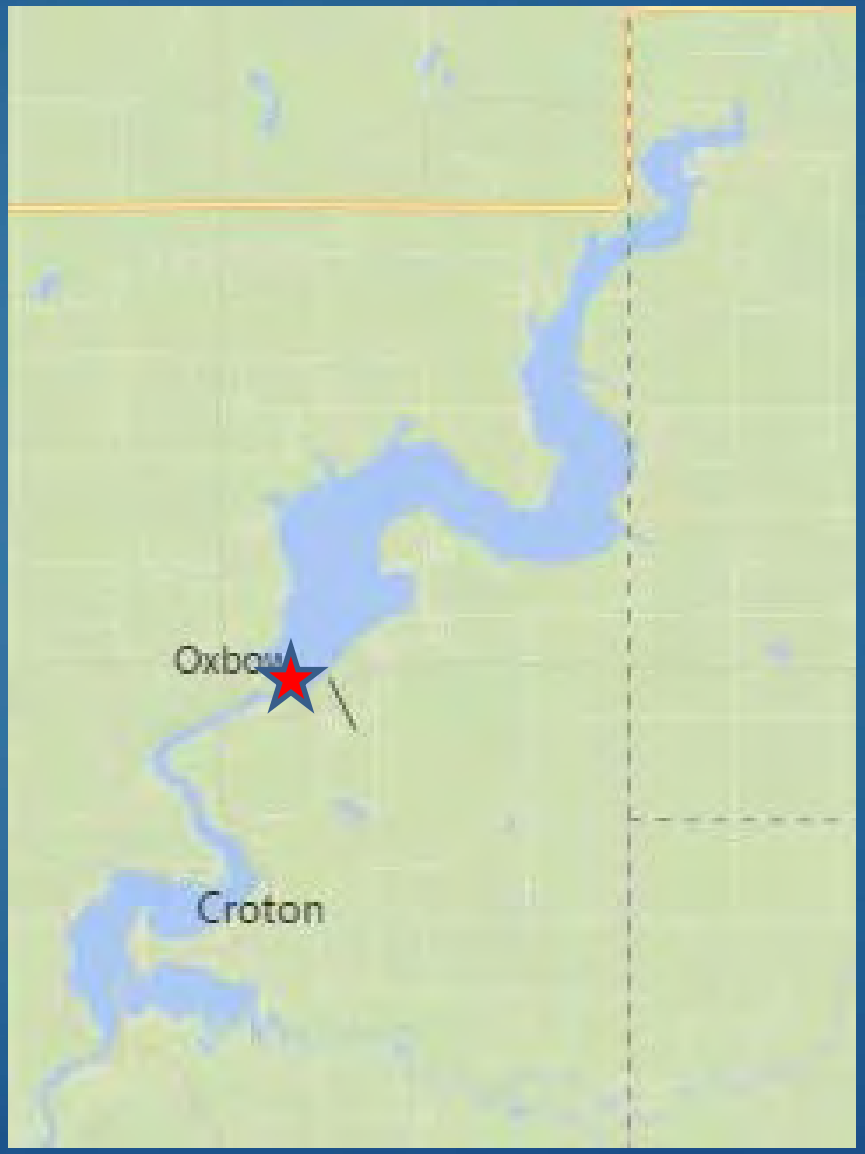
Hardy Dam

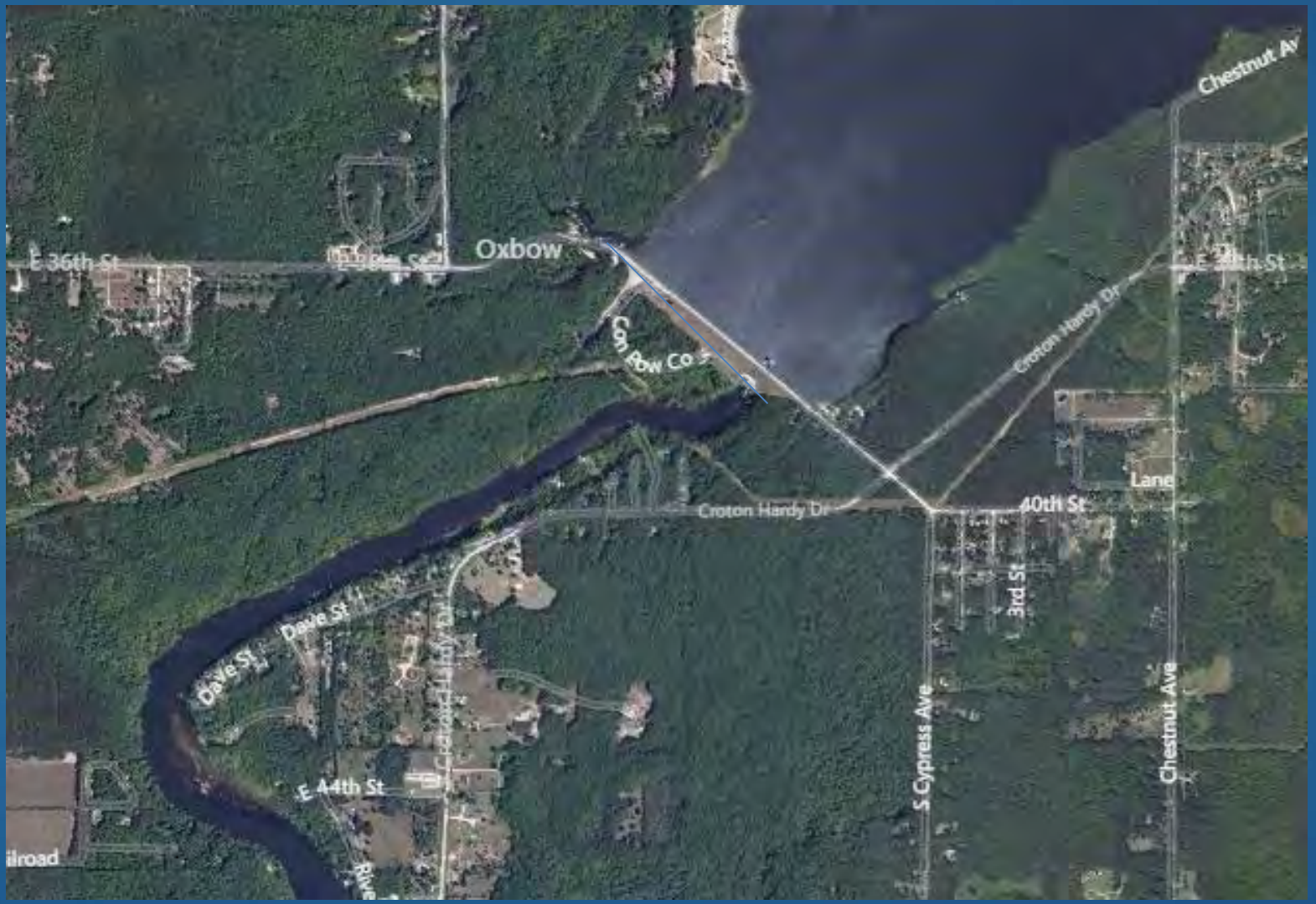
How 100 Years of Old Dusty Records, Observations by Karl Terzaghi and a Walk in the Woods Calmed the Artesian Anxieties

Gary D. Rogers, PG
Gerald Robblee, Loring P. Crowley
Adam Monroe, Marianne Walter, Consumers Energy
September 22, 2016

Where are We?
Glaciated Area of Michigan



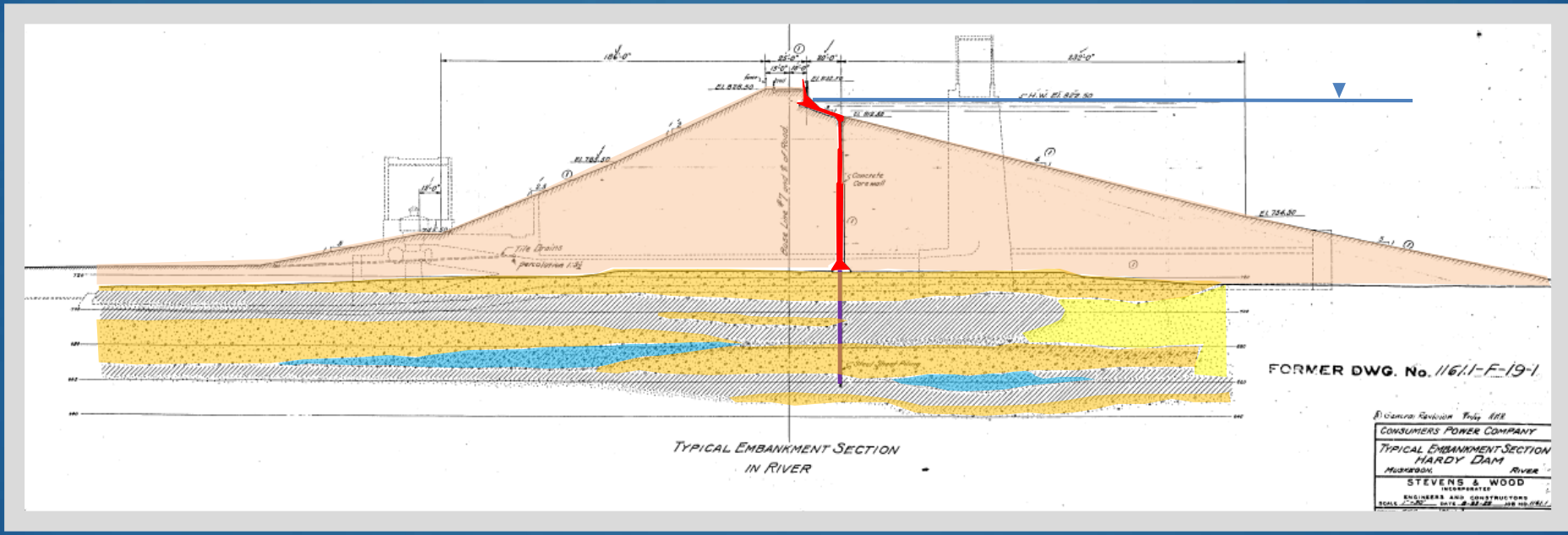
Where are We?
Incised Muskegon River Valley



Where are We?
Hardy Dam, Constructed 1929 -1931

Why All the Anxiety?

- Tallest dam in Michigan at 114 feet high
  - Largest dam east of Mississippi River when constructed



Why All the Anxiety?

- Constructed of uncompacted sand around a concrete corewall

Why All the Anxiety?

- Artesian pressures of 23 feet above tailrace water elevation, 13 feet above ground

Why All the Anxiety?

- Active springs and boils on land and in river

Why All the Anxiety?

- High permeability confined aquifer, capable of flowing 100s of gpm

Why All the Anxiety?

- Well, who wouldn’t be worried?

LETS DIG INTO THIS

1928 Karl Terzhagi and Arthur Casagrande

Geologic and Geotechnical Evaluation, and Conceptual Design

I have checked the report and signed it for Dr. Terzaghi.

Charles Terzaghi,
A. Casagrande

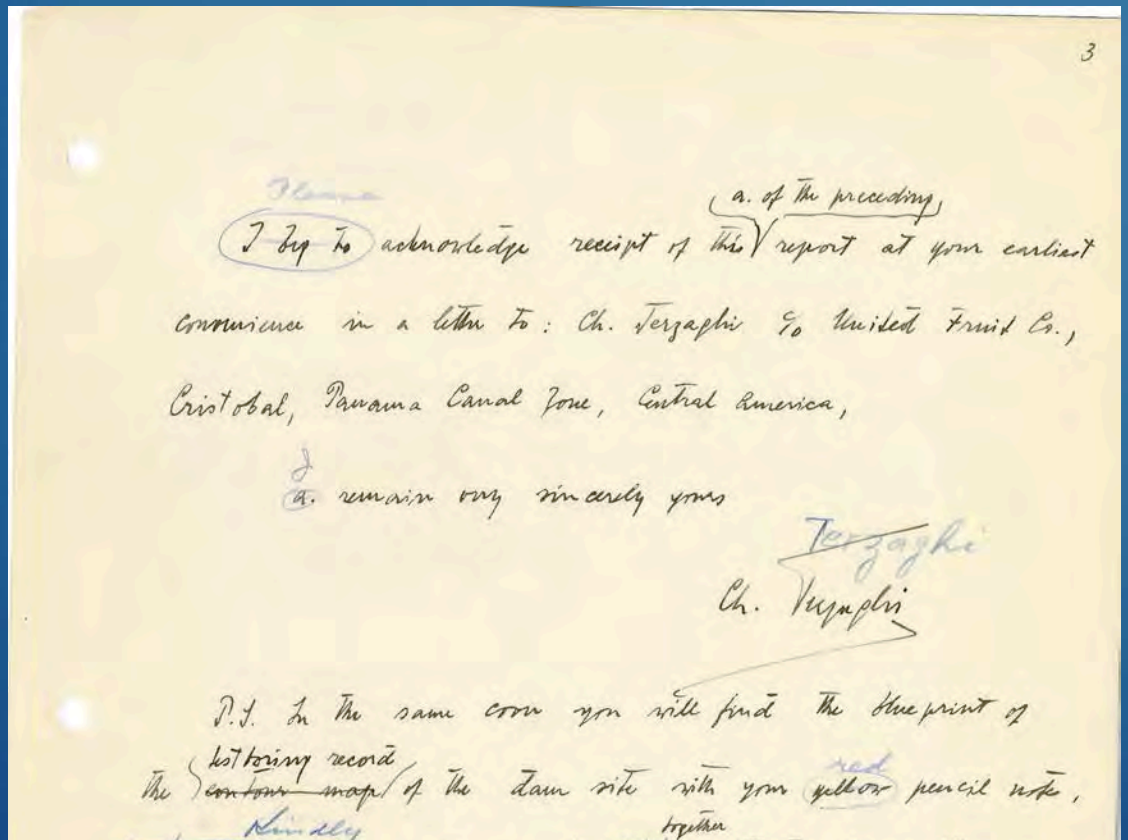
CHARLES TERZAGHI

Very truly yours,

Arthur Casagrande

Arthur Casagrande

Cambridge, Mass.
June 12, 1928.



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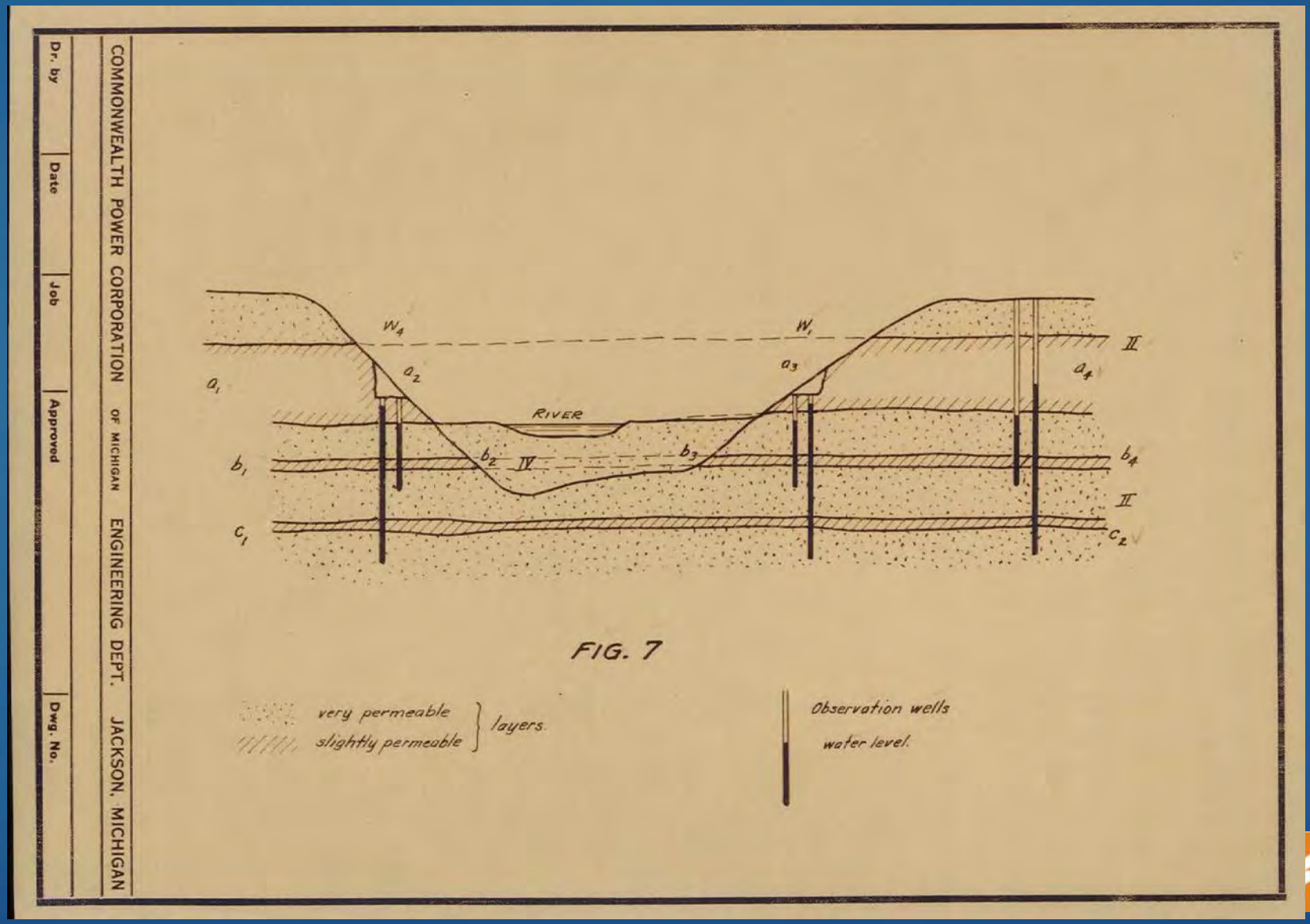
I beg to acknowledge receipt of the preceding report at your earliest convenience in a letter to: Ch. Terzaghi c/o United Fruit Co., Cristobal, Panama Canal Zone, Central America,

I remain very sincerely yours

Ch. Terzaghi

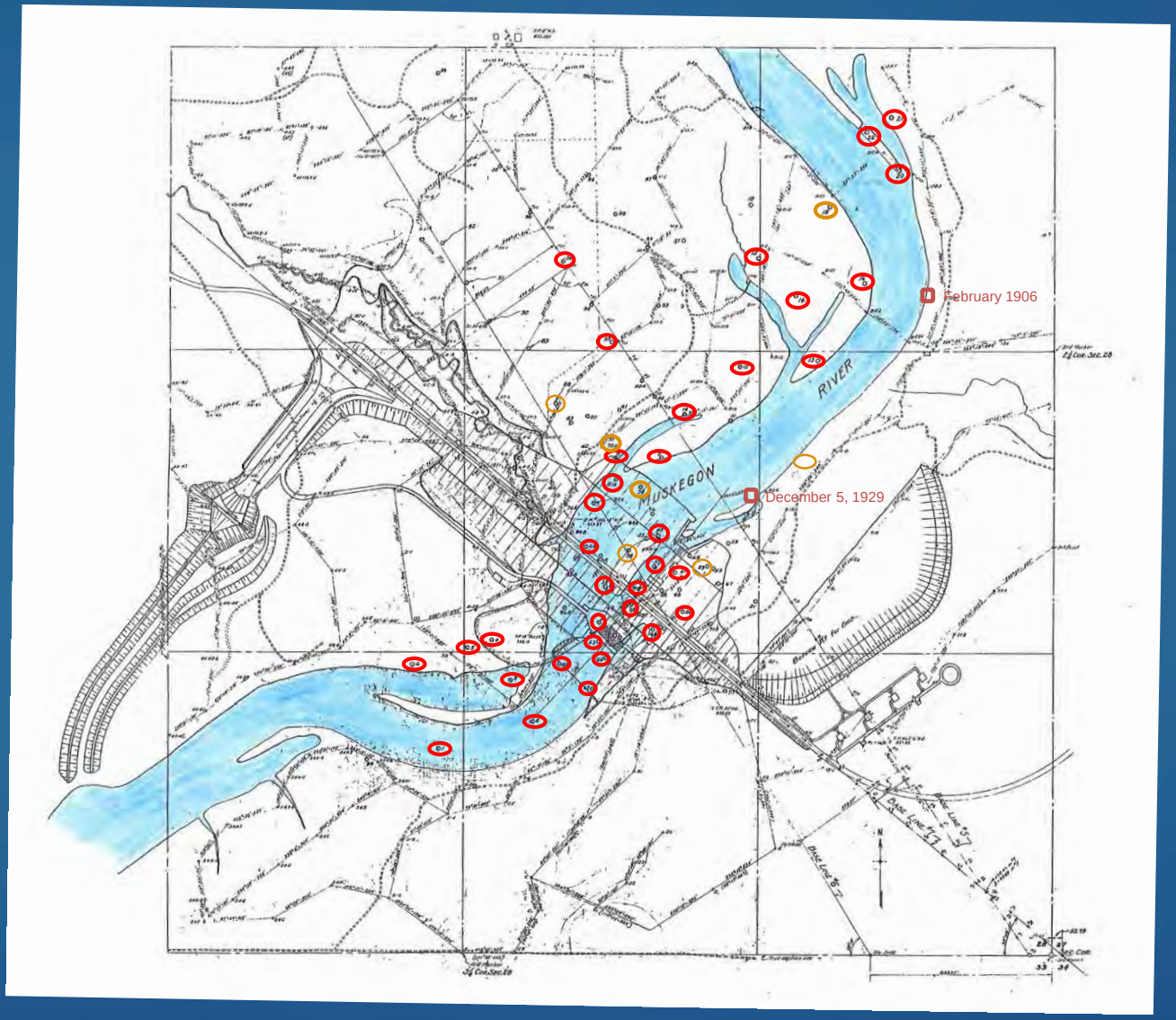
P.S. In the same cover you will find the blue print of the lettering record contour map of the dam site with your red yellow pencil note, kindly together

1928 Karl Terzhagi Conceptual Model



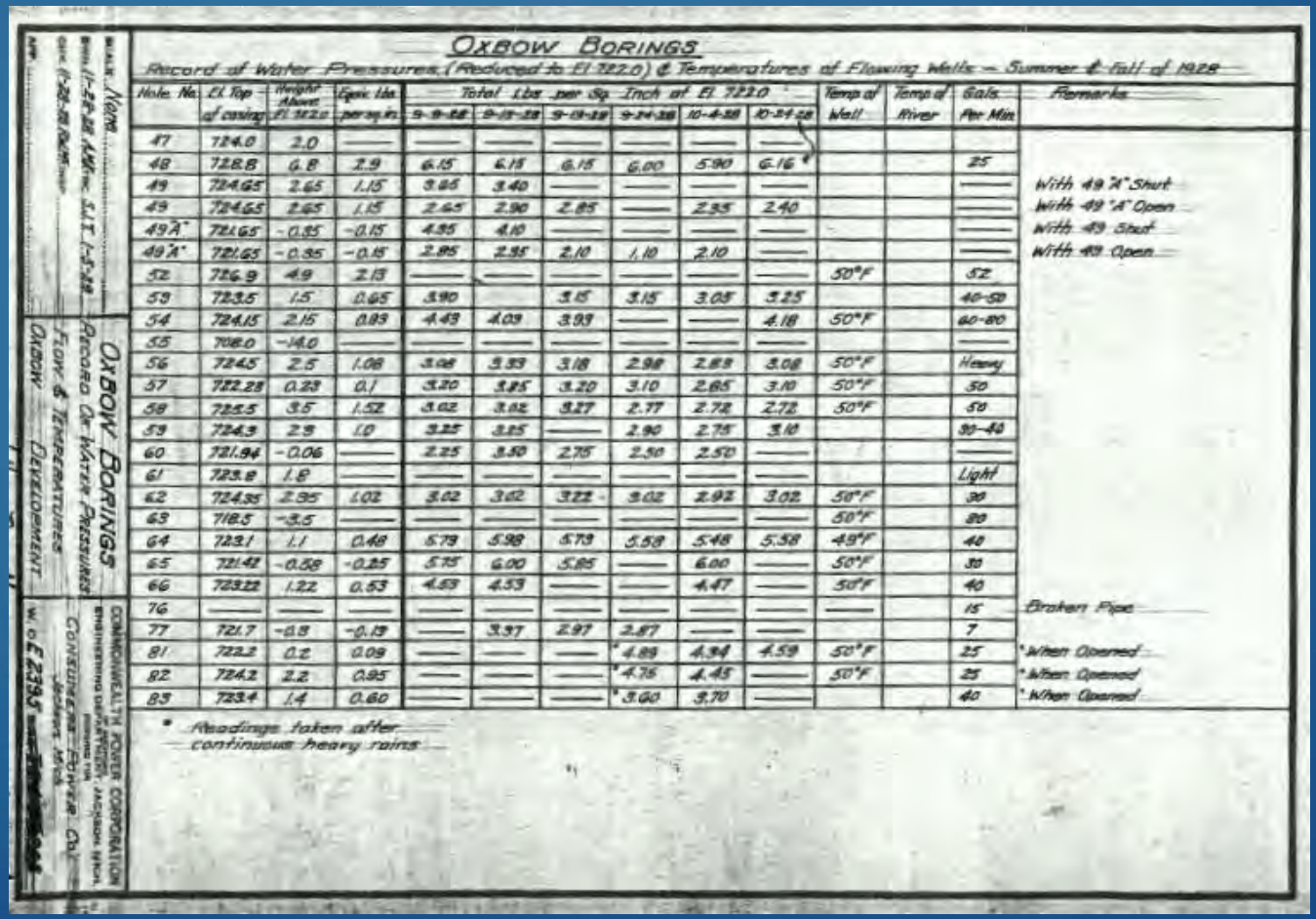
1907 – 1928 Artesian Conditions

- Heaved
- Flowing Water
- Boil/Spring



1928 Boring Temperatures and Pressures

- Artesian head at 7 ft above river level (El 736.2 ft)



OXBOW BORINGS

Record of Water Pressures (Reduced to El 722.0) & Temperatures of Flowing Wells — Summer & Fall of 1928

Hole No.	El. Top of casing	Height Above El 722.0	Equiv. lbs. per sq. in.	Total Lbs. per Sq. Inch at El 722.0 9-9-28	9-13-28	9-19-28	9-24-28	10-4-28	10-24-28	Temp. of Well	Temp. of River	Gals. Per Min.	Remarks
47	724.0	2.0	——	——	——	——	——	——	——				
48	728.8	6.8	2.9	6.15	6.15	6.15	6.00	5.90	6.16			25	
49	724.65	2.65	1.15	3.85	3.40	——	——	——	——			——	With 49 "A" Shut
49	724.65	2.65	1.15	2.65	2.90	2.85	——	2.35	2.40			——	With 49 "A" Open
49 "A"	721.65	-0.35	-0.15	4.35	4.10	——	——	——	——			——	With 49 Shut
49 "A"	721.65	-0.35	-0.15	2.85	2.35	2.10	1.10	2.10	——			——	With 49 Open
52	726.9	4.9	2.13	——	——	——	——	——	——	50°F		52	
53	723.5	1.5	0.65	3.90		3.15	3.15	3.05	3.25			40-50	
54	724.15	2.15	0.89	4.43	4.09	3.93	——	——	4.18	50°F		60-80	
55	708.0	-14.0	——	——	——	——	——	——	——			——	
56	724.5	2.5	1.08	3.08	3.33	3.18	2.98	2.88	3.08	50°F		Heavy	
57	722.28	0.23	0.1	3.20	3.25	3.20	3.10	2.85	3.10	50°F		50	
58	725.5	3.5	1.52	3.02	3.02	3.27	2.77	2.72	2.72	50°F		58	
59	724.3	2.3	1.0	3.25	3.25	——	2.90	2.75	3.10			30-40	
60	721.94	-0.06	——	2.25	3.50	2.75	2.50	2.50	——			——	
61	723.8	1.8	——	——	——	——	——	——	——			Light	
62	724.35	2.35	1.02	3.02	3.02	3.22	3.02	2.92	3.02	50°F		30	
63	718.5	-3.5	——	——	——	——	——	——	——	50°F		20	
64	723.1	1.1	0.48	5.73	5.98	5.73	5.58	5.48	5.58	48°F		48	
65	721.42	-0.58	-0.25	5.75	6.00	5.85	——	6.00	——	50°F		30	
66	723.22	1.22	0.53	4.53	4.53	——	——	4.47	——	50°F		40	
76	——	——	——	——	——	——	——	——	——	——		15	Broken Pipe
77	721.7	-0.8	-0.19	——	3.37	2.97	2.87	——	——			7	
81	722.2	0.2	0.09	——	——	——	*4.89	4.34	4.59	50°F		25	*When Opened
82	724.2	2.2	0.95	——	——	——	*4.75	4.45	——	50°F		25	*When Opened
83	723.4	1.4	0.60	——	——	——	*3.60	3.70	——			40	*When Opened

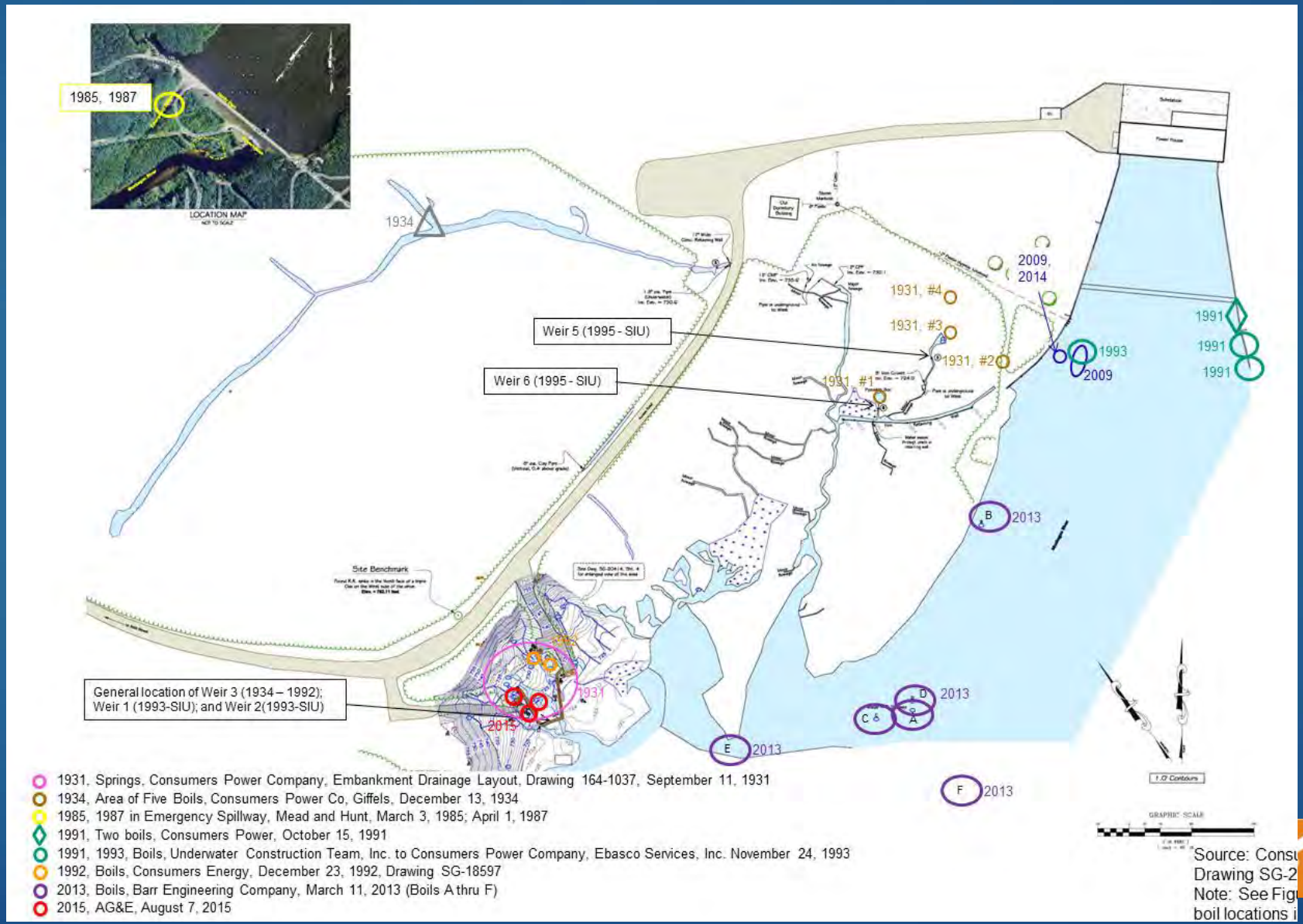
* Readings taken after continuous heavy rains

OXBOW BORINGS
RECORD OF WATER PRESSURES
FLOW & TEMPERATURES
OXBOW DEVELOPMENT

COMMONWEALTH POWER CORPORATION
CONSULTING ENGINEERS

BOIL IN RIVER - 1929

Location of Boils 1931- 2015



Let's Sidetrack for a Minute

FOUNDATION PREPARATION AND DRILLING, NOV 1929

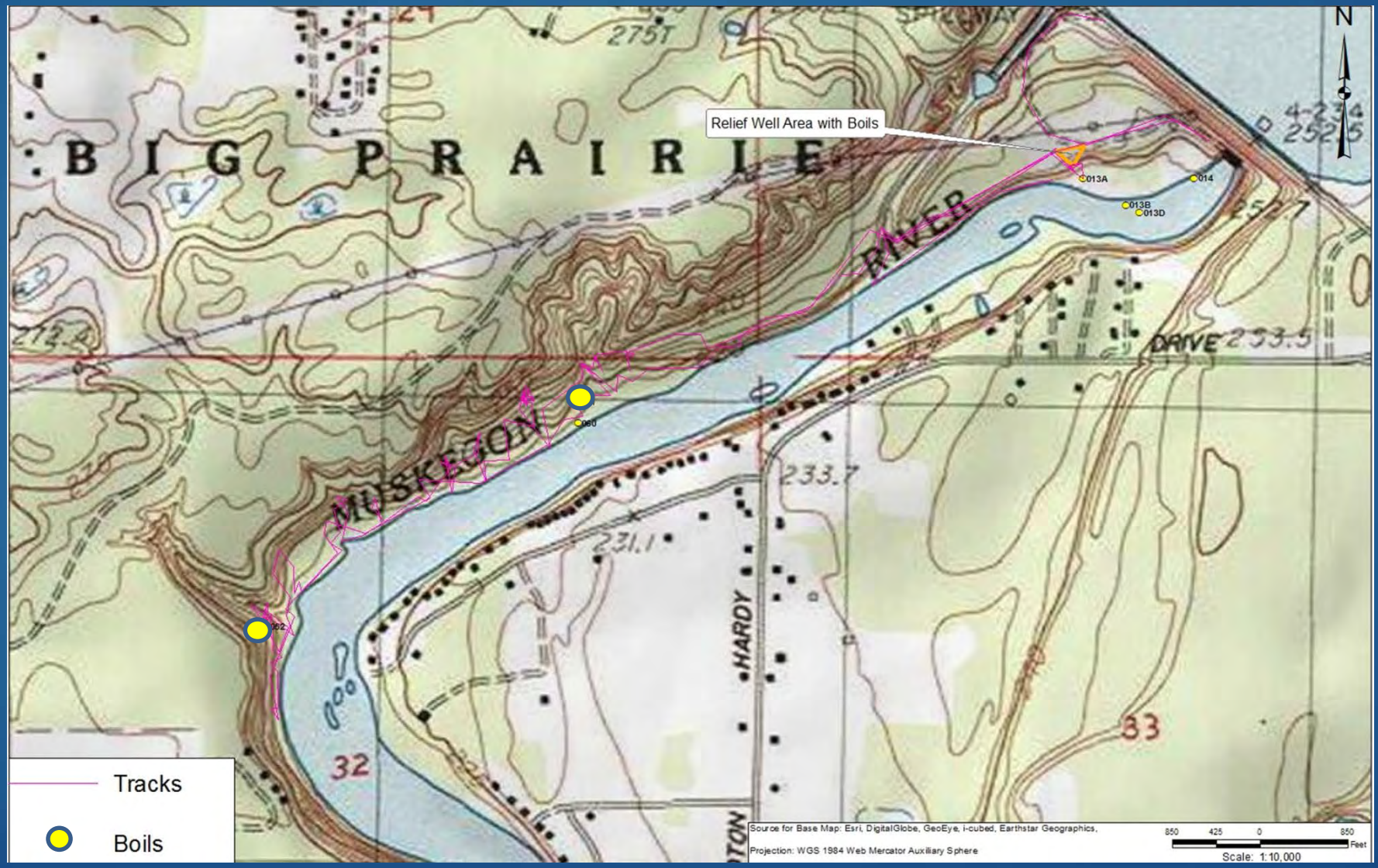
FOUNDATION EXCAVATION AND DRILLING, NOV 1929

POWERHOUSE AND TAILRACE AREA, MARCH 1930

Now, Let's Walk Around and Take a Wider (Geologist's) View

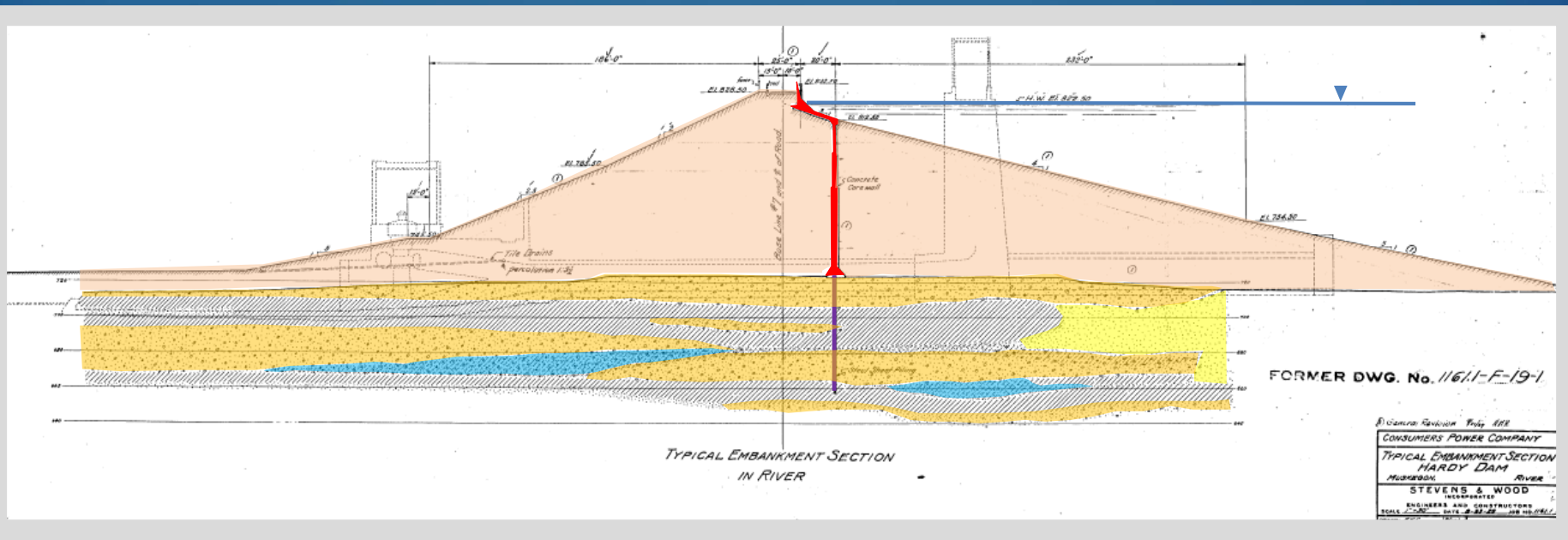
Muskegon River Downcut into Broad Upland Plain

Boils Downstream of Dam Found in 2015



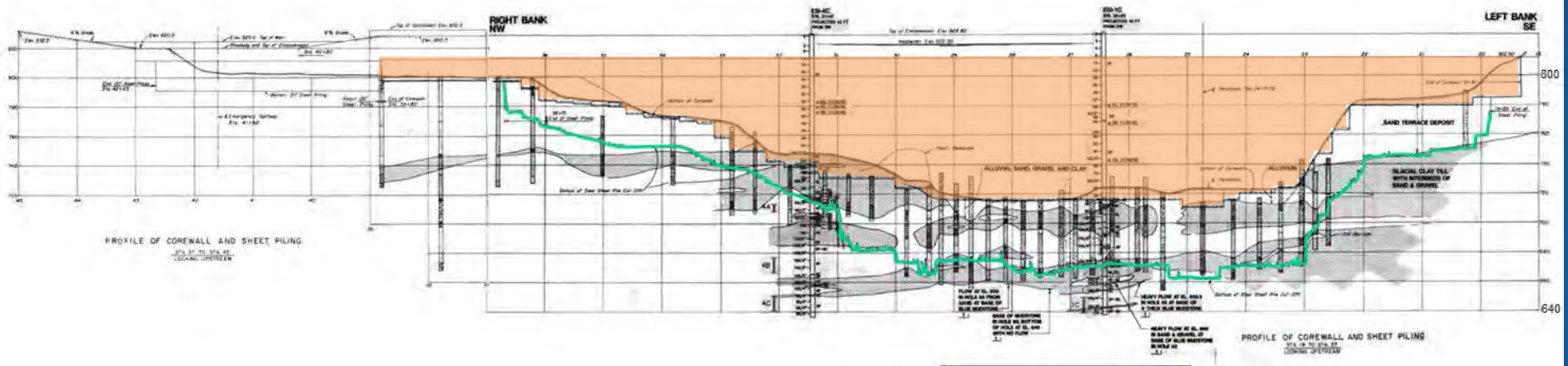
Boils Downstream of Dam

Dam Section

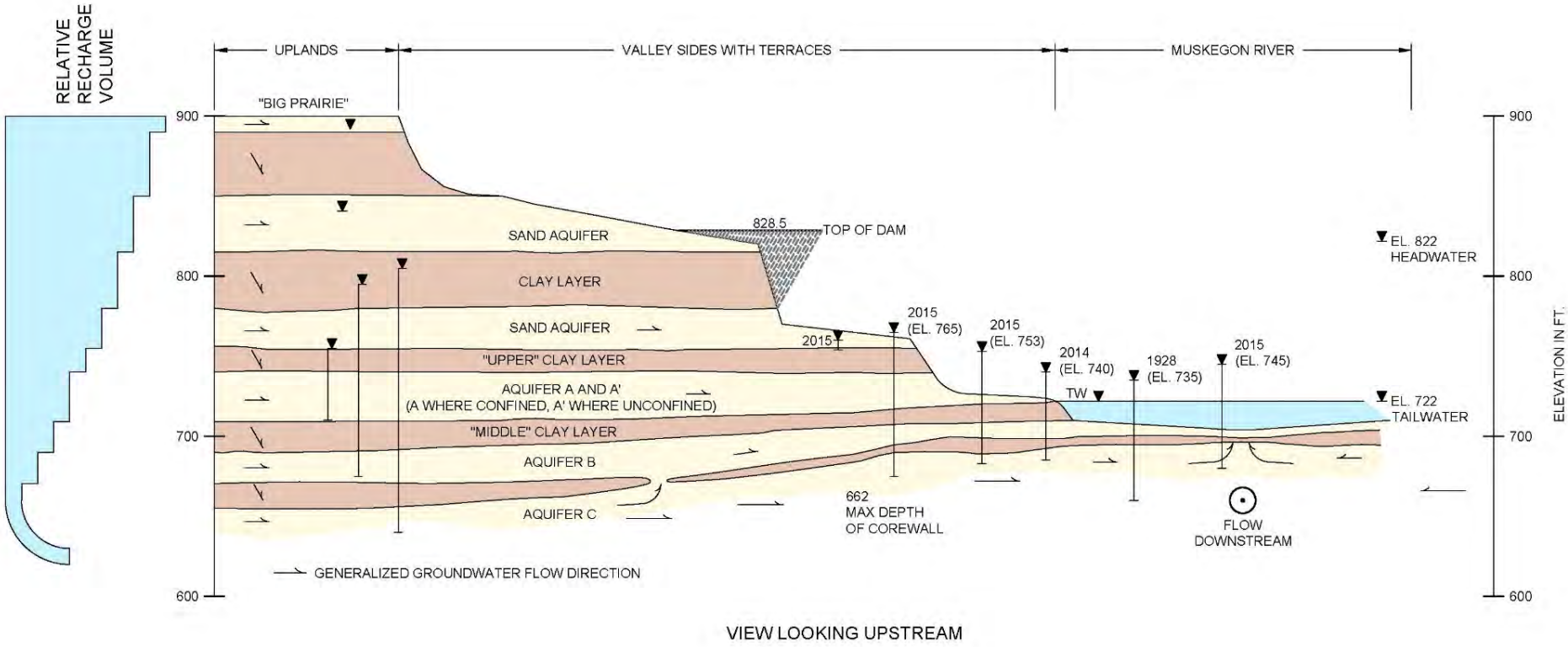


TYPICAL EMBANKMENT SECTION
IN RIVER

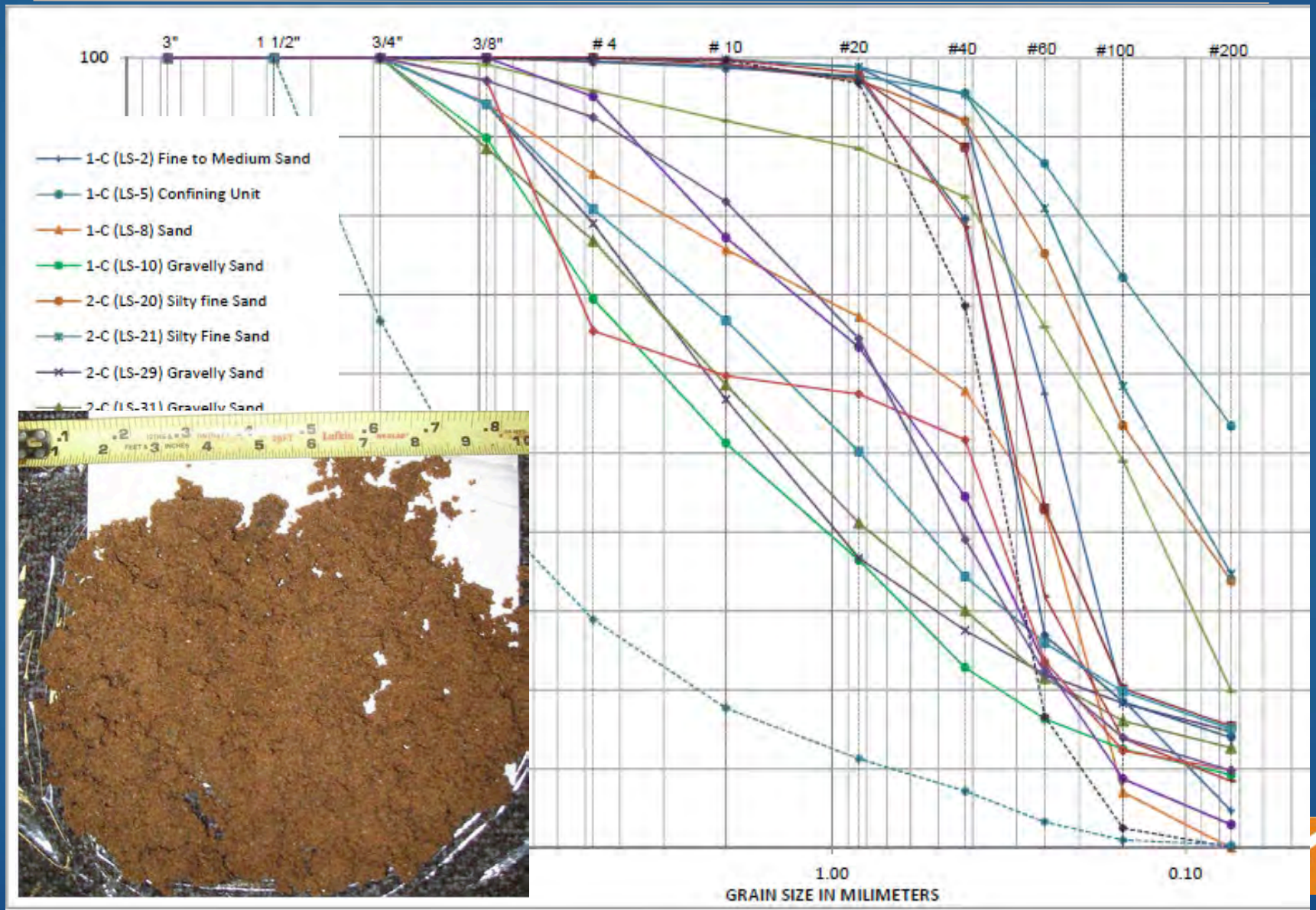
Dam Profile


RIGHT BANK
NW
LEFT BANK
SE
800
640
PROFILE OF COREWALL AND SHEET PILING
PROFILE OF COREWALL AND SHEET PILING
ALLUVIAL SAND, GRAVEL AND CLAY
ALLUVIUM
SAND TERRACE DEPOSIT
GLACIAL CLAY TILL WITH INTERBEDS OF SAND & GRAVEL
1929 Riverbank at Corewall Sta to 24+98 29+26
1929 Riverbank at End of Tailrace Sta 23+65 to 26+30
Base of ~ El 725 ft bluff at Corewall Sta to 23+00 to 29+50
Base of ~ El 725 ft bluff at End of Tailrace Sta to 23+55 to 29+30

2015 CONCEPTUAL MODEL



Self-filtering Analysis



Self-filtering Analysis - Example

Why be Calm?

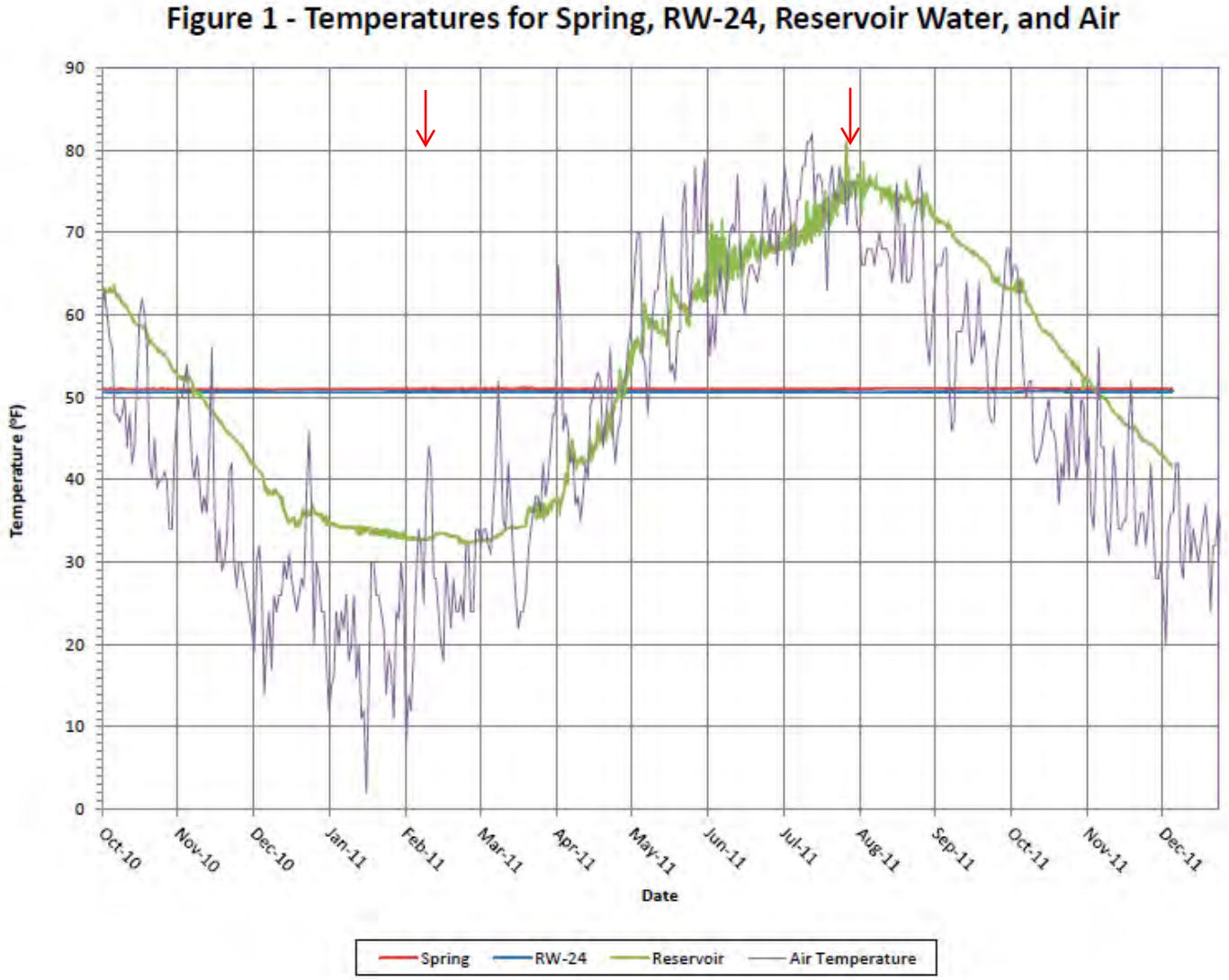
- Strong evidence that artesian pressures are abutment driven, not reservoir driven
- Clay aquitards reduce potential for artesian flow at surface
- Engineering evaluation shows that sand and gravel aquifers are well graded and will self filter
- Historical record of self filtering boils

Calm Does Not Mean Complacent

- Robust, ongoing monitoring program
- Daily and weekly documented visual observations
- Instrumentation program is migrating to vibrating wire piezometers and real time monitoring system

Thanks to the Crews Who Built the Plant

Groundwater Temperature

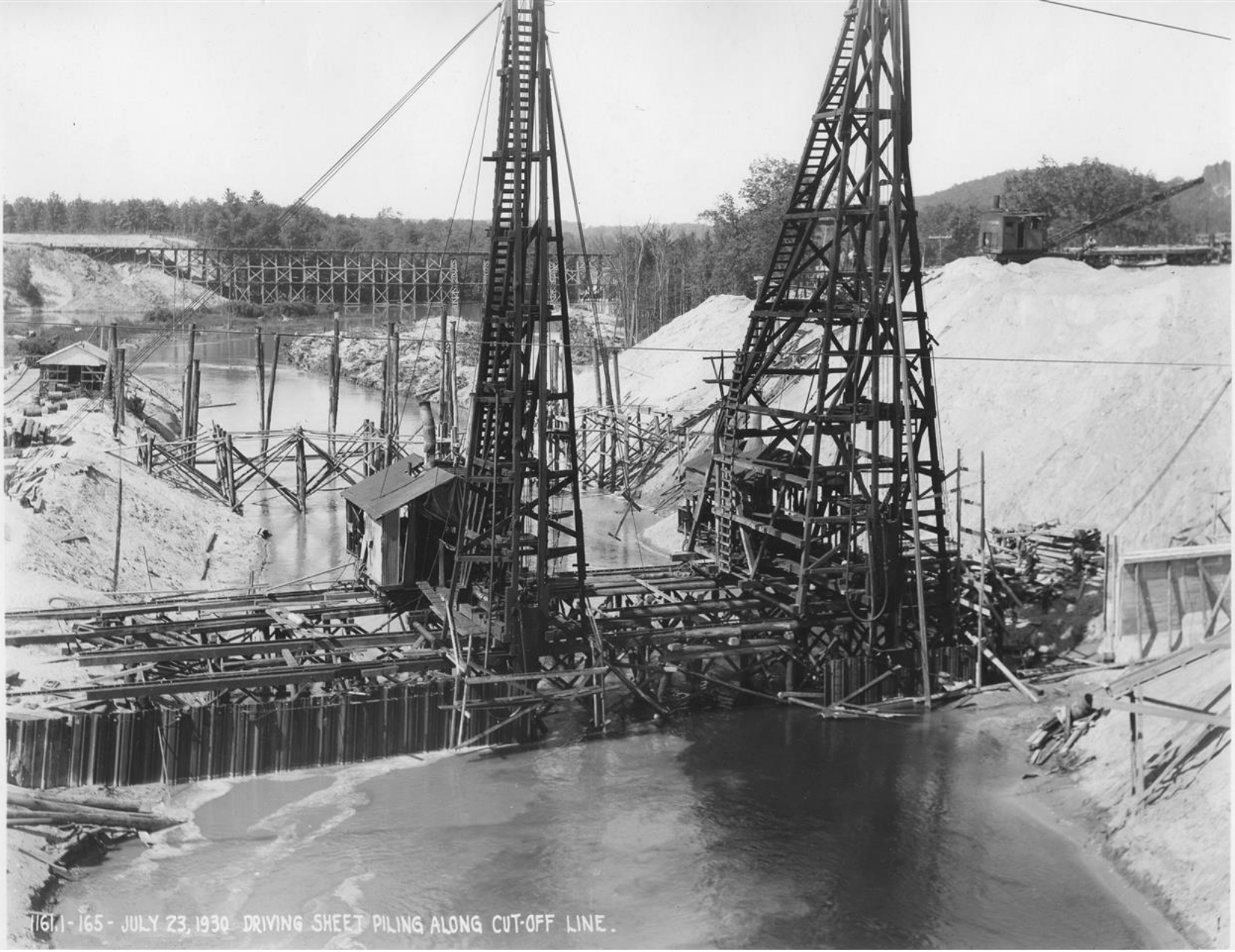


Three Things to Remember

- Use What You Own
- Look Around
- Tell the Story

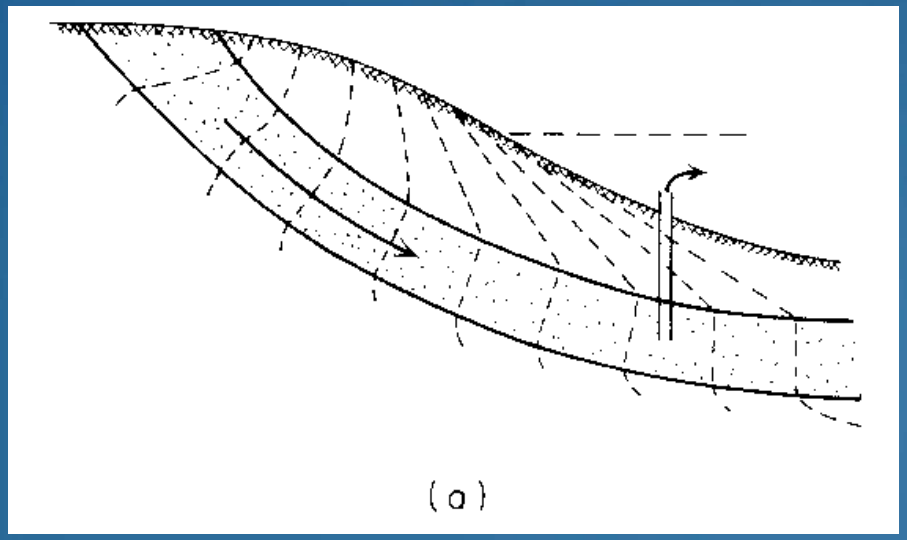
POWERHOUSE AND TAILRACE EXCAVATION, MAY 1930

CONSTRUCTION PROGRESS, JULY 1930

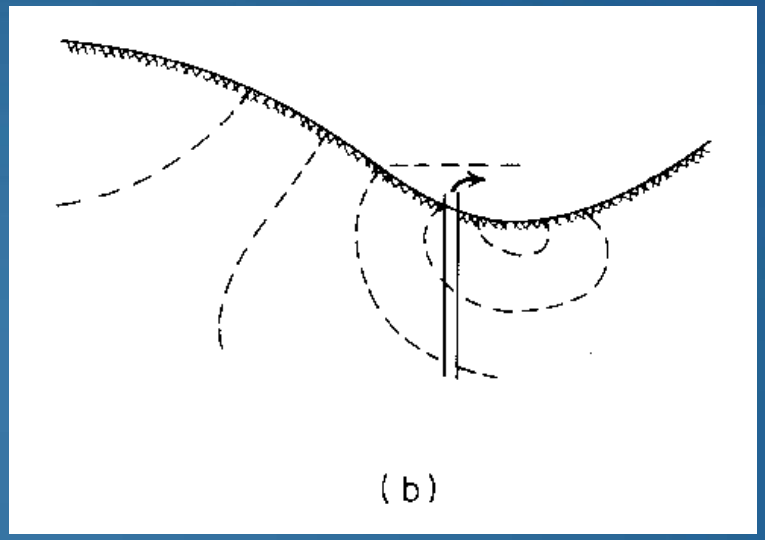


FINAL PILE DRIVING AT DAM CENTERLINE, JULY 1930

ARTESIAN CONDITIONS
Flowing Artesian Wells



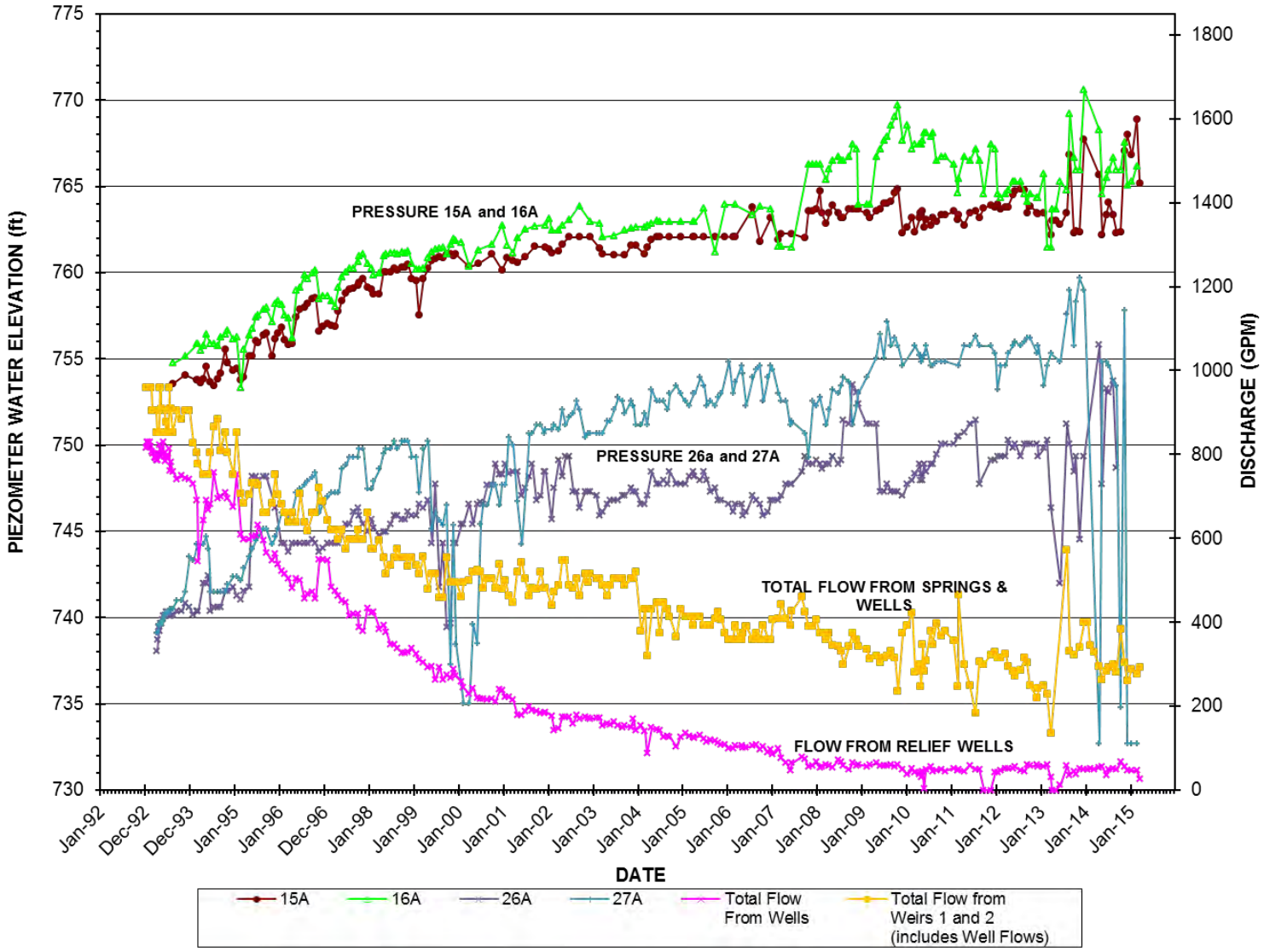
Geologically Controlled



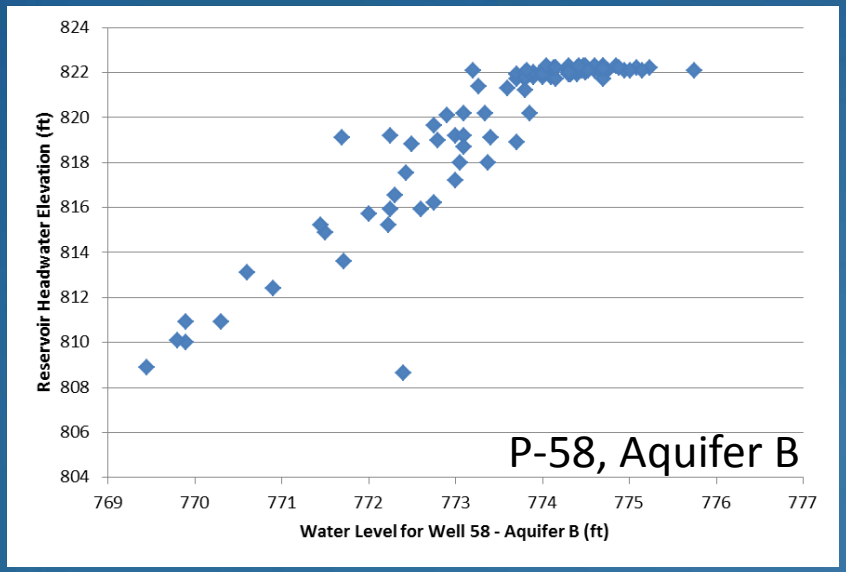
Topographically Controlled

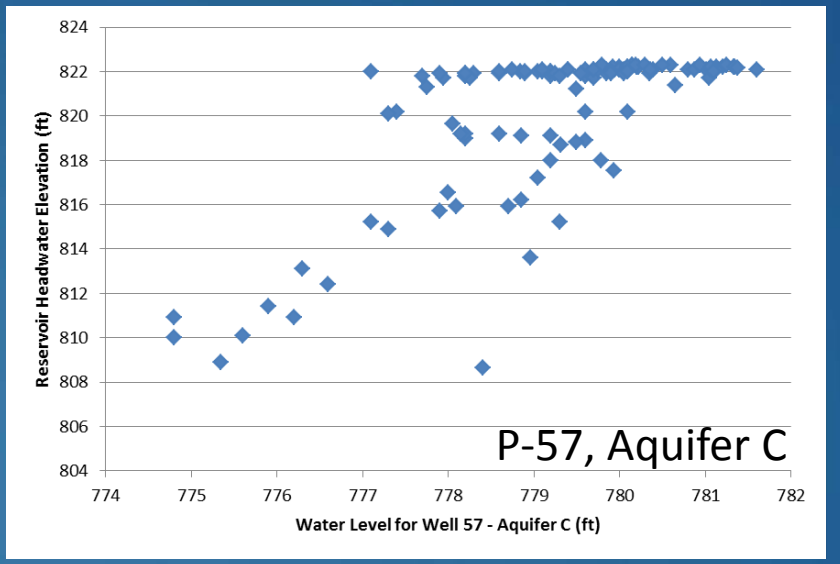
From Freeze and Cherry, 1979

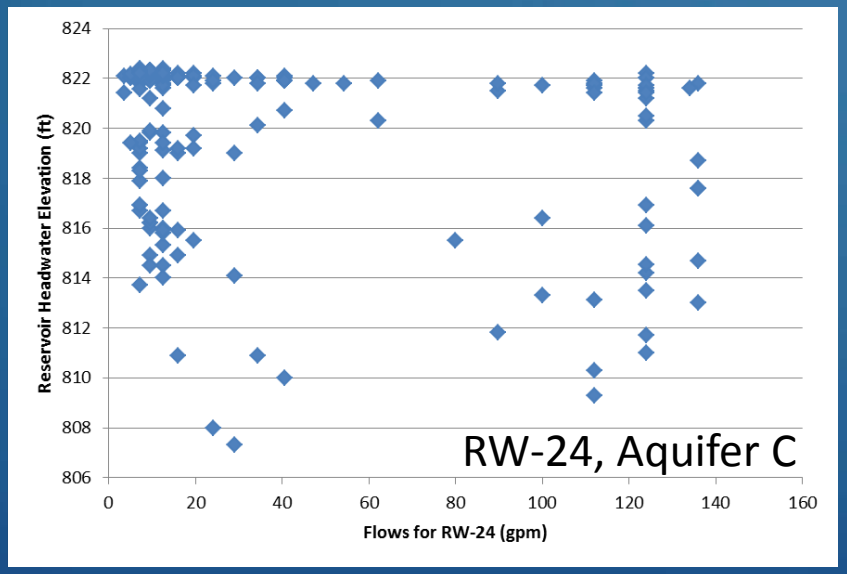
Relief Well Monitoring

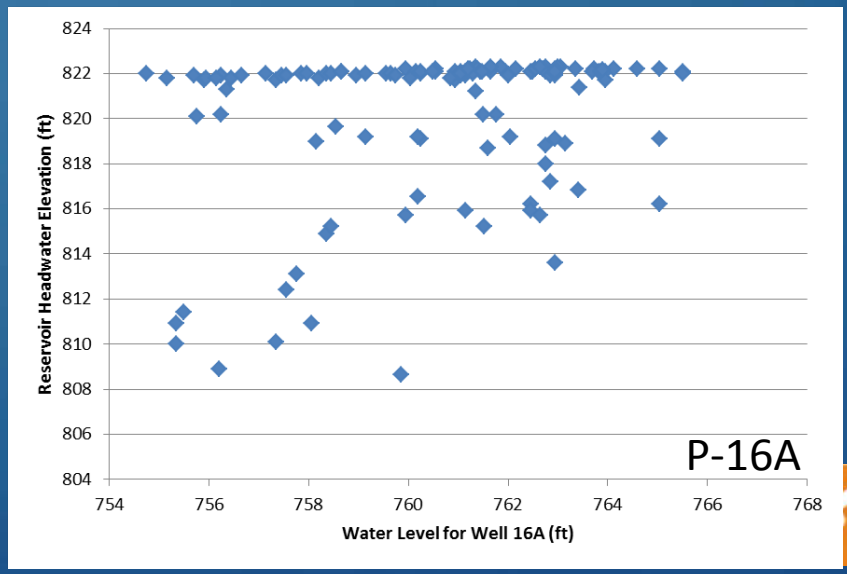


Correlation Charts









River Boils
Remediation Options