MISSOURI S&T

MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY

RISK-BASED ASSESSMENT OF LEVEES- LESSONS LEARNED FROM THE 2011 MISSISSIPPI RIVER FLOODS

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for

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Geotechnical and Geo-environmental Conference

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AMERICAN SOCIETY OF CIVIL ENGINEERS 1852

GEO INSTITUTE of ASCE

Mississippi River watershed

Funnel-shaped basin drains 41% of the continental United States

Average flow 640,000 cfs. Suspended sediment flux 180 million yds^3/yr, one third of all US rivers. Long duration floods transport enormous volumes of sediment

The Mississippi River & Tributaries Project

- began construction in 1929
- 3400 miles of levees
- five dams
- four floodways
- four backwater areas

1st Lt Herbert D. Vogel

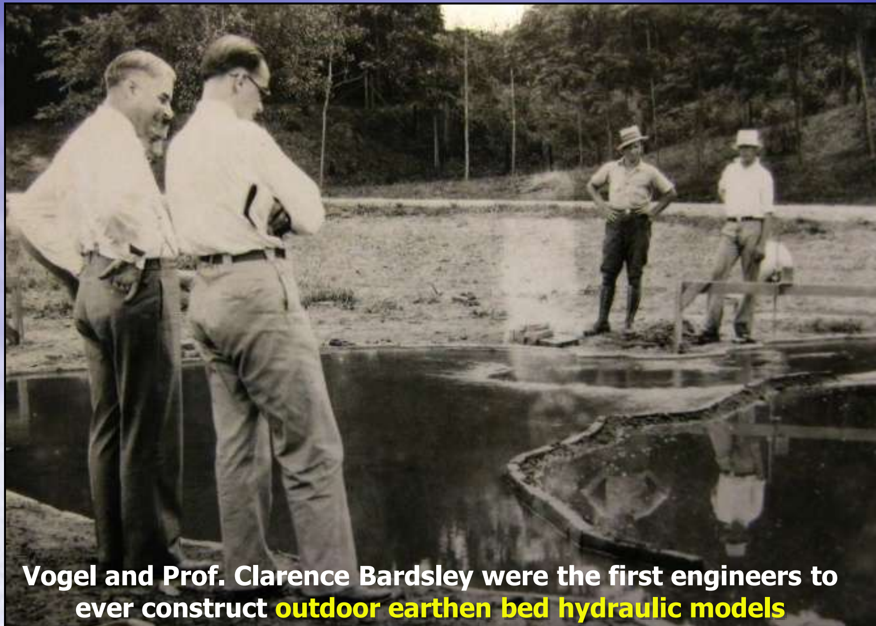
"Vog" Class of '24

West Point Class of 1924
MS Univ California Berkeley '28
DEng Berlin Technical Univ '29
MEng Univ Michigan '34
First Director of the Waterways Experiment Station at Vicksburg
1930-34

Dr. Vogel

The **Waterways Experiment Station** was established by the Army Corps of Engineers in 1928, following the disastrous floods of 1927 along the lower Mississippi River. The Army chose 1st Lieutenant Herbert D. Vogel with standing up the facility, which he directed for five years, between late 1929 and mid-1934

BGEN Harley Ferguson (West Point '97) was President of the Mississippi River Commission from 1932-39, during the formative years of the Mississippi River & Tributaries Project



Vogel and Prof. Clarence Bardsley were the first engineers to ever construct outdoor earthen bed hydraulic models

The loess soils in Vicksburg were ideal for carving precise scale hydraulic models , with vertical exaggeration

Vogel and Prof. Clarence Bardsley, of the Missouri School of Mines

Vogel employed the principles of similitude that had been pioneered by hydraulic modelers in Europe to examine various means to make the Mississippi River channel more hydraulically efficient

Vogel observing results of an overflow test of a full-scale railroad right-of-way


Model of Birds Point-New Madrid floodway under test

- The **Birds Point-New Madrid Floodway** was located in Missouri and starting just below the confluence of the Mississippi and Ohio Rivers at Cairo, IL, covering about 206 square miles.
- In 1932 WES performed a model study to determine the effects of operating the floodway on the lands lying within it and to predict the draw-down on the Mississippi River with the floodway in use.
- With more than 100 miles of river to simulate, Vogel built an 80-foot-long outdoor concrete model of the river channel, the overbank between levees, backwater areas, and the floodway.
- Vog took special care to correctly place drainage ditches, levee borrow pits, and other details that would affect water levels, and raised miniature levees with soil taken from actual on-site levee borings. These tests indicated that the new levees were of sufficient height to contain any projected flood

Design Intent of the Bird's Point Floodway

- The Corps of Engineers designed the floodway to save Cairo, IL, a key rail and highway junction
- They also designed a drainage system to reclaim floodway lands for agriculture

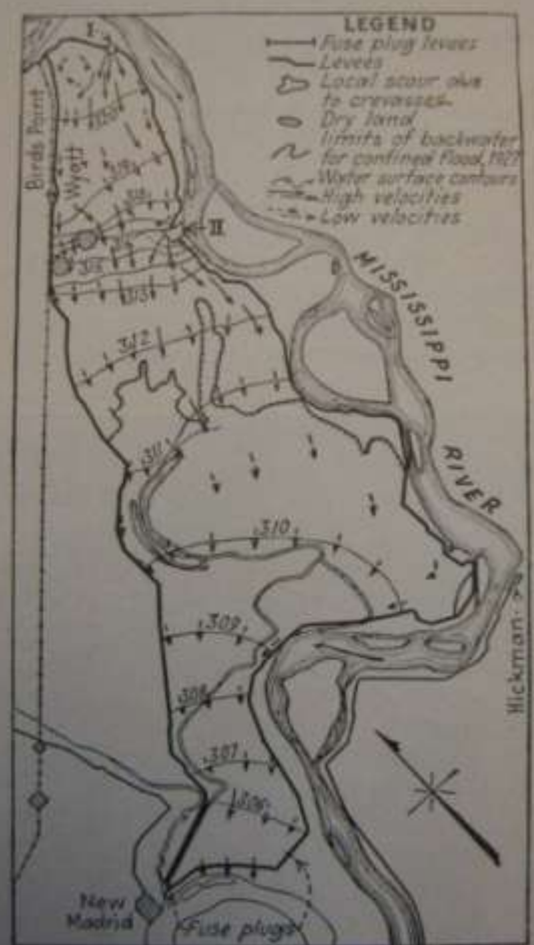


Fig. 4—Model map of New Madrid floodway, showing crevasses, backwater limits, current velocities and water-surface contours resulting from a simulated 1927 flood.

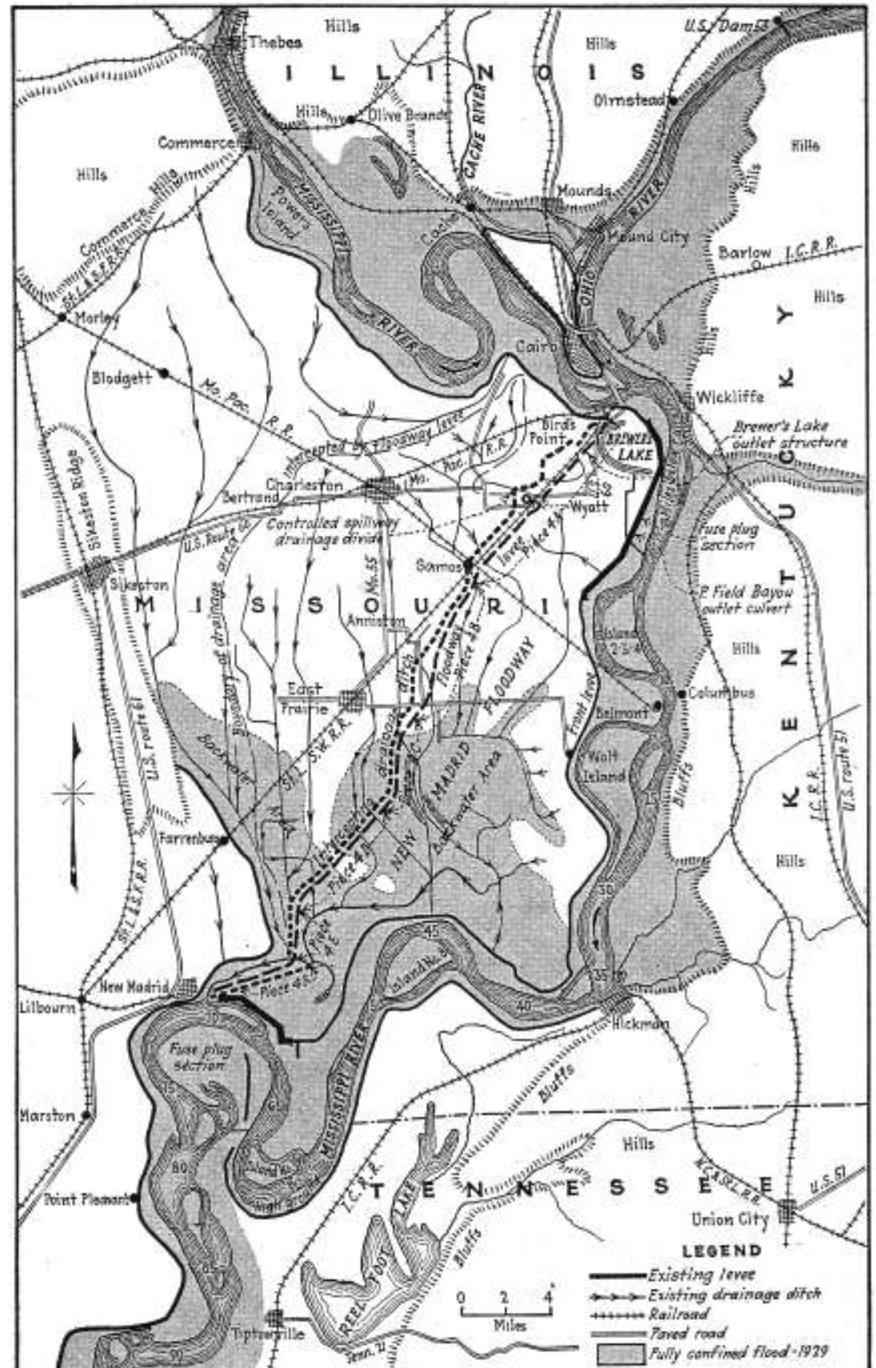
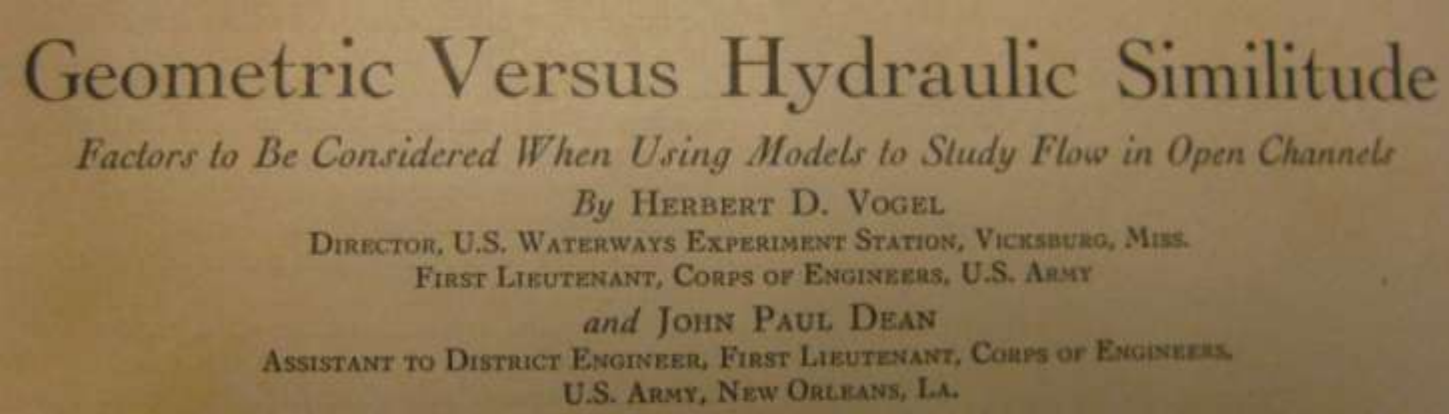


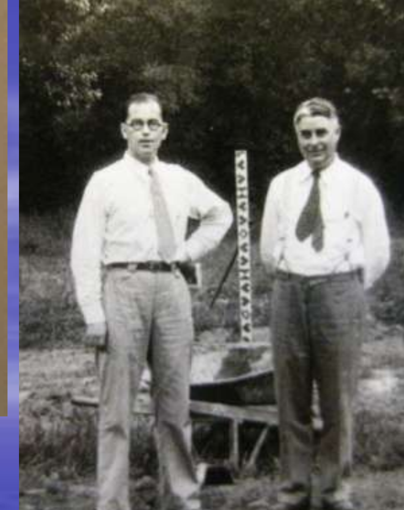
Fig. 1—Levee and drainage system of New Madrid floodway

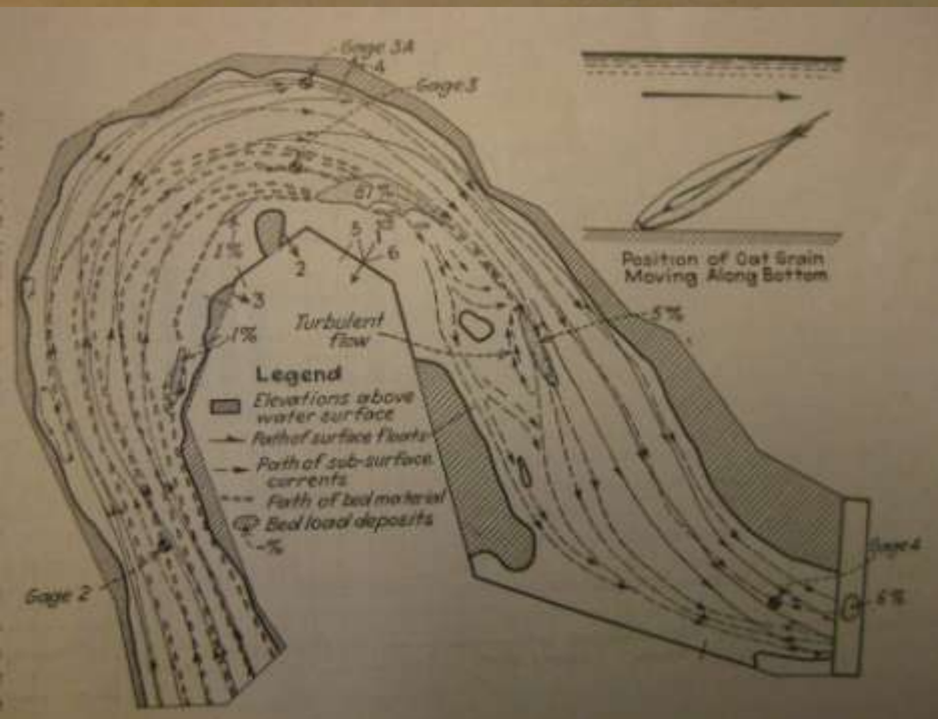


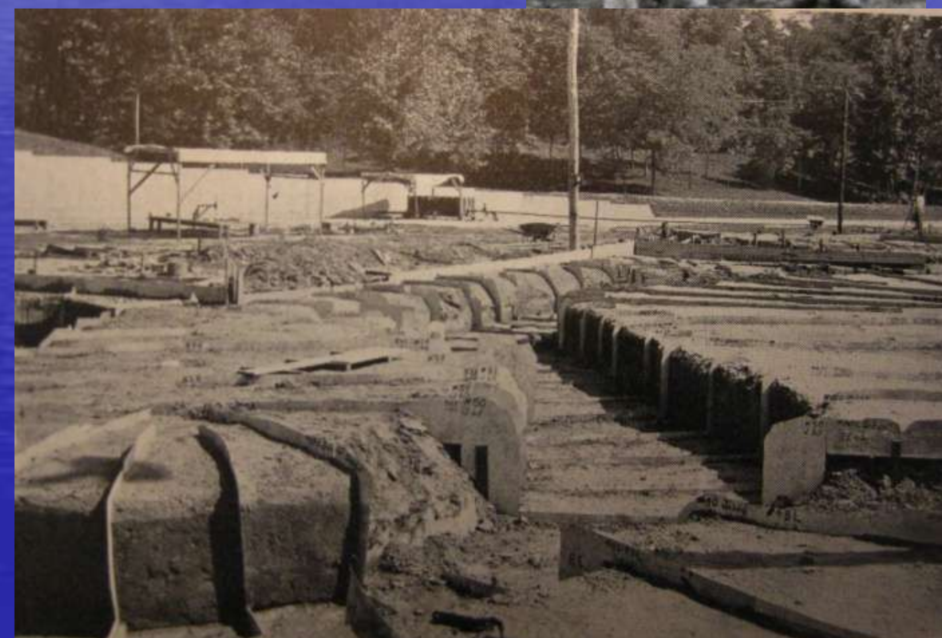
Geometric Versus Hydraulic Similitude

Factors to Be Considered When Using Models to Study Flow in Open Channels

By Herbert D. Vogel
Director, U.S. Waterways Experiment Station, Vicksburg, Miss.
First Lieutenant, Corps of Engineers, U.S. Army
and John Paul Dean
Assistant to District Engineer, First Lieutenant, Corps of Engineers,
U.S. Army, New Orleans, La.







One aspect the hydraulic models could not predict were long-term bed and bank adjustments, made over many decades by dramatically different flow regimens **(Herbert D. Vogel and Missouri Mines Professor Clarence Bardsley pictured at upper right).**

Major Elements of the MR&T

- 2,200 miles of levees and floodwalls (avg 30 ft high) below Cape Girardeau
- Bypass floodways: Bird's Pt-New Madrid (1931); Bonne Carre (1931); Morganza Diversion (1954); Old River Diversion (1960/1977)
- Channel improvements; incl. 16 cutoffs and two major chutes; and bank revetments. Initially lowered flood stages 16 ft at Ark City and 10 ft at Vicksburg
- Major tributary improvements, 4 dams in Yazoo Basin (Enid, Arkabutla, Sardis, Grenada) and Wappapello on the St Francis River

Effects of Mississippi River Cut-Offs

By Harley B. Ferguson

Member American Society of Civil Engineers

Brigadier General, Corps of Engineers; President, Mississippi River Commission, Vicksburg, Miss.

the controlling problem before the commission.

Stabilization and capacity increase

Mention of the Boeuf floodway will call to mind the controversy that raged around this part of the project. The people who live in the strip 10 or 12 miles wide and 150 miles long, which

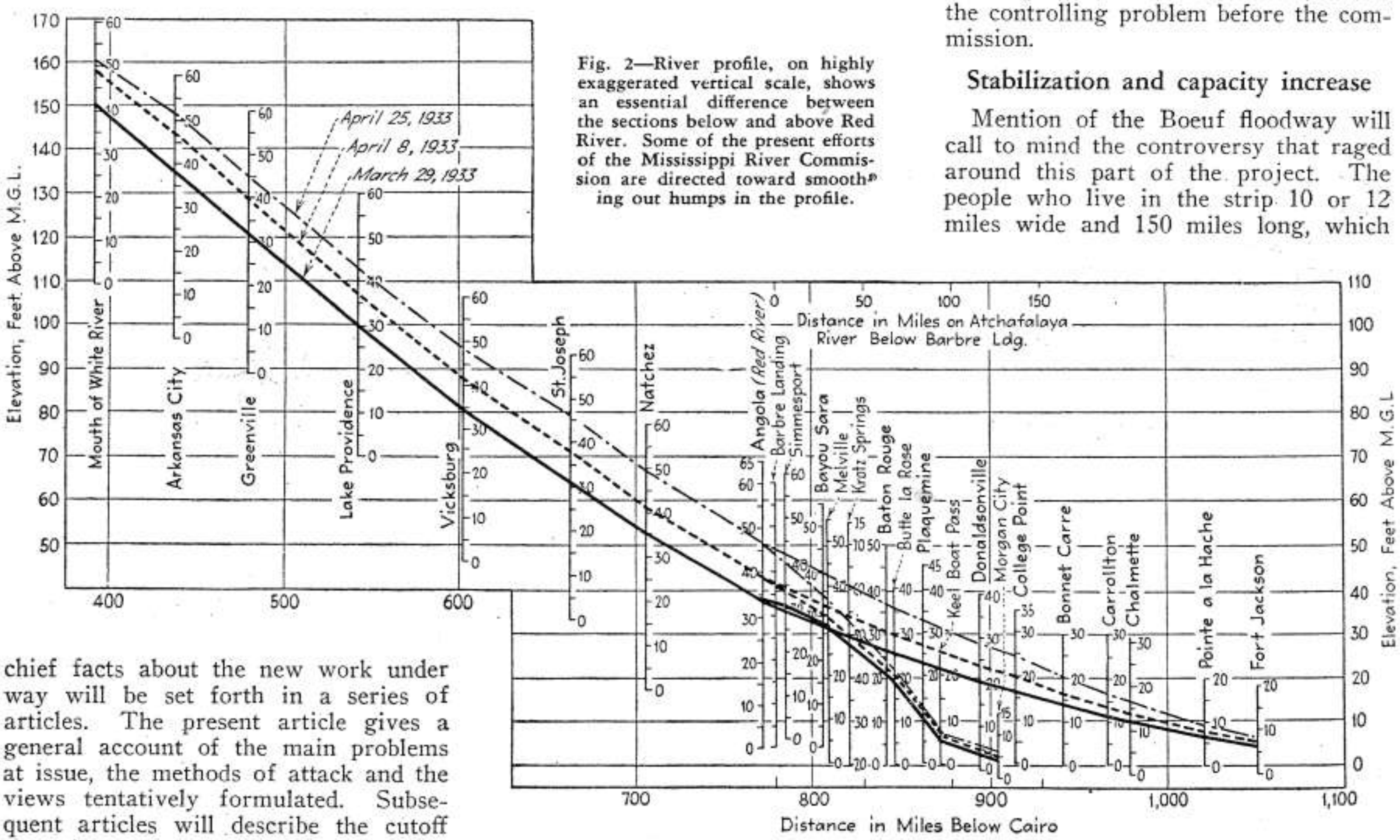


Fig. 2—River profile, on highly exaggerated vertical scale, shows an essential difference between the sections below and above Red River. Some of the present efforts of the Mississippi River Commission are directed toward smoothing out humps in the profile.

chief facts about the new work under way will be set forth in a series of articles. The present article gives a general account of the main problems at issue, the methods of attack and the views tentatively formulated. Subsequent articles will describe the cutoff operations, contraction works, new

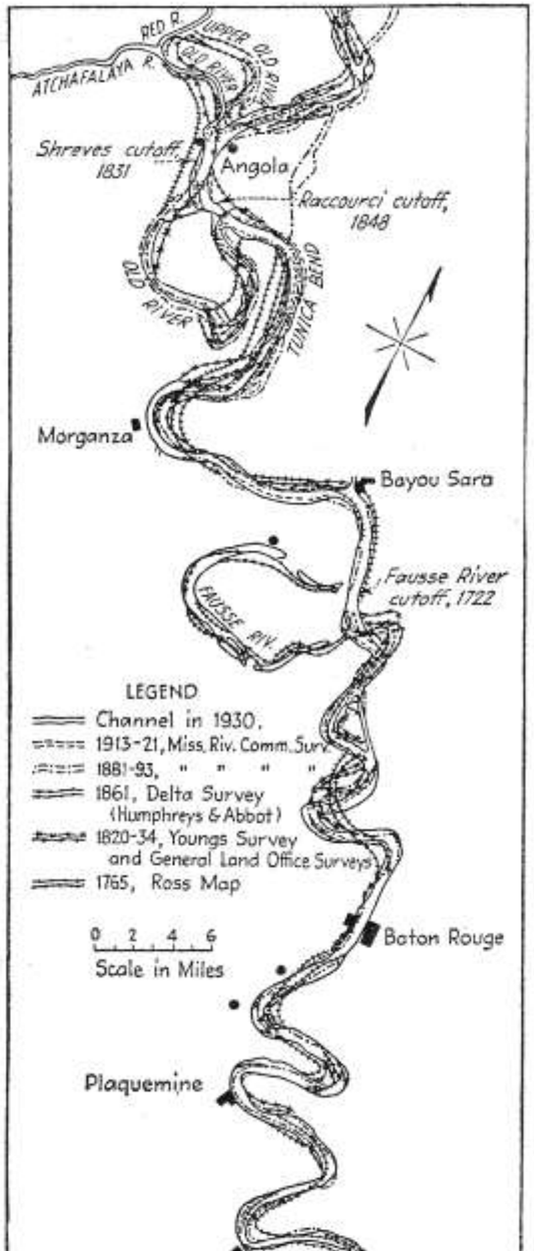


Fig. 5—Records of 165 years of channel changes below Baton Rouge reflect a high degree of stability. Compare with Fig. 4, which is typical above Red River.

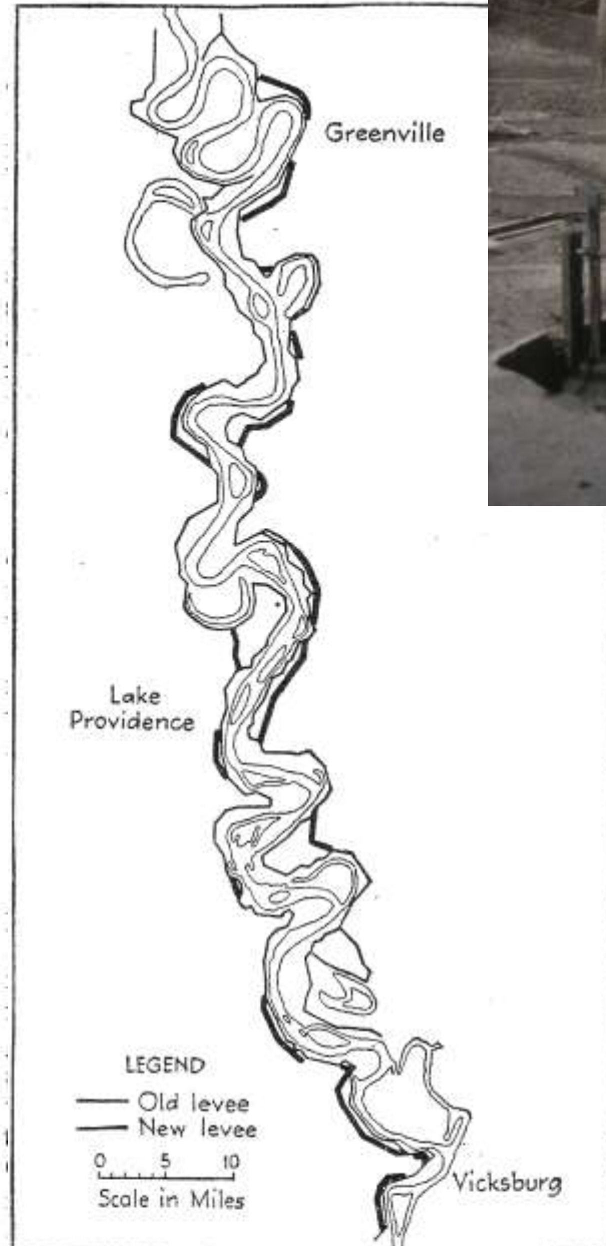
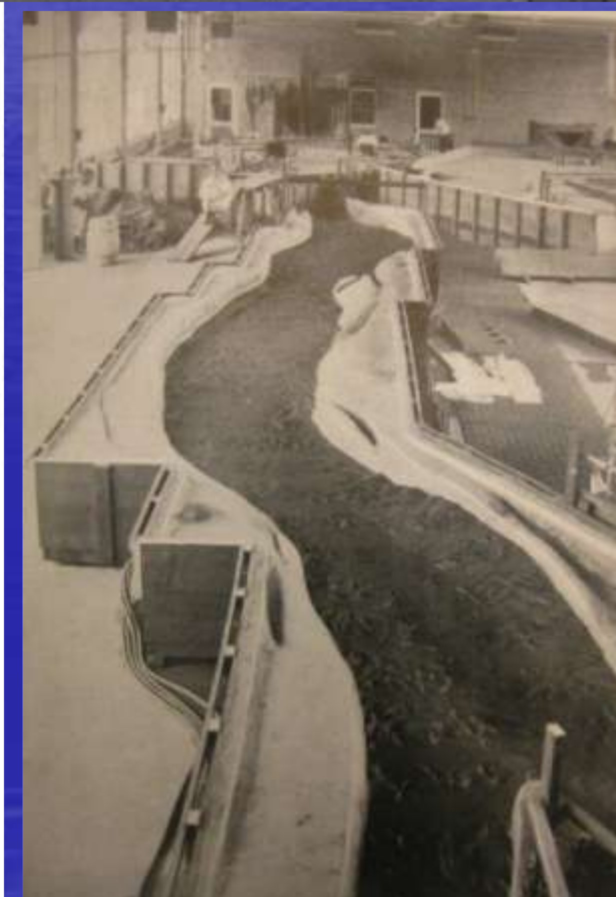
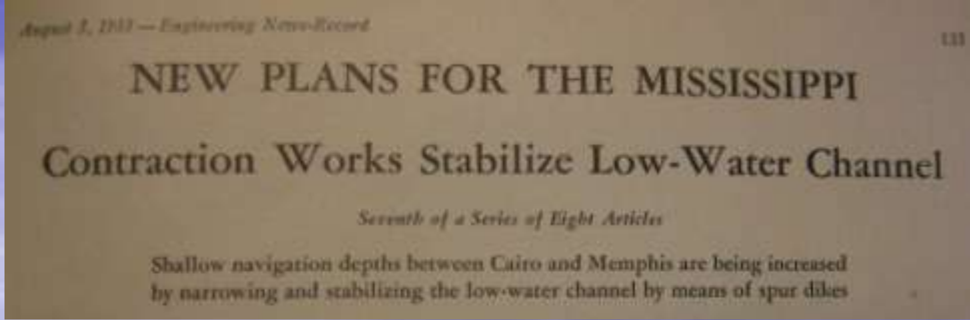


Fig. 6—Much rectification of the high-water channel has been accomplished by setting back the levee line at projecting points, as shown in this stretch between Greenville and Vicksburg.



WES strove to improve channel efficiency


Engineering News-Record — 131

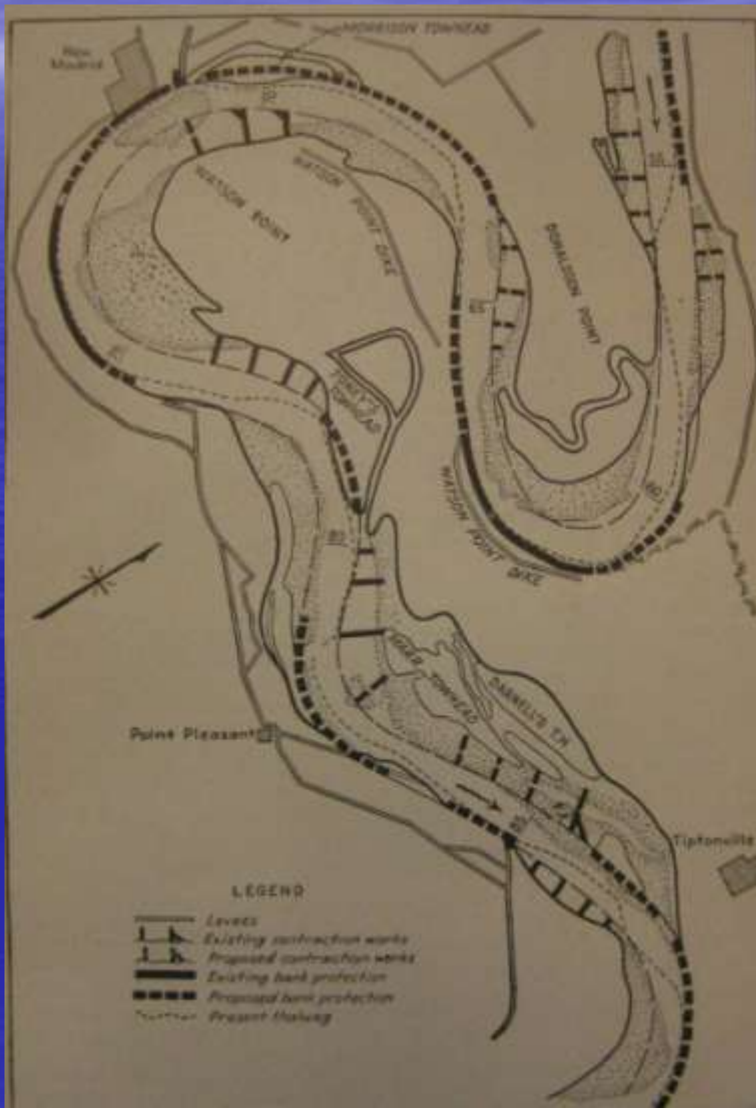
NEW PLANS FOR THE MISSISSIPPI

Contraction Works Stabilize Low-Water Channel

Seventh of a Series of Eight Articles

Shallow navigation depths between Cairo and Memphis are being increased by narrowing and stabilizing the low-water channel by means of spur dikes

Framed timber dike under construction



44 (Vol. p. 138) · ENGINEERING NEWS-RECORD · August 3, 1939

FIG. 1. INCREASING THE MISSISSIPPI'S CAPACITY: GILES CUTOFF IS BEING DREDGED AND VIDALIA POINT CUT BACK.

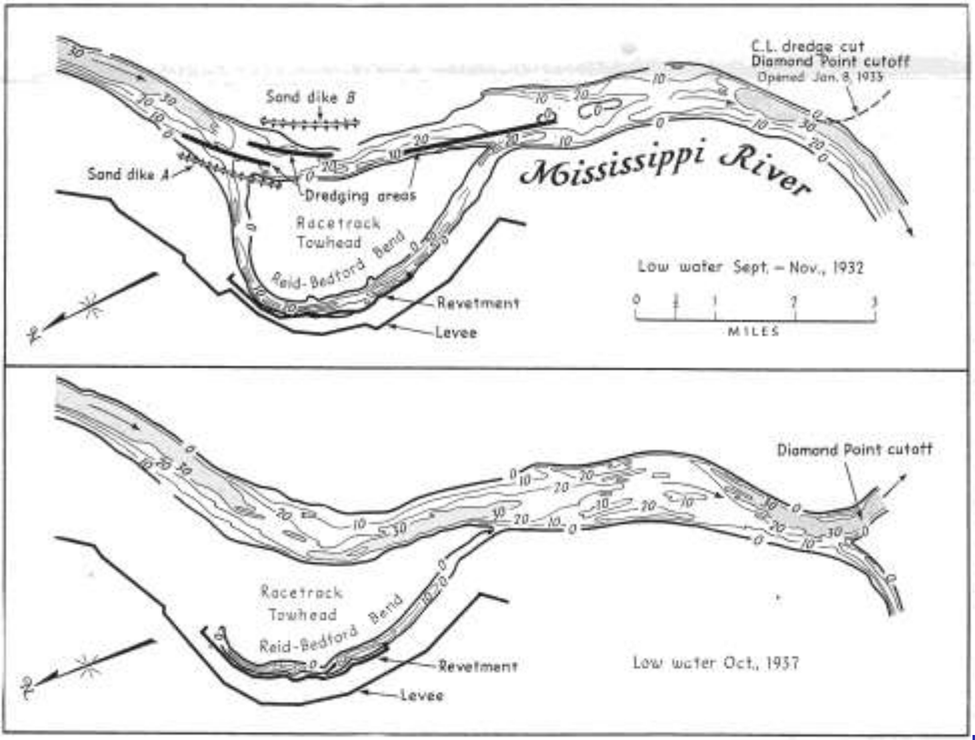
Mississippi River Cutoffs Effective

608 · ENGINEERING NEWS-RECORD · November 17, 1938

Cutoffs Lower Flood Crests

GEORGE R. CLEMENS
Mississippi River Commission, Vicksburg, Miss.

Fifteen cutoffs are rapidly redistributing the flow of the Mississippi River and have materially lowered flood crests above Red River Landing



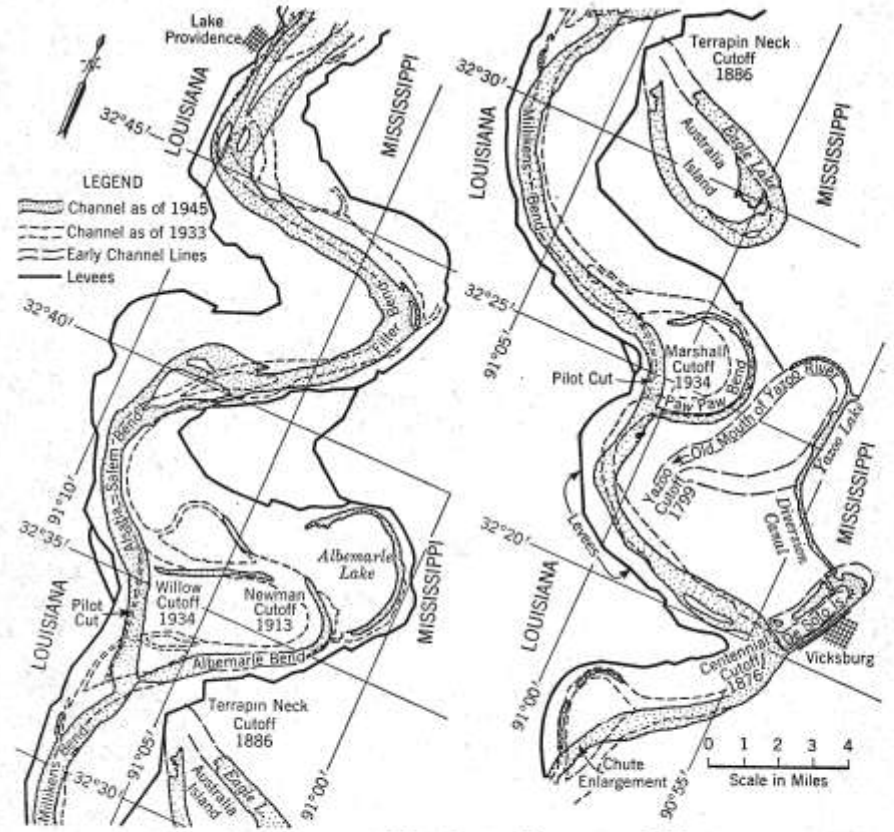


FIG. 2.—CUTOFFS IN THE 50-MILE SECTION UPSTREAM FROM VICKSBURG

Goal: reduce flood height thru increased channel efficiency: 16 cutoffs were made along the lower Mississippi River to increase grades and channel efficiency.

- **Timber dikes** were employed along the Mississippi River to confine flow and increase velocity along a preferred navigation channel. These dike caught organic debris which aided in their becoming backfilled with sediment.

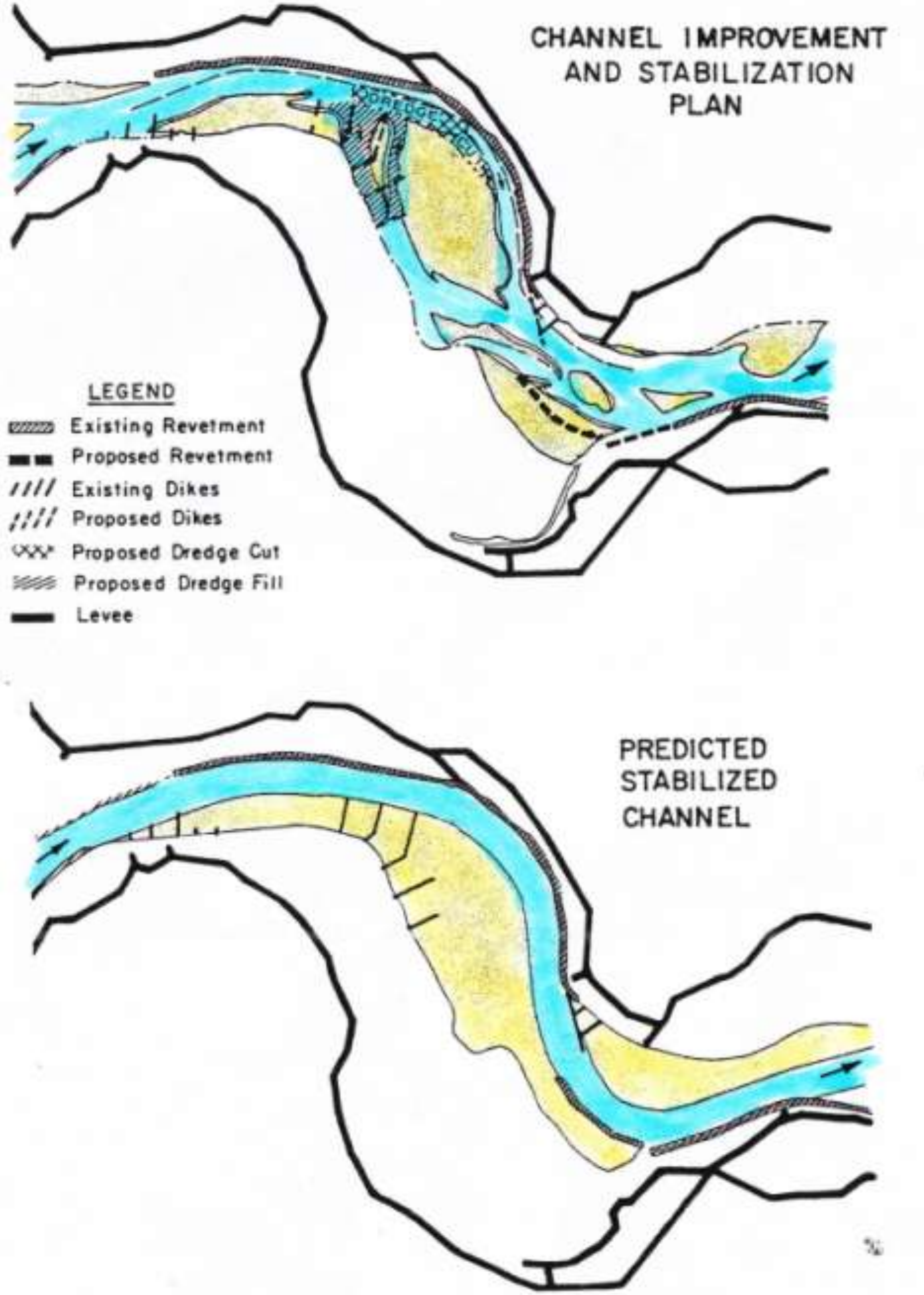
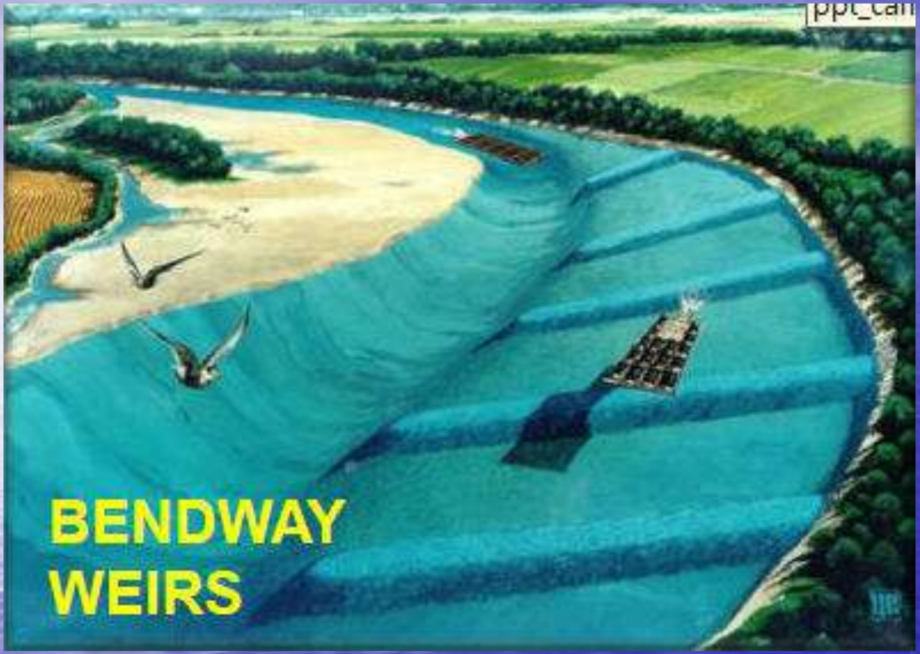


FIGURE 5 *Example of corrective works used to alleviate a troublesome divided-flow condition along a selected Mississippi River reach.*

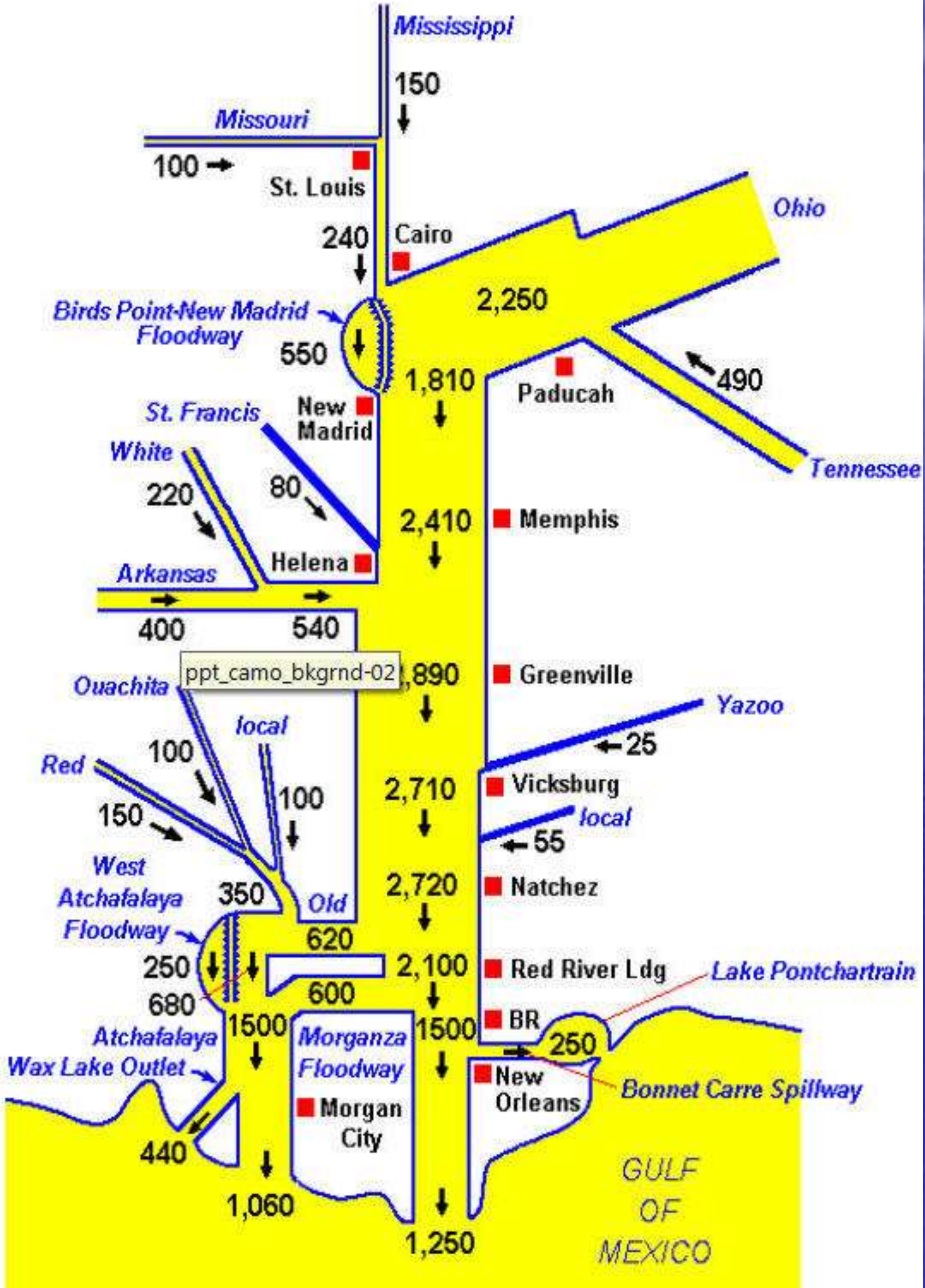
Split Flow Conditions

- **Channel improvements; incl. 16 cutoffs and two major chutes; and bank revetments (damaged during high flows).**
- **These improvements initially lowered flood stages 16 ft at Ark City and 10 ft at Vicksburg**
- **Requires corrective dredging**

Channel stabilization measures often increase boundary shear, increasing friction and "lifting" flood stages



Korneliussen (2012)

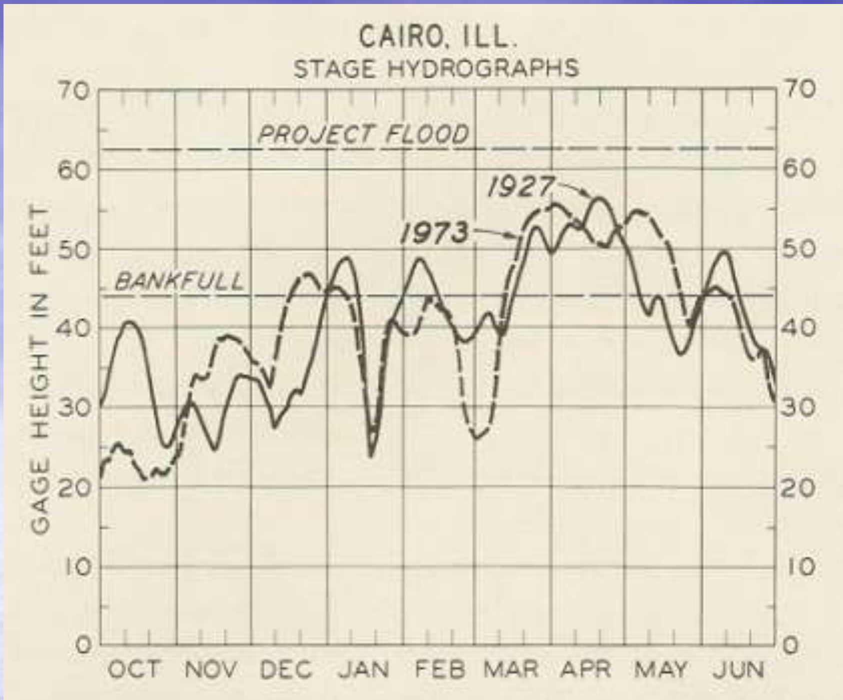


MR&T Design Flood

- The **Project Flood** was developed in 1956. It combines Jan 1937, Jan 1950, and Feb 1938 storms over the Ohio and Mississippi Basins
- The peak flow of the Project Flood is **3,000,000 cfs** at Red River landing
- The MR & T was constructed by the Army Corps of Engineers between 1928-60 for $8 billion
- Numerous additions since 1960
- Major diversions at Old River, Morganza Floodway, and Bonne Carre; which siphon off 54% of the maximum flow

The 1973 Flood – all sorts of surprises

Fallout from 1973 Mississippi River Flood



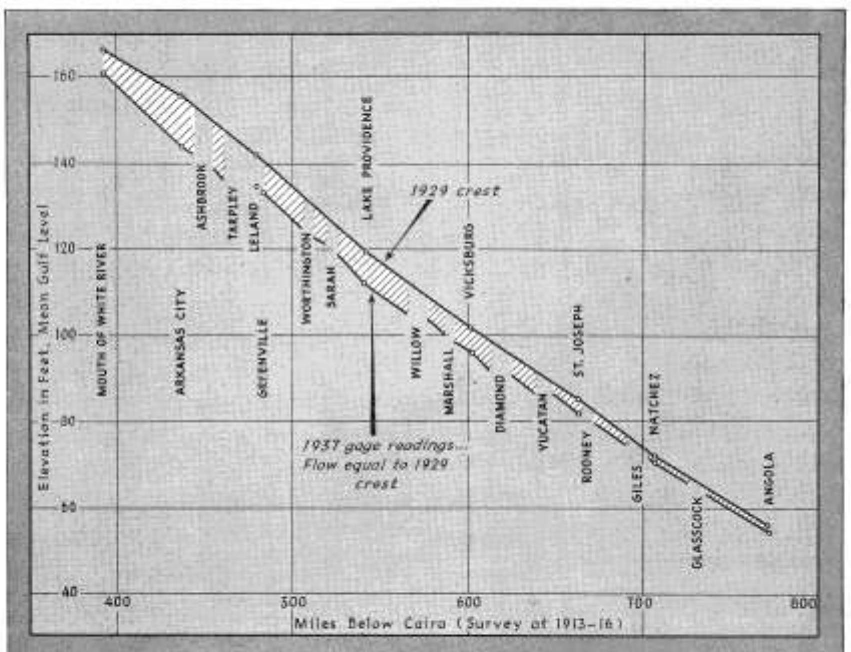
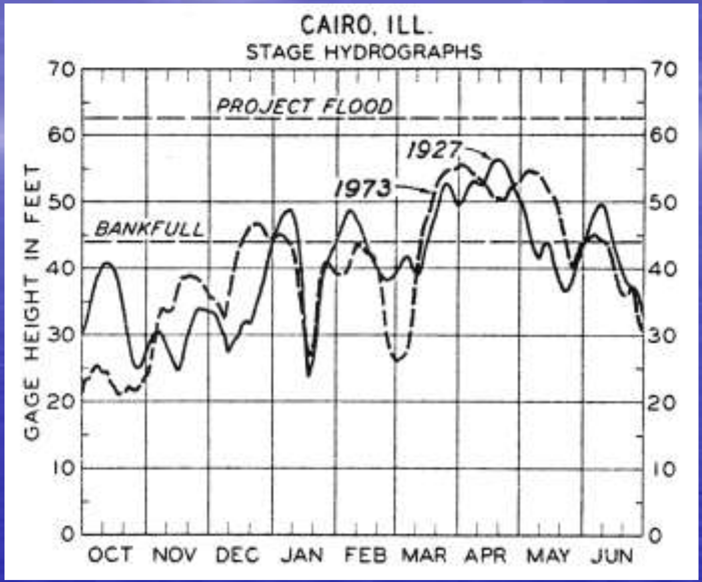


Fig. 1. Cutoffs have reduced crests of comparable Mississippi River floods as shown by the shaded zone.

- MR&T only 41% complete when flood occurred
- Set a record for days-out-of-bank at 62
- Damages of $183,756,000 to the MR&T system; $1 billion overall
- Flow levels at Cairo similar to 1927, but much higher downstream
- *The carrying capacity of the river had decreased*; meaning the flow of water would now be at a higher elevation
- This realization necessitated raising 800 miles of levees

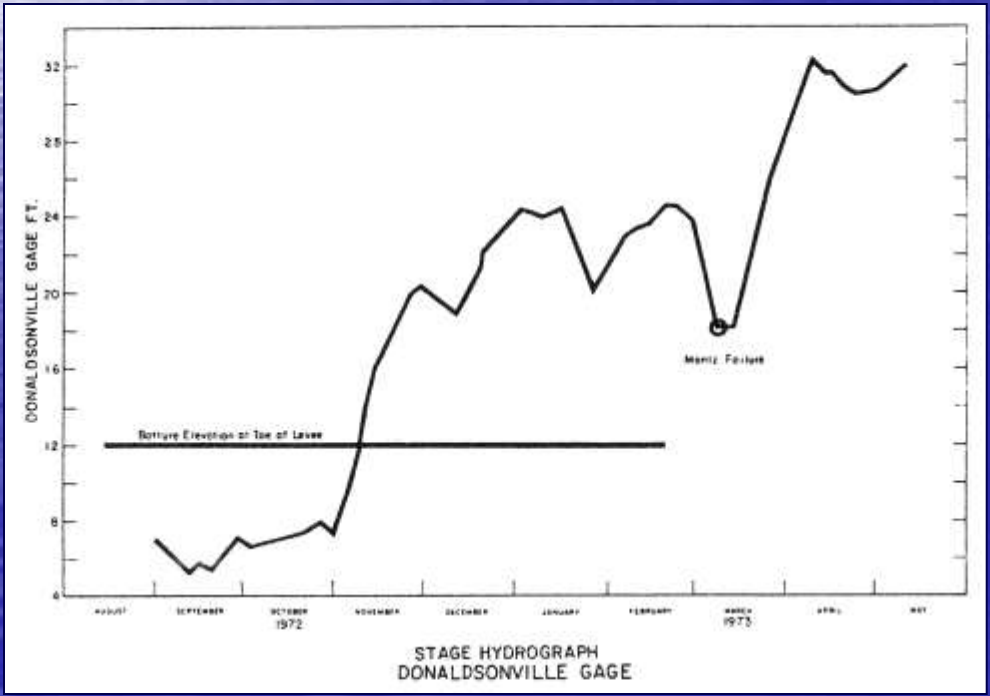
Rapid Drawdown induced failures



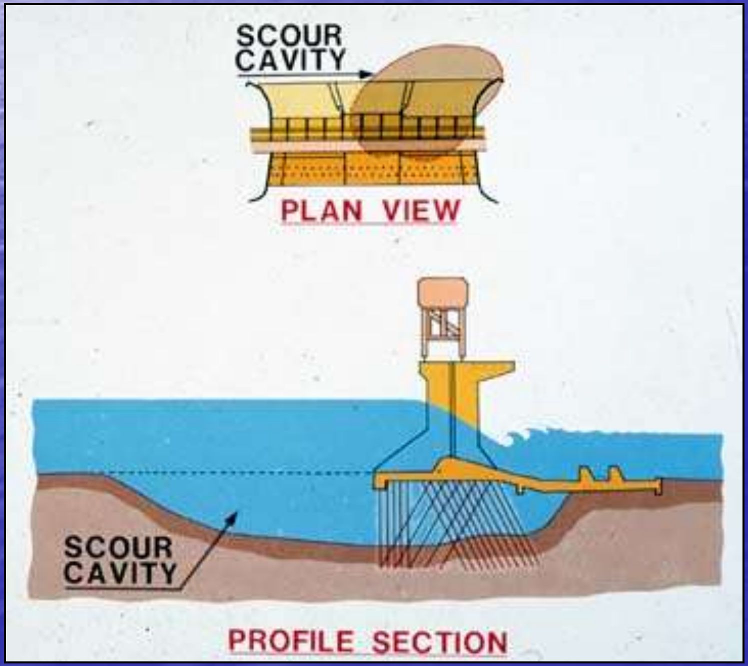
- The 1973 flood was unusual in its duration (62 to 90 days), and its multiple cycles (loop effect)
- Levees resisted peak flows, but many failed when the river dropped precipitously, after its initial early season peak, in January, February, and April

Bank Failures most sensitive to drawdown cycles

- 1973 flow hydrograph for Donaldsonville. River flowed between 20 and 25 ft for two months during the 1973 flood, then dropped 7 feet in 9 days, creating a severe ***rapid drawdown*** condition.



Near Disaster at the Old River Control Structure



- **During the '73 flood a large *back-eddy scour hole* developed on the up and downstream sides of the left abutment of the Low-Sill Diversion Structure**
- **Without the battered steel piles a new Mississippi River channel would have been carved down the Atchafalaya River to the Gulf !**

Aftermath of the ‘73 Flood

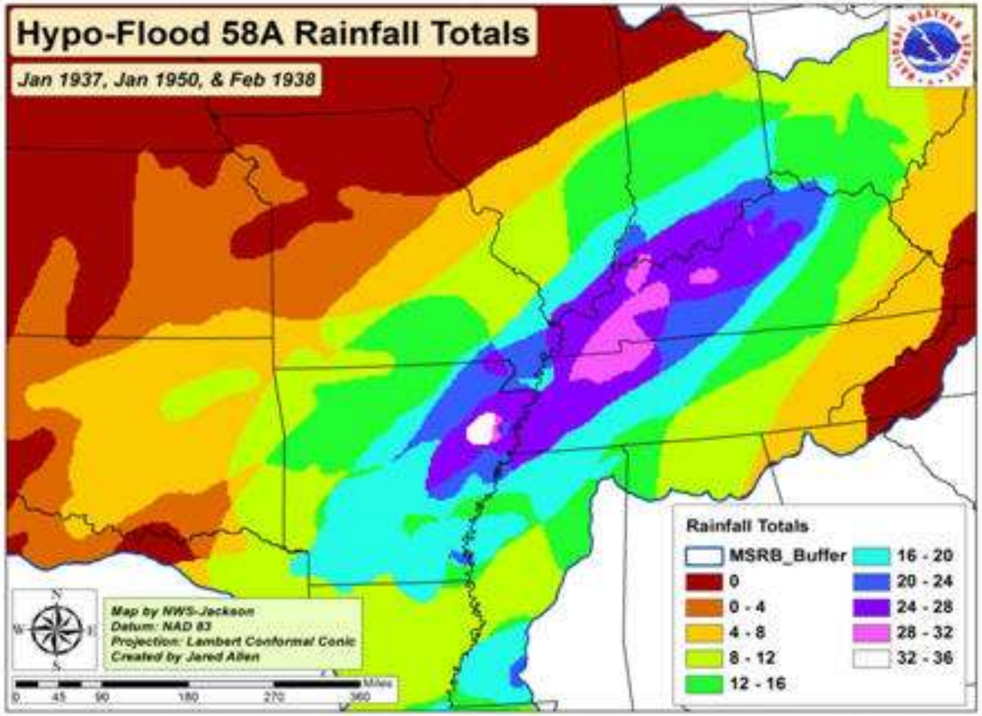
- Siltation of the lower Mississippi and at the Passes was without precedent, because of double crests and loss of channel efficiency
- Near loss of the Old River Control Structure
- Underseepage beneath levees
- Bank failures along lower reaches of the river
- Channel deterioration and flood cycles rendered stage-discharge relationships invalid
- 800 miles of levees along lower Mississippi had to be raised 3 to 6 ft

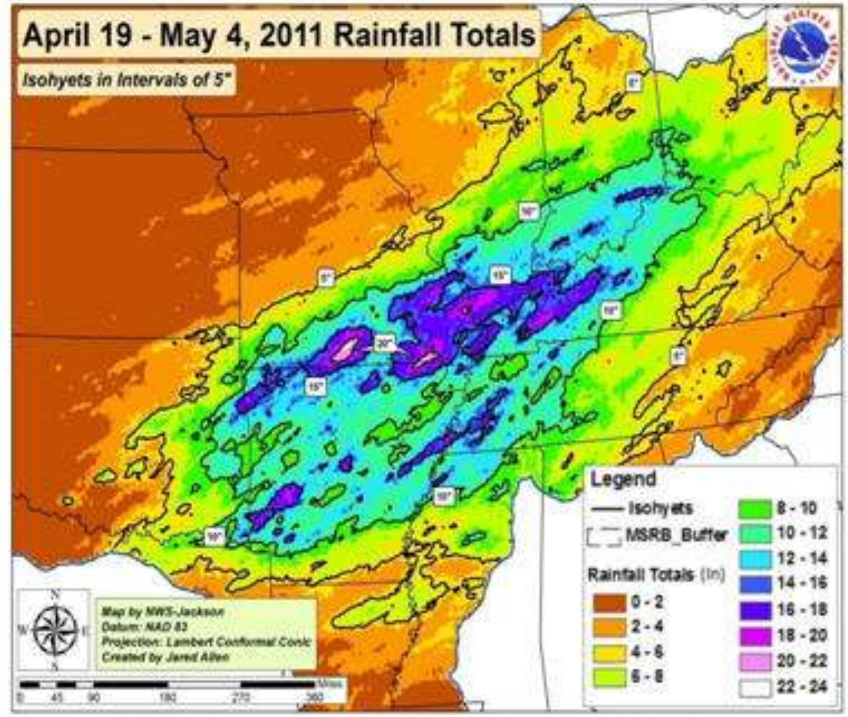
Old River Control Structure Complex was completely rebuilt following the '73 flood

2011 Flood

- The 2011 flooding of the Mississippi River recorded a peak flood flow of ~2,330,000 cfs (at Natchez on May 20^{th}); about 86% of the design capacity of 2.71 million cfs
- The 2011 event saw record stage levels everywhere, downstream of Cairo. e.g. the Natchez gage hit 62.5 ft, 4.5 ft above the previou record
- It was the first time in history that the four majo bypass floodways were opened together, for one flood [Bird's Point, Old River, Morganza, and Bonne Carre]

Total PDF Precipitation — Observed Apr 19-May 4 2011 Precipitation





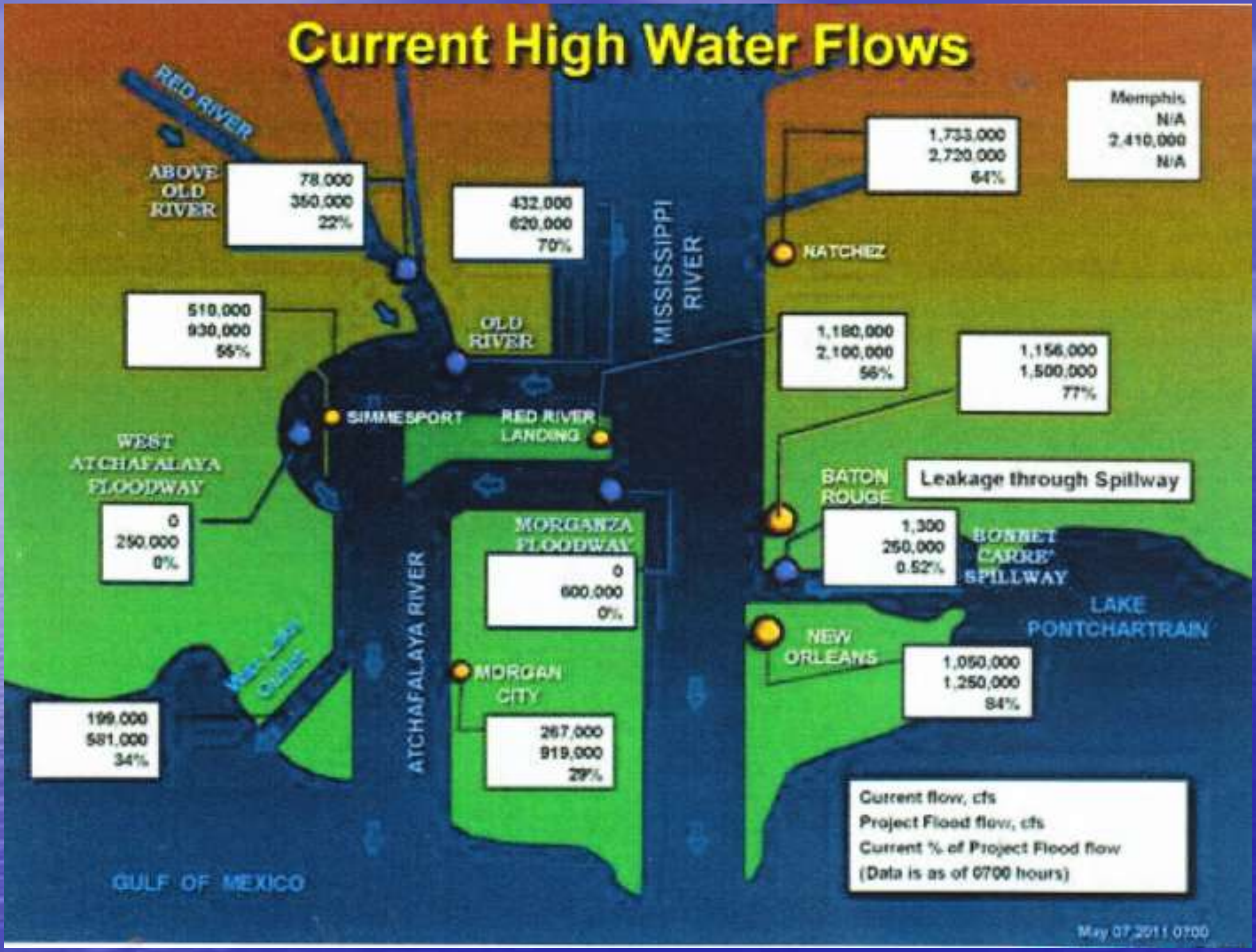
Comparison between the Project Design Flood (PDF) Precipitation events and the observed 2011 precipitation event.:

- The PDF occurred in 3 events.
- The axis of maximum precipitation for the PDF was along and south of the Ohio River.
- Maximum rainfall totals for PDF were 24-32" over KY and along the Ohio River
- The 2011 precipitation event occurred during 2 events 4/19-4/28 and 5/1-5/4.
- The axis of maximum precipitation for the 2011 event was along and just north of the Ohio River in unregulated areas.
- Maximum rainfall totals for 2011 event were 12-24" along and just north of the Ohio River.
- It should be noted that stages at Cairo were elevated (+10ft or 127% of normal) at the onset of the 2011 rainfall event due to heavy rains in late Feb/early Mar that produced a crest of 53.41' on 3/18.

- **Between April 21 & May3, rainfall in the Mississippi-Ohio River confluence area was as much as 900 to 1000% times the normal two-week average** From Mullen (2012)

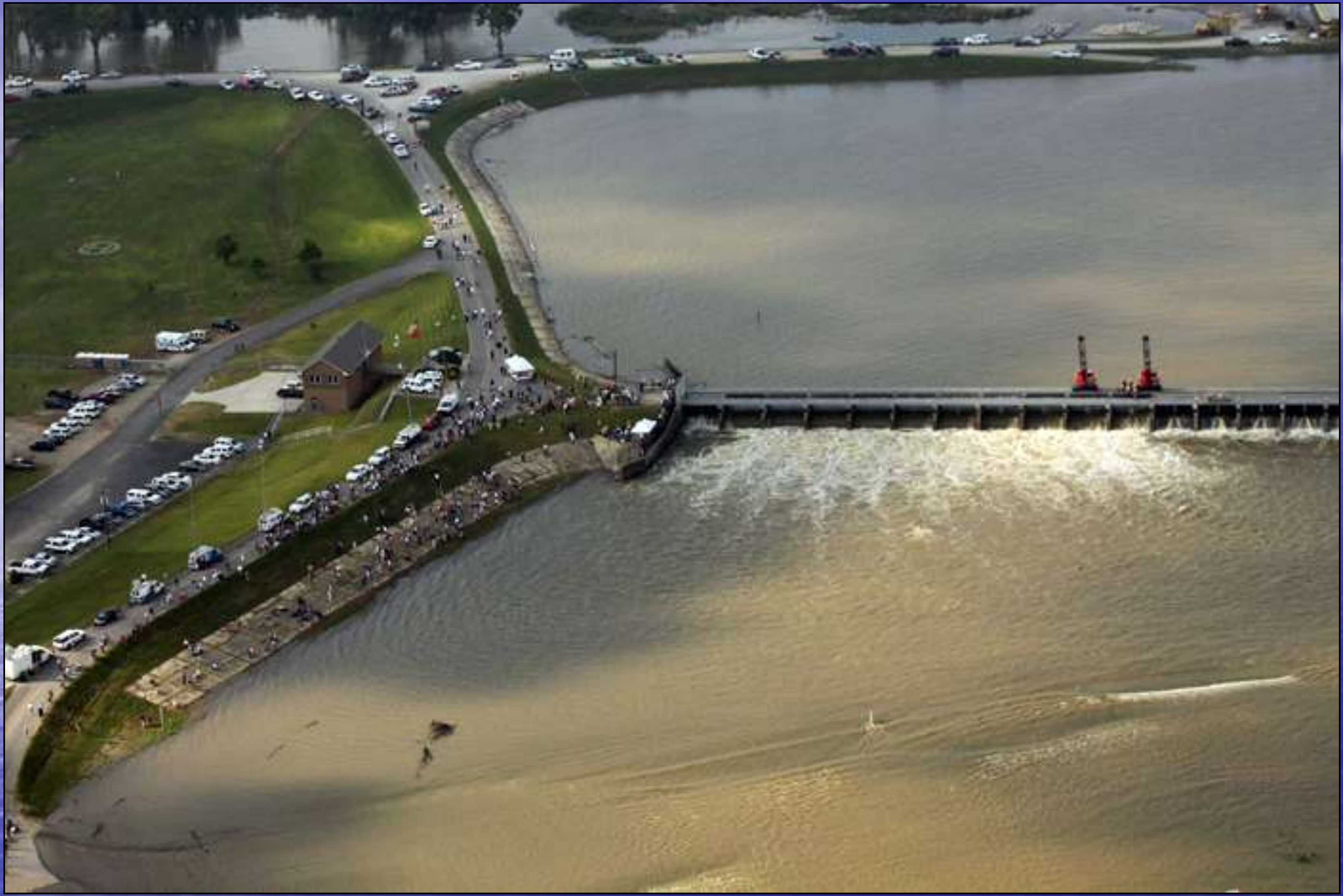
Flood Preparations

- An engineer from the Corps of Engineers Louisville District inspects the troubled floodwall at Hickman, Kentucky.
- The downtown area was destroyed by high groundwater in 1993 because of the sheetpile cutoff beneath this floodwall
- Volunteers unpack and assemble Hesco Bastion concertainers in Memphis. These can be filled with rock to create more substantial barricades than using sandbags.



- **Flood Routing situation in the Mississippi Delta on May 7, 2011**

- **About 1300 cfs was leaking through the needle logs prior to their being lifted at Bonnet Carre for the 10th time since 1932, on May 9th. The spillway is 7000 ft long.**

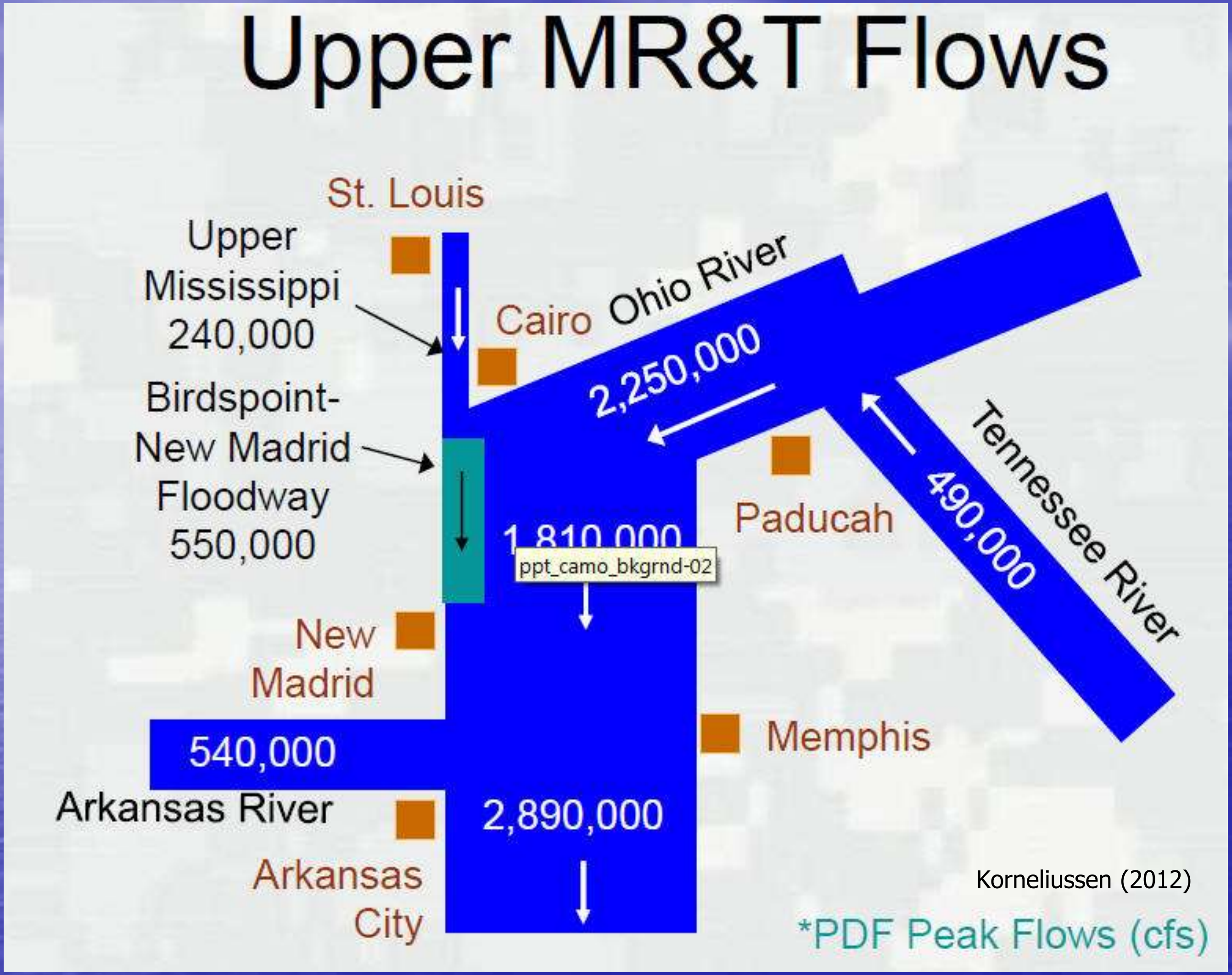


- **Bystanders gather to view the opening of the needle log gates at the southern end of the Bonnet Carre Spillway, constructed in 1929-32. 330 of the 350 spillway bays were opened in May 2011, discharging up to 316,000 cfs.**

- The design capacity of the spillway is 250,000 cfs, about one-fifth of the channel's capacity. It was completed in 1932 and the railroad and highway relocations completed in 1936. The spillway was opened in 1937, 1945, 1950, 1973, 1975, 1979, 1983, 1997, 2008, and in 2011. Not statistically significant…yet e.g. 3X 1st 20 yrs; 7X next 40 yrs

- The Bonnet Carre Bypass Spillway diverts flow 6 miles, into Lake Pontchartrain, which is at sea level. It was constructed a few miles downstream of a natural crevasse, which had breeched 6 times in the previous 120 years.
- Four million cubic yards of sediment was mucked from the spillway channel after the 1997 overflows, increasing the spillway capacity.

The Morganza Spillway was constructed in 1953-56, to retard the flow passing Baton Rouge to 1,500,000 cfs. It was only opened once previous to 2011, during the 1973 flood. This shows the first bay being opened on May 11th, 2011 and the structure discharged a peak flow of 172,000 cfs on May 17th.



- **The Bird's Point-New Madrid Floodway was conceived in 1929 as a 'safety valve' to spill an additional 550,000 cfs to reduce the flood stage at Cairo, Illinois, then an important commercial crossroads.**

BIRDS-POINT – NEW MADRID FLOODWAY

Korneliussen (2012)

- Located in Southeast Missouri, directly below the confluence of the Upper Mississippi and Ohio rivers
- 133,000-acre floodway contributes to protection of more than 2.5 million acres in five states
- Authorized 1928, completed 1932, operated 1937 and 2011

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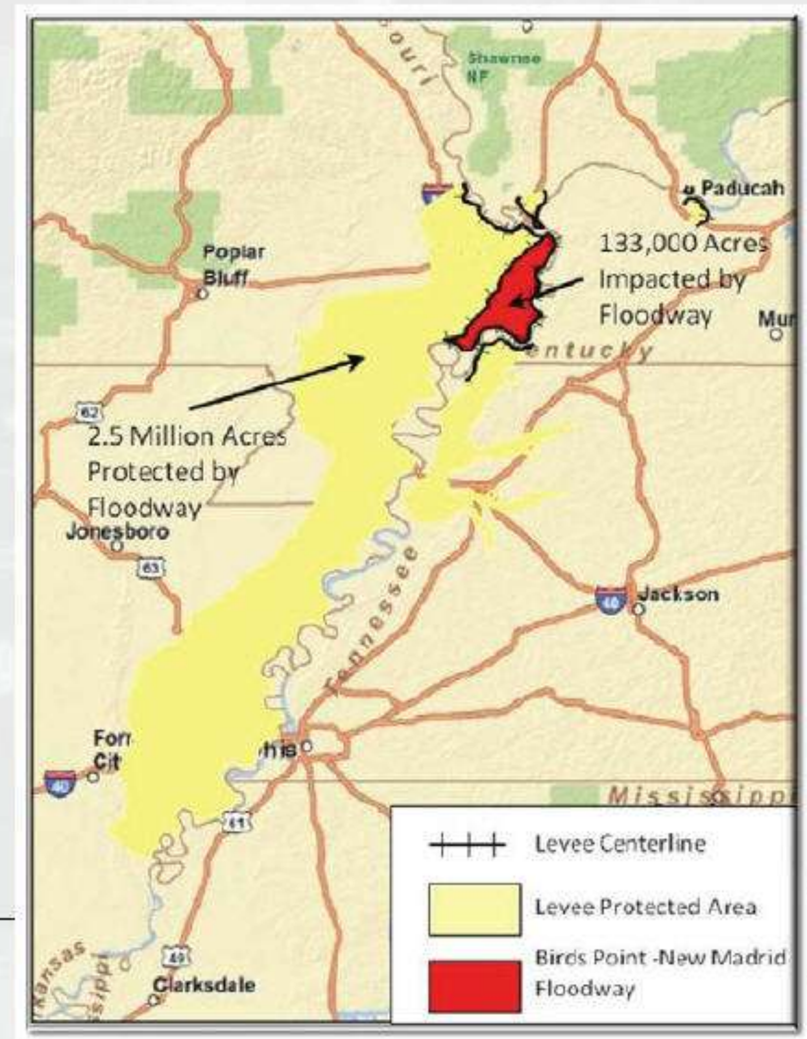
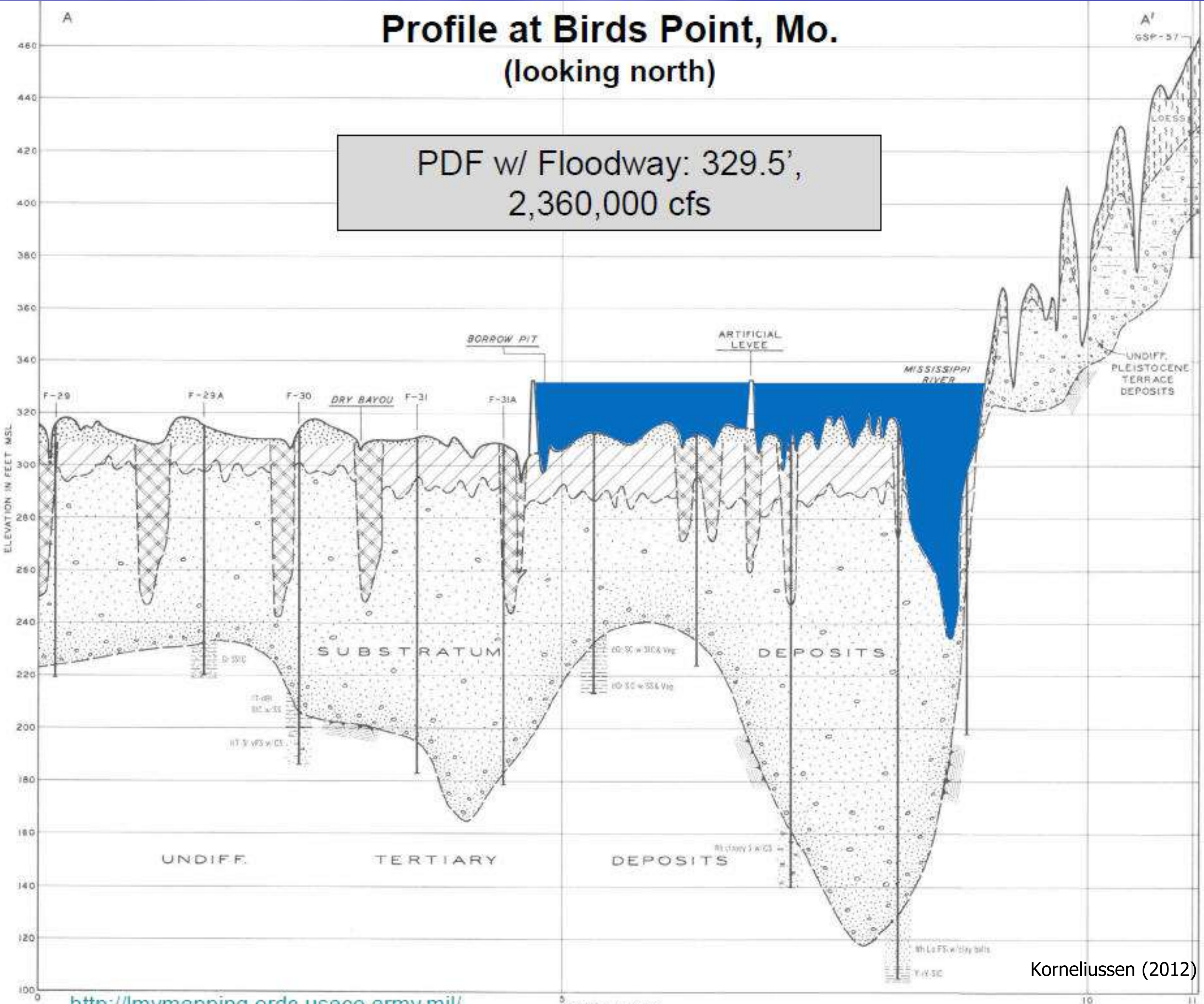


Profile at Birds Point, Mo.
(looking north)

PDF w/ Floodway: 329.5', 2,360,000 cfs



Korneliussen (2012)

http://lmvmapping.erdc.usace.army.mil/

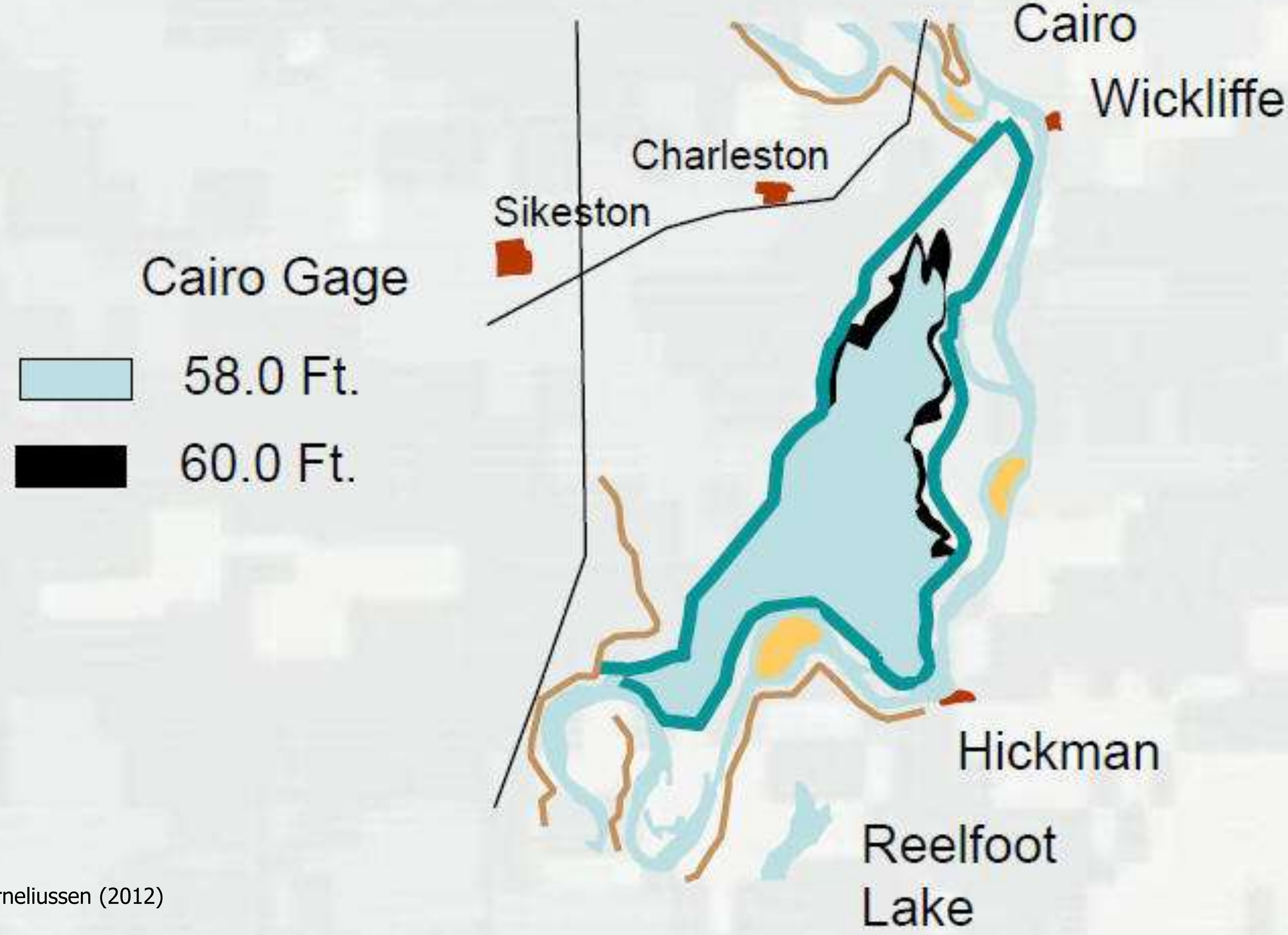
Backwater flooding of the Bird's Point New Madrid Floodway area

April 30, 2011:

Backwater over HWY 80 in Floodway between Setback Levee and HWY 77

Korneliussen (2012)

Backwater Flooding



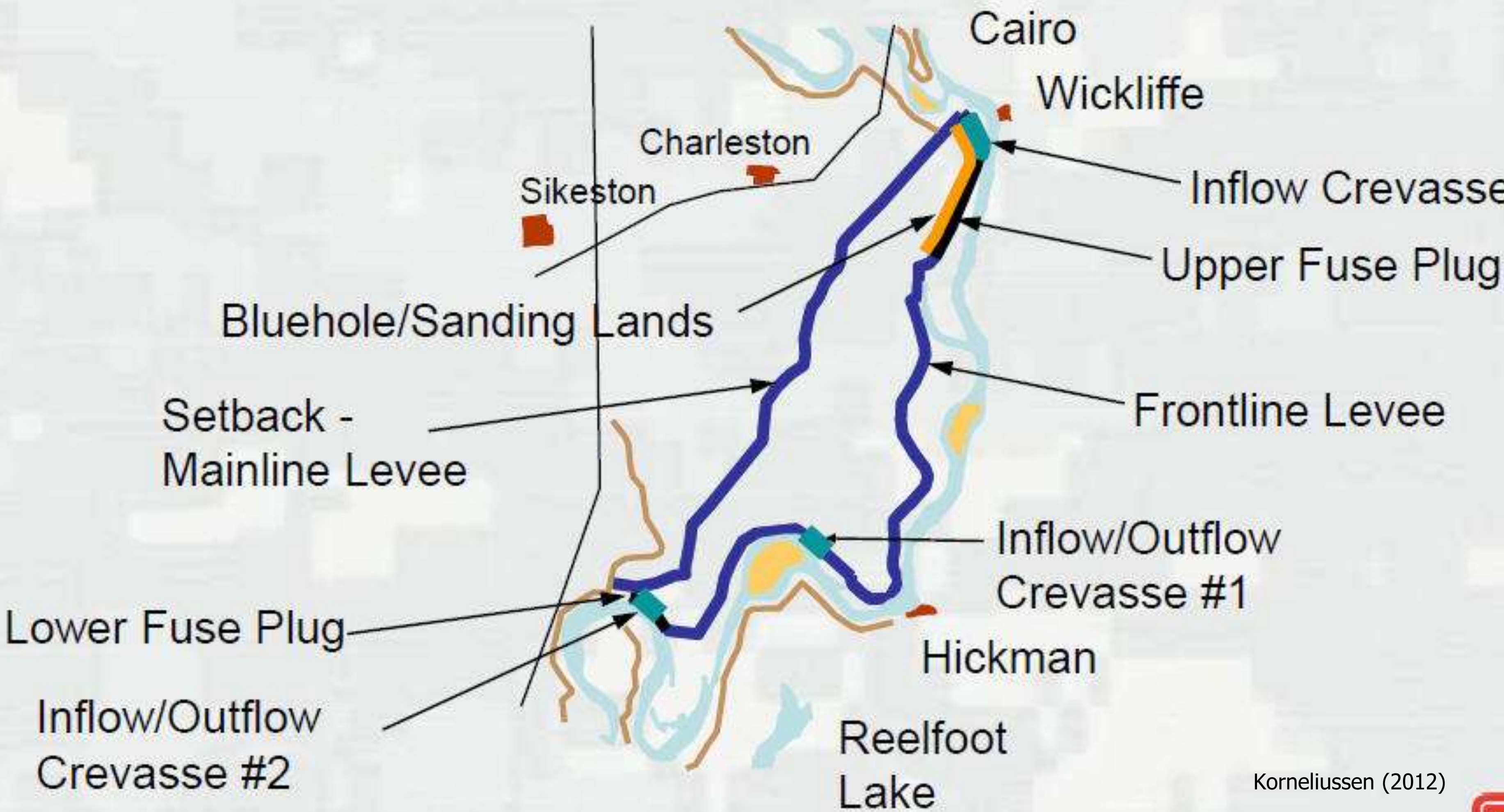
Korneliussen (2012)

Explosives Barge

The barge carrying the blasting agents was parked at this location throughout the memorable 1993 flood of the lower Missouri and middle Mississippi Rivers It was moved into position was moved north on April 26th and loaded into the levee at 7 AM on May 2nd

- Several thousand lineal feet of hollow PVC pipe was embedded in the *fuse plug levee* at Bird's Point. When the time came to blow the dike, the pipes were filled with blasting agent and detonated

Location and Description



Korneliussen (2012)

- **Locations of fuse plug and outflow crevasse**


Detonation at Bird's Point

- The use plug section was detonated a 10 PM CDT on May 2, 2011, creating an artificial crevasse 11,000 feet long, diverting 335,000 to 375,000 cfs of the river's flow


The edge of the inflow section of the levee which was breached May 2nd
Korneliussen (2012)

- Approximately 200,000 acres of essentially level flood plain within the Bird's Point-New Madrid Floodway was inundated within 36 hours of the detonation.
- The USGS deployed 40 hurricane *storm surge sensors* to monitor excavation of the crevasse scour hole and flow velocities, every 30 seconds.

Bird's Point-New Madrid Floodway

Fuse plug dike blown at New Madrid to allow flood waters to flow back into the Mississippi River

- The State of Missouri appealed to the US Supreme Court to prevent the Bird's Point diversion, on basis of economic cost-benefit
- The U.S. Government maintains flowage rights in the four designated floodways, regardless of their post-1928 development

'Hard points' and backwater flooding in Memphis

- Some of the high-value developments in Memphis were afforded increased protection
- Older neighborhoods bereft of any recent flood protection were inundated for the first time, under *record high gage flows*

The monster sand boil in Cairo

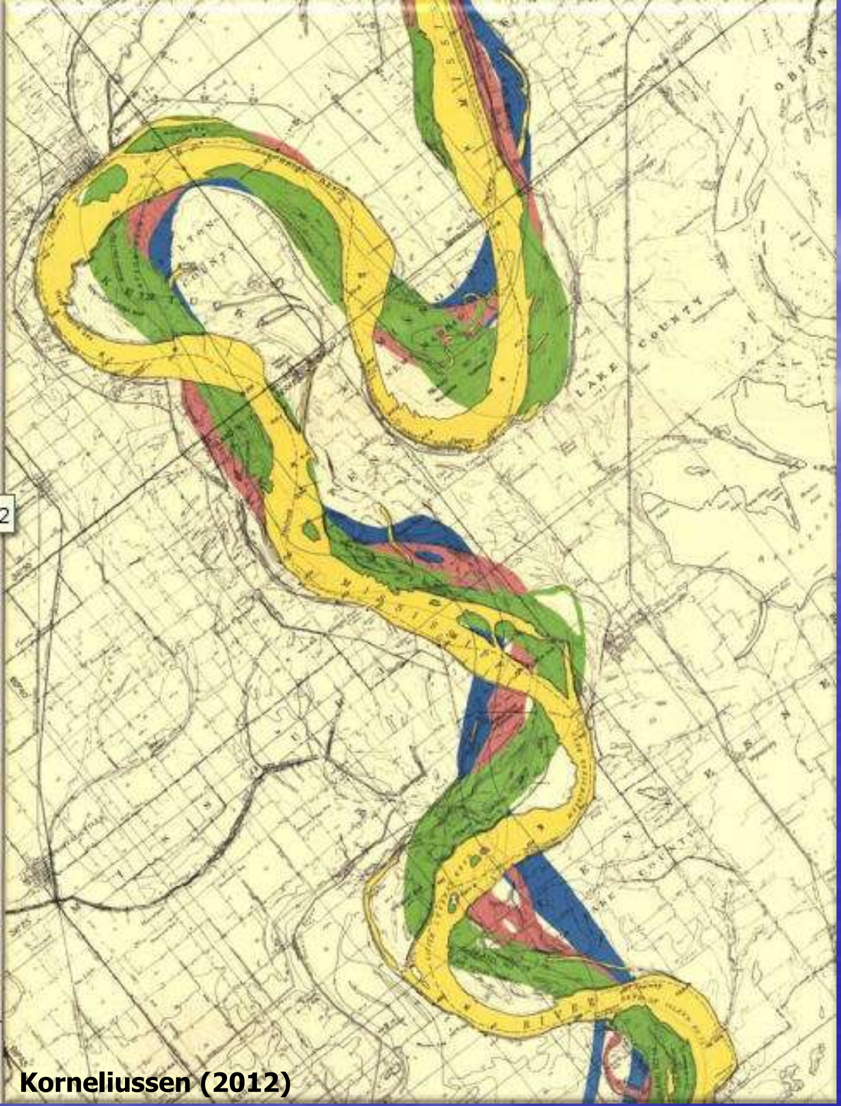
From Mullen (2012)

Heroic flood fighting

- **The MR&T system is designed to withstand a project flood provided the Corps six district can perform *"heroic flood fighting efforts,"* such as those shown here**

Images from Mullen (2012)

The vexing problem - underseepage

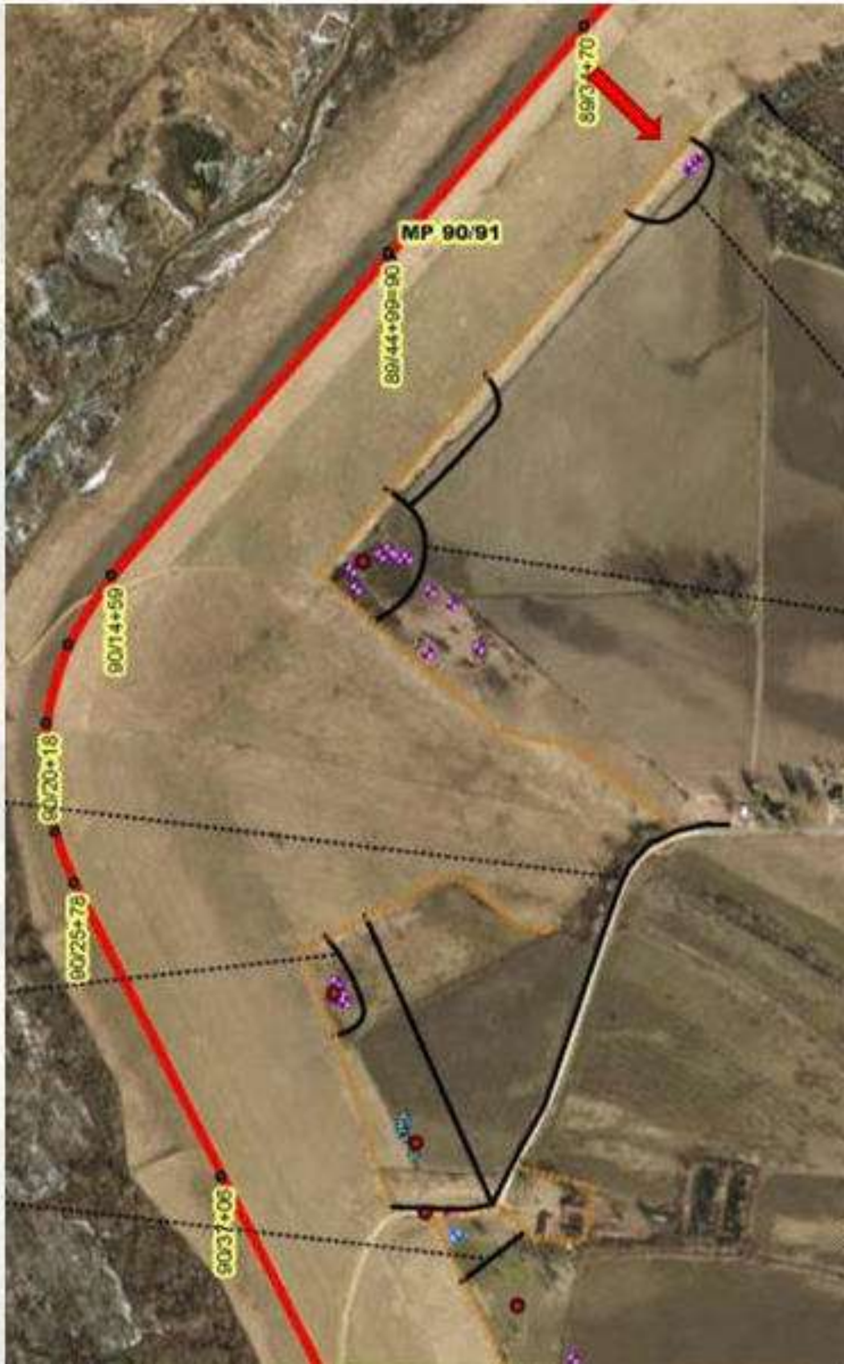


Korneliussen (2012)

From Mullen (2012)

- **Map at left shows historic channels of the Mississippi River near New Madrid, MO. Most of the levees downstream of Cairo are built on *old channels*, which provide ready conduits for underseepage.**

Numerous Large Sand boils in Rena Lara, MS



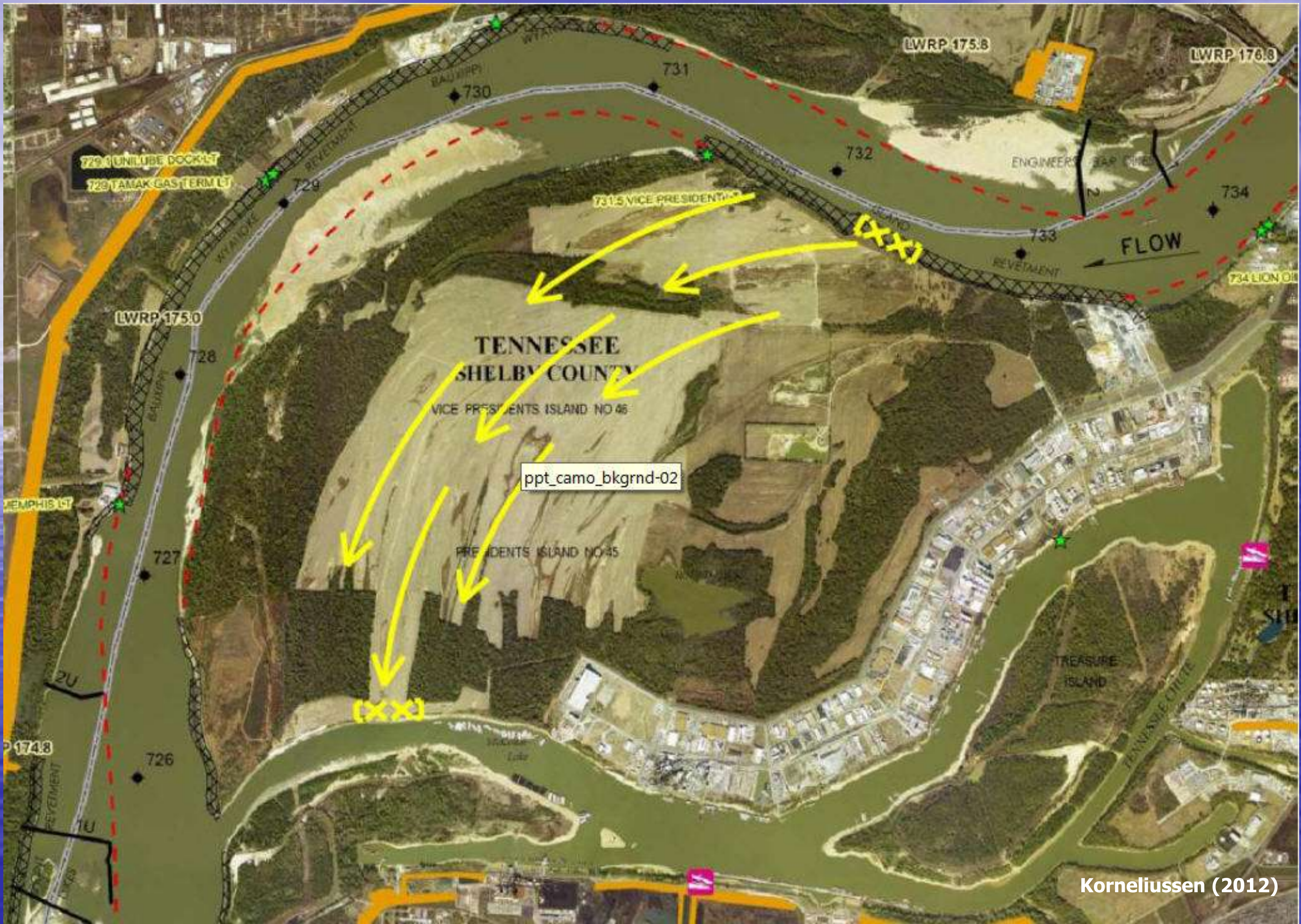
From Mullen (2012)

Large Sand boils at Buck Chute, MS

From Mullen (2012)

Overbank flow along Sheep's Ridge Road and the Merriwether-Cherokee Revetment

Overflow of Vice President's Island No 46 in Memphis



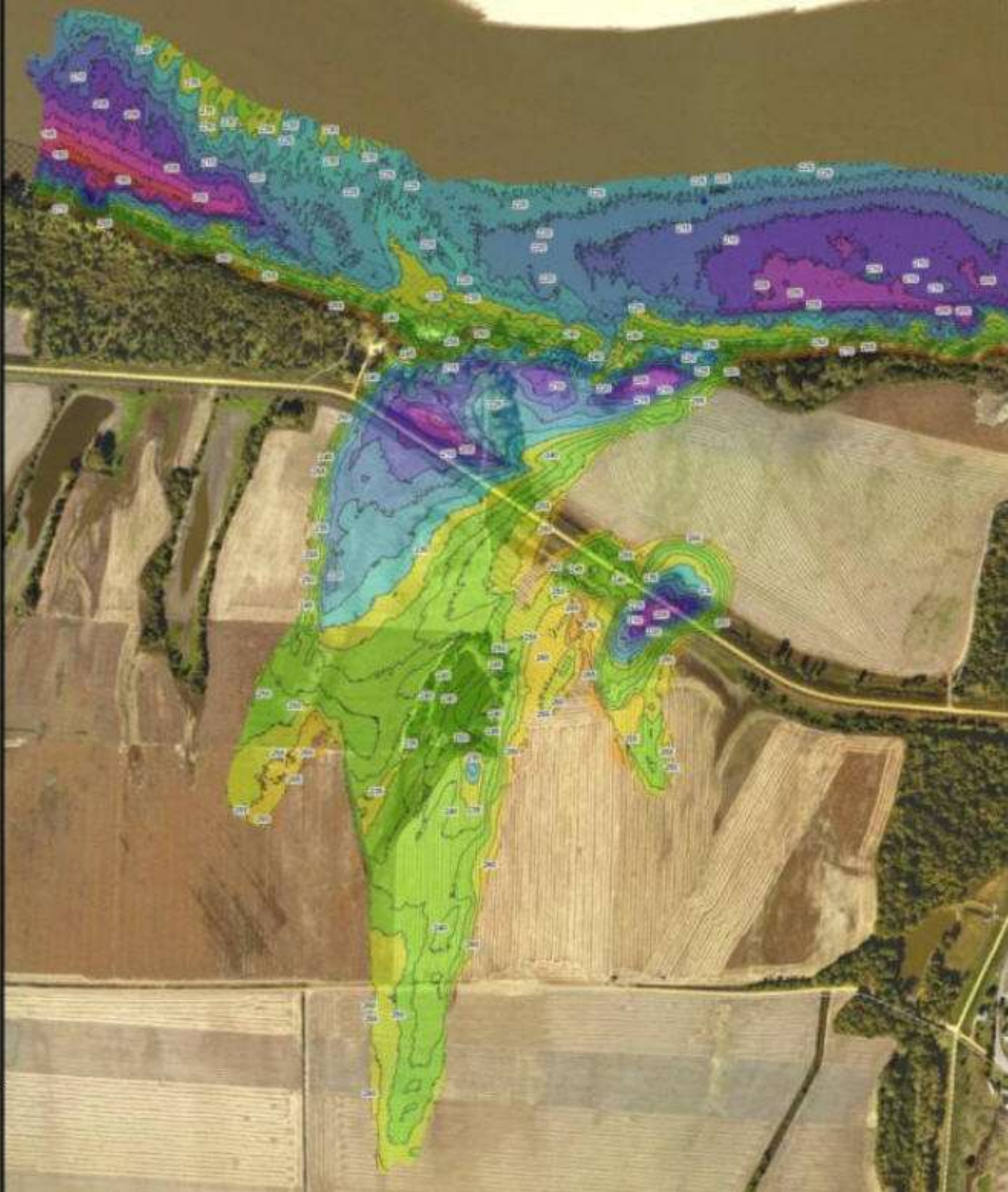
Wappapello emergency spillway and washout of Highway "T"

Korneliussen (2012)

Bathymetry of scour erosion along Merriwether-Cherokee Revetment overflow

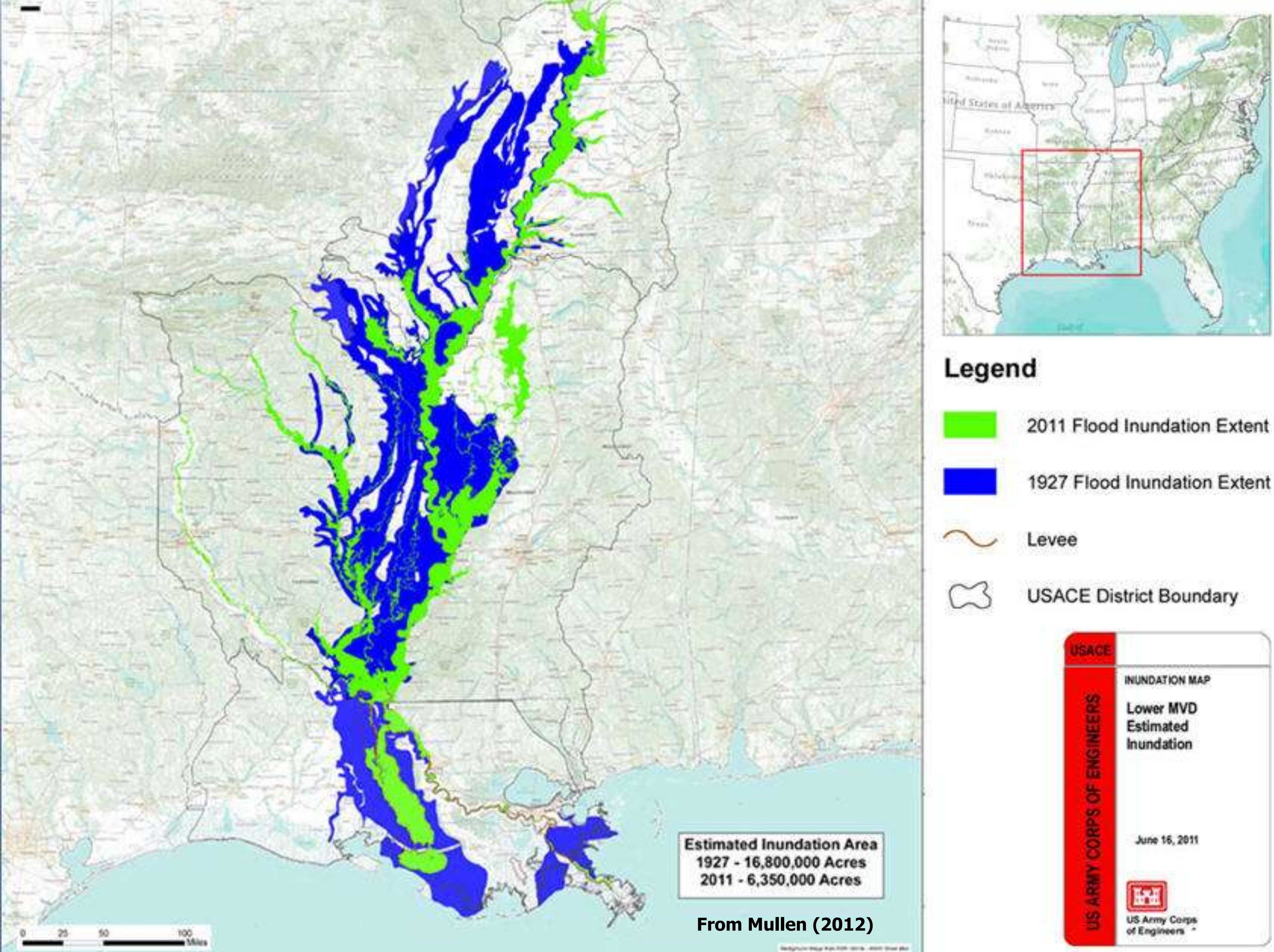
- Sheep's Ridge Road – Meriwether Cherokee Revetment
- Top bank scour approx. 2,200' wide and 50-60' deep along existing revetment
- Overbank scour approx. 80' deep and runs inland approx. 3,000-4,000'

From Korneliussen (2012)



Tailwater Effects

- The areas initially impacted by high flows are often those inundated by low gradient tributaries to the Mississippi River



From Mullen (2012)

OPERATION MAKE SAFE PROGRESS

- Upper crevasse:
  - Five 25-foot-deep scour holes filled to grade with sand and clay
  - All 9,000 feet of crevasse is to a (Cairo) gage elevation of 51' or higher as of Oct. 28
  - HESCO barriers to protect to 55 feet were installed as of Dec. 14
  - Repairs to 55 feet will resume after the spring seasonal highwater recedes

From Korneliussen (2012)

OPERATION MAKE SAFE PROGRESS

- Center crevasse:
  - Scour hole filled with more than 300,000 cubic feet sand
  - Clay cap to fill scour hole to grade
  - 800 feet of levee reconstructed to a (Cairo) gage elevation of 55 feet as of Dec. 3
  - 4,700 feet of levee that was explosively activated but did not degrade has been reshaped to Make Safe elevations


During operation

From Korneliussen (2012)


Completing the levee


Photo courtesy of Great Lakes Dredge & Dock, Inc.
Early progress

OPERATION MAKE SAFE PROGRESS

- Lower crevasse:
  - Make Safe repairs complete Oct. 10 except for turfing
  - 4,700 feet of levee repaired
  - Work performed by a hired-labor crew from Vicksburg

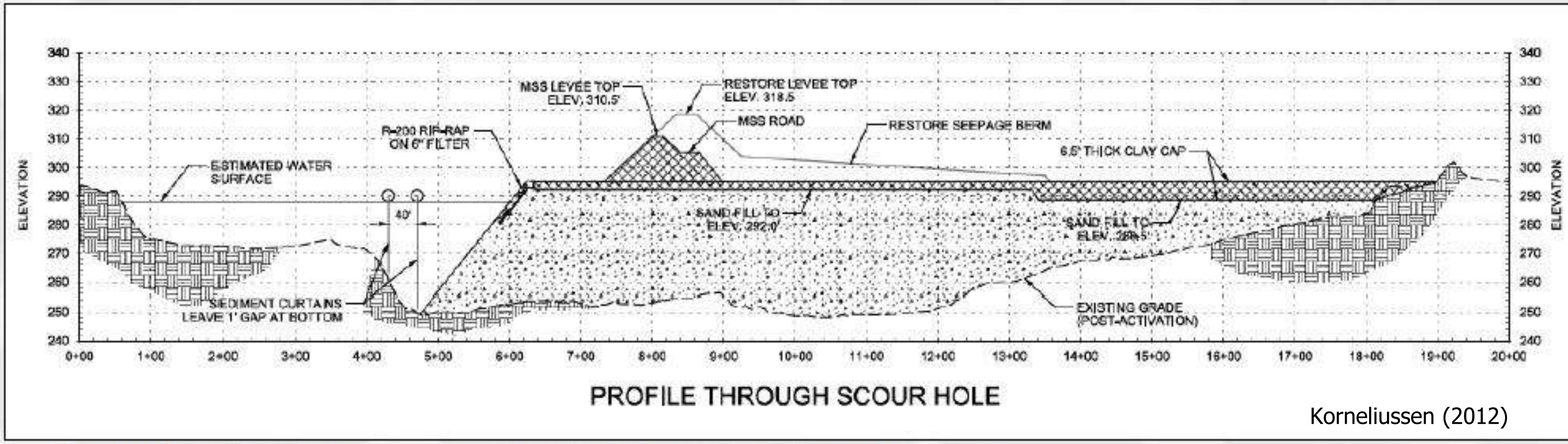
From Korneliussen (2012)

Immediately after operation

Completing the levee

Early progress

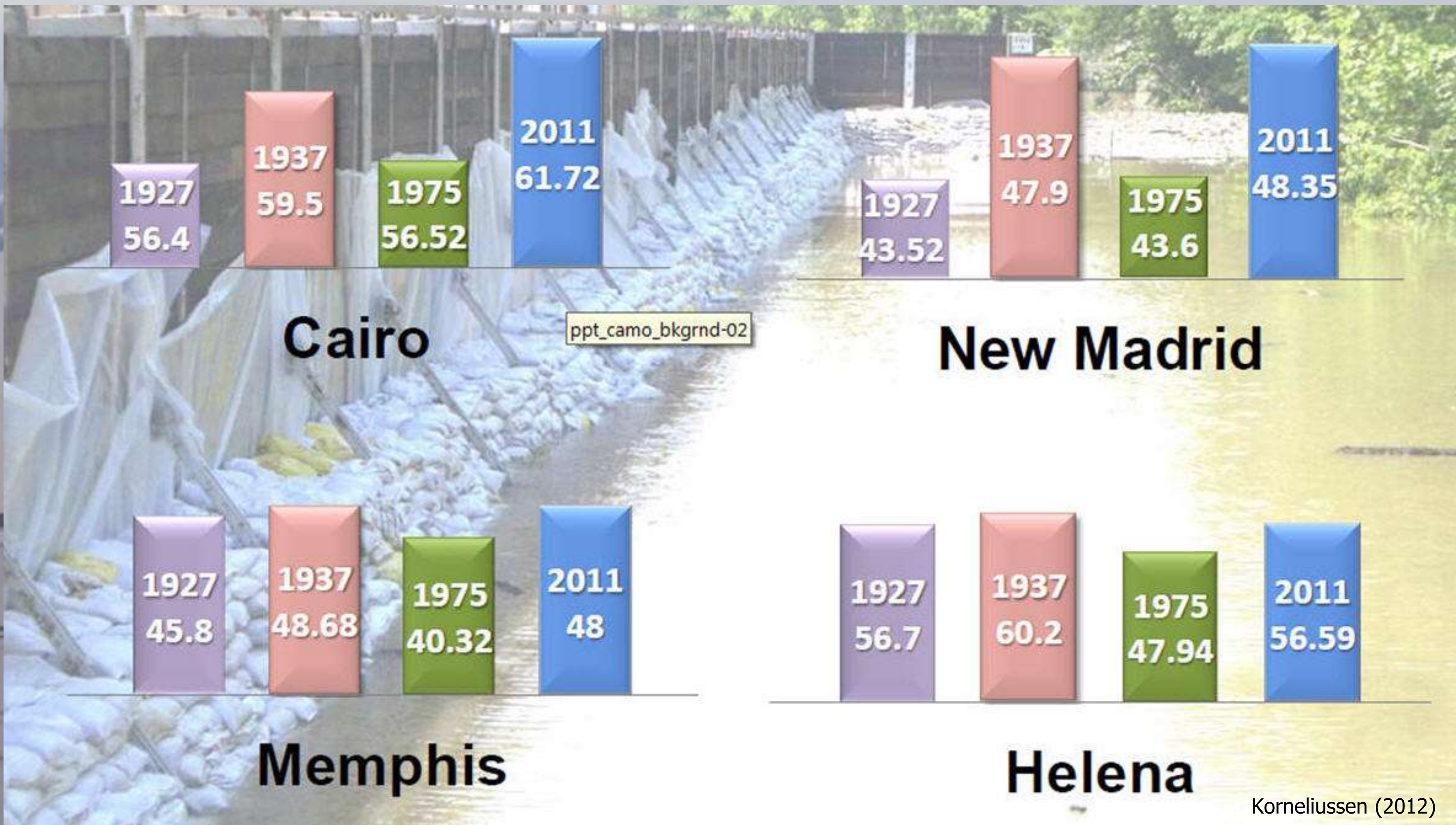
Costly repairs to crevasses



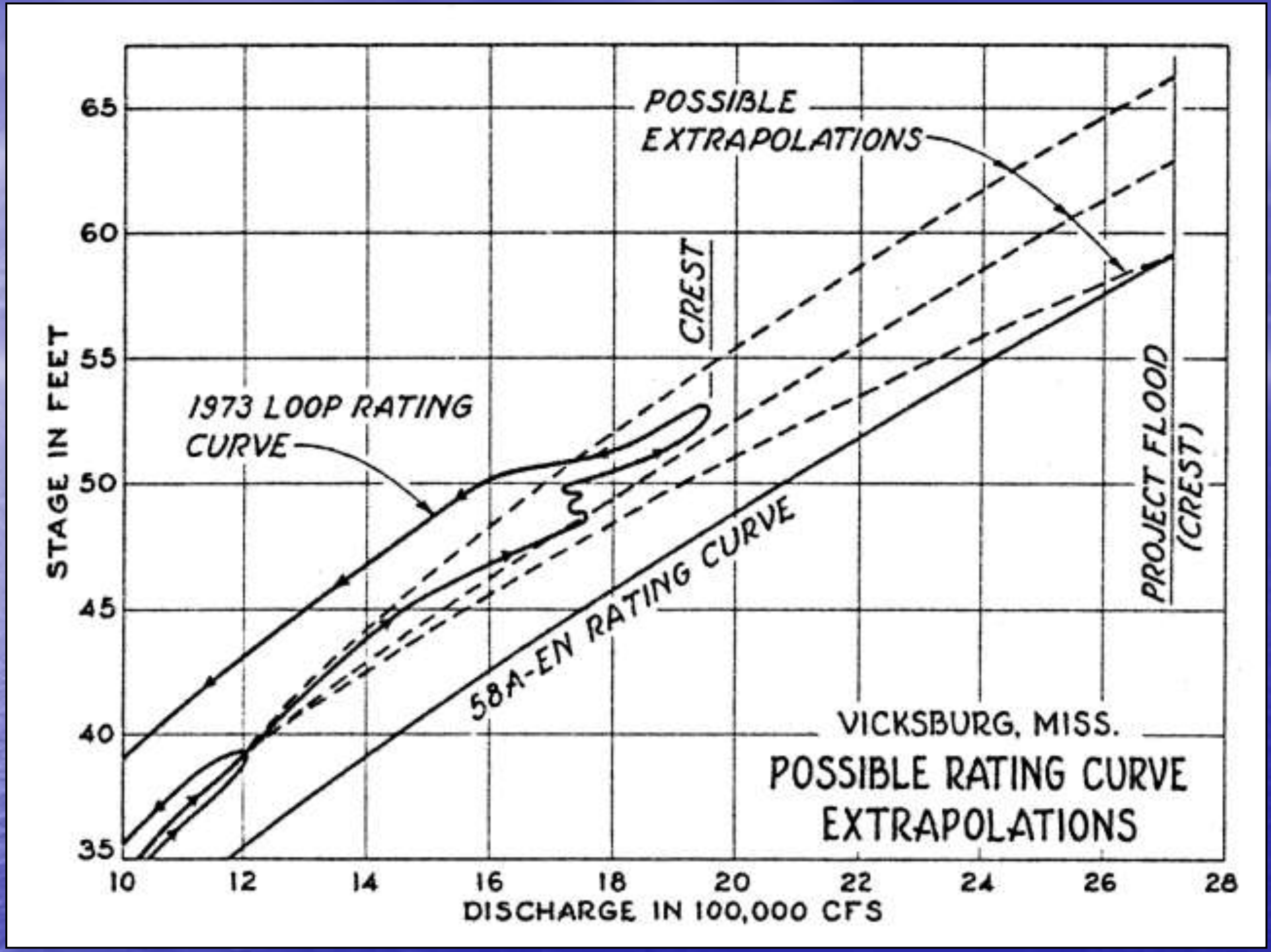
A profile of repairs at the center crevasse comparing Make Safe repairs to full Restore of the levee.

- Many engineers have criticized the Corps costly repairs of deep scour holes formed on accidental and intentional crevasses, assuaging that the Corps could install spillway crests or gates for the same cost

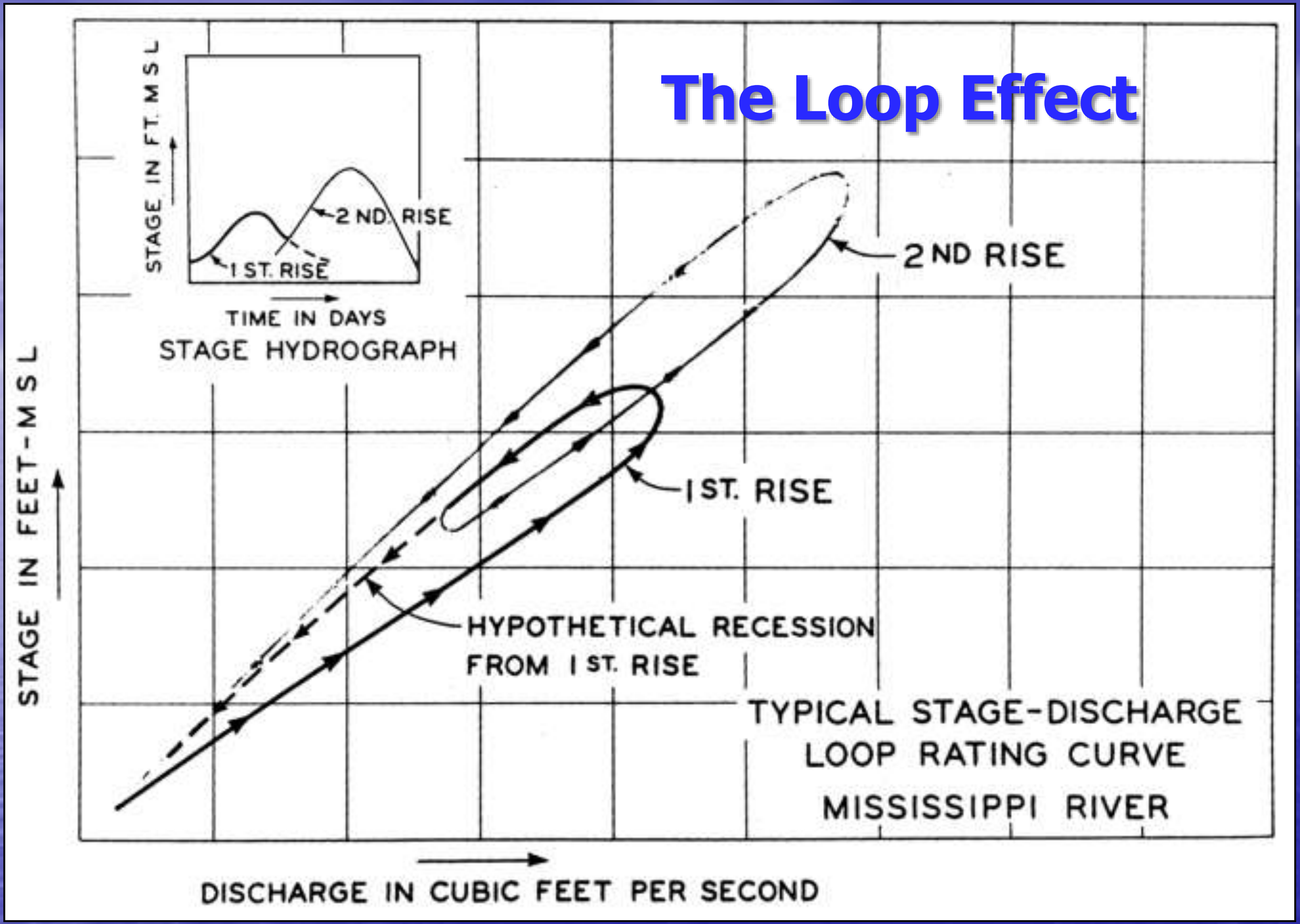
Why are the river's stage-discharge relationships on the rise ?



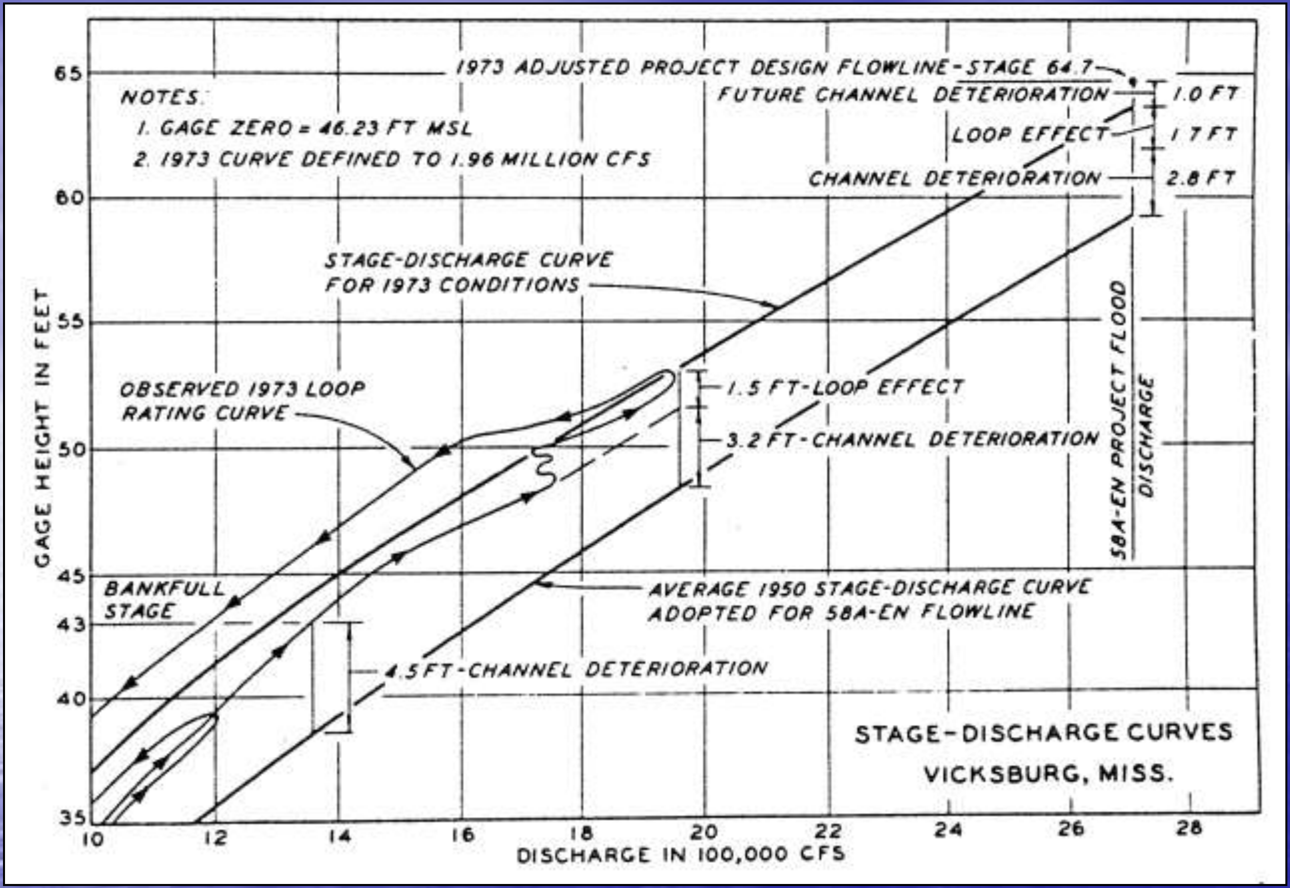
Korneliussen (2012)



- **'Aging problems' with Stage-Discharge relationships.** River stages recorded in 1973 were far higher than assumed in design of the MR&T Project. At Vicksburg (shown here) the river was 8 ft higher than its design elevation.

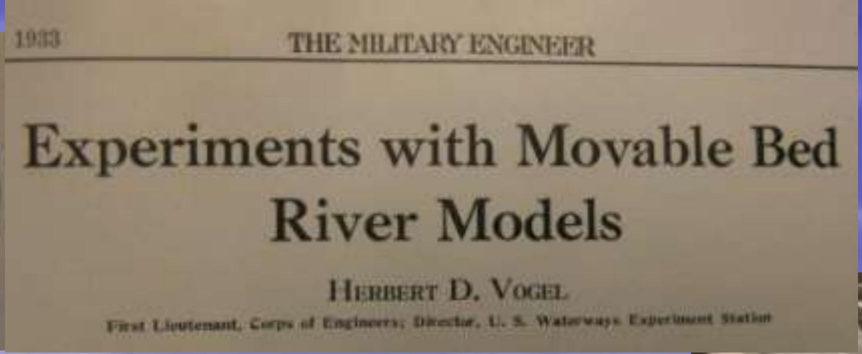


- **Stage-Discharge 'Loop Rating Curve:' Typical increases in flow stage that accompanies successive peak flows, as observed in the 1973 Flood.**



Sediment is deposited adjacent to and within most of the structural cutoffs when high flows drop rapidly. These deposits degrade channel efficiency.
Other complications: sediment starvation by reservoirs and submerged navigation training structures, such as groins.

- **Reasons for unstable stage-discharge relationships:** sand waves, bank migration, changing bed movements during successive high flow cycles during peak discharge years, like 1973, 1993, and 2011.
- **Since 1950 the river has been working via entropy to *re-establish its original length*, losing some of the channel capacity gained by the streamlining carried out during the two previous decades.**


1933 THE MILITARY ENGINEER

Experiments with Movable Bed River Models

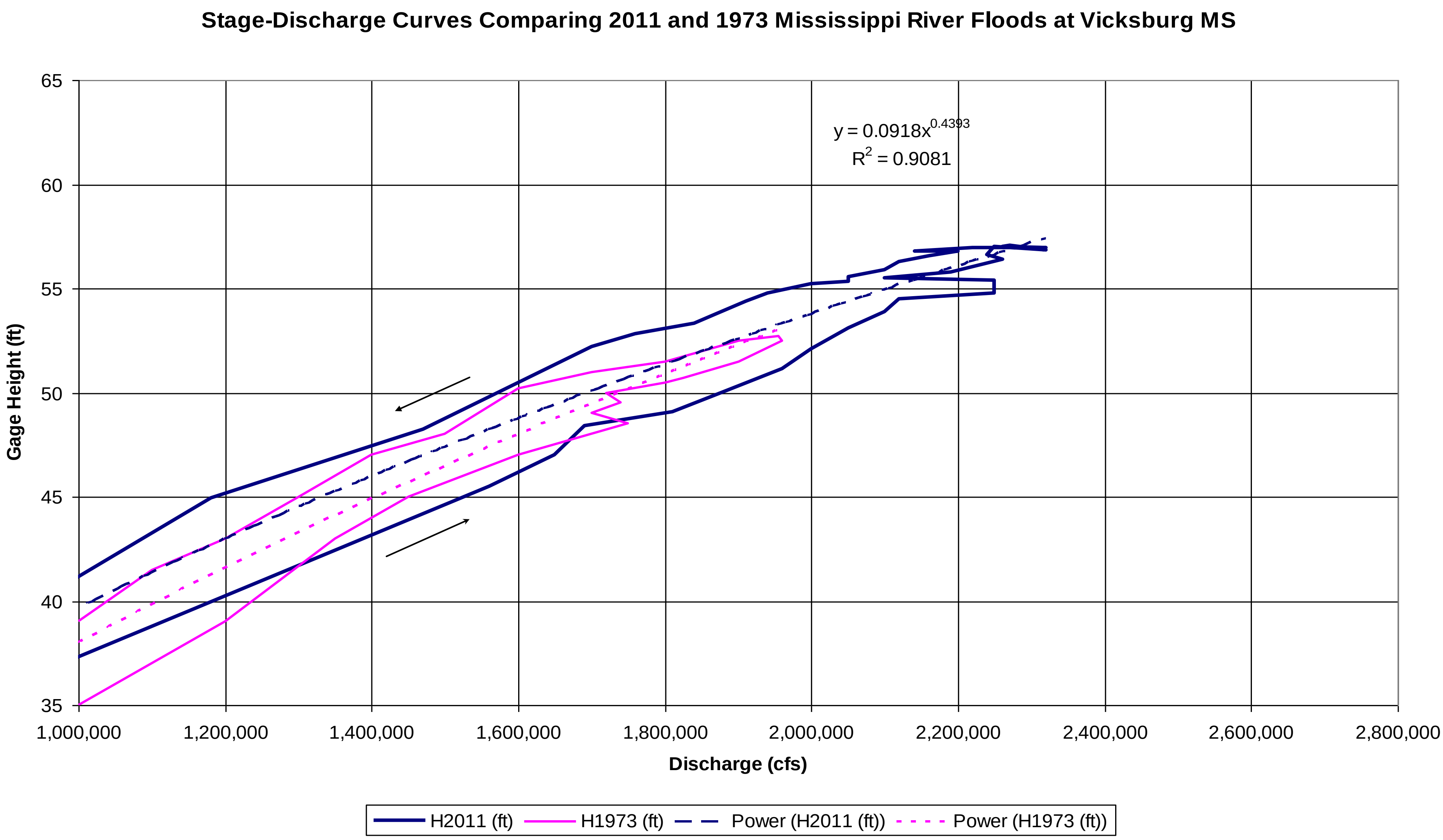
HERBERT D. VOGEL

First Lieutenant, Corps of Engineers; Director, U. S. Waterways Experiment Station

Examining transient bed effects at constant flow values

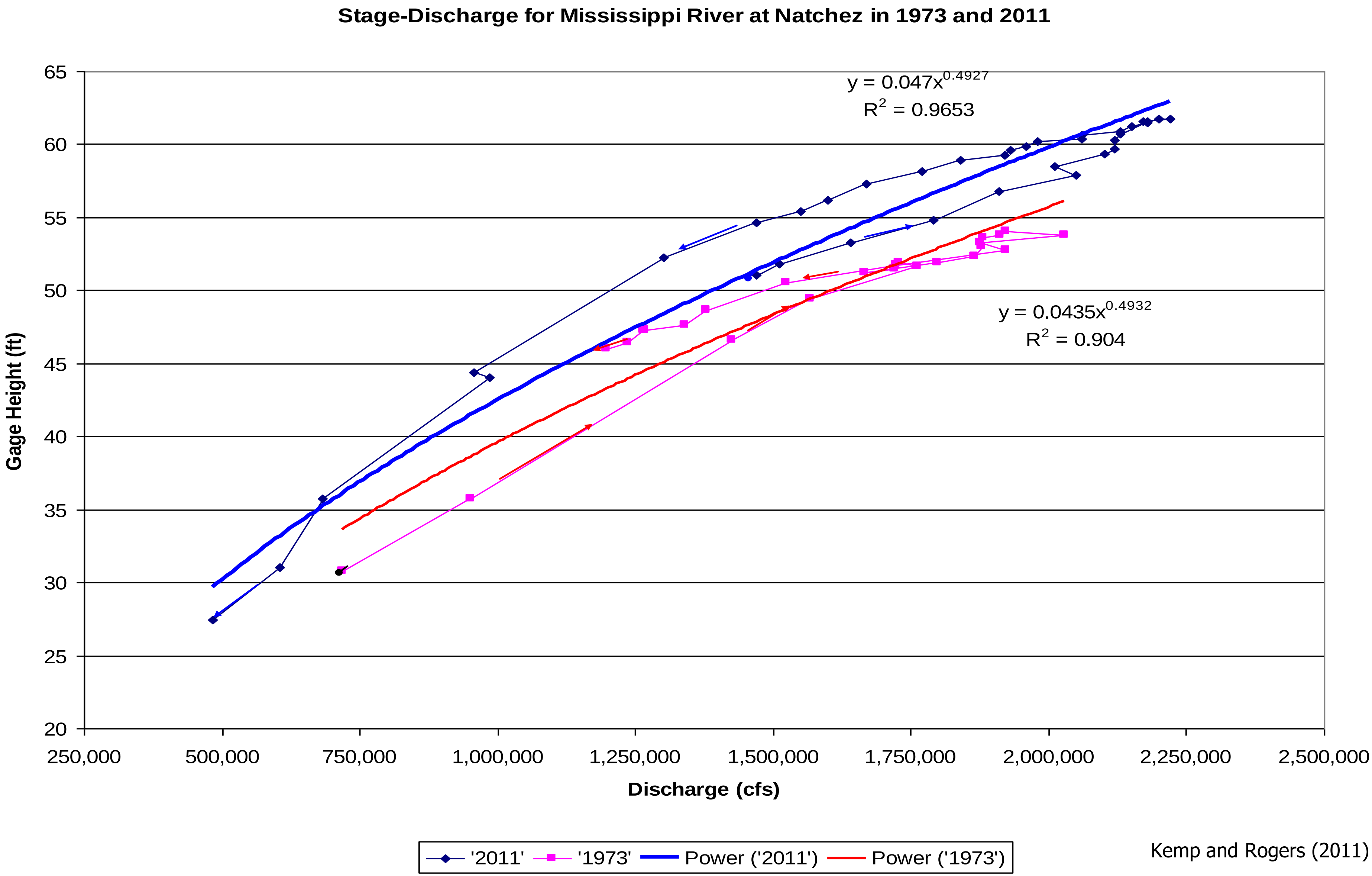
Natural sand bed channel (lower left); dredged channel (upper right); and impact of structural dikes (lower right)

Comparison of 1973 & 2011 at Vicksburg



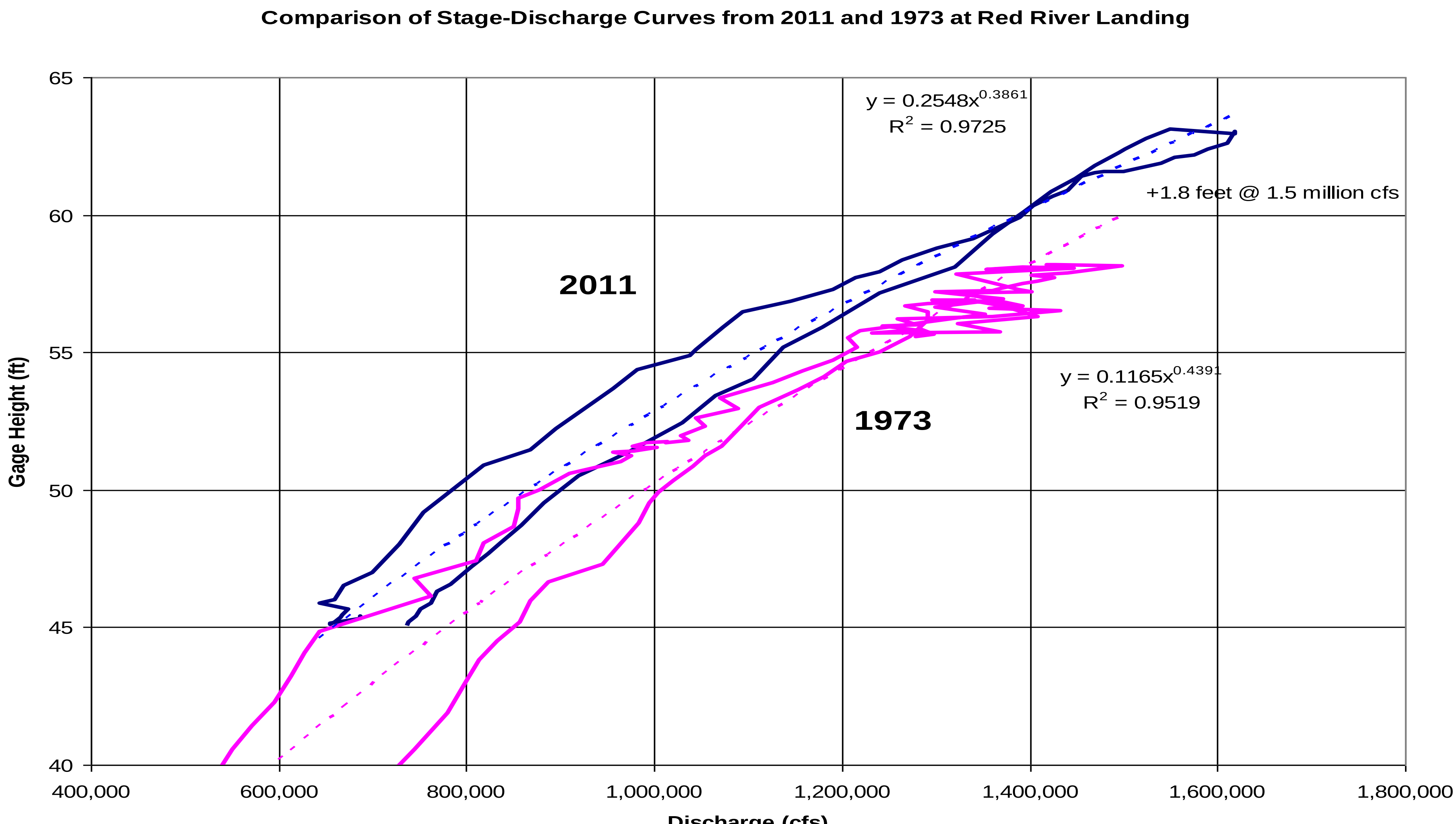
Kemp and Rogers (2011)

Comparison of 1973 & 2011 at Natchez



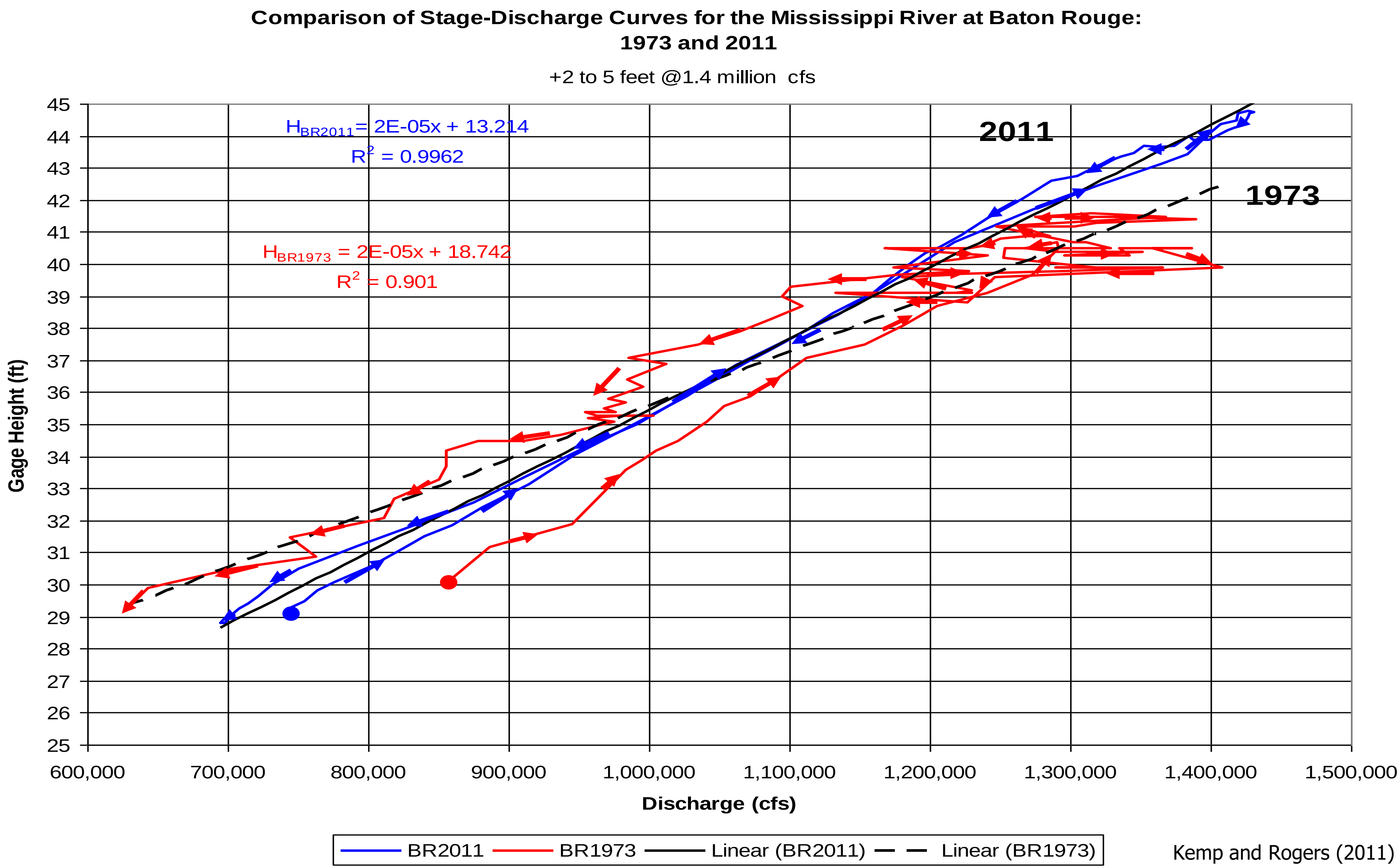
Kemp and Rogers (2011)

Comparison of 1973 & 2011 at Red River Landing



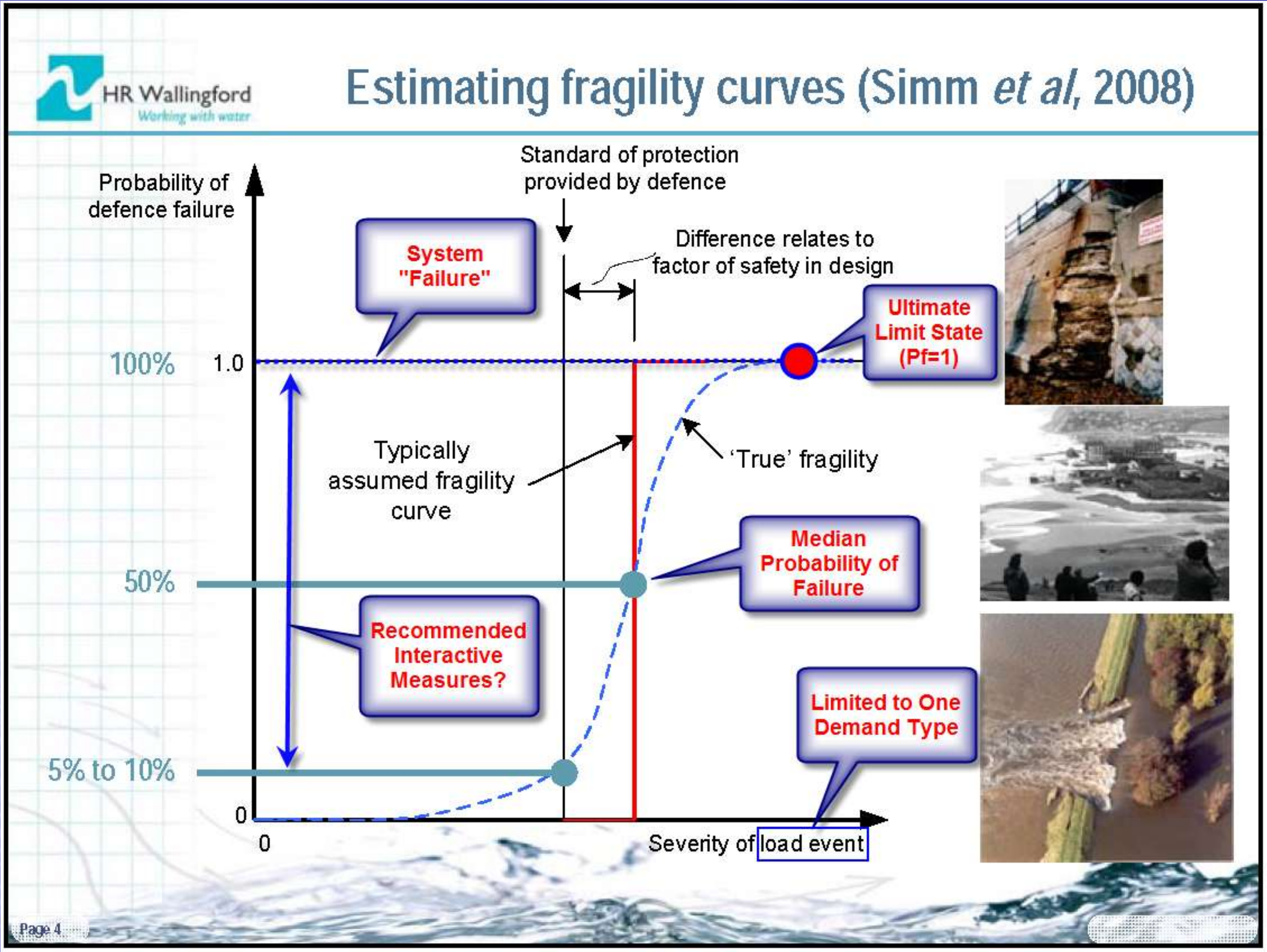
Kemp and Rogers (2011)

Comparison of 1973 & 2011 at Baton Rouge



Kemp and Rogers (2011)

We are shifting to a *risk-based assessment* of levees for design of flood protection, estimating flood damage losses, and setting realistic insurance rates



- **Overview diagram of a fragility curve.** The y-axis represents the annualized probability of failure, while the x-axis represents loads of interest (such as river stage). Failure of the system occurs at a probability of failure equal to 1 (also known as the Ultimate Limit State). It can be very difficult to identify recommended interactive measures to manage increasing hazard levels. (modified from Simm, 2008; and Simm et al., 2010).

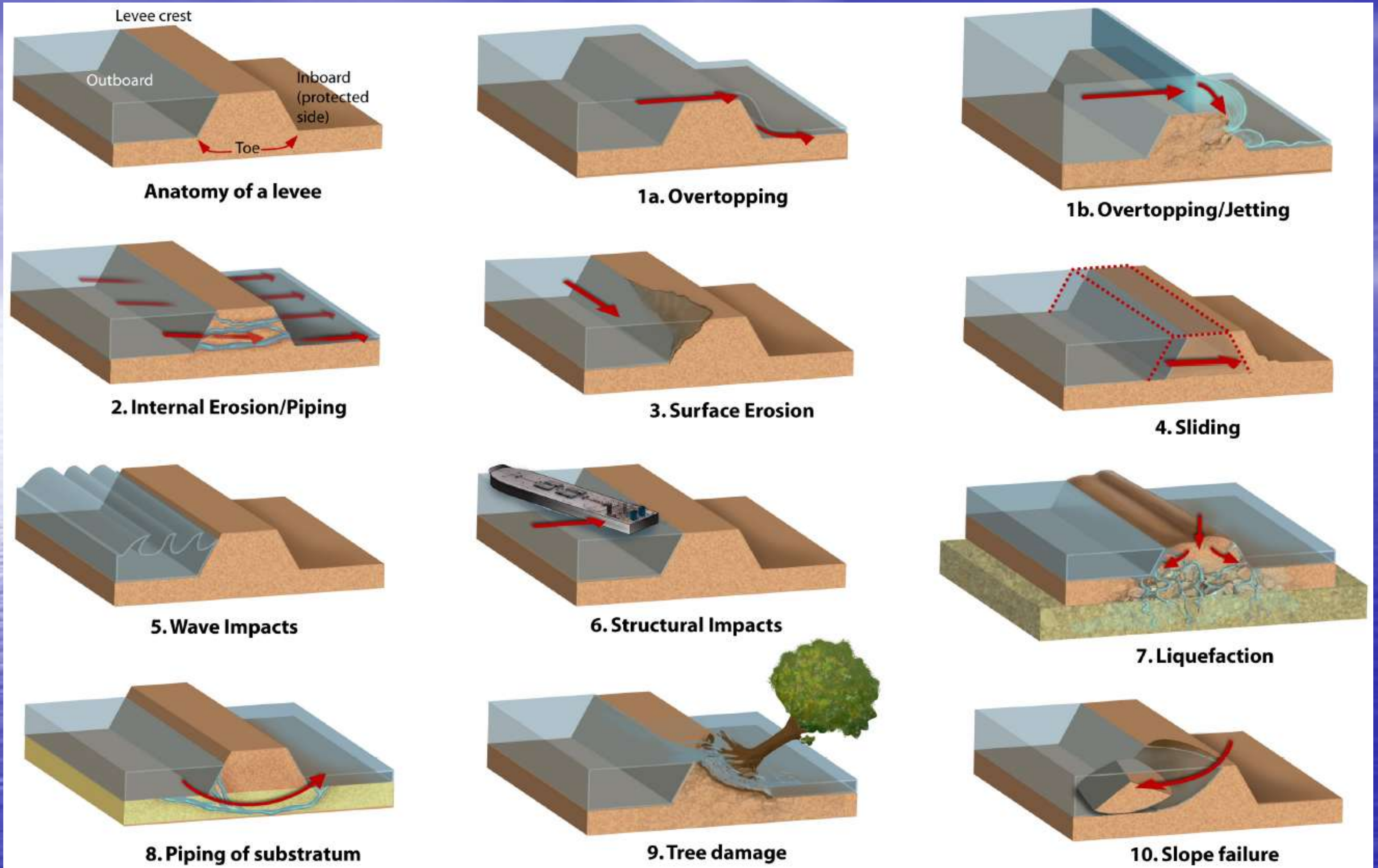
Four common approaches are employed to delineate Levee Fragility Curves (Schultz 2010)

- **Judgmental** – Fragility curves that are based on some form of expert opinion are classified as judgmental. There are no limits to the number of methods that may be used to elicit judgments from experts, and these procedures can vary widely in terms of the level of rigor with which they are implemented.

- **Empirical** – Empirical fragility curves are based on observational data documenting the performance of structures under a variety of loads. Observations may be obtained systematically through controlled experiments or may be collected in an opportunistic fashion, which is uncontrolled.

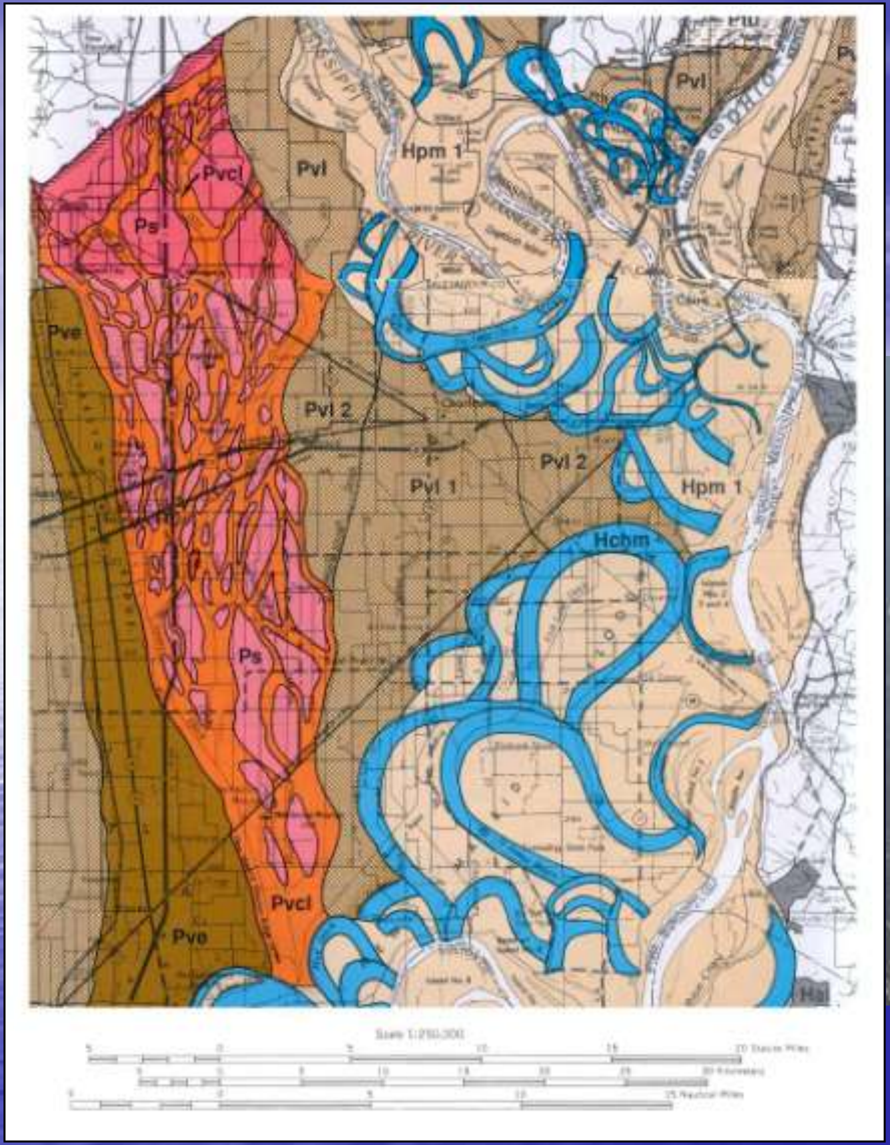
- **Analytical Approaches** – Analytical fragility curves are based on structural models that characterize the performance limit state of the structure…Limit state functions may be either explicit or implicit. An explicit limit state function is one that could be written explicitly in terms of basic variables. An implicit limit state function is one that cannot be written in closed form as a function of basic variables, but is implied through some sort of numerical model.

- **Hybrid Approaches** – A hybrid approach to developing fragility curves uses a combination of two or more of the three approaches described above in an attempt to overcome their limitations.



- **The quality of the risk assessment is limited by the magnitude of uncertainties (including data gaps) in the (a) system definition, (b) system demands, (c) system capacities, and (d) the suite of considered failure modes, shown here. A truly comprehensive LFC evaluates systems based on an 'all-hazards' approach (image from NSF).**

Why are levees 1000X more likely to fail than dams?



Map of Mississippi River Valley showing abandoned meanders.

- A major shortcoming of levee is the differing foundation conditions upon which they are founded.

Levee construction techniques for the MR&T in 1930s

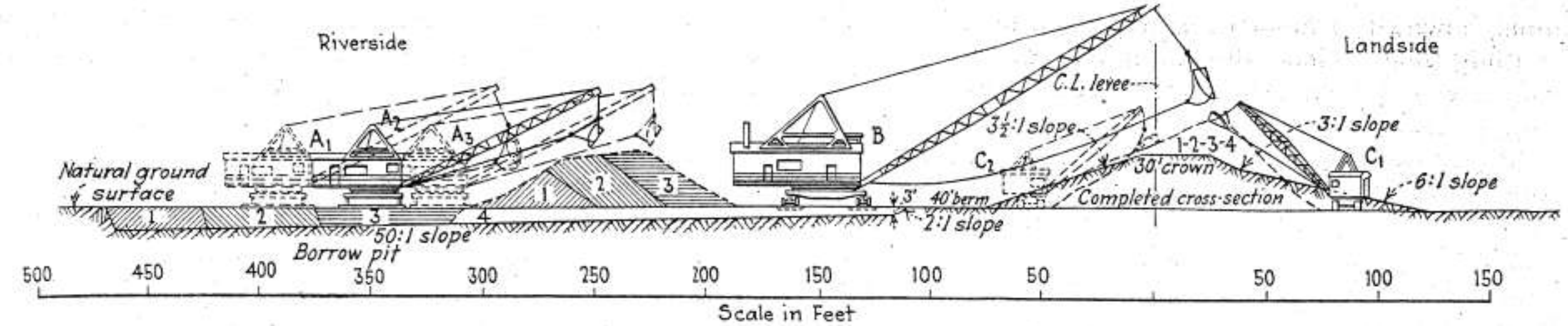


Fig. 3—Levee construction with draglines operated in series

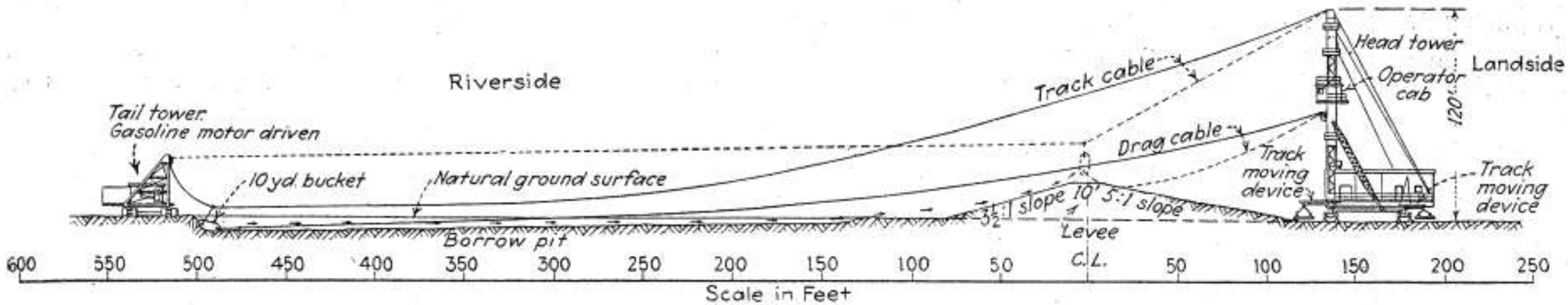


Fig. 4—Levee construction with electric tower excavator

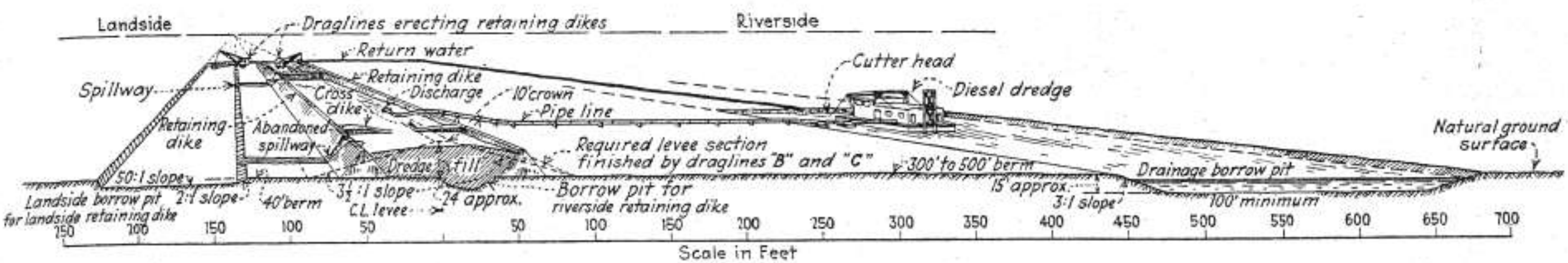
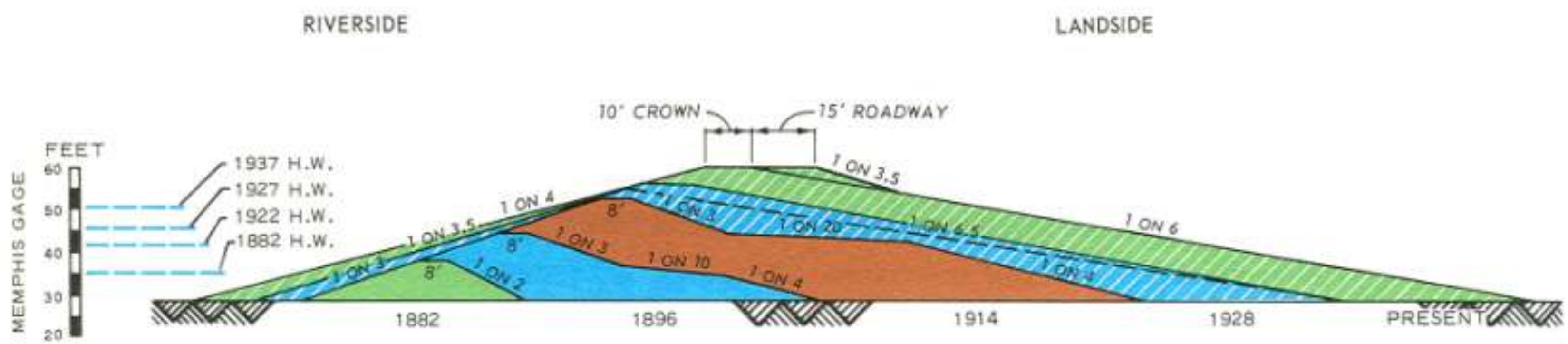
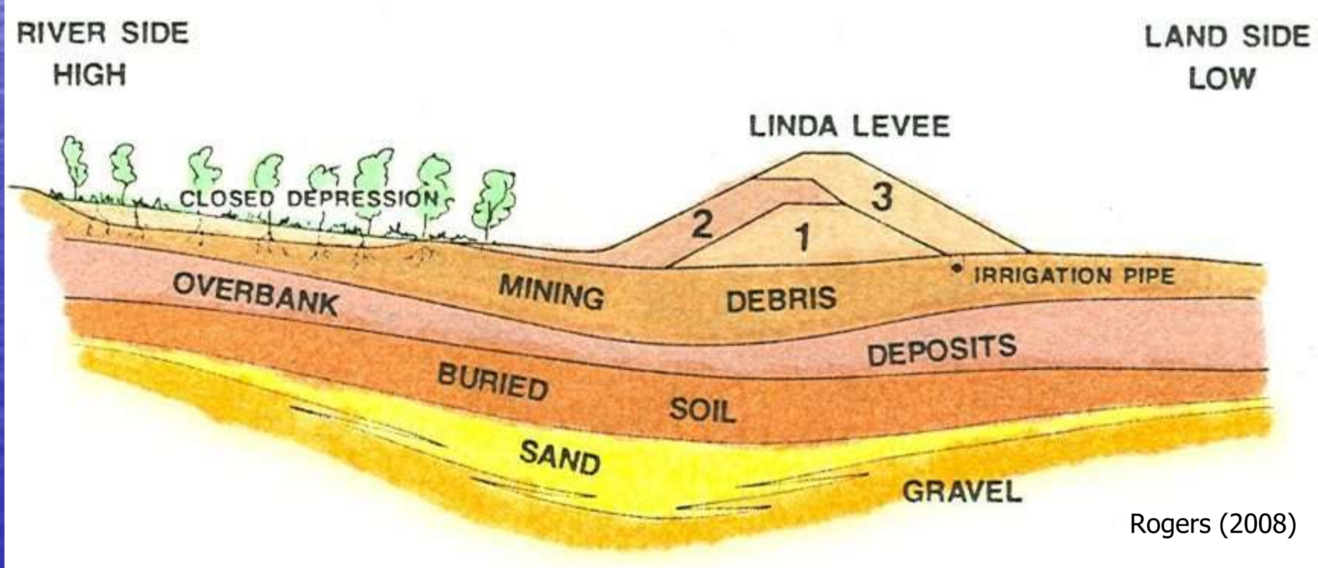


Fig. 7—Hydraulic-fill levee construction with pipe-line dredge

Many levees have become 'legacy structures'

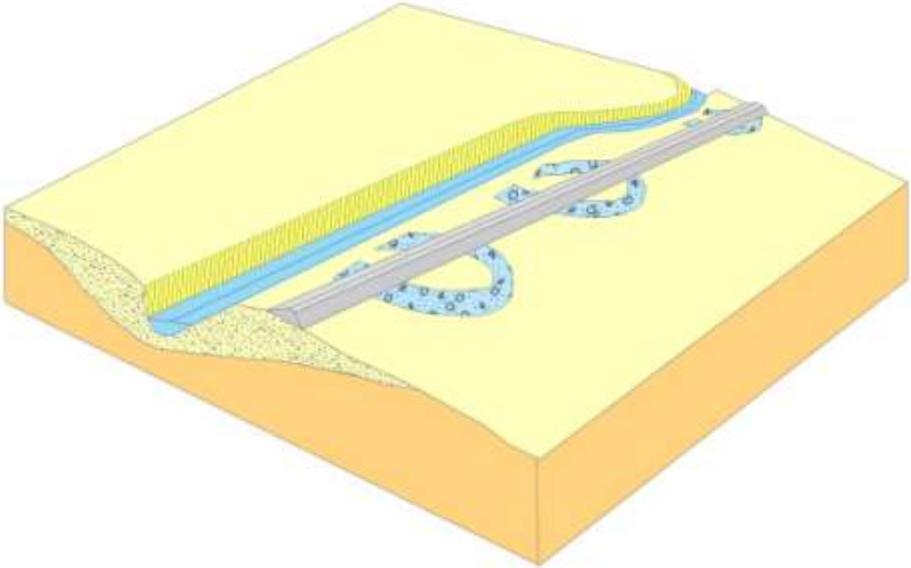


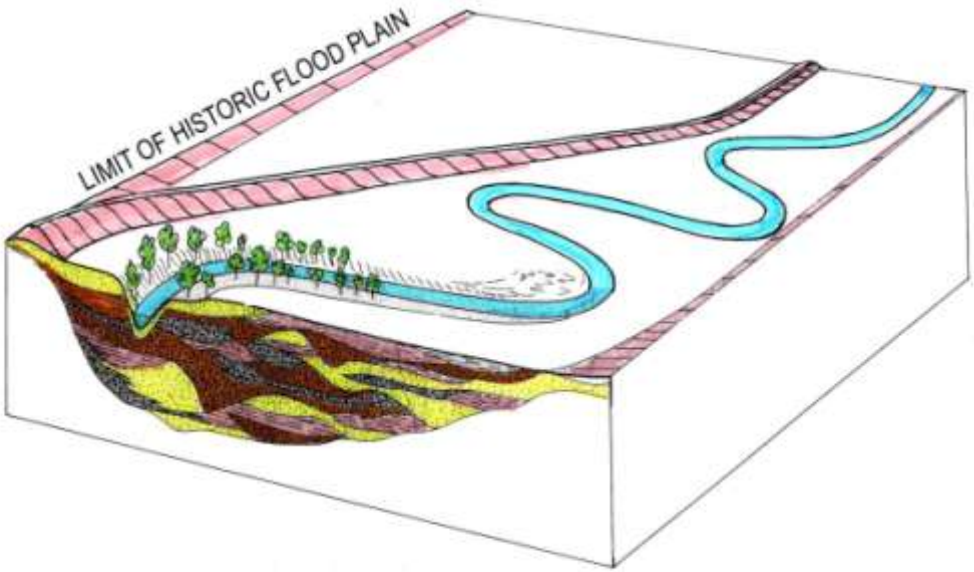
Moore (1972)



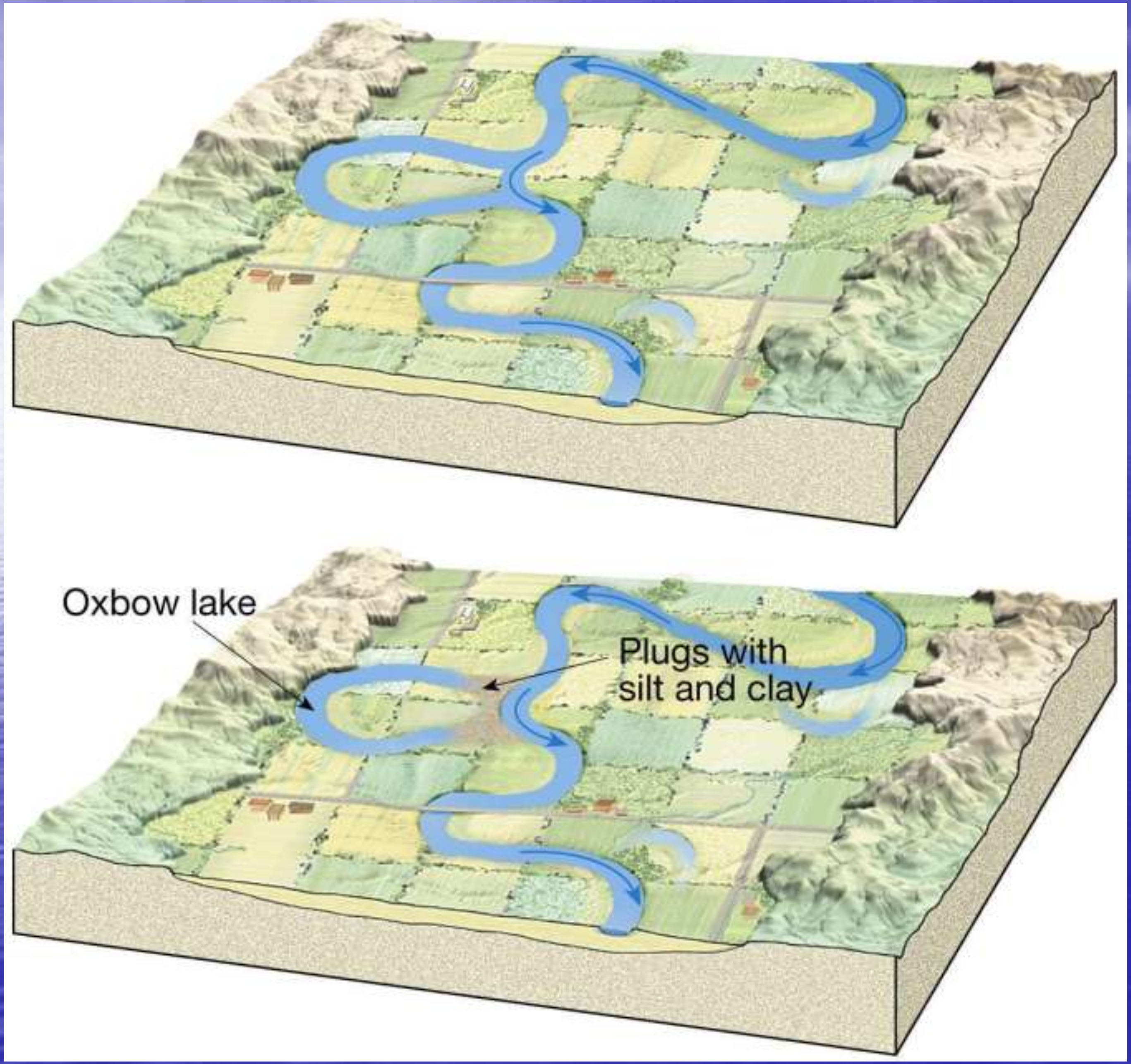
Rogers (2008)

Levees are constructed down on the floodplains, with variable foundation conditions



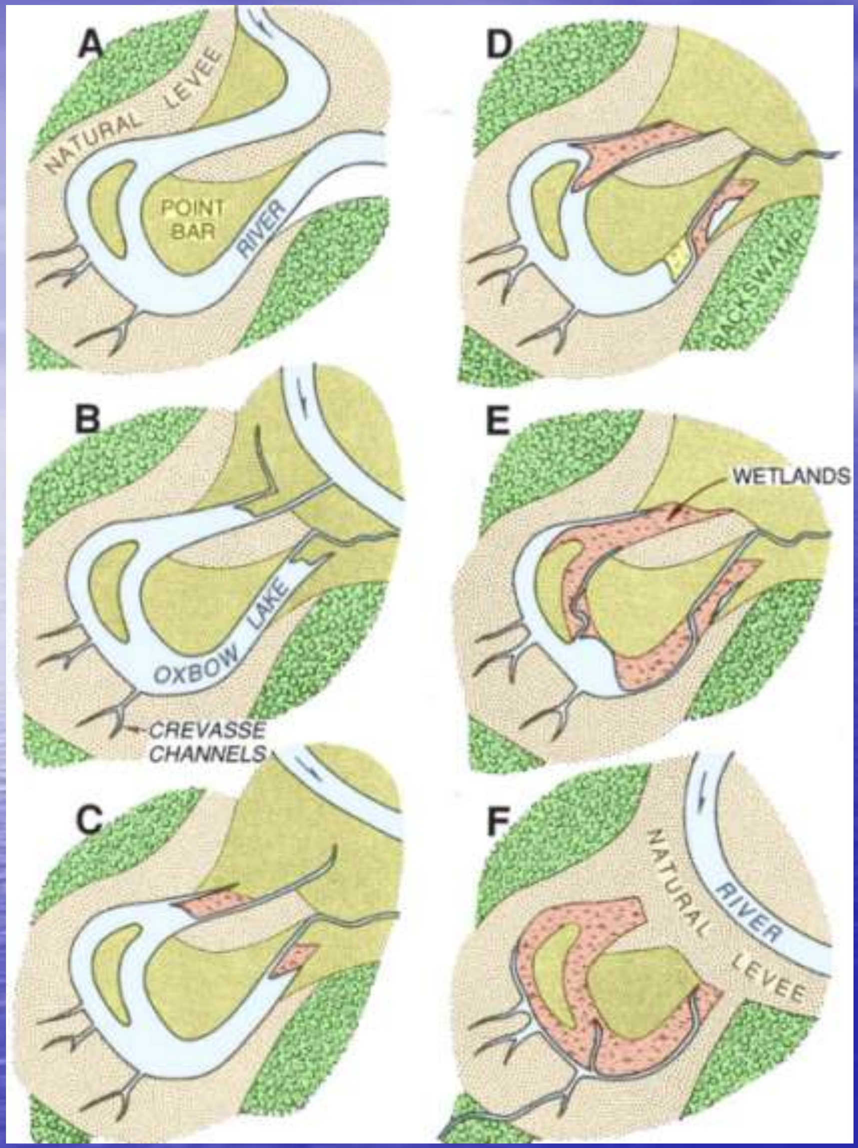


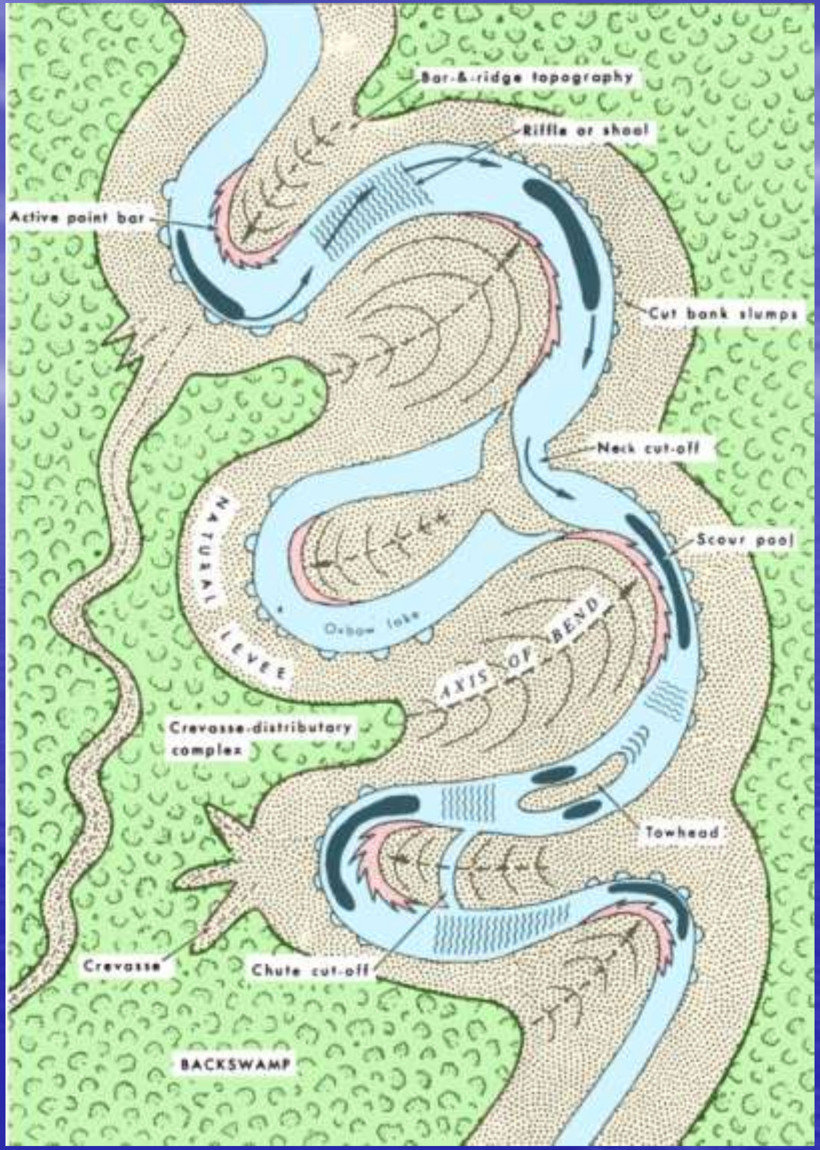
- **1796 Map of the St. Louis area by George Henri Victor Collot and P.F. Tardieu. Note all the lakes in the floodplain that no longer exist**



from Earth, by Tarbuck, Lutgens, and Tasa (2010)

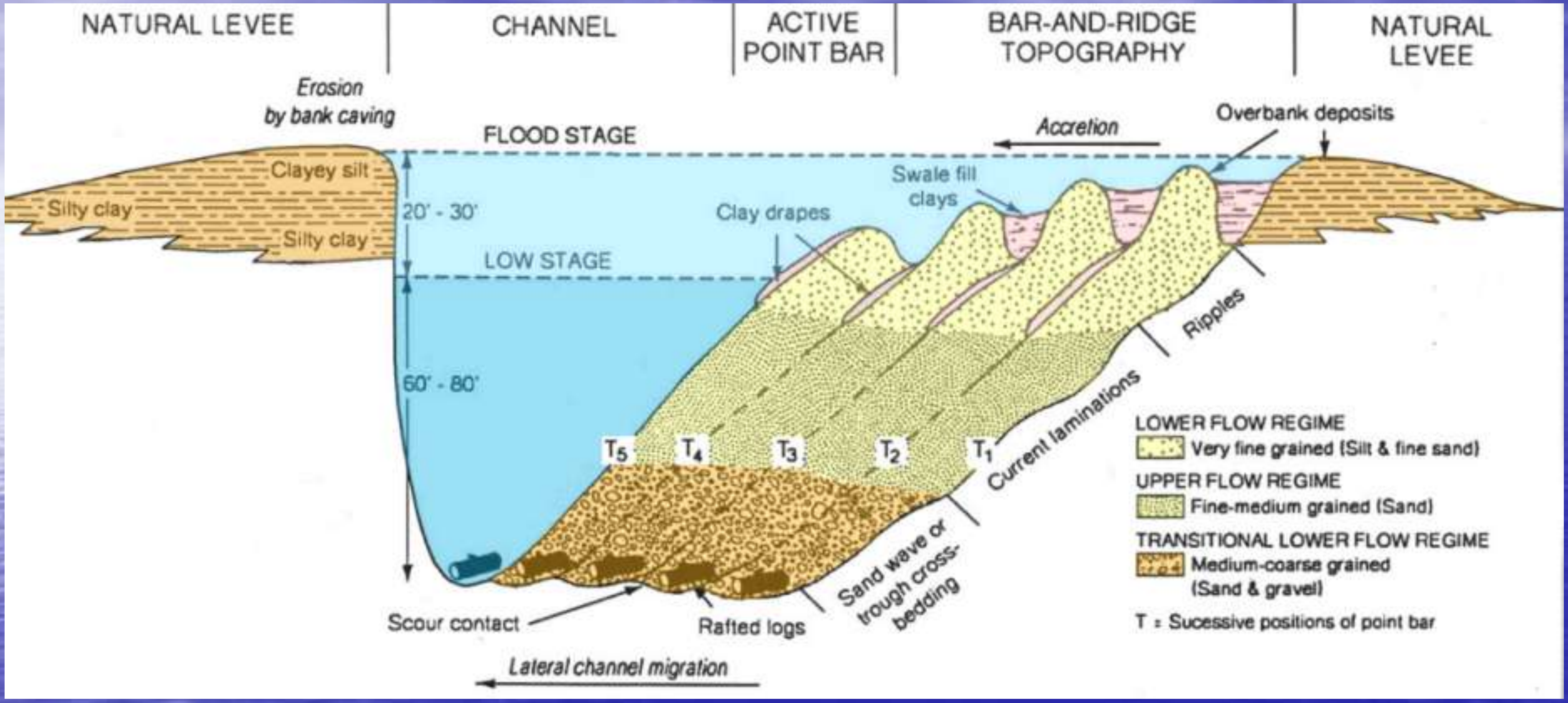
- **Most levees are constructed along relatively low gradient, meandering channels**
- **Oxbows are old meander bends that are truncated and isolated when the river cuts back into its own channel, as shown here.**





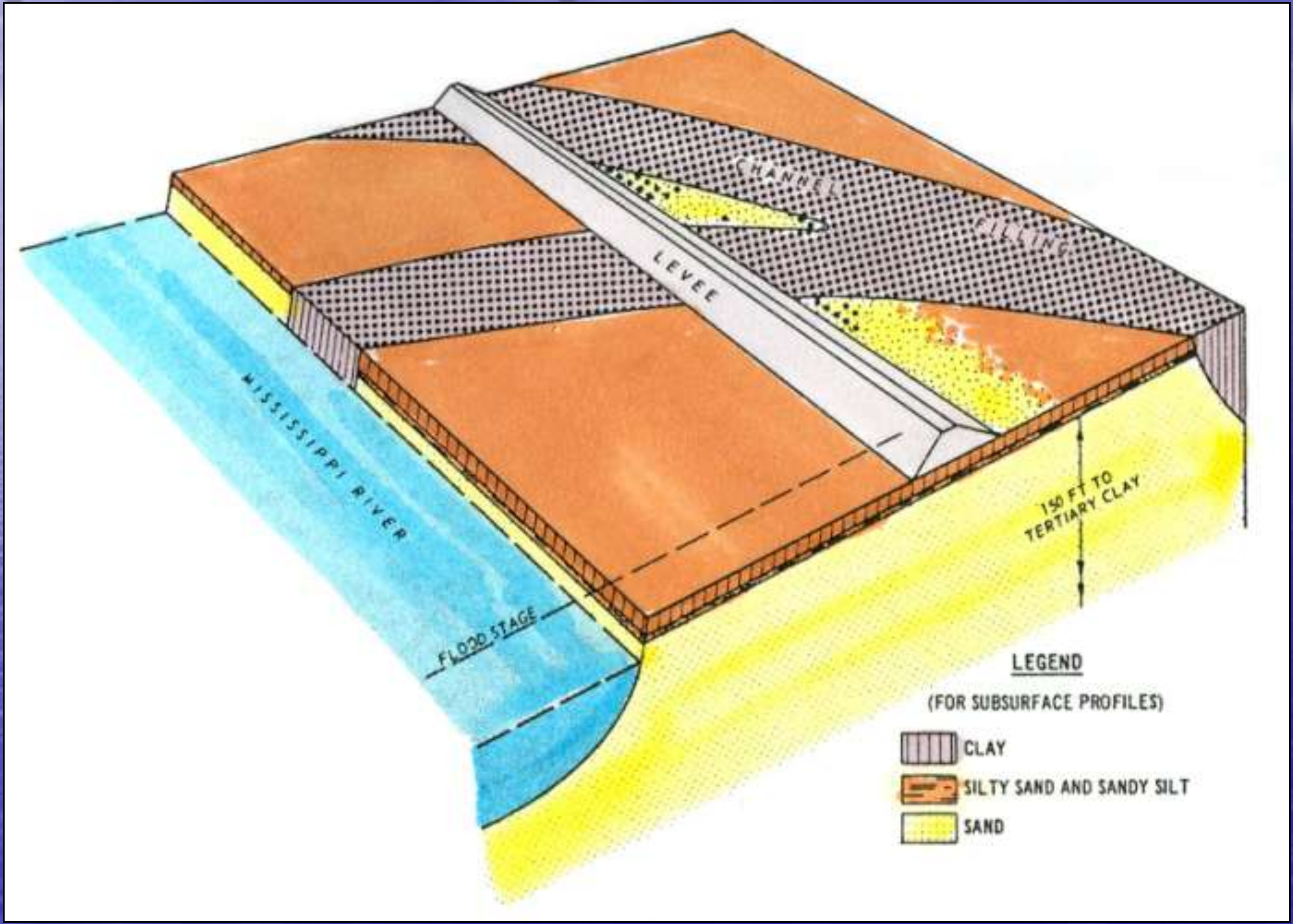
- **Most levees are constructed along low gradient channels. The geologic conditions underlying most levees are fraught with uncertainties, due the nature of fluvial depositional systems.**

Danger of horizontal correlations



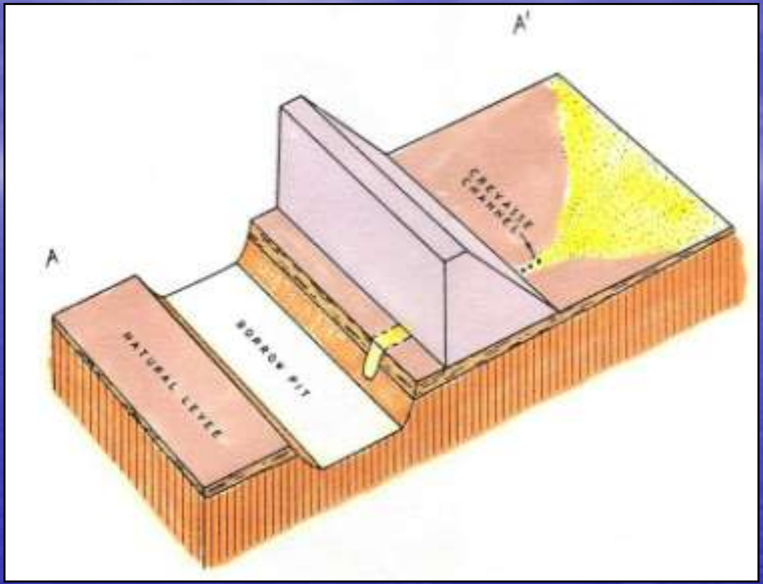
- **Inclined character of point bar deposits in a sinuous channel system. Note clay drapes; and how these might easily be mis-characterized by straight line correlations between adjacent borings.**

Underseepage problematic in permeable point bar sands

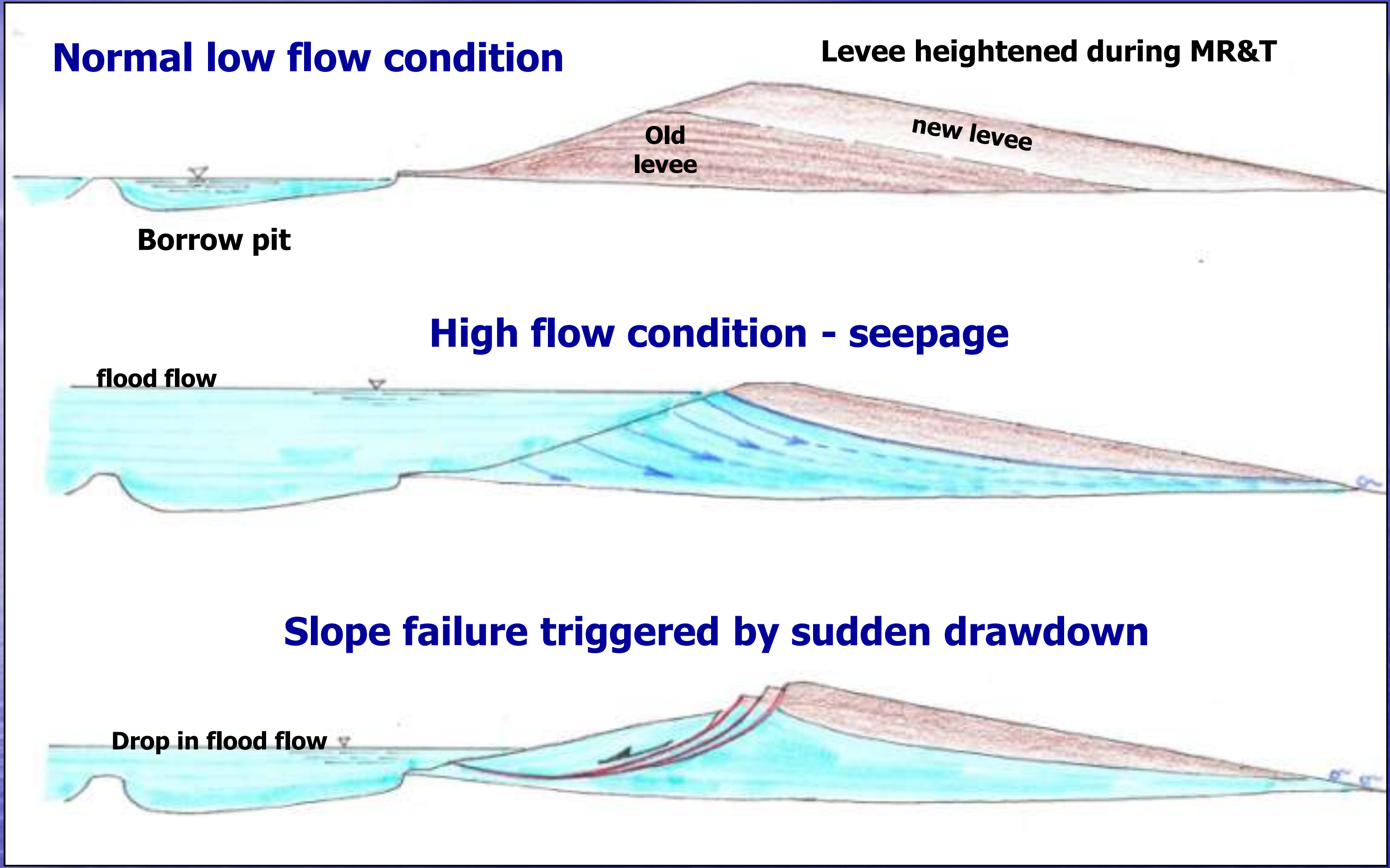


- **The worst combination of foundation conditions is the 'gore point' formed between two infilled oxbows, as shown here (Kolb, 1976)**

Natural crevasses beneath levees



Crevasses lie beneath earthen levees like *ticking time bombs*, waiting to explode.



- ***Rapid drawdown*** **is generally the most severe loading condition for earthen levees. The severity is a function of how many flood cycles and how rapidly the high flow cycles drop, after peaking. Rapid drawdown can also impact natural river banks in a similar manner.**

CONCLUSIONS

- The MR&T Project will continue to demand significant expenditures, to battle aging effects and rising stage levels
- Coordinated nation-wide flood routing during the 2011 flood likely prevented more than $2 billion in damages, compared to previous floods of similar magnitude. The Corps of Engineers is to be congratulated.
- Risk-based assessment of levees will require the *most significant input* and *engineering judgment* from geotechnical engineers and engineering geologists.

Acknowledgements

The following individuals contributed significantly to this presentation:

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Rune Storesund, D.Eng, P.E., G.E., consulting geotechnical engineer

This lecture will be posted as a pdf file for easy downloading.

www.mst.edu/~rogersda/levees/

Mississippi Delta Region