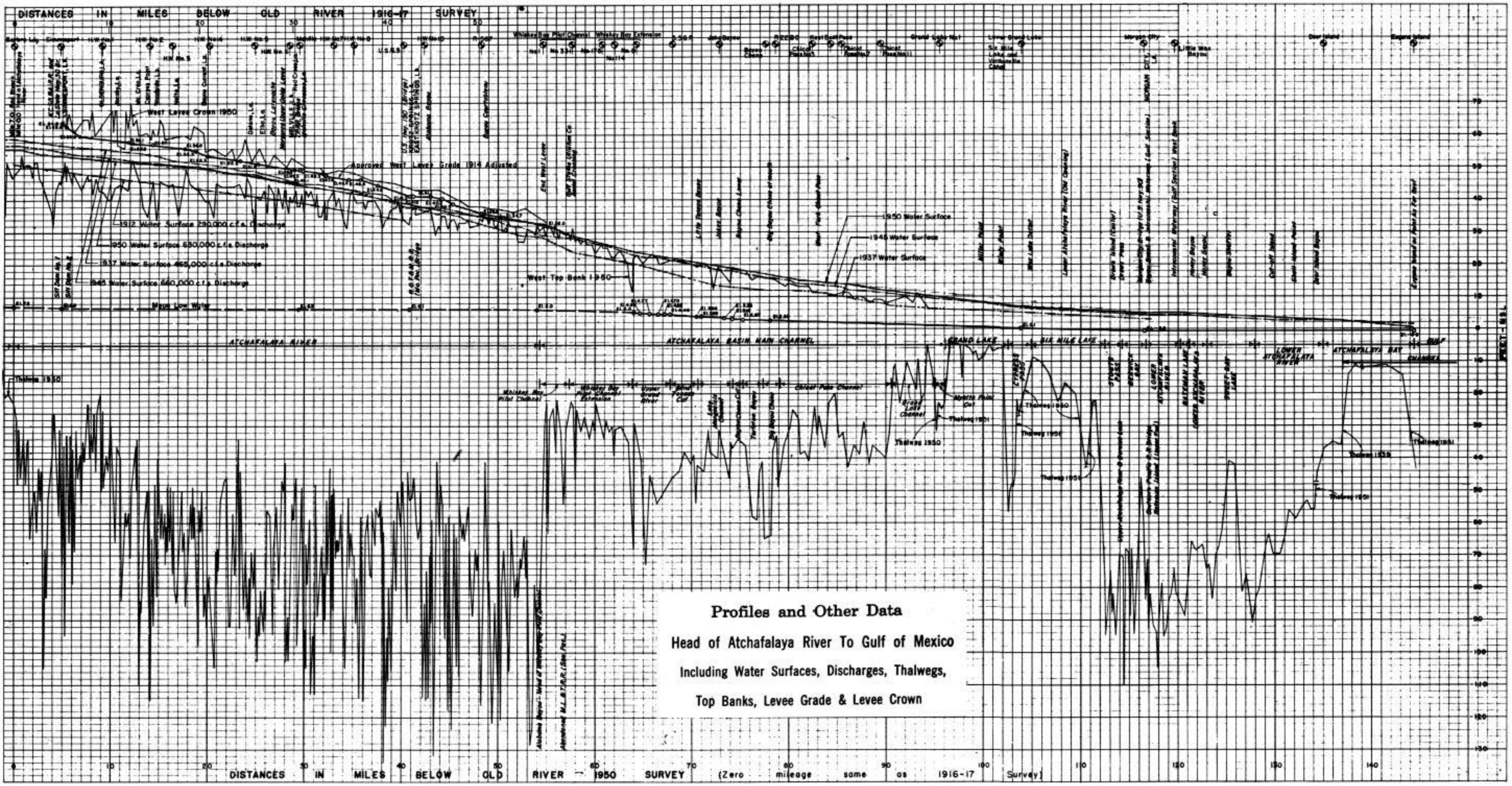
Flexibility will be key aspect

So, what portion of the lower Mississippi River could be targeted for massive flow diversions and serve as a receptacle for new sediment ?

Atchafalaya River

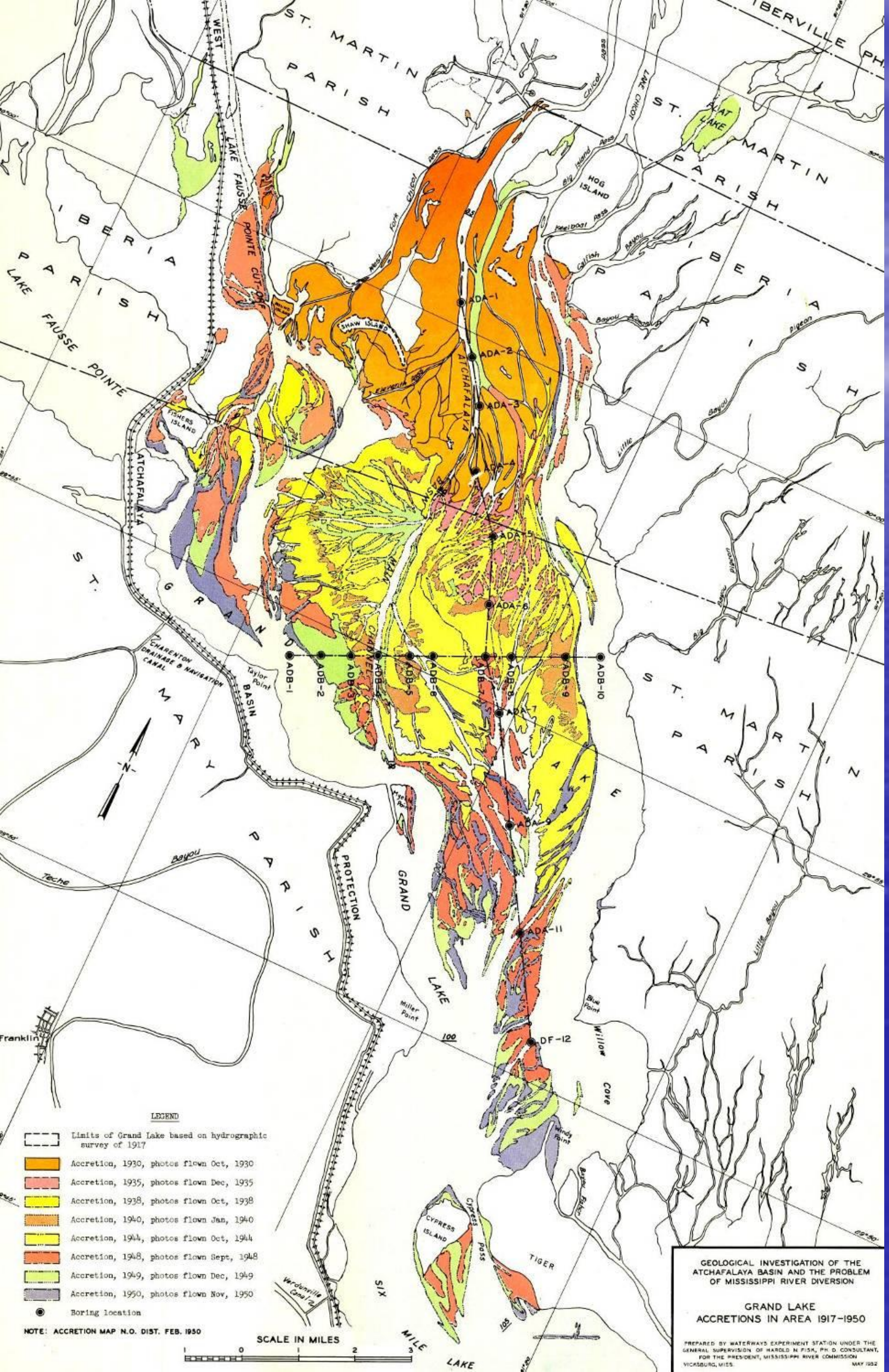


- The Atchafalaya River is both steeper than the Mississippi (3:1 ratio in bed slope) and shorter (225 kilometers to the Gulf of Mexico from the Red River entrance versus 480 kilometers for the Mississippi).
- Under natural conditions, the Mississippi River would probably have switched its course to the Gulf of Mexico via the Atchafalaya distributary between 1965 and 1975, if not for the levees.
- Since 1963, the Atchafalaya now drains about 30% of the combined flows of the Mississippi and Red Rivers to the Gulf of Mexico.



- **Profiles of the Atchafalaya River. Its *steeper gradient* would be much more efficient for sediment diversion, transport, and distribution than the lower Mississippi River.**

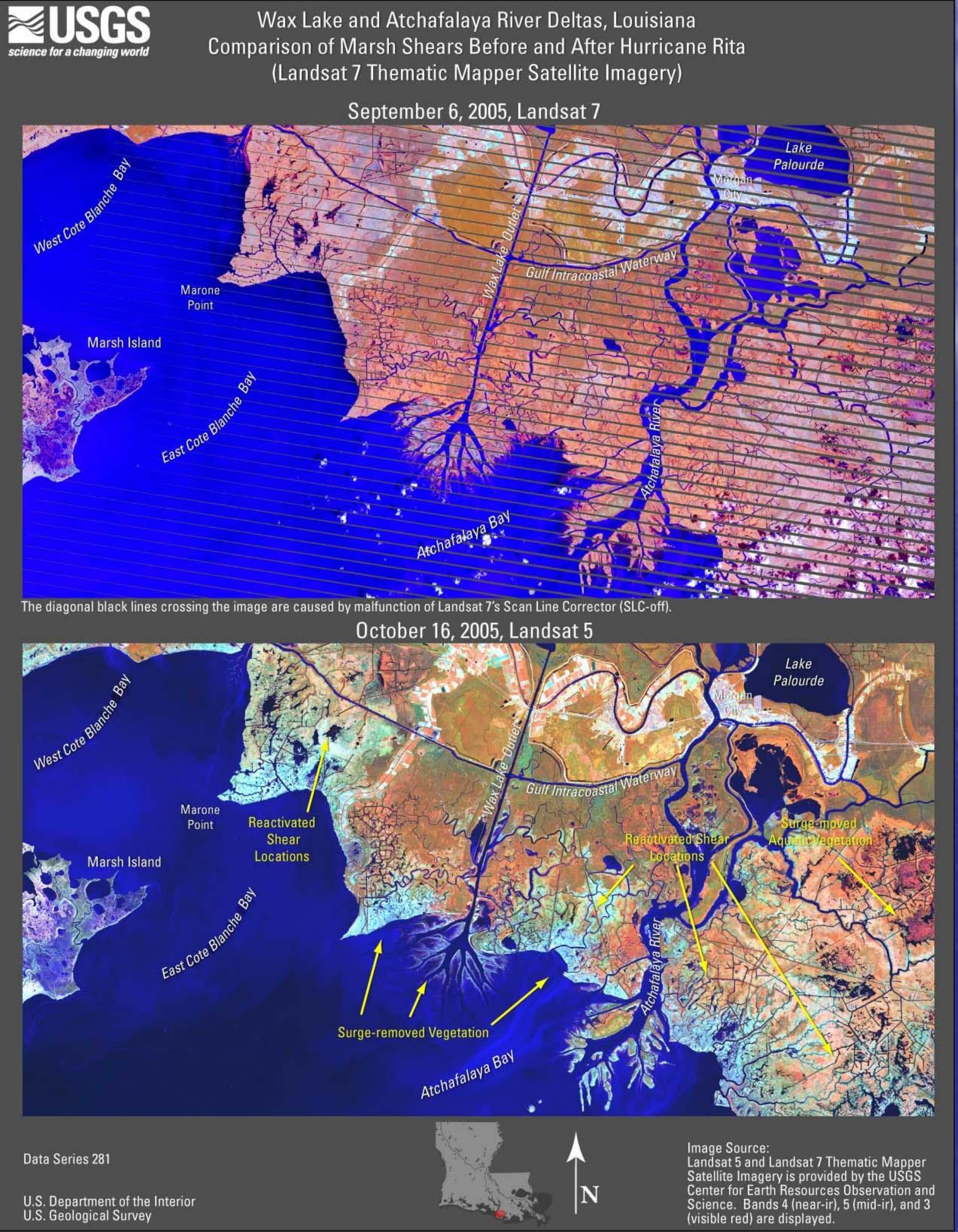
Sediment Accretion at Grand Lake 1917-1950



- The Atchafalaya Basin is one of our best analogs for sediment accretion in the Mississippi Delta
- Historic data on sediment accretion here needs to be analyzed and thoroughly understood

- **Since 1950 the Atchafalaya River has been discharging into Wax Lake, siphoning off about 30% of the combined flows of the Mississippi and Red Rivers. Between 1950-73 most of the sediment was deposited into the waters of Wax Lake, leading ,most people to conclude that very little land-building was being accomplished.**

- **The deltas on Wax Lake grew dramatically during the near-record floods of 1973, because of the increased sediment load, and the fact that the subaqueous "base" of the new deltas had been accumulating over the previous 23 years.**
- **So, *it will be important to find a workable scheme for monitoring subaqueous deposition, not just subaerial accretion*.**



Factoring in ongoing damage

- Before and after views of the Wax Lake and Atchafalaya River Deltas caused by Hurricane Rita in Sept 2005
- Storm surge removed stabilizing vegetation mat

The likely target of any massive diversion scheme…

- Every physical factor save one, would seem to favor the Atchafalaya River for a prototype sediment deposition scheme involving the lower Mississippi River
- The sediment has be diverted from the Mississippi channel.
- We should probably begin by evaluating enhancements; options that would use existing facilities, like the Old River Control Structures

- This presentation will be posted in pdf format for easy downloading at:

[www.umr.edu/~rogersda/levees]