A Reservoir Level Restriction Toolbox

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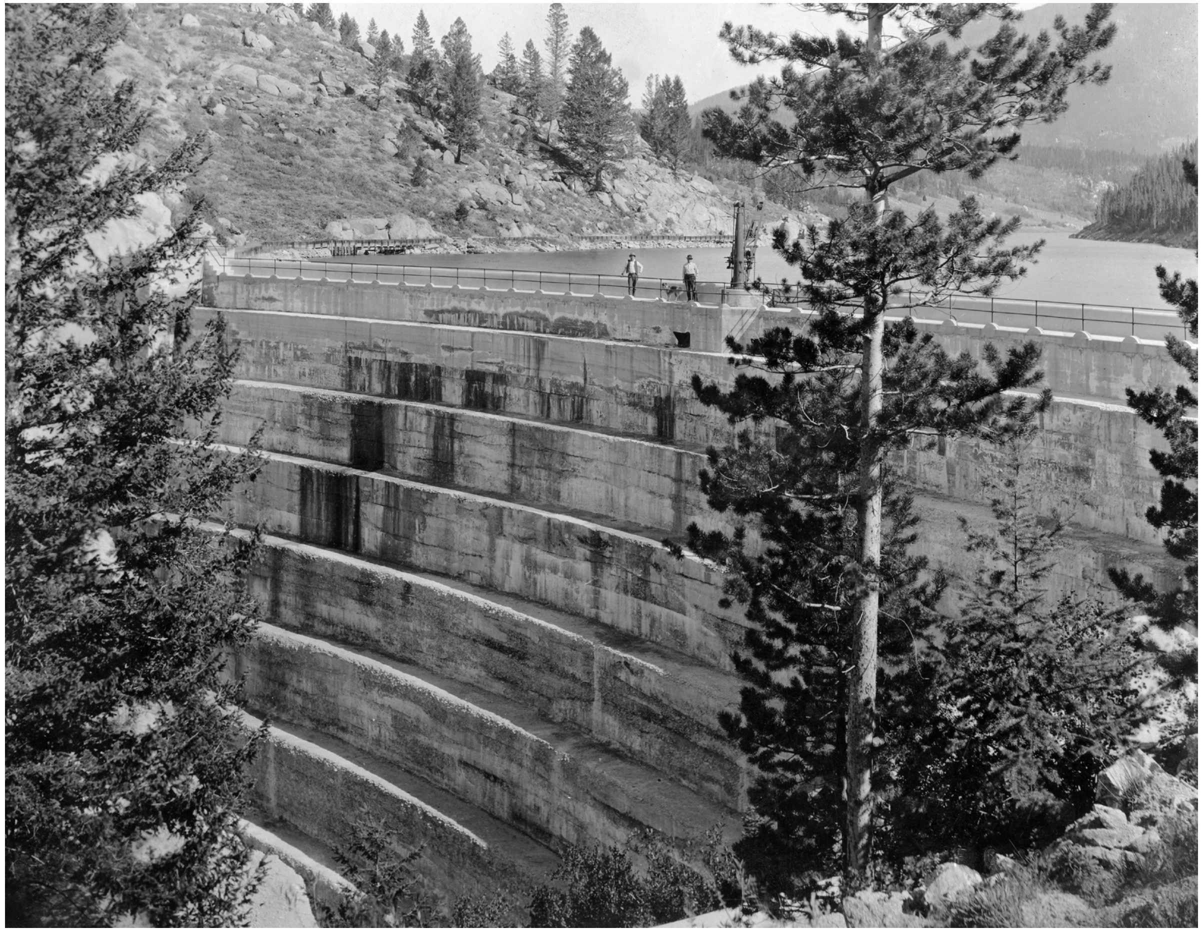


The Montana Department of Natural Resources & Conservation

DAM SAFETY
Palm Springs
SEPTEMBER 17-21, 2023

Why Do We Restrict Dams?

- Most effective way to reduce risk
  - Reduces load/pressure on all parts of system
  - Reduces downstream consequences

Why are restrictions contentious?

- Property rights
  - Government taking
  - Require justification
- Downstream public
  - Also have rights
  - Risks partially borne by them

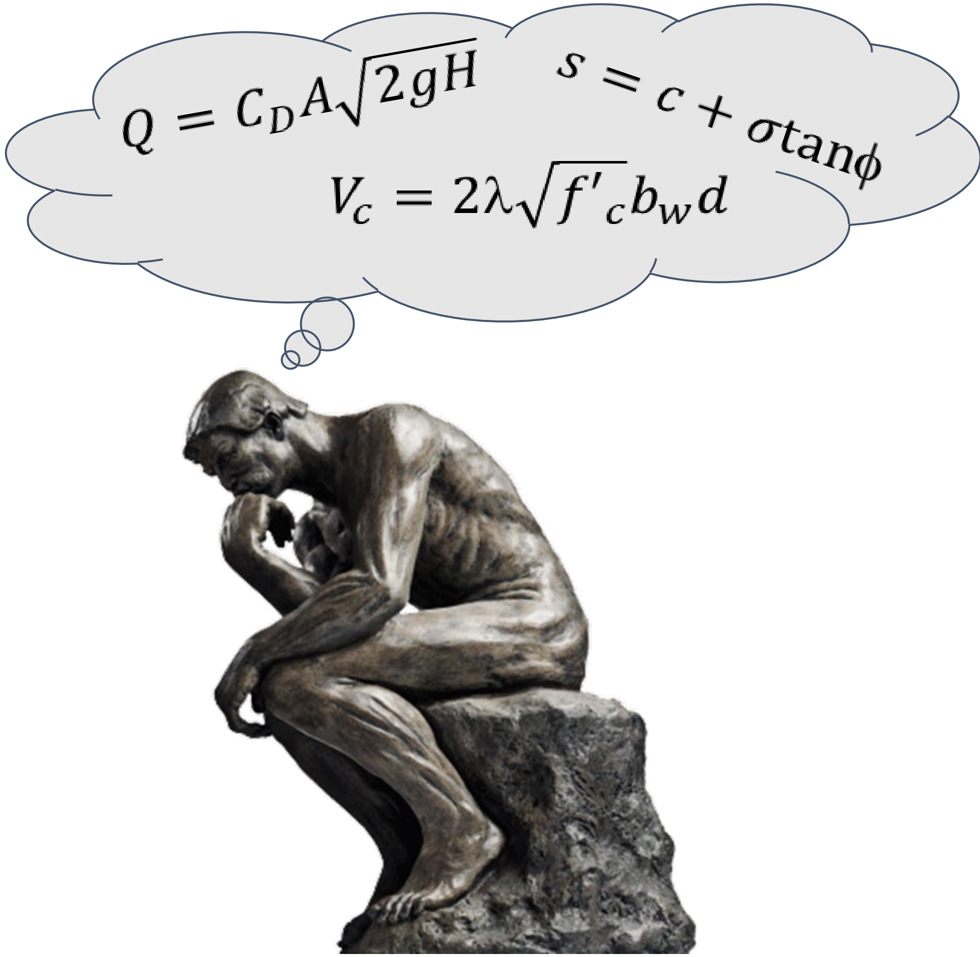
How much is enough?

- It depends…
  - Consequences
  - Critical loading
  - Failure mechanism
  - Owner diligence
  - Instrumentation/monitoring
  - Emergency action plan
  - Early warning system
  - Access to dam

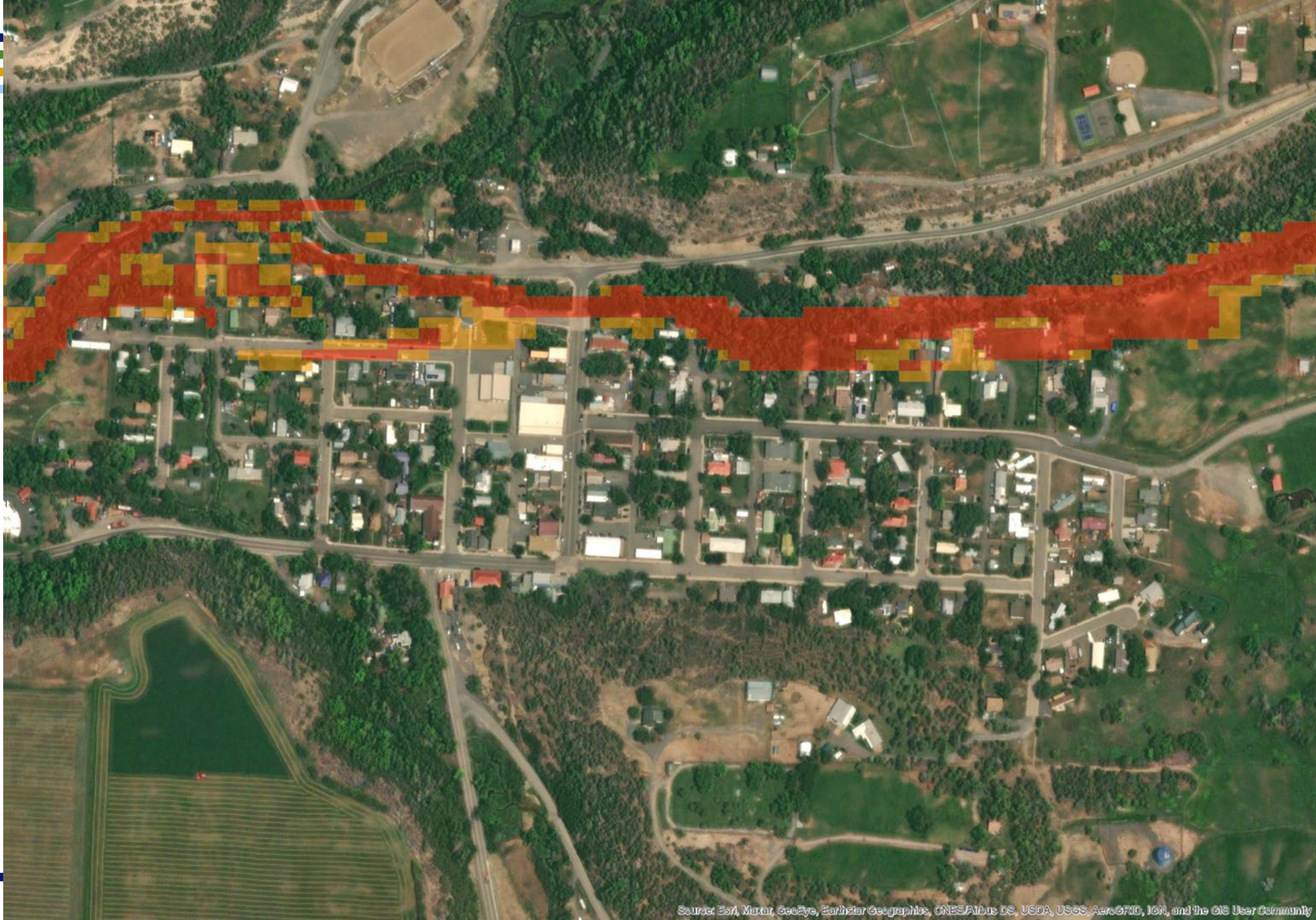
Source: Reuters.com

How much analysis is needed to justify?

- It depends…
  - Consequences
  - Critical loading
  - Failure mechanism
- Burden of proof
- Enough to stand up in court?
- Prove me wrong

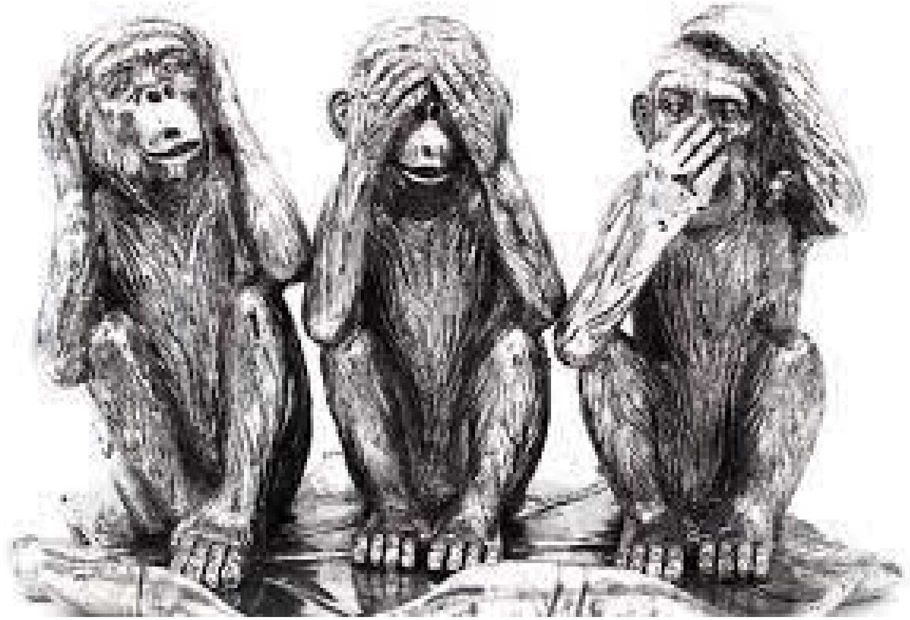


Consequ


Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Simple observational approach

- A first-pass approach relies on:
  - Visual observations
  - Instrumentation/monitoring data
- Limited data and simplifying assumptions require a conservative approach

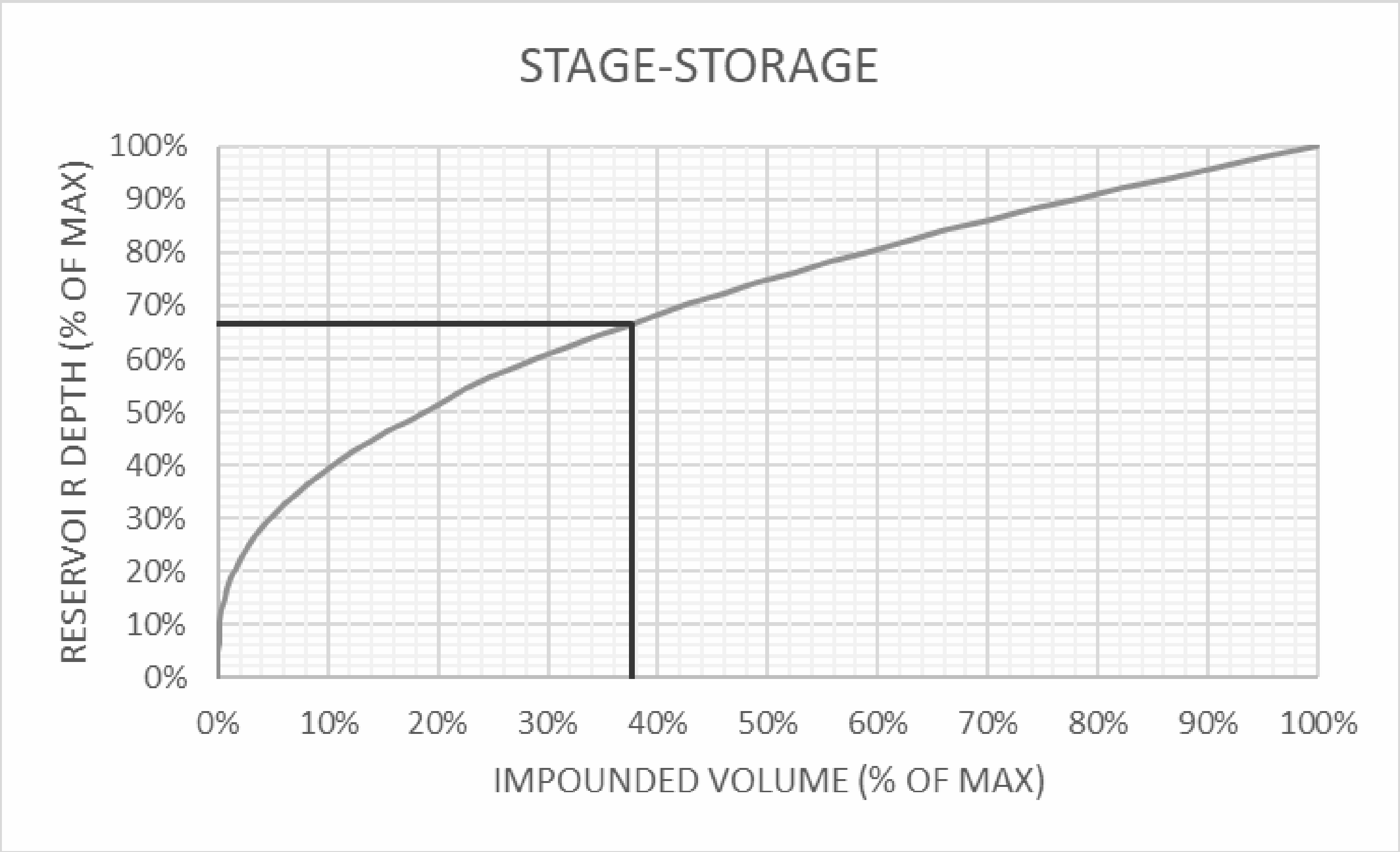


Simple observational approach

- Examples:
  - Cloudy seepage
  - Increasing seepage over time
  - Phreatic surface changes observed in piezometers
  - Unfiltered seepage emanating on the downstream face
  - Spillway/outlet structures deteriorated

Simple observational approach

- Potential starting point :
  - Lower reservoir by one-third depth; roughly halve hydrostatic head by
  - UK Environment Agency (2017)



Simple observational approach

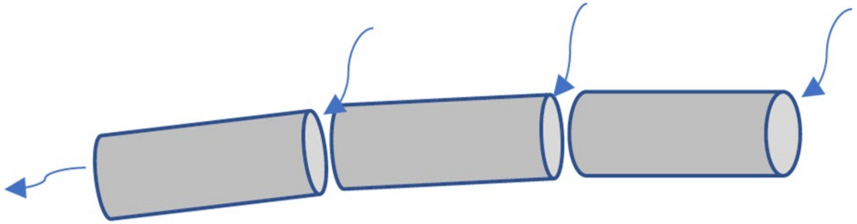
- Regulator document and describe observations to owner
  - Owner’s engineer should further evaluate
- Adequacy must be evaluated
  - E.g., if restriction eliminates cloudy seepage, would high-frequency rainfall event load dam beyond acceptable limits?
  - Proceed to Intermediate Approach

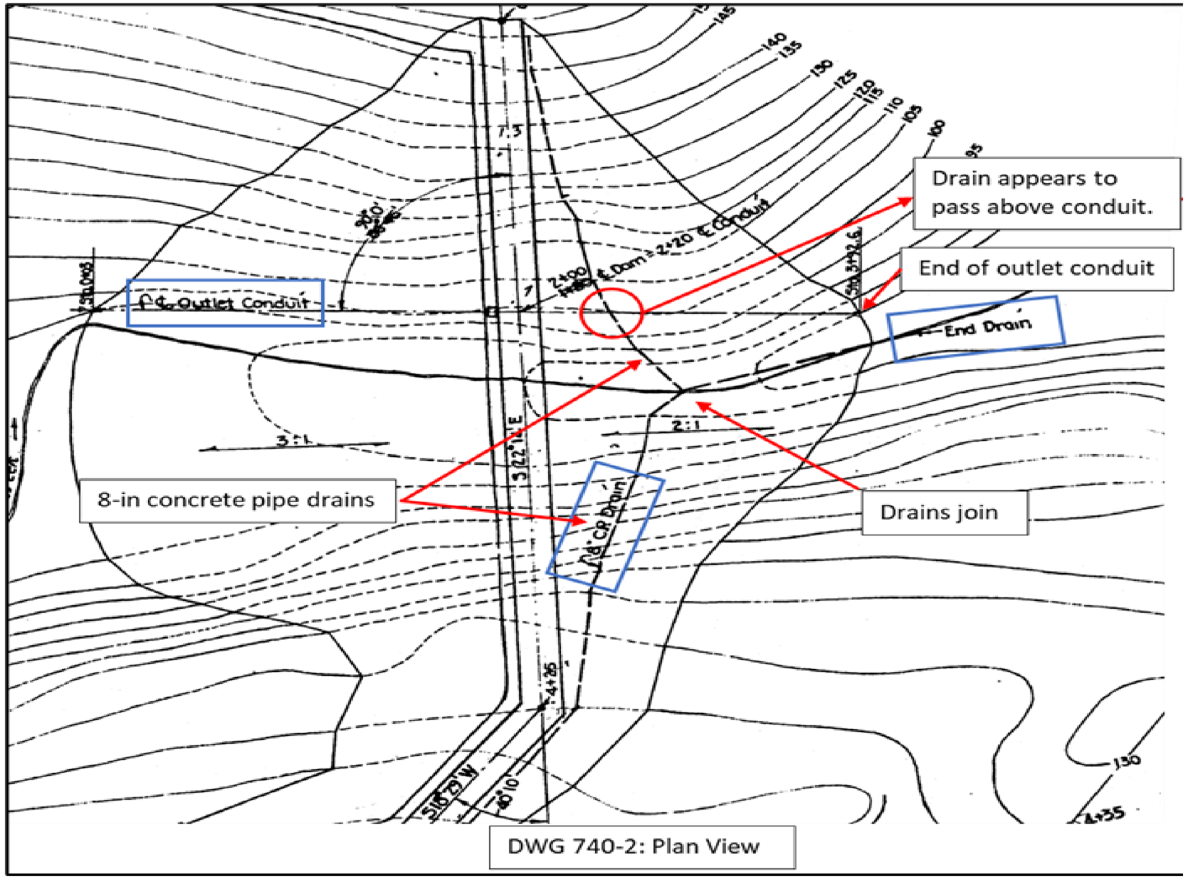
Case study – Muddy Waters

- 1950s construction, 80-ft, 1,500 AF high-hazard dam
- Historically very high seepage rates through embankment, glacial moraine – failed grouting attempt
- Sinkholes in reservoir; seepage upwelling downstream

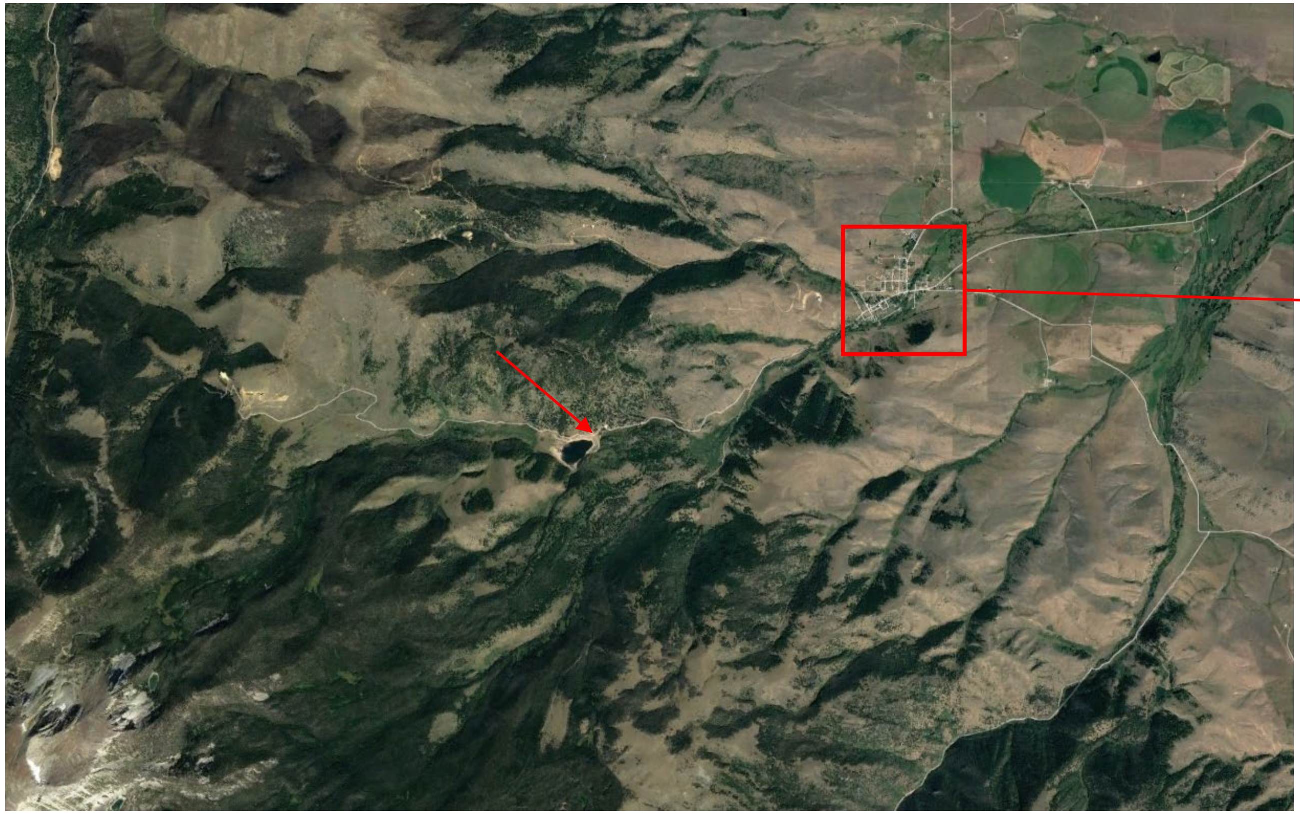
Case study – Muddy Waters

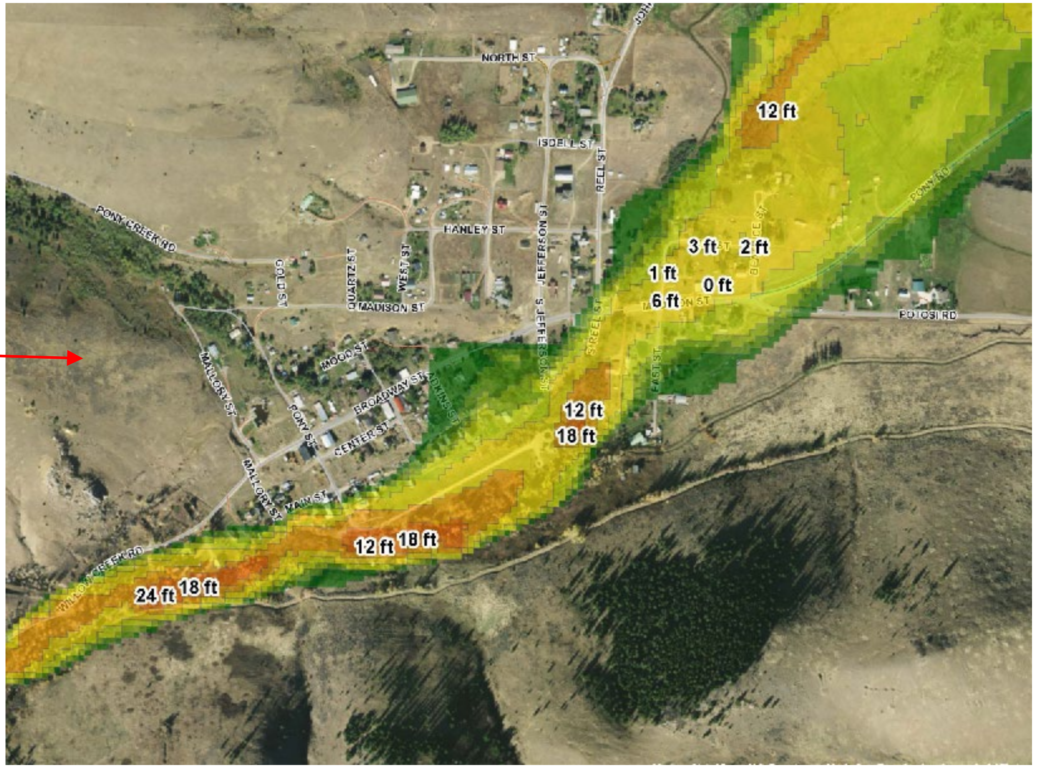
- Back-to-back “first fills” in 2010s
- Evidence of internal erosion



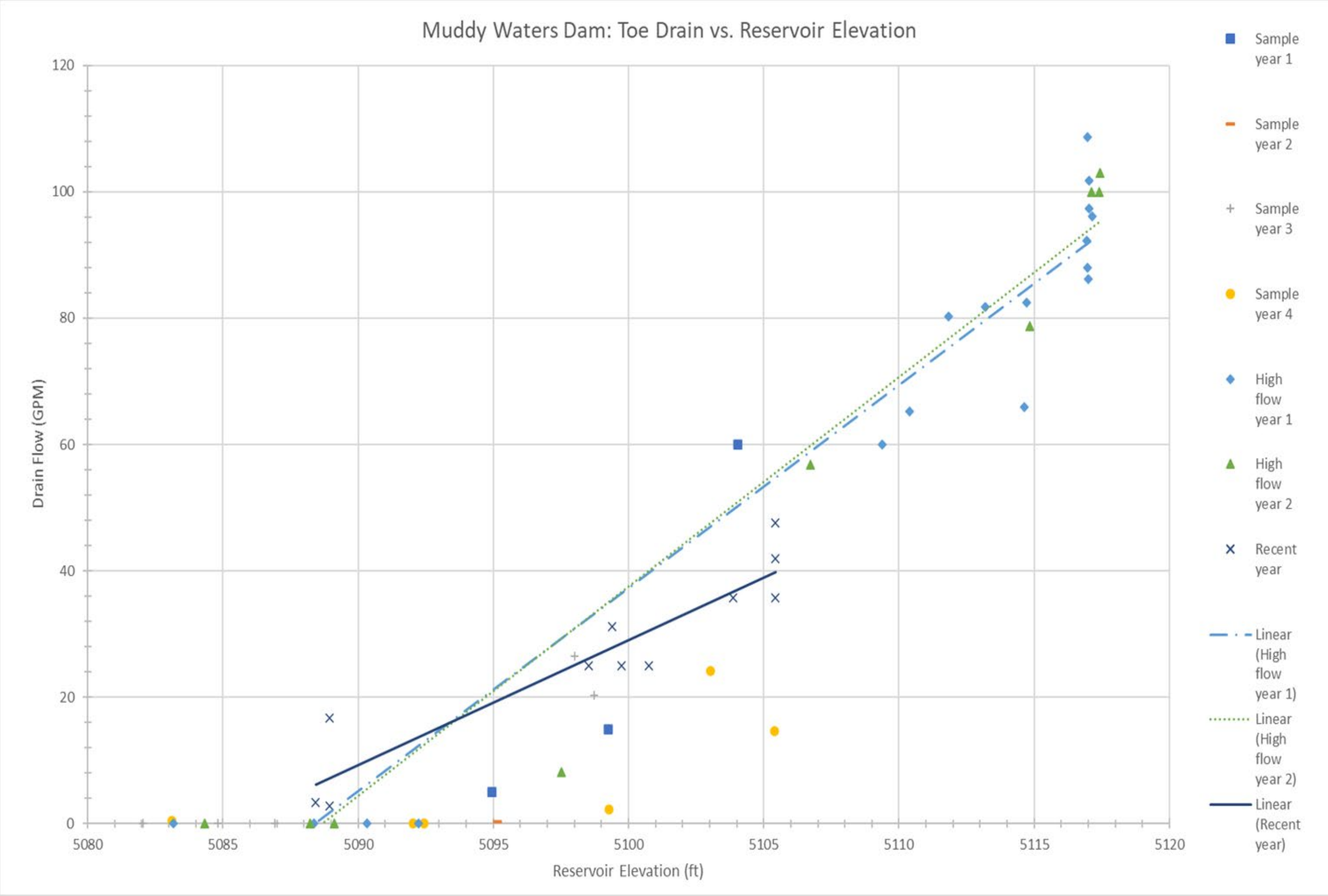


Case study – Muddy Waters





Case study – Muddy Waters

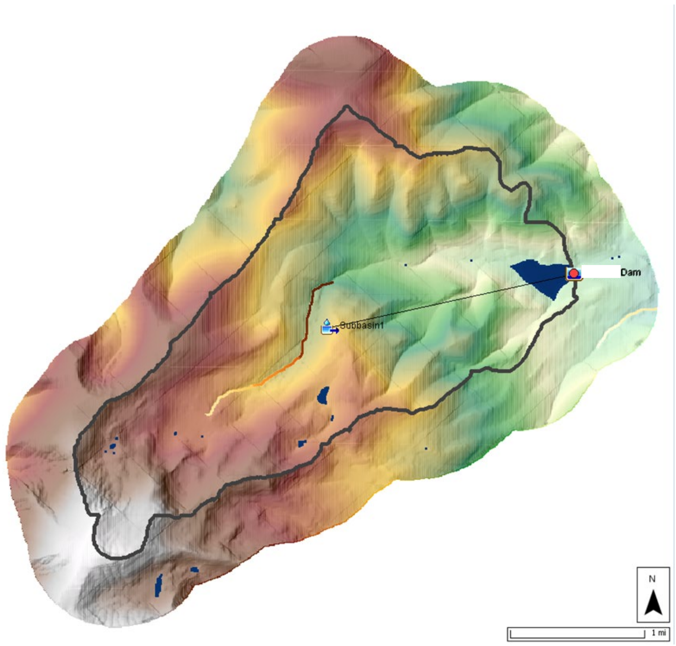


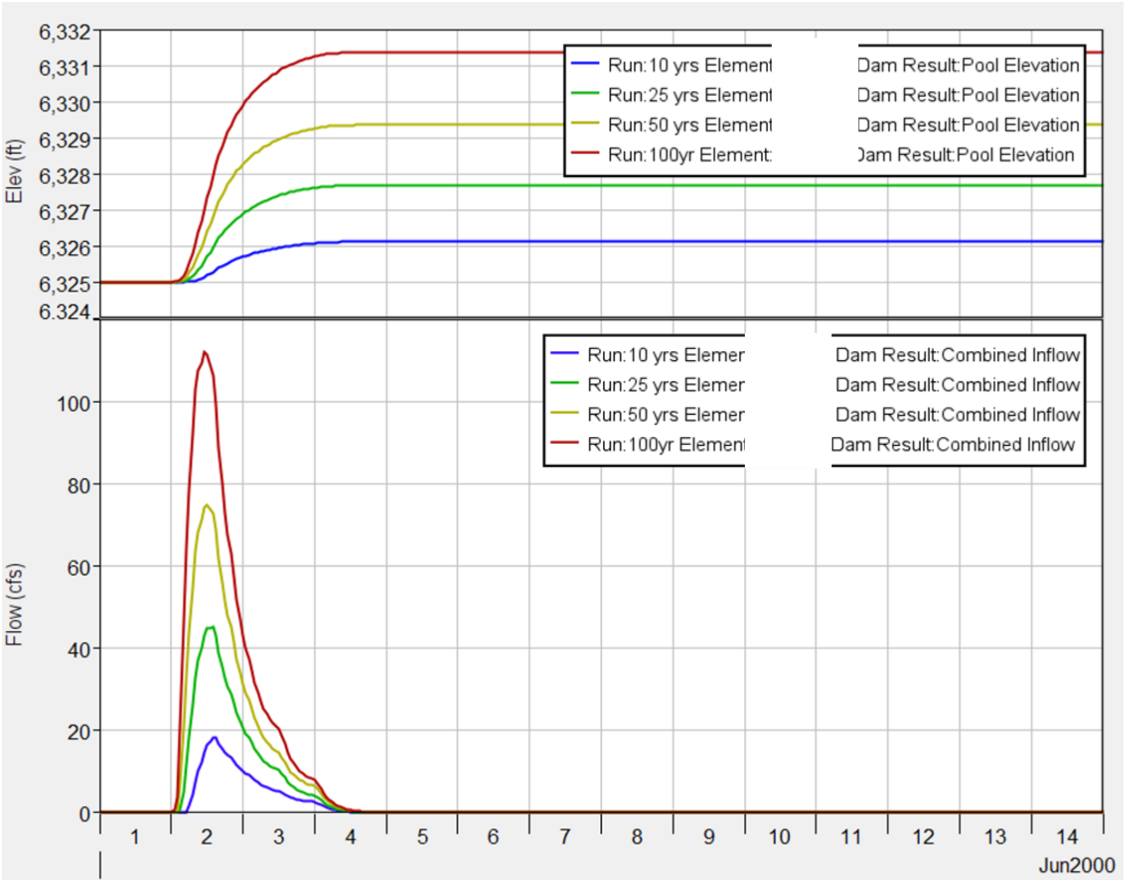
Case study – Muddy Waters

- Historical inspections: Drain flow initiates at 23 ft below spillway
- Recent measurements:
- Drain flow of 30 GPM at this elevation
- No sediment if flow under 20 GPM
- Restriction set 28 ft (1,000 AF) below spillway to minimize/eliminate flow
- Remote monitoring

Case study – Muddy Waters

- Evaluate adequacy of Simplified Approach



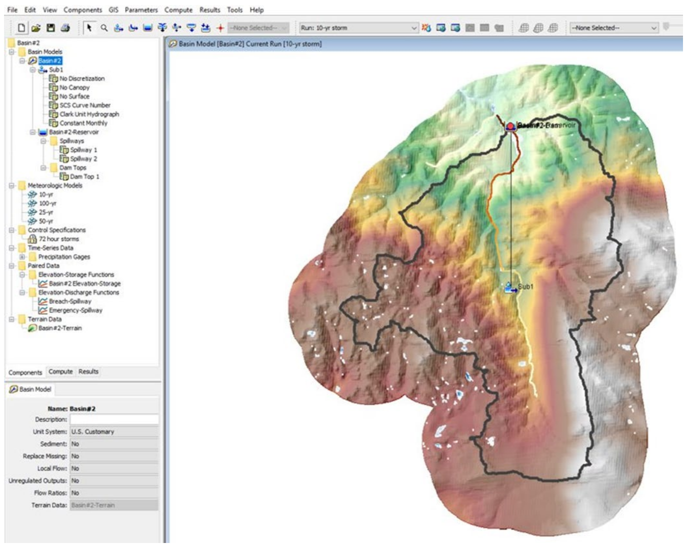


Intermediate approach

- Requires engineering analyses, calculations, or modeling
  - Hydrologic
  - Hydraulic
  - Geotechnical
  - Structural
  - Mechanical

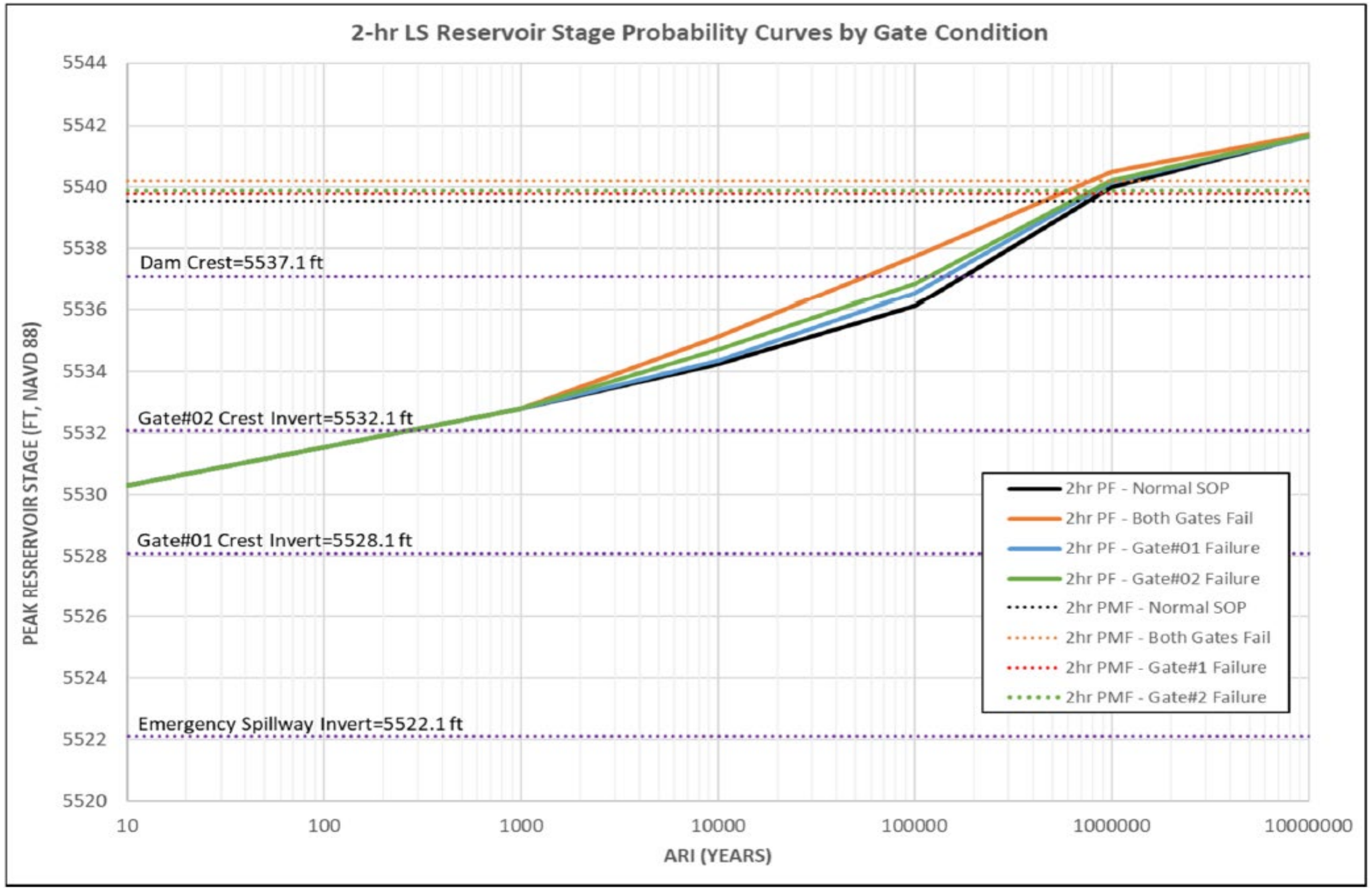
Hydrologic

- Compute volume for storms of varying frequencies
- Set restriction accordingly for:
  - IDF
  - 1% event
  - More frequent event
- Or otherwise avoid loading above certain elevation



Hydrologic

- Example loading curve



Hydraulic

- Compute flow velocity, depth, shear stress, cavitation for failure mode
- Establish outlet or spillway restrictions based on H&H
- Soil erosion or head-cutting for unlined spillway

Source: Colorado River Water Users Association

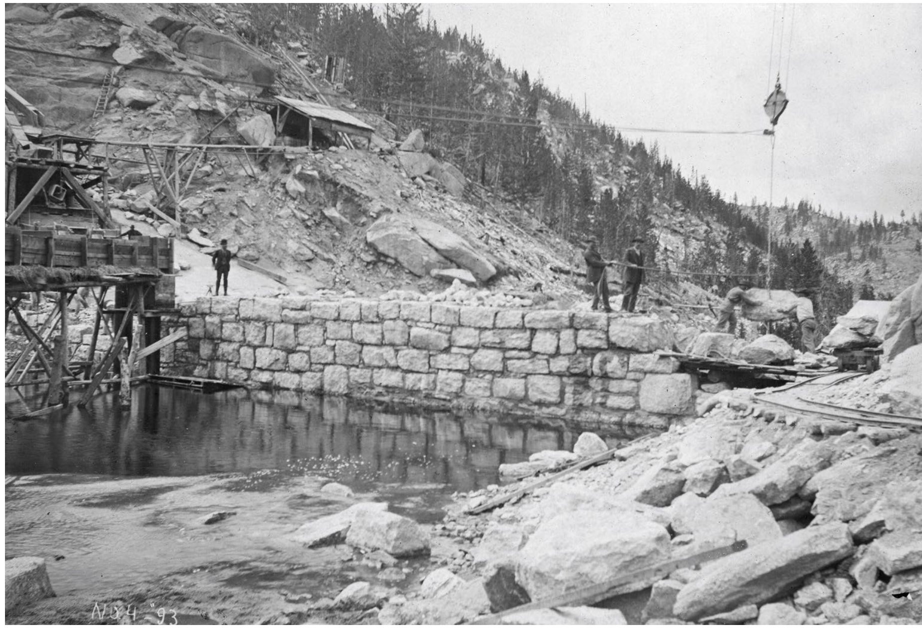
Geotechnical

- Seepage modeling
- Hydraulic gradients
- Slope stability

- USACE Risk Management Center toolboxes
- German Federal Institute for Hydraulic Engineering, 1V:10H hydraulic gradient

Structural

- Modeling under various load combinations
- Restrict reservoir or limit other loads, e.g., bridge weight restriction



Mechanical

- Reservoir restriction and standard operating procedures
- Gates and valves
- Water hammer
- Air demand

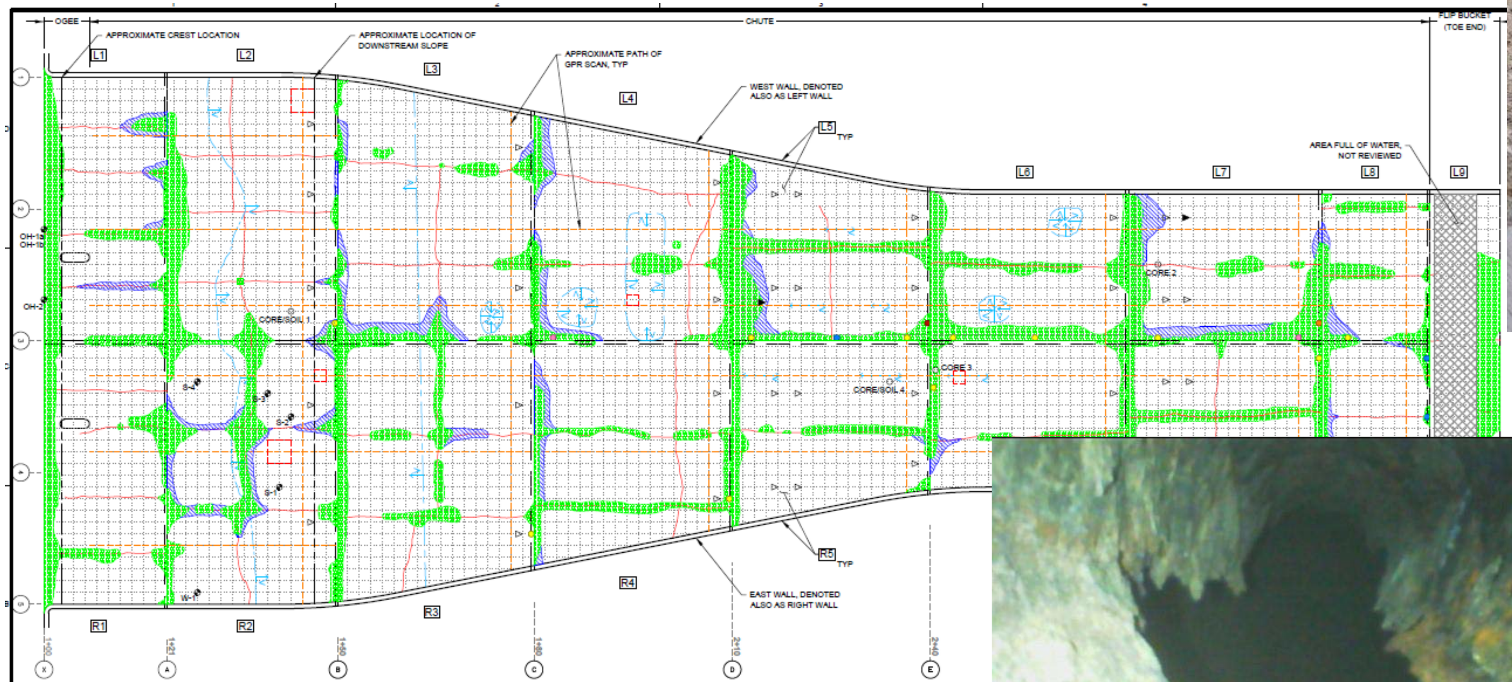
Case study – Stovepipe

- New Deal Era, 100-ft, ~20,000 AF high-hazard dam

Case study – Stovepipe

- 20+ years of spillway deterioration (spalling, delamination, exposed waterstops)
- Extensive deficiencies discovered: joint-faulting, sub-slab voids, ASR

Case study – Stovepipe



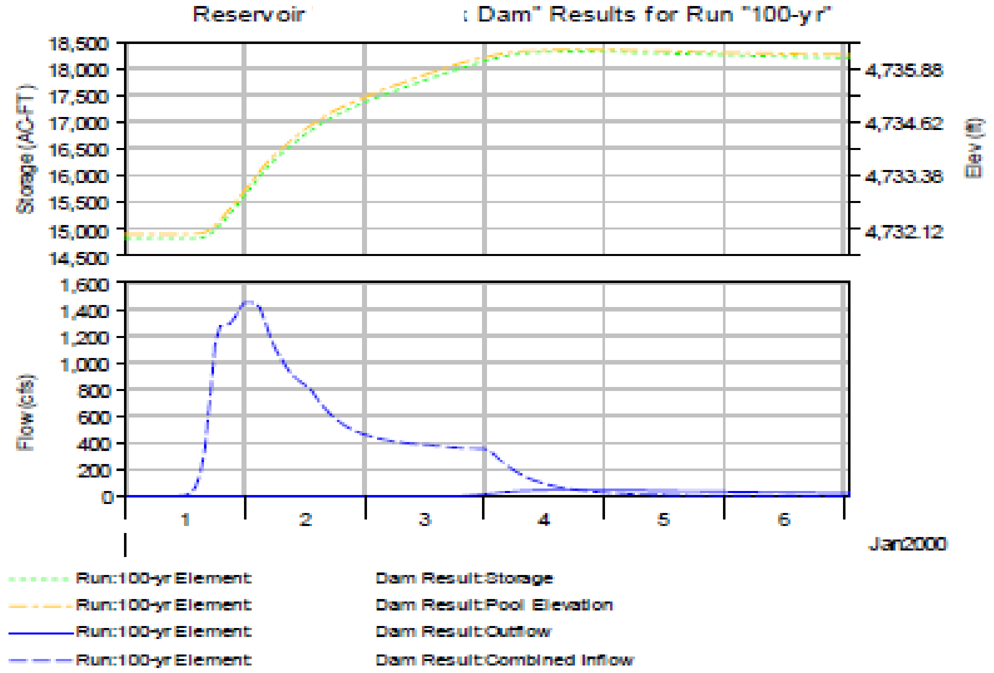
Case study – Stovepipe

- Review of historical spillway performance to recommend max depth over ogee crest
- Outlet 350 CFS + spillway 100 CFS = 450 CFS
- Pass routed 1% AEC event

Case study – Stovepipe

- Restriction of 4 ft / 3,200 AF
- Owner + regulator
- Feasibility study underway

Figure B-1b 100-year inflow, Initial elev. = 4732.0
Max outflow: 47 cfs (4,736.3 ft)

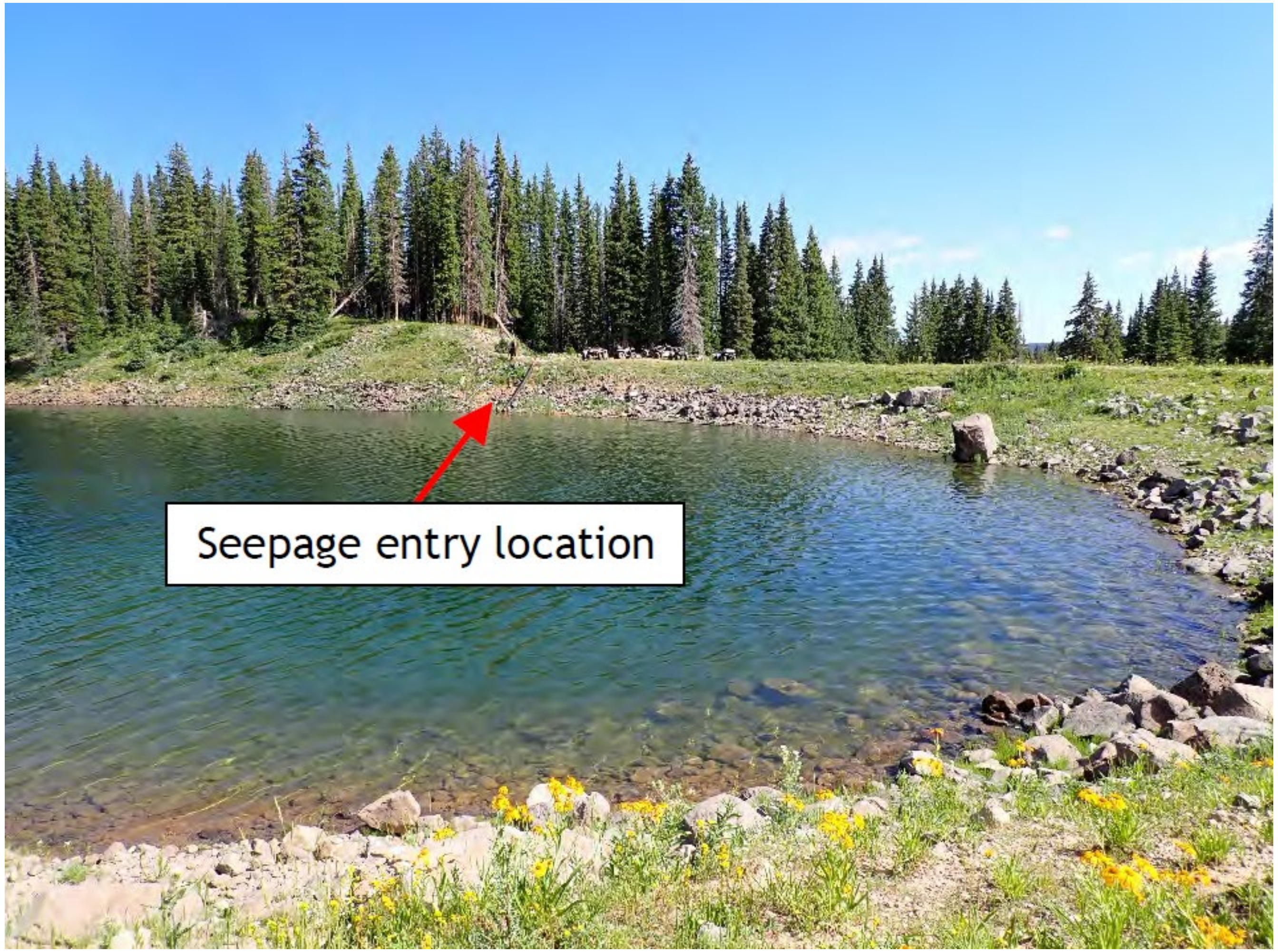


Risk-based approach

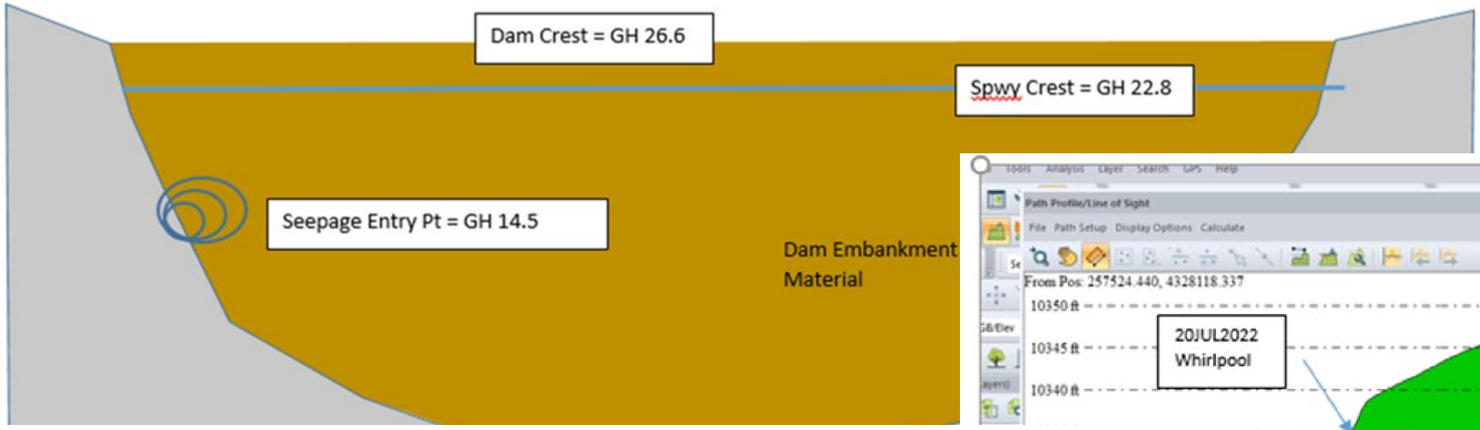
- Qualitative
- Semi-Quantitative
- Fully Quantitative

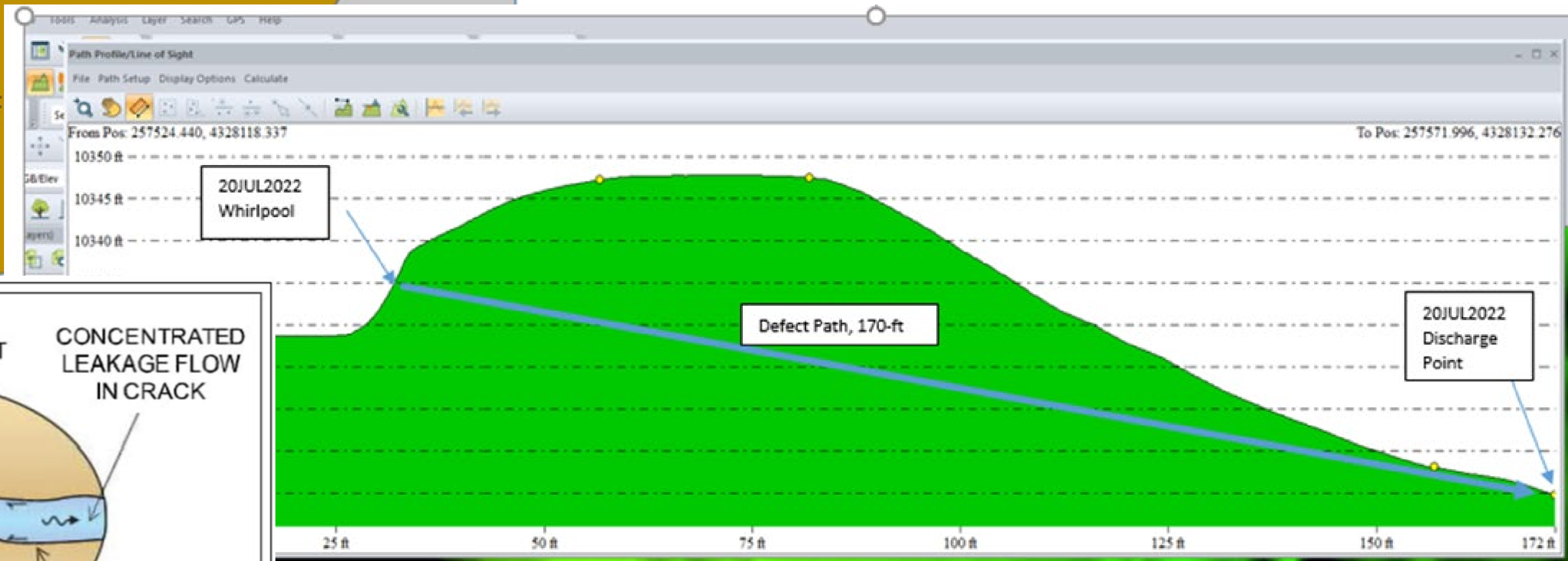
Risk-based case study – Lion Pool

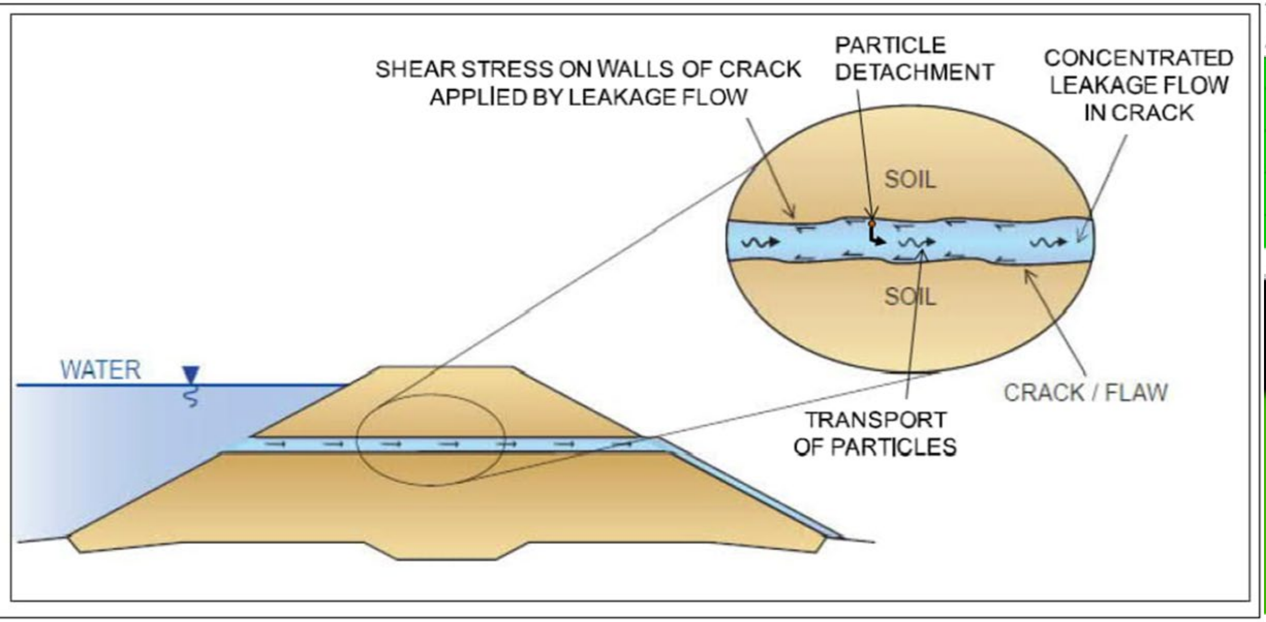
- 2022 inspection revealed seepage entry point at upstream groin
- Relatively impervious embankment on pervious foundation
- PFM of concern: contact erosion of embankment fill adjacent to pervious foundation

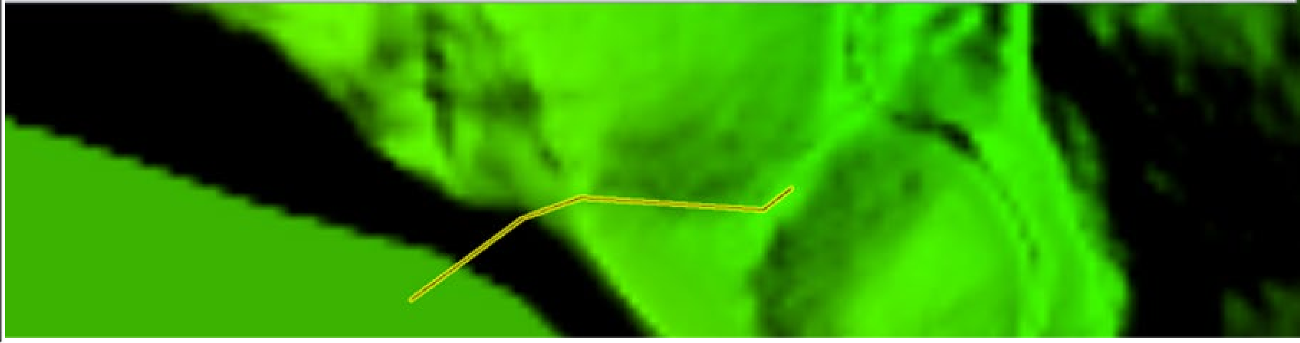


Case study – Lion Pool

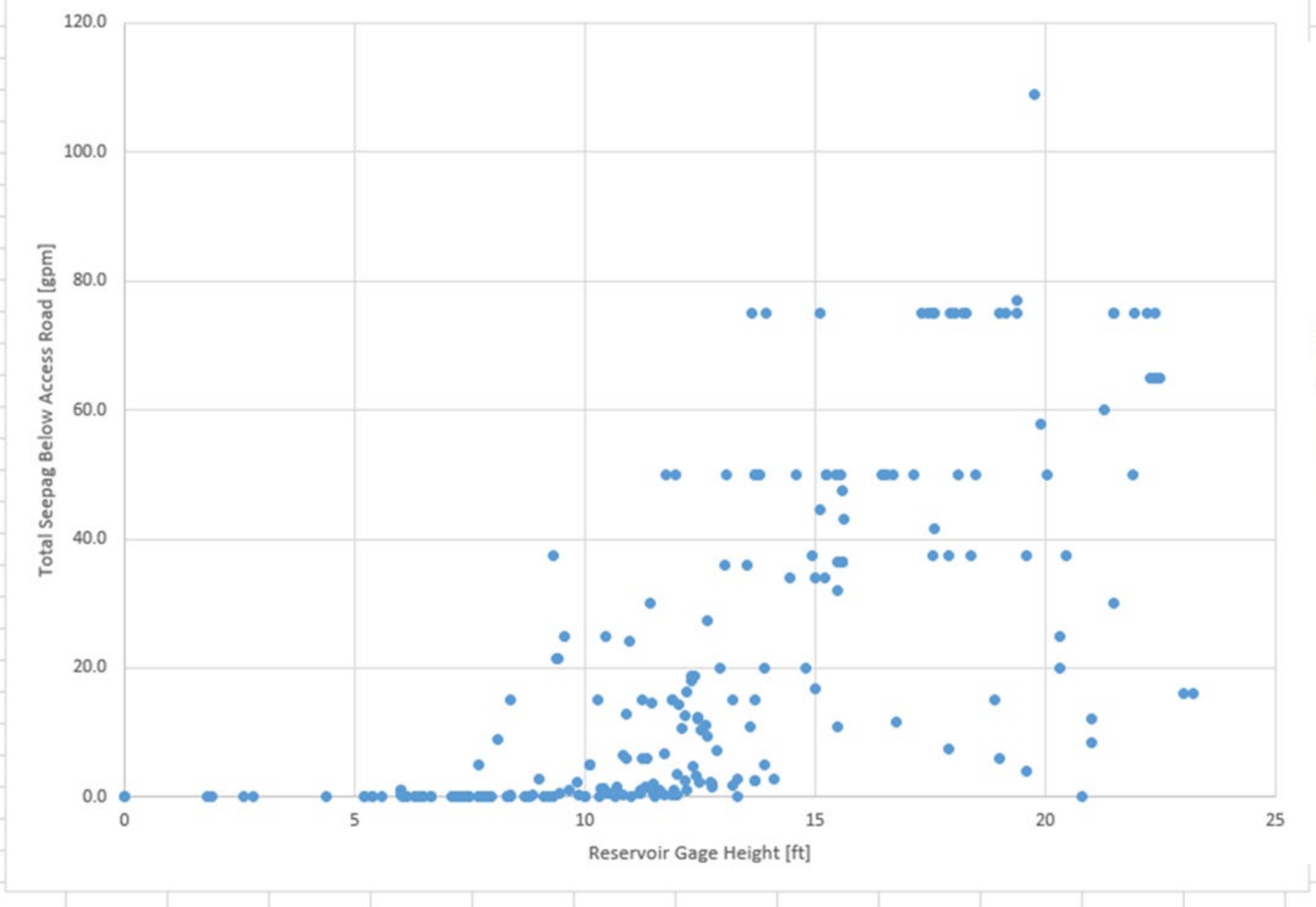


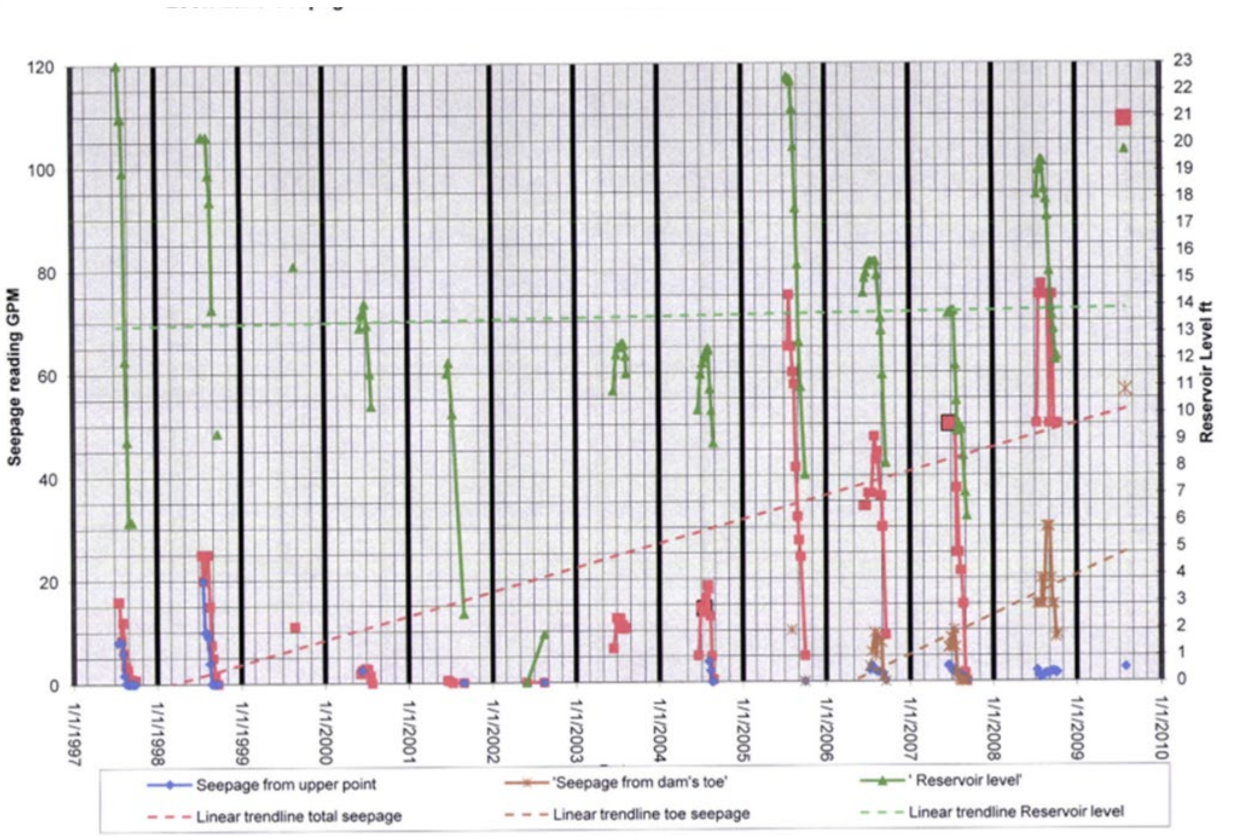






Case study – Lion Pool, monitoring data





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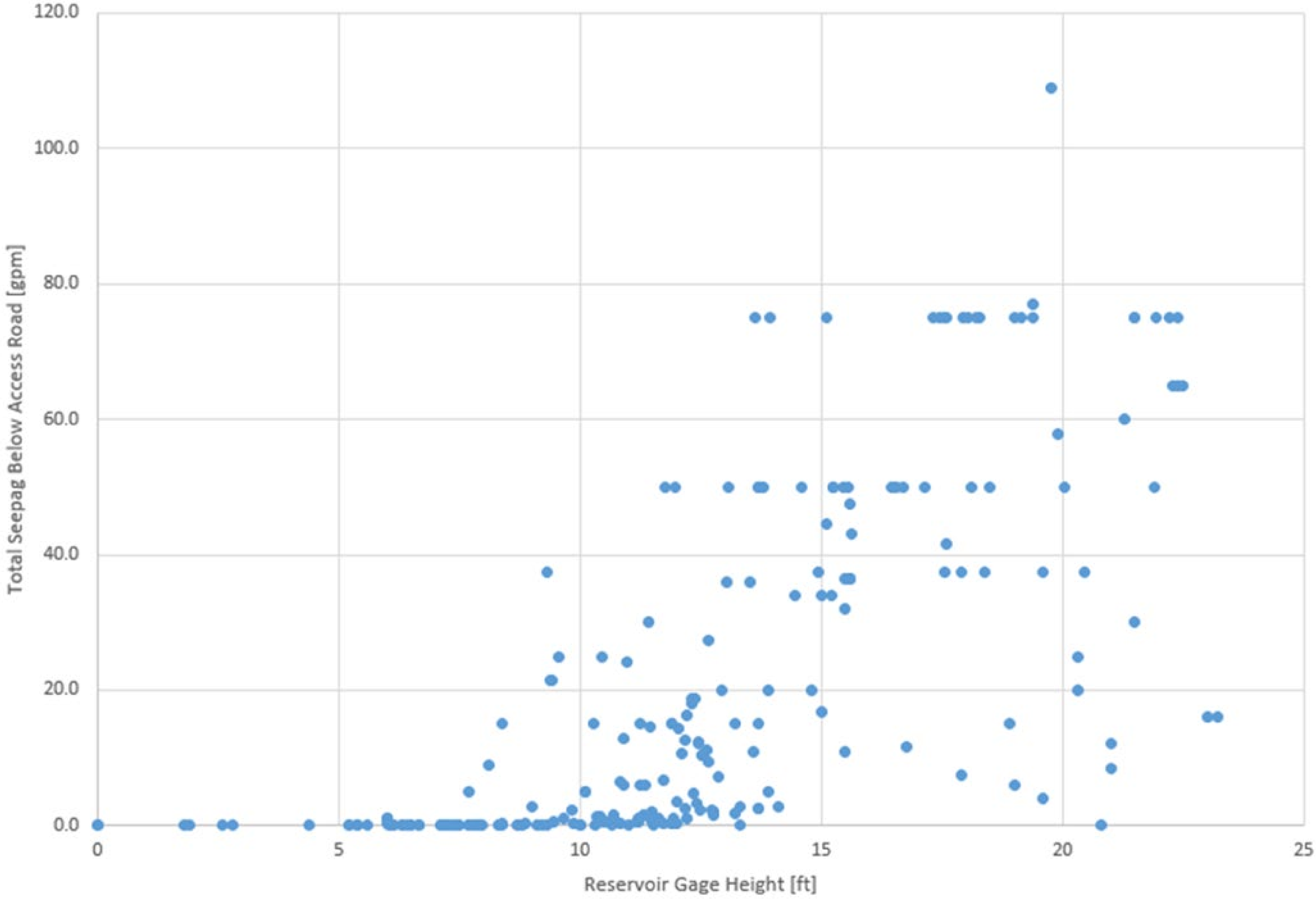
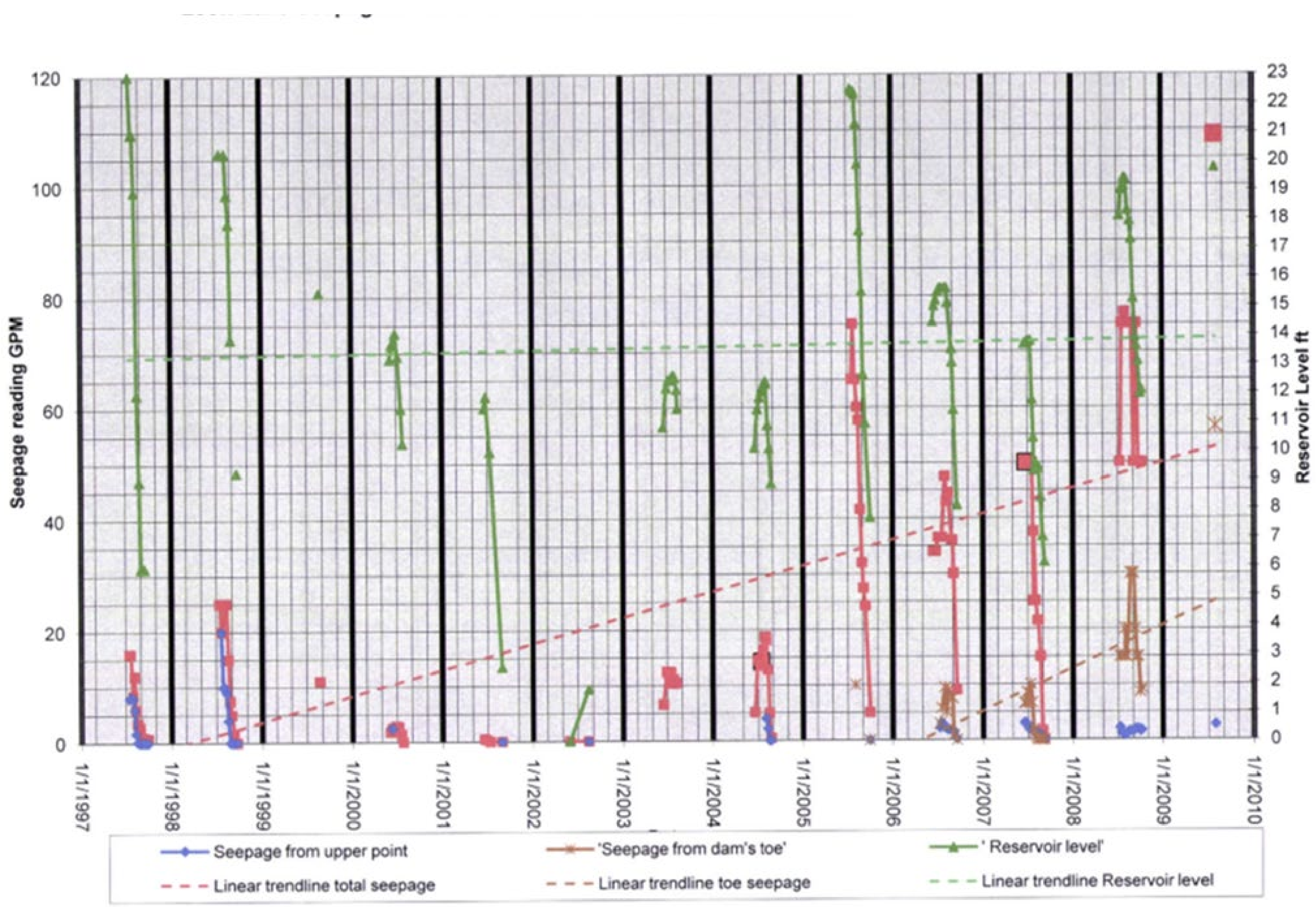


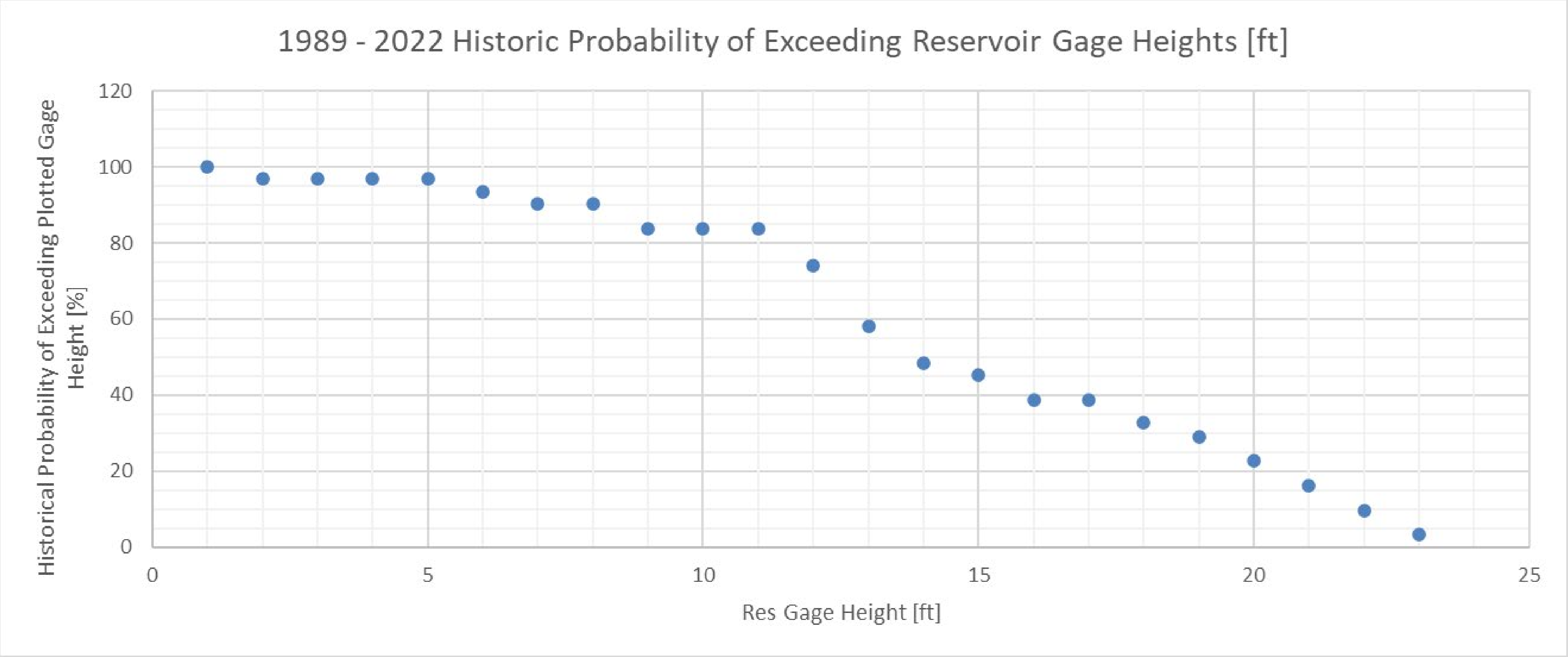
120.0
100.0
80.0
60.0
40.0
20.0
0.0
Total Seepag Below Access Road [gpm]
0
5
10
15
20
25
Reservoir Gage Height [ft]

Ca



Seepage reading GPM
Reservoir Level ft
120
100
80
60
40
20
0
23
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
1/1/1997
1/1/1998
1/1/1999
1/1/2000
1/1/2001
1/1/2002
1/1/2003
1/1/2004
1/1/2005
1/1/2006
1/1/2007
1/1/2008
1/1/2009
1/1/2010
Seepage from upper point
'Seepage from dam's toe'
' Reservoir level'
Linear trendline total seepage
Linear trendline toe seepage
Linear trendline Reservoir level

Probability of loading

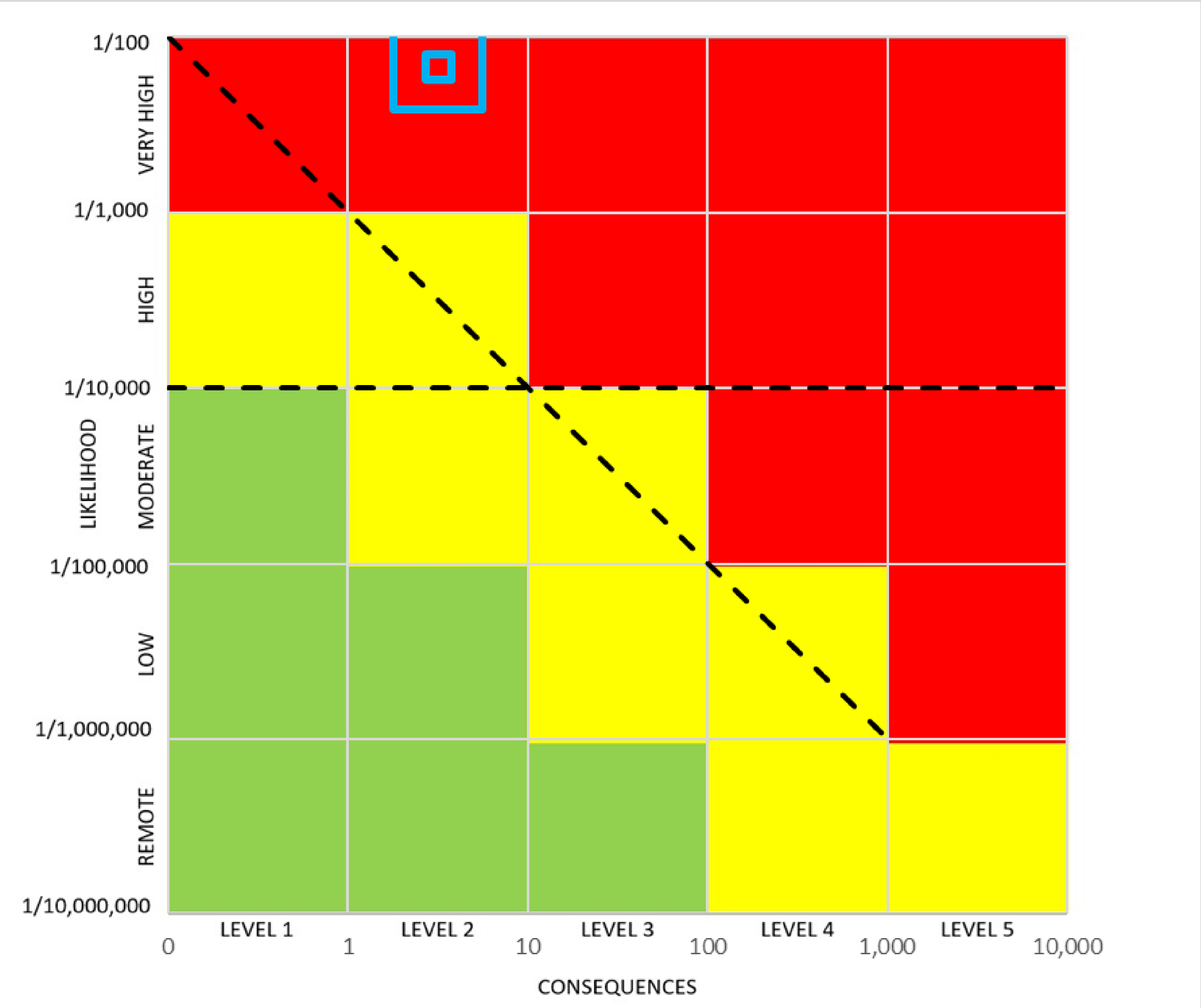


Event tree

- Loading: Reservoir Rises to GH 14.5
  - Flaw Exists: Observed Seepage Entry Point at Whirlpool U/S Groin
    - Initiation: Contact Erosion - Seepage Velocity Sufficient to Erode Soil
      - Continuation: No Effective Filter Present, Eroded Mat’l Exits D/S
        - Progression: Embankment Holds Roof, Erosion Continues
          - Progression: No Features Present to Restrict Flow
            - Progression: No Self-Healing (Crack Stopper) Material U/S, Pipe Formation Progresses to Upstream Face, Reaching Reservoir
              - Intervention: Event Not Detected, or, If Detected, Intervention is Unsuccessful
                - Breach: Flow Increases, Pipe Enlarges, Collapses Crest, Uncontrolled Release of Reservoir, Breach Progresses to Foundation Soils, Downstream Consequences Result

Likelihoo

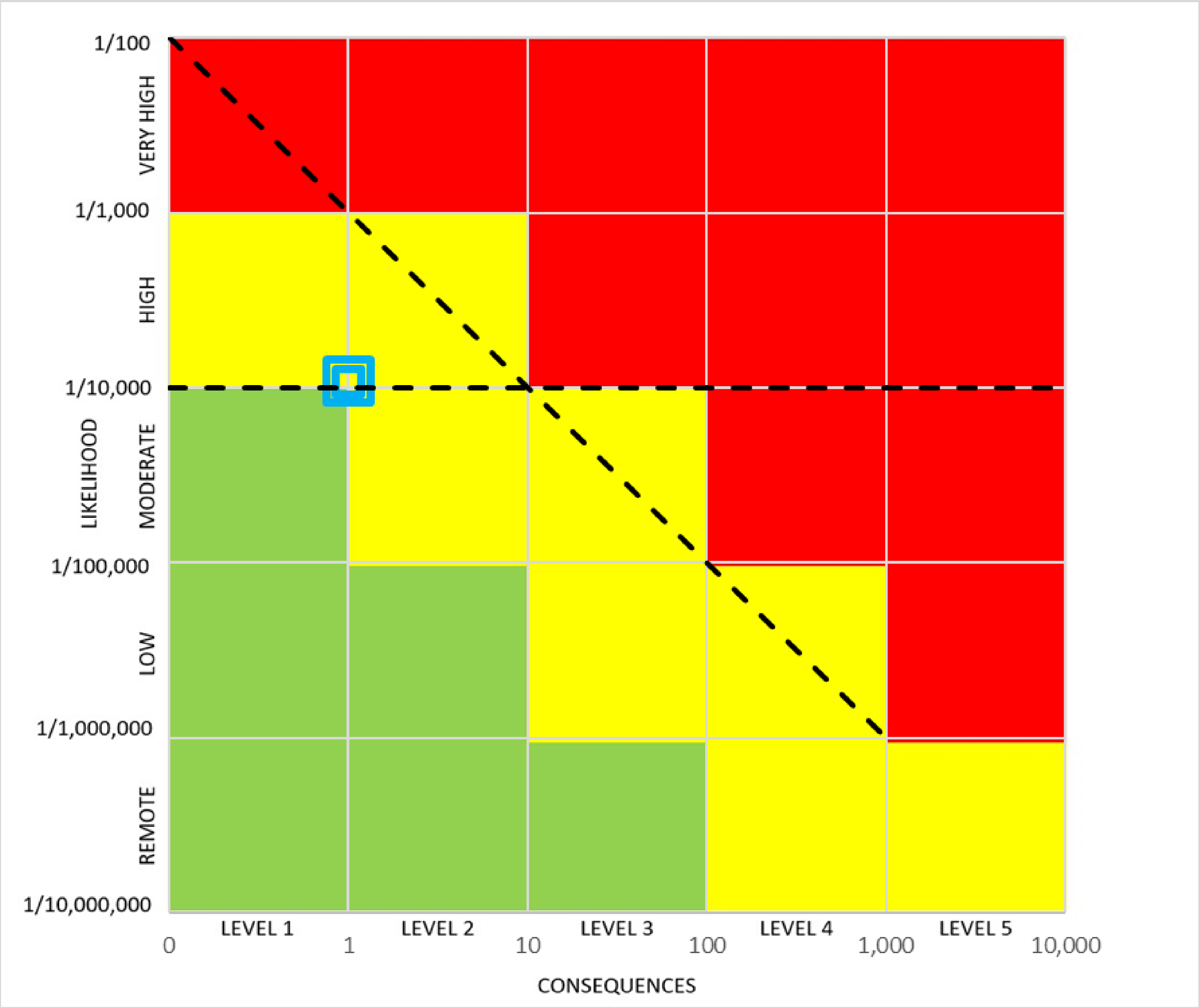
PFM # 14	Contact (Scour) Erosior		
Consequence Le	Level 2	3.16	
Node		ood Desc.	Node Probability
1	Initiation	ely	0.3
2	Flaw Exists	ertain	0.999
3	Initiation		0.5
4	Continuation		0.9
5	Progression		0.7
6	Progression		0.9
7	Progression		0.9
7	Intervention Unsucessfu		0.3
8	Breach		0.3
9	Consequences		
Annual Probability			6.9E-03



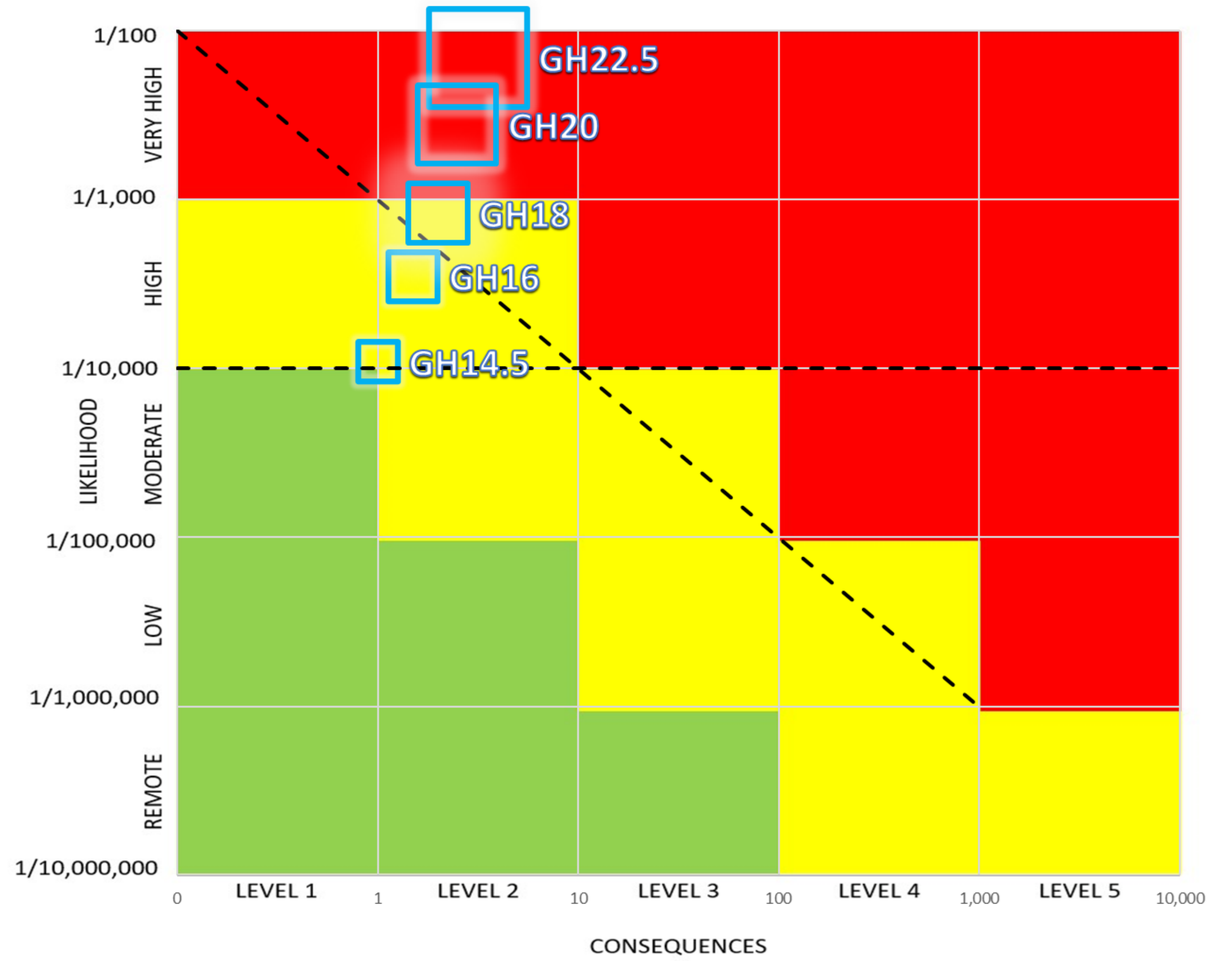
Probability
0.999
0.99
0.9
0.5
0.1
0.01
0.001

Likelihood C

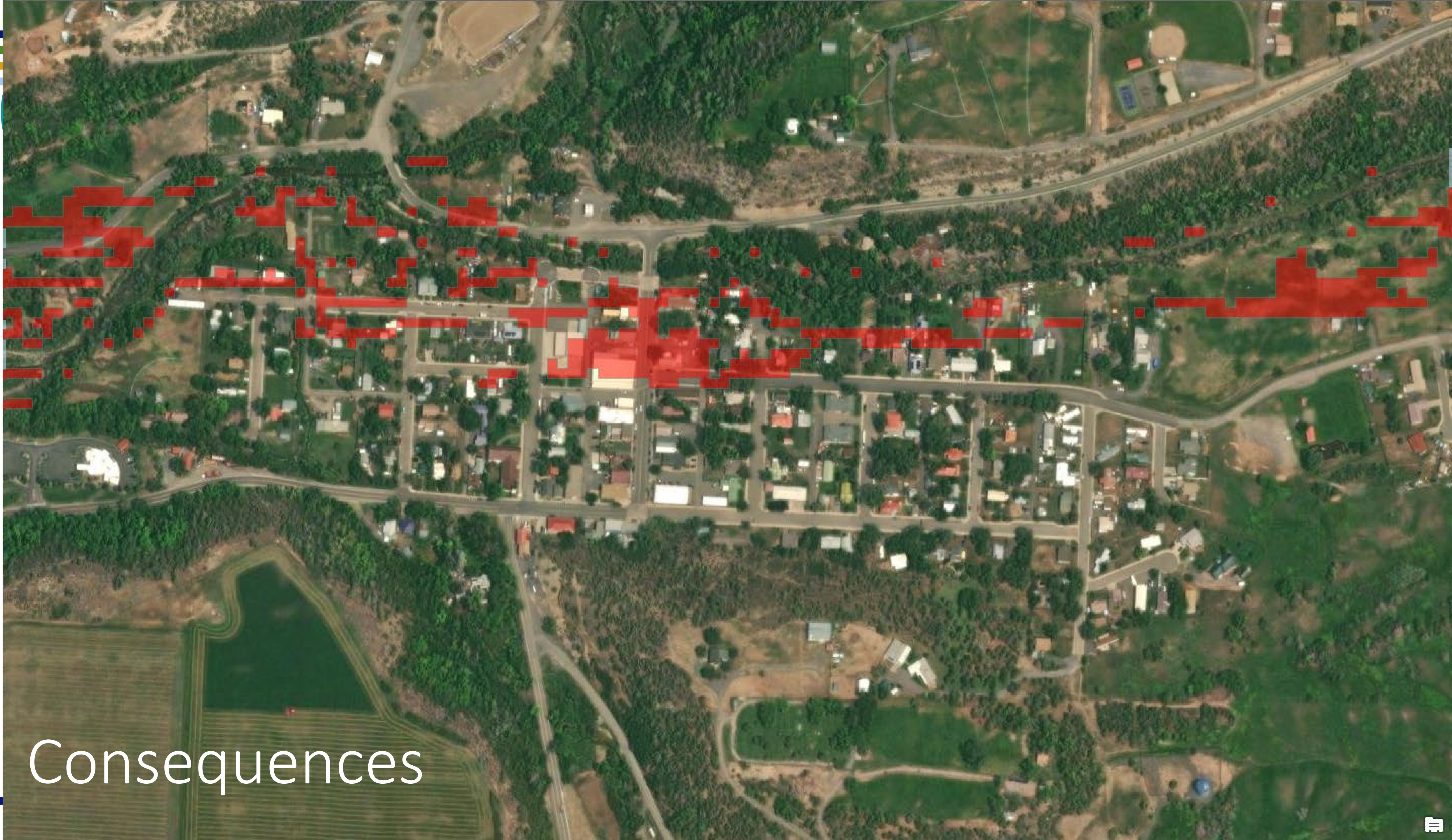
PFM # 14	Contact (Scour) Erosion			
Consequence Le	Level 2	Li	.00	
Node			esc	Node Probability
1	Initiation	R		0.5
2	Flaw Exists	Fl		0.999
3	Initiation	Er		0.03
4	Continuation	Ur		0.9
5	Progression	V		0.5
6	Progression	N		0.9
7	Progression	N		0.9
7	Intervention Unsucessful	D		0.1
8	Breach	Fl pi le		0.2
9	Consequences	Li		
Annual Probability				1.1E-04



Risk matrix



GH22.5
GH20
GH18
GH16
GH14.5
LIKELIHOOD
VERY HIGH
HIGH
MODERATE
LOW
REMOTE
1/100
1/1,000
1/10,000
1/100,000
1/1,000,000
1/10,000,000
0
LEVEL 1
1
LEVEL 2
10
LEVEL 3
100
LEVEL 4
1,000
LEVEL 5
10,000
CONSEQUENCES



Consequences

Other considerations

- Access
  - To the dam
  - Around the dam
- Owner resources
  - On-site dam tender?
  - Equipment and materials
- Path toward full storage
  - Compliance plan
  - Data collection
  - Mitigation design/implementation
  - Restriction Revisions

Source: Cornelius Poppe & Bard Langvandslien/NTB Scanpix via AP

Restriction revision/removal

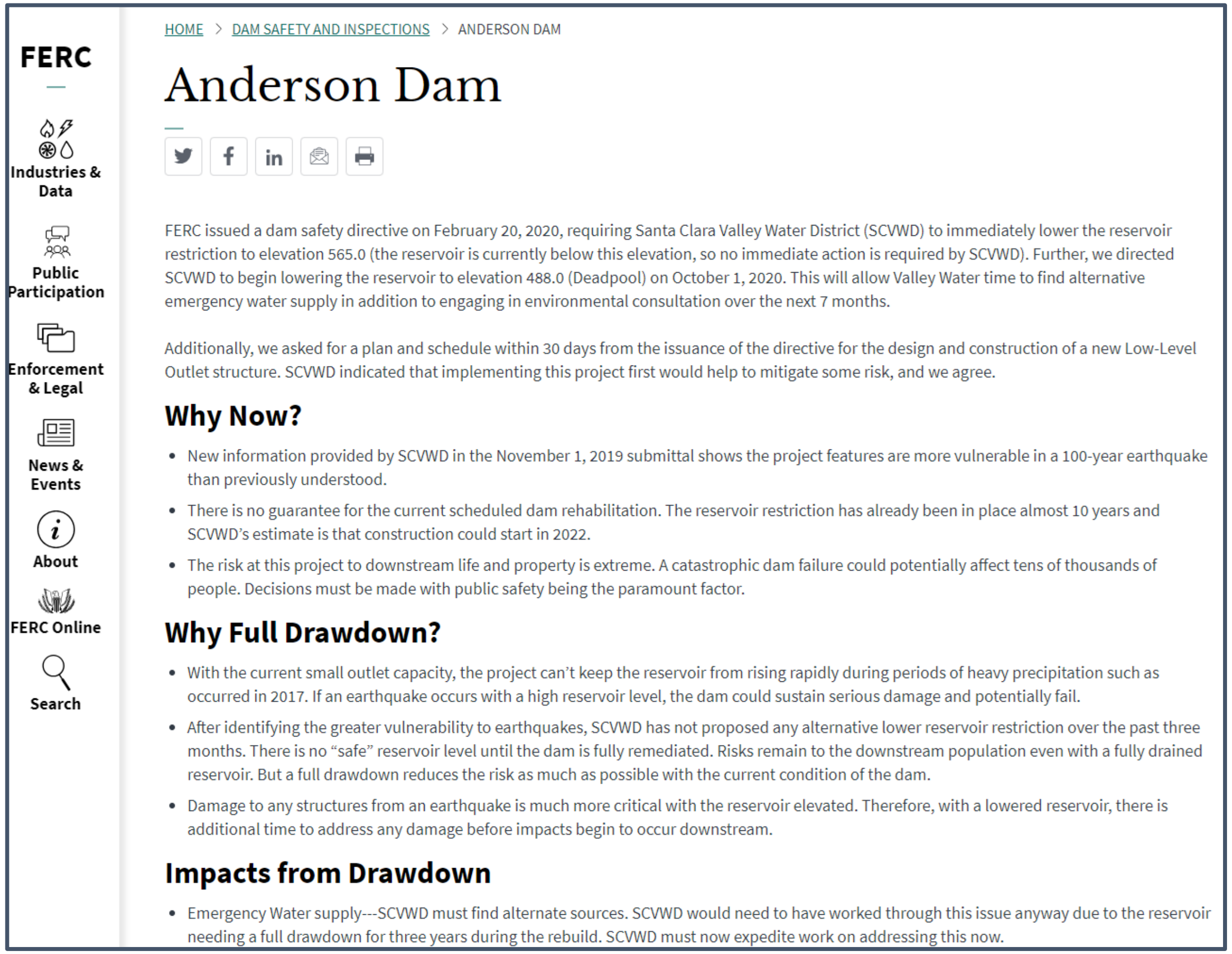
- First filling
- Instrumentation & monitoring
- Frequent visual observation
- Hold points
  - Evaluate performance
  - Download monitoring data
  - Analysis as needed

Source: DamFailures.org

Zero storage restrictions & breach orders

- Sometimes warranted
- Unsafe for any storage
- Owners lack sufficient resources
- May require legal action

Source: Wikimedia Commons



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Anderson Dam

FERC issued a dam safety directive on February 20, 2020, requiring Santa Clara Valley Water District (SCVWD) to immediately lower the reservoir restriction to elevation 565.0 (the reservoir is currently below this elevation, so no immediate action is required by SCVWD). Further, we directed SCVWD to begin lowering the reservoir to elevation 488.0 (Deadpool) on October 1, 2020. This will allow Valley Water time to find alternative emergency water supply in addition to engaging in environmental consultation over the next 7 months.

Additionally, we asked for a plan and schedule within 30 days from the issuance of the directive for the design and construction of a new Low-Level Outlet structure. SCVWD indicated that implementing this project first would help to mitigate some risk, and we agree.

Why Now?

- New information provided by SCVWD in the November 1, 2019 submittal shows the project features are more vulnerable in a 100-year earthquake than previously understood.
- There is no guarantee for the current scheduled dam rehabilitation. The reservoir restriction has already been in place almost 10 years and SCVWD's estimate is that construction could start in 2022.
- The risk at this project to downstream life and property is extreme. A catastrophic dam failure could potentially affect tens of thousands of people. Decisions must be made with public safety being the paramount factor.

Why Full Drawdown?

- With the current small outlet capacity, the project can't keep the reservoir from rising rapidly during periods of heavy precipitation such as occurred in 2017. If an earthquake occurs with a high reservoir level, the dam could sustain serious damage and potentially fail.
- After identifying the greater vulnerability to earthquakes, SCVWD has not proposed any alternative lower reservoir restriction over the past three months. There is no "safe" reservoir level until the dam is fully remediated. Risks remain to the downstream population even with a fully drained reservoir. But a full drawdown reduces the risk as much as possible with the current condition of the dam.
- Damage to any structures from an earthquake is much more critical with the reservoir elevated. Therefore, with a lowered reservoir, there is additional time to address any damage before impacts begin to occur downstream.

Impacts from Drawdown

- Emergency Water supply---SCVWD must find alternate sources. SCVWD would need to have worked through this issue anyway due to the reservoir needing a full drawdown for three years during the rebuild. SCVWD must now expedite work on addressing this now.

Source: https://ferc.gov/dam-safety-and-inspections/anderson-dam

Case study
Spoon Dam

Conclusions

- Restrictions are a critical and effective tool for dam safety regulators
- Justification should be provided for setting safe storage level
- Level of analysis should be tailored to each individual case
- Sliding scale of effort based on consequences and impacts to public and water users
- Document issues so owners know what engineer to hire and engineer knows what mitigation is needed
- More tools in the toolbox are always welcome!

Thank you!

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