SITE CHARACTERIZATION AND LEVEE FAILURE MODES:

With special reference to the Paterno Flood Case

J. David Rogers, Ph.D., P.E., P.G., C.E.G., C.HG.
Karl F. Hasselmann Chair in Geological Engineering
Missouri University of Science & Technology
and
Richard L. Meehan, P.E., G.E.
Department of Civil & Environmental Engineering
Stanford University

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- The communities of **Marysville**, **Yuba City**, **Linda**, and **Olivehurst** are located about an hour's drive north of Sacramento, in the Sacramento Valley.

- **Aerial view of the junction of the Yuba and Feather Rivers. Marysville is at upper left, while Linda occupies the area at lower right.**

The Linda breach

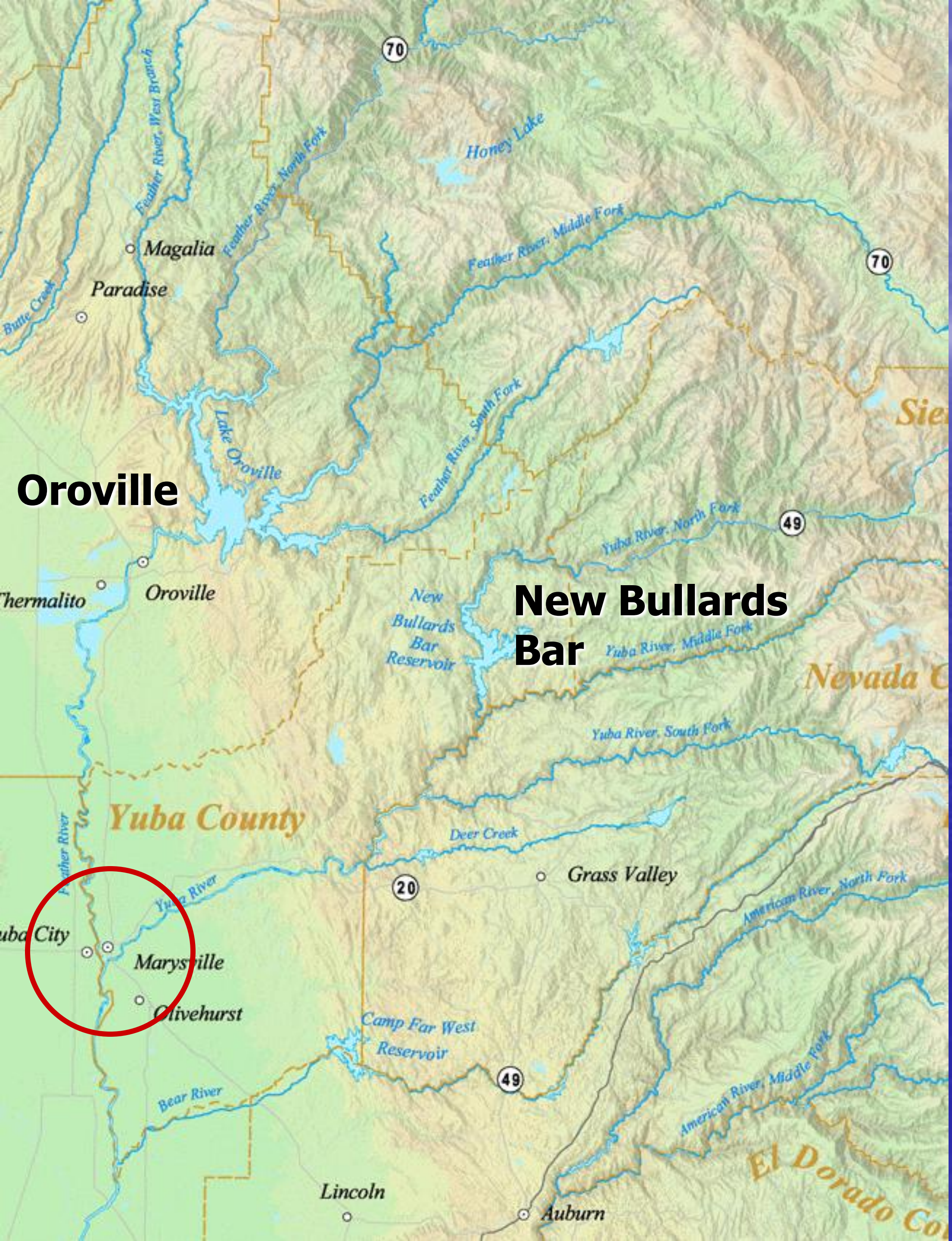
- **The breach of the Linda Levee along the south side of the Yuba River near its mouth was *only 170 feet wide,* even after flood waters had poured through the opening for five days.**

- Around 6 PM on February 20, 1986 the Linda Levee suddenly broke, on the south side of the Yuba River about half a mile above its junction with the Feather River.

- **The flooding spread through the area south of the Yuba River and east of the Feather River, inundating the communities of Linda and Olivehurst. The flooding caused upwards of *$1.5 billion* in damages.**

- Entire neighborhoods were flooded, and relief efforts were complicated by the inundation of Highway 70, shown at right, the main access route serving the area.

Inundation of CA Route 70 in Olivehurst, looking northerly, towards Sutter Buttes.



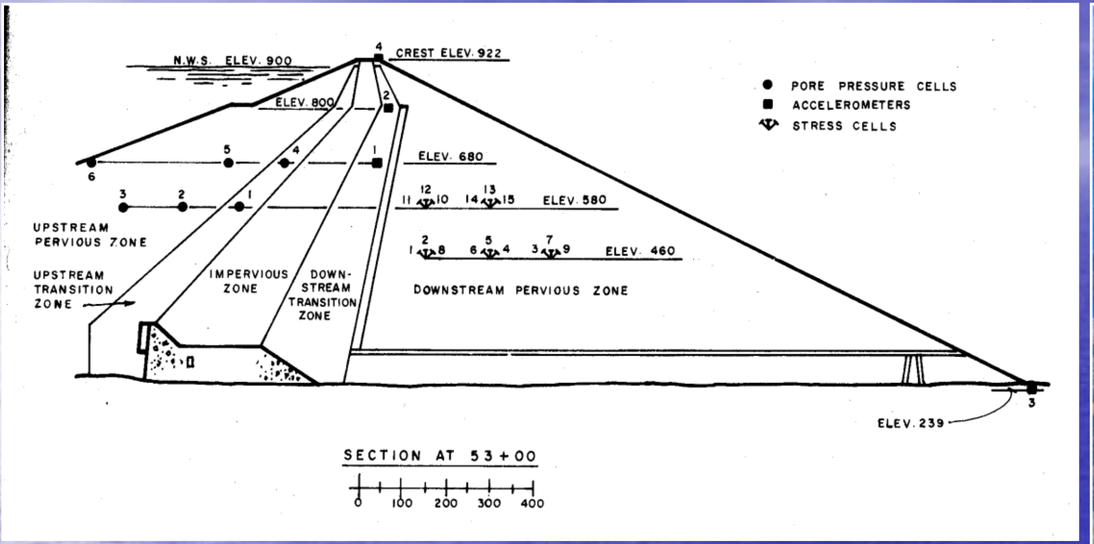
Flood Control

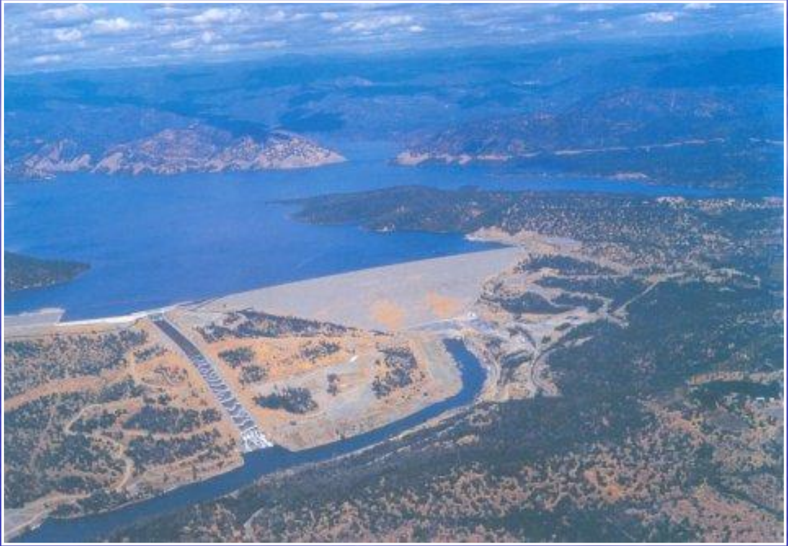
- **Oroville Reservoir was intended to store runoff for several days, so peak flows of the Feather River would not coincide with those of major downstream tributaries, like the Yuba River.**

HIGHEST DAM IN THE WORLD (1967)

- At 770 feet high and 5,600 feet long, **Oroville Dam** was the <u>highest dam in the world</u> when it was completed on the Feather River in 1967. It was deigned by the CA DWR , with embankment volume of 80 million yds^3.
- Oroville Dam is the kingpin structure of the massive **California Water Project**, which diverts water from the Feather River to southern California.

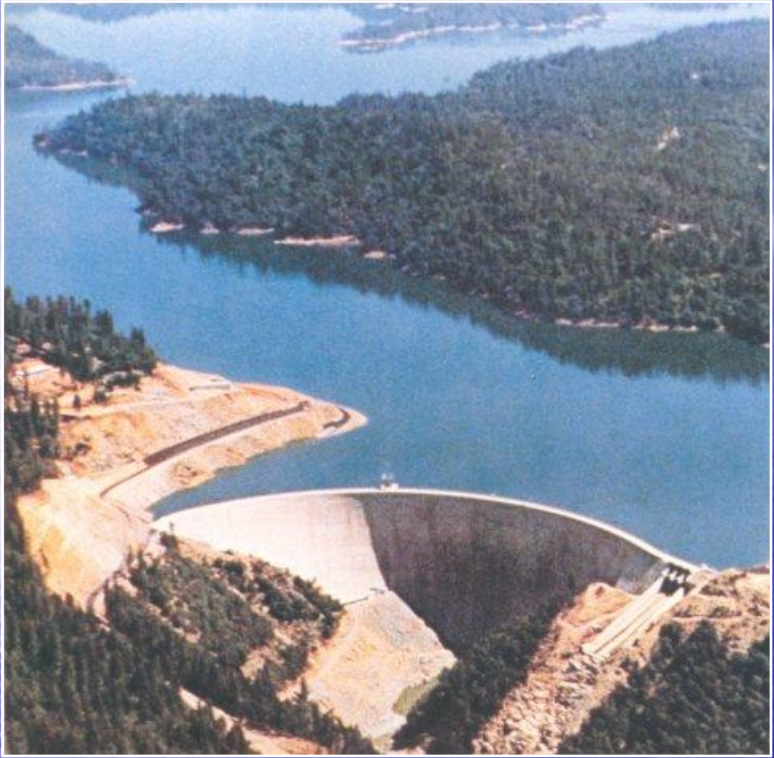
OROVILLE DAM (1967)

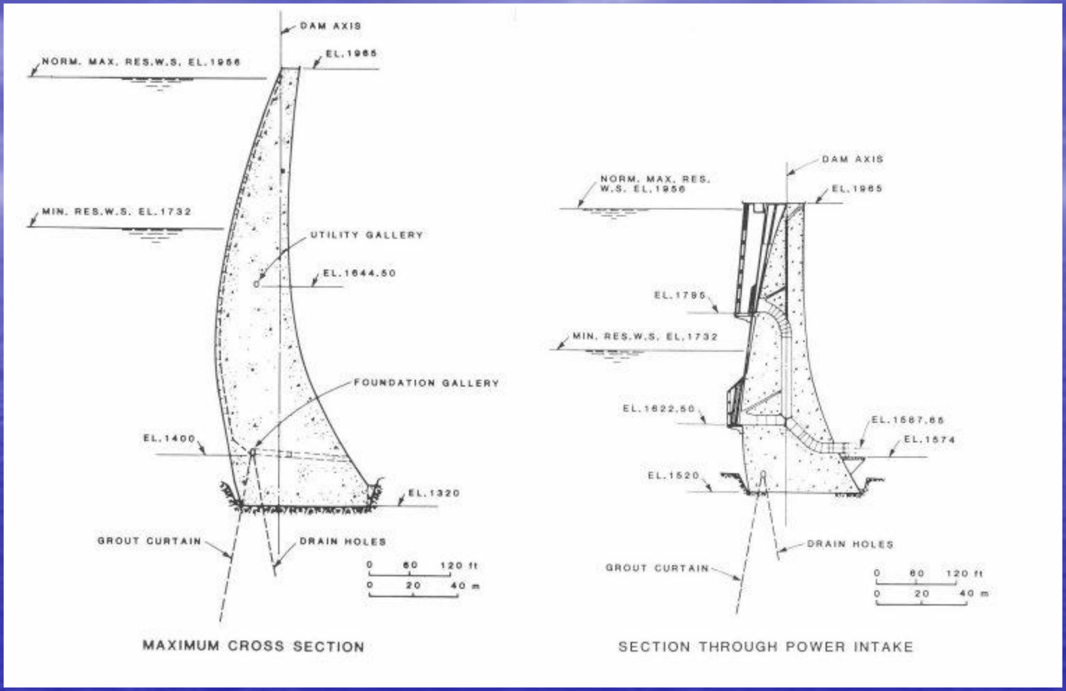




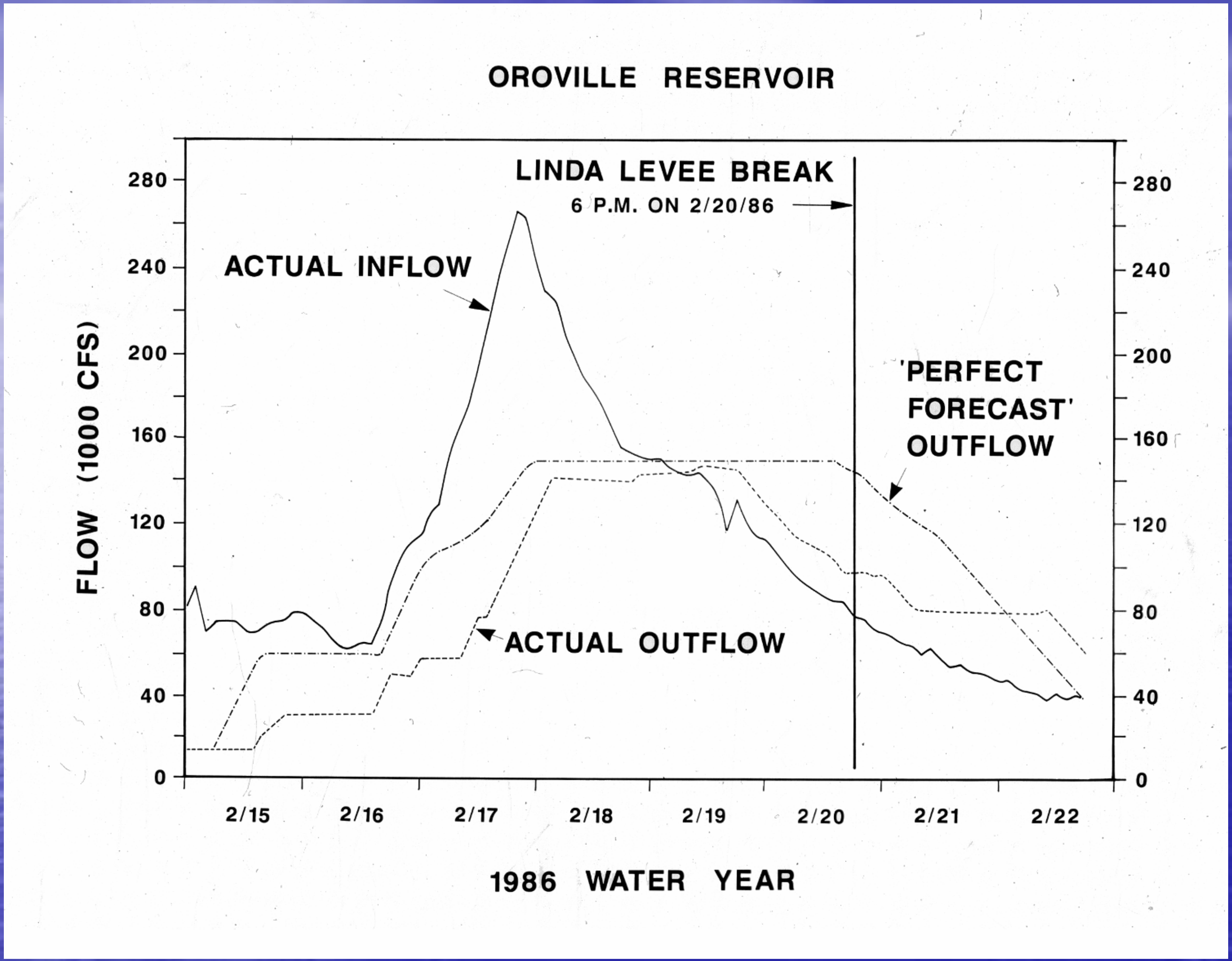
- **Oroville was the largest non-federal dam ever built in the United States.**
- **It utilized a novel concrete '*base core*' structure and took advantage of coarse aggregate piles left over from hydraulic dredge mining**
- **It was the most heavily instrumented earthen dam up to that time**

NEW BULLARDS BAR DAM (1969)

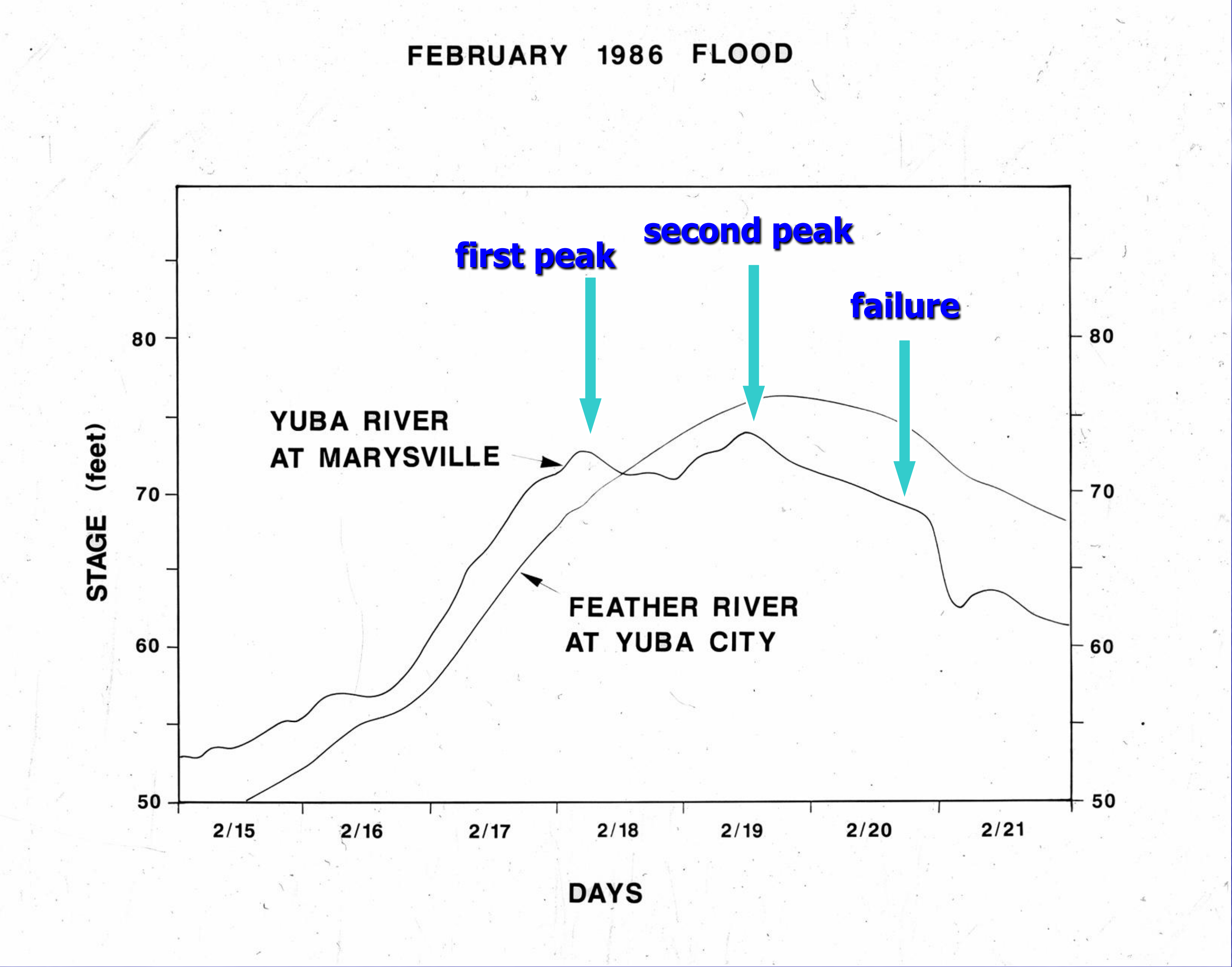




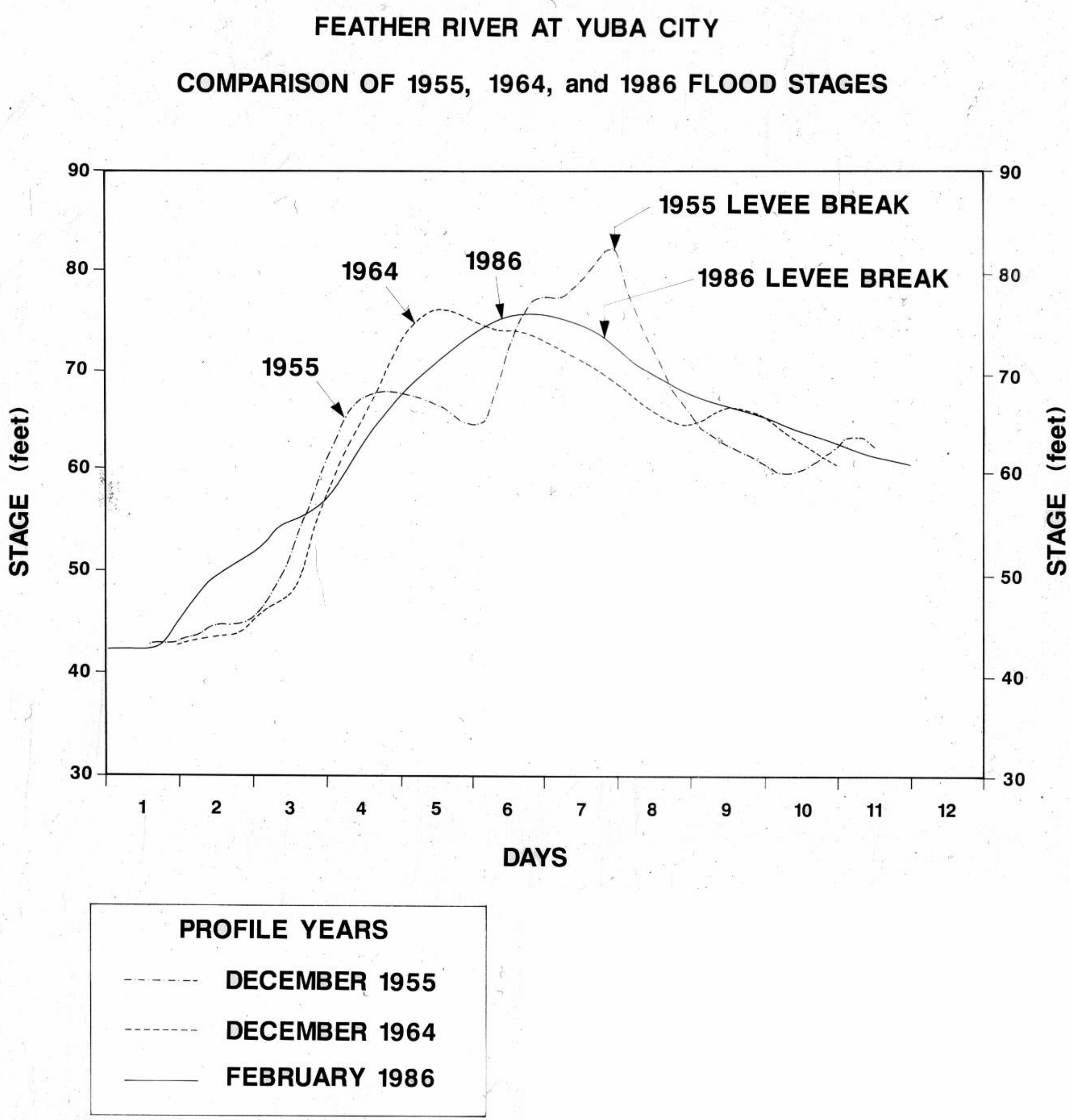
- **The largest double curvature concrete arch dam in the USA was completed along the North Fork of the Yuba River in November 1969, replacing an older dam**
- **The dam is 635 ft high with a 2,200 ft long crest.**
- **It was not designed for seismic loading**



- **Inflow and discharge from Oroville Reservoir during the February 1986 storm, compared to the forecast outflow by State DWR when the project design was modified, following the December 1964-January 1965 storm sequence.**



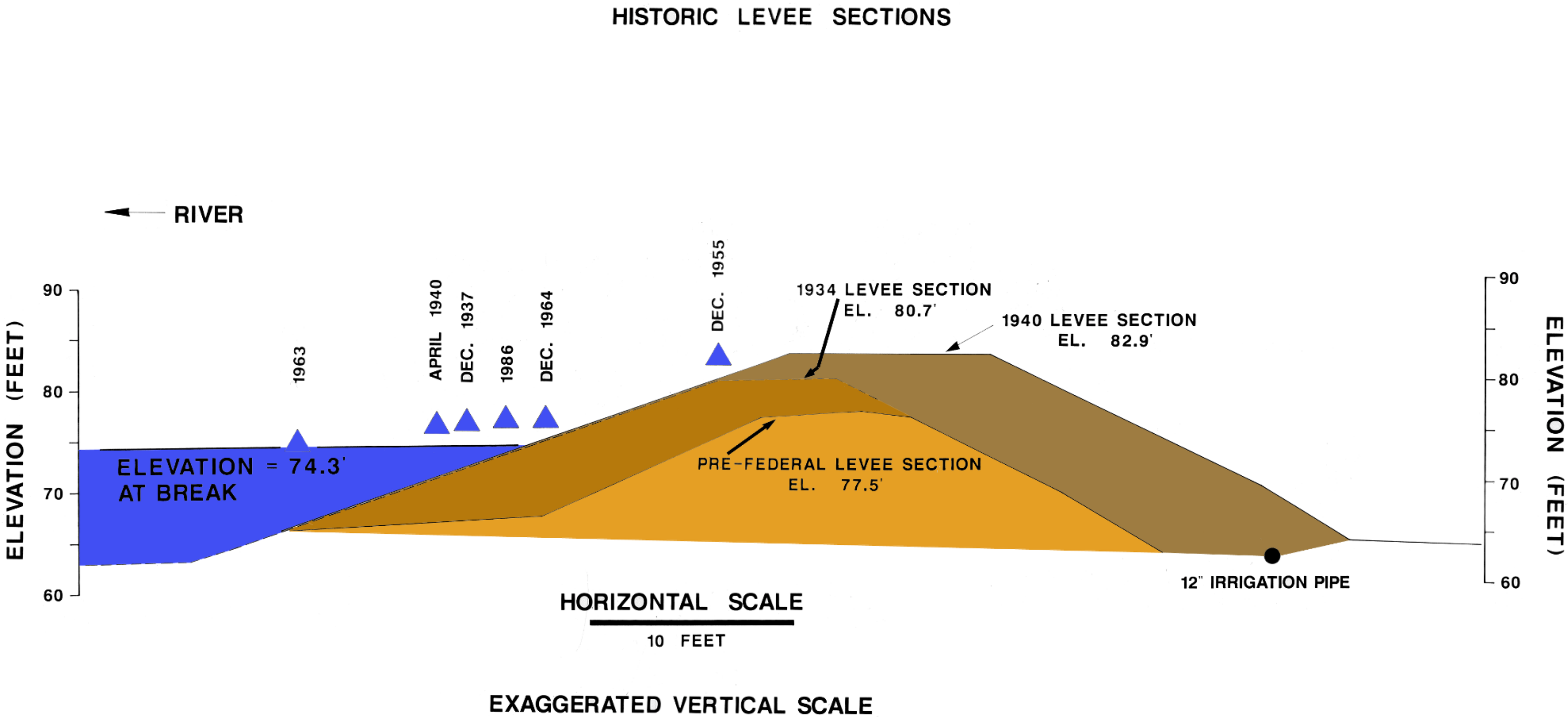
- Unfortunately, the peak flows of the two rivers nearly coincided with one another, as shown here.



- **Historic hydrographs of the Feather River at Yuba City, illustrating river stages where major levee failures have occurred, in 1955, 1964, and 1986.**

February 1986 floods

- Views showing the high flows disgorging through the Yuba Narrows in Feb 1986
- On February 11th a series of warm tropical storms struck Northern California, lasting 10 days.
- This included the *heaviest 24-hr event ever recorded in the Central Valley*, 17.60 inches, on Feb. 17th at Four Trees, in the Feather River Basin.

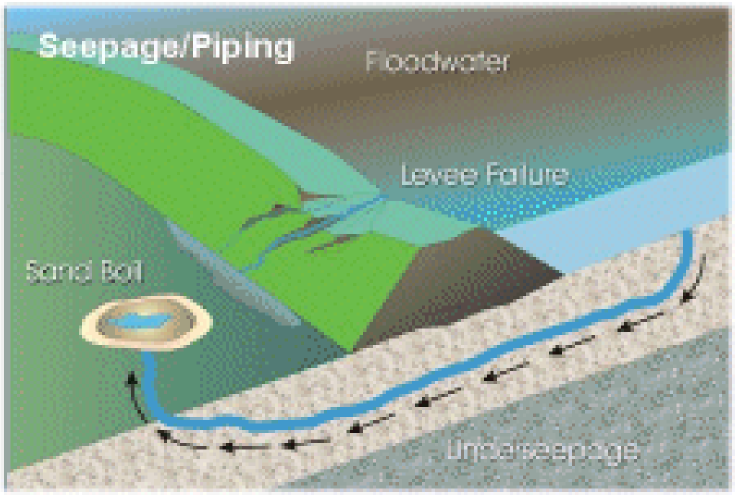


- **The February 20th failure occurred *after* the flood had crested, 8.6 feet *below* the levee crest. *This is what fascinated us*.**

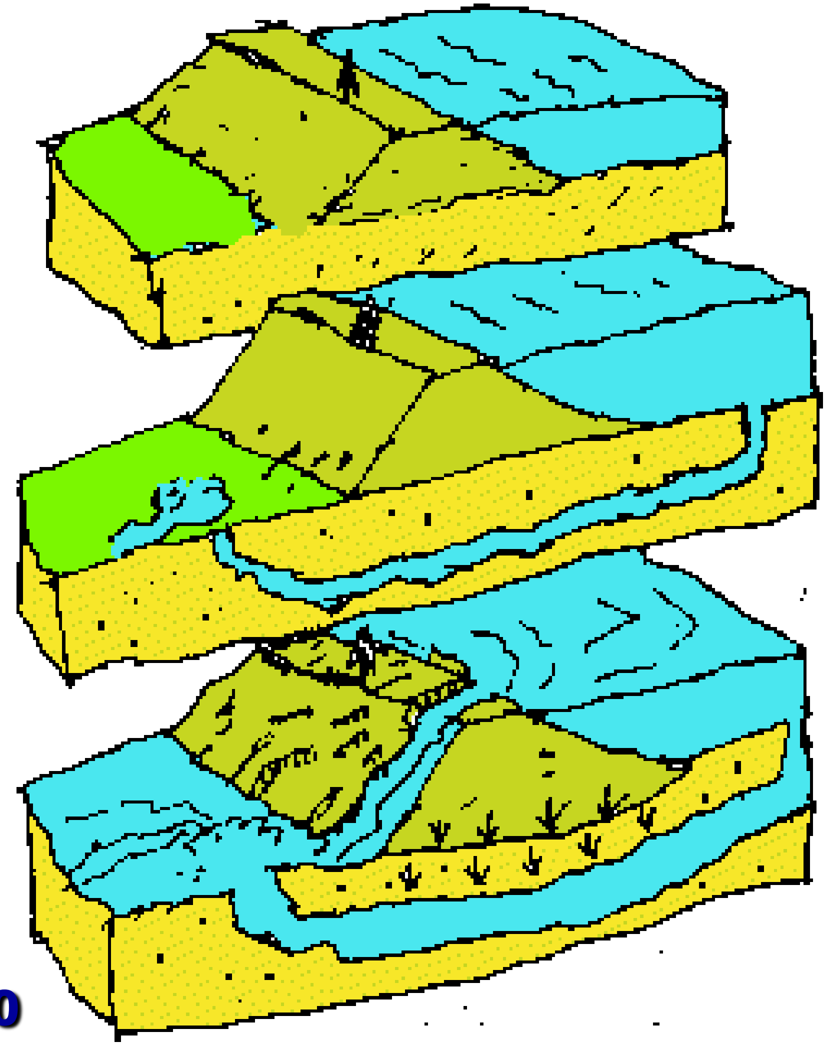
The baffling eye witness accounts….

- The failure occurred during daylight, when dusk was approaching, at 6 PM.
- Five eye witnesses described the same failure sequence, seen from the landward side of the failed levee:
- The ground at the base of the levee essentially *turned to mush*; and water began bubbling up, across a very narrow area, just 170 feet wide. This was followed by the sudden "*collapse*" of the landward side of the levee embankment "*into a hole*;" after which the river side of the levee quickly collapse, and the flood waters began pouring through the breach. It was as if "*a bomb had gone off….*"

The traditional model for piping-induced failure



from State of California website in 1997



From Meehan deposition in 1990

- **The precise mode of failure remained a major mystery.** Eyewitness accounts described a catastrophic landslide-style failure, not the conventional piping style failure we all assume when analyzing earthen levees, as shown here.

Some observations by our predecessors…. .

- "*For every complex problem, there is a solution that is simple, neat, and wrong*"

  H. L. Menken

- "*Nothing irritates engineers more than eyewitness accounts that contrast with established theorems …. {used in assessing the stability of structures}.*"

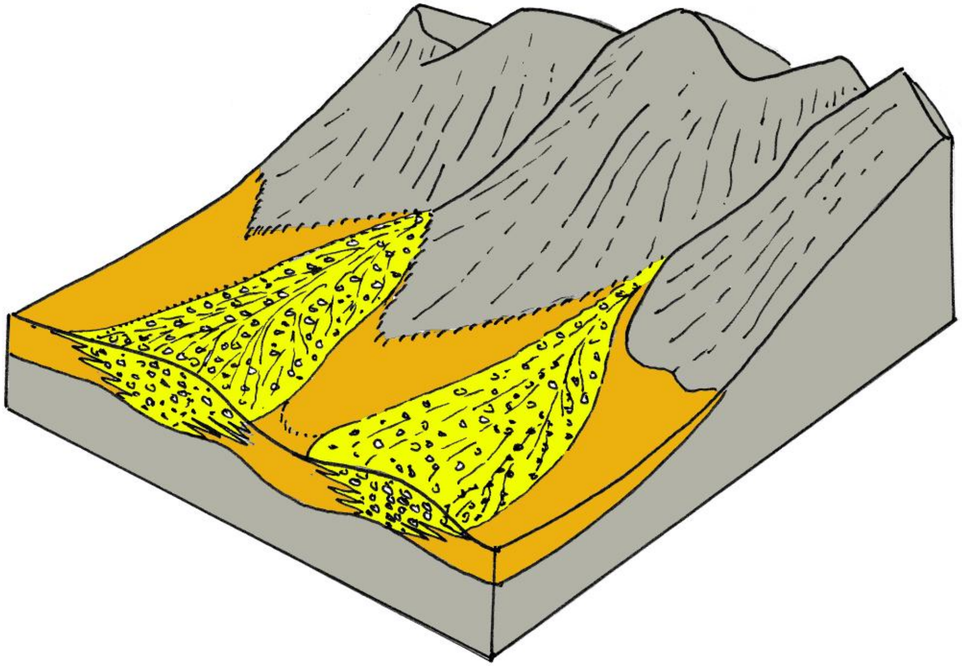
  Karl Terzaghi

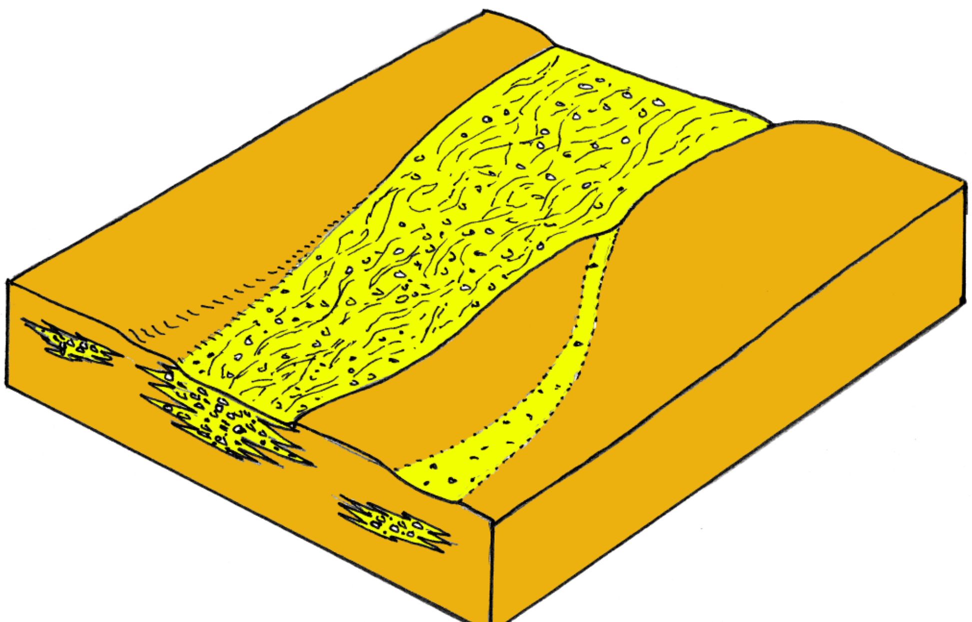
HALLMARKS OF GOOD SITE CHARACTERIZATION

1) **Research geologic and geomorphic setting**
2) **Review site history (floods, changes in channel course, etc);** ***search for performance analogs with similar physiographic and climatologic features***
3) **Review subsurface investigations by others**
4) **Perform independent site-specific subsurface investigations;** ***critically assess sample recovery (its what you don't recover that's usually most important)***
5) **Develop subsurface models that include** ***three-dimensional aspects*****;** <u>**never analyze or design an embankment based on a *single* cross section**</u>**.**

Good site characterization involves critical assessment of the GEOLOGIC AND GEOMORPHIC SETTING

- **How did the site evolve ? On both large and small scales…** ***Look at the big picture, not just your job site***
- **What were the controlling physical factors?** ***Paleo megafloods tend to control channel geometry***
- **Contrast** ***late Pleistocene conditions*** **with those during the Holocene (last 11 ka)**
- **Where are the "young soils," as opposed to the "old soils"? Why?**
- **Has the geologic interpretation of this area undergone re-evaluation since the original maps, papers, or articles appeared?** ***Almost always, the answer is "yes"***

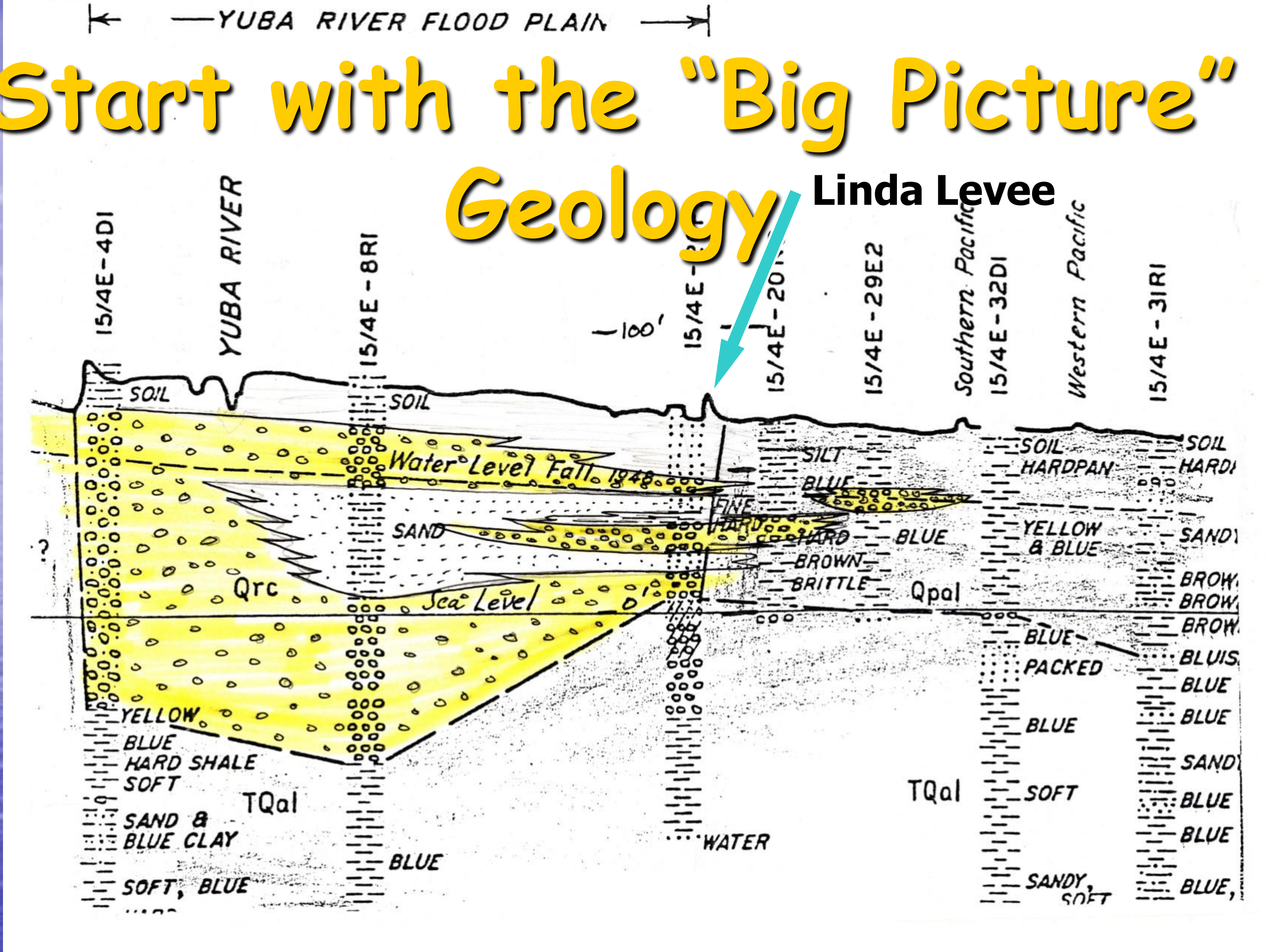




What defines the geomorphic setting?

- **During the Pleistocene epoch the Sierras were shedding *coarse debris* from confined bedrock canyons.**
- **These gravels were deposited in *braid bar channels* along fairly narrow corridors, often *with outliers***

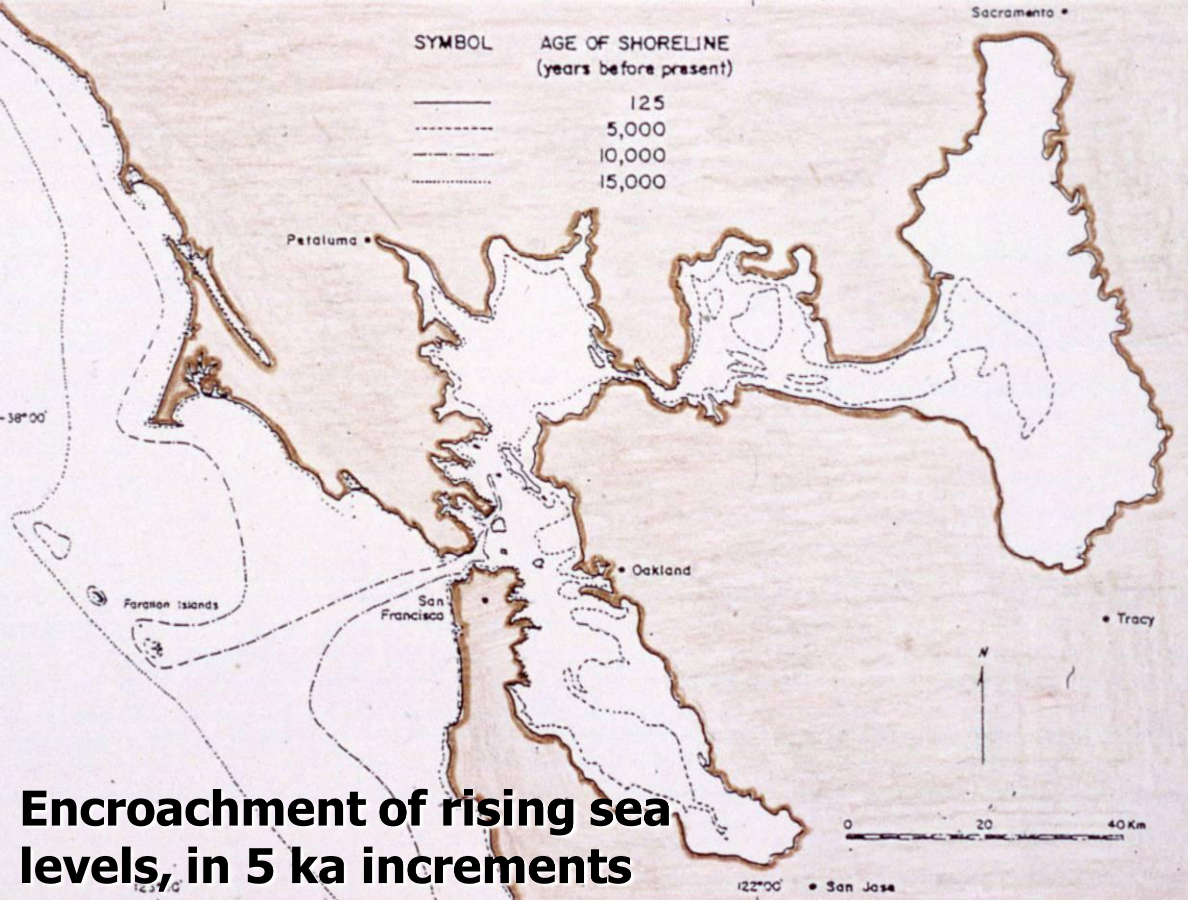
Start with the "Big Picture" Geology



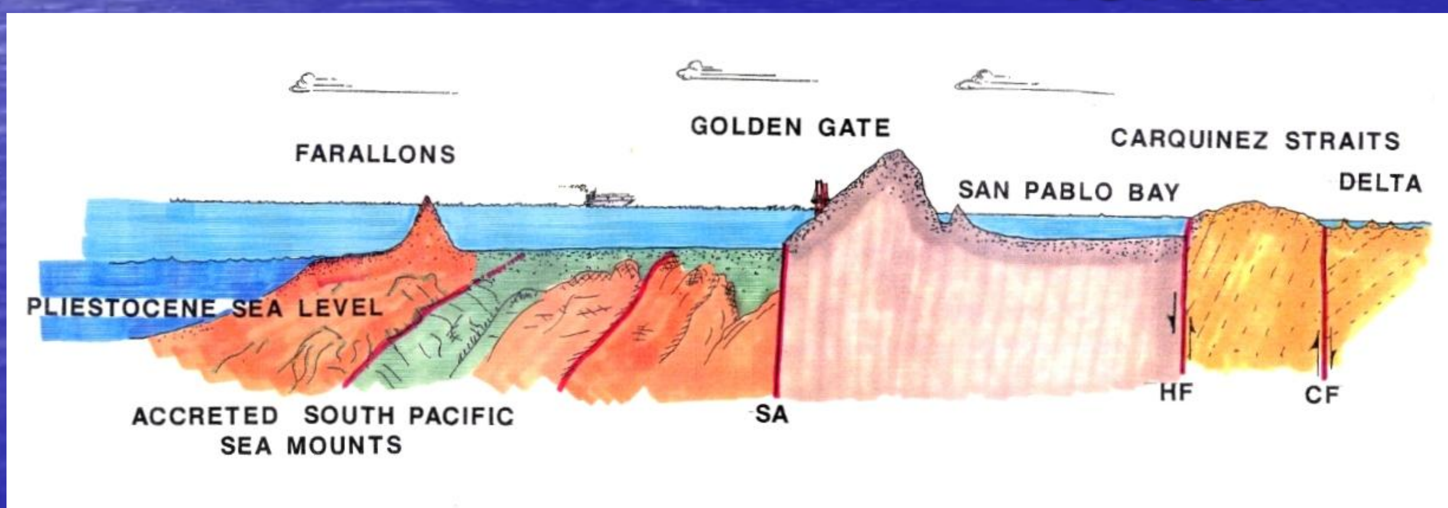
- The lower Yuba River exhibits an *asymmetric profile*, filled with *coarse cobbles and sands*. Note numerous "orphan channels" extending *beyond* the southern margins of the modern flood plain.

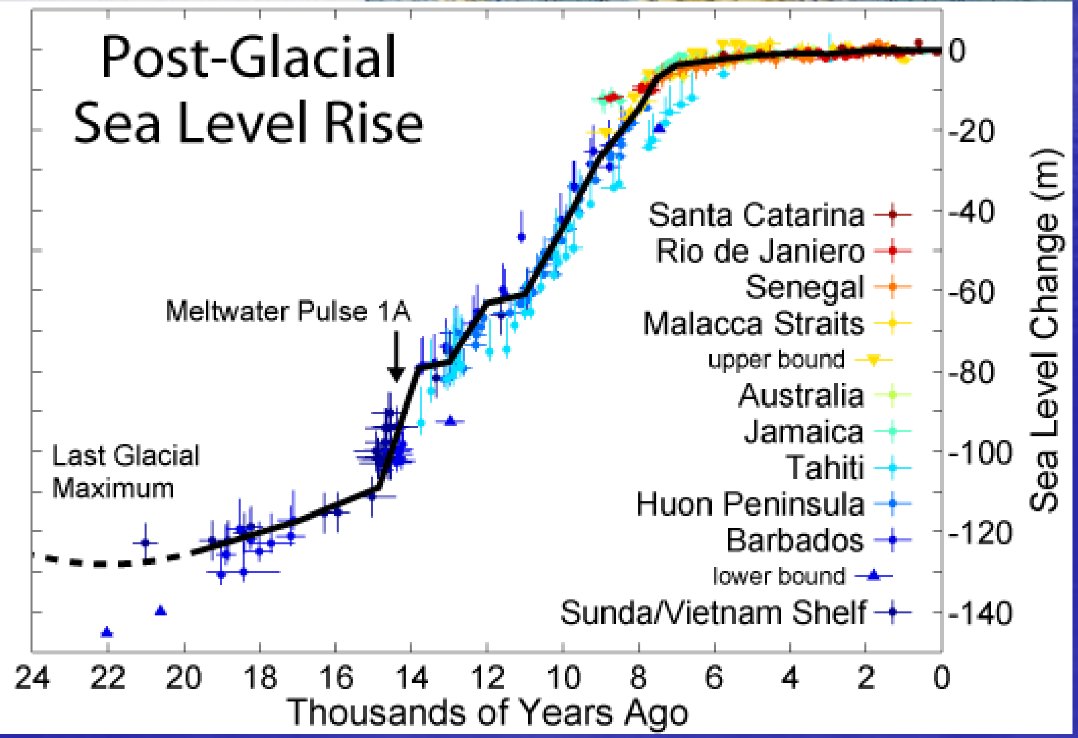
Sea level rise

- **Over the last 14,500 years sea level has risen about 360 feet; drowning bays and *raising base levels***



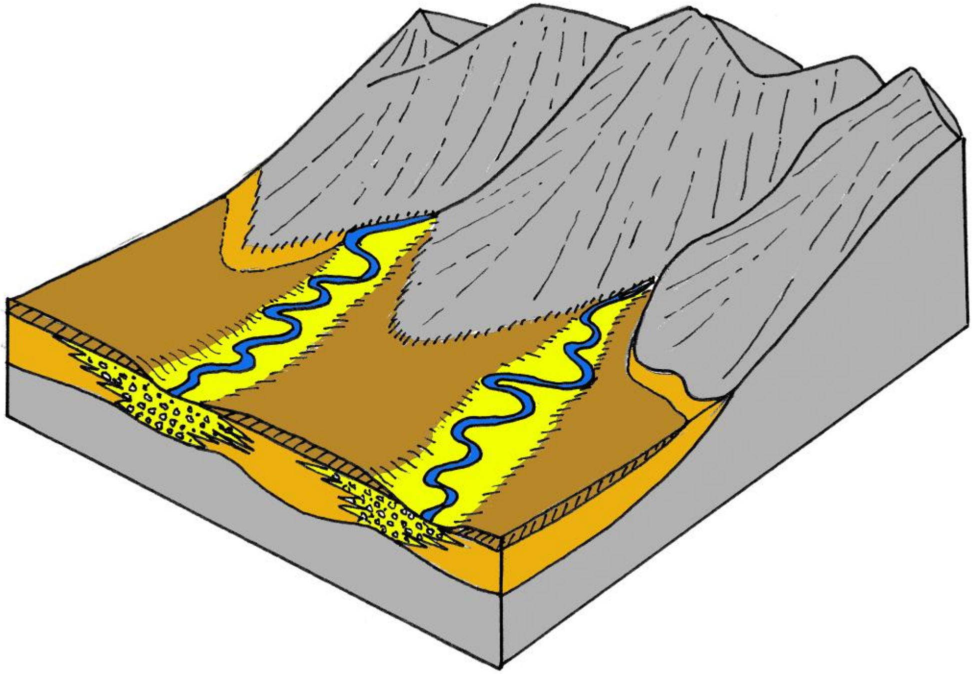
Encroachment of rising sea levels, in 5 ka increments

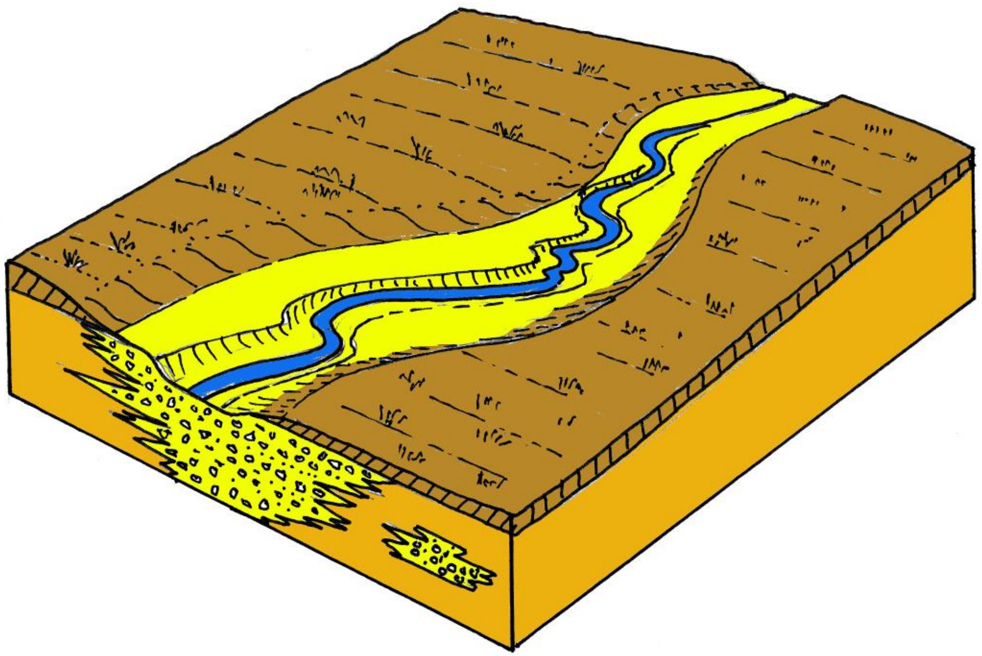




An Inverted Delta

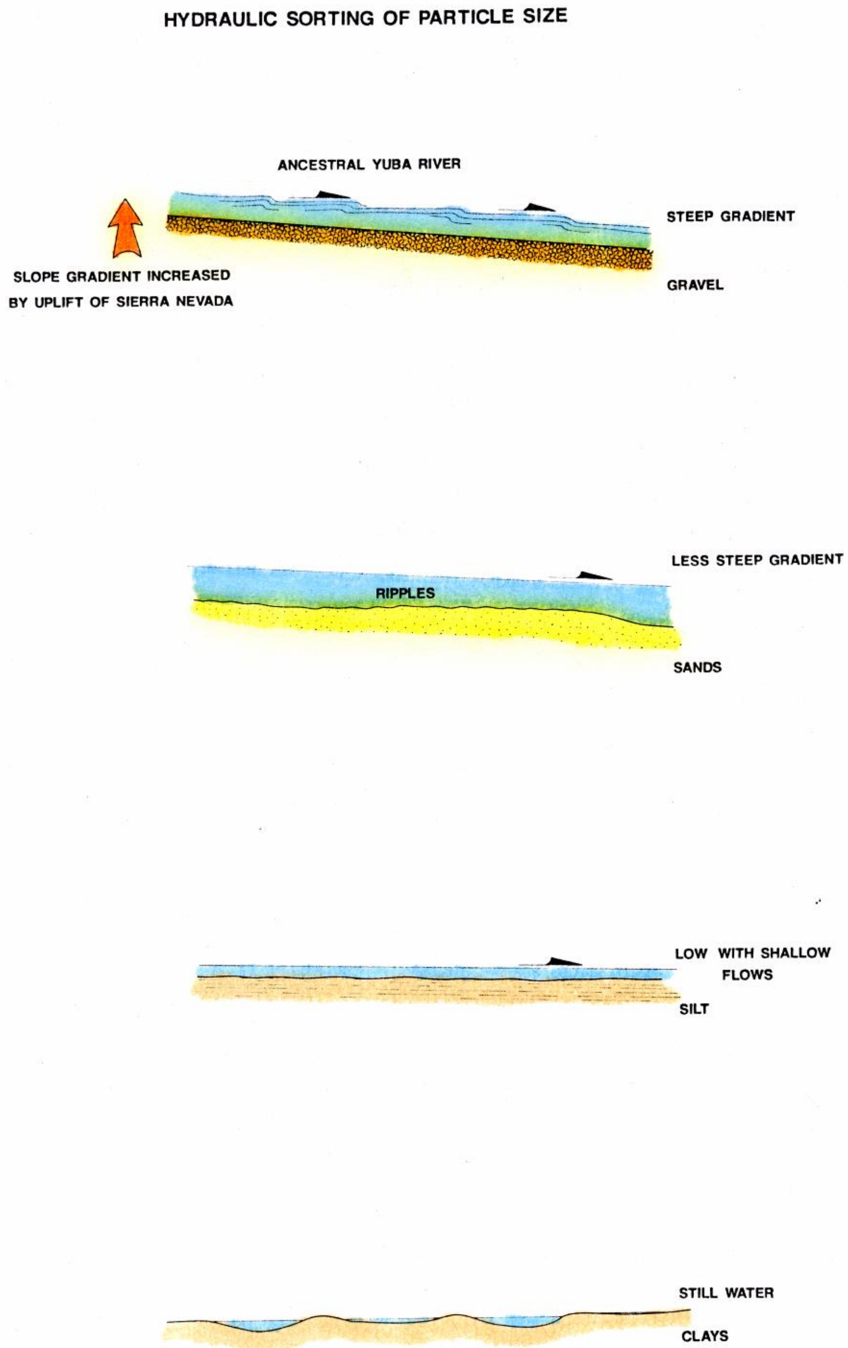
- **Upper left view shows sea level in 1849, before hydraulic mine slickens choked the rivers and delta**
- **Sea level began a rapid rise about 14.5 ka, leveling off about 7 ka**
- **This dropped river gradients and lowered stream power**
- **Smaller D_{50} sediment size**





Late Pleistocene weathering

- **Sea level rise *lowers channel gradients***
- **Shift to drier summers enhances *channel entrenchment* and development of distinctive weathered horizon**
- **These *Riverbank Terraces* are a compact dark brown to red alluvium, composed of gravel, sand and silt, with minor clay**

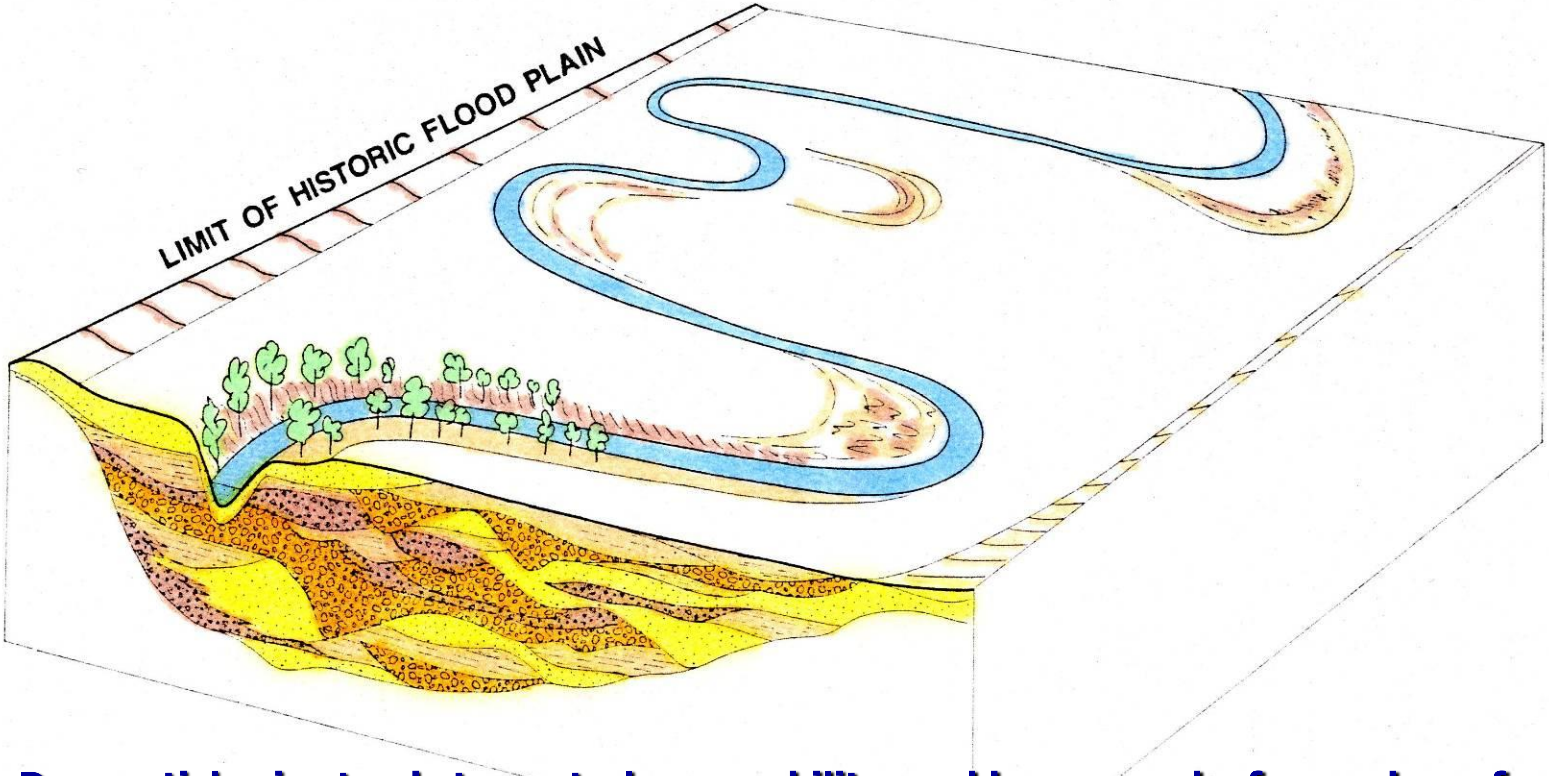


Hydraulic sorting of particles in a river channel

- **Alluvial bedload is hydraulically sorted in accordance with flow volume, hydraulic grade, channel depth, roughness, and sinuosity.**
- **During Holocene, coarse point bar gravels least common, while flood plain silts most numerous, spread over large areas.**

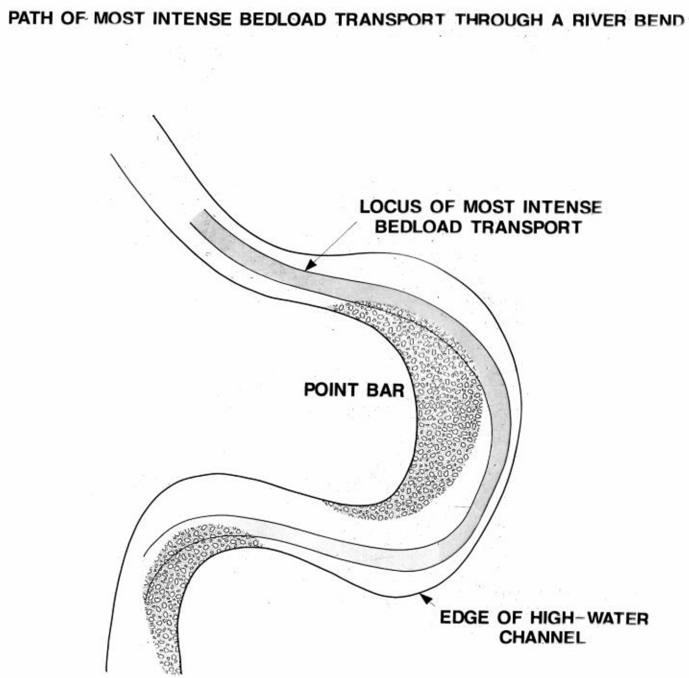
- Serpentine character of modern channels in the Sacramento Valley, caused by the river's desire to conserve energy.

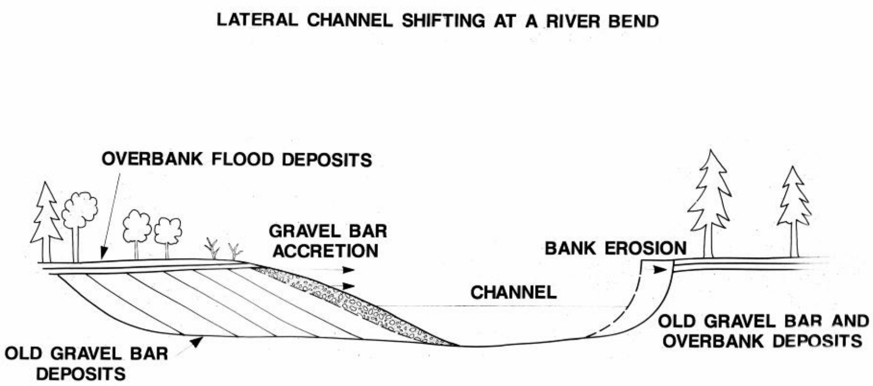
These *meander belts* conceal a complex understory of <u>pinched and truncated channels of varying permeability</u>



The D_{15} particle size tends to control permeability; and k can vary by four orders of magnitude in adjacent channel deposits. If you miss the high permeability channels, you fail to characterize the site conditions for any meaningful seepage analyses.

- **Coarse lag gravels tend to accumulate in braided bars and point bars, as sketched here.**
- **Proximity to the main stem channel controls the relative percentage of *high permeability materials* filling the channel.**





- **The hydraulic gradient of the Yuba River is about 27X that of the lower Mississippi River, which has, historically, influenced Corps of Engineers design doctrine.**
- **The lower Yuba River deposited coarse gravels in *laterally restricted point bars*.**
- **Note how these tend to be *discontinuous features*, accreting on the inside bends of the channel, and non-horizontal**
- **These create an *acute* 3D site characterization problem**

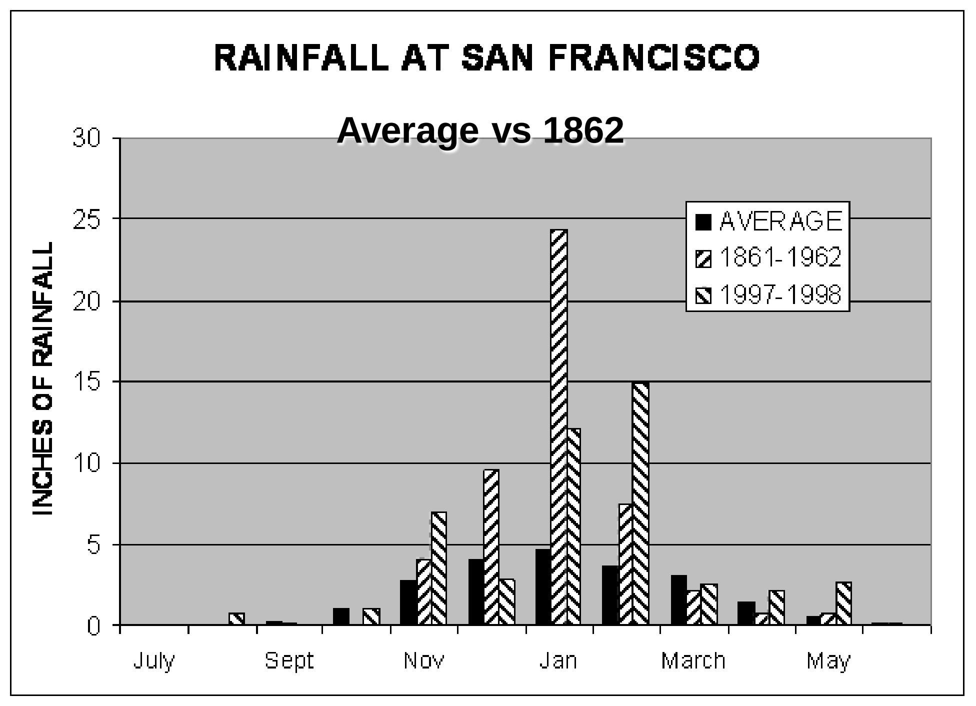
California Gold Rush

- Gold discovered at Sutter's Mill in early 1848.
- 50,000 Americans descended upon California between 1849-52.
- Marysville established at confluence of Feather and Yuba Rivers, the head of riverine navigation.

Hydraulic mining

- **In 1852-53 a French-Canadian mining engineer named Anthony Chabot and his partner Edward Matteson began using hydraulic monitors to excavate gold-bearing Tertiary age gravels at Buckeye Hill and American Hill, near Nevada City.**

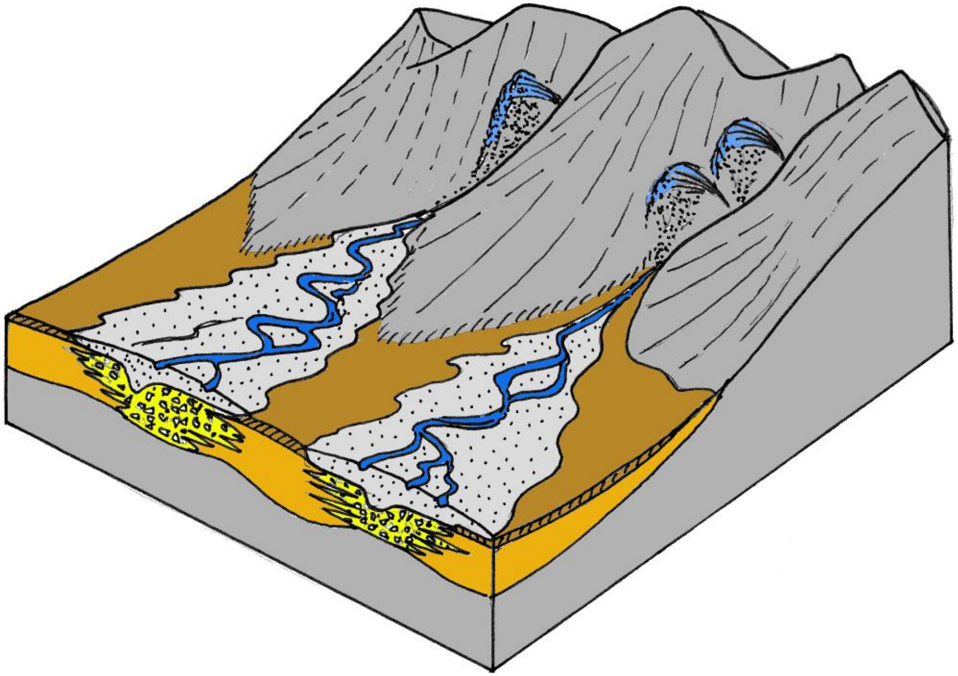
Great Flood of 1862

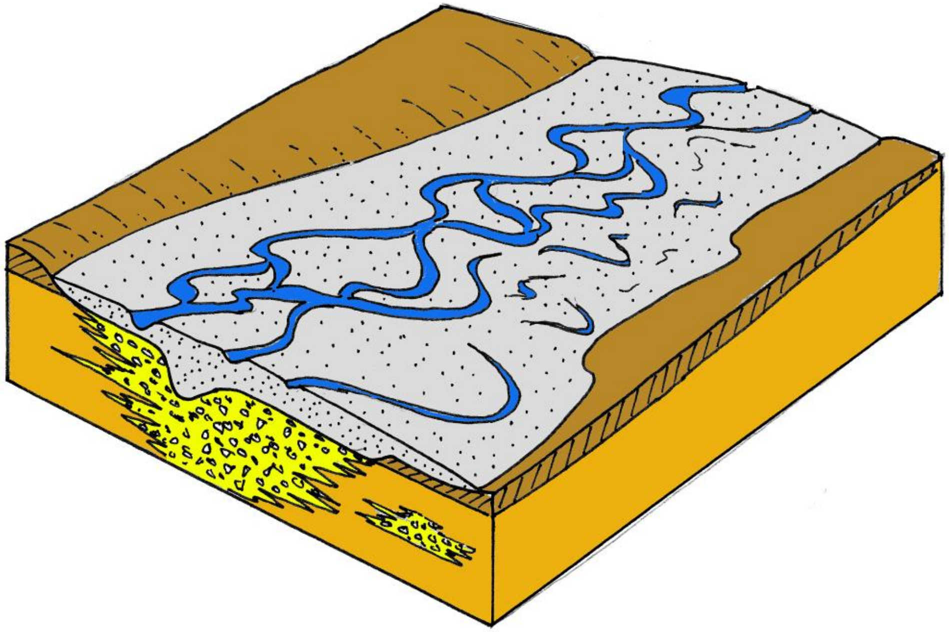


The great flood of 1862 brought record seasonal rainfall, the maximum event since western Europeans descended upon Alta California in the late 18th Century.

It caused massive flooding of Sacramento (K Street, shown at left)

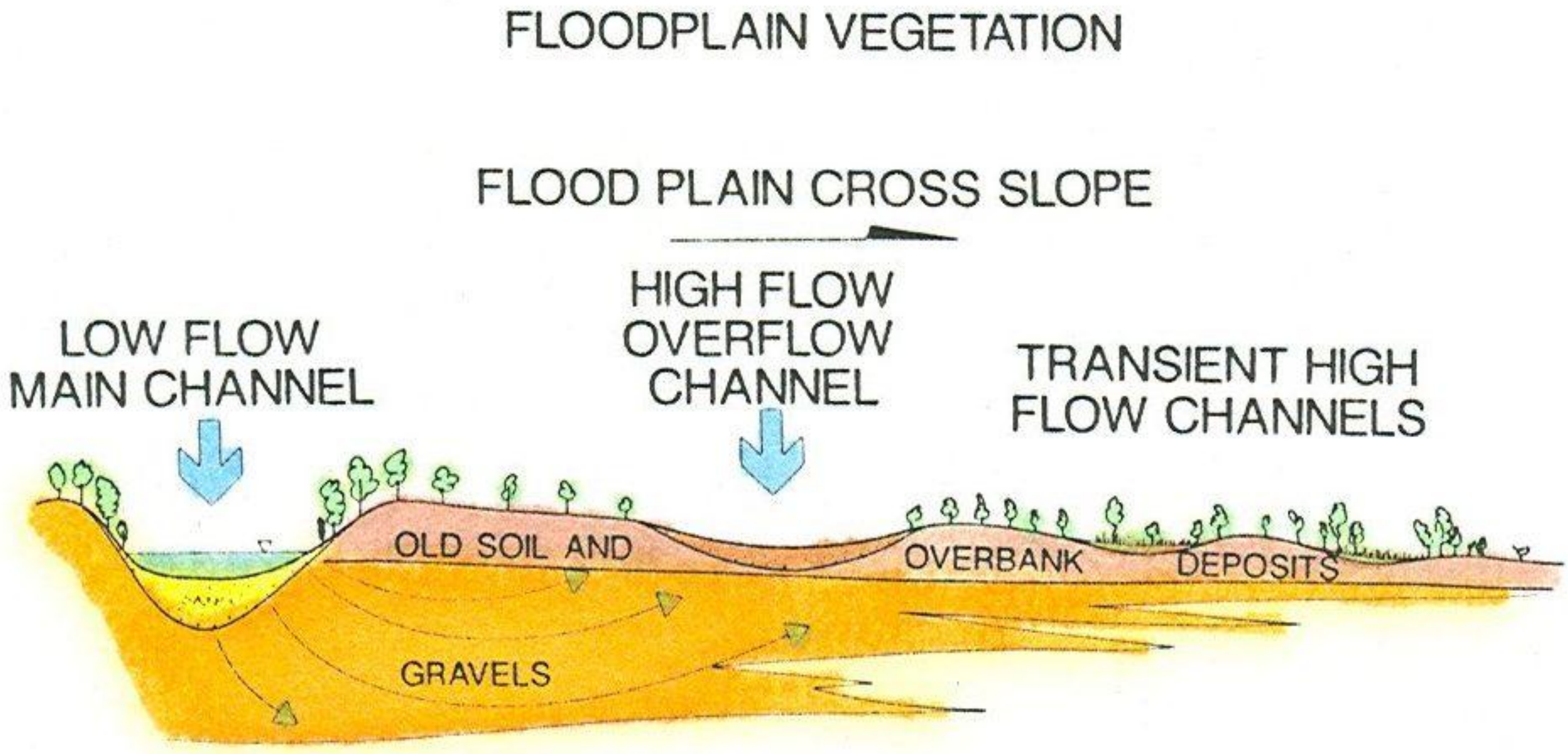
Over the next 40 years, mountain channels disgorged nearly one cubic mile of mine slickens upon the Sacramento Valley and areas downstream.



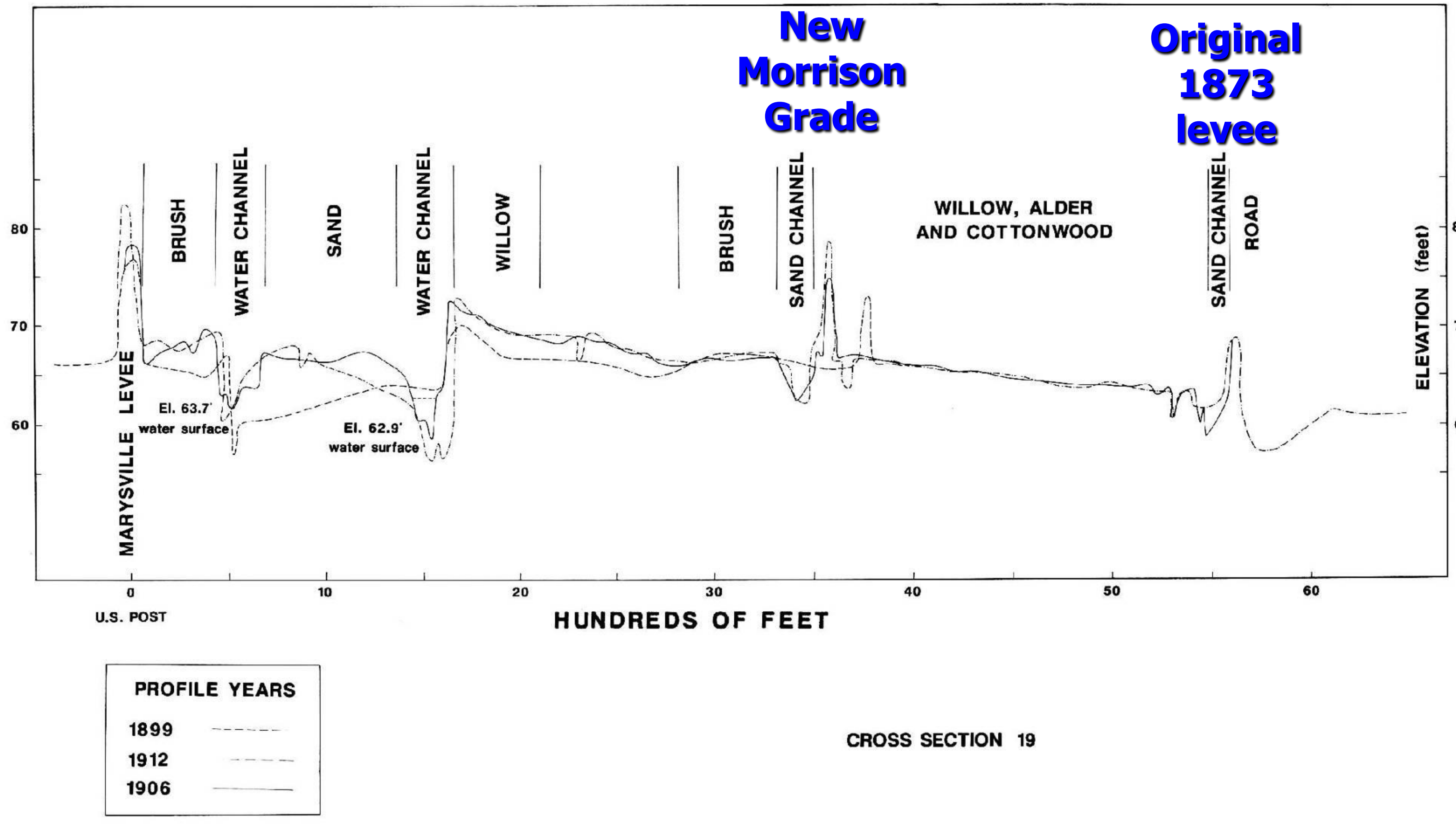


Environmental Catastrophe

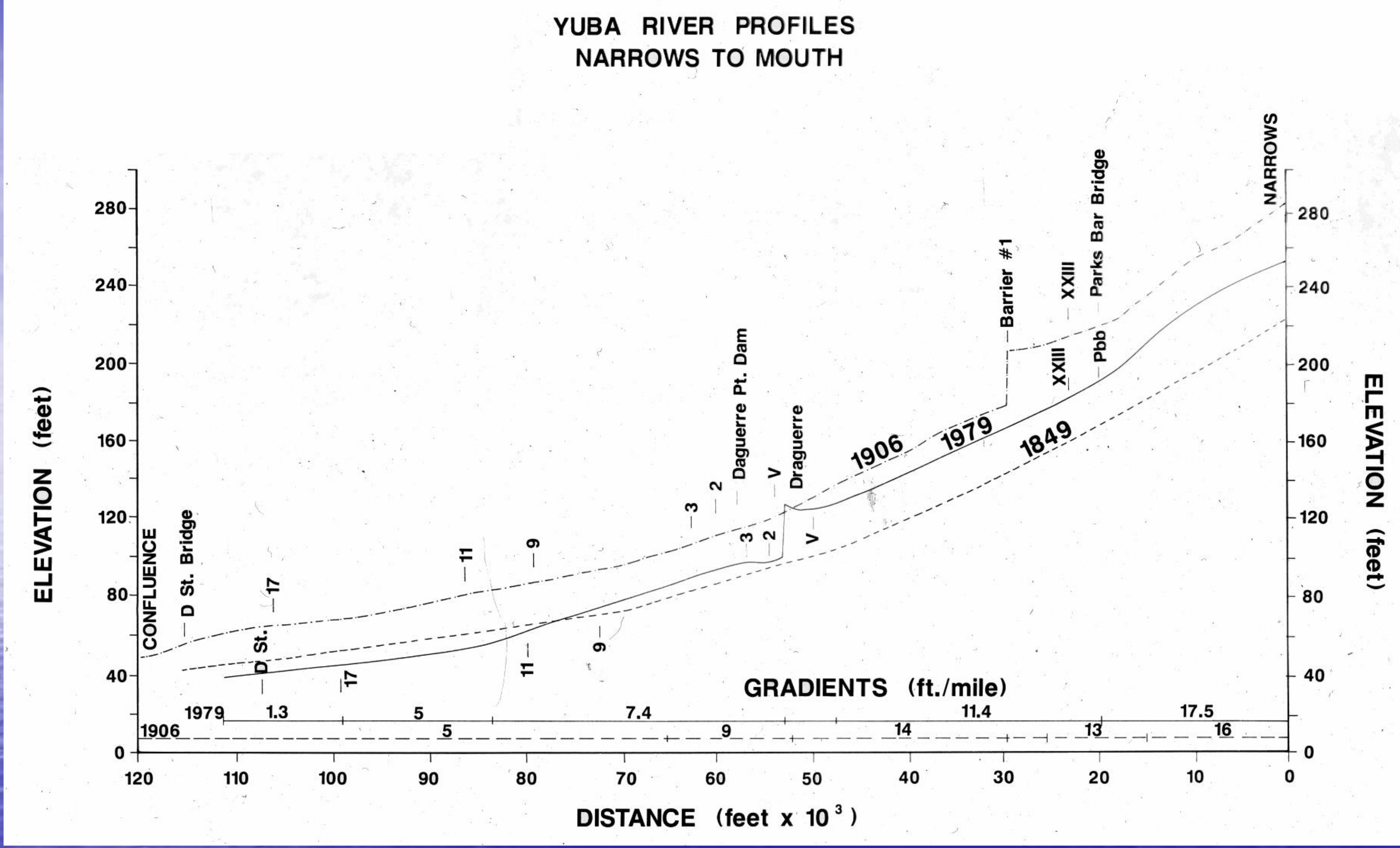
- **The Yuba, Bear, Feather, and American River Basins produced the greatest quantities of silt, termed "*mine slickens*"**
- **The debris choked the channels, stymied river navigation, and destroyed farmland in the Sacramento Valley.**
- **After 20 years of lawsuits, the Wright Act of 1884 forbade uncontrolled hydraulic mining**



- Like any **overbank silt**, the hydraulic mine slickens deposited after 1862 tended to be thickest near the main stem channels, diminishing outward. Overflow channels would periodically carve material off, reducing thickness of the slickens and overbank silts along those ephemeral channels.

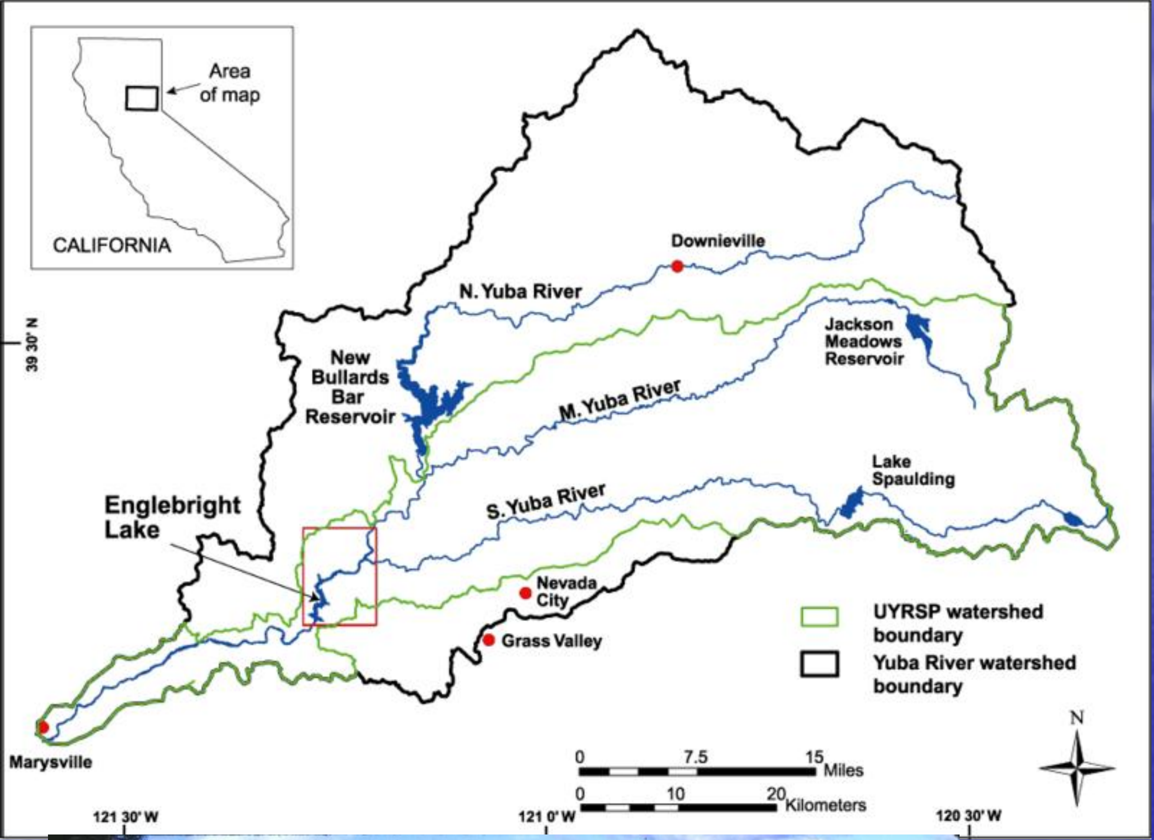


- Cross section of the lower Yuba River prepared by the California Debris Commission in 1907. Note gradient of the clogged flood plain, diminishing with increasing distance from the main channel.



- Longitudinal profile of the lower Yuba River, from Lori Alder's UCLA thesis (1980). The mine slickens raised the bed of the Yuba River by **20 ft** (mouth) to **80 ft** (Yuba Narrows).

- **The deposition of 20 to 30 feet of mine slickens at the mouth of the Yuba River, and about 18 feet in the Feather River, increased the flood threat posed to Marysville.** Photo taken in 1913, looking up the lower Yuba River and the old D Street Bridge (from UC Water Resources Center Archives, Berkeley).

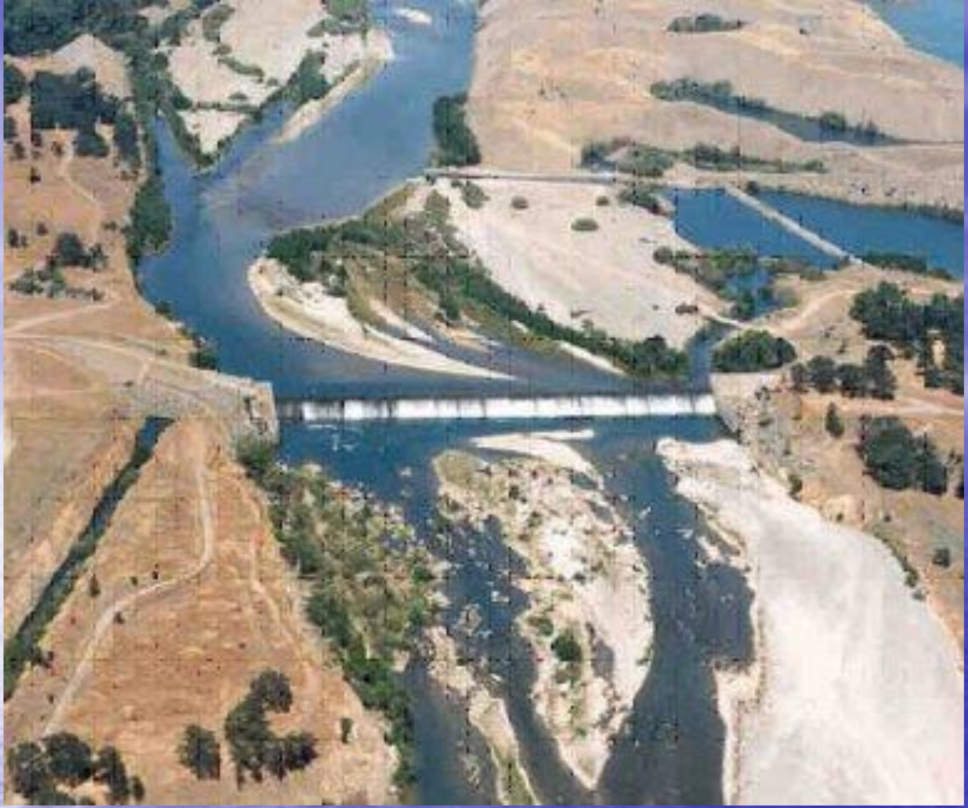


California Debris Commission

- A debris commission was established by Congress in 1893
- It was composed of three Corps of Engineers officers.
- The commission was eliminated by Congress in 1986.

Englebright Dam – completed in 1941

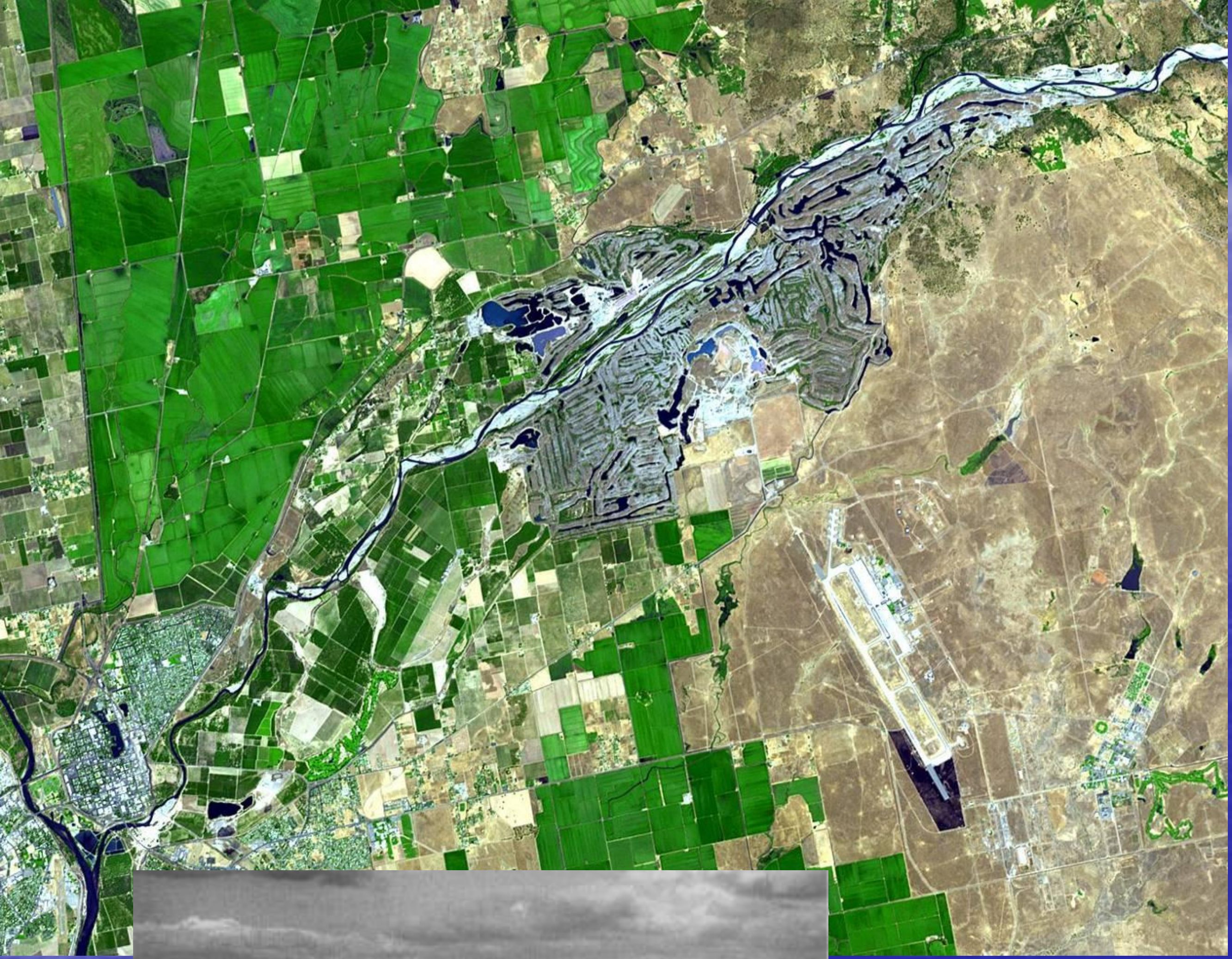
Debris Storage



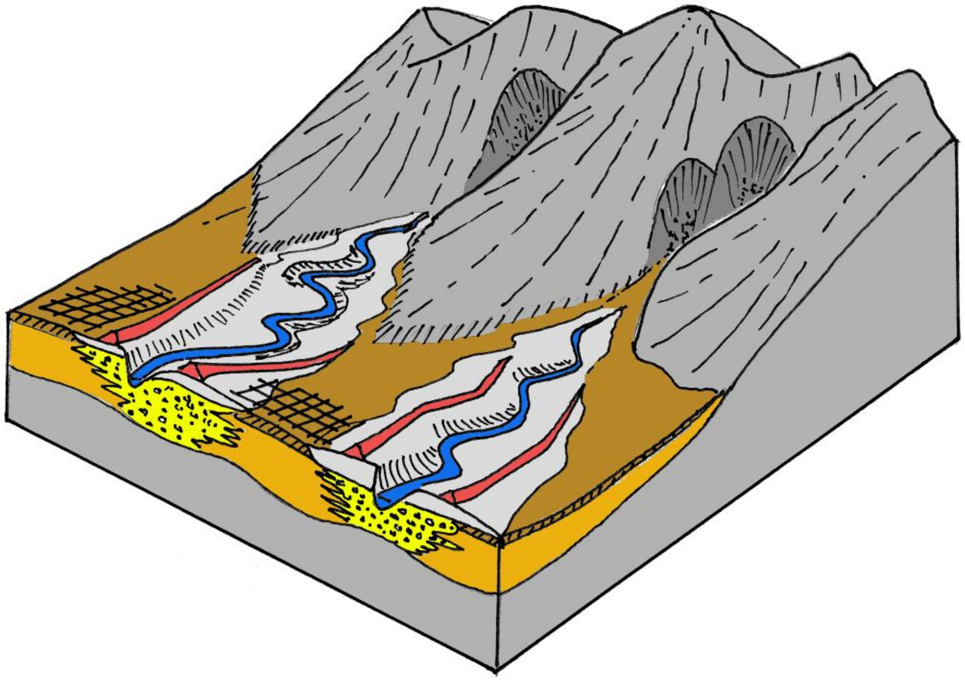
Flood flow over Daguerre Pt Weir in 1913

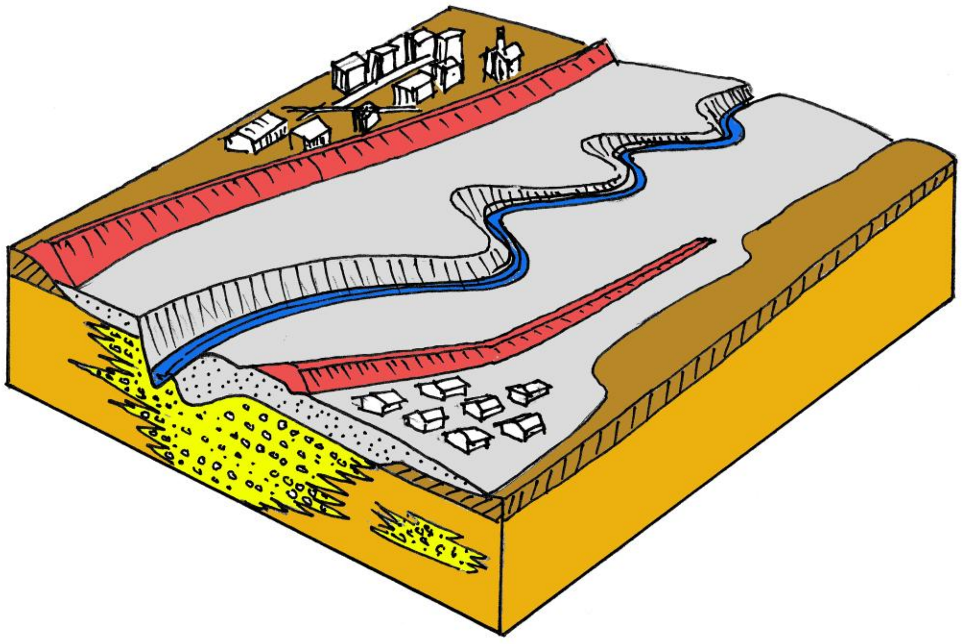
- **Most of the early barriers constructed by the Corps of Engineers in the Yuba Basin failed during floods in 1907 and 1909.**
- **The lone exception was Daguerre Point Dam, a 24 ft high overflow weir constructed in 1906.**

Dredge Mining until 1970



- **The Wright Act allowed hydraulic mining and dredging, if the permitee could guarantee that no debris would be carried downstream. The Yuba Gold Field near Hammonton was the last active gold dredging activity in California.**

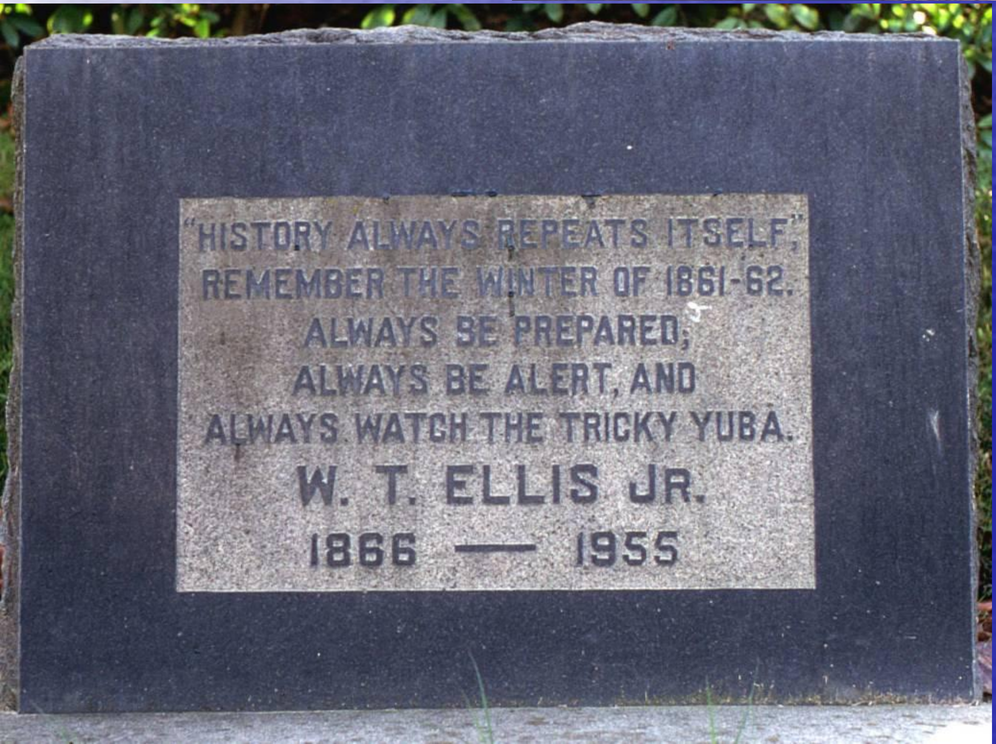




Levees Required

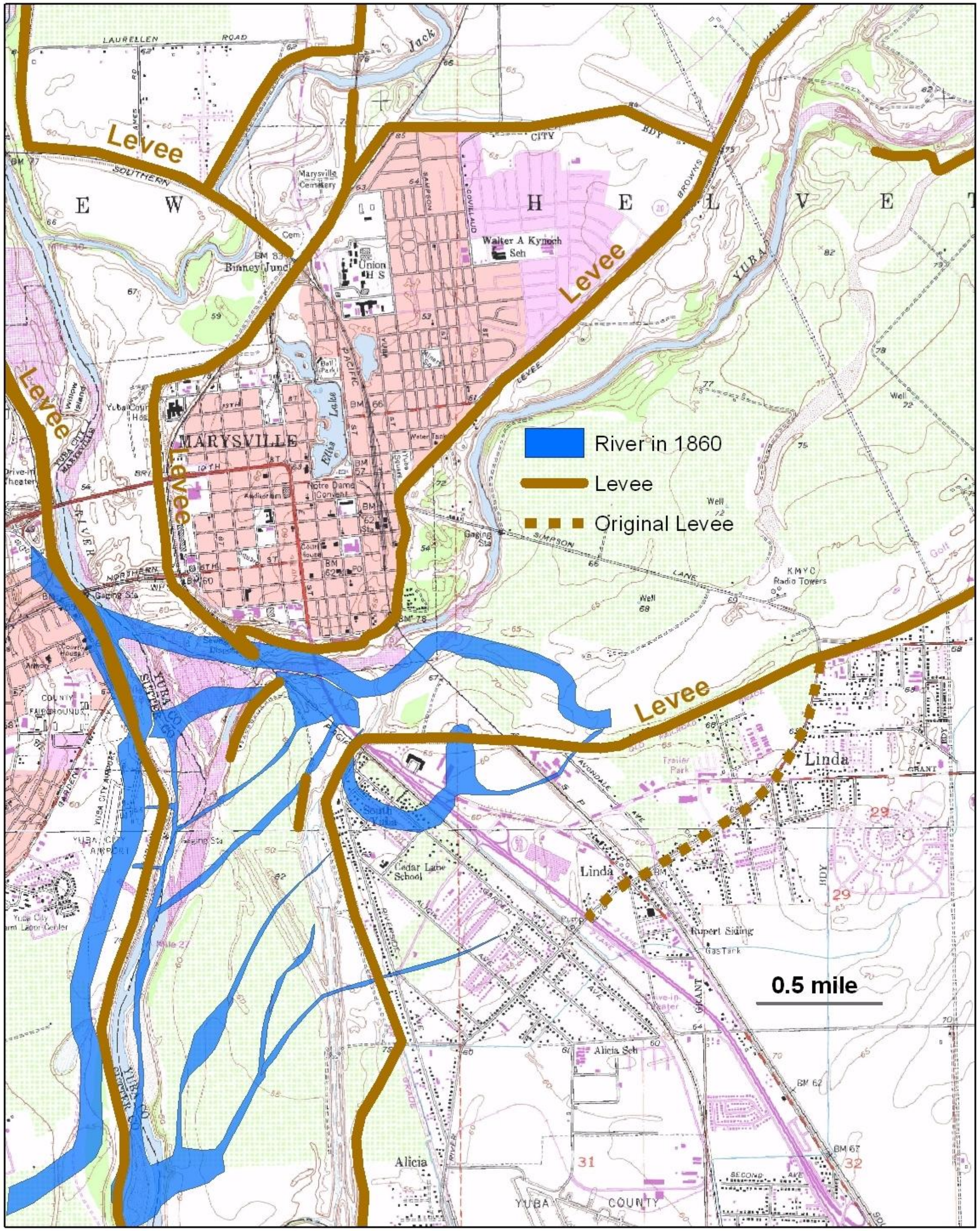
- Marysville began building a protective ring levee after the 1862 floods
- The city was obliged to continue raising the levees incrementally, until 1960, as the flood levels continued rising.

Protective levee that encircles Marysville



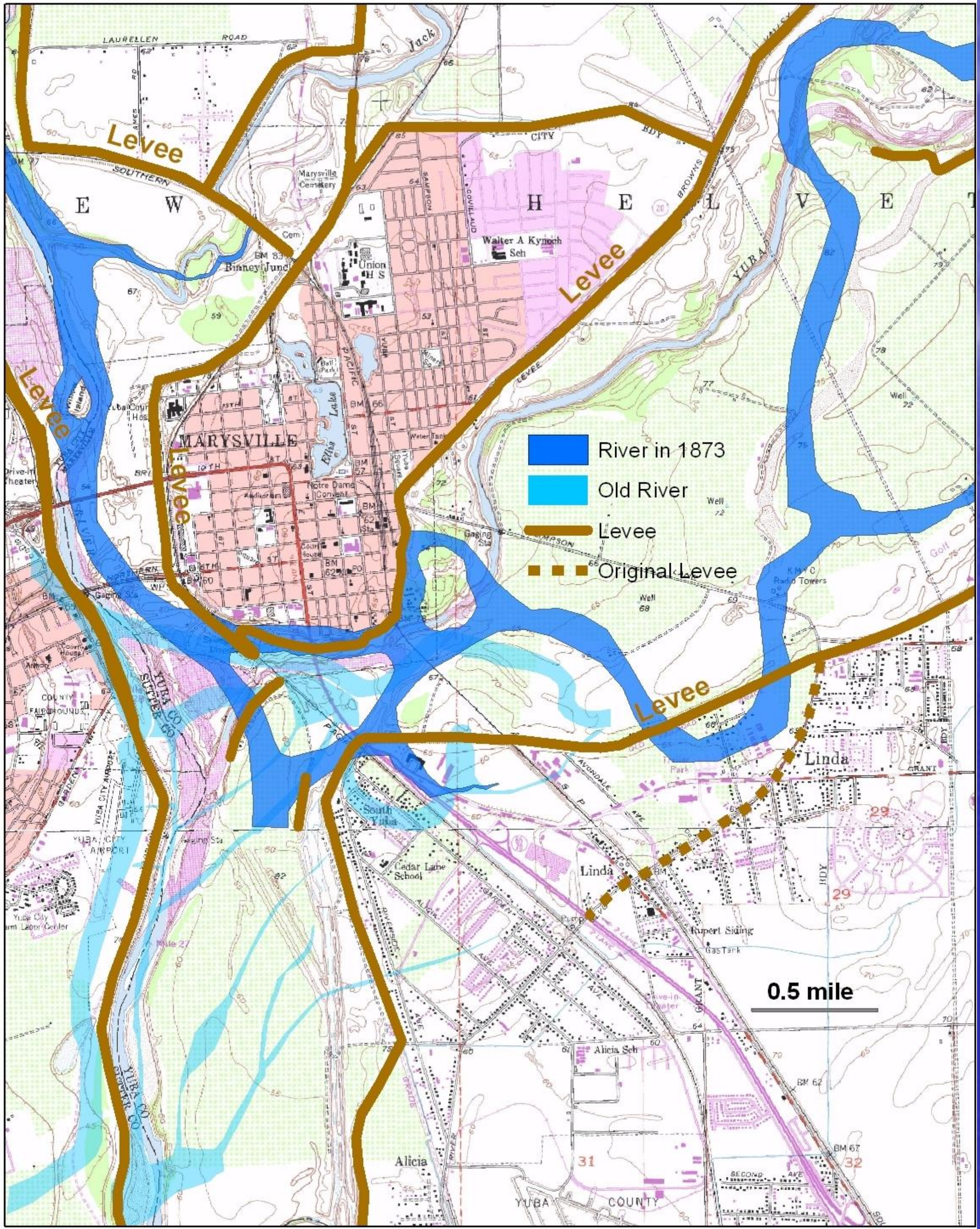
- **Legendary Marysville flood engineer W.T. Ellis warned the city to *"always watch the tricky Yuba"***
- **He died a few months before the disastrous December 1955 floods that annihilated Yuba City, across the Feather River**

HISTORIC WANDERINGS OF THE LOWER YUBA RIVER 1860-1973



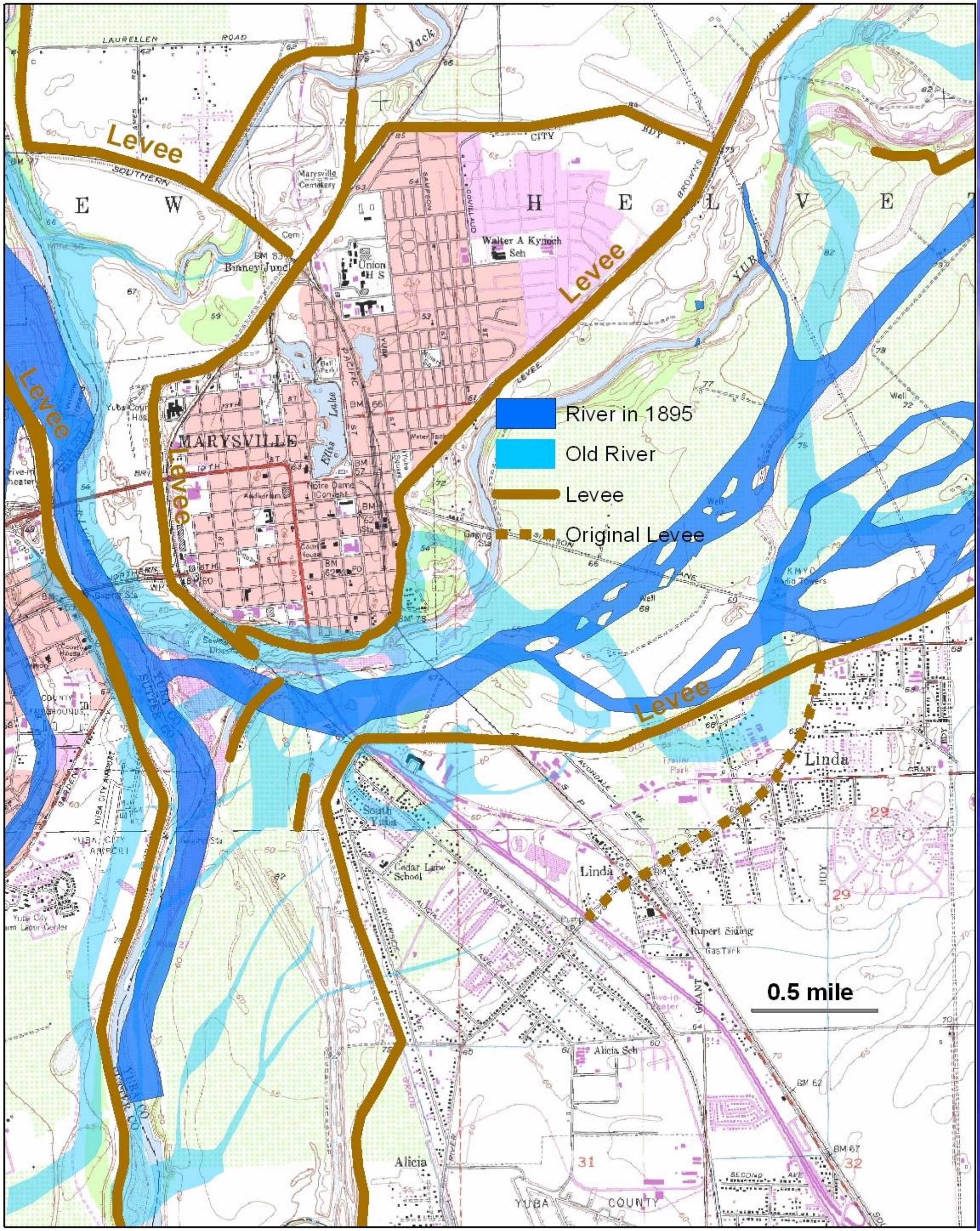
1860

- The only reliable map of the lower Yuba River prior to the Great Flood of 1862
- Modern levees shown in brown, simply for reference.
- Note meander cutoffs on south side of floodplain.



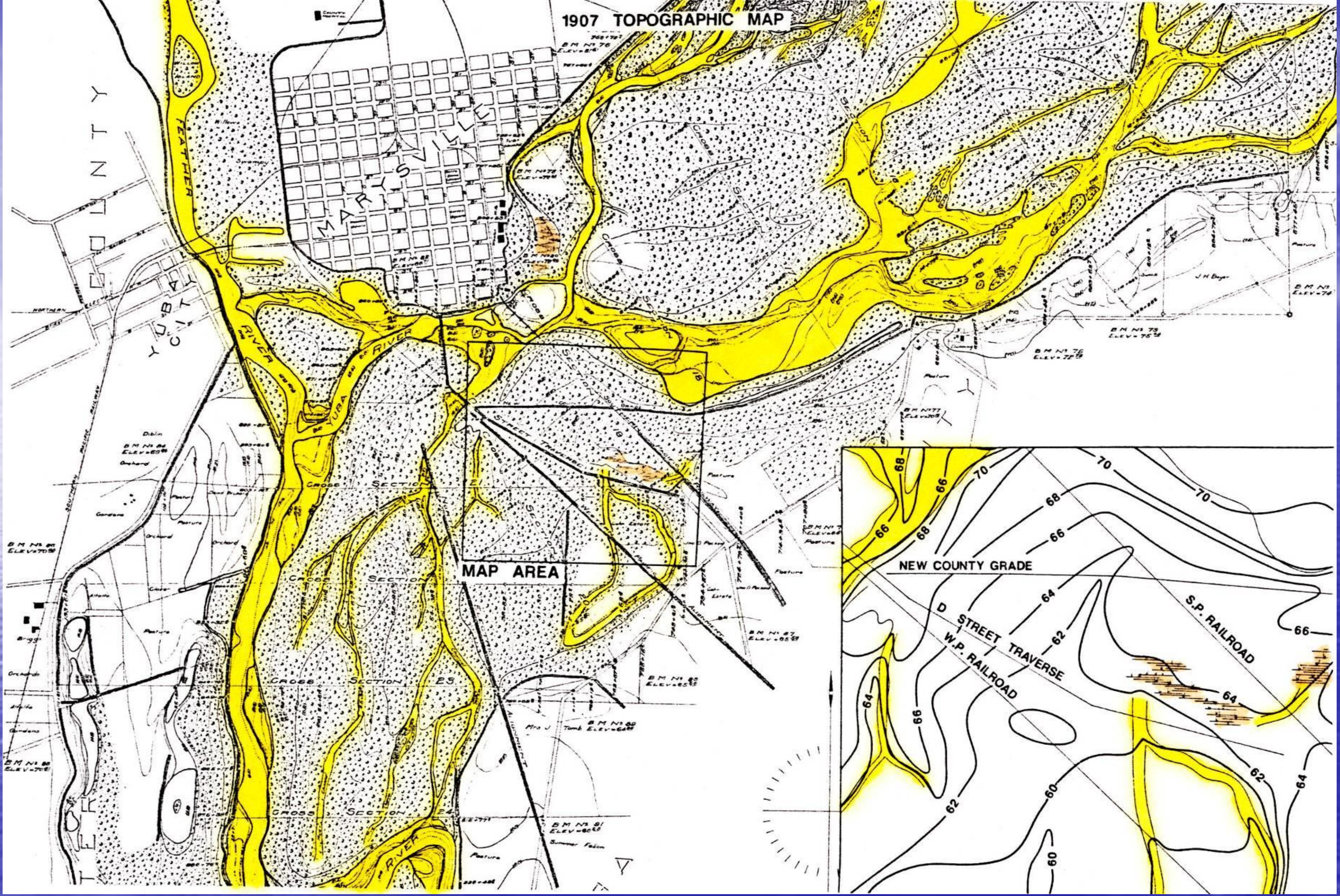
1873

- Note bifurcated channels, typical of a channel with ***insufficient stream power*** to move the imposed sediment load
- Original Linda Levee graded ~1873 shown as dashed brown line

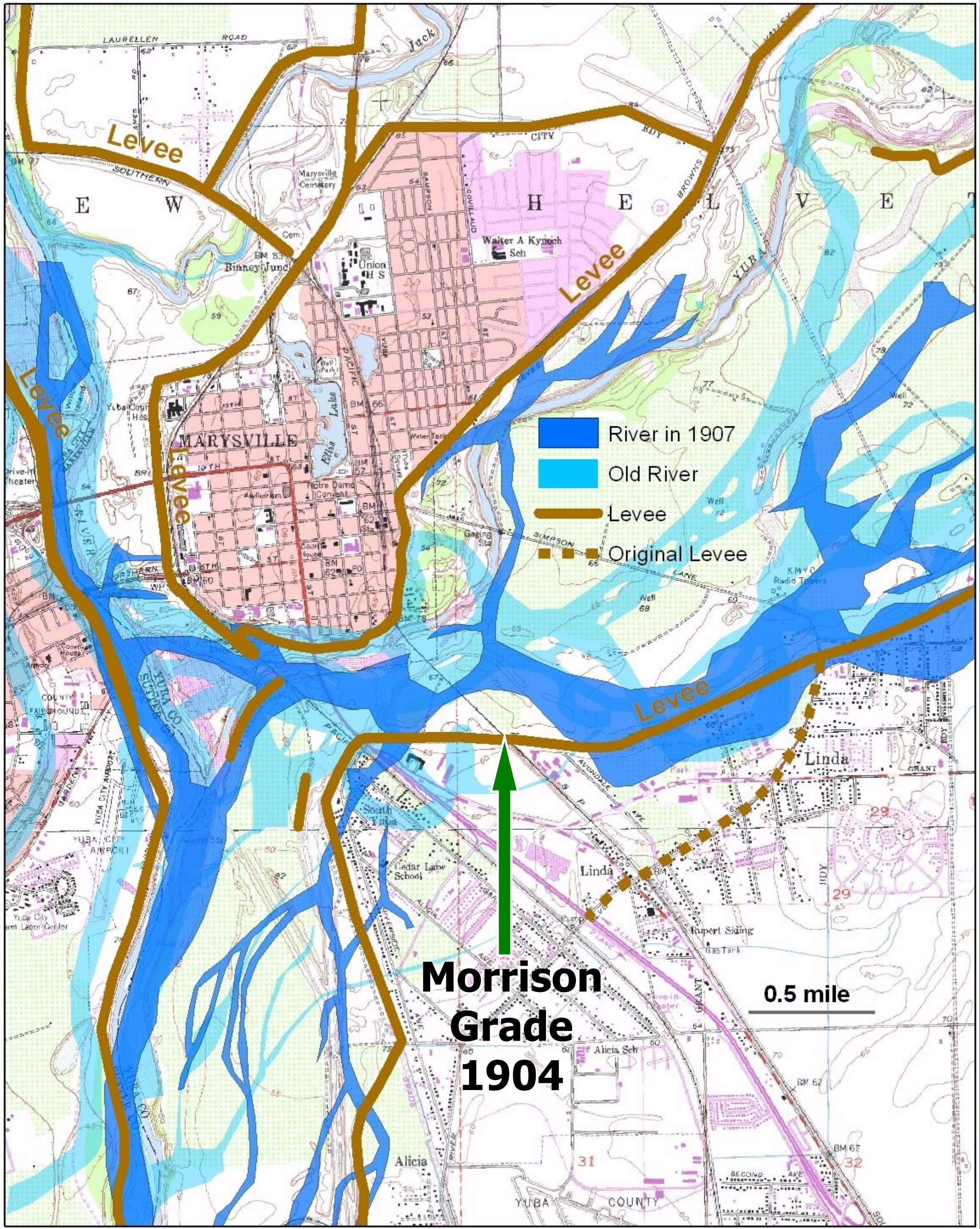


1895

- Taken from first USGS topographic sheet of this area
- The choked channel has widened considerably, bifurcated, and developed numerous islands and bars.

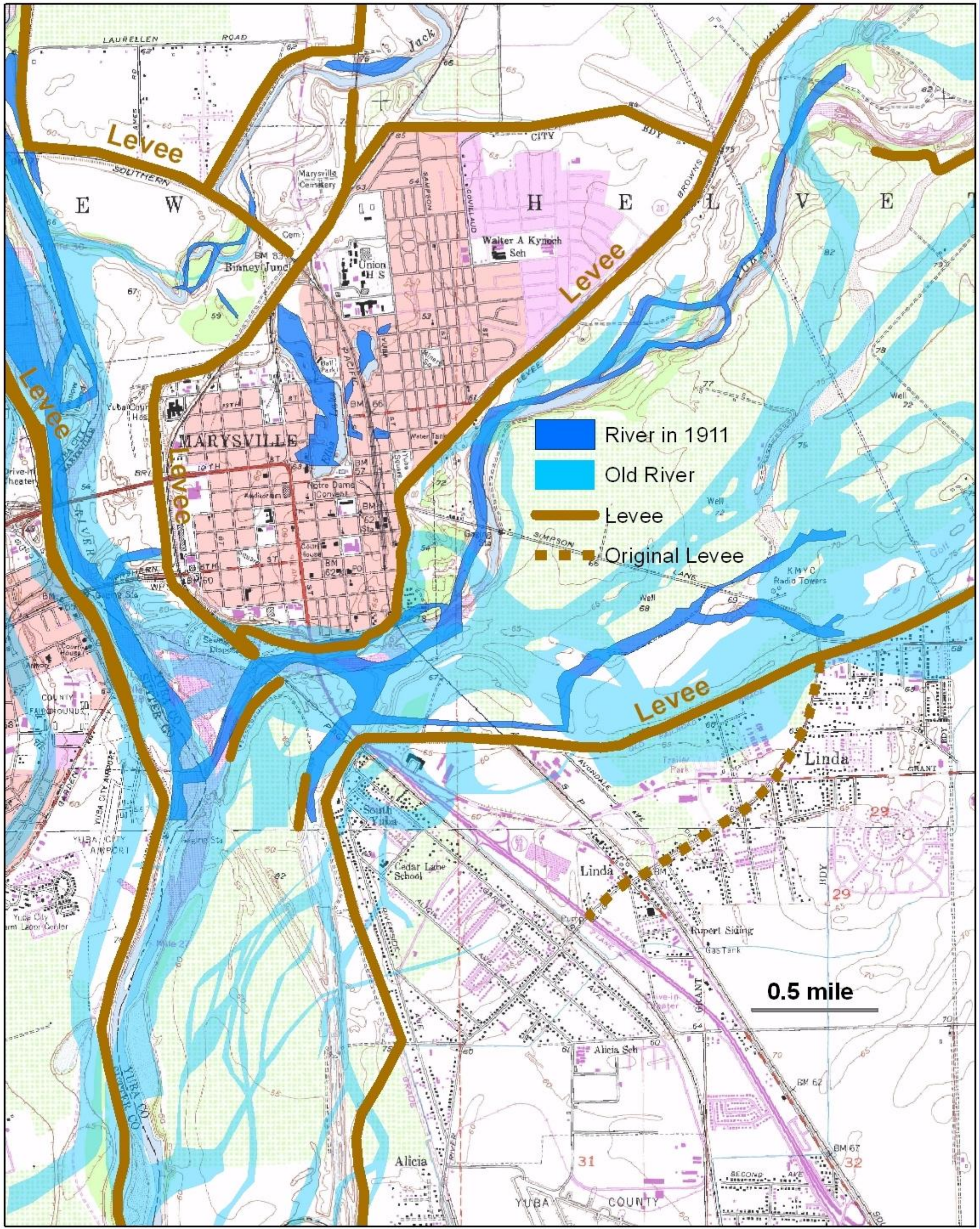


- **This is a map of the lower Yuba and Feather Rivers prepared by the Army's California Debris Commission in 1907. Yellow colors denote the active low flow channel.**



1907

- Detailed survey by California Debris Commission, shortly after the new Linda Levee, or 'Morrison Grade' was built by Yuba County in 1904.
- They sought to confine the channel, so it would excavate the mine slickens, and offer shorter span for the D Street Bridge



1911

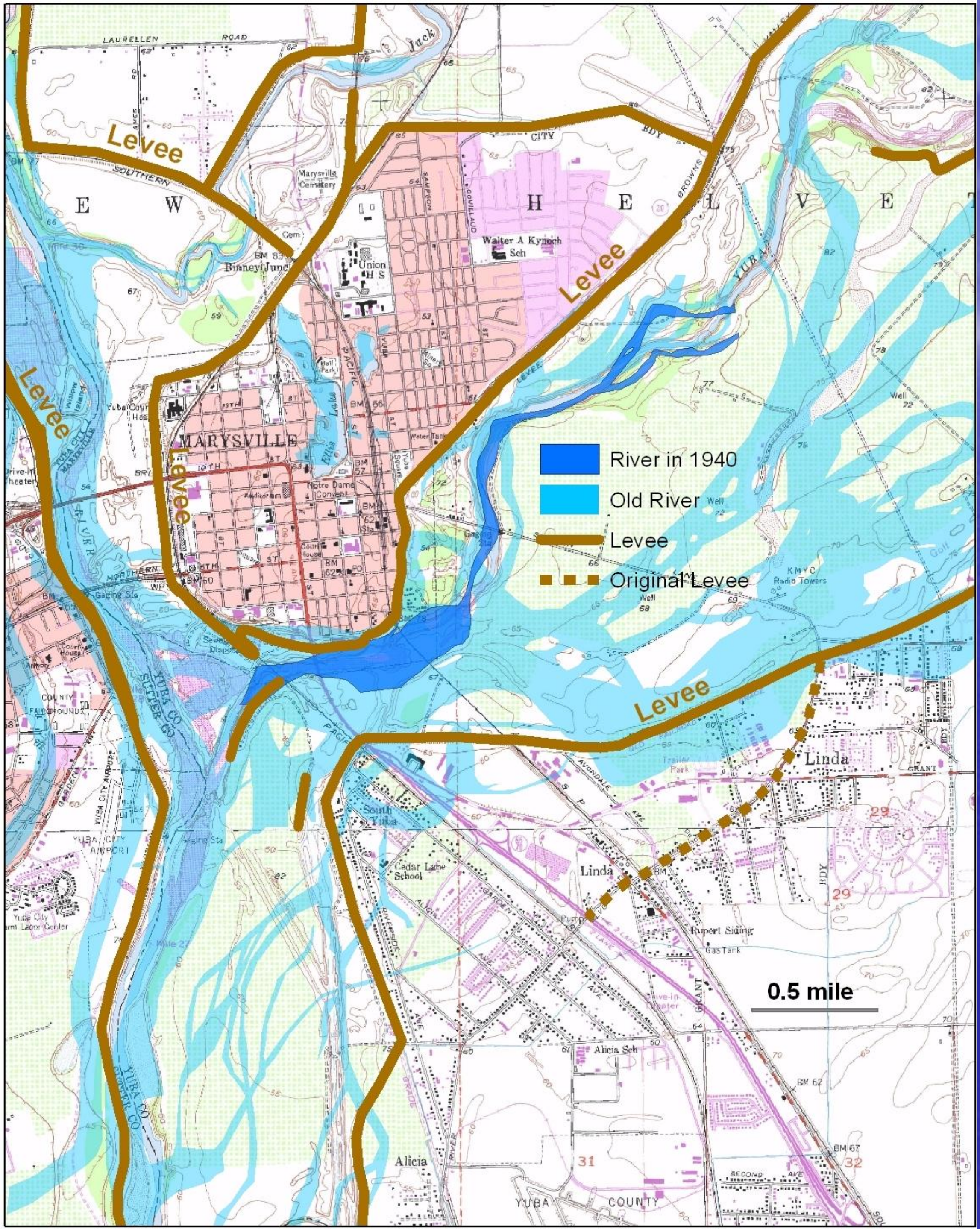
- Record flooding in 1907 and 1909 ran up against the new Morrison Grade, protecting Linda on the south side of the river
- Note the scour channel along the grade and the channel bifurcation at the confluence

Break in east levee of the Feather River just south of Marysville during flood of January, 1914.

- **The Yuba and Feather Rivers experienced severe flooding in 1907, 1909, 1914 (shown here), and 1940. The 1940 flood was the last one that inundated the Linda-Olivehurst area prior to 1986.**

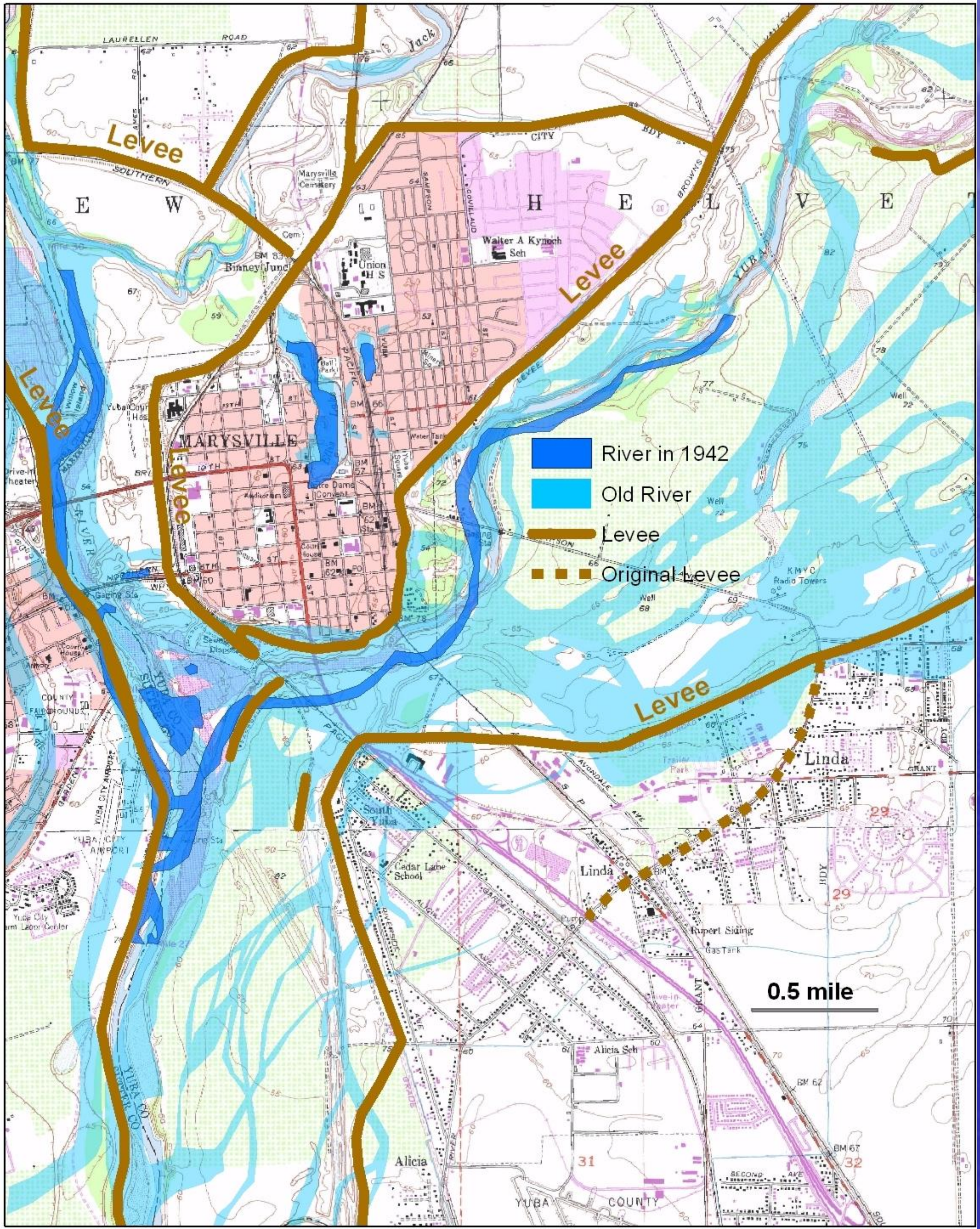
Levee Heightening

- The Linda Levee was heightened by the local reclamation district in 1936
- In 1940 this new levee was overtopped, and other parts of the Sutter Basin were also flooded, as shown here
- The Army Corps of Engineers raised the levee again in 1940



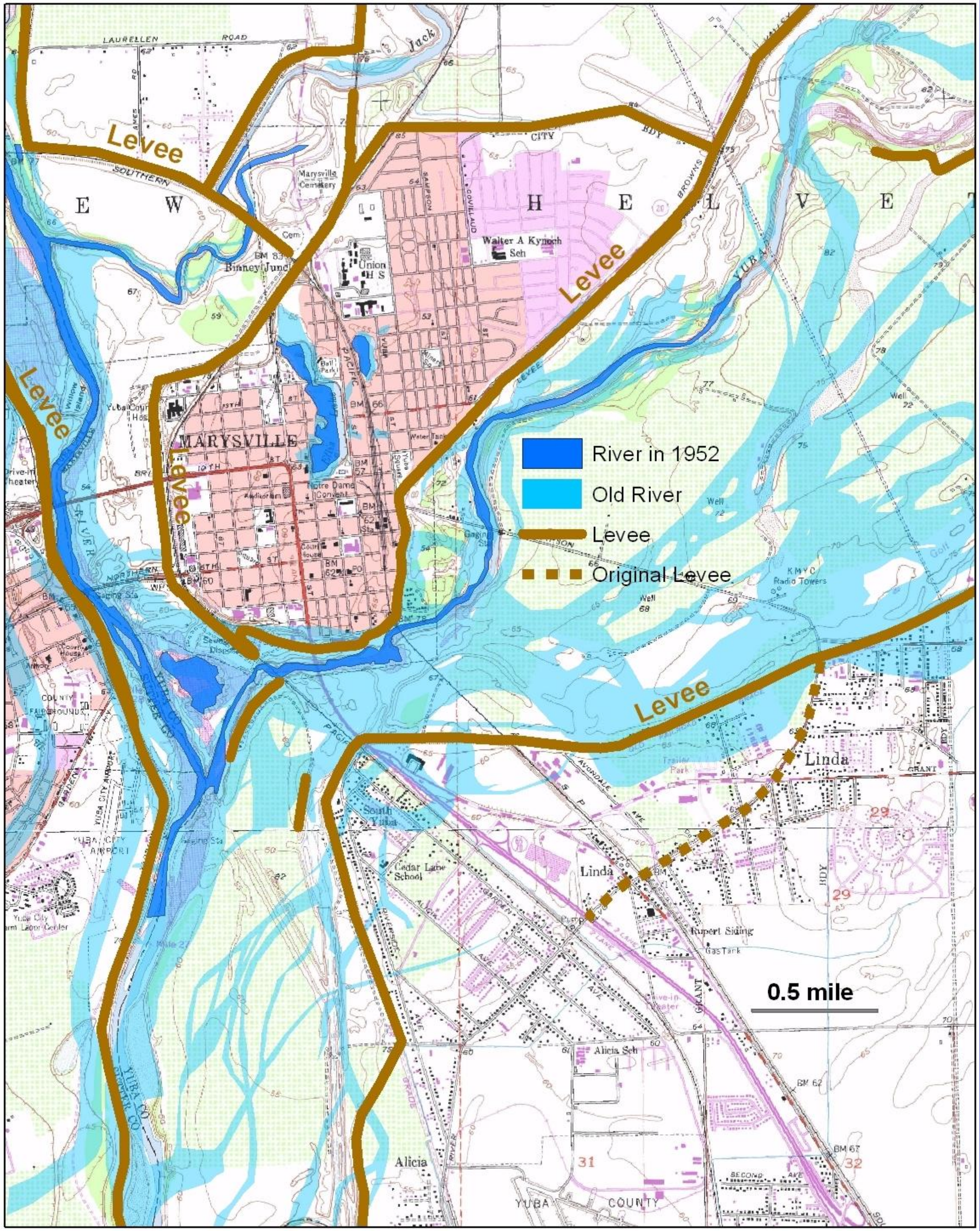
1940

- Taken from a map prepared by the Corps of Engineers after the 1940 flood
- The attempts to train the main channel were starting to pay off, as *the bed had dropped 14 to 16 feet since 1862*



1942

- Taken from USGS 15-min quadrangle
- It shows the low flow channel about midway between the Marysville and Linda Levees, near the river's mouth.
- Training dikes, shown here in brown, were not yet installed in this vicinity

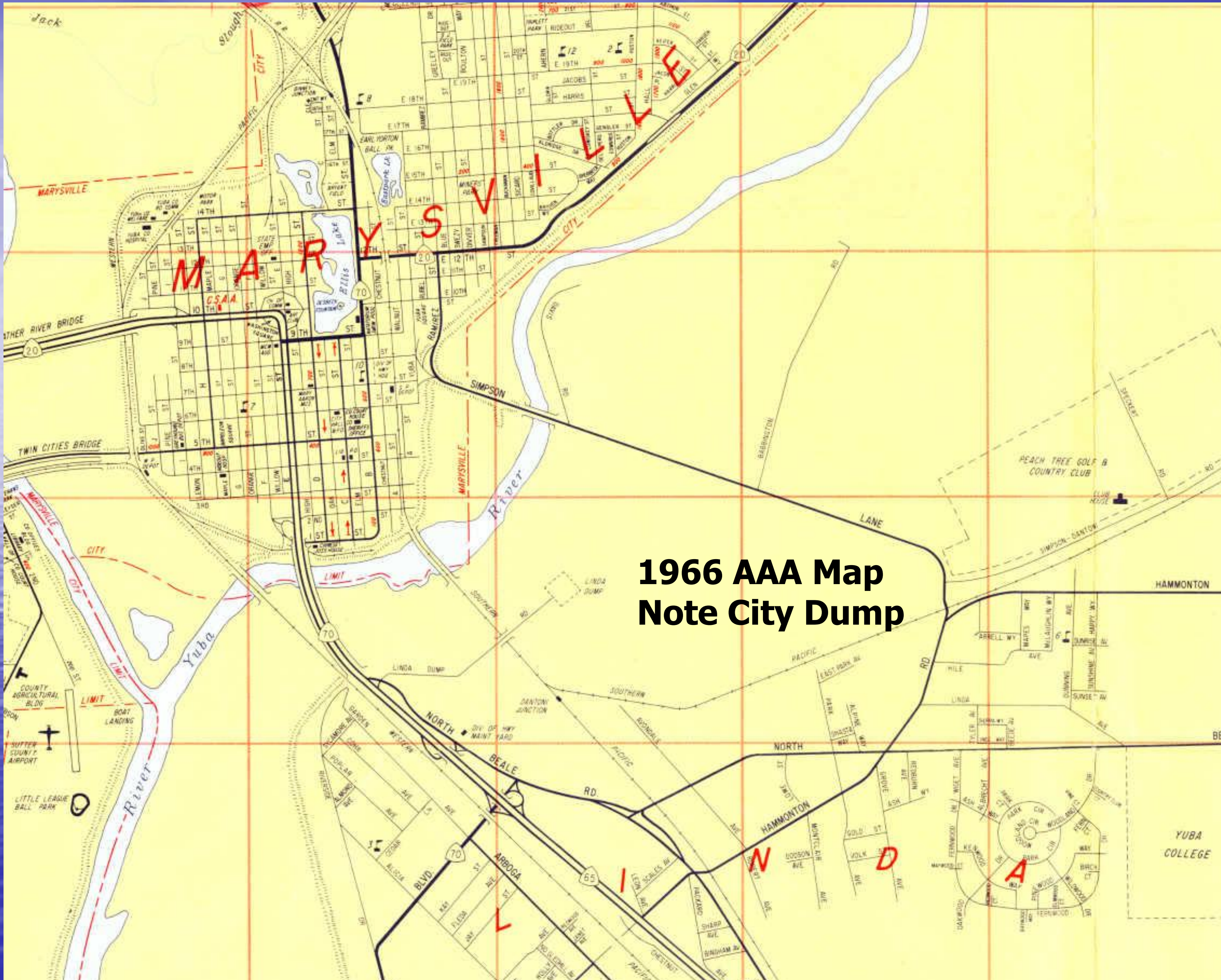


1953

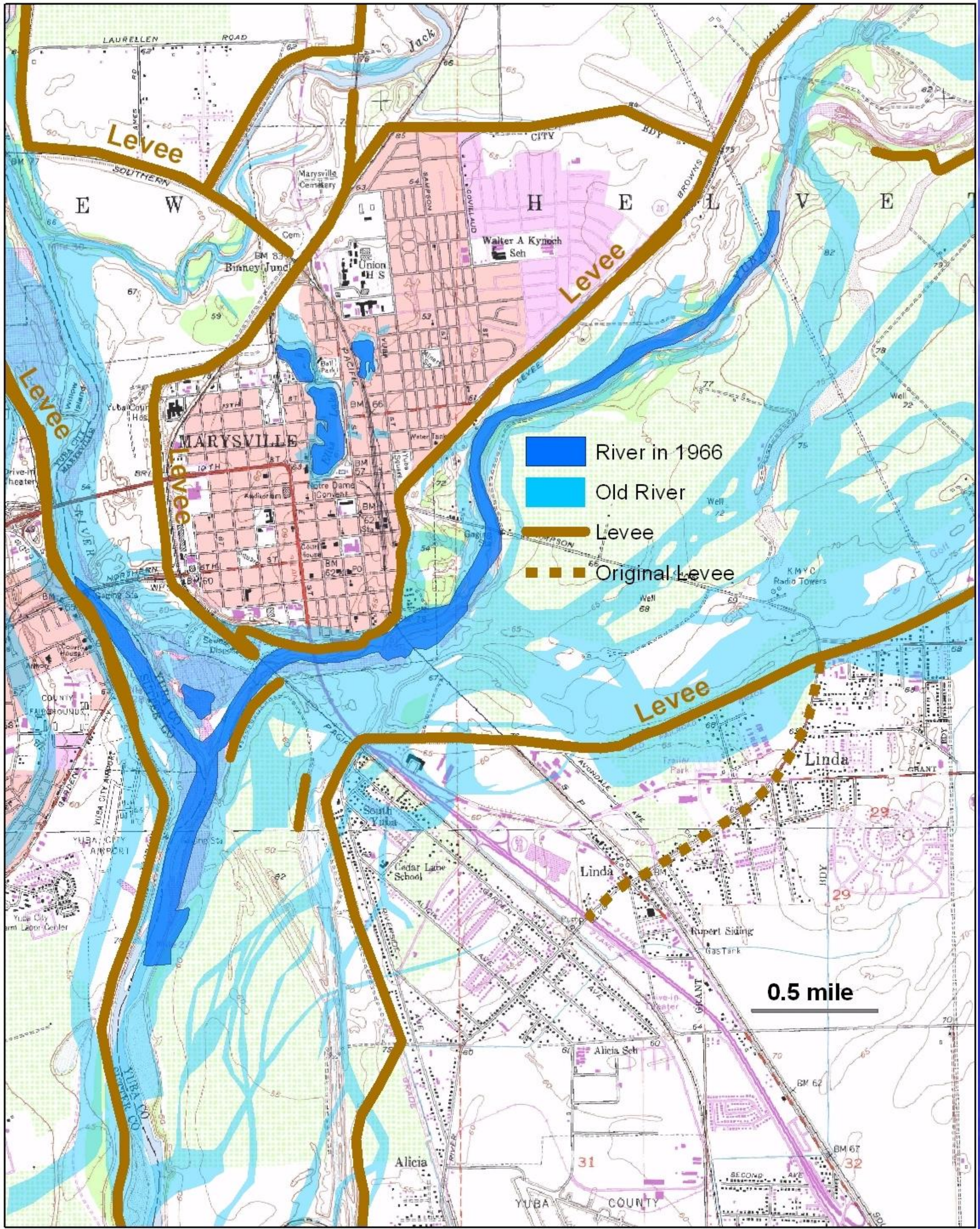
- Taken from first USGS 7.5 min quadrangle
- The low flow channel is essentially stabilized, incised in the mine slickens and hugging the northern bank.

December 1955 floods

- The most disastrous flooding impacting the Marysville-Yuba City-Linda area was the Christmas Eve storm of December 1955, which killed 38 people in Yuba City (upper image)
- The ring dike surrounding Marysville held (lower image)

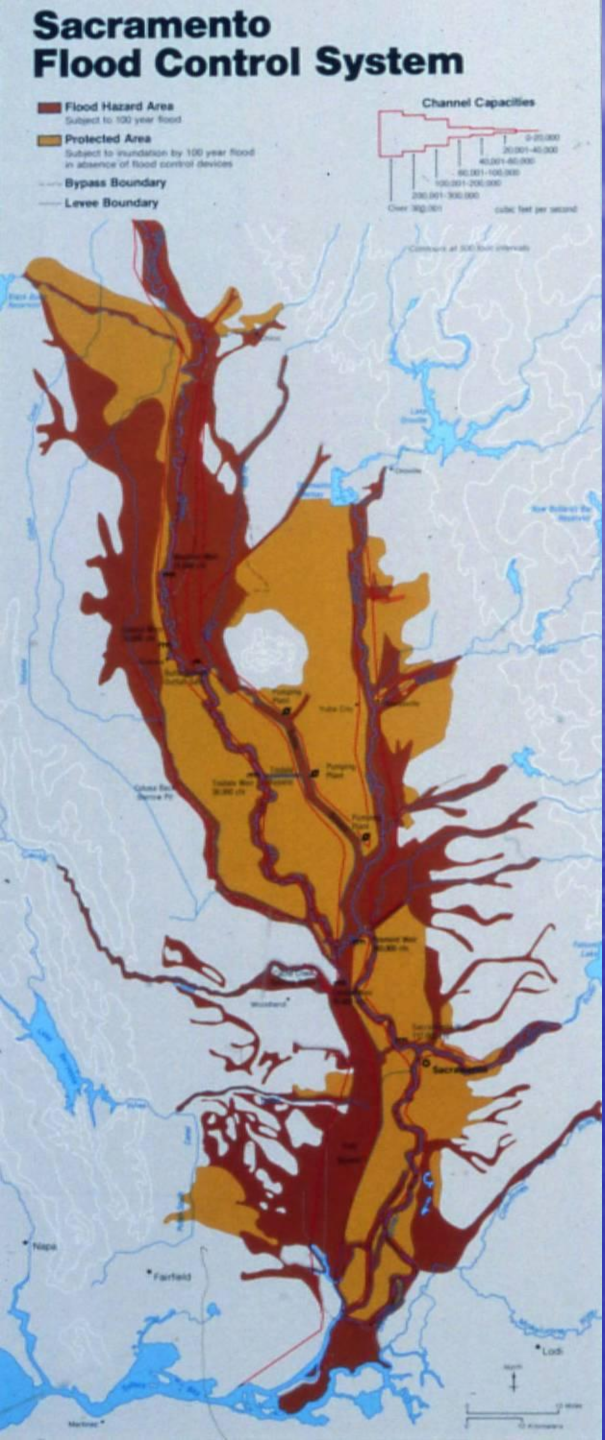


1966 AAA Map
Note City Dump



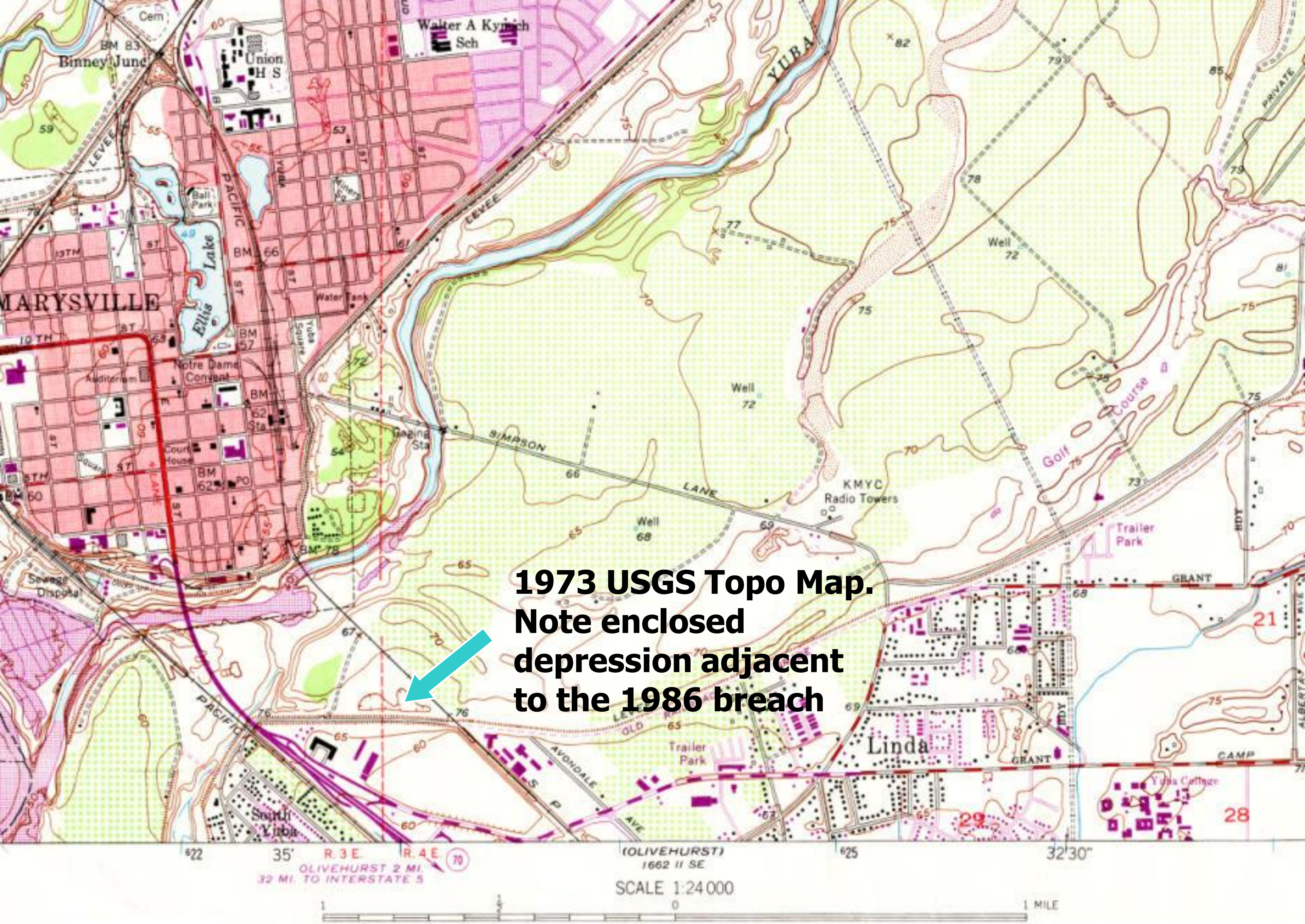
1966

- In the wake of the Dec 1955 and Jan 1956 floods, numerous improvements were carried out by the Corps of Engineers in 1960
- AAA Map shows a semi-stabilized low flow channel on the lower Yuba River
- Note training dikes in area of confluence with the Feather River



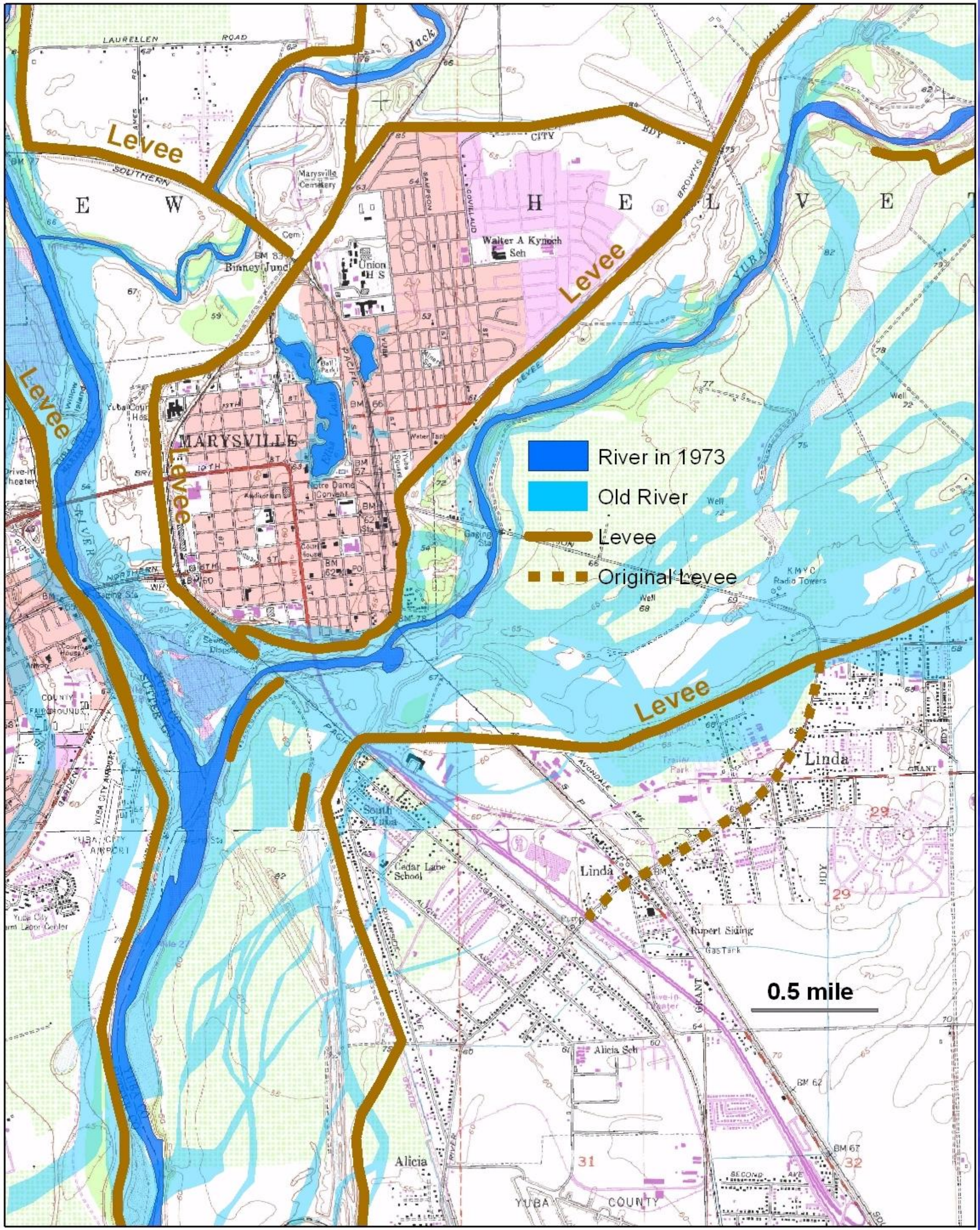
Sacramento Valley Flood Control System

- Developed by Carl E. Grunsky and approved by the California Debris Commission/Corps of Engineers in 1913; Constructed between 1914-60
- It employs earthen levees to protect populated areas
- It conveys excess flood waters through a system of **bypass weirs** that spill into large basins (shown in dark brown), limited to agricultural usage



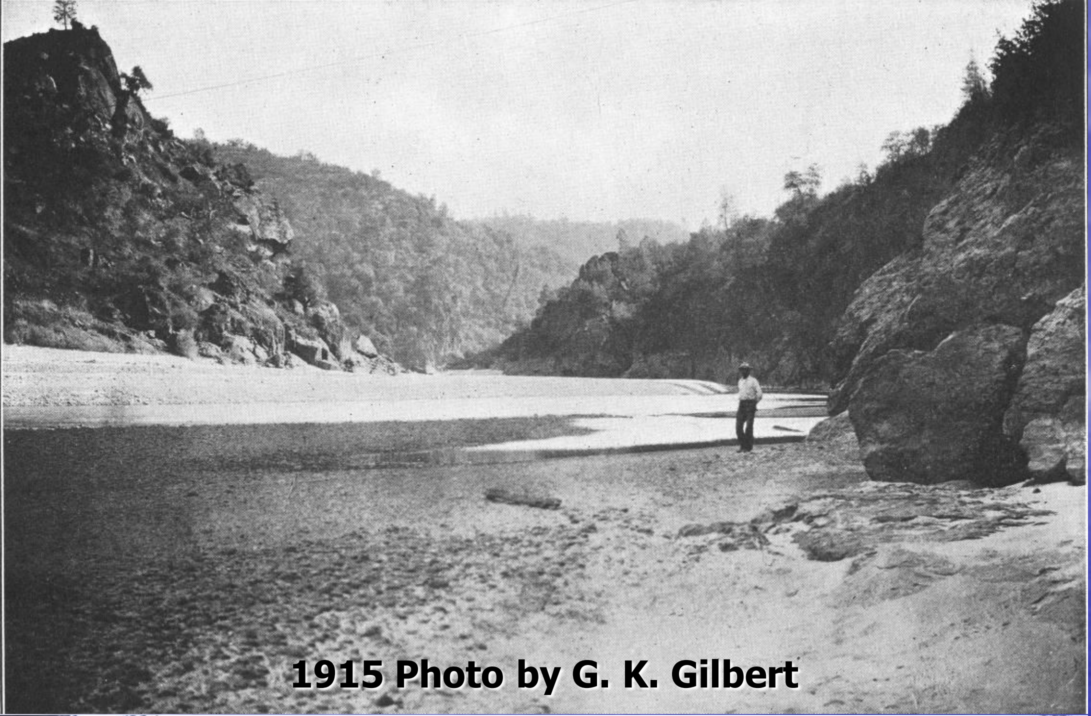
1973 USGS Topo Map. Note enclosed depression adjacent to the 1986 breach

1973



- **Taken from updated USGS 7.5 min topographic sheet**
- ***The low flow channel had now dropped 20 feet since 1900*, and was within 6 or 7 feet of its 1849 bed level**

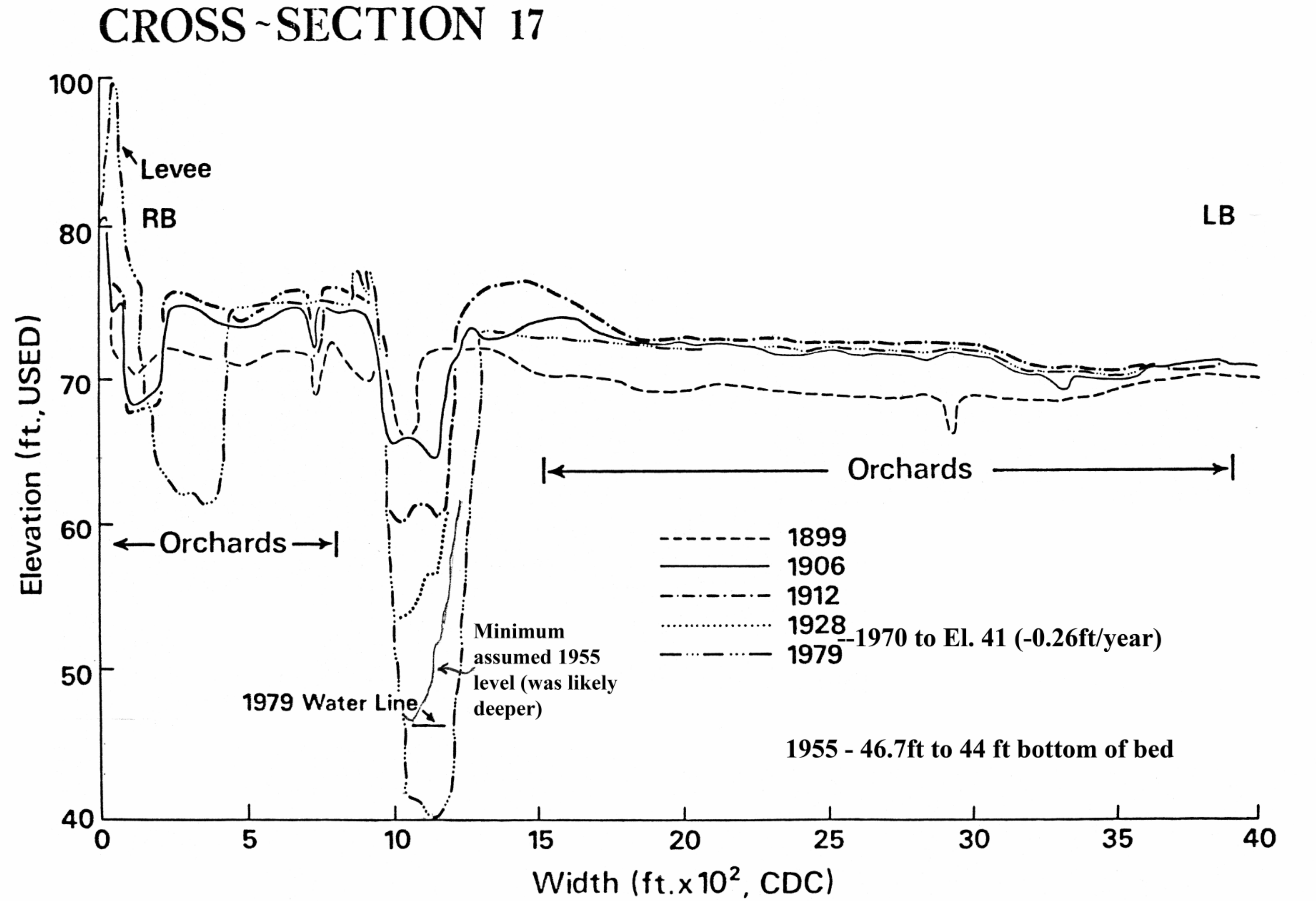
Downcutting channel = changing conditions



1915 Photo by G. K. Gilbert

1988 Photo by P. H. Rahn

- The Yuba River excavated its bed **80 vertical feet** at the Yuba Narrows, between 1915 and 1988, when these two pictures were taken.
- Rivers have a remarkable capacity to re-seek their equilibrium grade

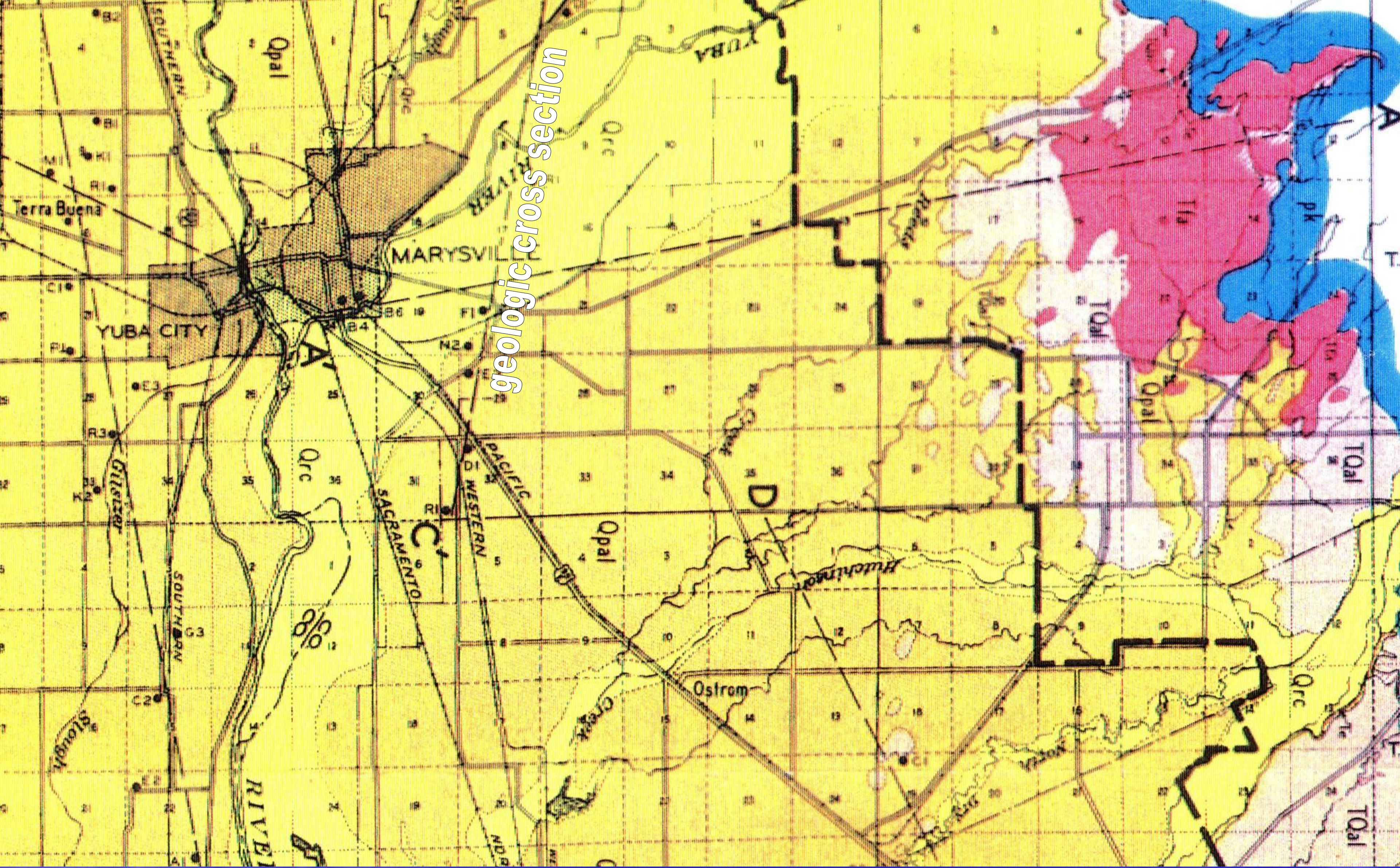


By 1983, the main stem channel of the Yuba River retrenched itself to its pre-1862 level, as shown here. Orchards were planted on the mine slickens (silt).

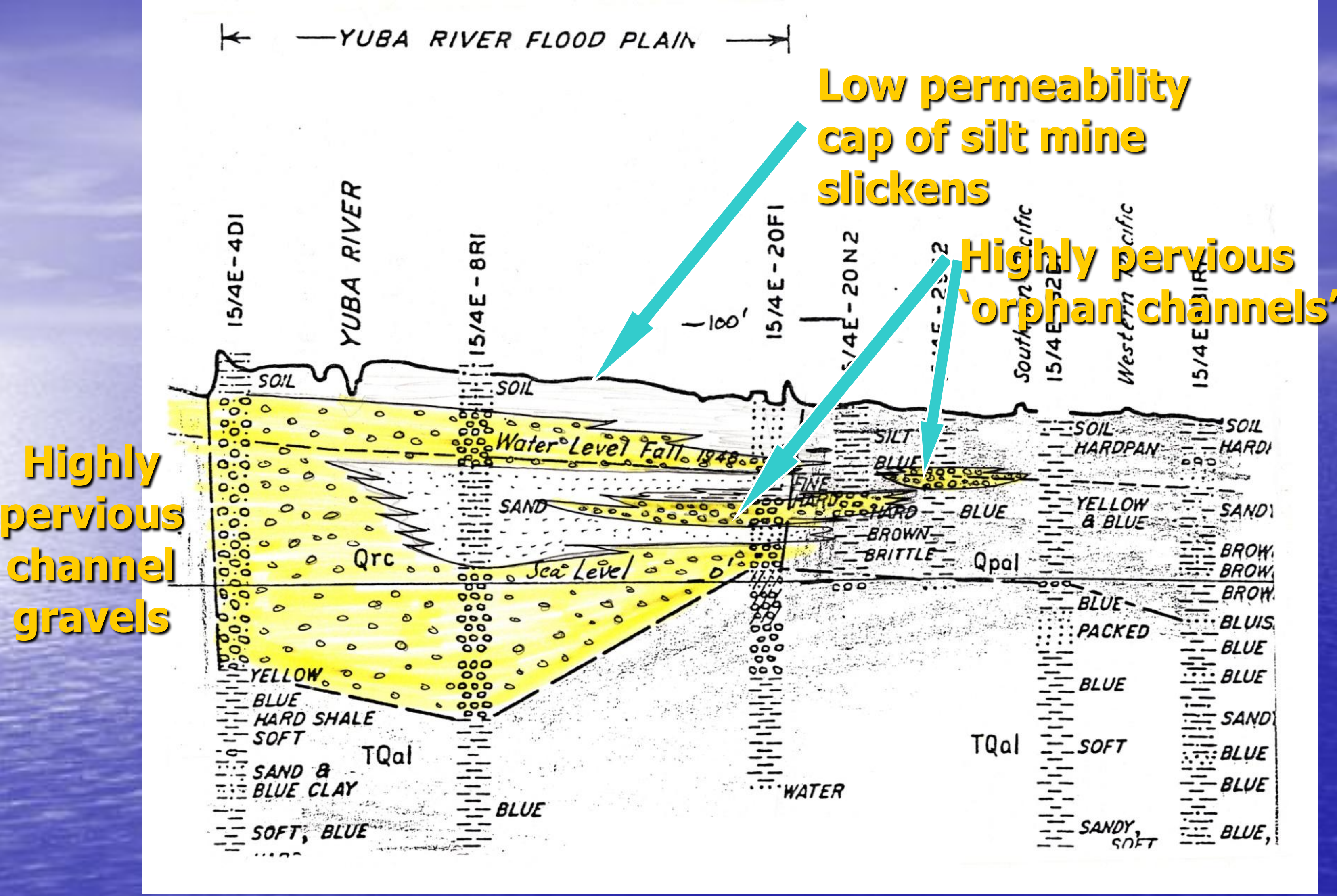
The Southern Pacific Railroad constructed their line across the Yuba River in 1872, followed by the Western Pacific in 1909, and Sacramento Northern in 1914.

As the channel excavated its bed downward, the bridge supports had to be retrofitted to accommodate to increased height of the bents.

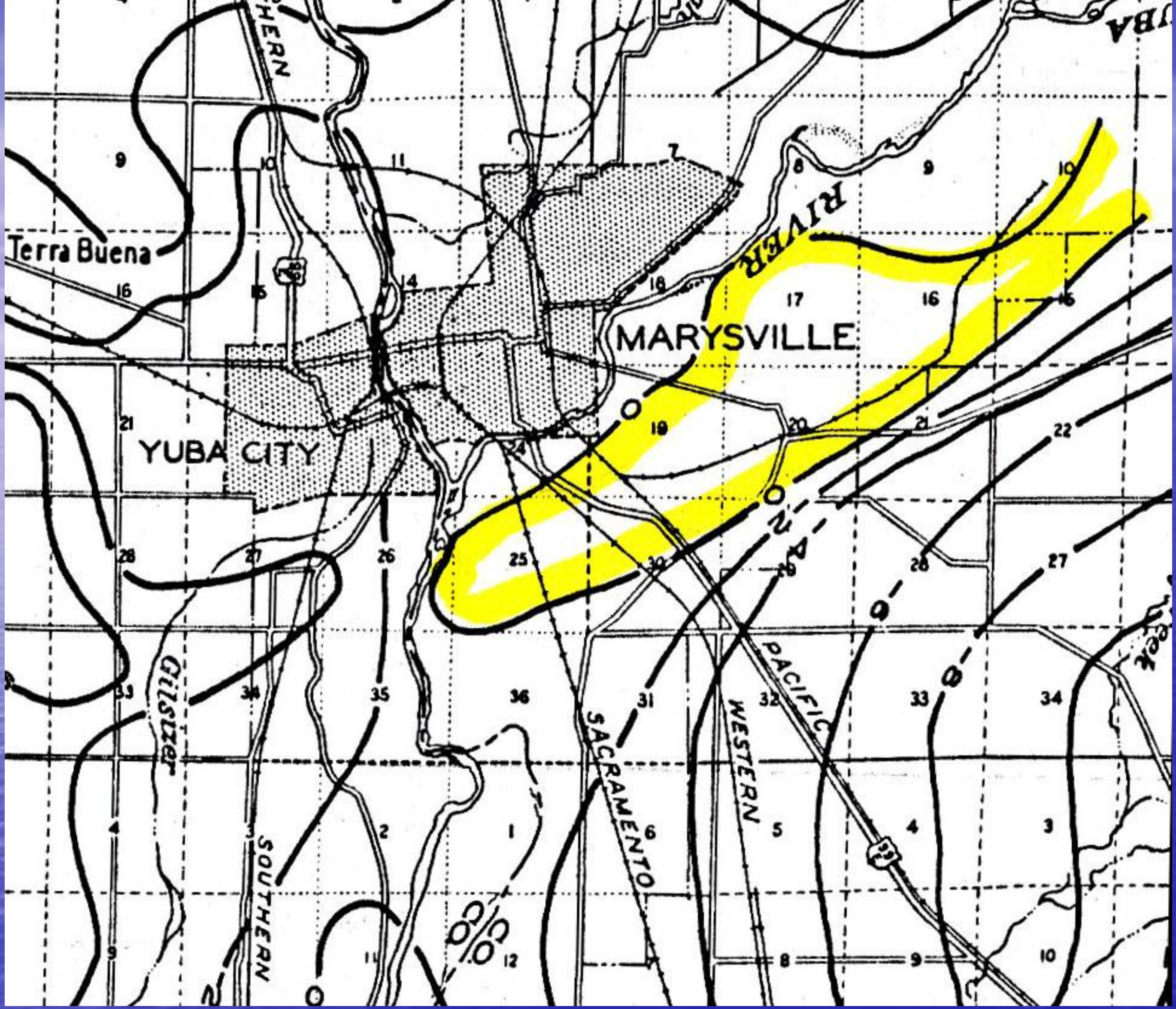
INSIGHTS ON SITE CHARACTERIZATION – examining the published literature



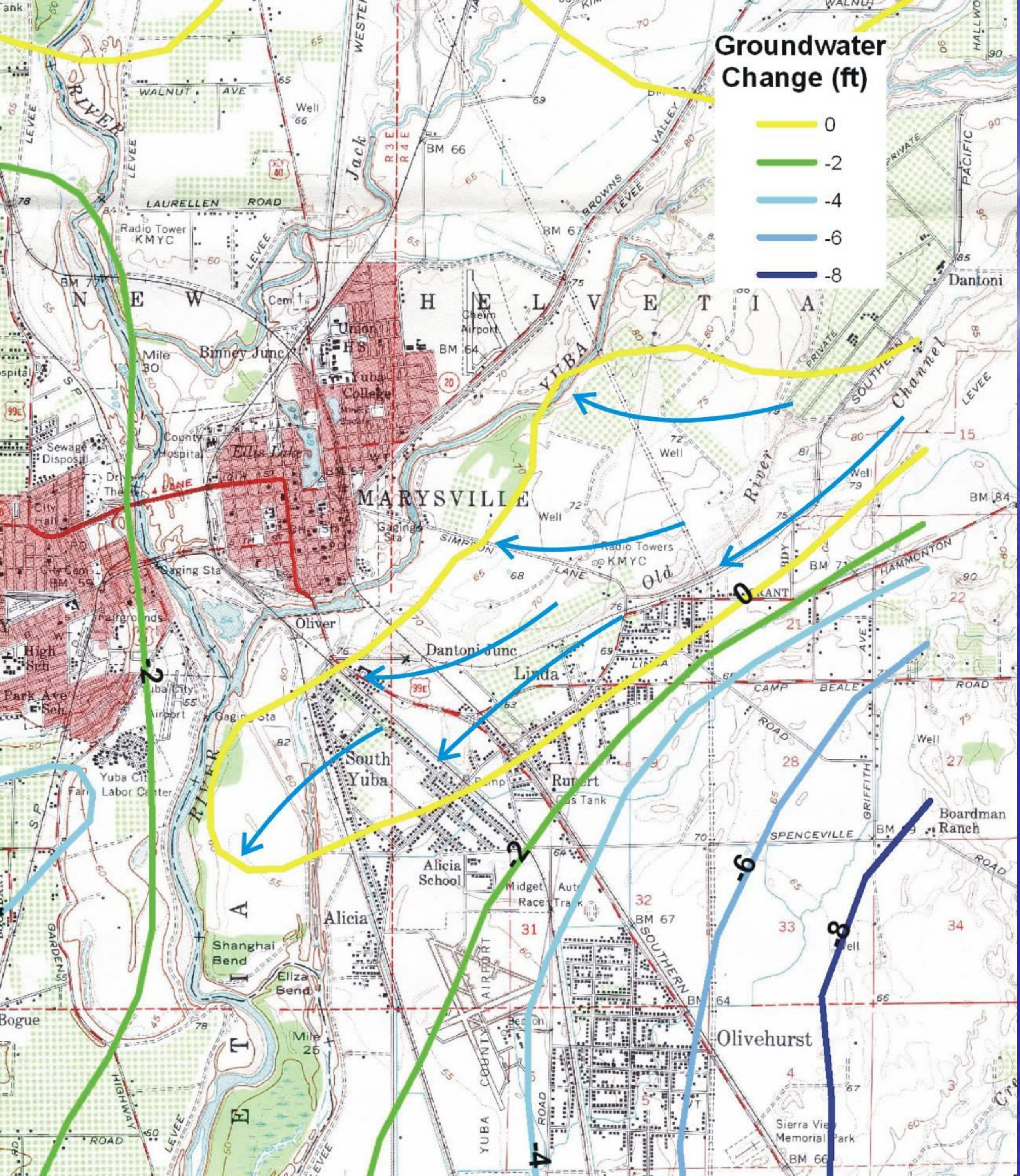
- **Geologic Map from California State Water Resources Board Bulletin 6, Sutter-Yuba Counties Investigation, released in 1952.**



- **Our interpretation of the well logs along a section through the lower Yuba River, about three miles upstream of its mouth (from Bulletin 6). Water levels were rapidly declining along the south (right) side of the flood plain in the late 1940s. The farmers were drafting water from the channel gravels.**

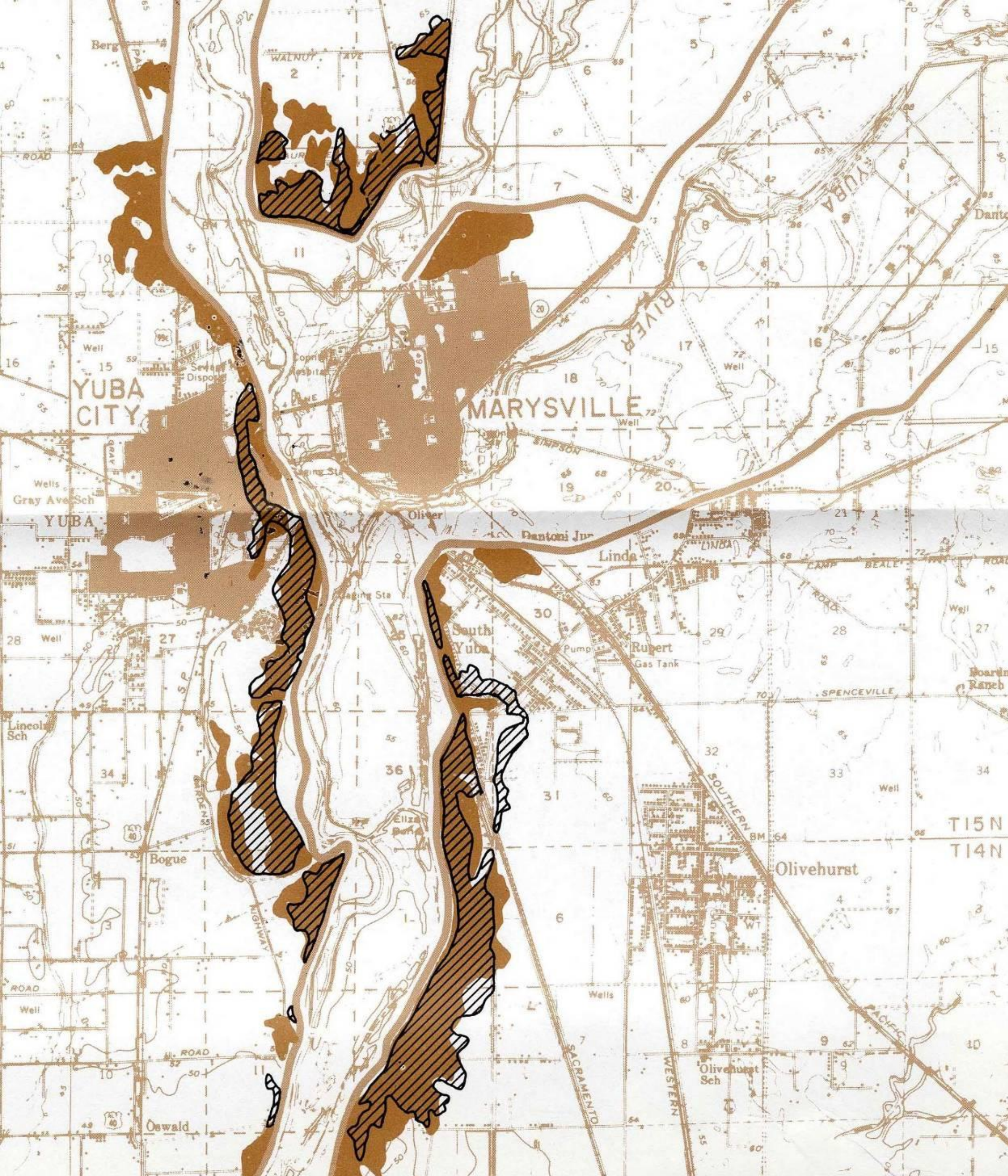


- **Contours illustrating falling groundwater table adjacent to the Lower Yuba River, between 1947-51.** ***Yellow denotes zone of no change; suggesting active recharge.***



Inferences on recharge

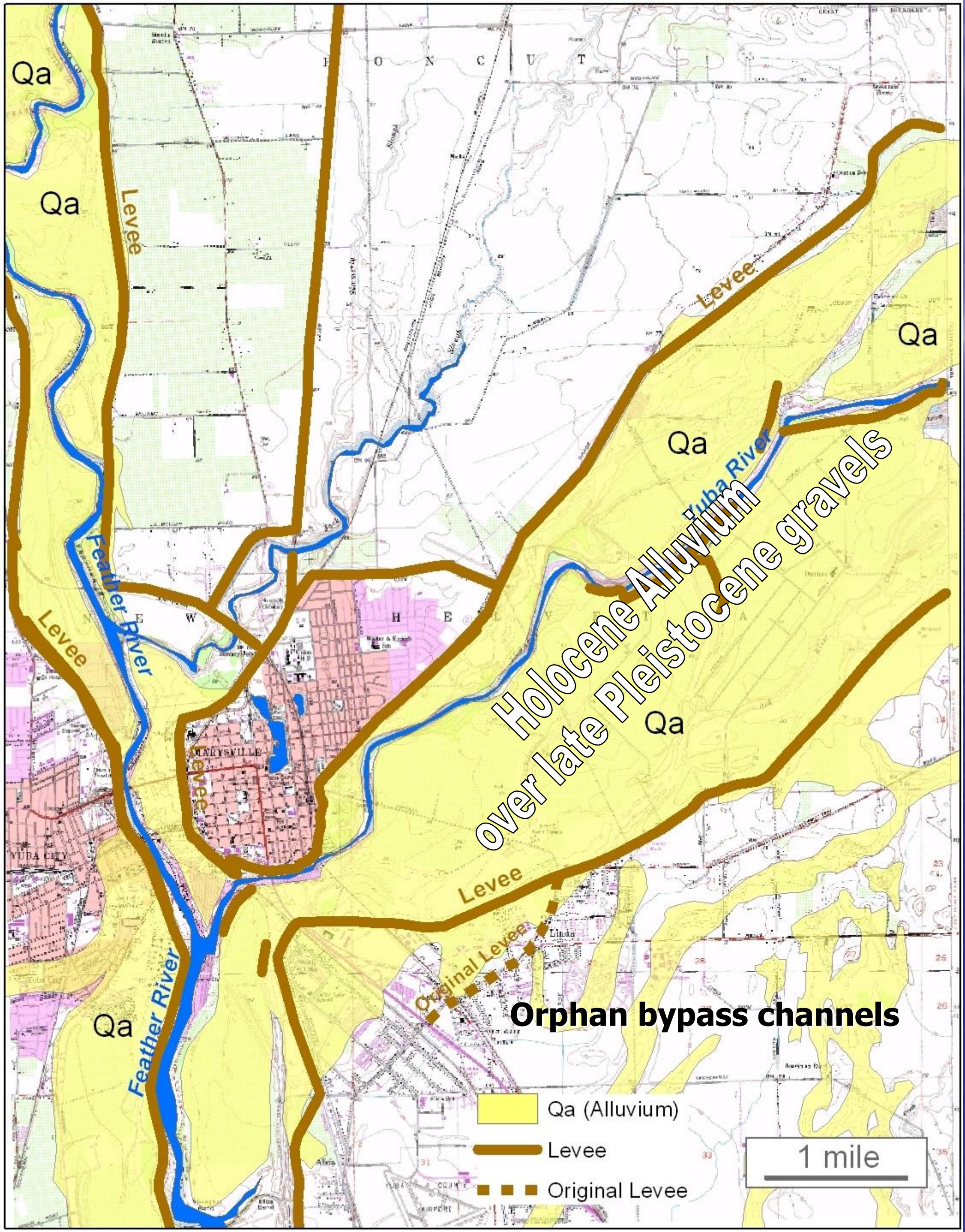
- The water well data tells a consistent story about how the Yuba River recharges the local groundwater table
- Note directions of seepage, to the southwest



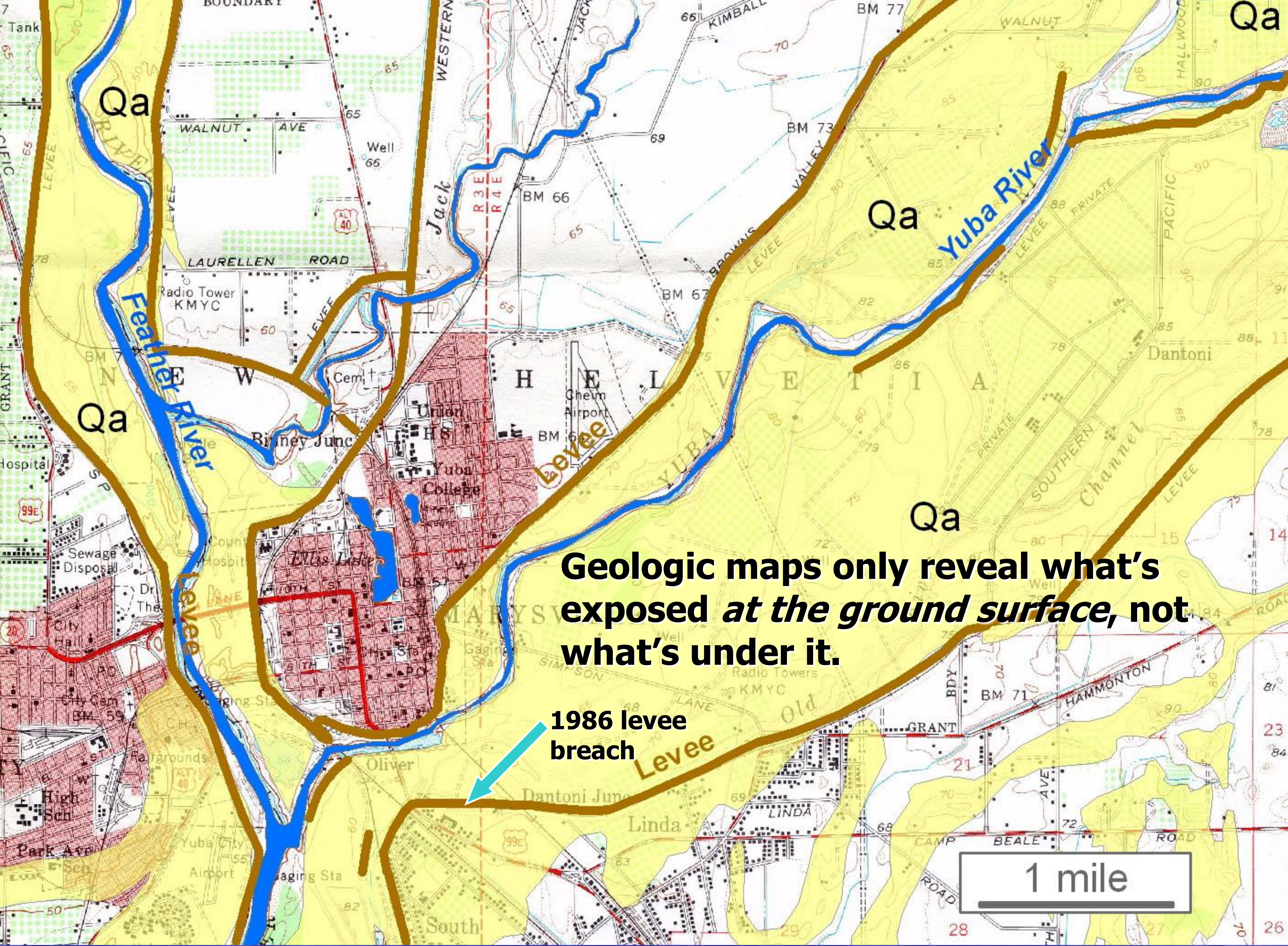
1967 seepage study

- **Prepared by the Corps of Engineers**
- **Note wet area along the protected side of Linda Levee, which failed 19 years later, in 1986**
- ***Proximity to the late Pleistocene gravel channels and Holocene sand channels drives seepage problems.***

Second Generation Geologic Map

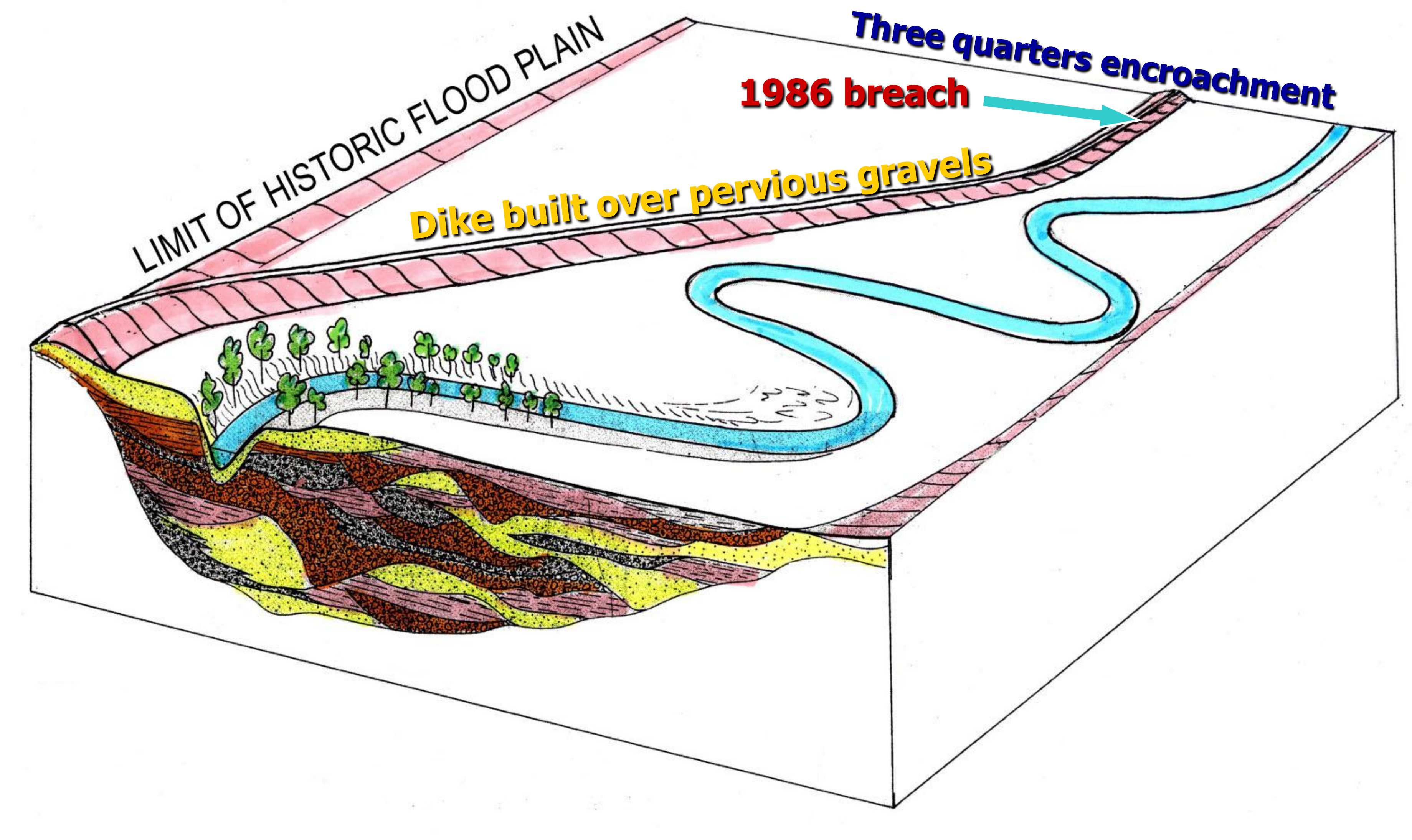


- **Excerpt from geologic map prepared by Helley and Harwood of the U.S. Geological Survey in 1985.**
- **Note encroachment of the flood plain by the Linda Levee, shown as thick brown line**
- ***Note "orphan" bypass channels on land side of the Linda Levee***



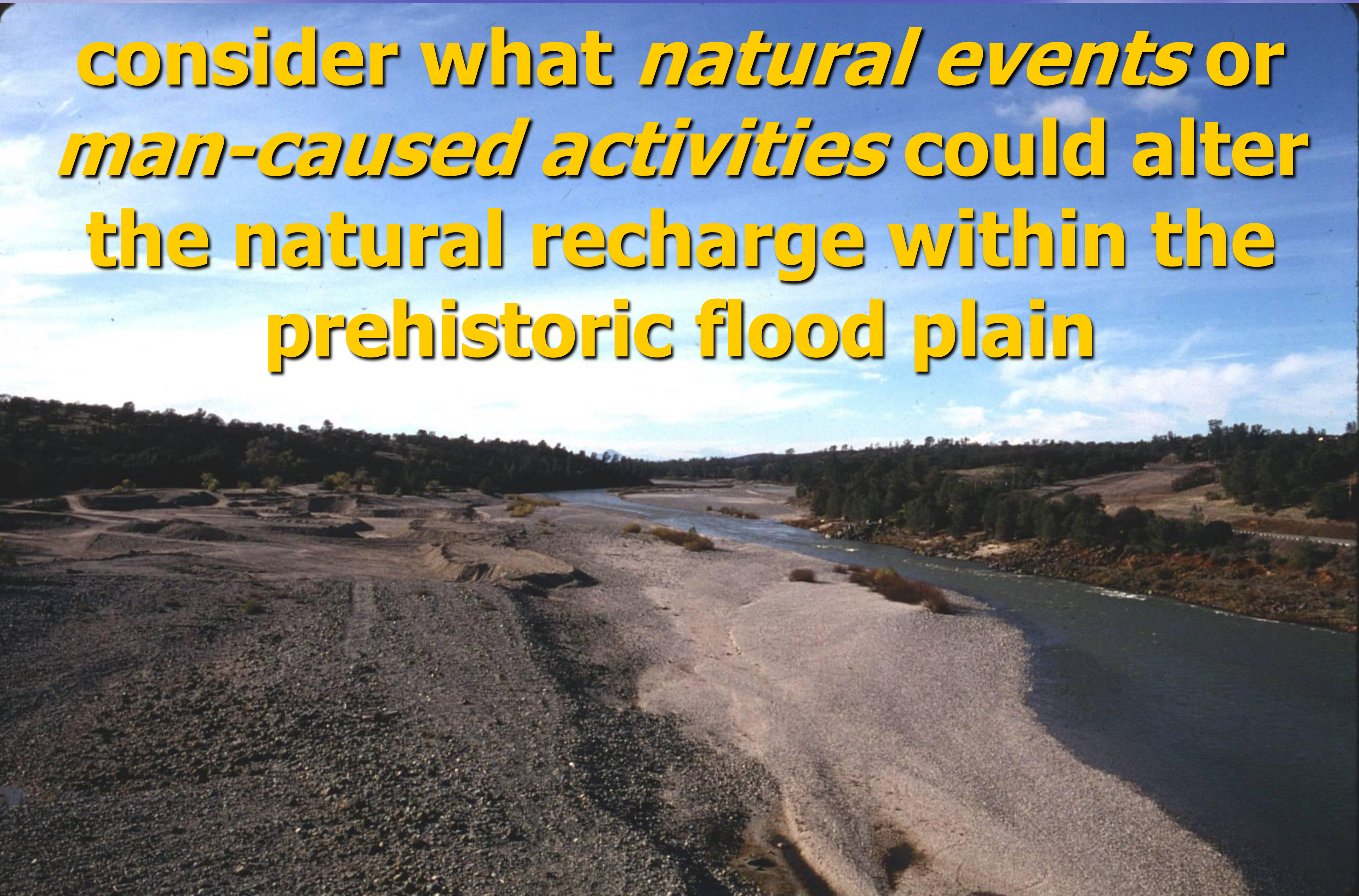
Geologic maps only reveal what's exposed *at the ground surface*, not what's under it.

Good Site Characterization should consider the *geographic position* on the prehistoric flood plain



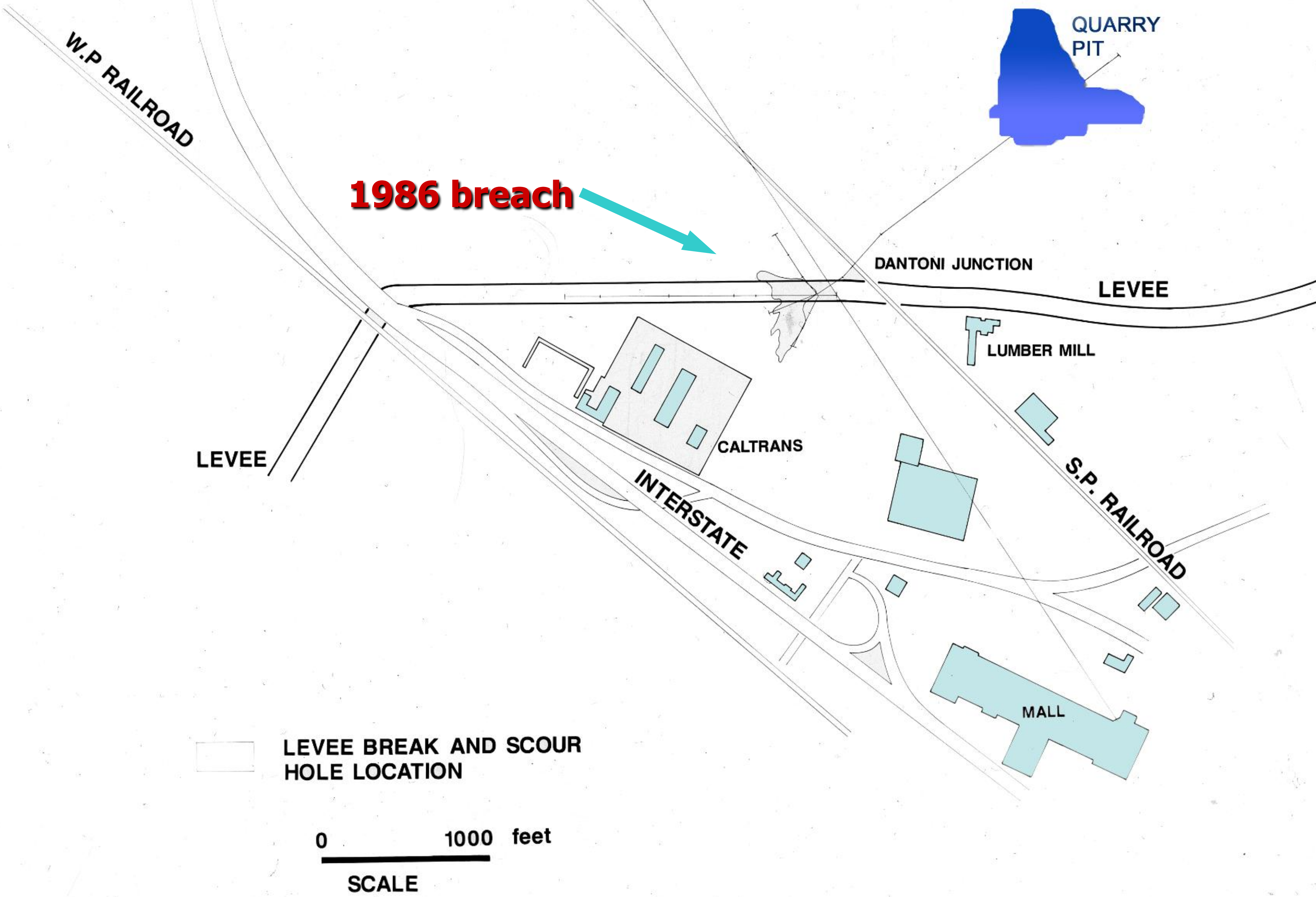
- The original protective dike graded in 1873 was along the southern margins of the Yuba River's *modern flood plain*. The Morrison Grade completed in 1904, and heightened in 1936 and 1940, <u>encroached *three quarters of the river's flood plain*</u>*, as depicted here.*

Site Characterization should also consider what *natural events* or *man-caused activities* could alter the natural recharge within the prehistoric flood plain




Speckert gravel pit established in the Yuba River channel in 1973
pit
SPRR Viaduct and dike
Linda Levee
Linda Levee

Proximity of the Speckert Gravel Pit begun in 1973 to the Linda Levee Failure in 1986

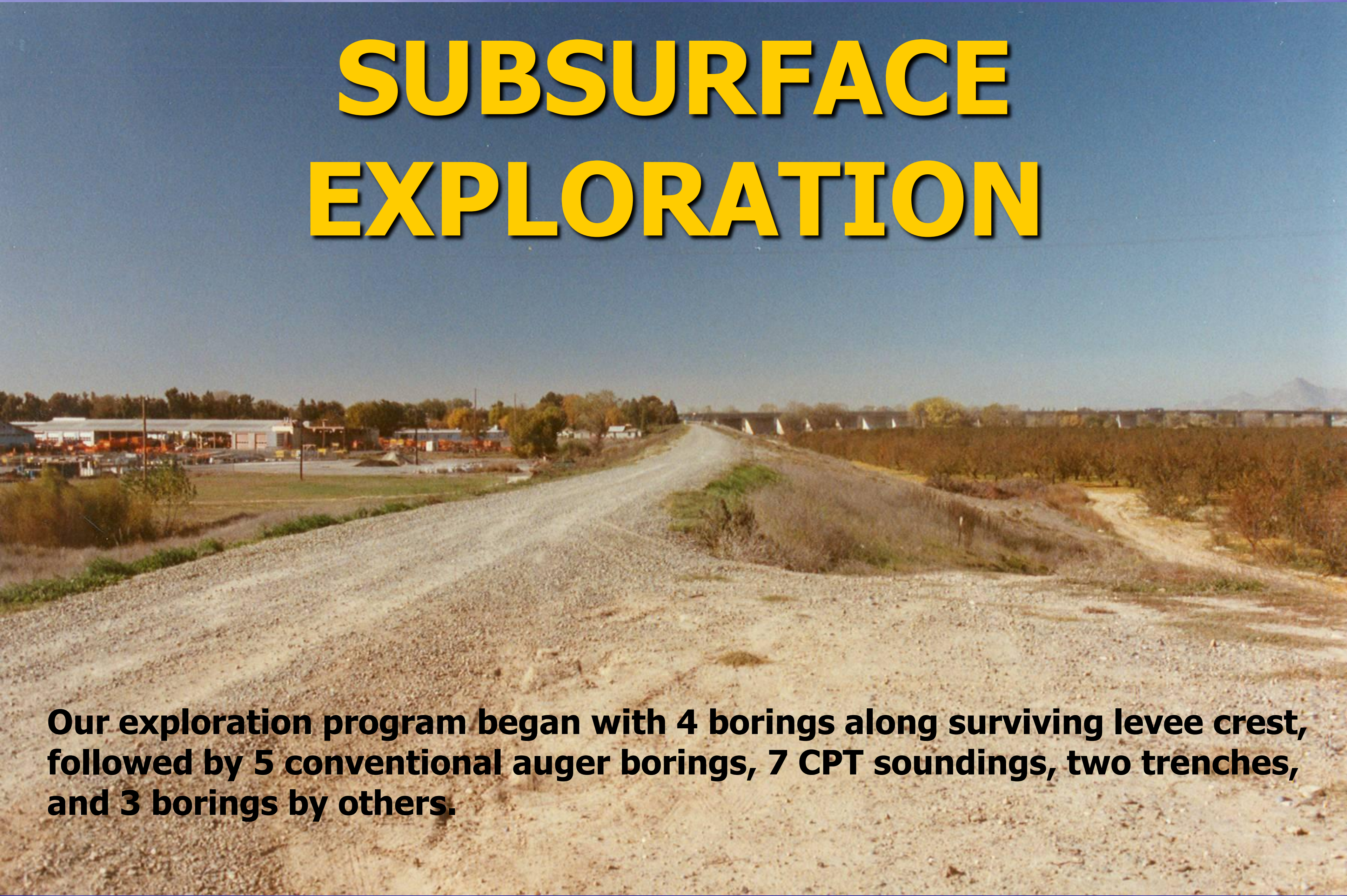


Speckert Pit

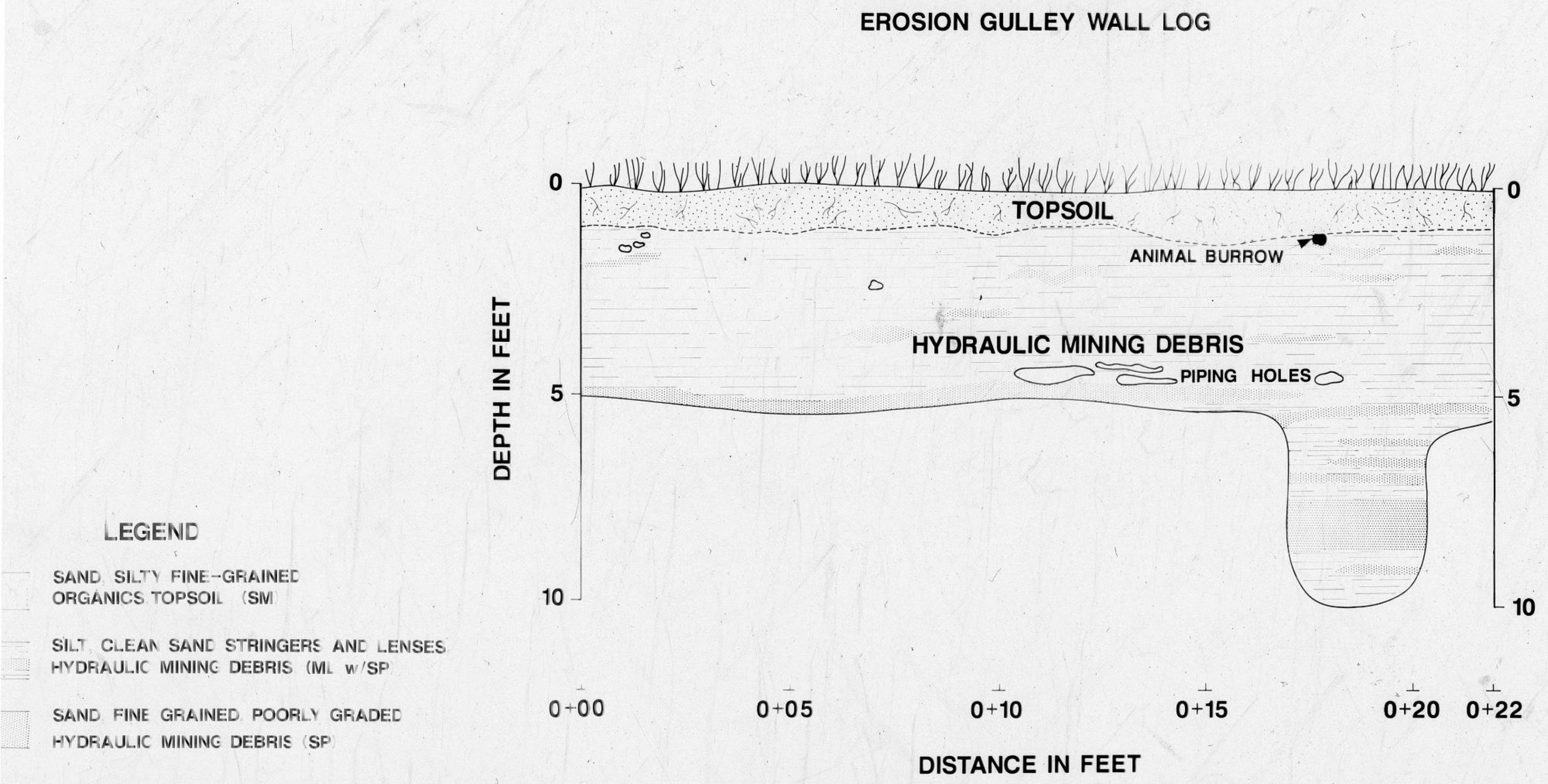
In-stream mining can pose a threat to adjacent levees if they pierce *conductive materials* (gravels) and are subject to inundation during floods

The Speckert Pit pierced a veneer of gravelly Holocene sands and mined the late Pleistocene cobble gravels, to depths of 37 feet.

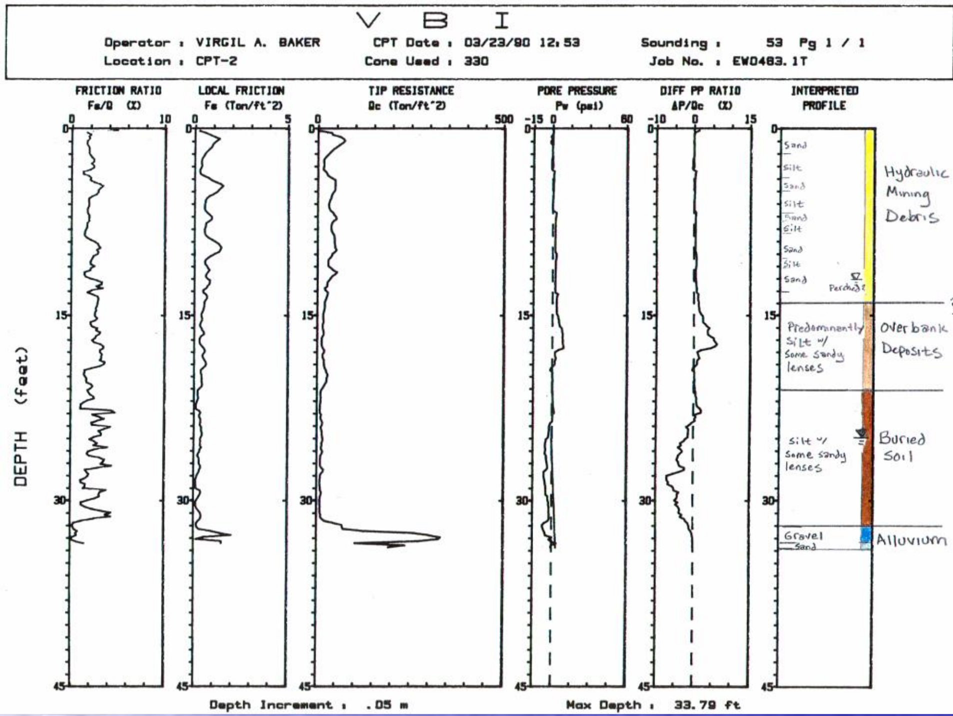
SUBSURFACE EXPLORATION

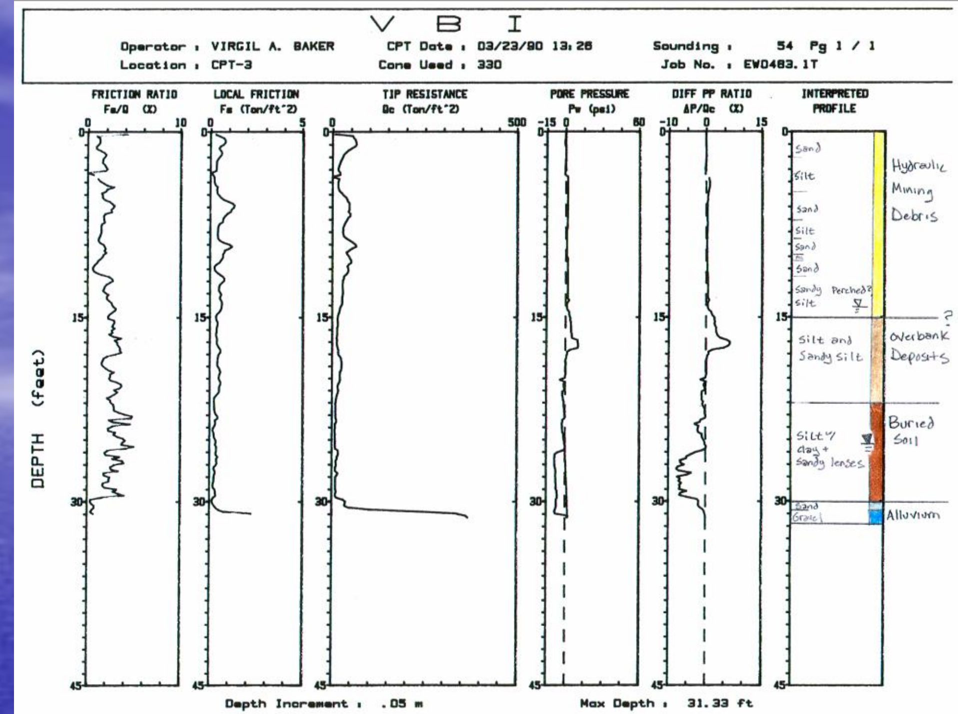


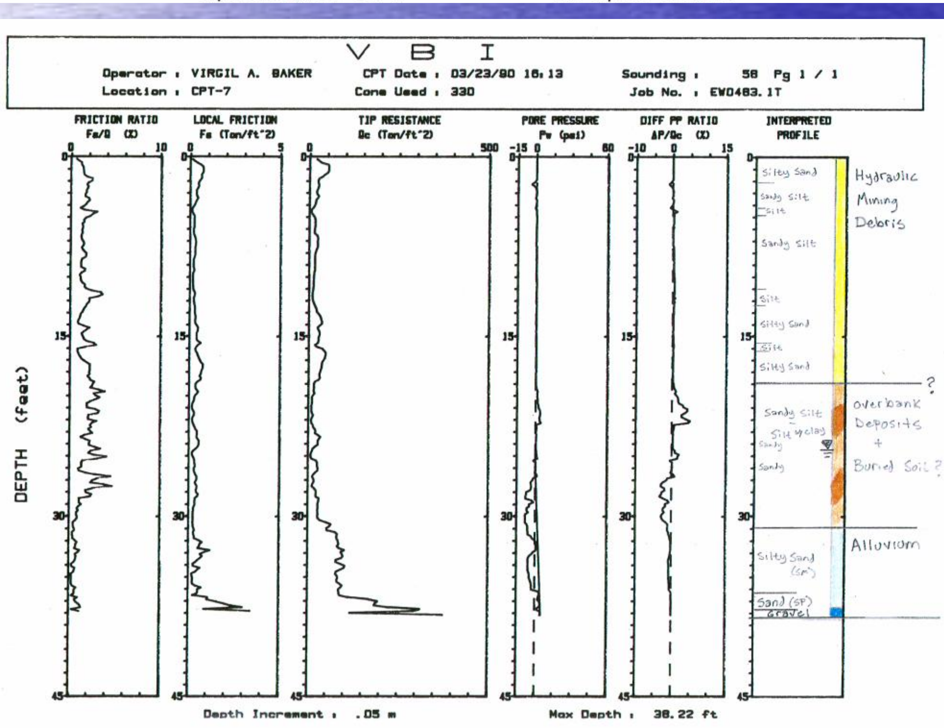
Our exploration program began with 4 borings along surviving levee crest, followed by 5 conventional auger borings, 7 CPT soundings, two trenches, and 3 borings by others.



- Our site exploration began with a series of trenches along the bounding walls of the channel scoured by the breach outflow. It is important to SEE the stratigraphy in its natural setting BEFORE engaging in subsurface sampling, whenever possible.







CPT logs can be very useful for analyzing *discrete horizons*, *zones of saturation*, and unraveling subsurface stratigraphy; to ascertain the *continuity* of various units. Errant crosshole correlations are a common problem in geotechnical engineering.

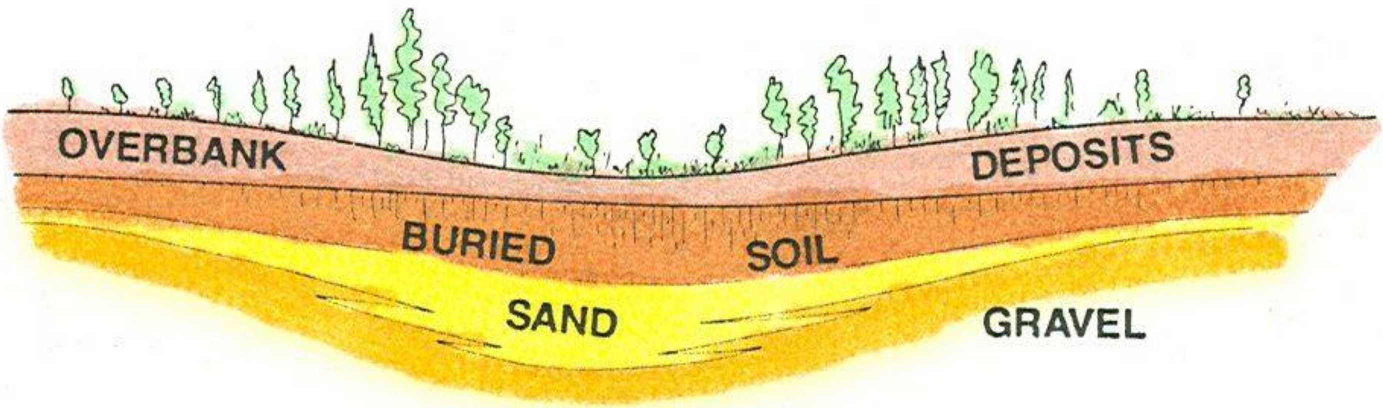
B-3 and B-4

- **The borings encountered mine slickens over a vibrant paleosol marker, over channel sands, over coarse granitic gravel and cobbles**

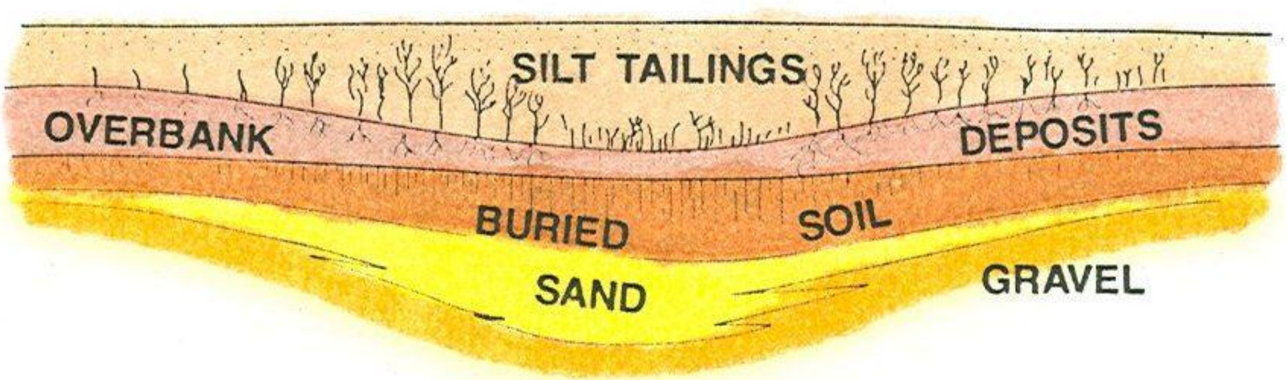
- ***The stratigraphy always leaves a distinctive fingerprint;*** **testifying to the depositional history at any given site**

- **The following slides summarize what we learned about the foundation underlying the 1986 levee breach at Linda**

LIKELY FLOODPLAIN CONFIGURATION AROUND 1849

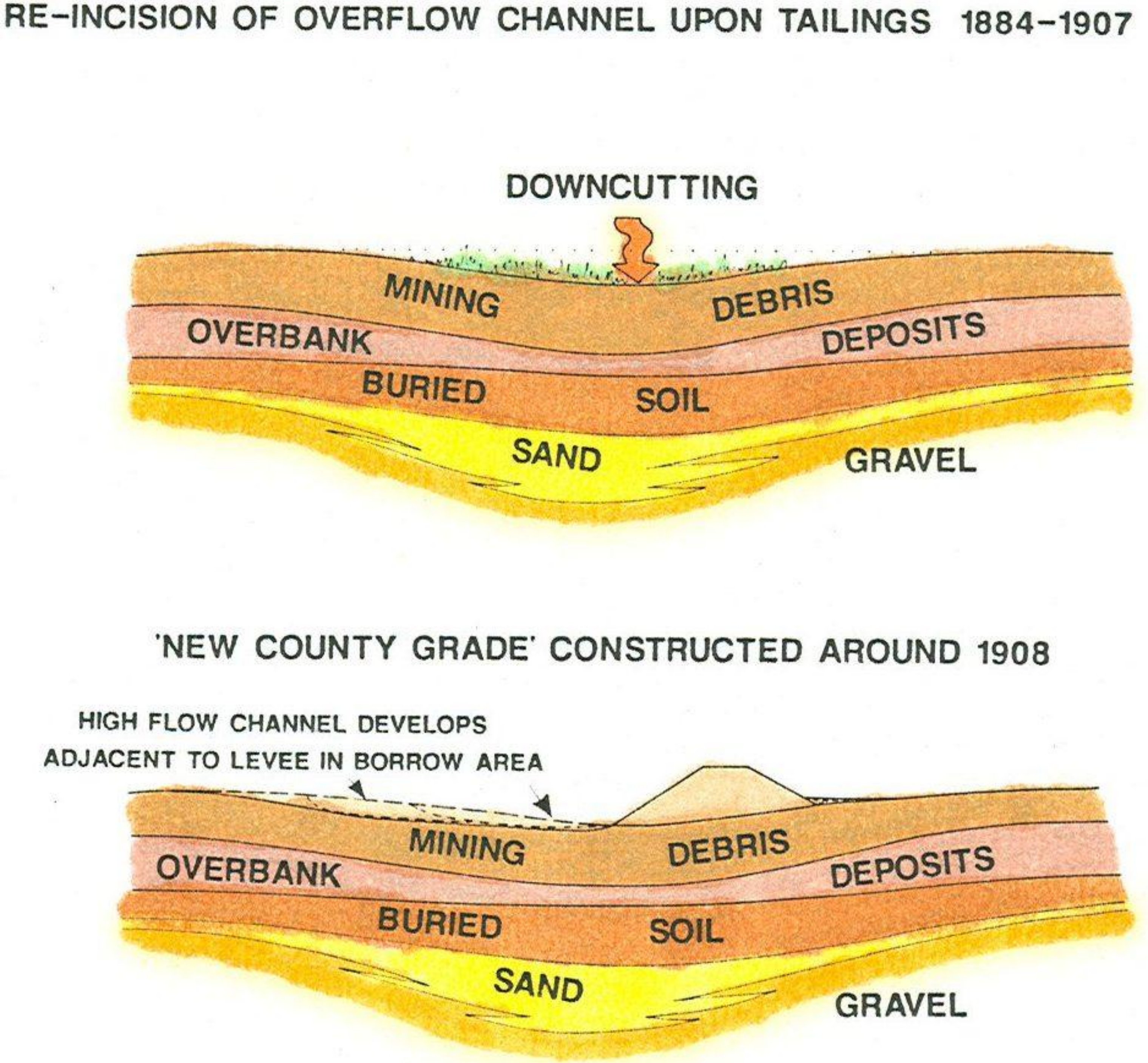


DEPOSITION OF MINE TAILINGS 1860 TO 1884



1849 to 1884

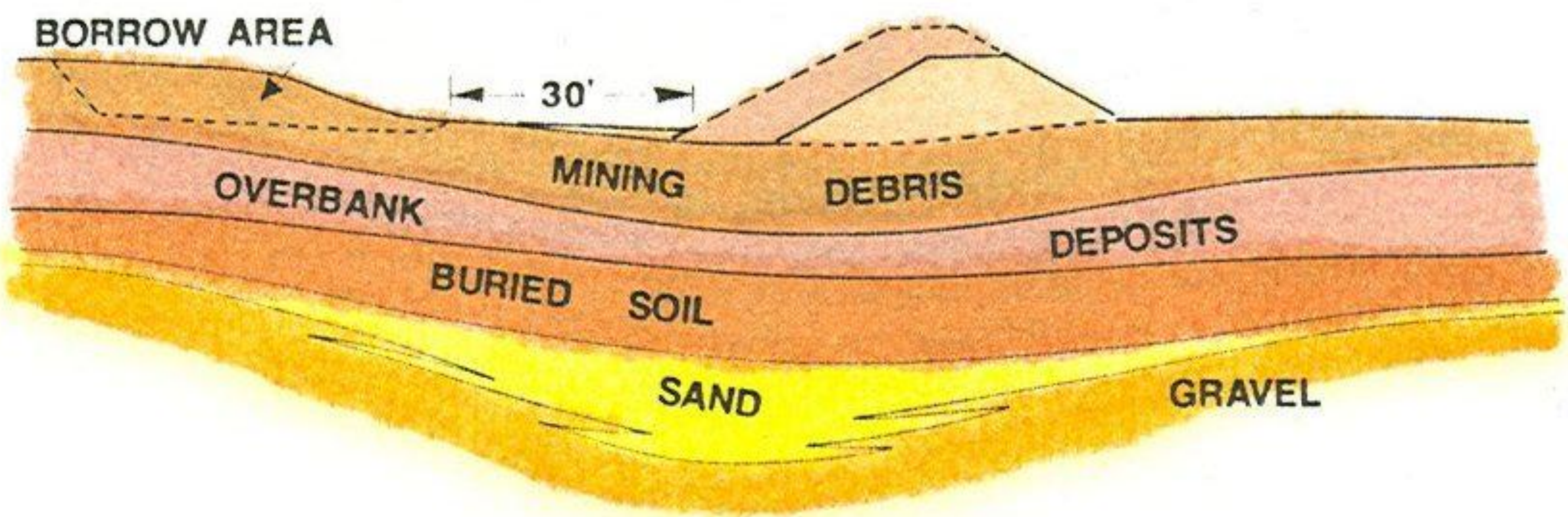
- **The pre-1849 flood plain was inundated by silt tailings from 1862 till at least 1884**
- **Note axis of swale, beneath breach area**



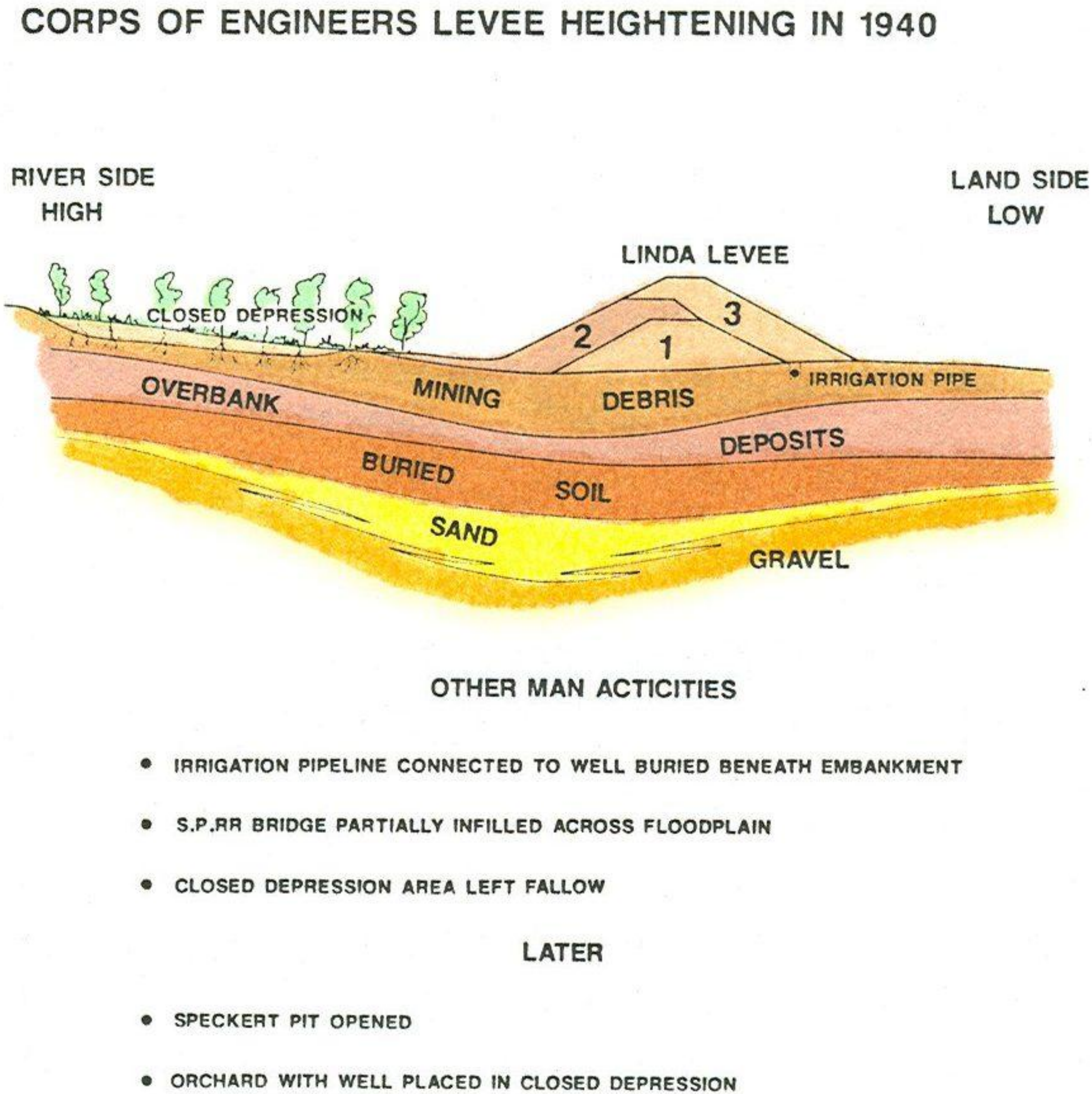
1884 to 1908

- The **mine slickens** were reworked several times by major floods, then used as fill for the original levee in 1904

CONSTRUCTION OF THE MORRISON GRADE IN 1936



- The **Morrison Grade** was heightened in 1936, using borrow material from the river side of the embankment.



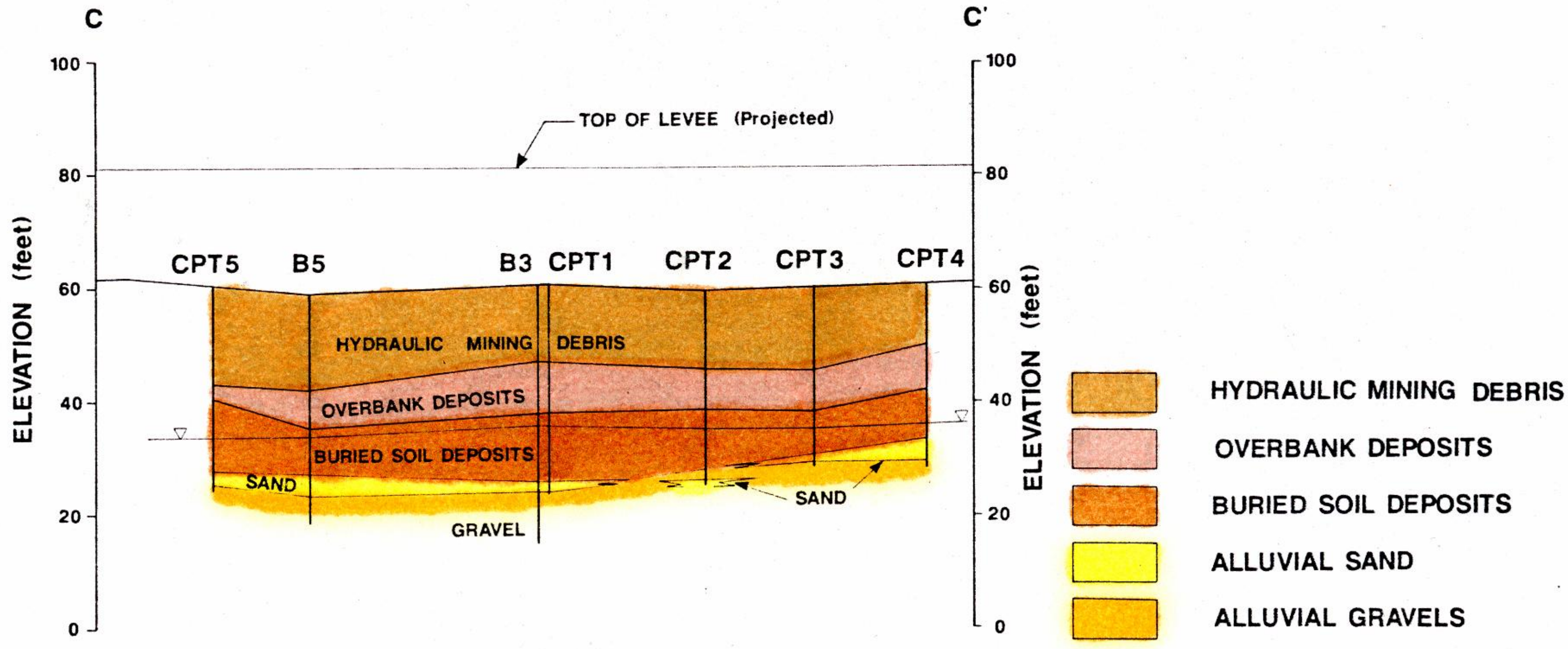
1940

- The Corps of Engineers raised the Morrison Grade a third and final time in 1940

HOW MANY CROSS SECTIONS SHOULD WE CONSTRUCT TO ANALYZE A LEVEE ?

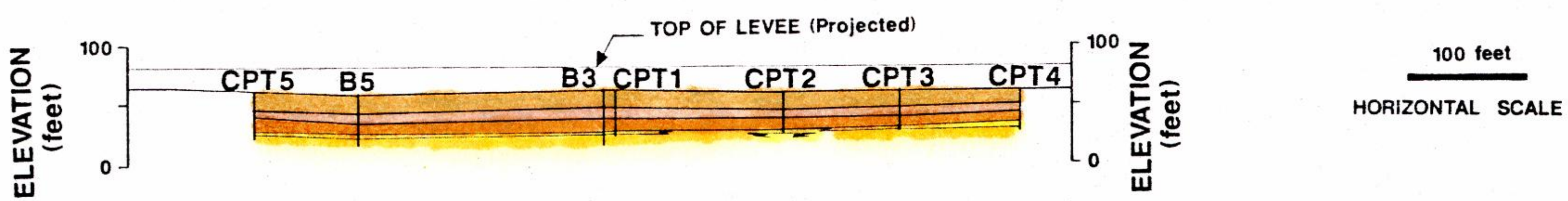
ROGERS/PACIFIC CROSS-SECTION C-C'

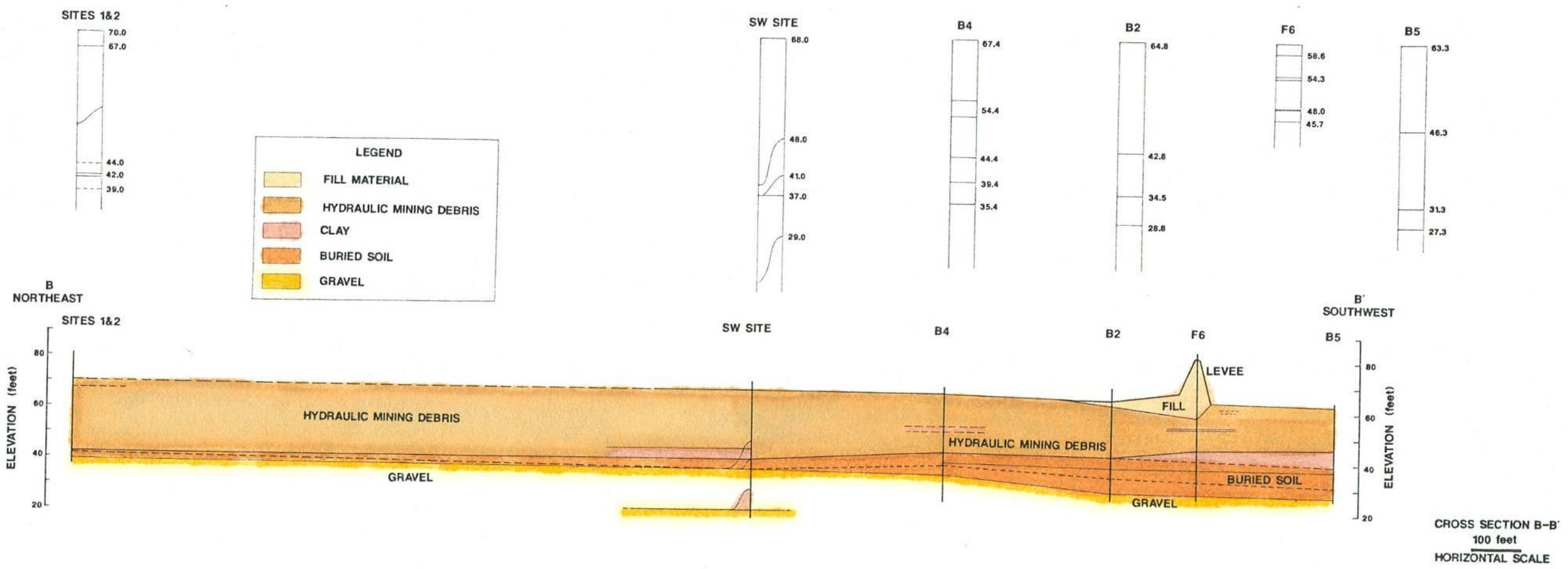
EXAGGERATED VERTICAL SCALE



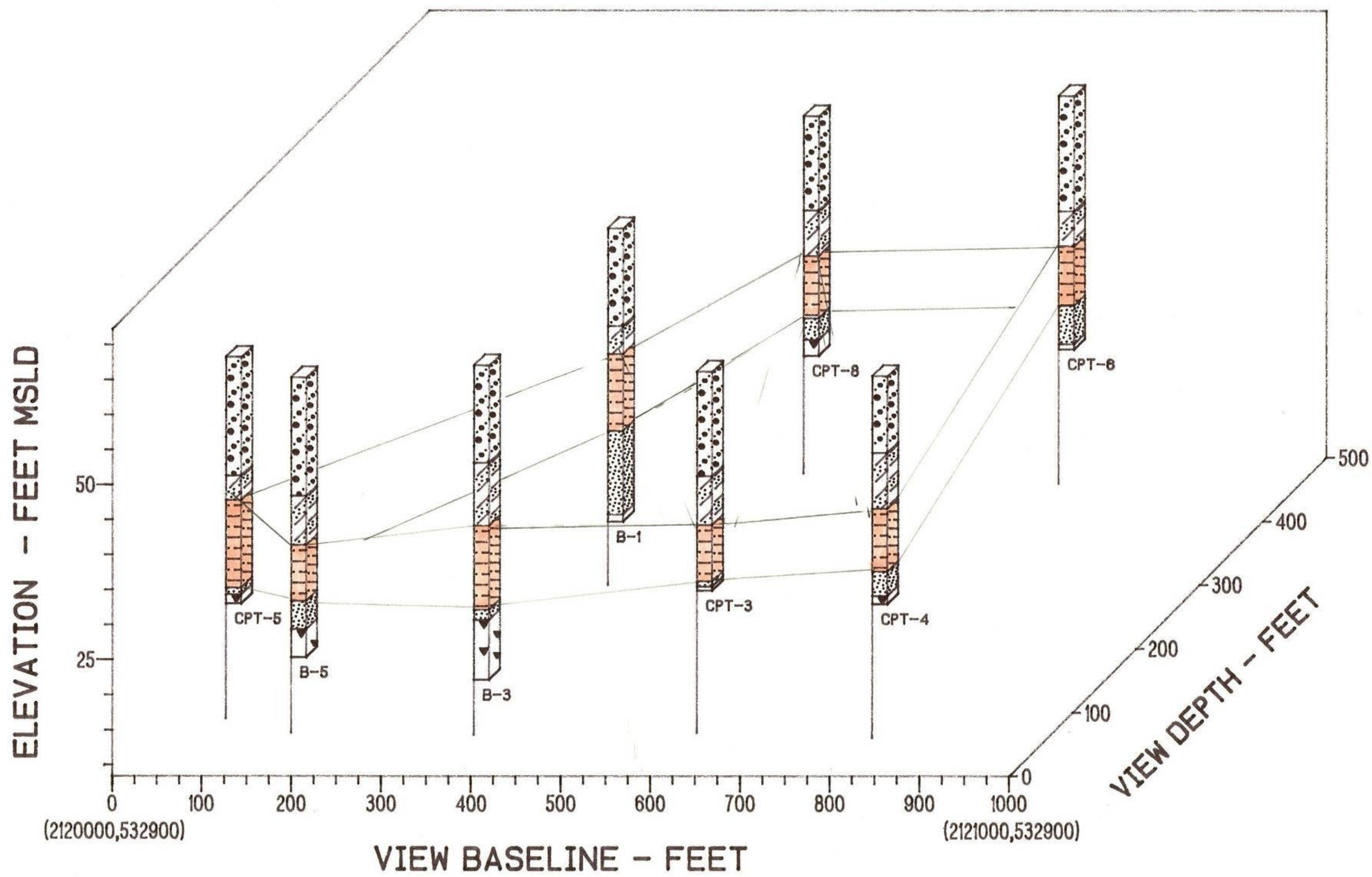
The underlying units appear as rather ordinary layers in this section, parallel to the axis of the failed levee.

ACTUAL VERTICAL SCALE

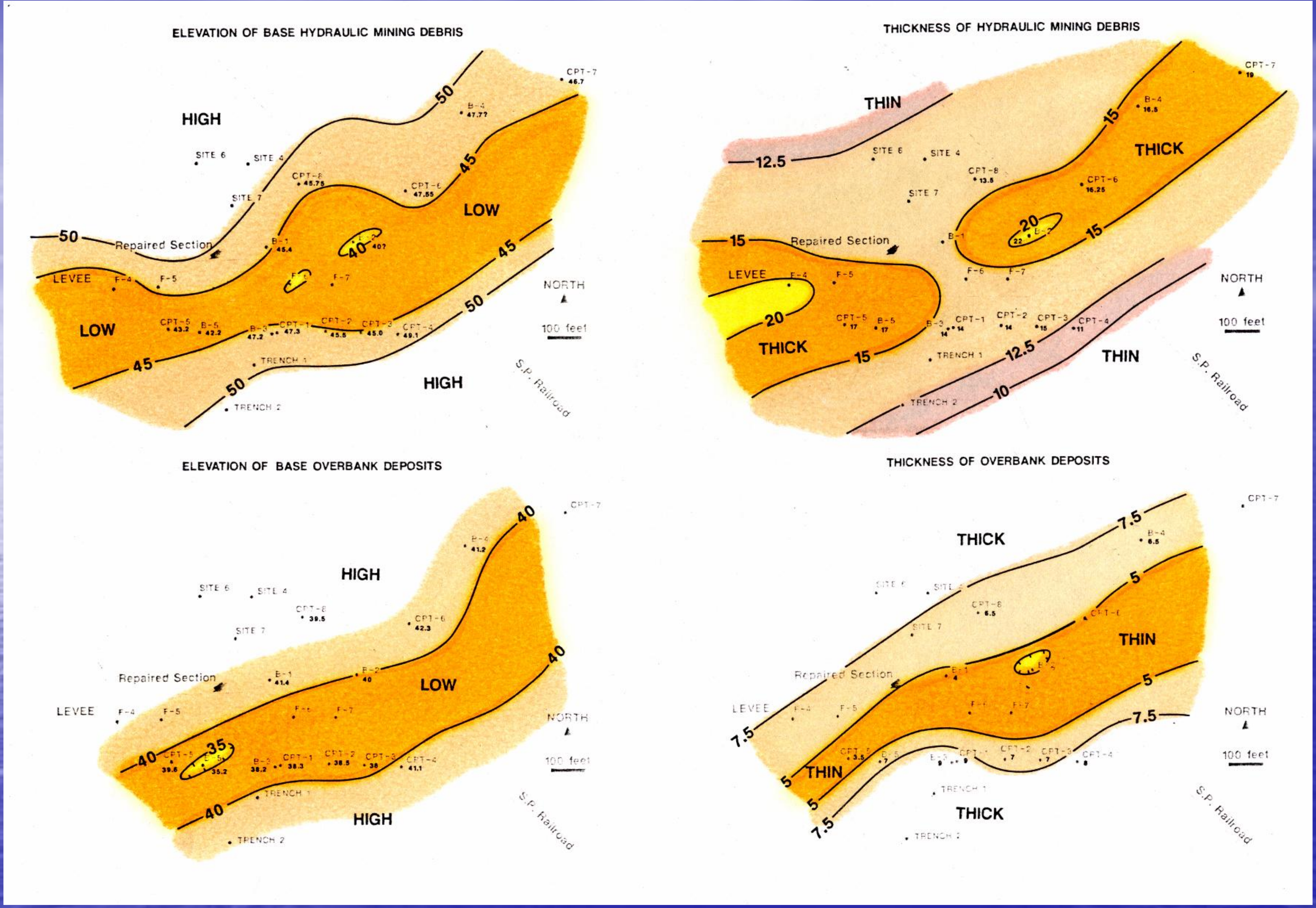




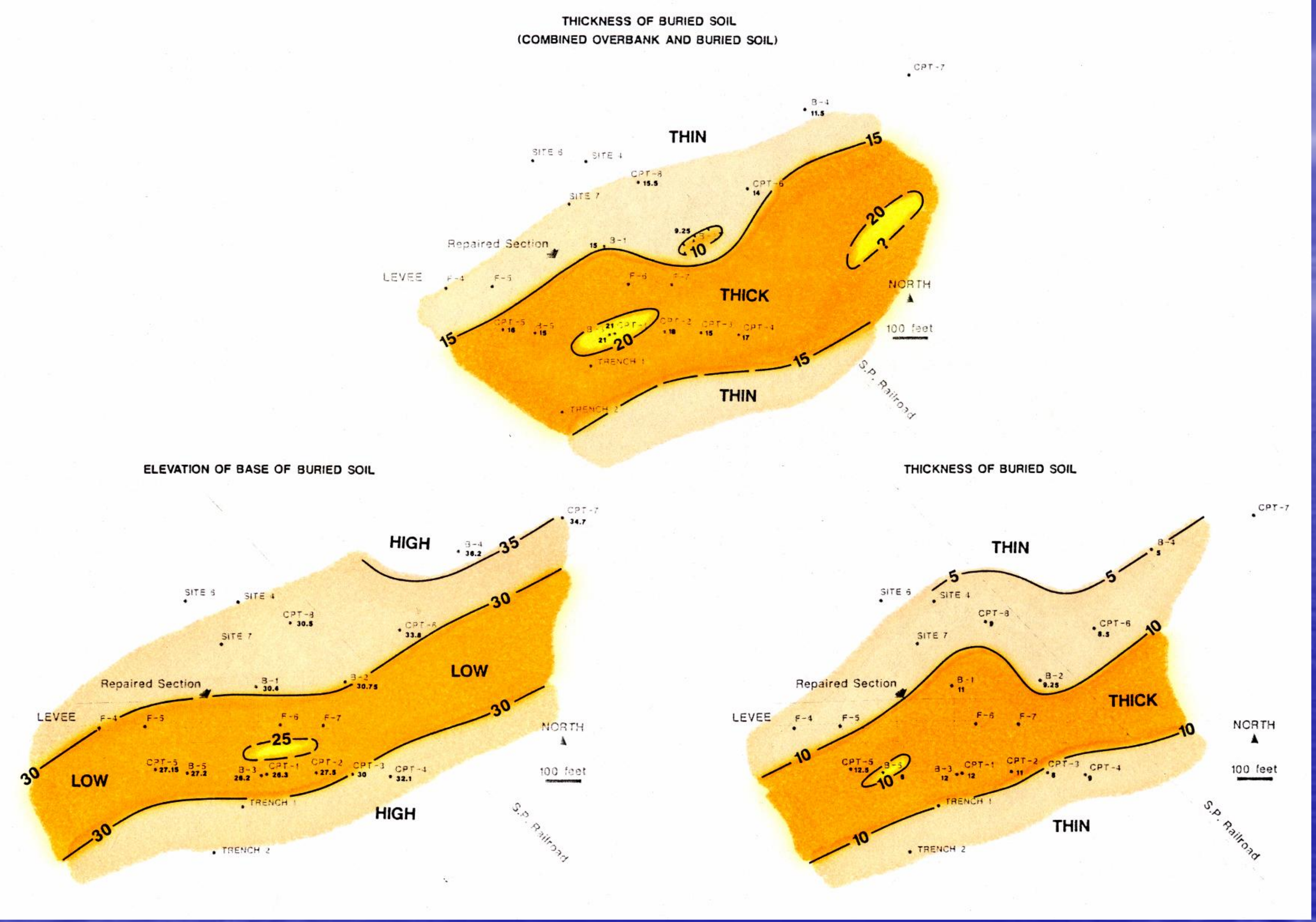
- **Section B-B' extends from the breach area northwest, towards the main stem channel of the Yuba River.**
- **This is the section most engineers would choose for their seepage analyses, <u>normal to the dike axis</u>.**
- **But, *the overall trend of the Yuba River channel is more or less normal to the viewing plane*. If the layered media exhibit any anisotropy (which is a reasonable assumption), the seepage assessment would not be properly oriented.**



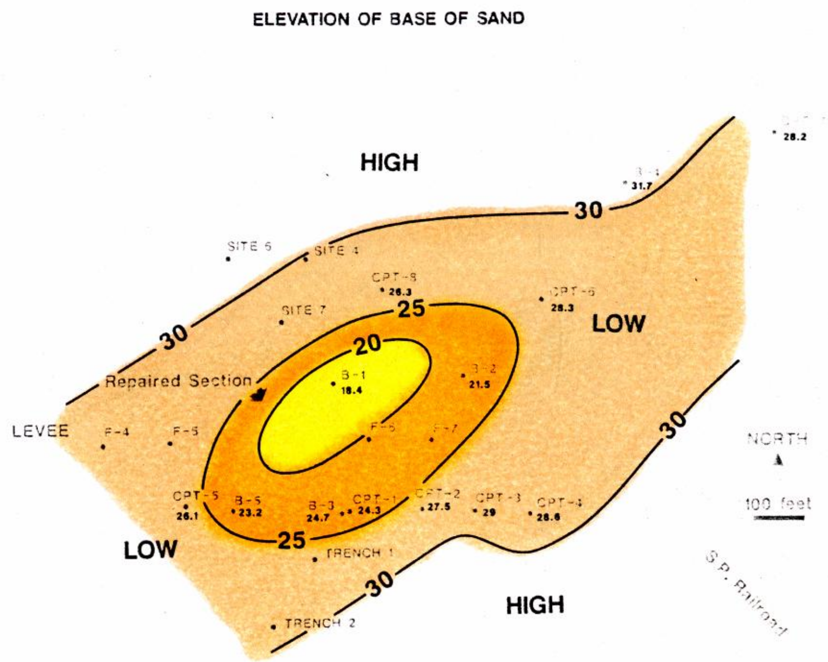
- **Fence diagrams are useful for assessing *three-dimensional aspects of the stratigraphy*, which are characteristic features of low gradient river channels.**

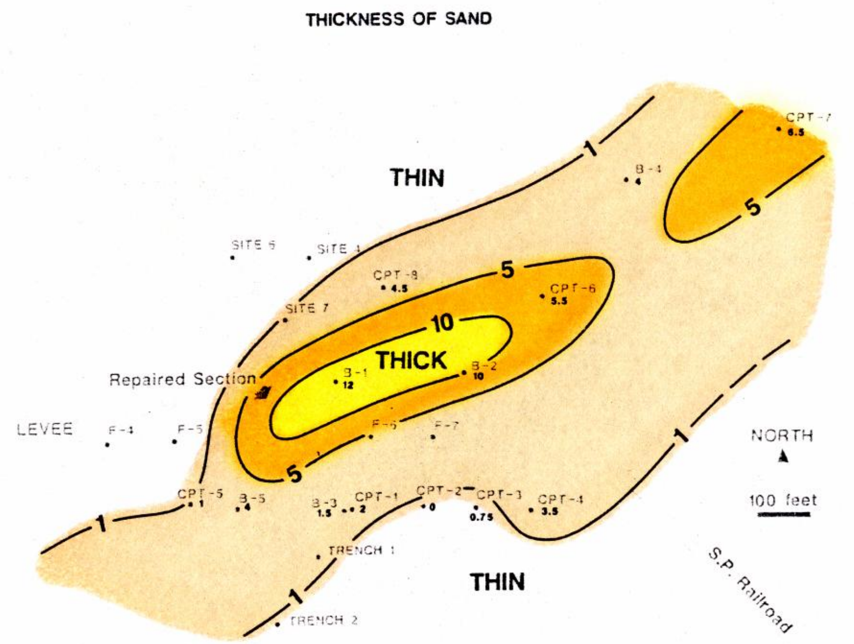


- **Isopleth and isopach maps of the mine slickens and pre-1862 overbank silt blankets. These suggest a swale, or ephemeral channel, passes through the breach area.**

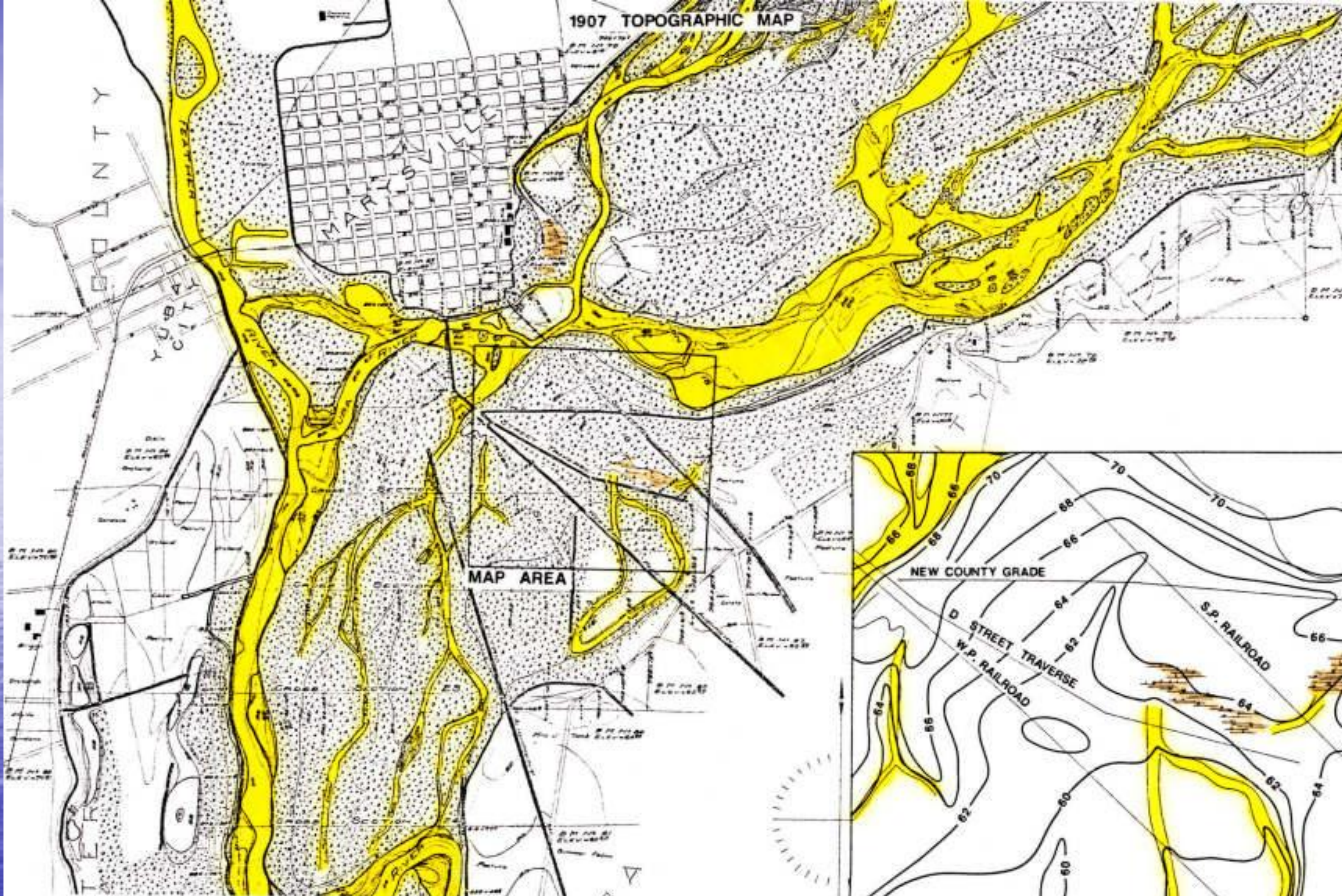


- **Elevation of buried paleosol; thickness of buried paleosol, and combined thickness of overbank silts and buried paleosol. These units form the *low permeability cap* on the *leaky aquifer* undelying the site.**

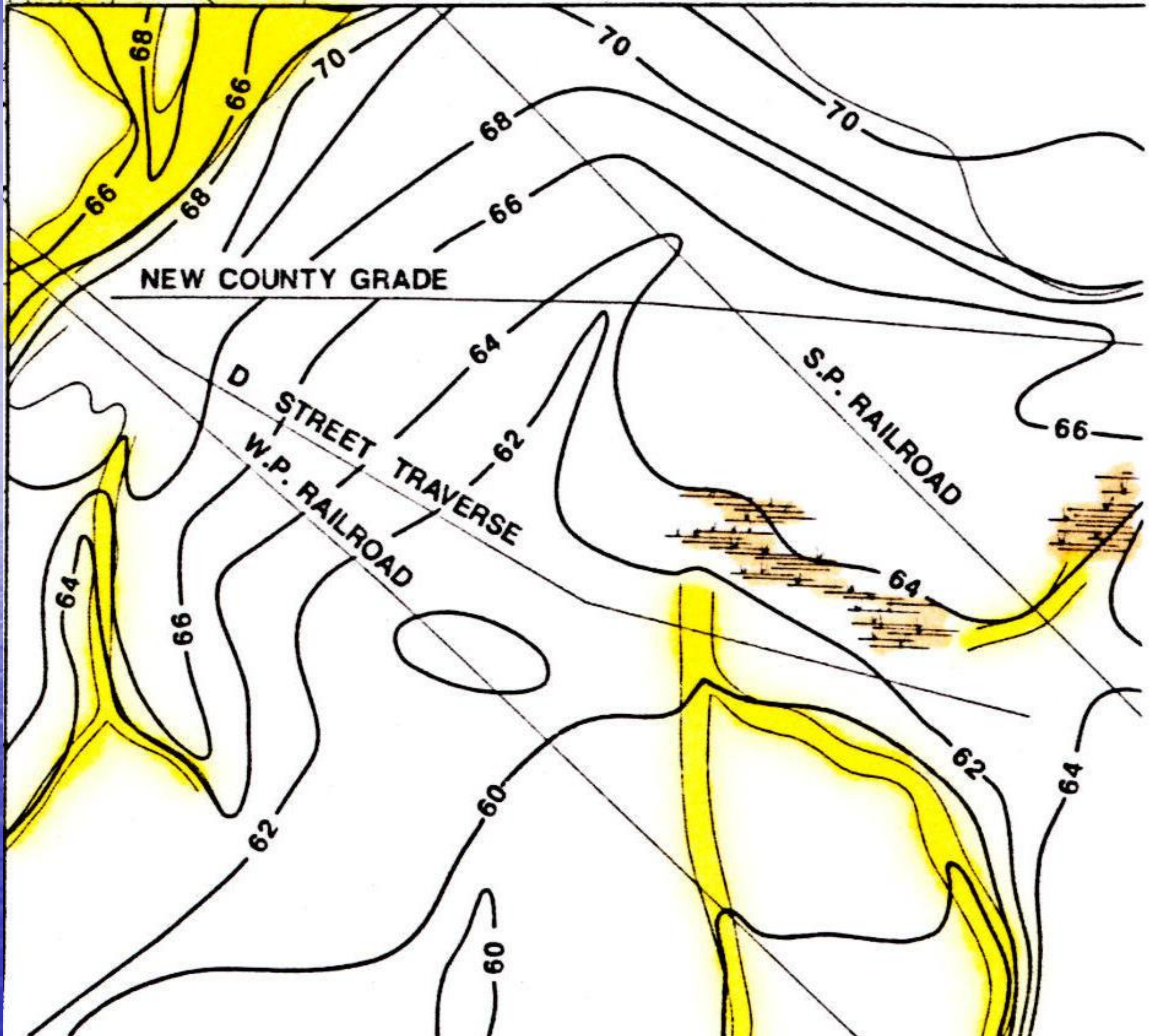




- **Isopleth and Isopach contours of the Holocene channel sands overlying the late Pleistocene channel gravels.**
- **Note the thickening and thinning character of these channel deposits – *none of the units exhibit planar, linear, or semi-constant thickness……***



- **1907 California Debris Commission survey; yellow highlights low flow channels. Insert shows enlargement of the area where the 1986 breach occurred.**



NEW COUNTY GRADE
D STREET TRAVERSE
W.P. RAILROAD
S.P. RAILROAD
70
70
70
68
68
68
66
66
66
66
66
64
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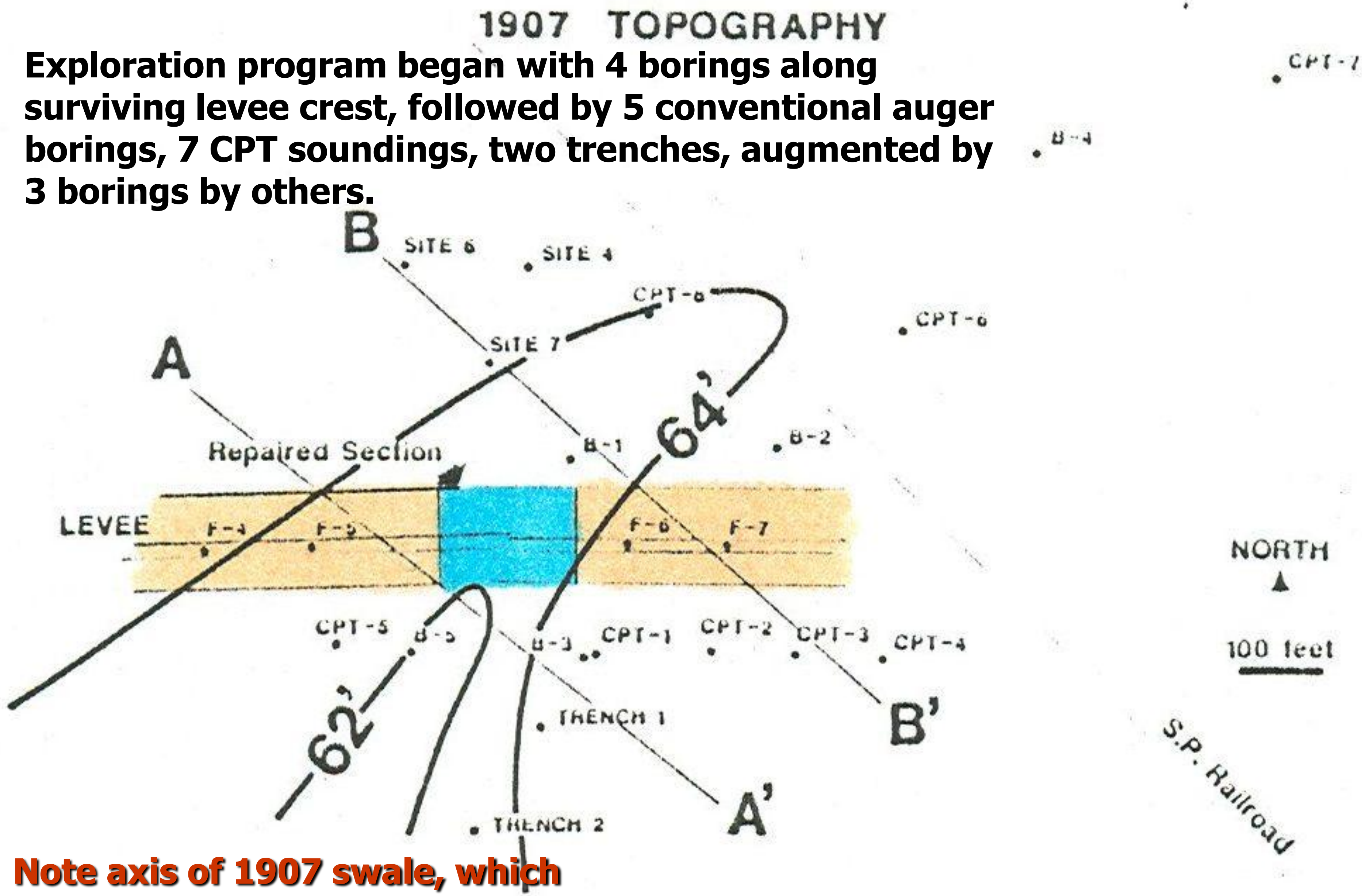
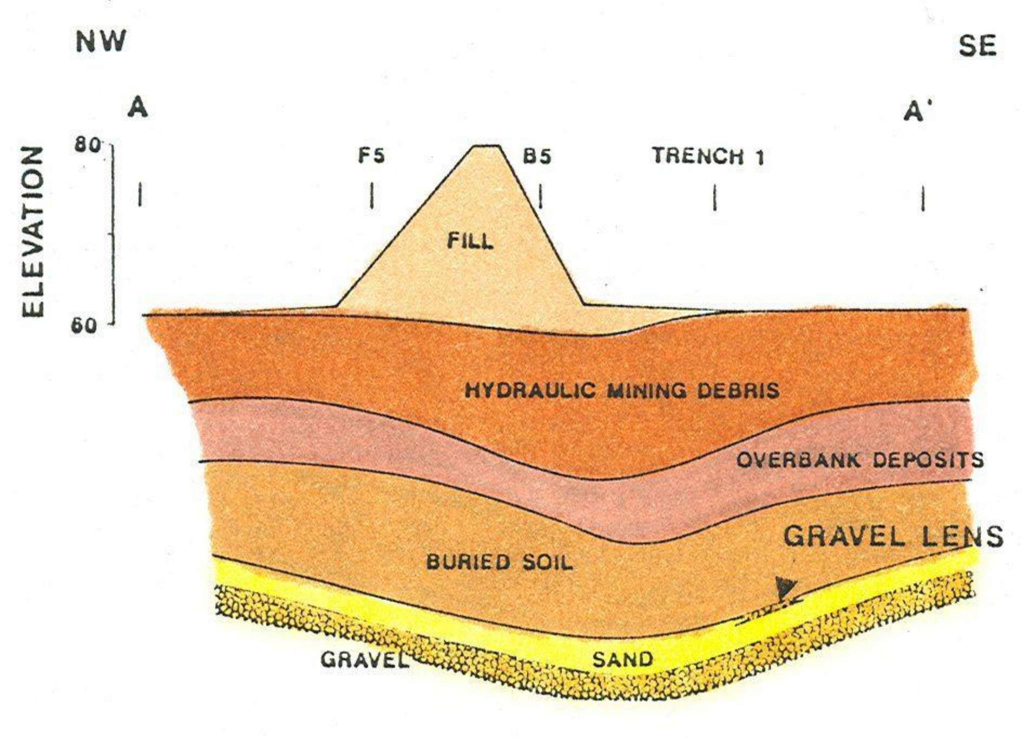
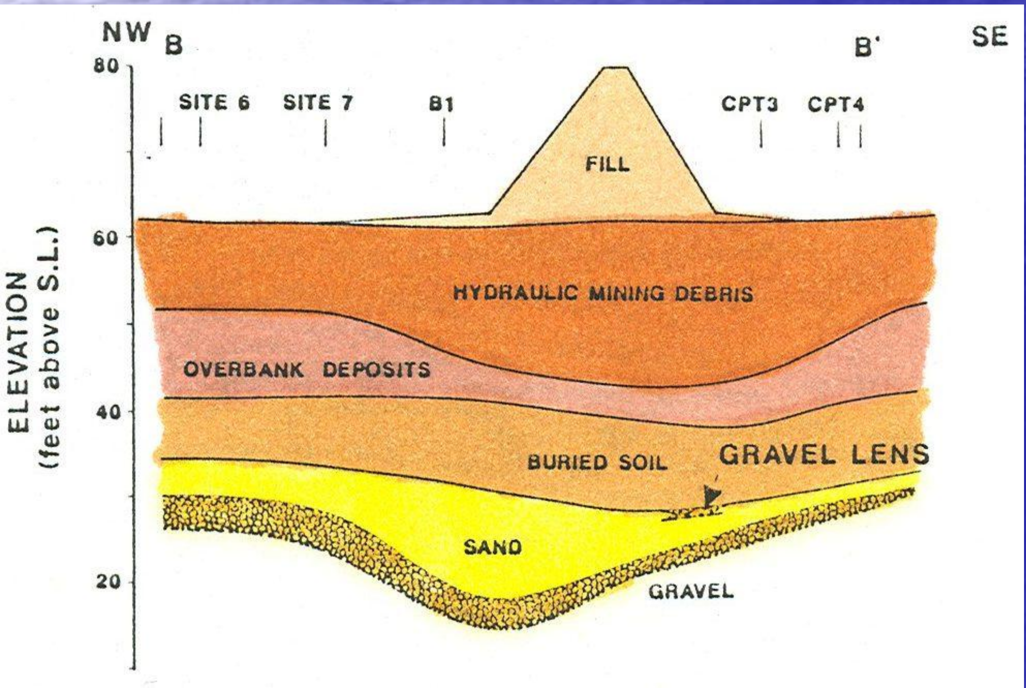
60

Exploration program began with 4 borings along surviving levee crest, followed by 5 conventional auger borings, 7 CPT soundings, two trenches, augmented by 3 borings by others.



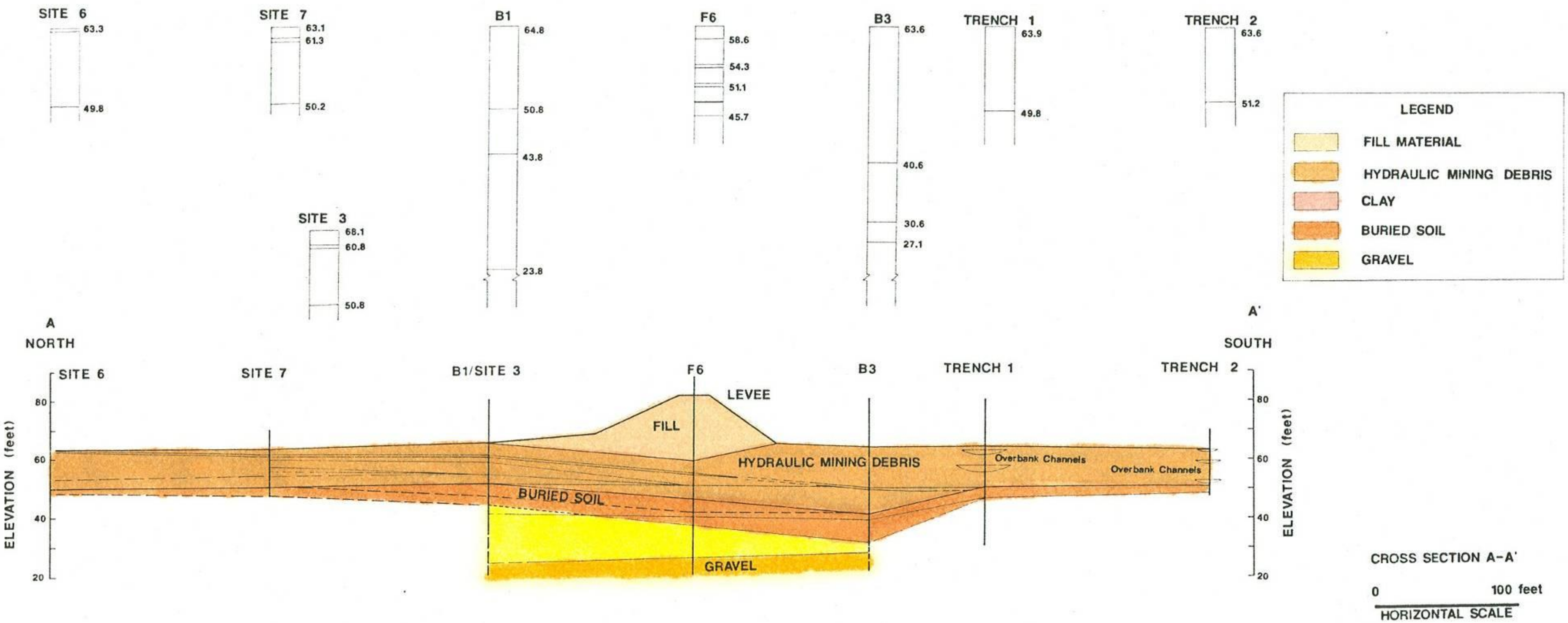
Note axis of 1907 swale, which coincides with the 1986 breach



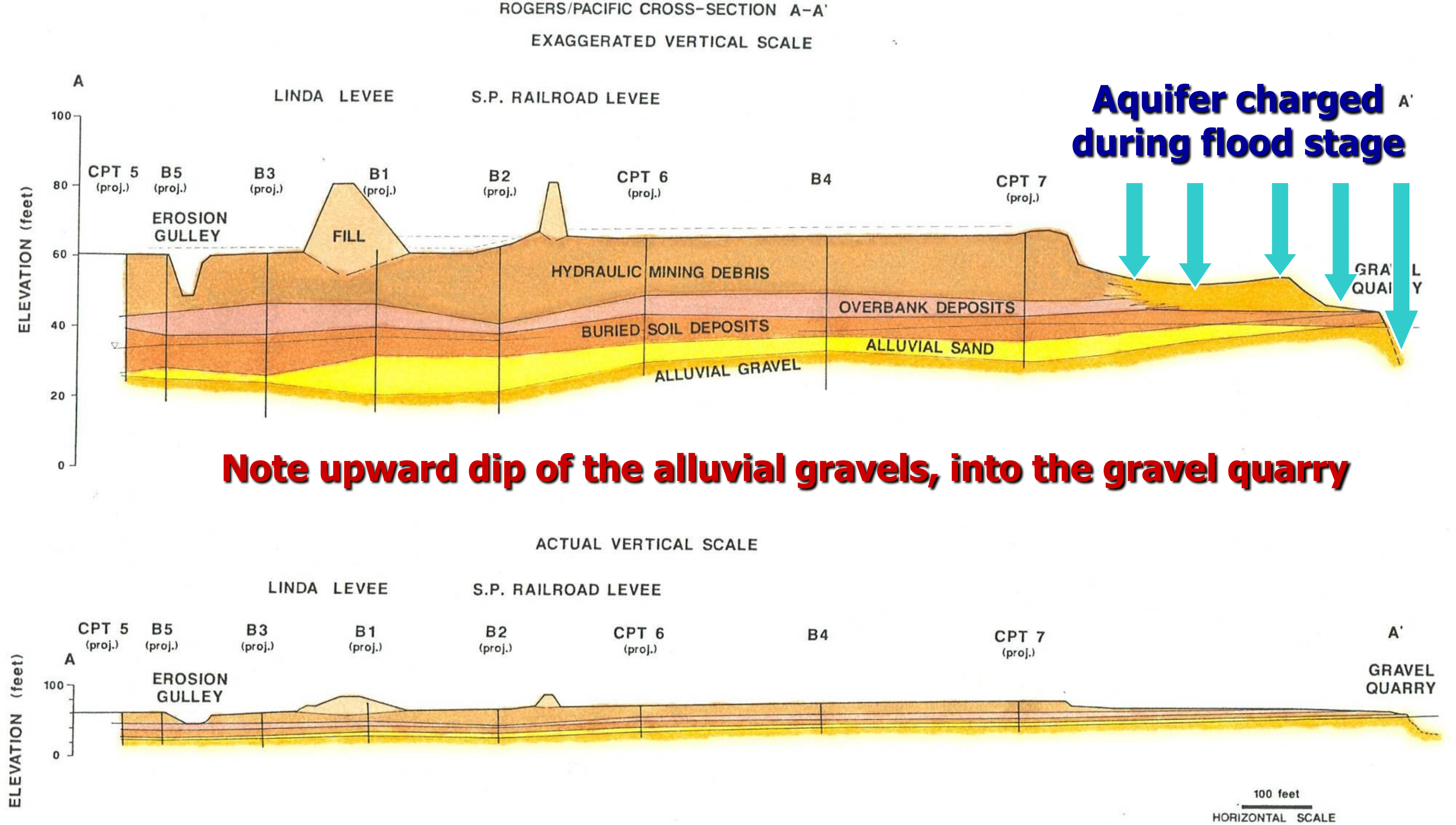


Sections through breach area

- **Sections A-A′ and B-B′ were cut perpendicular to the 1907 swale, normal to the historic direction of flow of the Yuba River. Note *axes of previous swales* in succeeding deeper units.**

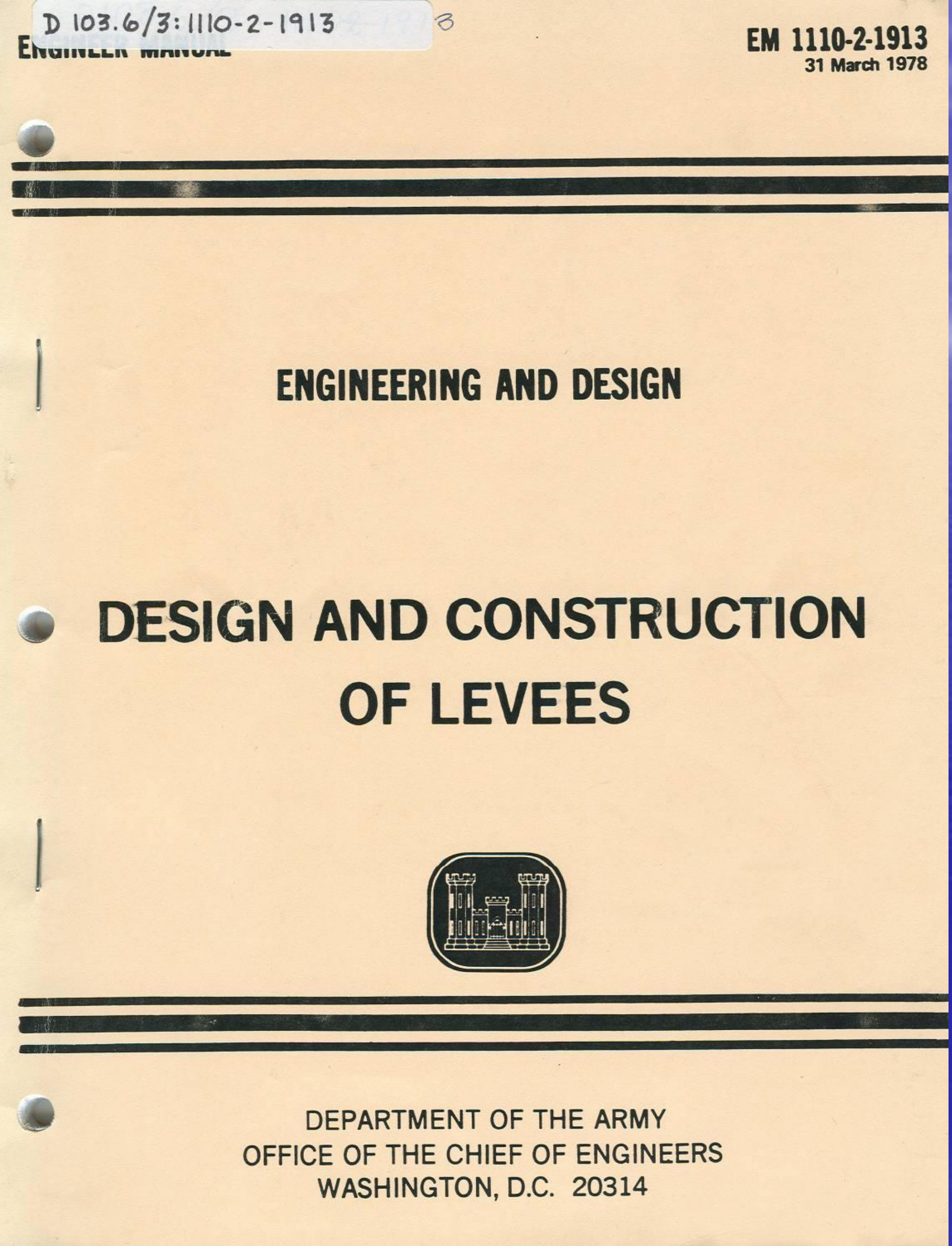


- **Preliminary Section A-A' cut the levee at 50 degrees to its alignment, along the 'flow path' of the river channel.**
- **It highlighted what might be a serious problem: highly conductive channels feeding *upward*, into a lower permeability paleosol cap, deposited in previous overflow channels.**
- **This is a classic "leaky aquifer" condition.**



- **Section A parallels the line of expected seepage and surface flow, from NE to SW. This was extended 1800 ft, to the Speckert Gravel Pit.** ***Note slope of the alluvial materials between the pit and the levee.***

STANDARDS ESTABLISHED BY THE CORPS OF ENGINEERS FOR ANALYSIS OF SEEPAGE BENEATH LEVEES



1978 edition of the Corps Levee Design manual

- Heavily influenced by Corps experience on the lower Mississippi River; with much lower hydraulic gradients than California channels

b. Depth. Depth of borings along the alignment should be at least equal to the height of levee but not less than 10 ft. Boring depths should always be deep enough to provide data for stability analyses of the levee and foundation. This is especially important when the levee is located near the riverbank where borings must provide data for stability analyses involving both levee foundation and riverbank. Where pervious or soft materials are encountered, borings should extend through the permeable material to impervious material or through the soft material to firm material. Borings at structure locations should extend well below invert or foundation elevations and below the zone of significant influence created by the load. The borings must be deep enough to permit analysis of approach and exit channel stability and of underseepage conditions at the structure. In borrow areas, the depth of exploration should extend several feet below the practicable or allowable borrow depth or to the groundwater table. If borrow is to be obtained from below the groundwater table by dredging or other means, borings should be at least 10 ft below the bottom of the proposed excavation.

- **Most Corps projects specified borings to a *depth equal to the overall height of the levee*. If the levee was 18 ft above original grade, borings were usually limited to maximum depth of 36 ft below levee crest.**

Excerpts from April 2000 Corps manual

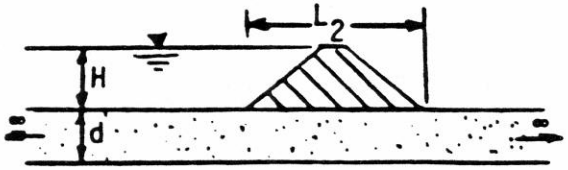
2-9. Borings

a. Location and spacing. The spacing of borings and test pits in Phase 1 is based on examination of airphotos and geological conditions determined in the preliminary stage or known from prior experience in the area, and by the nature of the project. Initial spacing of borings usually varies from 60 to 300 m (nominally 200 to 1,000 ft) along the alignment, being closer spaced in expected problem areas and wider spaced in nonproblem areas. The spacing of borings should not be arbitrarily uniform but rather should be based on available geologic information. Borings are normally laid out along the levee centerline but can be staggered along the alignment in order to cover more area and to provide some data on nearby borrow materials. At least one boring should be located at every major structure during Phase 1. In Phase 2, the locations of additional general sample borings are selected based on Phase 1 results. Undisturbed sample borings are located where data on soil shear strength are most needed. The best procedure is to group the foundation profiles developed on the basis of geological studies and exploration into reaches of similar conditions and then locate undisturbed sample borings so as to define soil properties in critical reaches.

b. Depth. Depth of borings along the alignment should be at least equal to the height of proposed levee at its highest point but not less than 3 m (nominally 10 ft). Boring depths should always be deep enough to provide data for stability analyses of the levee and foundation. This is especially important when the levee is located near the riverbank where borings must provide data for stability analyses involving both levee foundation and riverbank. Where pervious or soft materials are encountered, borings should extend through the permeable material to impervious material or through the soft material to firm material. Borings at structure locations should extend well below invert or foundation elevations and below the zone of significant influence created by the load. The borings must be deep enough to permit analysis of approach and exit channel stability and of underseepage conditions at the structure. In borrow areas, the depth of exploration should extend several feet below the practicable or allowable borrow depth or to the groundwater table. If borrow is to be obtained from below the groundwater table by dredging or other means, borings should be at least 3 m (nominally 10 ft) below the bottom of the proposed excavation.

Corps Seepage Models

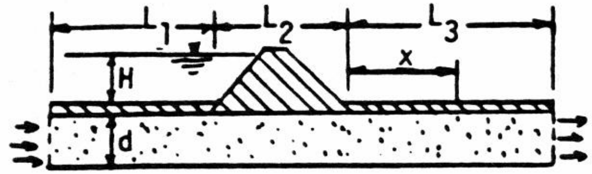
a. CASE 1 - No top stratum



$$\S = \frac{d}{L_2 + 0.86d}$$

$$h_o = h_x = 0$$

b. CASE 2 - Impervious topstratum both riverside and landside



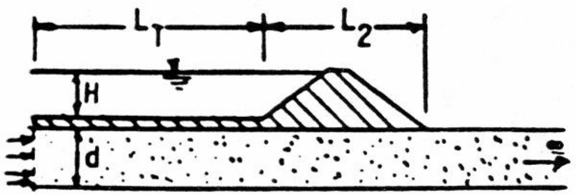
$$\S = \frac{d}{L_1 + L_2 + L_3}$$

$$h_o = H\left(\frac{L_3}{L_1 + L_2 + L_3}\right)$$

$$h_x = h_o\left(\frac{L_3 - x}{L_3}\right) \text{ for } x < L_3$$

$$h_x = 0 \text{ for } x > L_3$$

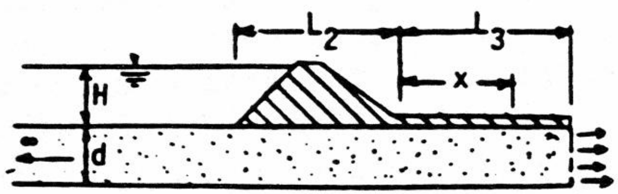
c. CASE 3 - Impervious riverside top stratum & no landside top stratum



$$\S = \frac{d}{L_1 + L_2 + 0.43d}$$

$$h_o = h_x = 0$$

d. CASE 4 - Impervious landside top stratum & no riverside top stratum



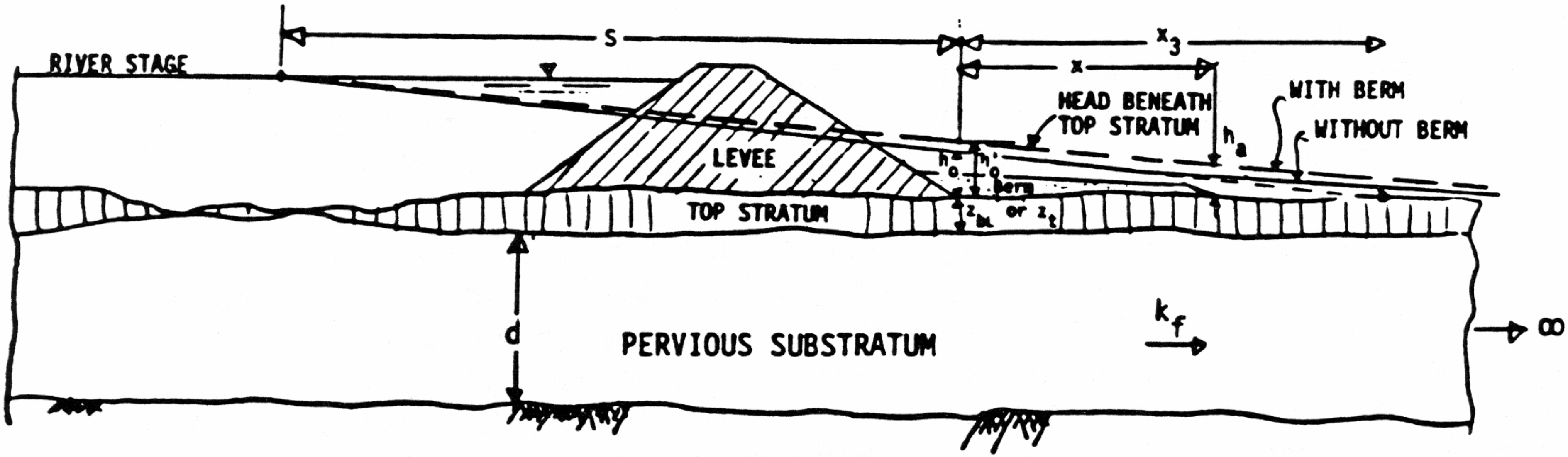
$$\S = \frac{d}{0.43d + L_2 + L_3}$$

$$h_o = H\left(\frac{L_3}{0.43d + L_2 + L_3}\right)$$

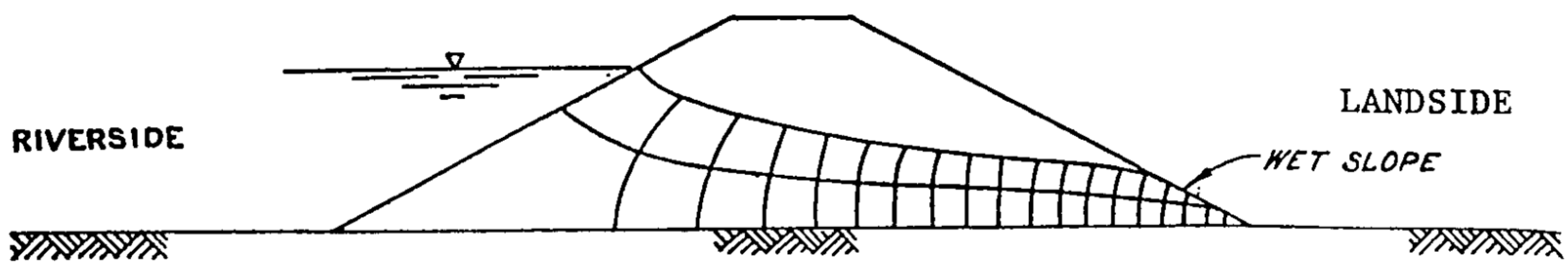
$$h_x = h_o\left(\frac{L_3 - x}{L_3}\right)$$

- These are the four basic seepage models presented in the Corps 1978 Levee Design Manual
- *Note H vs D and linear sand foundations*
- If geology was this simple, we wouldn't need geologists

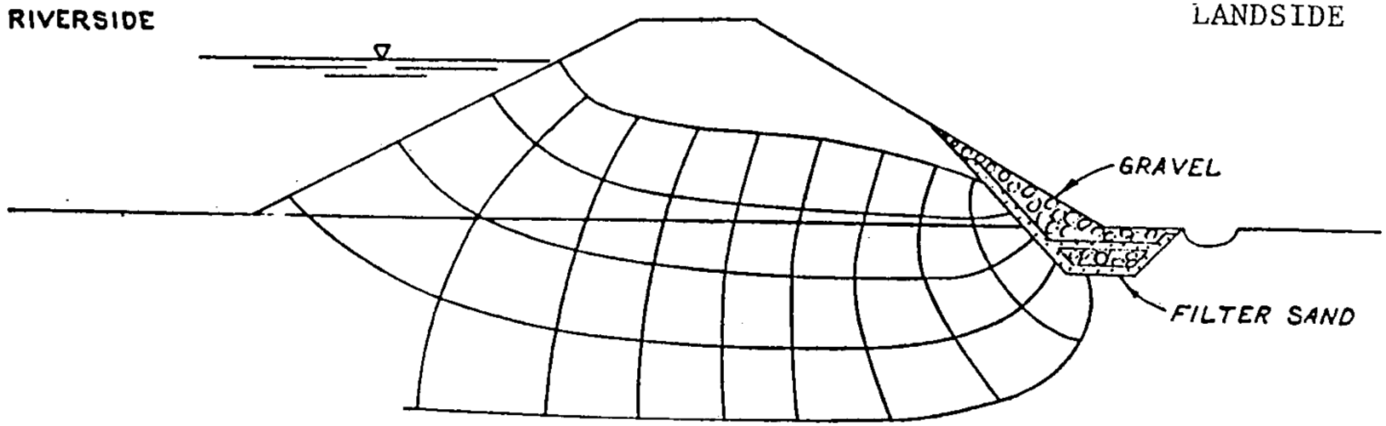
Lane's Weighted Creep Ratio



- **Lane was a civilian engineer at WES-Vicksburg. His procedure was summarized in an article for the 1961 ICOLD Congress in Rome, summarizing experiences with dams along the Missouri River**
- **Developed a simple index of levee underseepage vulnerability- based on *total seepage distance divided by the assumed head,* which he termed "*foundation resistance*"**
- **Assumes all levee foundations on clay, silt, or sand**
- **Useful to evaluating width of *seepage blankets* and *toe berms* for levees**



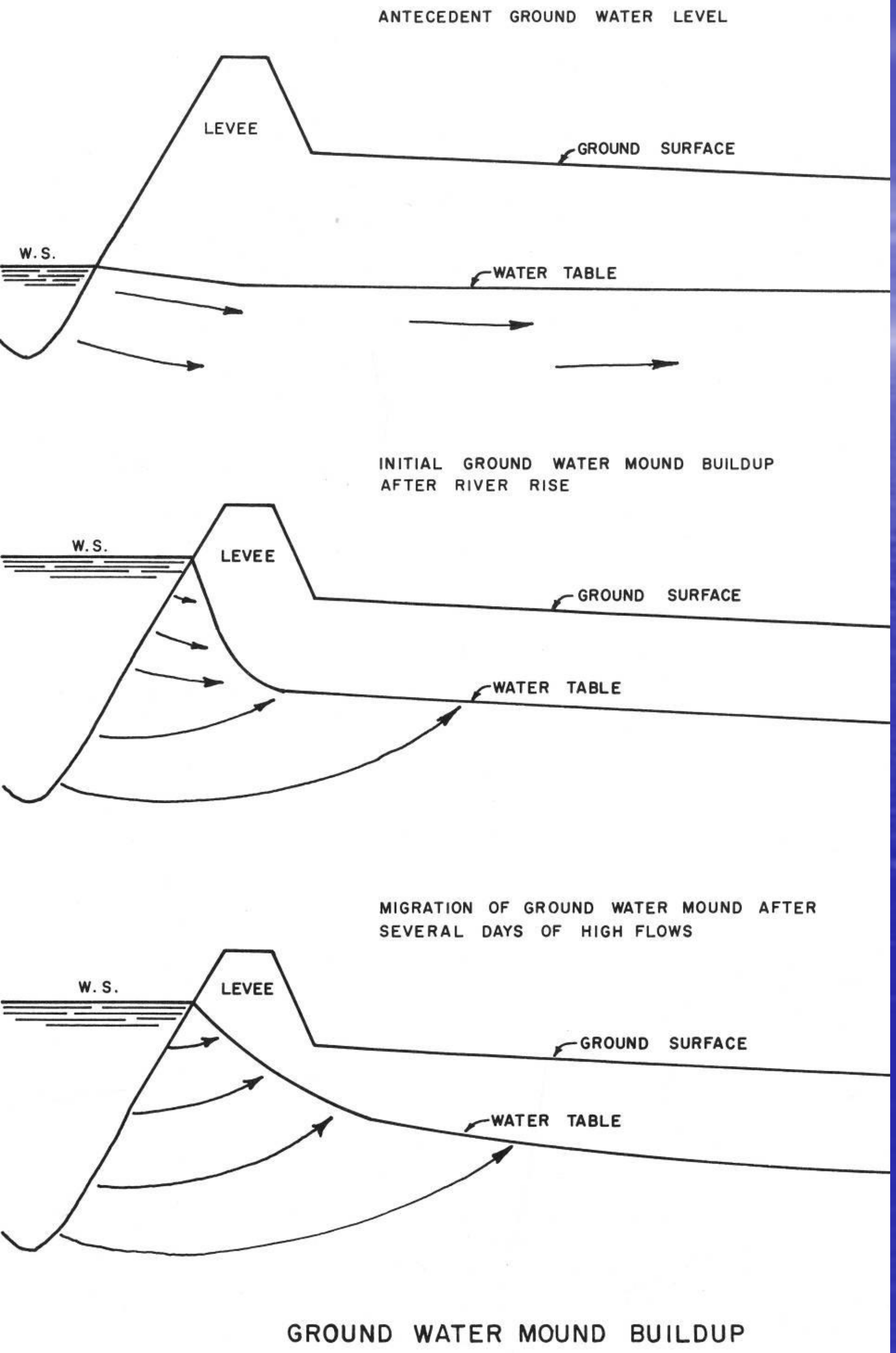
a. Homogeneous section on impervious foundation seepage emerging on landside slope



c. Pervious toe combined with partially penetrating toe trencn

- **Seepage models in Corps Manual for homogeneous section on impervious (clay) foundation; and**
- **Considers underflow to a *maximum depth of H*, the overall height of the levee**

Levees near channels



- Whenever a levee is situated close to the main flow channel; you can't use H=D seepage models
- The seepage analyses immediately become more complicated, as the wetting front moves up beneath the embankment
- This is always a more dangerous condition, and flow duration often controls behavior

d. Computer programs to use for seepage analysis.

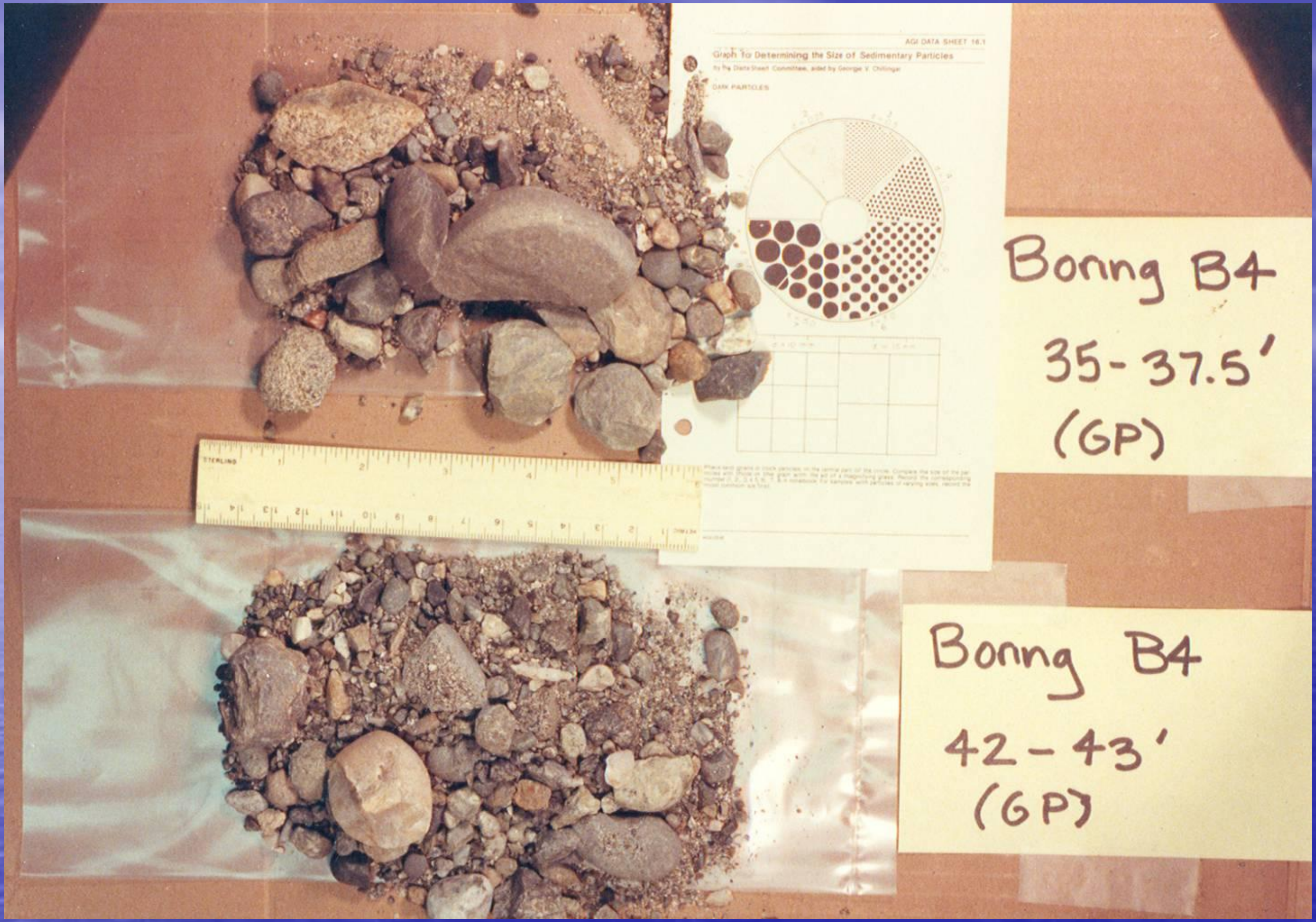
(1) If the soil can be idealized with a top blanket of uniform thickness and seepage flow is assumed to be horizontal in the foundation and vertical in the blanket, then LEVSEEP (Brizendine, Taylor, and Gabr 1995) or LEVEEMSU (Wolff 1989; Gabr, Taylor, Brizendine, and Wolff 1995) could be used.

(2) If the soil profile is characterized by a top blanket and two foundation layers of uniform thickness, and seepage flow is assumed to be horizontal in the foundation, horizontal and vertical in the transition layer, and vertical in the blanket, then LEVEEMSU or the finite element method (CSEEP) could be used (Biedenharn and Tracy 1987; Knowles 1992; Tracy 1994; Gabr, Brizendine, and Taylor 1995). LEVEESMU would be simpler to use.

(3) If the idealized soil profile includes irregular geometry (slopes greater than 1 vertical to 100 horizontal), more than three layers and/or anisotropic permeability ($k_v \neq k_h$), then only the finite element method (CSEEP) is applicable. When using CSEEP it is recommended that FastSEEP, a graphical pre- and post-processor, be used for mesh generation, assigning boundary conditions and soil properties, and viewing the results (Engineering Computer Graphics Laboratory 1996).

- **Excerpt from the Corps new *Levee Design and Constriction Manual*, released in 2000, *Recommendations for seepage analyses…***
- **The authors have seldom viewed foundation conditions in California that could reasonably be approximated using the assumptions necessary for Cases (1) or (2).**

So, how important was it to model the underlying cobble gravel ?



- **The coarse channel gravels had not been detected in any of the previous geotechnical investigations, <u>not even those FOLLOWING the 1986 levee failure</u>! Ouch!!**

Range of Values of Hydraulic Conductivity and Permeability

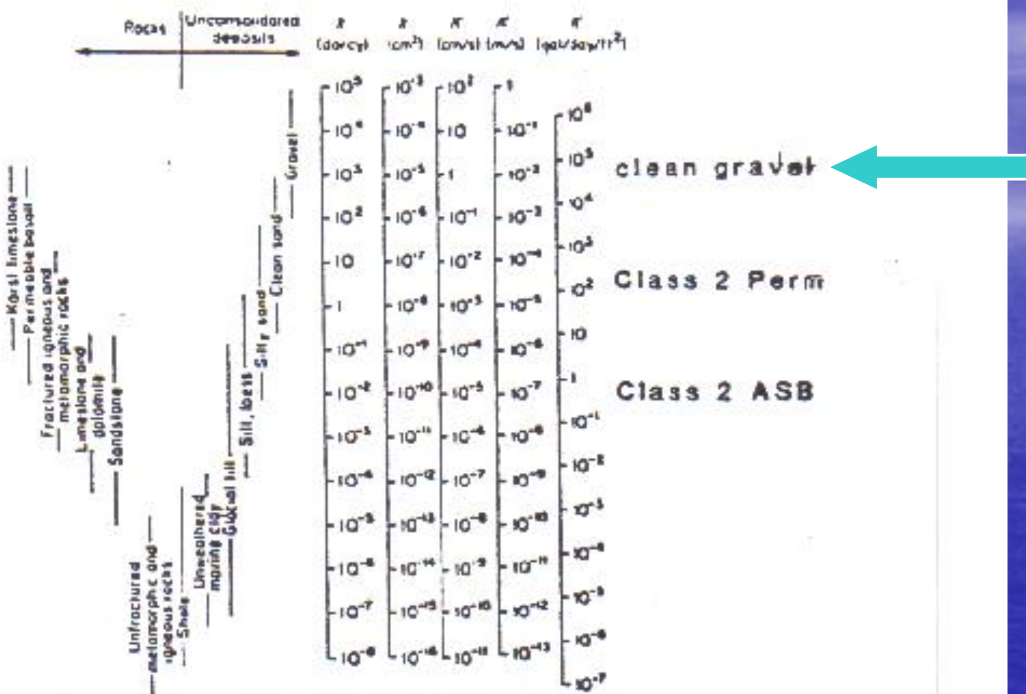


Table 2.3 Conversion Factors for Permeability and Hydraulic Conductivity Units

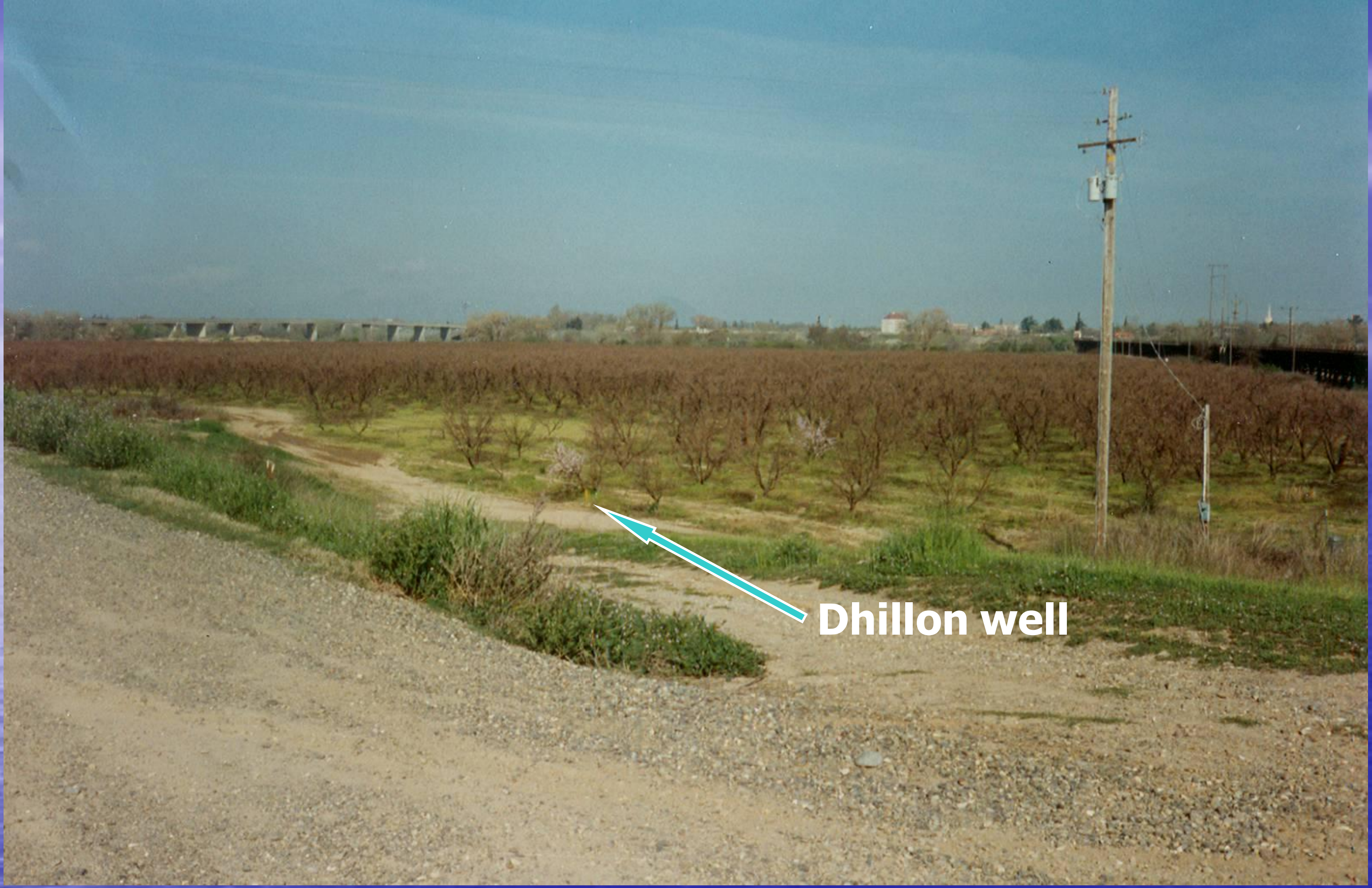
	Permeability, k*			Hydraulic conductivity, K		
	cm²	ft²	darcy	m/s	ft/s	gal/day/ft²
cm²	1	1.08×10^{-3}	1.01×10^{8}	9.80×10^{2}	3.22×10^{3}	1.85×10^{9}
ft²	9.29×10^{2}	1	9.42×10^{10}	9.11×10^{5}	2.99×10^{6}	1.71×10^{12}
darcy	9.87×10^{-9}	1.06×10^{-11}	1	9.66×10^{-6}	3.17×10^{-5}	1.82×10^{1}
m/s	1.02×10^{-3}	1.10×10^{-6}	1.04×10^{5}	1	3.28	2.12×10^{6}
ft/s	3.11×10^{-4}	3.35×10^{-7}	3.15×10^{4}	3.05×10^{-1}	1	5.74×10^{5}
gal/day/ft²	5.42×10^{-10}	5.83×10^{-13}	5.49×10^{-2}	4.72×10^{-7}	1.74×10^{-6}	1

*To obtain k in ft², multiply k in cm² by 1.08×10^{-3}.

Average permeability values performed by Rogers/Pacific on random field samples, taken from truck loads upon delivery.

Tests performed with constant head permeameter, in accordance with ASTM D2434-74.

- **What would be a reasonable permeability value for water percolating through a confined, or semi-confined, aquifer comprised of coarse cobble gravel ?**
- **In the 1991 trial, Rogers and Meehan opined that they would expect hydraulic conductivities of 0.1 to 1.0 cm/sec in the coarse channel gravels lying beneath the failed levee section**



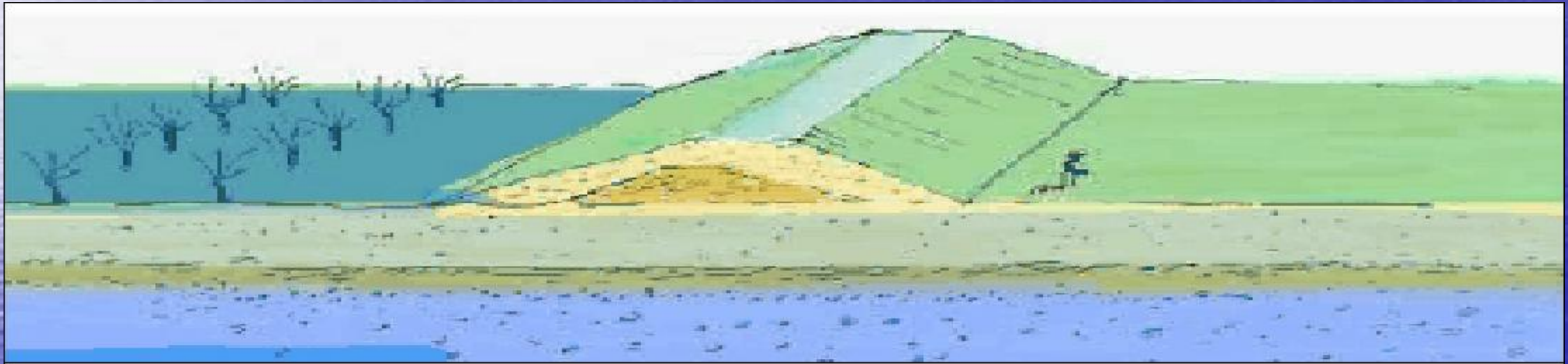
- **After Rogers and Meehan's depositions in 1990, the State Attorney General's Office asked the Department of Water Resources to undertake an aquifer testing program in the alluvium adjacent to the 1986 Linda Levee failure, using the Dhillon orchard well (arrow).**

Channel Gravel Permeability

- The pump test data was never presented by the State in their defense at trial. Meehan made a formal request of DWR, asking for the data in 1993.
- After the second trial was concluded in 2004, the State finally released the results of their 1990 pump tests on the Dhillon well, next to the 1986 breach. These pump tests revealed a hydraulic conductivity of k = 0.2 cm/sec
- This would correspond to a wetting front moving about 24 ft/hr, or 567 ft/day
- Under 15 ft of driving head, a 'wetting front' could have reached the land side of the levee breach area from the Speckert Gravel Pit in 3.2 days.
- The breach actually occurred 7.5 days after flood stage brought water up against the levee

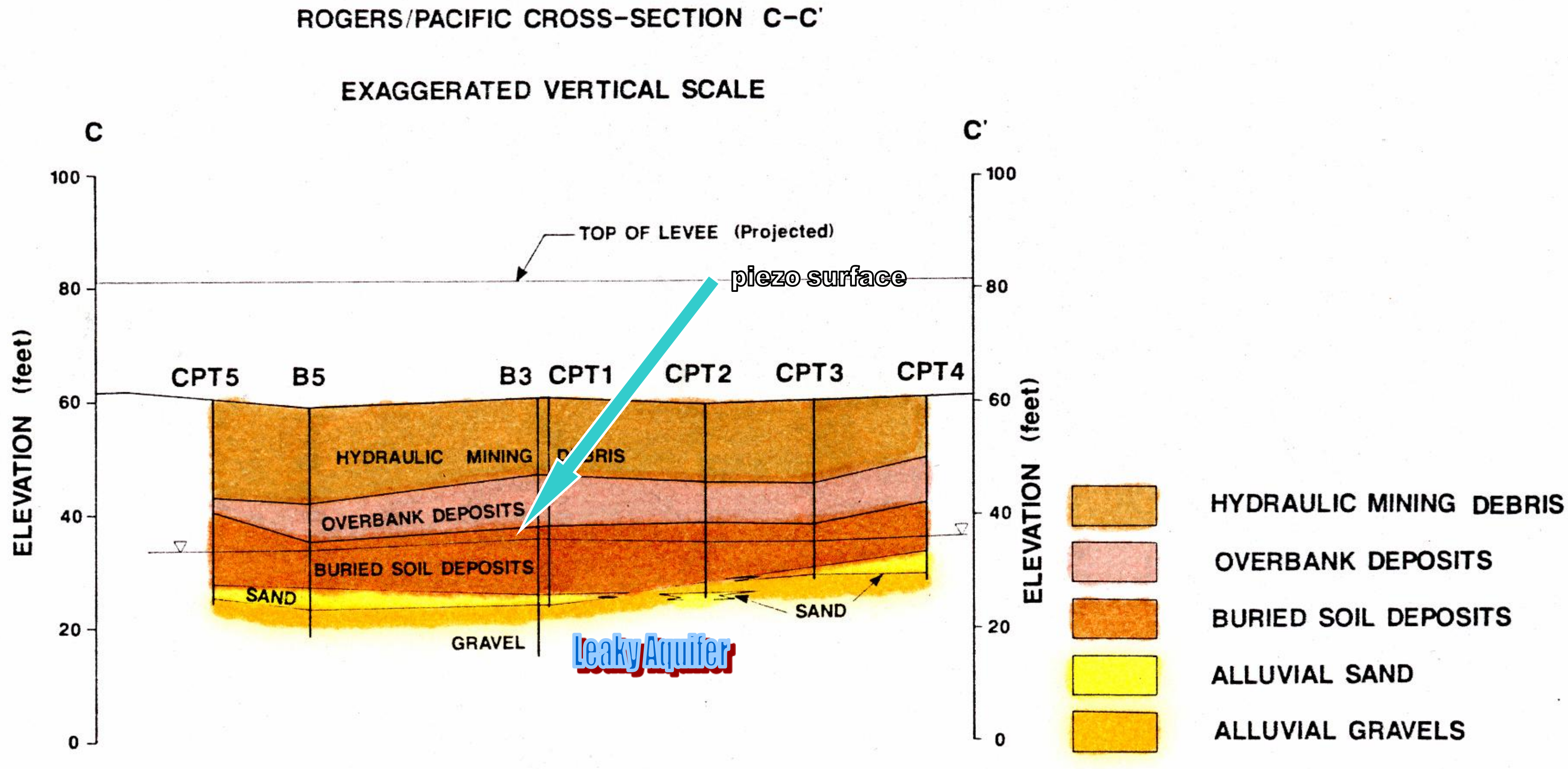
Wetting Front models

Three different wetting fronts can be assumed…



Movie11

‘Leaky aquifer’ versus ‘wetting front’ models



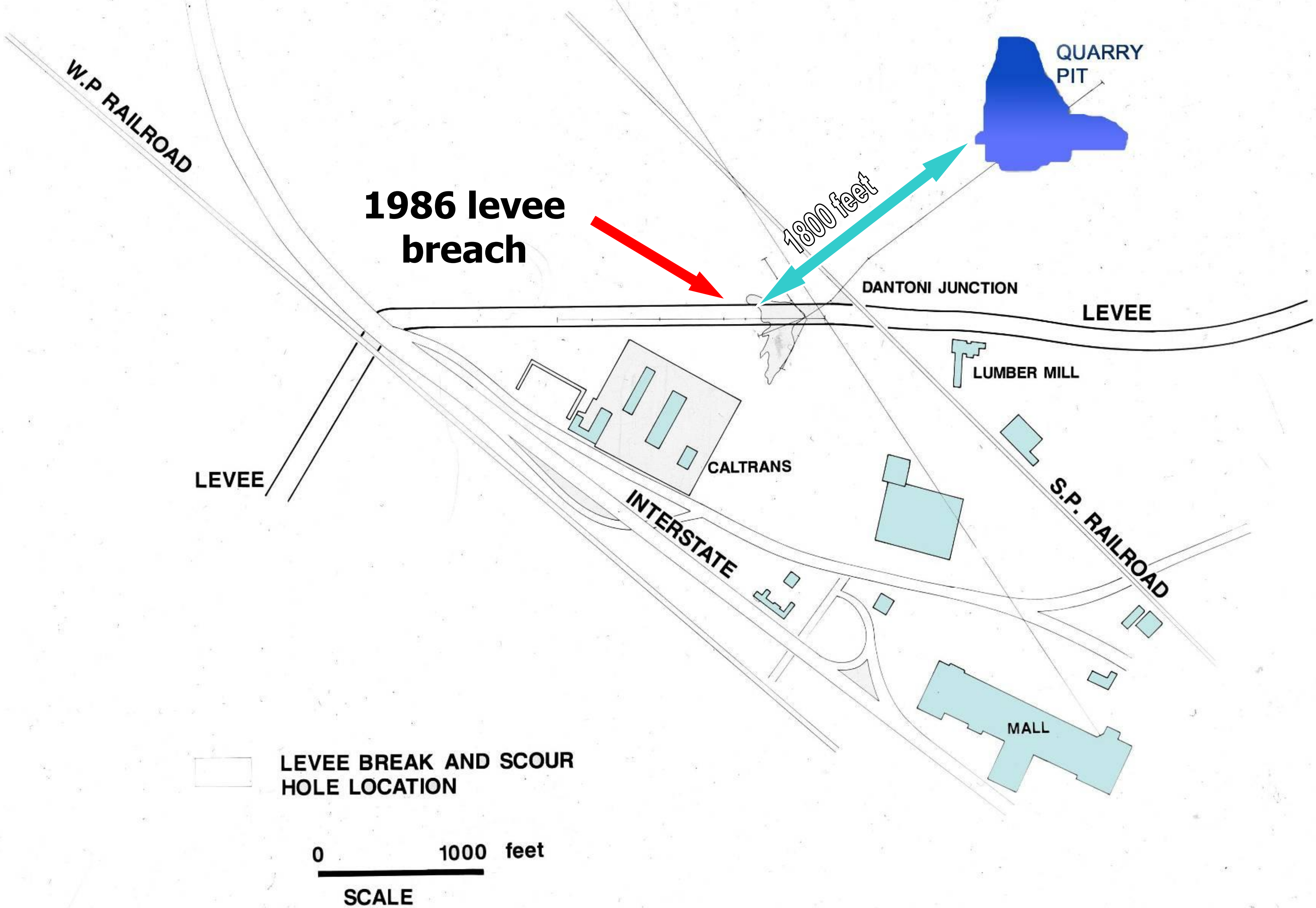
Pore pressures emanating from the cobble gravels extend into the low permeability paleosol cap. As soon as flood waters filled the Speckert gravel pit, that pressure head would have acted on the leaky aquifer, engendering considerable uplift

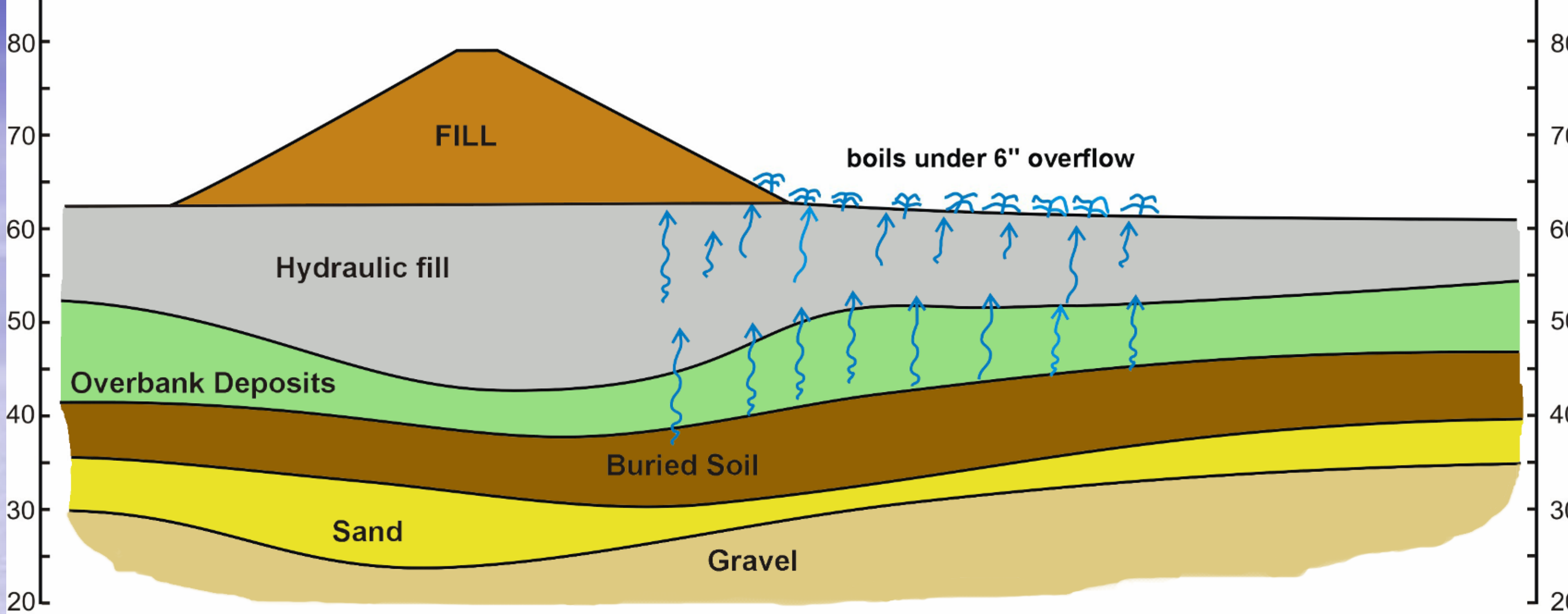
ACTUAL VERTICAL SCALE

Full-blown liquefaction-induced 'softening' versus pore pressure-induced destabilization

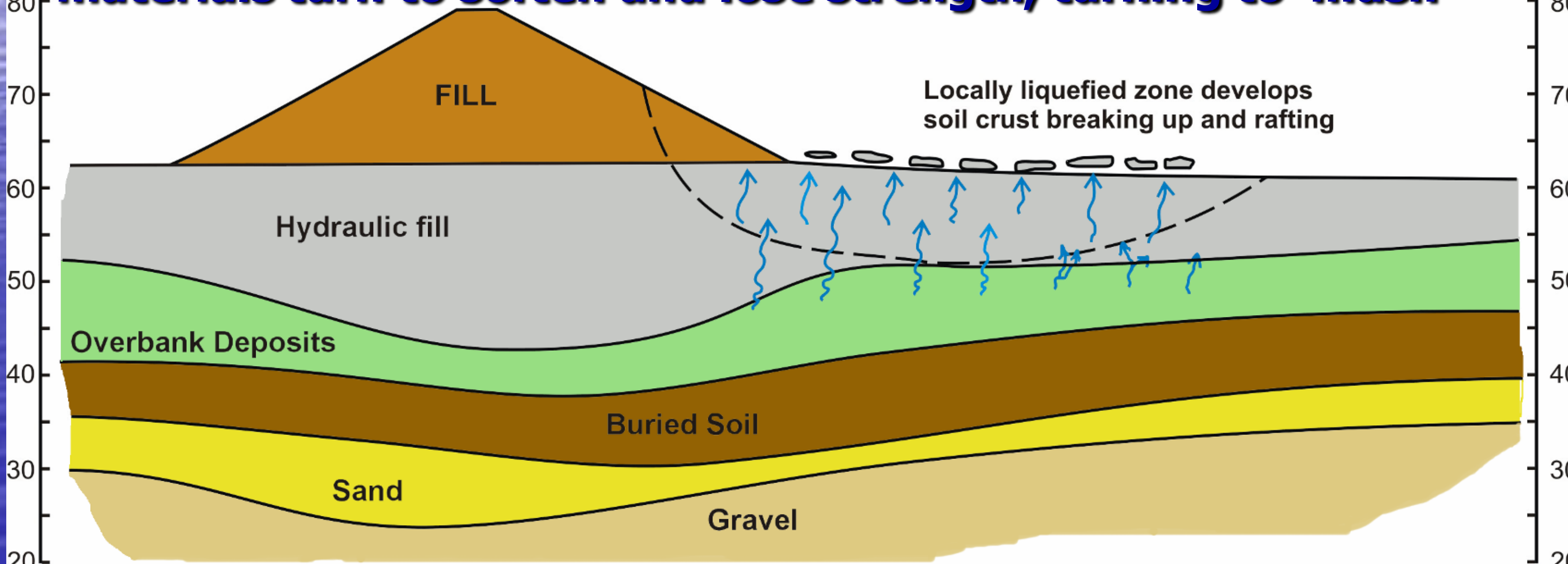
- After more than two decades of study, including post-failure assessments of levee failures in New Orleans in 2005;
- The authors have come to the conclusion that most levee foundation failures are not actually driven by incremental hydraulic piping and liquefaction, but by **sufficient pore water pressure** to cause **destabilization** of the soil fabric; which triggers a rapid failure sequence, not necessarily preceded by significant development of sand boils

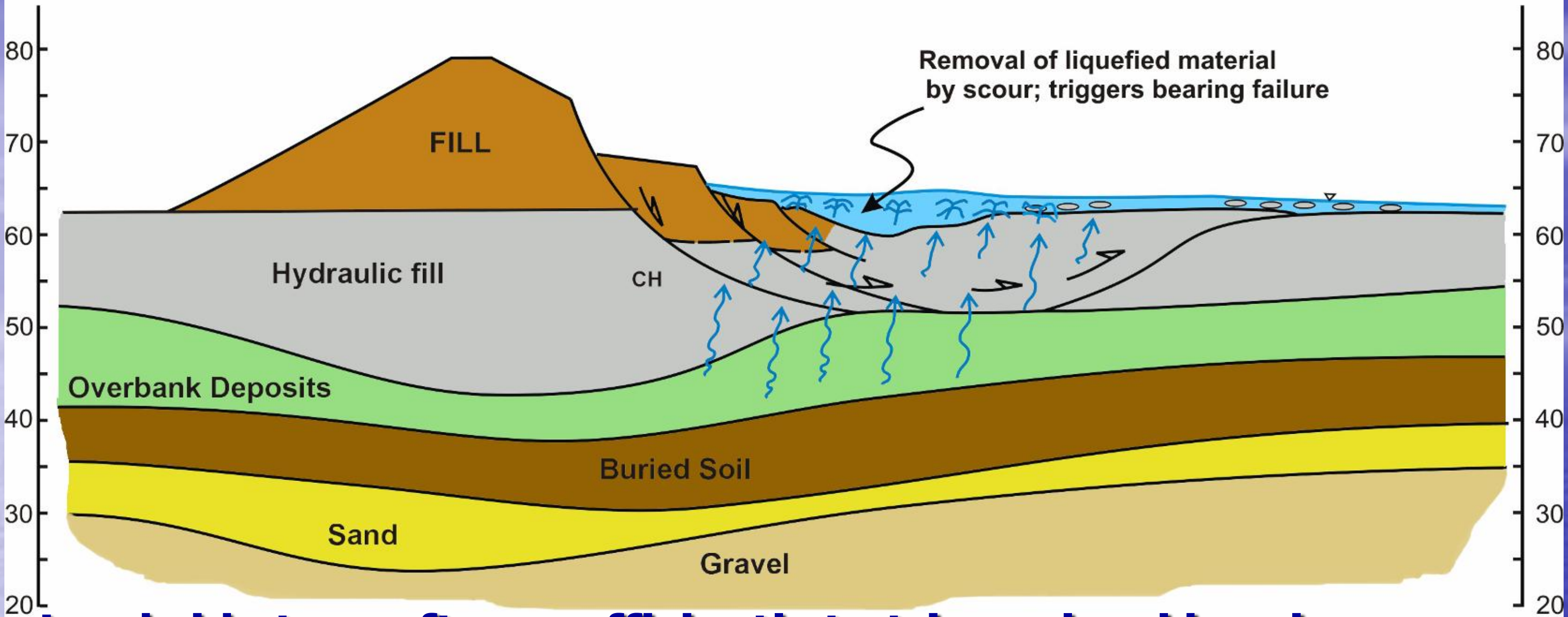
What likely happened in February 1986



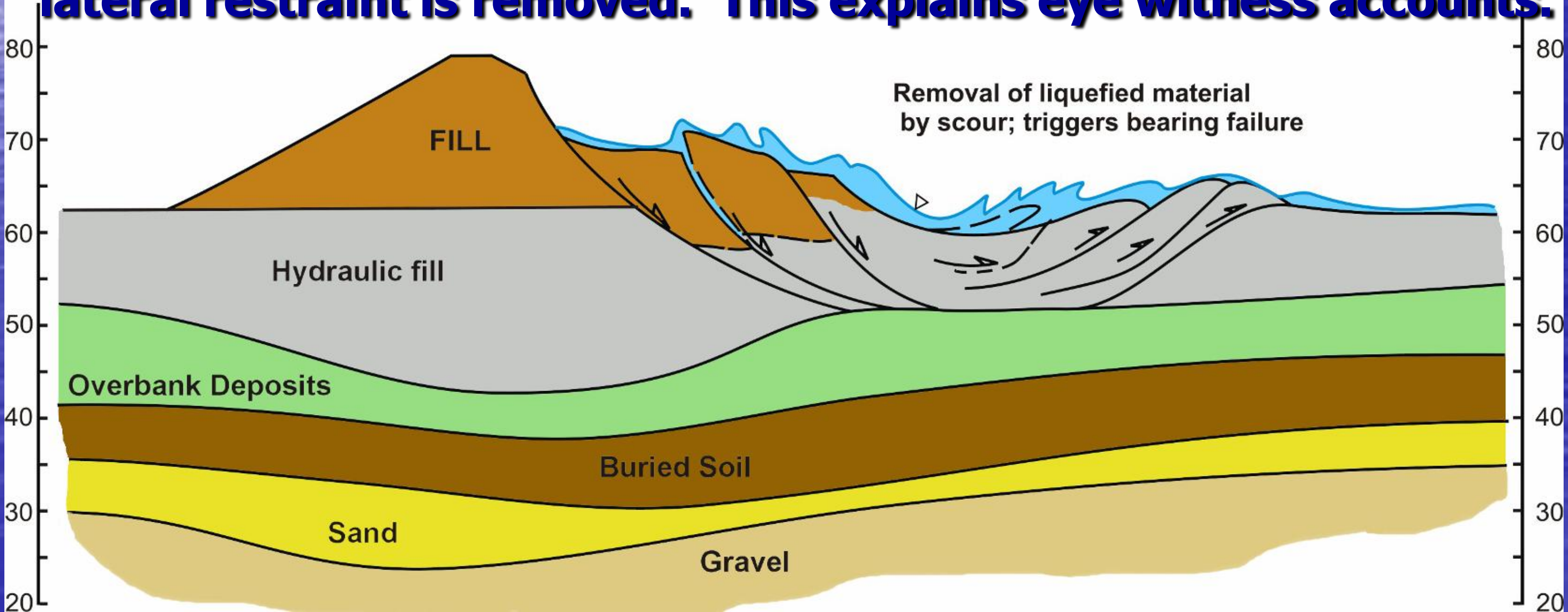


Hydraulic uplift from confined gravel aquifer under considerable pressure head. As head increases, unconsolidated low density materials turn to soften and lose strength, turning to 'mush'





Land side toe softens sufficiently to trigger local bearing capacity failure; which triggers retrogressive slumping, as lateral restraint is removed. This explains eye witness accounts.



Brief Summary and Implications of the

Paterno et al vs State of California decision in 2005

The 1986 Linda Flood Case

- The levee break in February 1986 along the south side of the Yuba River flooded an area of 15 square miles, inundating the communities of Linda and Olivehurst in up to 10 feet of water
- Multiple lawsuits involving 1500 plaintiffs were filed against the local reclamation district and the State of California, which had issued permits for instream mining along the lower Yuba River, 1800 feet from the break.

Paterno vs State of California case

- The case went to trial for the first time in 1991 in Sacramento. Judge Thomas F. Mathews agreed that the levee was in a deplorable condition and ruled for the plaintiffs under state constitutional principles of inverse condemnation. An appeal was filed by defendants State of California and Reclamation District 784.
- In the first California Court of Appeal decision in 1999, the appellate court ruled that the plaintiffs had not proven their case for inverse condemnation, because they failed to prove that the state had exercised an "unreasonable" plan of flood protection. They remanded the case back to the trial court to make express determinations as to the existence and reasonableness of the State's plan.
- A second trial was convened before Judge John Golden in 2001 in Olivehurst, near Linda. Judge Golden found no liability on the part of the State of California or RD 784 in that no particularized plan existed on the part of either public agency.

Paterno vs State of California case

- Judge Golden noted that the levee had been aligned improperly, so as to overlie old river channels; and that nearby borrow and mining pits in those same channel gravels had been approved by the State. He also found that the levee had never met engineering standards at any time in its life.
- Having found no actual plan of flood protection, Judge Golden could not determine whether or not such plans were reasonable. The plaintiffs went back to the California Court of Appeal.
- On Nov 26, 2003 the Court of Appeal issued a decision which found that inverse condemnation liability *did exist* on the part of the State of California, but not for Reclamation District 784, because the latter had no part in levee's construction or acceptance. *The State of California's liability rested in substantial part upon its formal acceptances of the levee dating back at least to 1951, and upon federal law that made the State responsible for the levee.*

The Paterno decision

- **The appellate court reasoned that the subject flood control project *failed to function as intended* by applying a constitutional balancing test that weighed the benefits provided by the project against the gravity of the harm caused.**
- **This resulted in a finding of unreasonable conduct that the plaintiffs, if left uncompensated, would unconstitutionally bear more than their fair share of the costs of the public project (the Sacramento River Flood Control Project).**
- **The Paterno decision was not the first time that the State of California had been held liable for damage caused by the failure of a project levee. The State, for example, had been held liable in inverse condemnation in the Adams litigation that arose from the failure of a Feather River levee in December 1955.**

Implications of the Paterno case

- The Paterno case was resolved with payment to plaintiffs in excess of ***$450 million*, the largest award in a flood litigation case in the United States**.
- The Paterno decision has ushered in a new era in government-approved infrastructure, which affects every taxpayer in California , and will, inevitably, have impact on how natural hazards, such as floods, are treated in the rest of the USA.
- The California Department of Water Resources estimates the that the construction backlog of critical levee repairs at more than **$2 billion**
- The State has embarked upon a **$60 million** dollar engineering assessment of levee stability in the lower Sacramento and San Joaquin Valleys over the next five years.

- **Will the people of California continue developing at-risk properties within recognized flood plains?**
- **The entire Central Valley and Sacramento-San Joaquin Delta is a flood plain. Staying out of the flood plain isn't a realistic outcome**

CONCLUSIONS -1

- **Site characterization for seepage analyses requires a critical assessment of the *geomorphic setting*; asking:**
- **1) Does our levee *encroach* the natural high flow channel? If so, how much? How much matters, a lot.**
- **2) Have historic channels migrated significantly within their respective flood plains?**
- **3) What are the physical limits of buried channels? We have to make careful assessments of adjacent water wells.**
- **3) What *direction* were the paleo channels flowing, in comparison to levee alignments?**
- **4) How much seepage anisotropy can we expect to be exerted by the *depositional 'fabric'* of such channels?**
- **5) Be careful near the confluence of two channels. We may encounter "*groundwater mounding*," as a higher gradient/higher permeability system converges with a lower gradient/lower permeability system**

CONCLUSIONS - 2

- **6) Are we able to model *multiple wetting fronts* with maximum, mean, and minimum k values? *We must appreciate the uncertainties involved.***
- **7) Are we modeling seepage conditions at sufficient depths, and not allowing the analyses to be driven by '*cookbook' generalizations*?**
- **8) Are we modeling seepage crossing the levee at oblique angles?**
- **9) Are we modeling potential impacts of in-stream mining, or other excavations in proximity to a levee?**
- **10) How *far away* do we need to be looking? *Depends on duration of design events*. A long-duration event is a different animal than a short-lived event. We usually assume short-lived events (3 to 8 days).**

This lecture will be posted Online at:

www.mst.edu/~rogersda/levees

Or write to rogersda@mst.edu