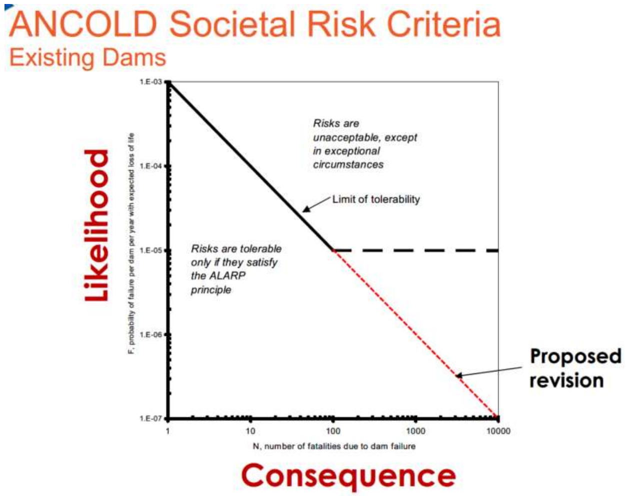
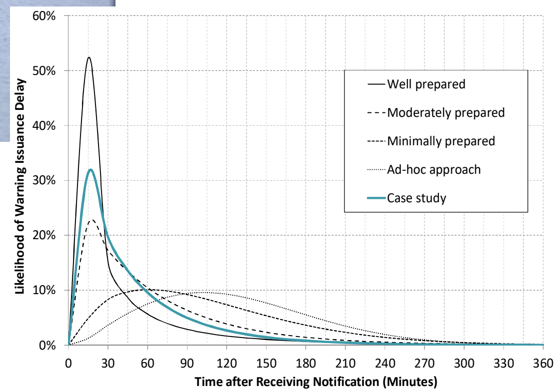
How to Model Societal Consequences of Dam Break and an Introduction to Risk Assessment





Mohammad (Mike) Ahmadi
Lead Dam Safety Engineer

Items to be discussed

Population at Risk and Potential Loss of Life

- Hydraulic Characteristics (Depth and Velocity) overtime
- Structure Inventory and Associated Properties (Including Structural Stability Curve)
- Warning (and Protective Action Initiation Timeline) and Population Redistribution (Evacuation)
- Roads and Destinations,
- Fatality Rates and PLL
- Hec-LifeSIM (USACE)

An Introduction to Risk Assessment

- Identification and Assembly of all relevant data,
- Hazard and Failure Mode Identification,
- Failure Mode Development (Event Tree),
- Failure Mode Analysis,
- Introduce Risk Plots,
- Total Risk (RMC-USACE)

Population at Risk and Potential Loss of Life

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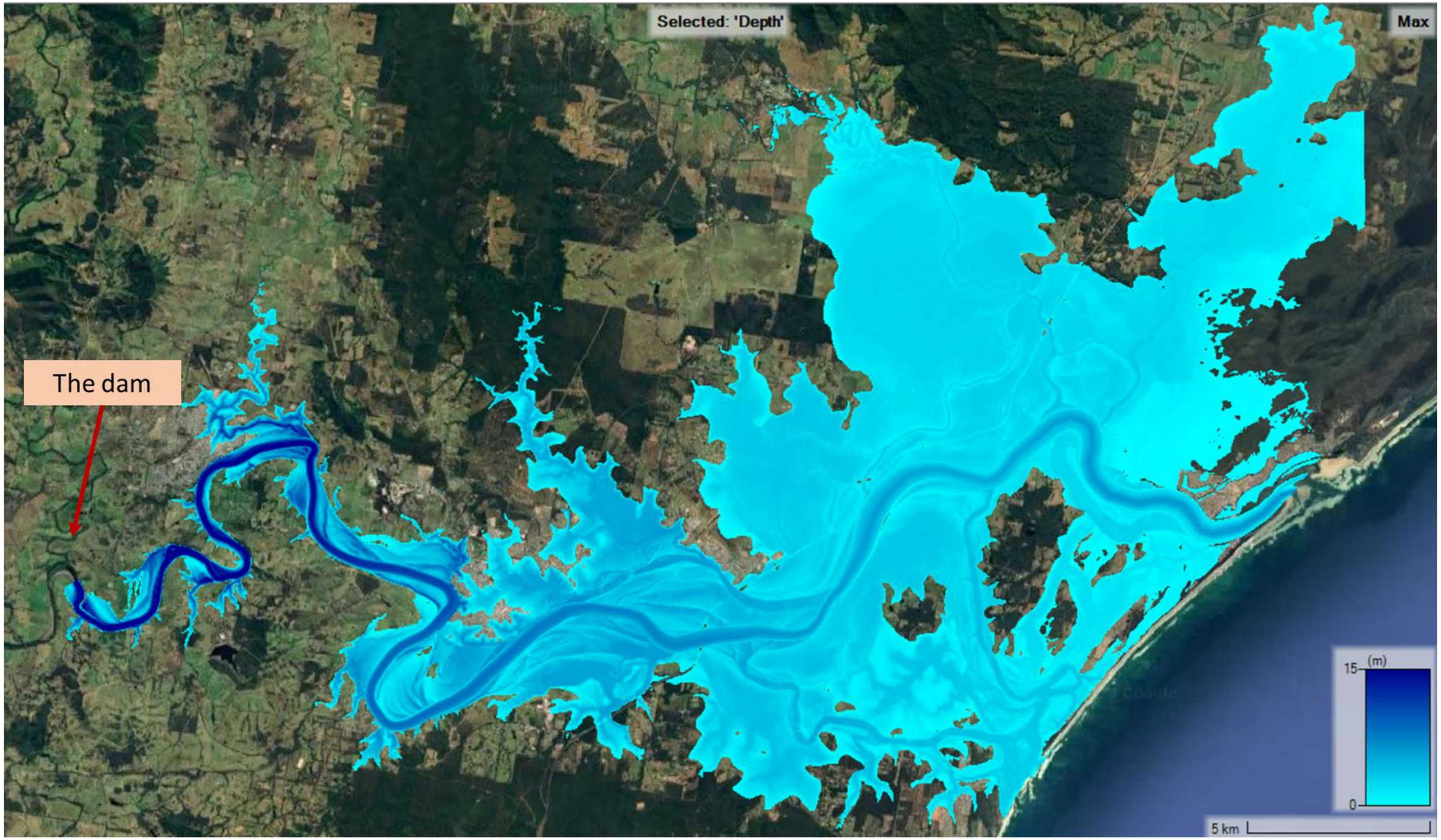
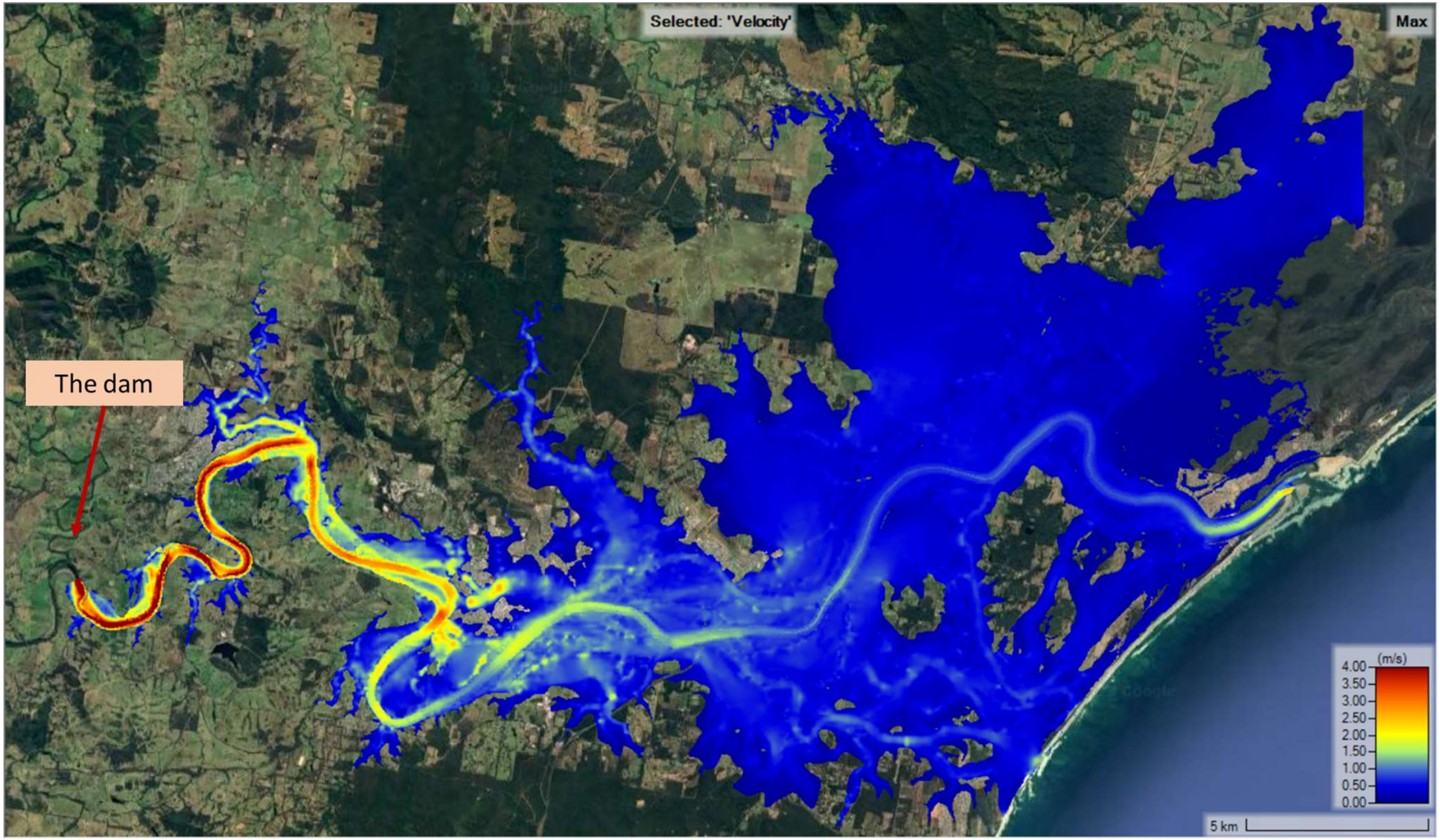
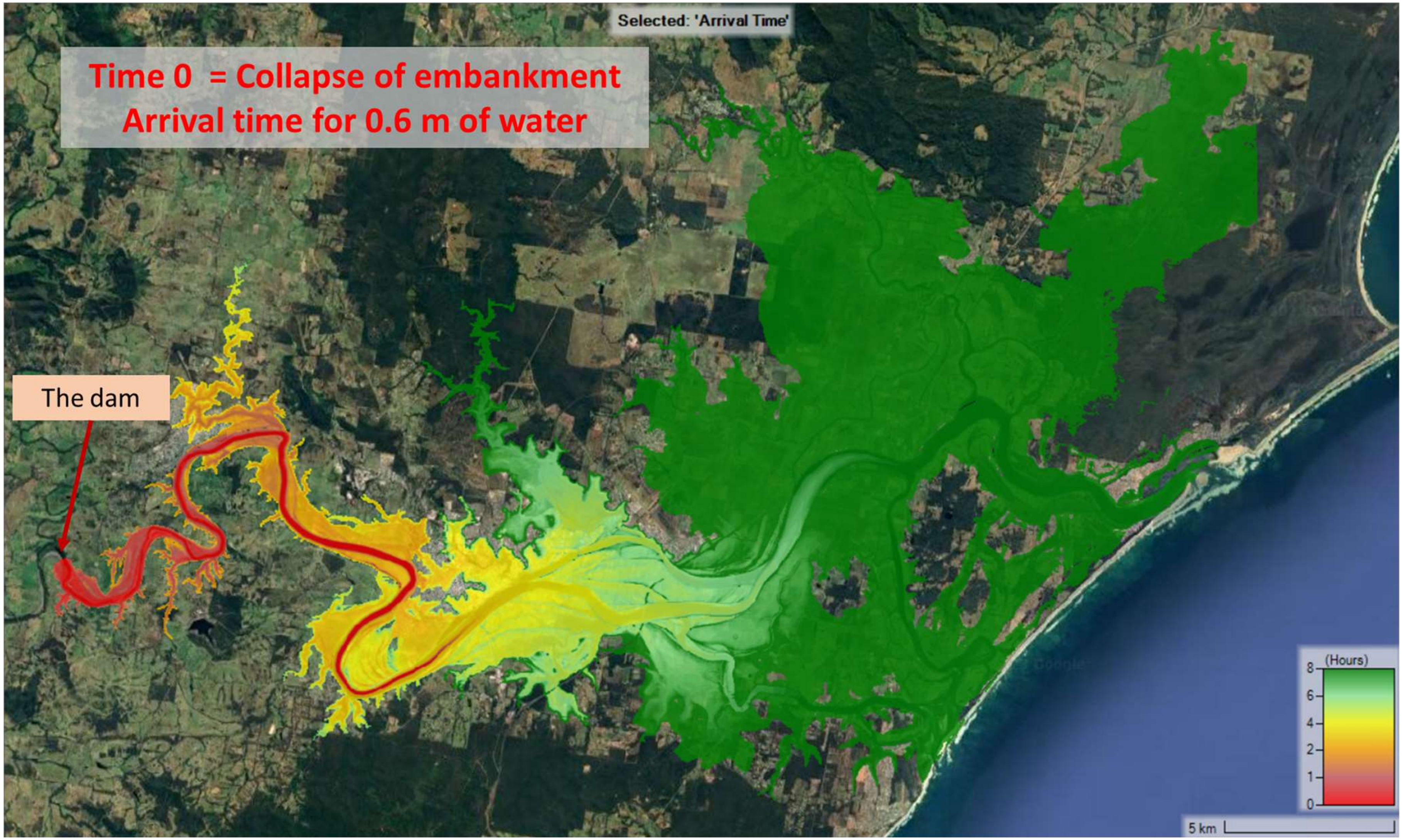
Hydraulic Characteristics (Depth and Velocity) overtime



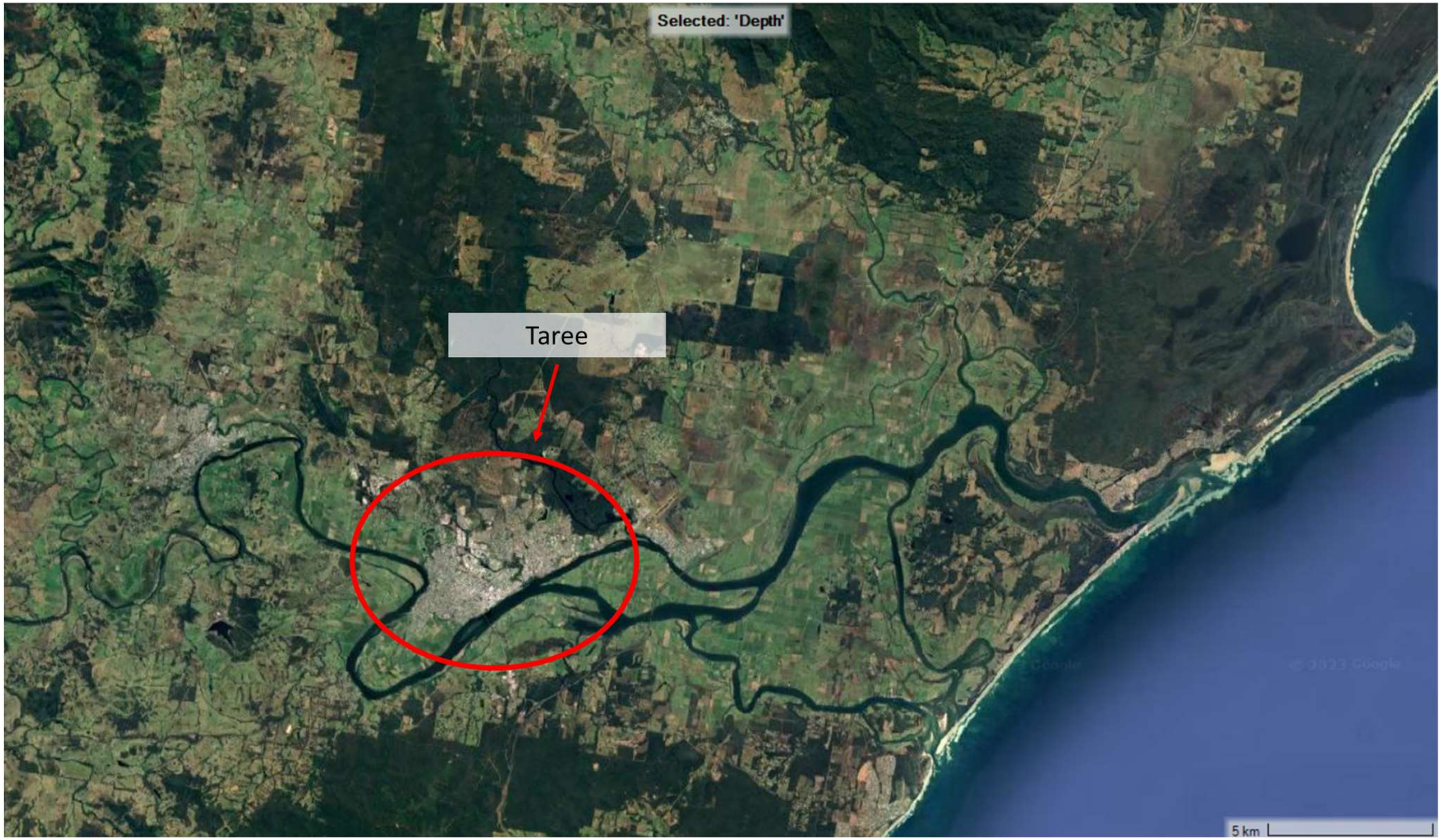
Hydraulic Characteristics (Depth and Velocity) overtime



Hydraulic Characteristics (Depth and Velocity) overtime



Hydraulic Characteristics (Depth and Velocity) overtime



We need to "Check Sensibility"

- Do the hydraulics make sense?
  - For instance, if a levee is overtopped, is the correct area inundated?
  - Are there isolated inundation areas that are disconnected from main flow areas?
  - Is the edge of the water surface getting cut off?(Cross sections don't extend to high ground?)
  - Are depths within reasonable ranges?
  - Are velocities within reasonable ranges?
  - Watch the animation, check the max depths and velocities

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Definition of attributes required for structure (shape file)

Required attribute	Definition
Occupancy type	Describes a class of structures (e.g., single family, no basement, raised foundation, one story).
Number of stories	Number of stories of a structure.
Construction type	Describes what the structure is made of, predominant building material.
Foundation height	The difference between the ground elevation and the ground floor elevation.
Ground floor height	Difference between the floor elevation and ceiling elevation of the ground floor.
Above ground floor height	Difference between the floor elevation and ceiling elevation for each story above the ground floor.
Attic height	Difference between the ceiling elevation of the highest story and the roof elevation, may be zero in some structures.

Required attribute	Definition
Population under 65 (night)	Estimate of people within a structure under the age of 65 during the night, (assumed to be 2AM).
Population over 65 (night)	Estimate of people within a structure over the age of 65 during the night, (assumed to be 2AM).
Population under 65 (day)	Estimate of people within a structure under the age of 65 during the day (assumed to be 2PM).
Population over 65 (day)	Estimate of people within a structure over the age of 65 during the day (assumed to be 2PM).
Structure value	Value of a structure, typically in thousands of dollars.
Content value	Value of what is inside the structure.
Other value	User defined category.
Vehicle value	Value of vehicle(s) associated with structure.

Definition of attributes required for structure (shape file)

1. **Engineered** - Steel and reinforced concrete construction where the walls are non-load bearing and instead the columns and beams carry the load. Walls may be masonry, wood, glass, etc. and are susceptible to collapse separate from the superstructure.

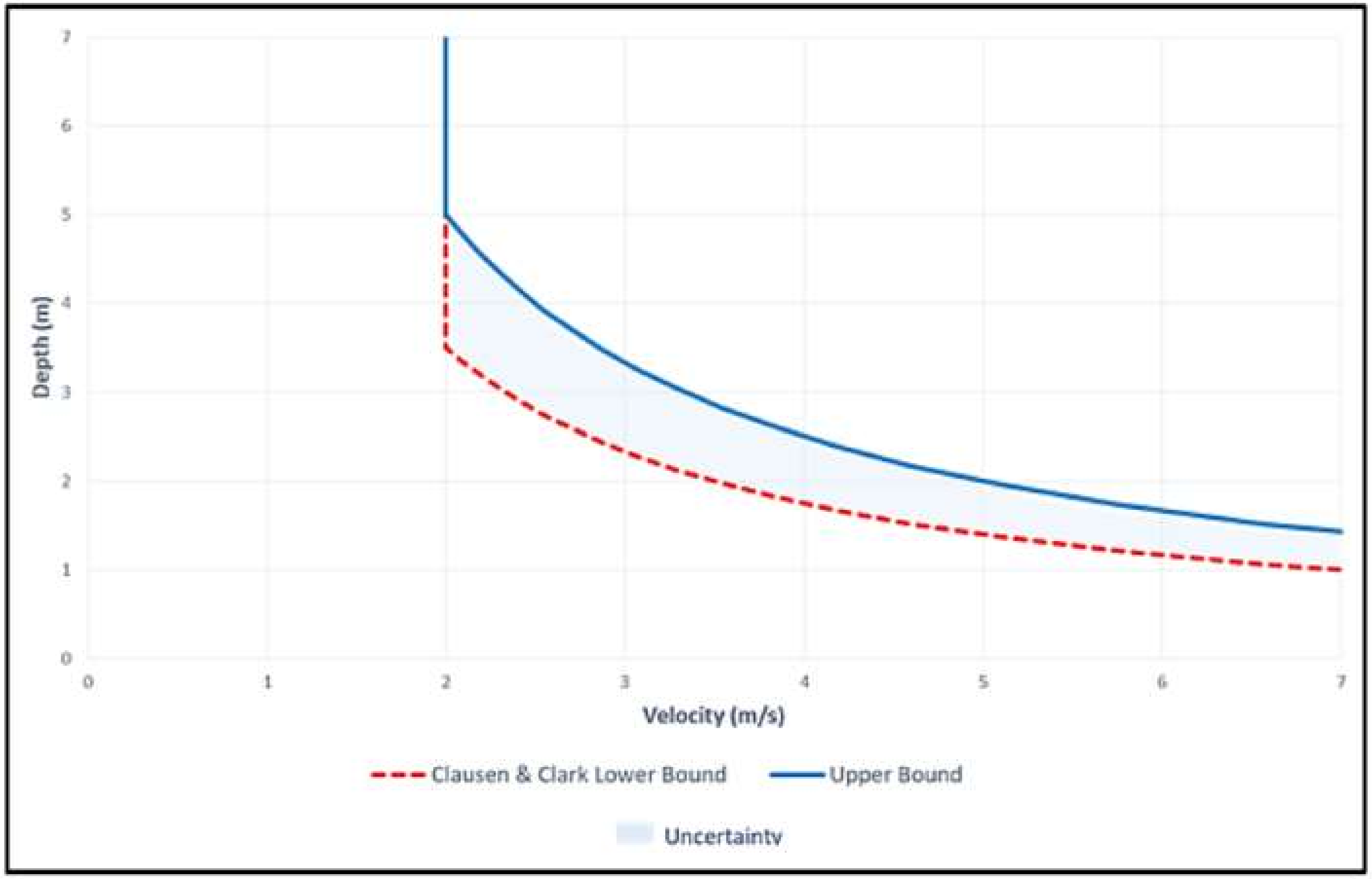
2. **Wood-Anchored** - Typical wood frame structure with load bearing walls that is bolted or anchored to the foundation and therefore less susceptible to floating off the foundation. Heavy construction structures made of heavy materials such as large timbers, homes with a brick façade, and homes with 2 or more stories are also more likely to resist floating and therefore may also be considered "anchored."

3. **Manufactured** - Prefabricated houses that are constructed off-site and then assembled at the building site in sections e.g., mobile homes.

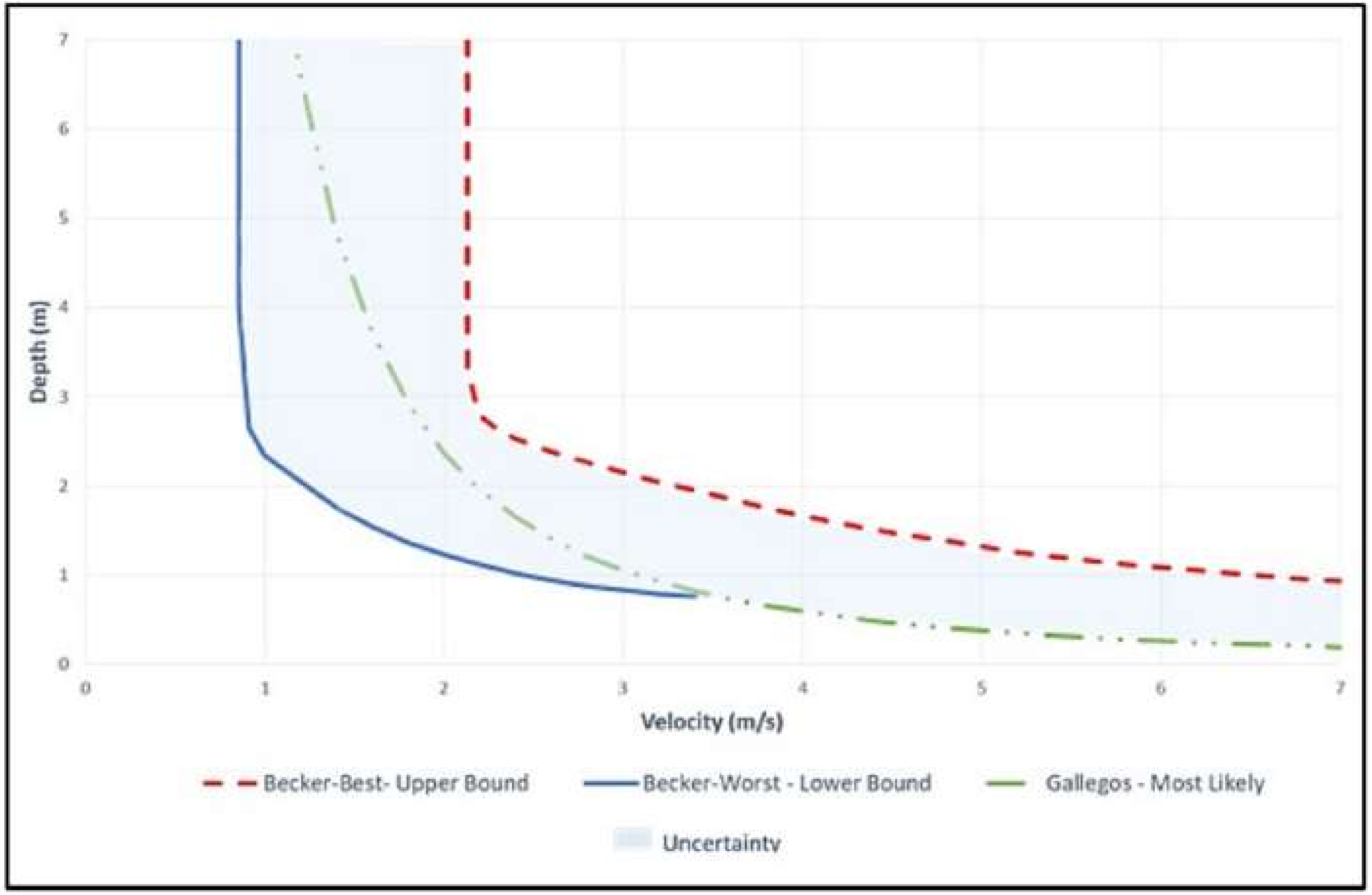
4. **Masonry** - Unreinforced stone or block structures.

5. **Wood-Buoyant** - Typical wood frame structure with load bearing walls that is not anchored or bolted to the foundation and is therefore highly susceptible to floating off the foundation.

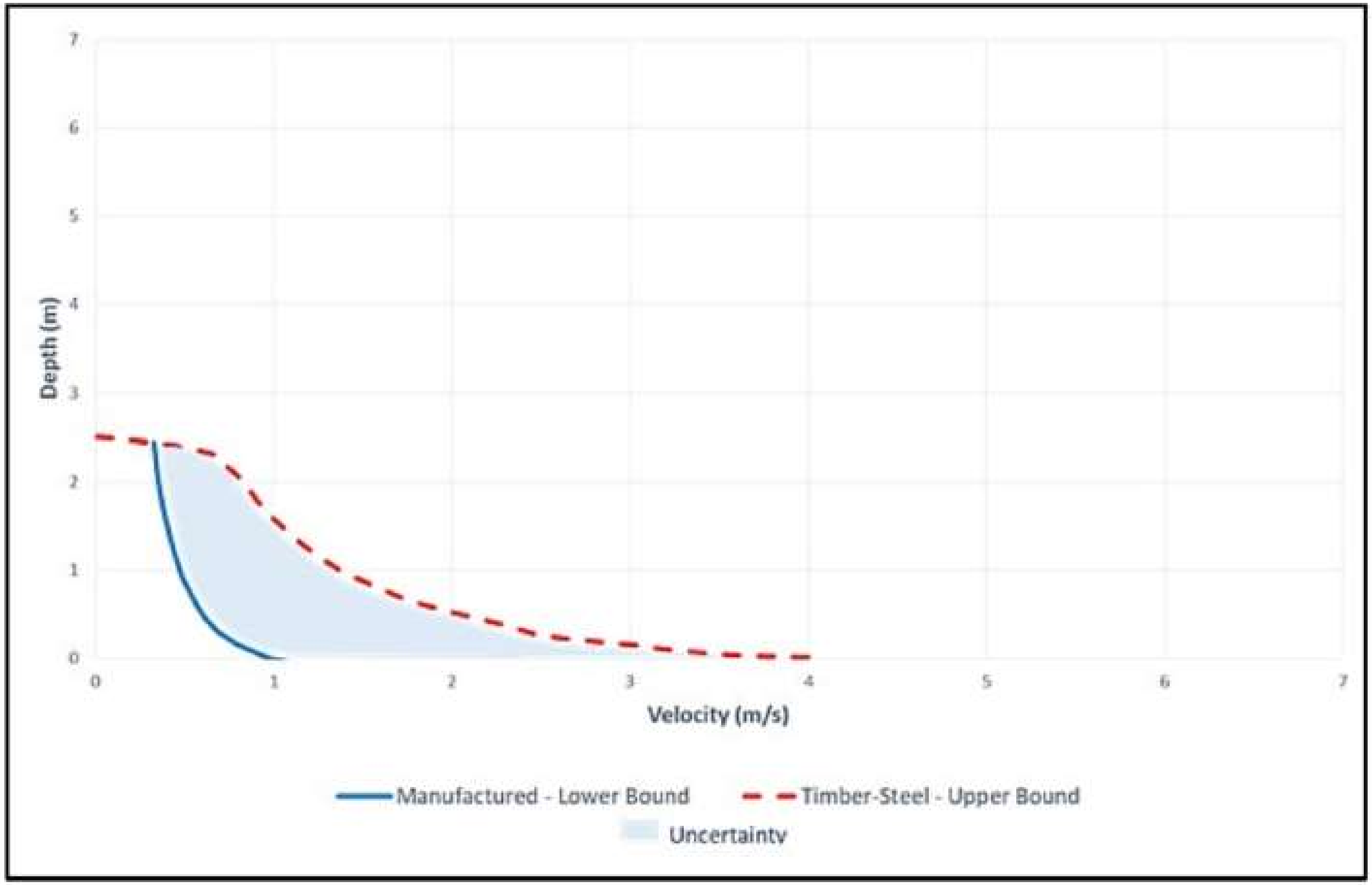
Default Stability Criteria for engineered construction, uniform distribution



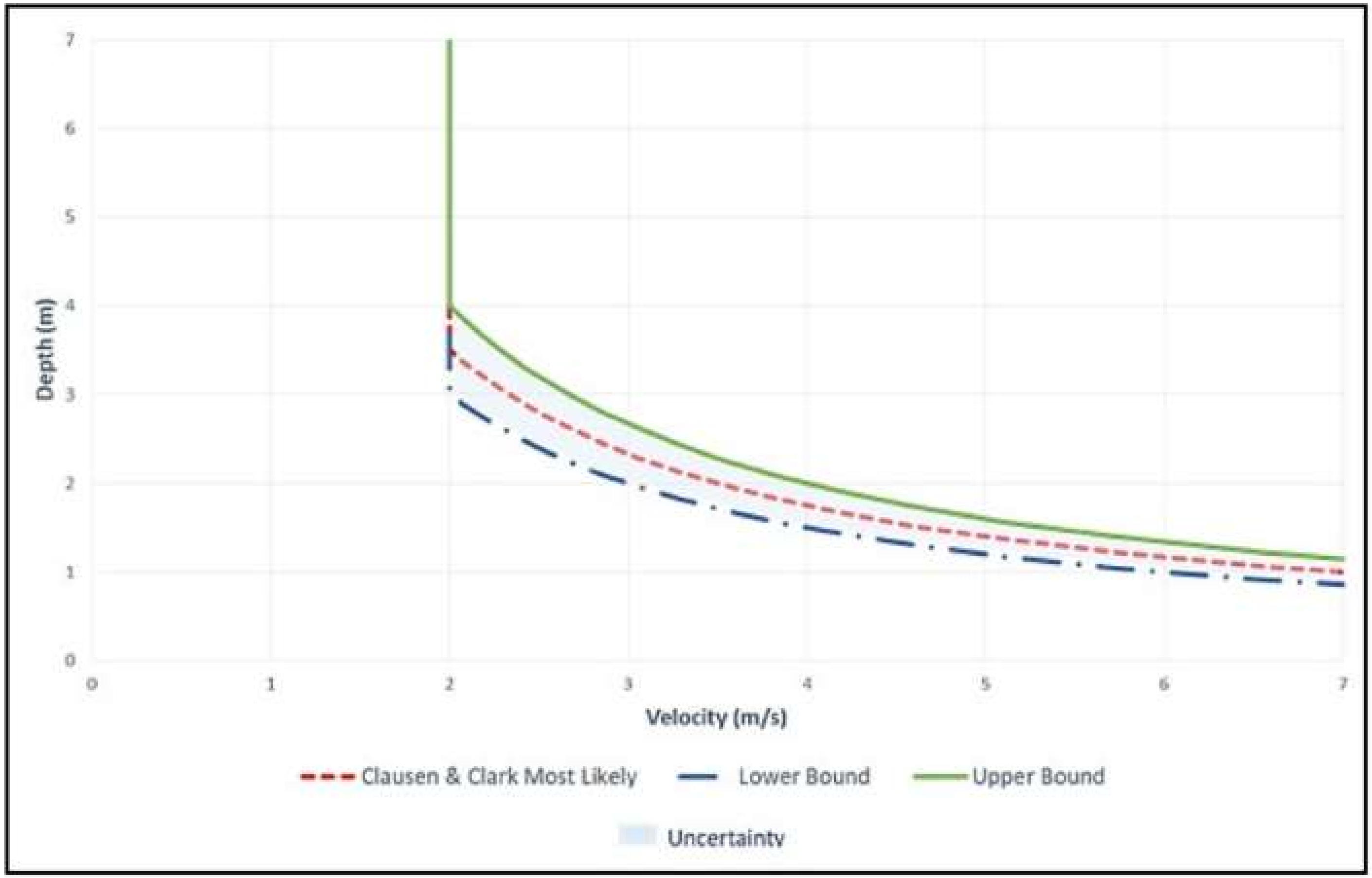
Default Stability Criteria for wood-anchored construction, triangular distribution



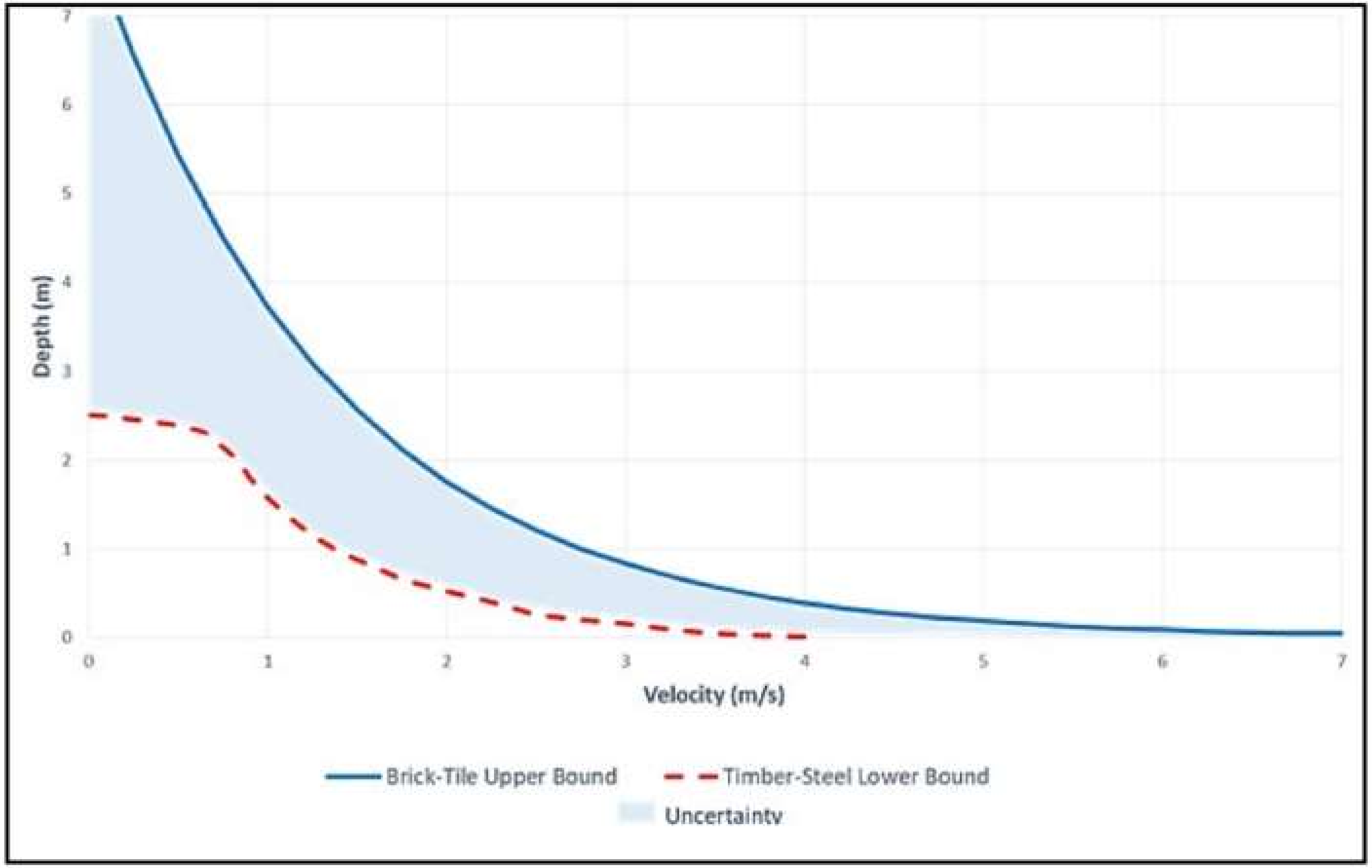
Default Stability Criteria for manufactured construction, uniform distribution



Default Stability Criteria for masonry construction, triangular distribution

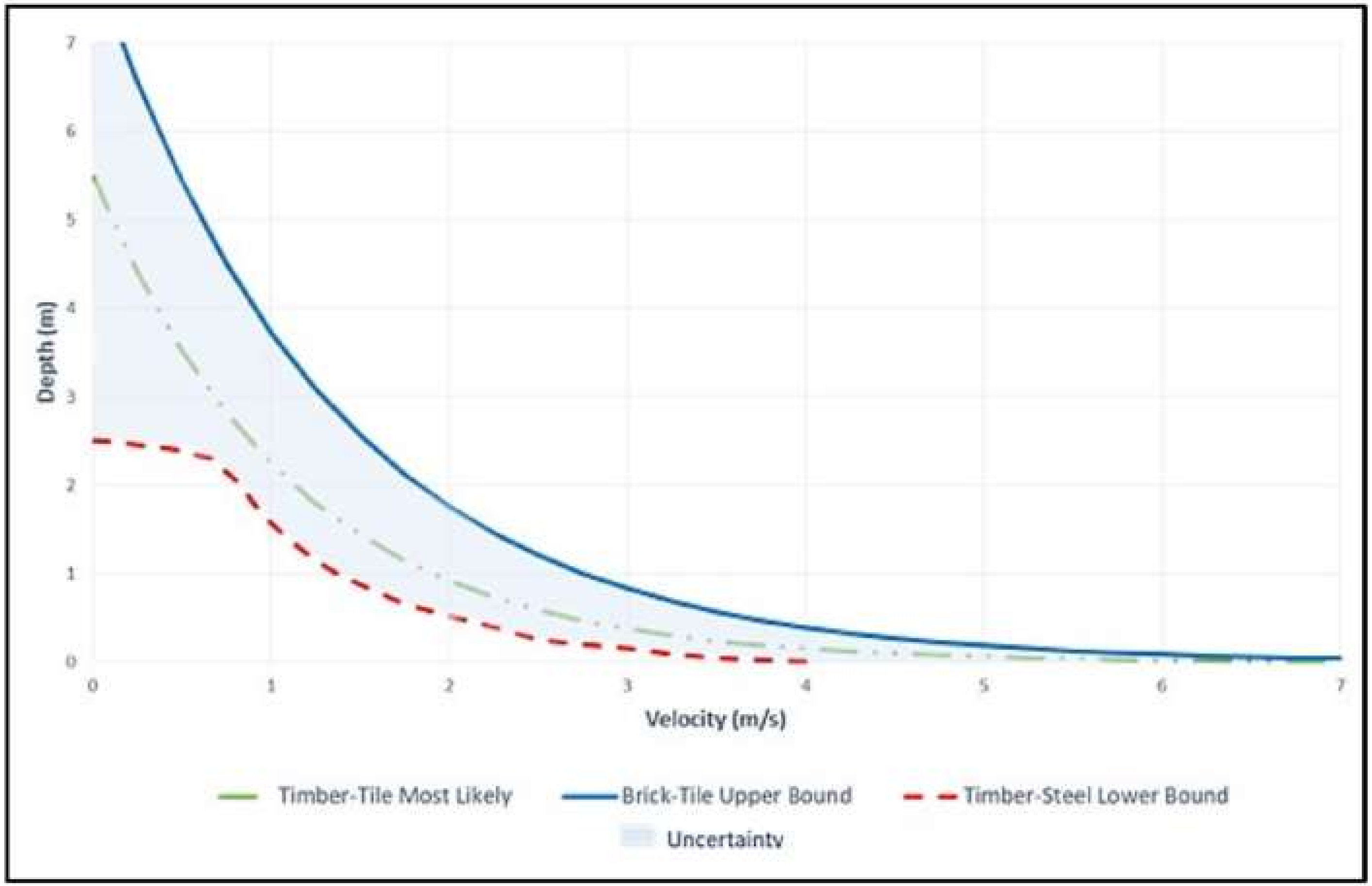


Default Stability Criteria for wood-buoyant construction (unknown weight), uniform distribution



Default Stability Criteria for wood-buoyant construction (known weight/light), triangular distribution

- If the weight of the structure is less than 33,623 kilograms (kgs), then use the light threshold.
- If the weight of the structure is greater than or equal to 33,623 kilograms (kgs), then use the heavy threshold.



Default Stability Criteria for wood-buoyant construction (known weight/heavy), triangular distribution

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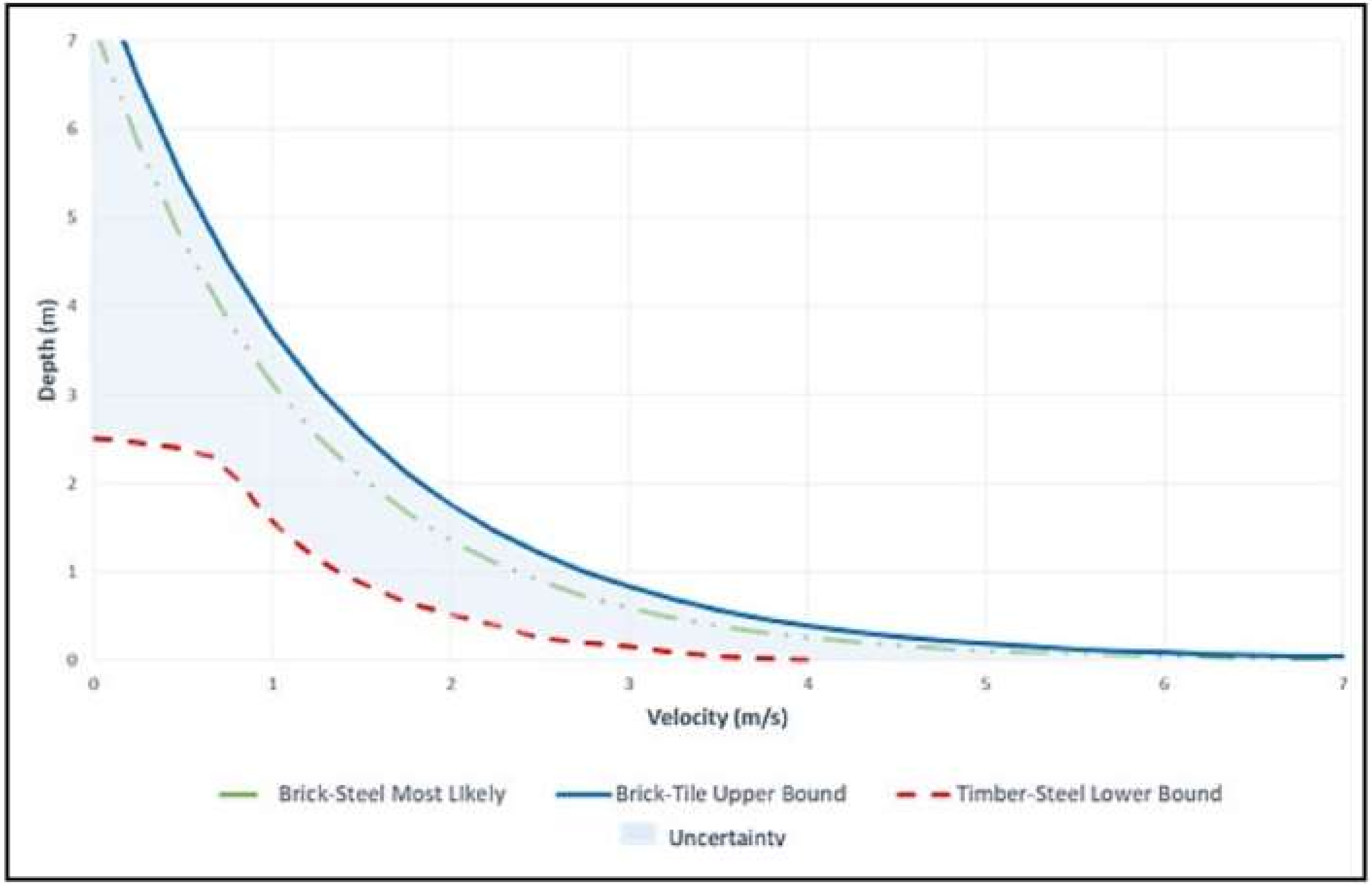
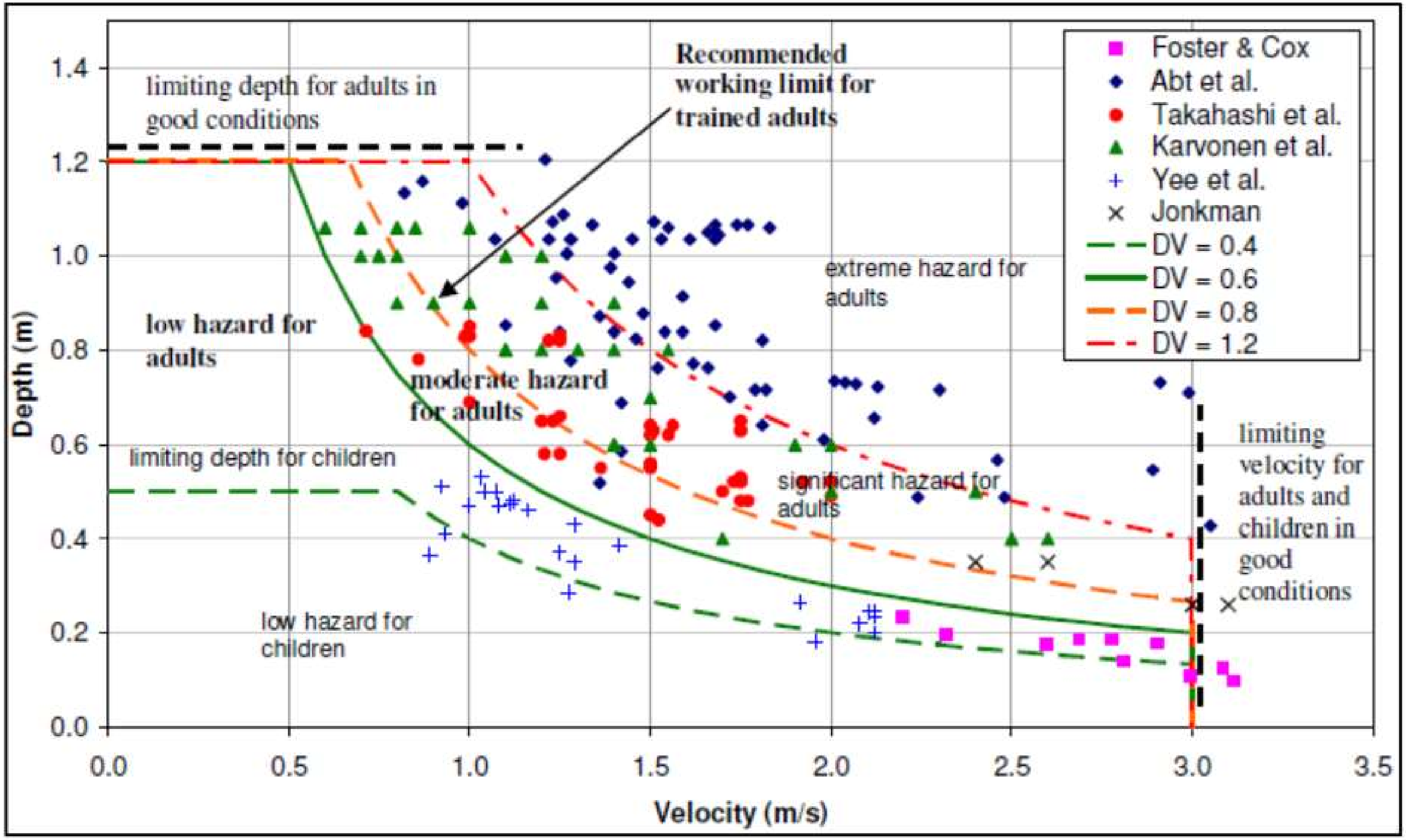


Proposed hazard regimes compard to available experimental data (Shand et al., 2014)



Population at Risk and Potential Loss of Life

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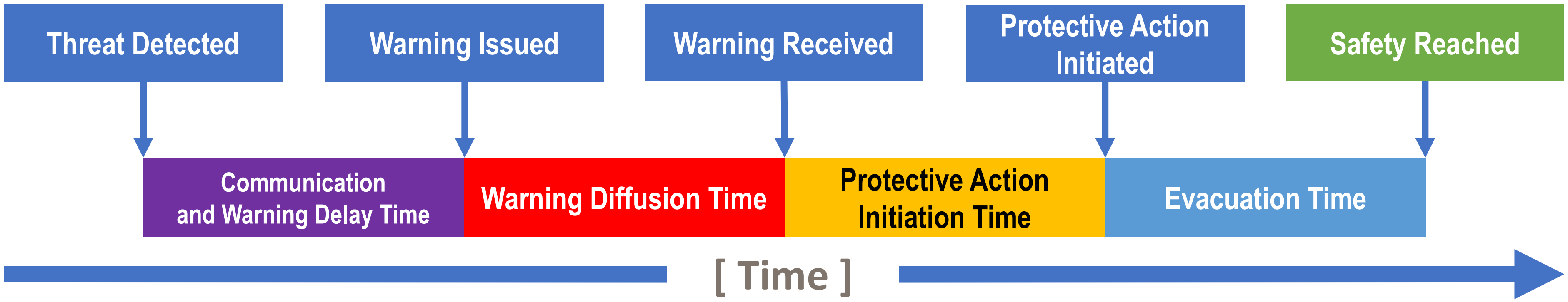
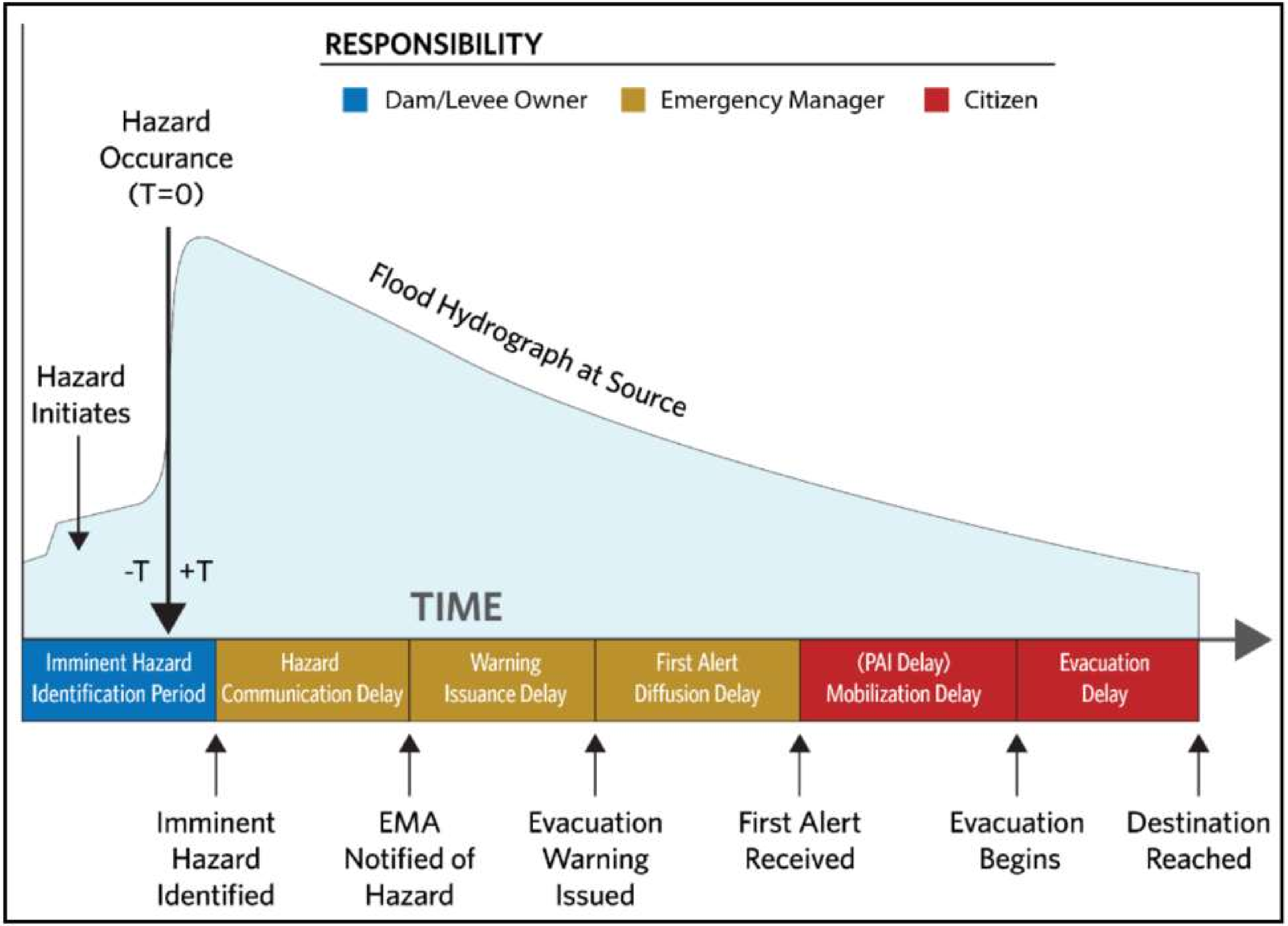
Warning and Protective Action Initiation Timeline



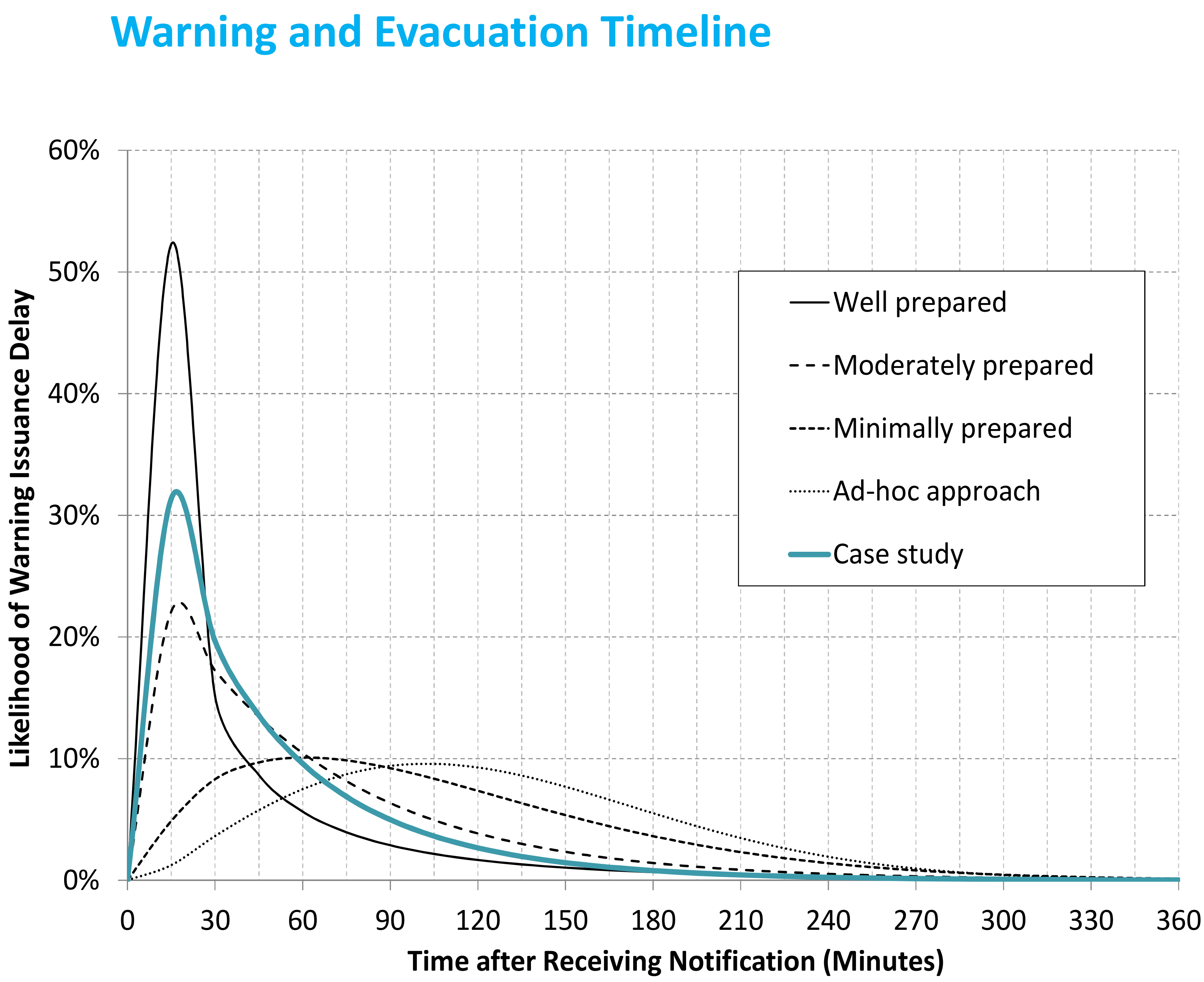
Warning and Evacuation Timeline



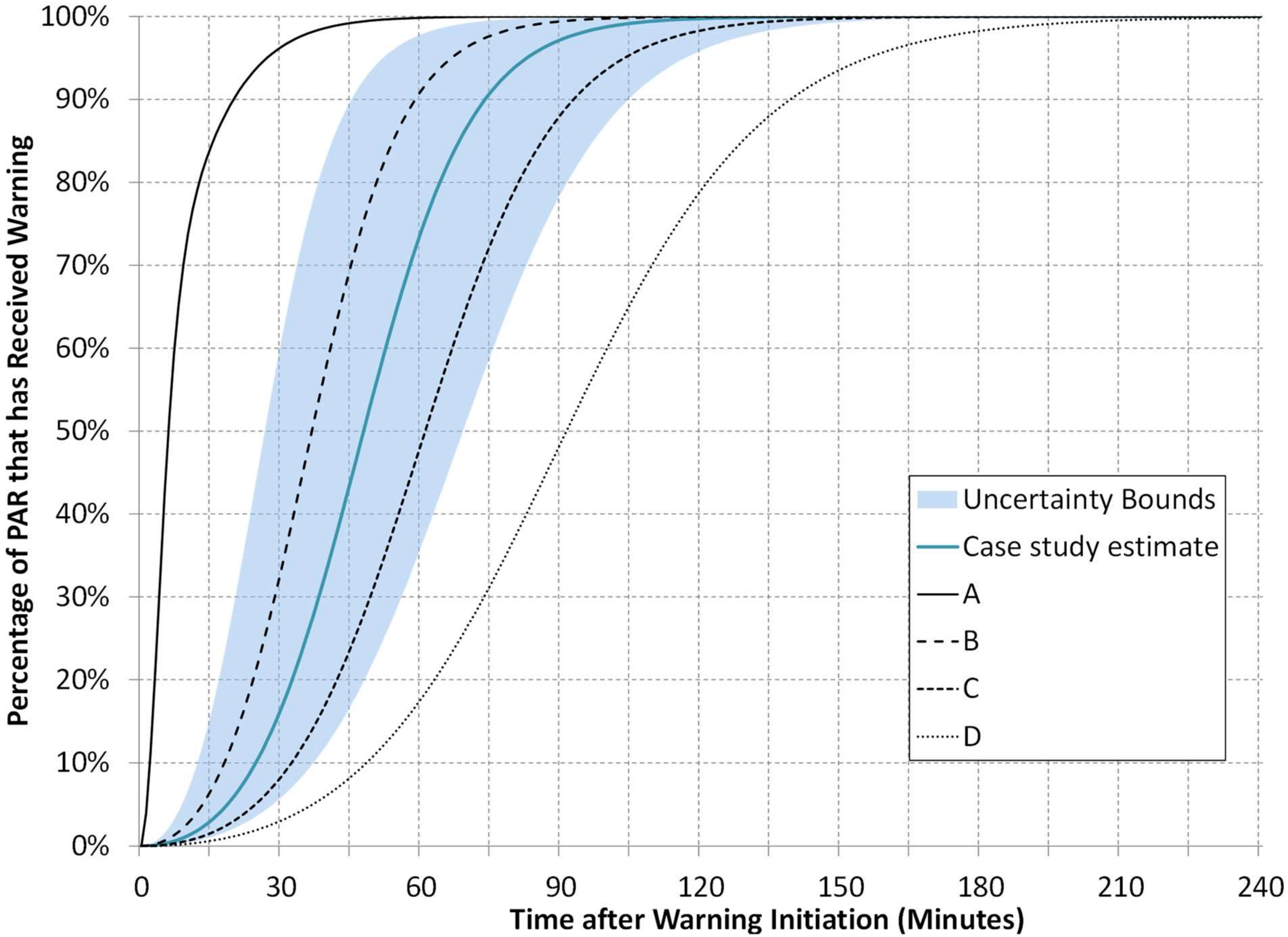
Warning and Evacuation Timeline

US Army Corps
of Engineers
Risk Management Center

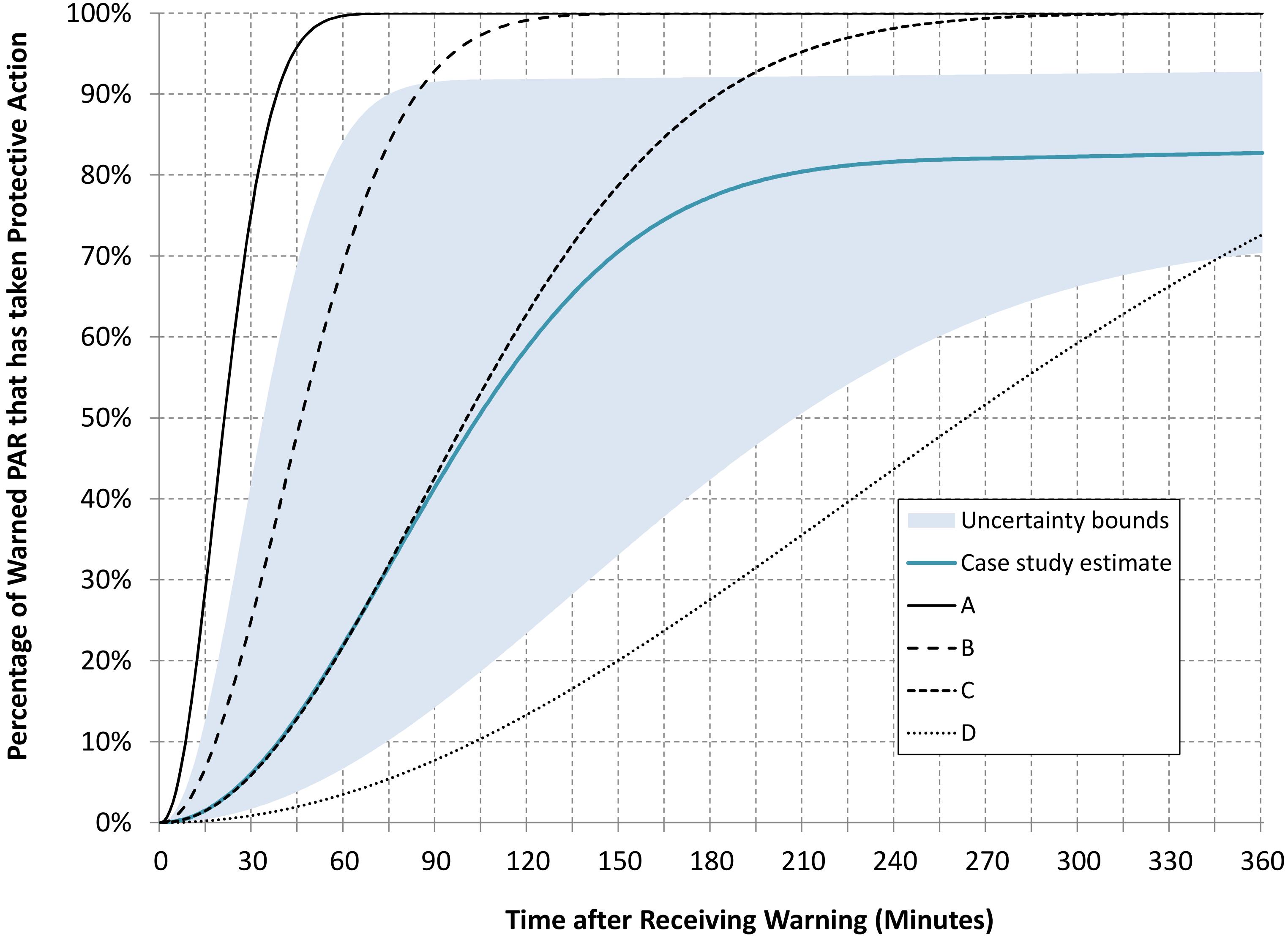
First Alert and/or Warning Issuance Time Estimation for Dam Breaches, Controlled Dam Releases, and Levee Breaches or Overtopping


Warning and Evacuation Timeline
60%
50%
40%
30%
20%
10%
0%
Likelihood of Warning Issuance Delay
0
30
60
90
120
150
180
210
240
270
300
330
360
Time after Receiving Notification (Minutes)
Well prepared
Moderately prepared
Minimally prepared
Ad-hoc approach
Case study

Warning and Evacuation Timeline



Warning and Evacuation Timeline



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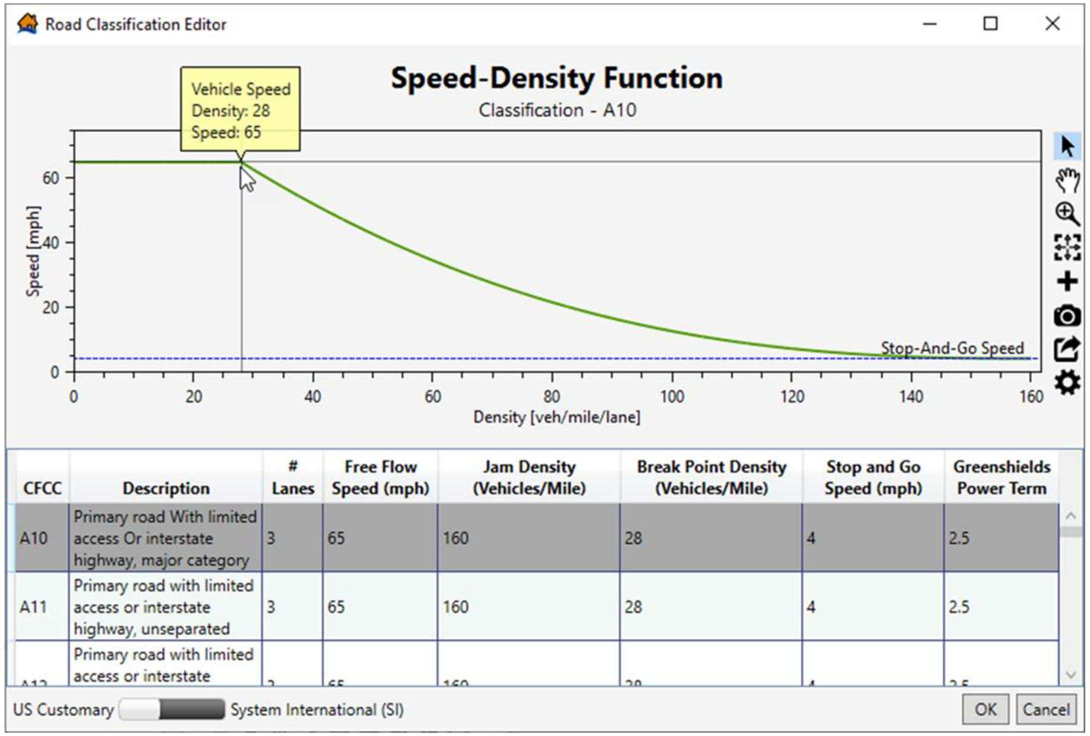
Population Redistribution (Evacuation)

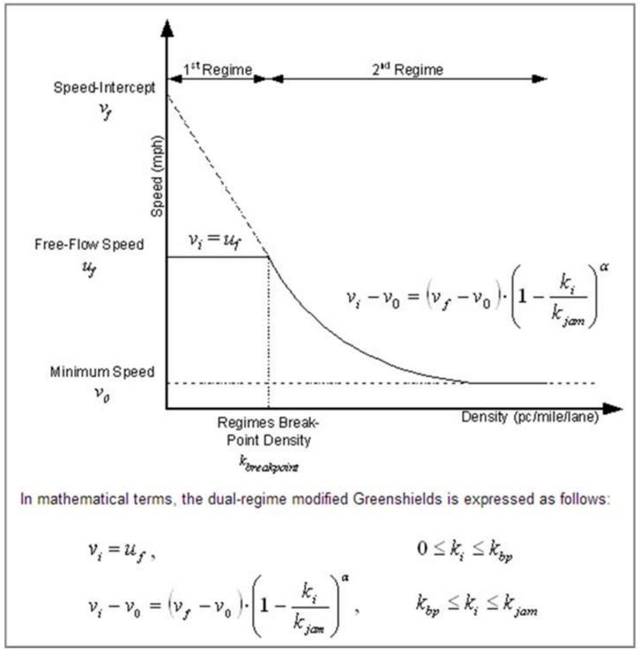
Can people get to safety before water arrives?

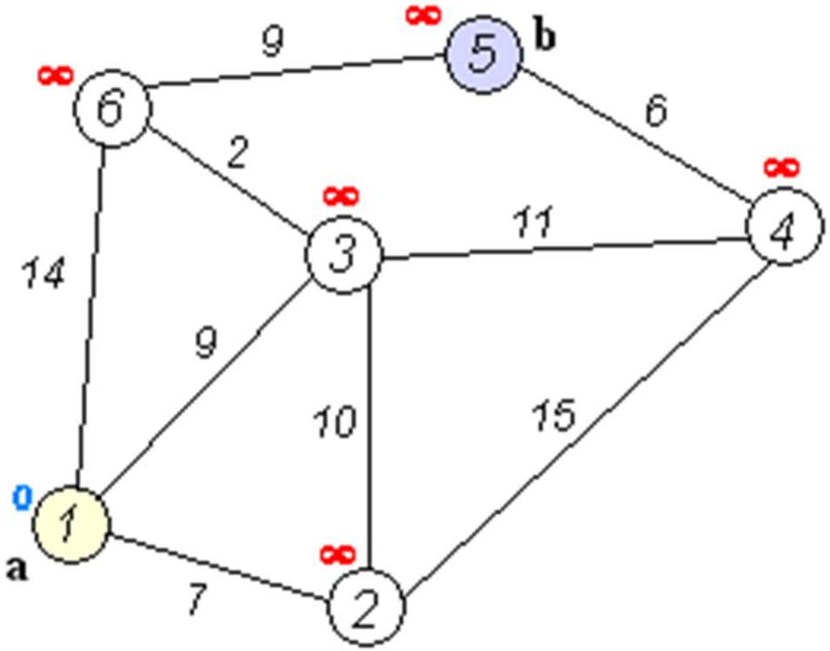
Population Redistribution (Evacuation)

- # of lanes
- Free Flow Speed
- Jam Density
- Break Point Density
- Stop and Go Speed
- Greenshields Power Term



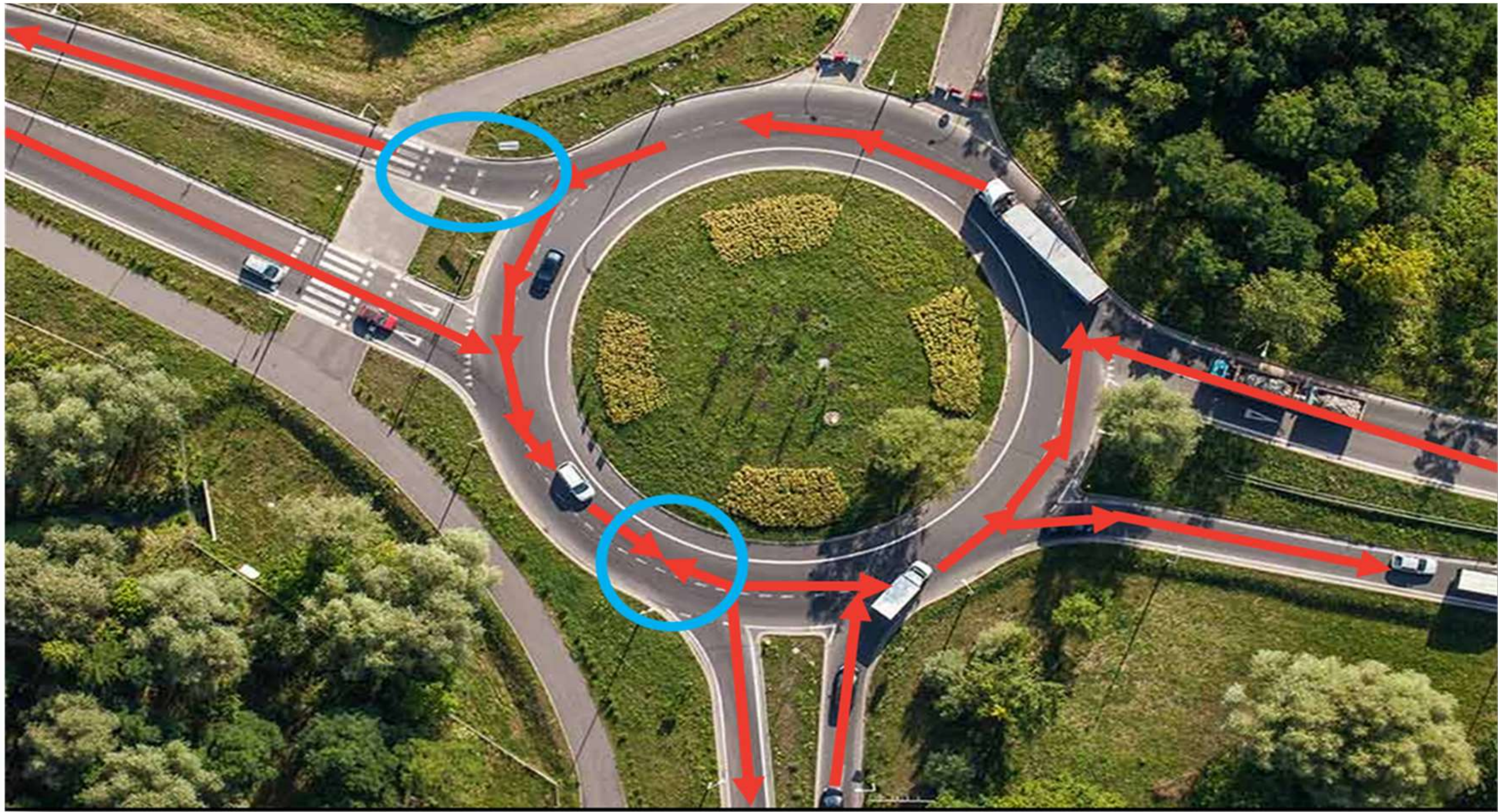
Population Redistribution (Evacuation)

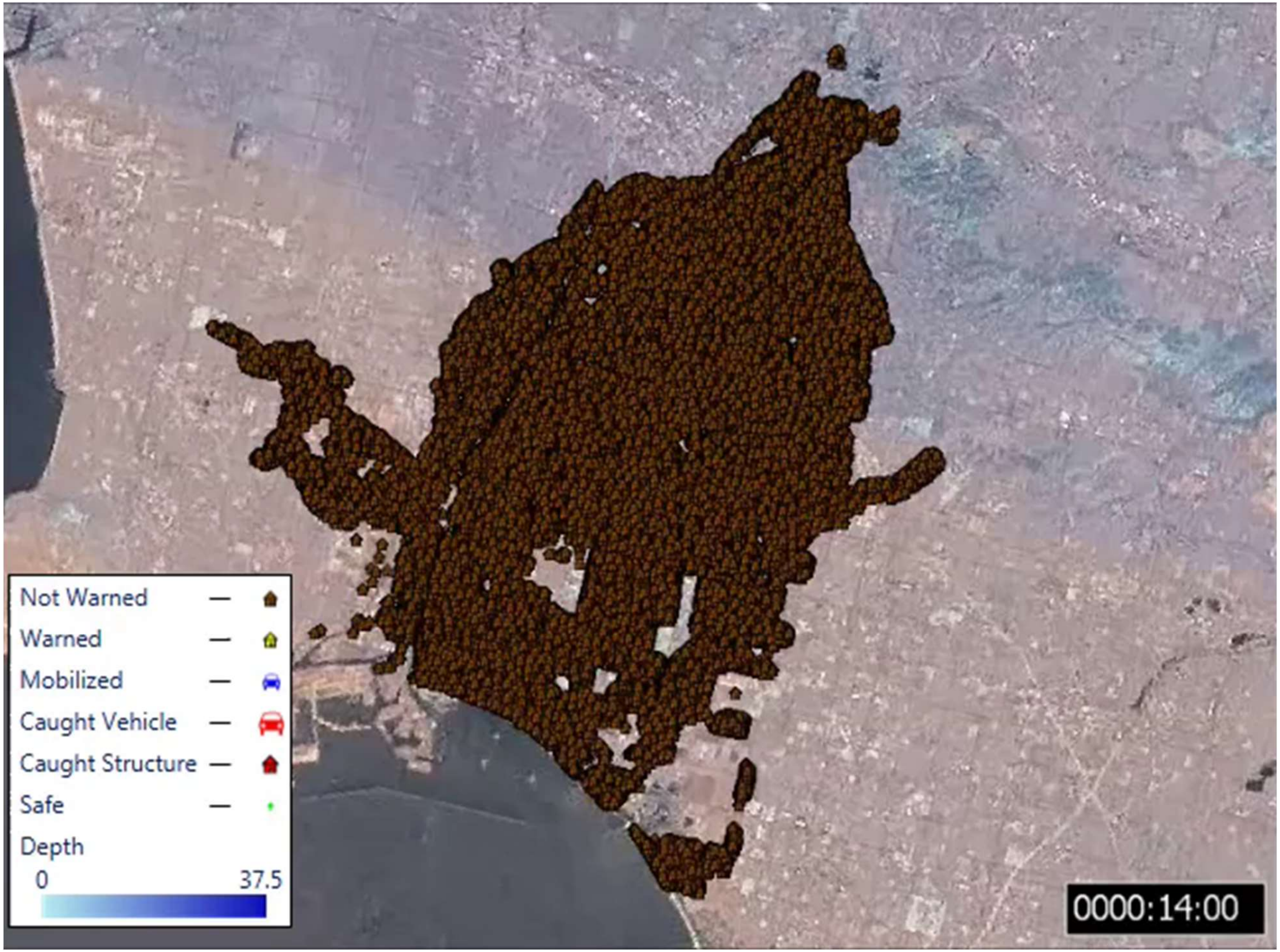




Destination is chosen by shortest travel time
Djikstra's Shortest Path Algorithm

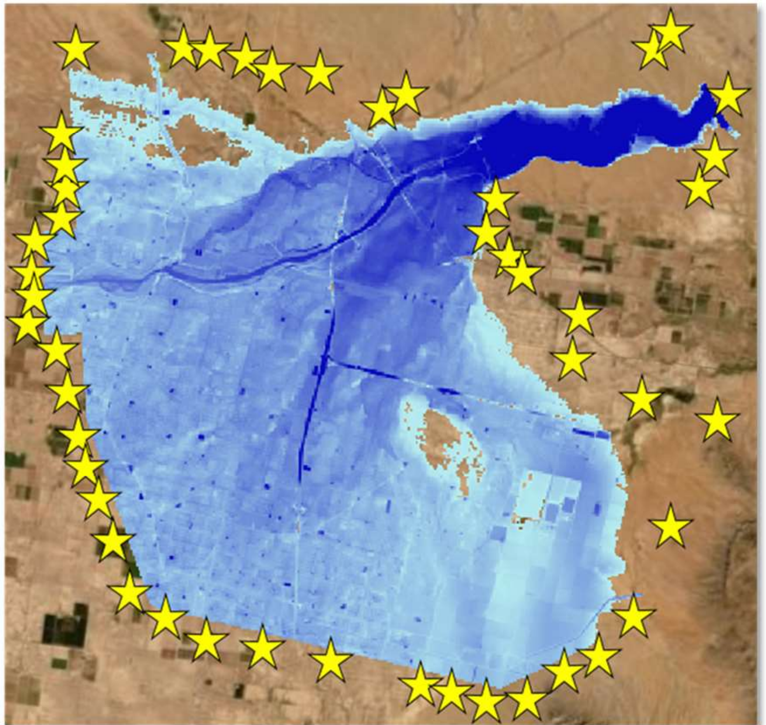
Population Redistribution (Evacuation)



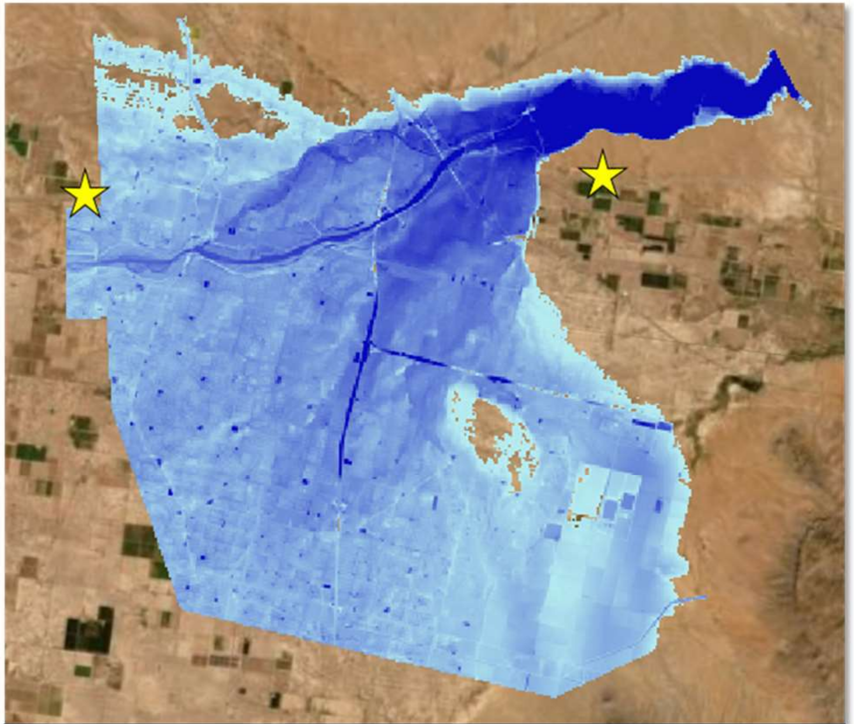


Not Warned
Warned
Mobilized
Caught Vehicle
Caught Structure
Safe
Depth
0
37.5
0000:14:00

Number of Destinations and Locations



Too many: LL < 1,700



Too few: LL > 5,100

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High and Low Hazard zones fatality function
(based on Flood Fatality Data base)

Low hazard:

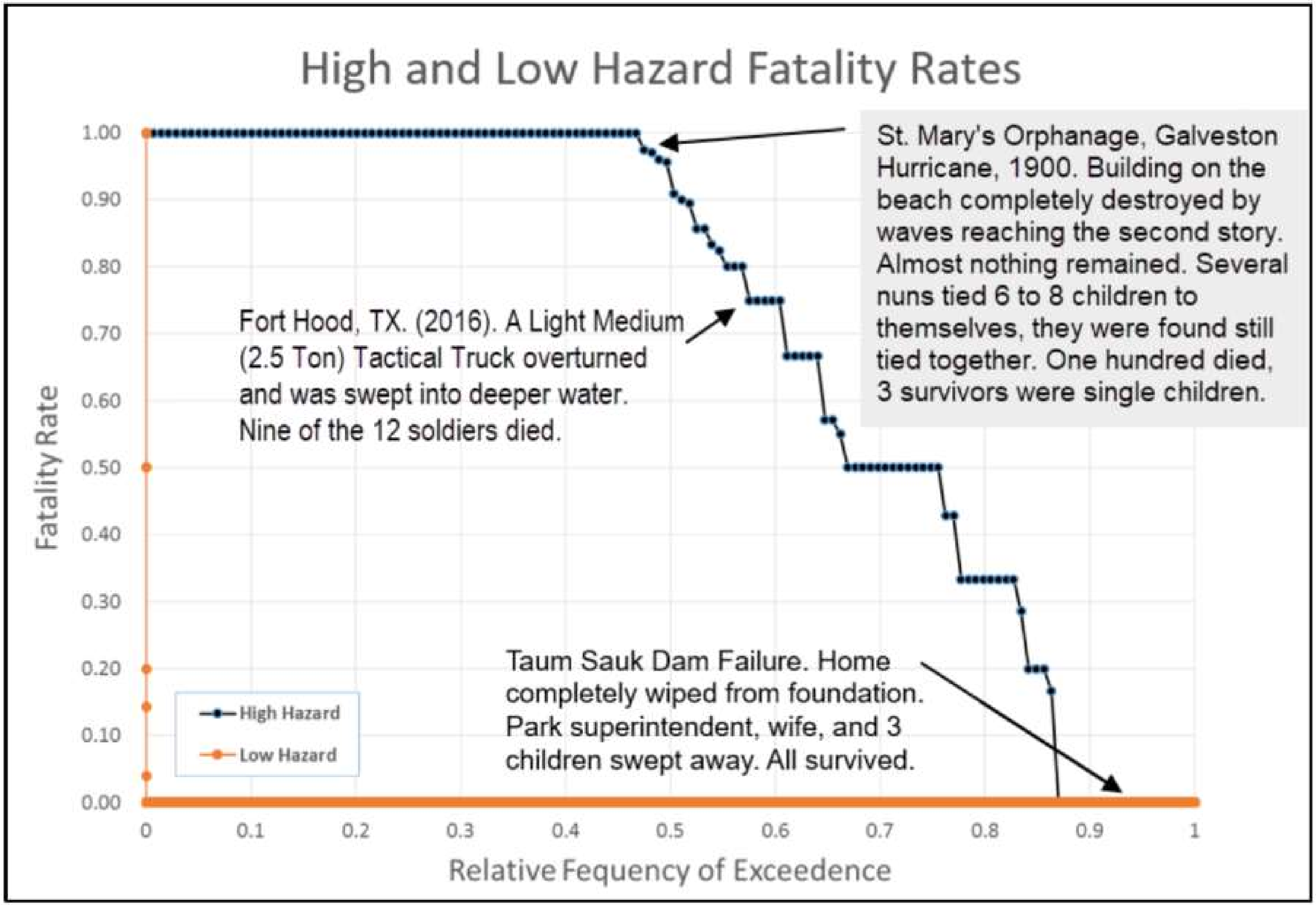
- Exposed to relatively calm floodwaters, where their stability or the stability of their shelter is not at risk. A hazard exists because people are coming in contact with water in locations not meant for such an interaction

High hazard:

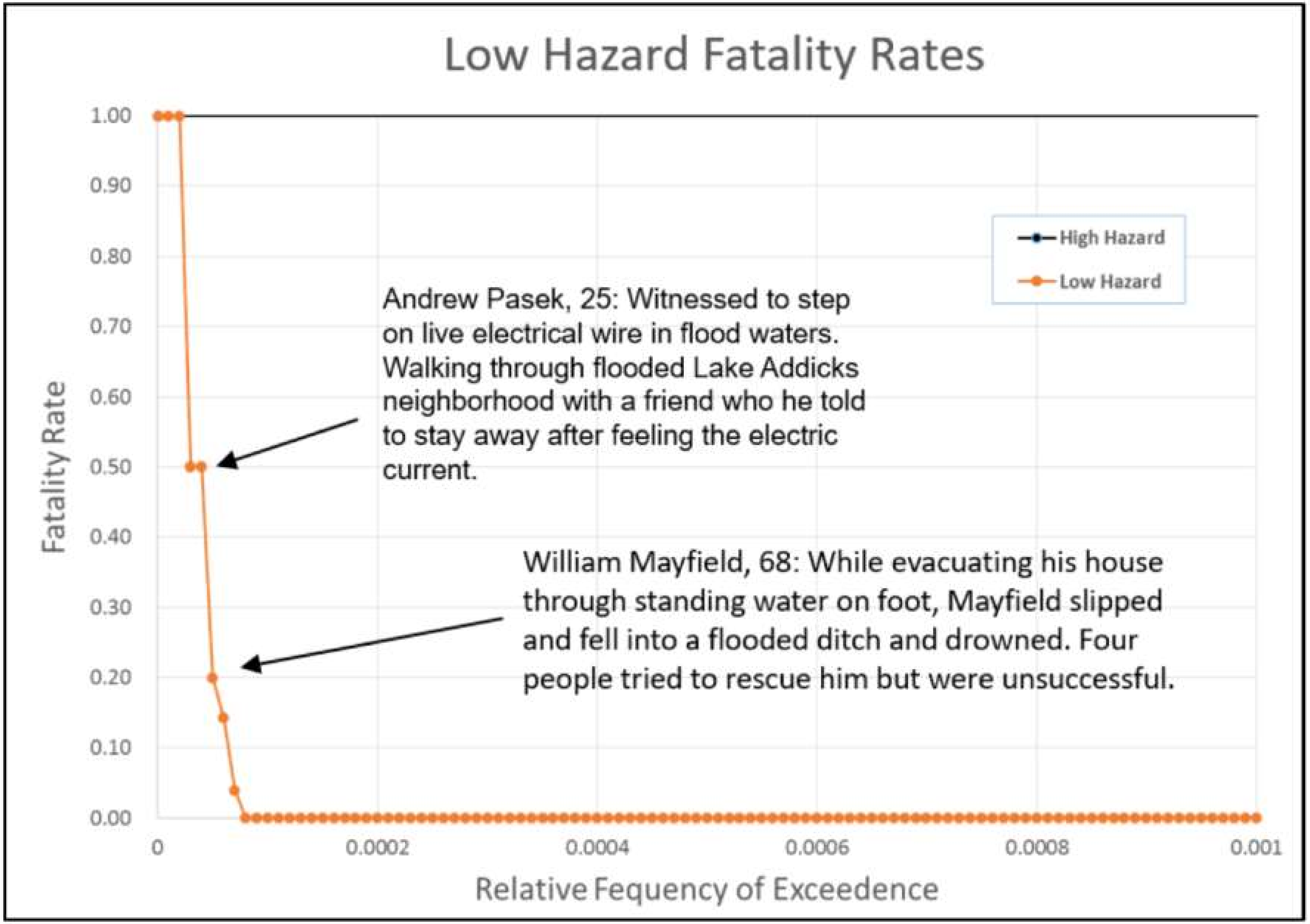
- Stability criteria or submergence criteria of the person (if out in the open), the vehicle (if caught while evacuating) or the structure (if not mobilized) has been exceeded. In that situation, the victims are typically swept downstream, trapped underwater or buried in a collapsed building

High and Low Hazard zones fatality function

(based on Flood Fatality Data base)



Low Hazard zones fatality function
(based on Flood Fatality Data base)



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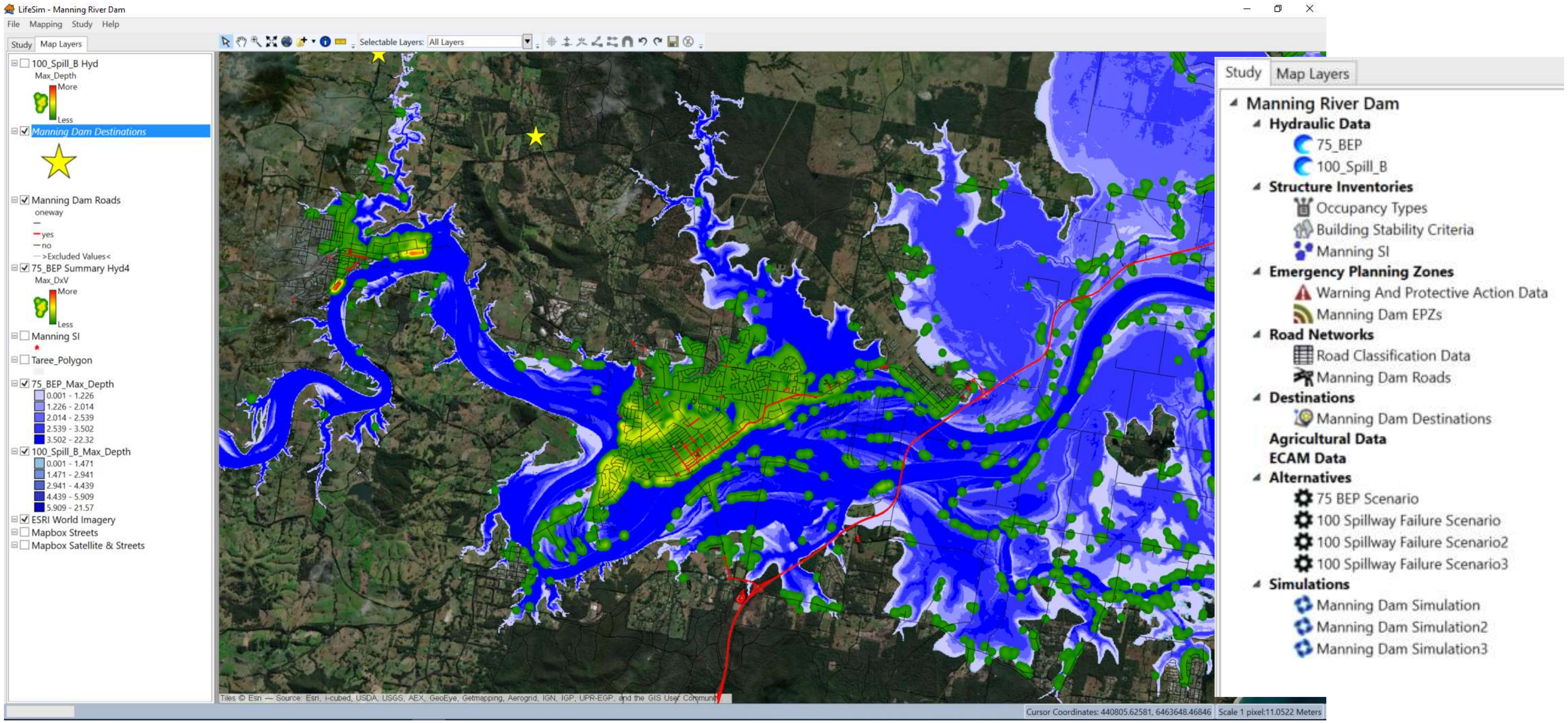
Hec-LifeSIM


LifeSim - Manning River Dam
File Mapping Study Help
Study Map Layers
Selectable Layers: All Layers
100_Spill_B Hyd
Max_Depth
More
Less
Manning Dam Destinations
Manning Dam Roads
oneway
yes
no
>Excluded Values<
75_BEP Summary Hyd4
Max_DxV
More
Less
Manning SI
Taree_Polygon
75_BEP_Max_Depth
0.001 - 1.226
1.226 - 2.014
2.014 - 2.539
2.539 - 3.502
3.502 - 22.32
100_Spill_B_Max_Depth
0.001 - 1.471
1.471 - 2.941
2.941 - 4.439
4.439 - 5.909
5.909 - 21.57
ESRI World Imagery
Mapbox Streets
Mapbox Satellite & Streets
Cursor Coordinates: 440805.62581, 6463648.46846
Scale 1 pixel:11.0522 Meters
Study Map Layers
Manning River Dam
Hydraulic Data
75_BEP
100_Spill_B
Structure Inventories
Occupancy Types
Building Stability Criteria
Manning SI
Emergency Planning Zones
Warning And Protective Action Data
Manning Dam EPZs
Road Networks
Road Classification Data
Manning Dam Roads
Destinations
Manning Dam Destinations
Agricultural Data
ECAM Data
Alternatives
75 BEP Scenario
100 Spillway Failure Scenario
100 Spillway Failure Scenario2
100 Spillway Failure Scenario3
Simulations
Manning Dam Simulation
Manning Dam Simulation2
Manning Dam Simulation3

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- Total Risk (RMC-USACE)

Identification and Assembly of all relevant data,

- Data mining,
- Gap analysis,
- Understand visual data and during construction information,
- Do not underestimate usefulness of Photos at different stages of project construction!
- Monitoring and observations,
- Surveillance,
- Dam Upgrades,
- Understanding of FMs.

Photo RW 8172. Late 1923/Early 1924 (estimated): Left abutment early works. Start of placement of earthifll on lower left abutment.

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- Do not underestimate usefulness of Photos at different stages of project construction!
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3 Photo 4871. 19 June 1924: Steam shovel used to place earthfill in Embankment No. 1. Local moving and spreading of earthfill using 0.5 yd^3 horse drawn wheeled scoops

Identification and Assembly of all relevant data,

- Data mining,
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- Do not underestimate usefulness of Photos at different stages of project construction!
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1 Photo 4907. 22 October 1924: Local moving and spreading earthfill using 0.5 yd3 horse drawn wheeled scoops and “compaction” by horse and wheels. Cobble drainage being placed downstream of corewall.

An Introduction to Risk Assessment

- Identification and Assembly of all relevant data,
- Hazard and Failure Mode Identification,
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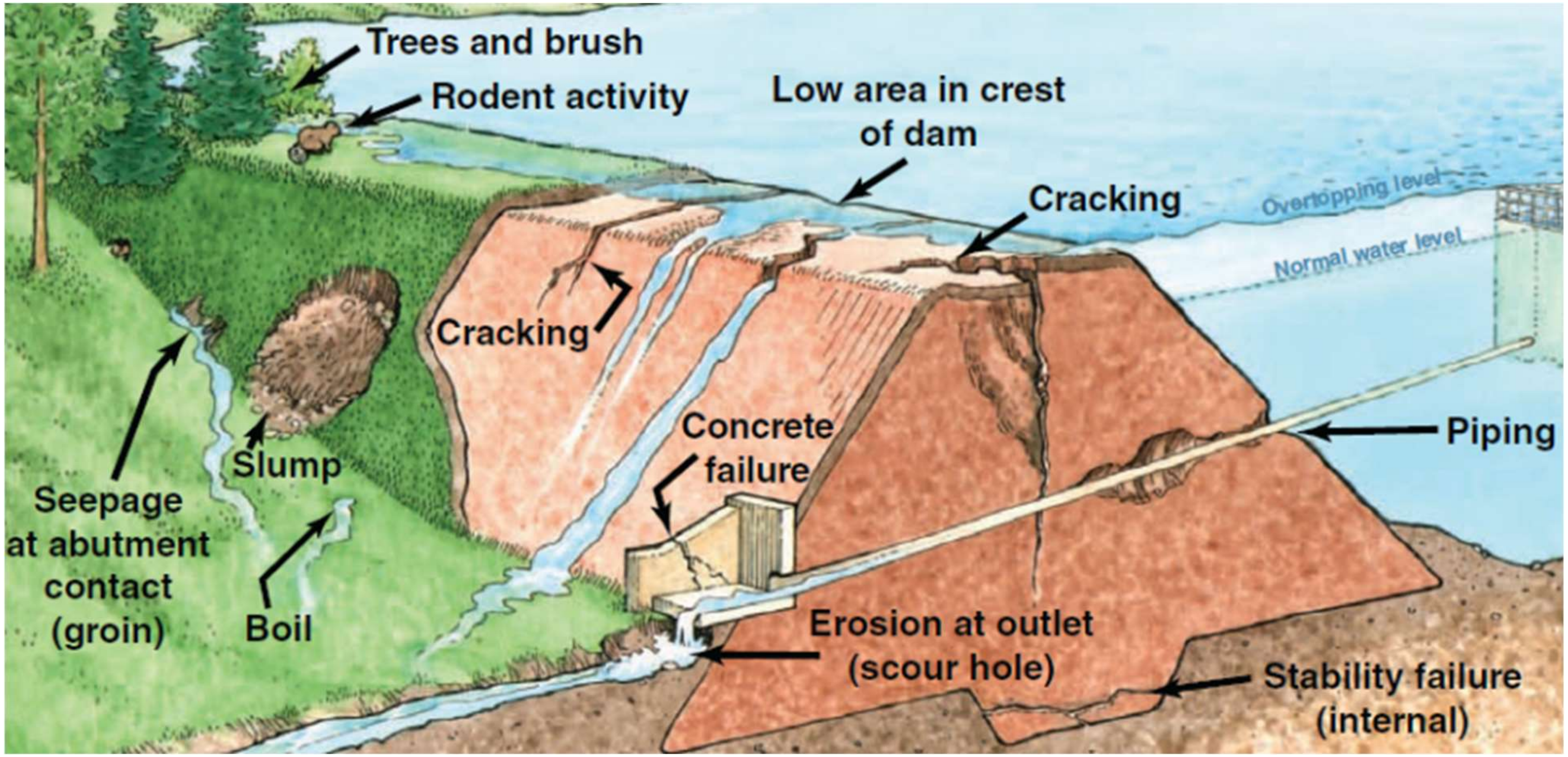
Event → SDF, FD, EQ

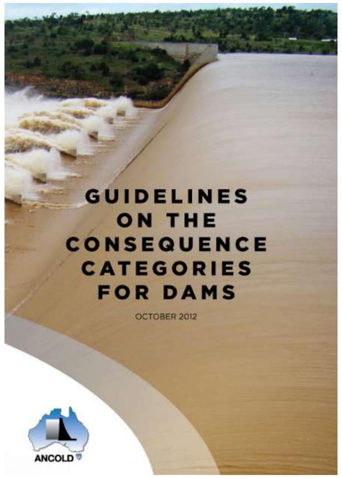
Likelihood → Probability of Failure due to the event

Consequences → Societal, Economical

Risk = **Event x Probability of Failure x Consequences**

Different Modes of Failure (Emb. Dams)





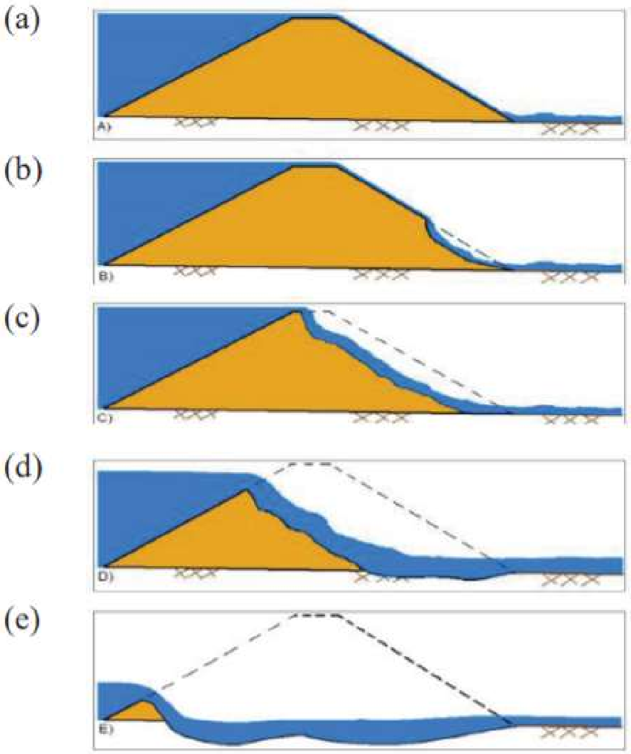


FIGURE 3. Breach Process for an Overtopping Failure

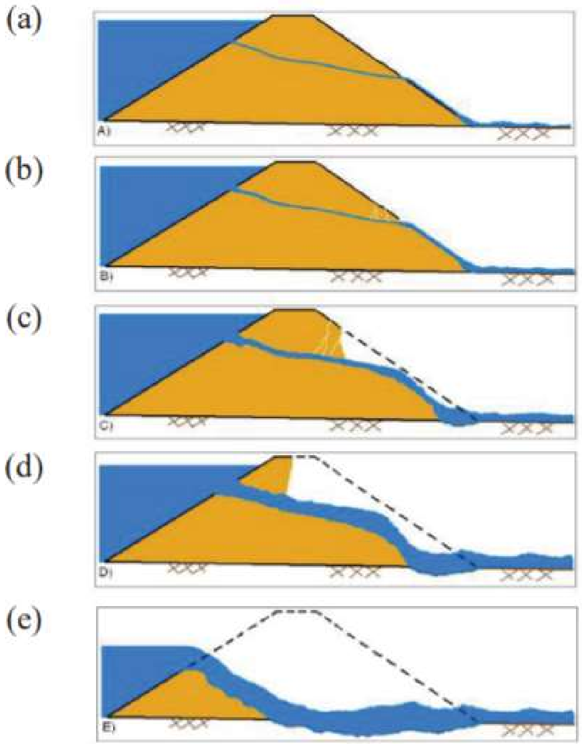


FIGURE 4. Breach Process for a Piping Failure


EXCLUSIVE VECTOR
DESIGNED BY vector open stock

10.1.4 Probability for Continuation – Scenario 3 (Filter/transition zone is present downstream of the core or a downstream shoulder zone which is not capable of holding a crack/pipe)

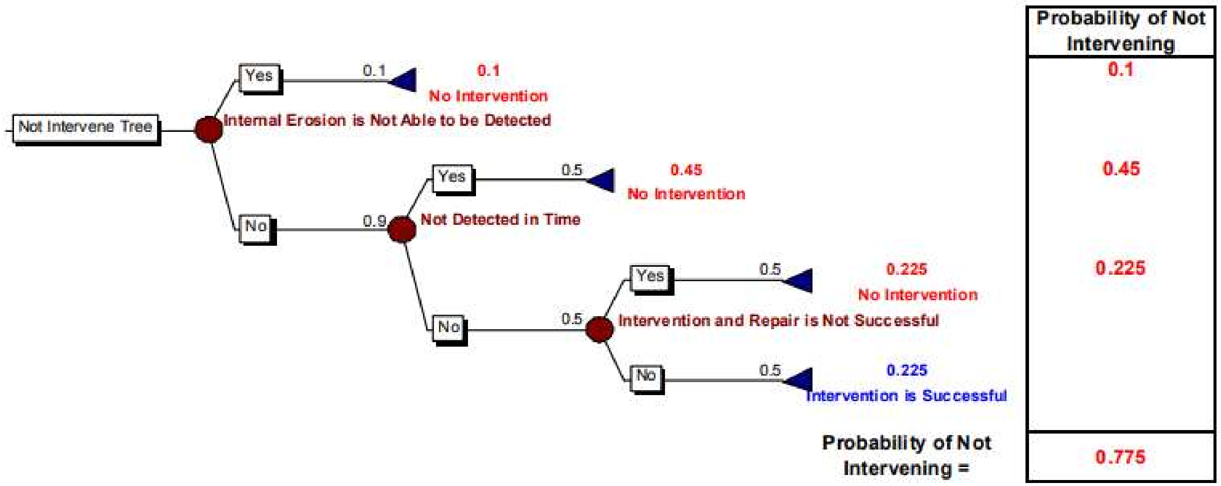
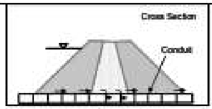
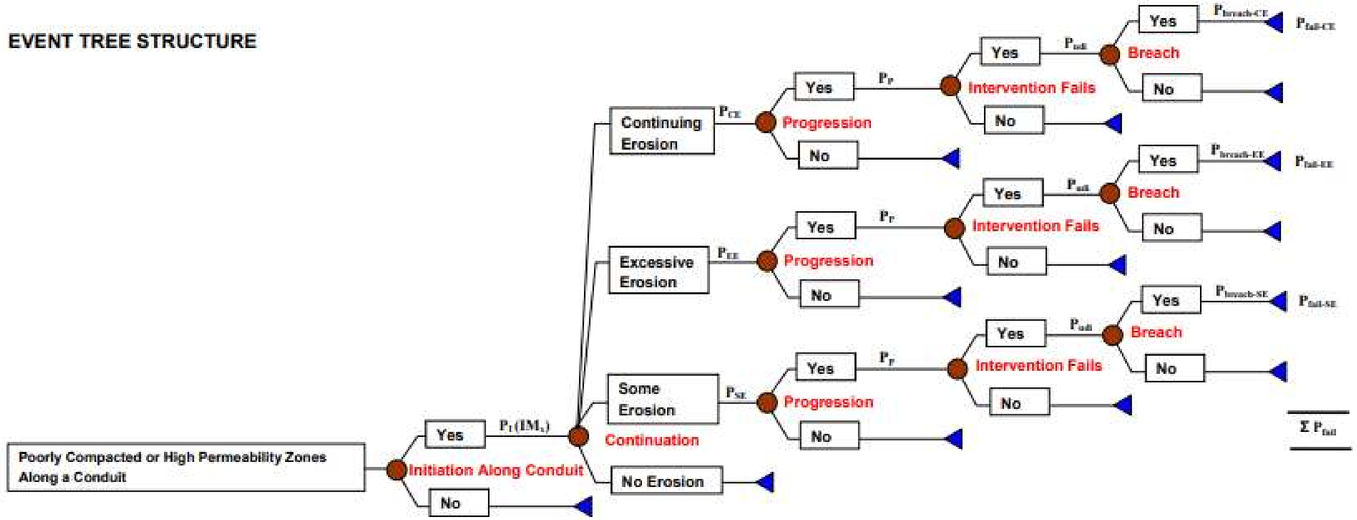


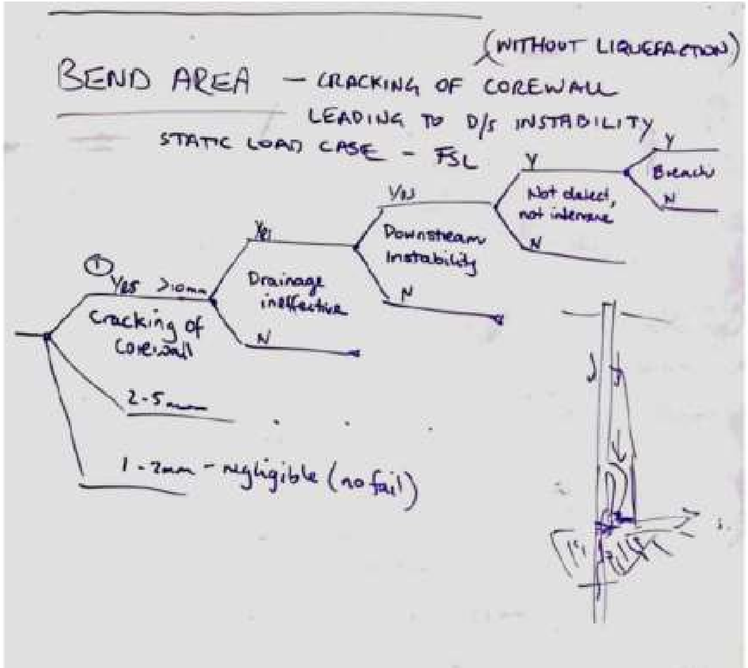
Figure 12.1 – Sub-event tree for calculating the probability of not intervening.

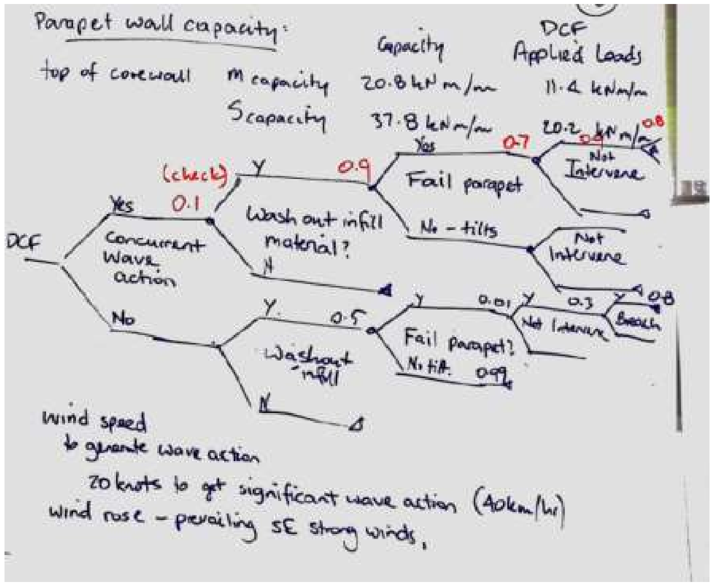
Table A1. Probability of Failure by Internal Erosion Through the Embankment (Sheet 4)

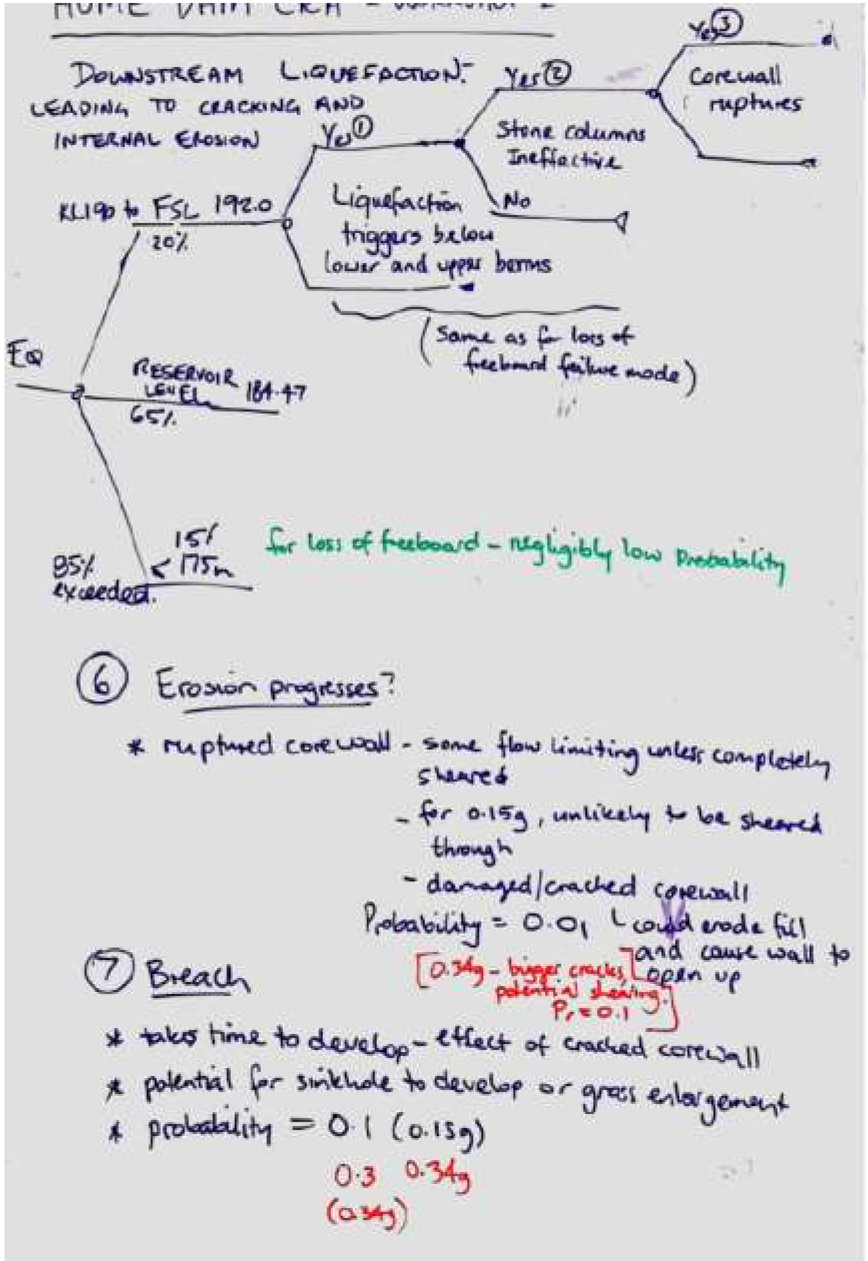
Initiating Mechanism	Sketch	(1) Failure Path Identification and Screening	(2) Evaluate the Probability of Initiation of Erosion P_I	(3) Probabilities for No, Some, Excessive and Continuing Erosion P_{NE}, P_{SE}, P_{EE}, P_{CE}	(4) Probability of Progression P_P	(5) Probability of Unsuccessful Detection and Intervention P_{udi}	(5) Probability of Breach P_{breach}	(6) Calculate the Probability of Failure
Initiation of Erosion in Poorly Compacted or High Permeability Zones Along a Conduit		Use Table A5 to identify and screen potential crack mechanisms	Use Table A5 to evaluate the probability of initiation for each initiating mechanism. **$P_I(IM_x)$**	Evaluate the probabilities for No, Some, Excessive and Continuing Erosion for the failure path under consideration using Table A7. **P_{SE}** **P_{EE}** **P_{CE}**	Estimate the probabilities for forming a roof (P_{PR}), crack filling action not stopping pipe enlargement (P_{PC}) and upstream zone fails to limit flows (P_{PL}) for the failure path under consideration using Table A8. **P_P** $= P_{PR} \times P_{PC} \times P_{PL}$	Estimate the probability for not detect and intervene using Table A9. **P_{udi}**	Estimate the probabilities of breach for the Some, Excessive and Continuing Erosion branches using Table A10. **$P_{breach-NE} = 0$.** **$P_{breach-SE}$** **$P_{breach-EE}$** **$P_{breach-CE}$**	Calculate the probability of failure for each IM using the event tree. $P_{fail} = P_I(IM_x) \times P_P \times P_{udi} \times$ $[(P_{SE} \times P_{breach-SE}) +$ $(P_{EE} \times P_{breach-EE}) +$ $(P_{CE} \times P_{breach-CE})]$

EVENT TREE STRUCTURE




(WITHOUT LIQUEFACTION)
BEND AREA – CRACKING OF COREWALL LEADING TO D/S INSTABILITY
STATIC LOAD CASE – FSL
① Yes >10mm
Cracking of corewall
Yes
Drainage ineffective
N
Y/N
Downstream Instability
N
Y
Not detect, not intervene
N
Y
Breach
N
2-5mm
1-2mm – negligible (no fail)


Parapet wall capacity:
Capacity
DCF Applied Loads
top of corewall
M capacity 20.8 kN m/m
11.4 kNm/m
S capacity 37.8 kN m/m
20.2 kN m/m
DCF
Yes 0.1
Concurrent wave action
(check) Y
Wash out infill material?
0.9
Yes 0.7
Fail parapet
Not Intervene
0.8
No – tilts
Not Intervene
N
0.8
No
Y. 0.5
Washout infill
Y 0.01
Fail parapet?
N: tilt 0.99
Y 0.3
Not Intervene
Y 0.8
Breach
N
wind speed to generate wave action
20 knots to get significant wave action (40km/hr)
wind rose – prevailing SE strong winds,


HUME DAM CRA – WORKSHOP 2
DOWNSTREAM LIQUEFACTION: LEADING TO CRACKING AND INTERNAL EROSION
RL190 to FSL 192.0
20%
Yes ①
Liquefaction triggers below lower and upper berms
Yes ②
Stone columns Ineffective
No
Yes ③
Corewall ruptures
(Same as for loss of freeboard failure mode)
EQ
RESERVOIR LEVEL 184.47
65%
15% <175m
85% exceeded.
for loss of freeboard – negligibly low probability
⑥ Erosion progresses?
* ruptured corewall – some flow limiting unless completely sheared
– for 0.15g, unlikely to be sheared through
– damaged/cracked corewall
└ could erode fill and cause wall to open up
Probability = 0.01
[0.34g – bigger cracks, potential shearing Pr = 0.1]
⑦ Breach
* takes time to develop – effect of cracked corewall
* potential for sinkhole to develop or gross enlargement
* probability = 0.1 (0.15g)
0.3 0.34g
(0.34g)

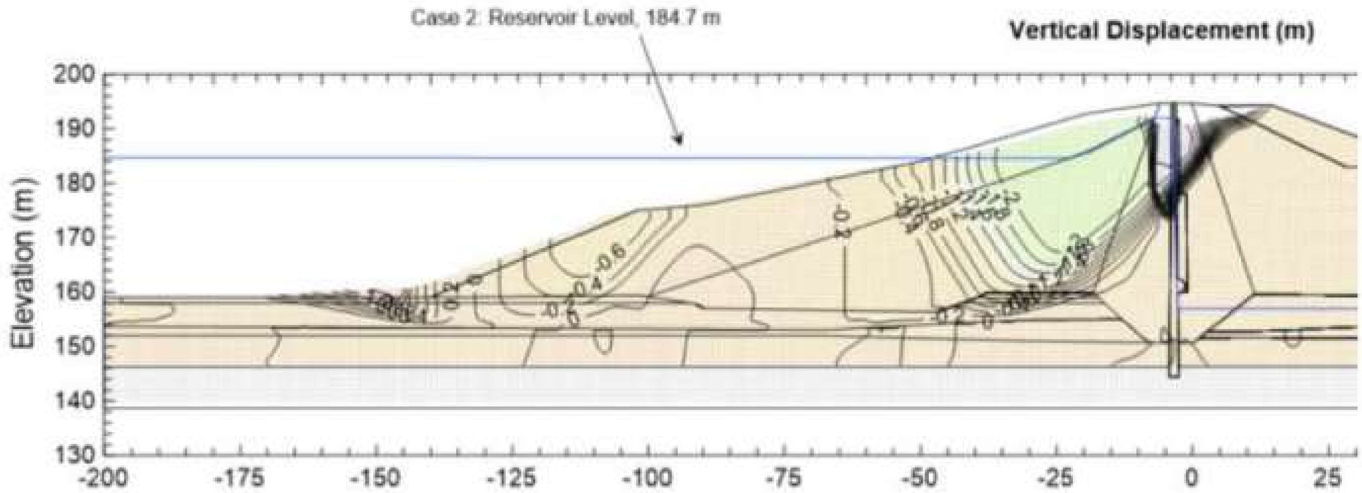


Figure 67: Vertical deformation contours predicted for the 1:25,000 AEP and 1: 50,000 AEP (0.24g and 0.34g) event with the reservoir at RL 184.7 m AHD.

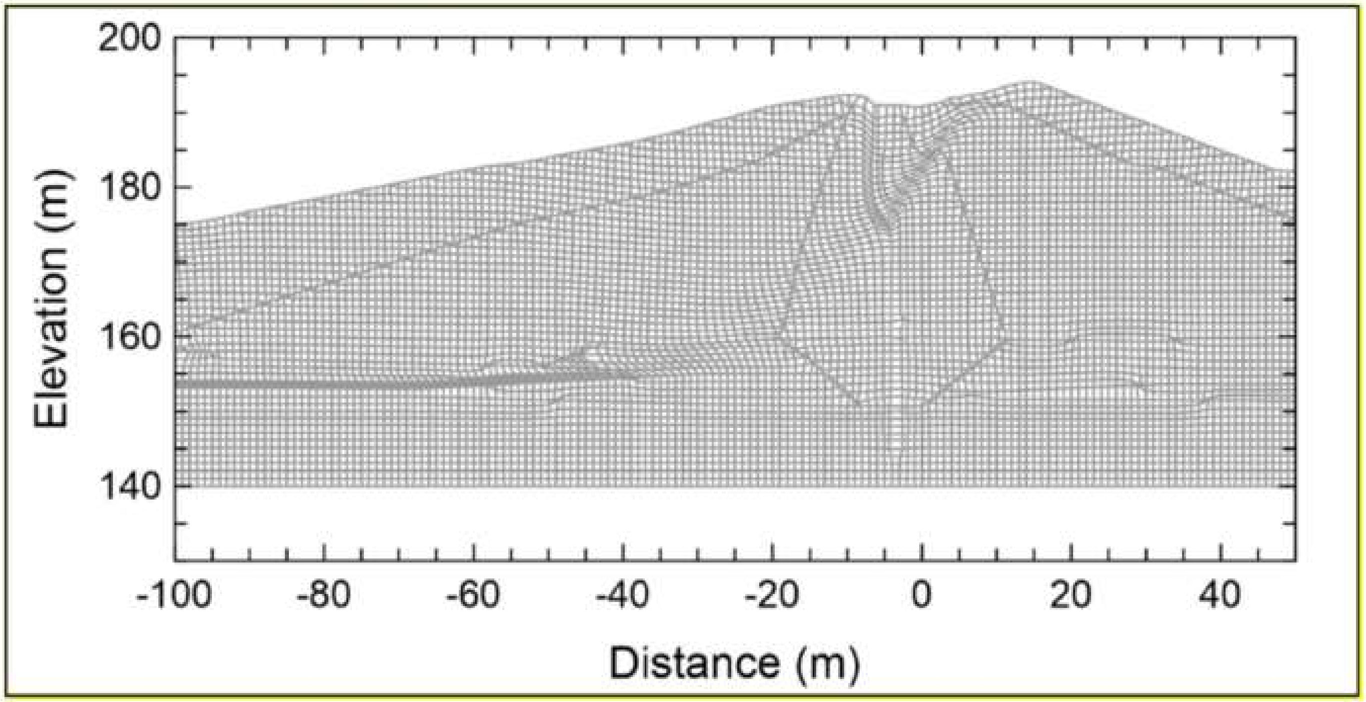
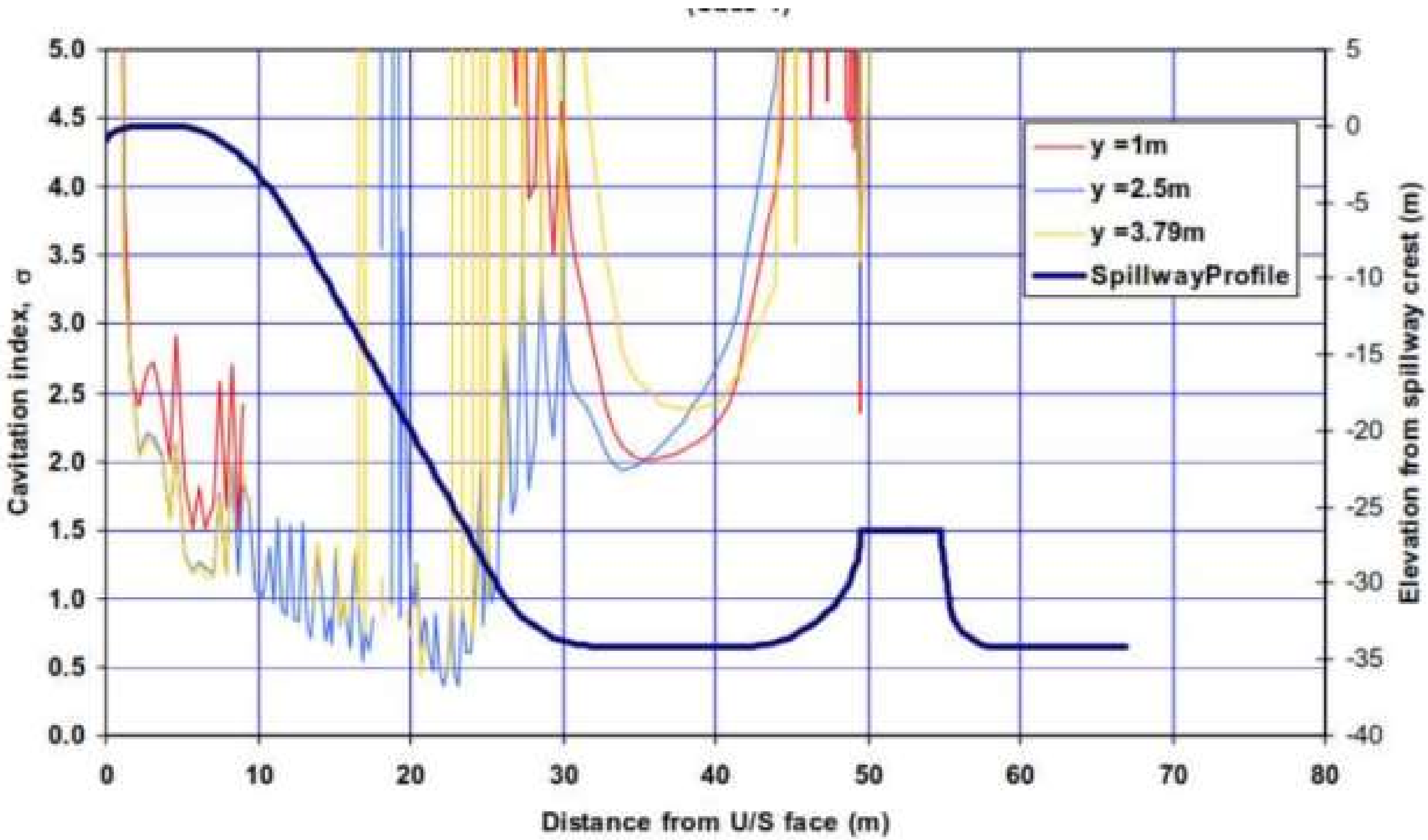
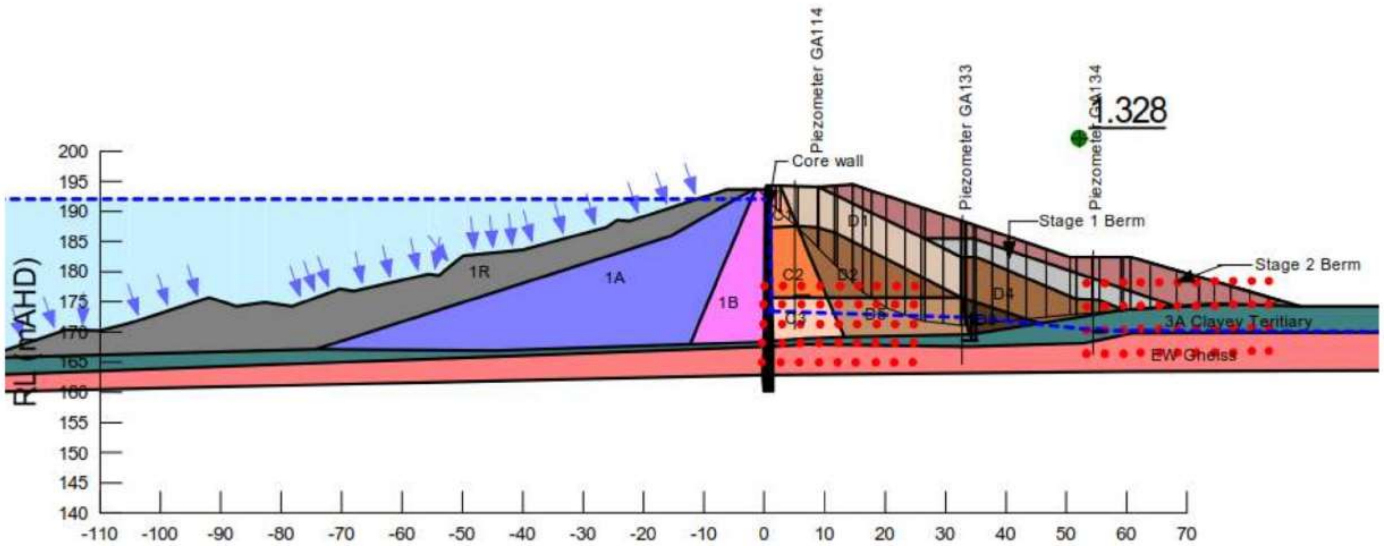


Figure 68: Typical deformed mesh for cases where the reservoir level is lower (RL 185.9 m AHD and RL 184.7 m AHD). Note the formation of the graben feature at the centre of the crest. This is consistent with other case histories of instability of the upstream slope (e.g. Silvan / O'Shannessy).


Cavitation index, σ
Elevation from spillway crest (m)
Distance from U/S face (m)
y =1m
y =2.5m
y =3.79m
SpillwayProfile
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
5
0
-5
-10
-15
-20
-25
-30
-35
-40
0
10
20
30
40
50
60
70
80

Depth of overtopping	Probability of breach Duration overtopping < 6 hours	Probability of breach Duration overtopping >6 hours	Probability of breach Duration overtopping < 6 hours	Probability of breach Duration overtopping >6 hours
	Downstream Slope 3H:1V	Downstream Slope 3H:1V	Downstream Slope 2H:1V	Downstream Slope 2H:1V
0 – 0.15m	0.05	0.1	0.1	0.2
0.15 – 0.3m	0.1	0.3	0.3	0.5
0.3 – 0.5m	0.3	0.5	0.5	0.8
0.5 - 1m	0.5	0.7	0.7	1
>1m	1	1	1	1



Component	Loading	FM Name	Number	FM Type	Description	Include	Comment
Navigable Pass	Hydrostatic	NP.IE.Clay/Interface	FM1-NP-IE	Internal erosion	Similar mechanism for both components. A continuous crack/gap/defect exists either within the foundation clay (due to fissuring) or at the concrete to foundation interface. This defect allows concentrated leak/scour erosion to occur due to the hydraulic gradient. An unfiltered exit exists and erosion occurs. Erosion reaches a point where collapse of the structure occurs resulting in a breach or the storage having an uncontrolled release through/underneath the structure.	Yes	Considered plausible at this stage, given the potential presence of fissuring in clay and/or settlements causing a crack at the foundation contact.
Sluice	Hydrostatic	SL.IE.Clay/Interface	FM2-SL-IE	Internal erosion			
Navigable Pass	Hydrostatic	NP.IE.Sand BEP	FM3-NP-IE	Internal erosion	Similar mechanism for both components. A sand lens underlying the clay foundations has a low PI and material properties necessary to allow backwards erosion piping to occur. An unfiltered exit exists, and erosion occurs. Erosion reaches a point where collapse of the structure occurs resulting in a breach or the storage having an uncontrolled release through/underneath the structure.	No	
Sluice	Hydrostatic	SL.IE.Sand BEP	FM4-SL-IE	Internal erosion		Yes	Considered plausible. Sluice section considered more likely, therefore the navigable pass failure is removed.
Navigable Pass	Hydrostatic	NP.Instability	FM5-NP-ST	Instability	Similar mechanism for both components. Differential upper and lower pool levels occur due to either loss of downstream storage, or due to normal/abnormal operations. This differential level induces destabilising horizontal sliding forces on the structure which exceed the shear strength. The upstream apron is unable to control uplift pressures sufficiently and/or the toe buttress is unable to provide sufficient resistance. Sliding/Overturning failure occurs resulting in a breach.	Yes	Considered plausible, based upon available stability analysis results.
Sluice	Hydrostatic	SL.Instability	FM6-SL-ST	Instability			
Navigable Pass	Seismic	NP.SeismicInstability	FM7-NP-SS	Seismic Instability	Seismic ground motions induce destabilising horizontal sliding forces on the structure which exceed the shear strength of both the foundation and the downstream buttress. Sliding/Overturning failure occurs resulting in a breach.	No	Rough pseudostatic assessment of the plinth operating in isolation gave FoS between 1.6-1.8 for 1:500 to 1:10,000 events. As such, this will not control the risk and the FM is excluded from this assessment.
Sluice	Seismic	SL.SeismicInstability	FM8-NP-SS	Seismic Instability			
Lock Gravity Wall	Hydrostatic	Lock.GW.Instability	FM9-LK-ST	Instability	Differential upper and the pool level within the lock creates destabilising forces on the lock gravity walls. This results in collapse of the upstream lock walls and filling of the lock structure. The downstream lock wall or the downstream lock gate also fails.	No	No credible uncontrolled release of storage considered possible, as both lock gravity wall and the downstream lock gate would have to fail simultaneously.
Lock Floor Slabs	Hydrostatic	Lock.FS.Instability	FM10-LK-ST	Instability	Differential upper and the pool level within the lock creates destabilising forces on the lock floor slabs. This results in uplift/removal of the floor slab and filling of the lock structure. The downstream lock gate also fails or is unable to be closed.	No	No credible uncontrolled release of storage considered possible, as both the lock floor slabs and the downstream lock gate would have to fail simultaneously. For maintenance activities, not included in risk assessment, water inflow considered small and life safety not at risk.
Lock Gates	Hydrostatic	Lock.Gate.Instabilty	FM11-LK-ST	Instability	Failure of both the upstream and downstream lock gates due to differential water load or a common cause defect resulting in uncontrolled release through the lock structure. Stoplogs are unable to be lowered into the flow.	No	Considering negligible risk, as both upstream and downstream gates must fail and stoplogs may be used to stop flow.
Sluice	Hydrostatic	SL.IE.Abutment	FM12-SL-IE	Internal Erosion	Internal erosion occurs through the left abutment of the sluice section. A defect exists and a seepage path to an unfiltered exit with sufficient gradient exits. The sheet piles are degraded or not extensive enough to reduce the hydraulic gradient. Erosion continues until uncontrolled release occurs around the structure.	No	Erosion around right abutment considered not credible as the lock structure ensures a seepage path that is too long, and therefore a gradient that Is too small. Erosion around left abutment considered low risk due to sheet piling presence, and the fishway structure that increases the required seepage path.

The probabilities for this PFM were estimated in risk workshops conducted following the completion of the SSJ Filter Drainage Works. Reported in URS (2012) MH1 Closure Risk Assessment: Hume Dam Spillway Southern Junction. Dated 18 July 2012. Basis for estimate (probabilities provided in the following tables from the 2012 report below.

LOADING:

SUM COND PROB:

Partition	Amount of Movement?	Cracking of Corewall	CLSM Wall Holds Crack?	Drainage Ineffective?	Downstream Instability?	Not Detect/Intervene?	Breach?	RESULT	
Normal (< EL 190.20 mAHD)	>10mm	0.0001	0.01	0.01	0.0001	0.01	0.1	1.00E-15	
	2-5mm	0.0005	0.01	0.0005	0.0001	0.01	0.1	2.50E-16	
	1-2mm (negligible no fail)	0.1	0.01	negligible - no fail					
FL1 (EL 190.30 to FSL mAHD)	>10mm	0.0001	0.01	0.01	0.0001	0.01	0.2	2.00E-15	workshopped
	2-5mm	0.0005	0.01	0.0005	0.0001	0.01	0.2	5.00E-16	workshopped
	1-2mm (negligible no fail)	0.1	0.01	negligible - no fail	0.0001				
FL2 (FSL to Discharge (1 in 100))	>10mm	0.0001	0.01	0.01	0.0001	0.01	0.2	2.00E-15	
	2-5mm	0.0005	0.01	0.0005	0.0001	0.01	0.2	5.00E-16	
	1-2mm (negligible no fail)	0.1	0.01	negligible - no fail					
FL3 (Discharge (1 in 100) to Discharge (1 in 1000))	>10mm	0.0003	0.01	0.01	0.0001	0.01	0.2	6.00E-15	
	2-5mm	0.002	0.01	0.0005	0.0001	0.01	0.2	2.00E-15	
	1-2mm (negligible no fail)	0.3	0.01	negligible - no fail					
FL4 (EL 192.20 to 192.40 mAHD)	>10mm	0.0005	0.01	0.01	0.0001	0.01	0.25	1.25E-14	
	2-5mm	0.003	0.01	0.0005	0.0001	0.01	0.25	3.75E-15	
	1-2mm (negligible no fail)	0.4		negligible - no fail					
FL5 (EL 192.40 to 193.00 mAHD)	>10mm	0.0007	0.01	0.01	0.00013	0.02	0.25	4.55E-14	
	2-5mm	0.005	0.01	0.0005	0.00013	0.02	0.25	1.63E-14	
	1-2mm (negligible no fail)	0.5		negligible - no fail					
FL6 (EL 193.00 to 194.30 mAHD)	>10mm	0.0008	0.01	0.01	0.00016	0.05	0.25	1.60E-13	
	2-5mm	0.007	0.01	0.0005	0.00016	0.05	0.5	1.40E-13	
	1-2mm (negligible no fail)	0.7		negligible - no fail					
FL7 (EL 194.30 to 195.20 mAHD)	>10mm	0.001	0.01	0.01	0.0002	0.1	0.3	6.00E-13	workshopped
	2-5mm	0.01	0.01	0.0005	0.0002	0.1	0.3	3.00E-13	workshopped
	1-2mm (negligible no fail)	0.8		negligible - no fail					
FL8 (EL 195.20 to 195.60 mAHD)	>10mm	0.003	0.01	0.01	0.0002	0.1	0.3	1.80E-12	
	2-5mm	0.03	0.01	0.0005	0.0002	0.1	0.4	6.00E-13	
	1-2mm (negligible no fail)	0.9		negligible - no fail					
FL9 (EL 195.60 to 196.40 mAHD)	>10mm	0.006	0.01	0.01	0.0002	0.1	0.3	3.60E-12	
	2-5mm	0.09	0.01	0.0005	0.0002	0.1	0.3	2.70E-12	
	1-2mm (negligible no fail)	0.9		negligible - no fail					
FL10 (> EL 196.40 mAHD)	>10mm	0.01	0.01	0.01	0.0002	0.1	0.3	6.00E-12	
	2-5mm	0.1	0.01	0.0005	0.0002	0.1	0.3	3.00E-12	
	1-2mm (negligible no fail)	0.9		negligible - no fail					

Cracking of Corewall?
Static-FSL
- Ongoing deformation during high reservoir level, building up stress, could rupture corewall
- Filter drainage works stiff block of material d/s of corewall to MH1, then original fill - not saturated like d/s of lower block
- Could have cracking at base of corewall below bitter gallery -differential stiffness - transitional, not abrupt and differential stiffness not as abrupt as at lower block rib
- diagonal cracking observed in MH1 and drainage channels
- Flexure of corewall in plan due to additional d/s deflection - gradual change beyond MH1 (MH1 - 160mm, MH2 - 130mm - 1964 to 2016)
- Rebar across vertical joints - could be corroded (key between corewall sections)
- Case Histories
  - Lake Endeavour, large deformation of corewall with no cracks at surface
  - O'Shannassy - cracks in corewall - 1m of deflection
- Eildon - cracks in corewall at base and at crest - large rapid movement
- horizontal curvature - compressional could offset and open up movement
- No cracks observed in upper 4m on upstream face of corewall in other locations (CH2220 ft)
- No cracks observed in test pits on d/s of corewall

*** 10mm crack**
- Difficult to envisage for a mechanism to create a 10mm open defect
- potential scenario: movement causing open crack below bitter gallery. Have buttresses, large vertical load on corewall
  - Pr for >10mm - 0.0001

*** 2-5mm crack**
Potential for diagonal open cracks. D/S face of corewall <1mm, D/S face of MH1 3mm
Pr = 0.0005

DCF (Flood)
*** 10mm crack**
- could open on a vertical joint, full pressure of water - >100mm of movement. Pr=0.001

2-5mm crack

CLSM Wall Holds A Crack?
- sand/gravel/cement
- under brittle loading, capable of holding a crack (eg. seismic)
- under gradual loading, likely to deform without cracking

Static/FSL and Flood case:
- Pr cracking? - designed for this condition
- Pr = 0.01 for all crack widths (remembering that corewall has had to move to cause a 10mm crack)

Drainage Ineffective?
- D/S channels and cobble drain - same factors for 840m and bend
- If crack/rupture below bitter gallery, than likely to hydraulic fracture through clay fill trench and exit to alluvium (alluvium capable of acting as a filter to fill)

"10mm open crack - equivalent to "rupture" at CH840m failure mode
Pr = 0.01 ruptured below bitter gallery gap under bitter gallery then discharge into alluvium

" 2-5mm open crack
- Single scenario - blockage of drainage system (i.e. inlets)
- Pr = 0.0005

"1-2mm crack
- Not credible to envisage enough flows to exceed capacity of drains = NEGLIGABLE/EXCLUDE

Downstream Instability?
Static-FSL
- Downstream Slope Stability - for CH495m FOS = 1.27 to 1.7, fully softened but non-critical surfaces (gher (check against lower collapse strength) > expect FOS > 1.4
- Confidence in strength parameters due to back analysis
- Large margin of safety
- If exceed capacity of drains, then saturate additional fill
- Difficult to envisage
- Pr = 0.0001 - can't envisage a mechanism

DCF (Flood)
- Marginal Decrease in FOS Pr = 0.0002

Not Detect/Intervene?
Static-FSL
- good monitoring to detect pressure changes and deformation (piezo's seepage, inclinometer, survey deformation)
- slow developing mechanism - not a brittle mechanism
- ability to drop water level quickly - only reduce small amount to make a different based on past performances
- stockpile of sand/gravel onsite + equipment onsite
- Pr (not intervening) = 0.01

DCF (Flood)
- Slow mechanism, instability develop after flood has past
- Probability Pr = 0.1

Breach?
Static-FSL
- Corewall may remain behind providing freeboard for FSL - capable of retaining 4.5m of fill.
- Probability = 0.2

DCF (Flood)
- Likely to have reduced water level back to FSL past flood
- Pr = 0.3

Type	Description	Water Level Differential (UPL – LPL)	AEP of loading*
Usual	Within historical record (35 years)	3.8m (30.86m – 27.7m)	1
Unusual	Interim between 'Usual' and 'Extreme'. Requires incorrect operation of downstream weir, or failure of downstream weir gates. Considered very unlikely as intervention possible to maintain safe operation range. Situation can be imagined with considerable effort.	7.65m (31.3m – 23.65m)	1,000
Extreme	Full loss of downstream pool with elevated upper pool level. A major crisis would have to occur for this condition to exist. No plausible scenario can be imagined.	11.5m (32.2m – 20.7m)	10,000

* as no hydrologic hazard curve of such loading exists, Barneich was used to estimate the probability of the loss of the downstream pool (via failure or miss-operation of the downstream weir) which must occur for such a load state.

AEP of Loading	Peak Ground Acceleration
250	0.015
500	0.02
1000	0.026
1500	0.03
2500	0.036
10,000	0.052

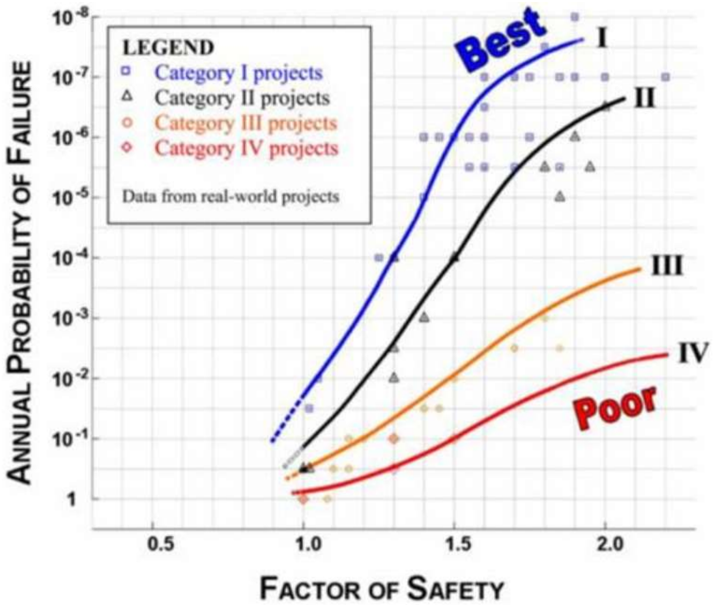
Load Condition	Load Partition	Section	Upstream Apron Effective*	Downstream Buttress Scoured	Factor of Safety	Conditional Probability of Failure**
1	Usual	NP	Yes	Yes	1.59	5.50E-04
2	Unusual	NP	Yes	Yes	0.84	5.00E-01
3	Extreme	NP	Yes	Yes	0.7	8.00E-01
4	Usual	SL	Yes	Yes	1.81	1.00E-04
5	Unusual	SL	Yes	Yes	1	3.00E-01
6	Extreme	SL	Yes	Yes	0.83	5.00E-01
7	Usual	NP	Yes	No	1.98	1.00E-05
8	Unusual	NP	Yes	No	1.03	3.00E-01
9	Extreme	NP	Yes	No	0.84	5.00E-01

Table 5: Contribution of Risk per Failure Mode

Failure mode	Annualised probability of failure	% contribution
FM1-NP-IE	8.83E-05	9%
FM2-SL-IE	3.48E-04	37%
FM4-SL-IE	5.88E-06	1%
FM5-NP-ST	3.01E-04	32%
FM6-SL-ST	1.88E-04	20%
TOTAL	**9.31E-04**	**100%**

Table 6: Contribution of Risk per Load Partition

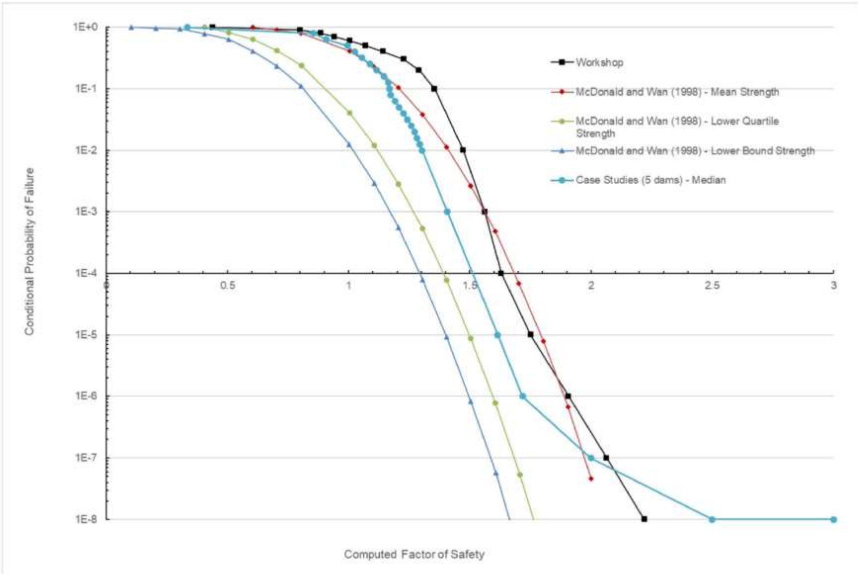
Load Partition	Likelihood of Loading	Conditional Probability of failure	% contribution
Normal	9.99E-01	0.05%	49%
Unusual	9.00E-04	43.19%	42%
Extreme	1.00E-04	88.37%	9%



Category I—facilities designed, built, and operated with state-of-the-practice engineering. Generally these facilities have high failure consequences;
Category II—facilities designed, built, and operated using standard engineering practice. Many ordinary facilities fall into this category;
Category III—facilities without site-specific design and sub-standard construction or operation. Temporary facilities and those with low failure consequences often fall into this category; and
Category IV—facilities with little or no engineering.

Relationship between Factor of Safety and Annual Probability of Failure (Silva et. al.)

Workshop
McDonald and Wan (1998) - Mean Strength
McDonald and Wan (1998) - Lower Quartile Strength
McDonald and Wan (1998) - Lower Bound Strength
Case Studies (5 dams) - Median



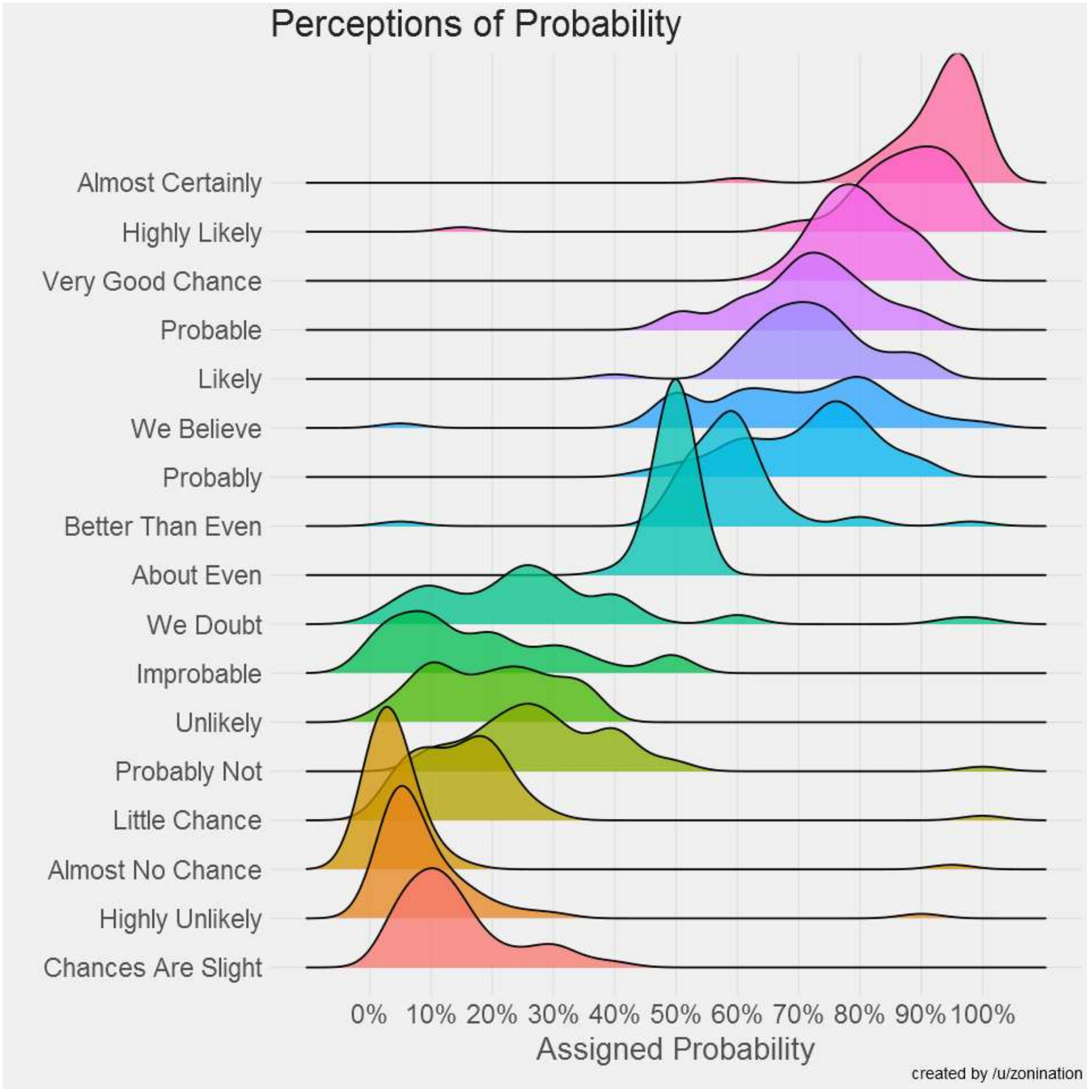
- Probability mapping scheme – Reclamation

Table I-6-2. Verbal Mapping Scheme Adopted by Reclamation

Descriptor	Assigned Probability
Virtually Certain	0.999
Very Likely	0.99
Likely	0.9
Neutral	0.5
Unlikely	0.1
Very Unlikely	0.01
Virtually Impossible	0.001

Barneich Verbal Mapping Table

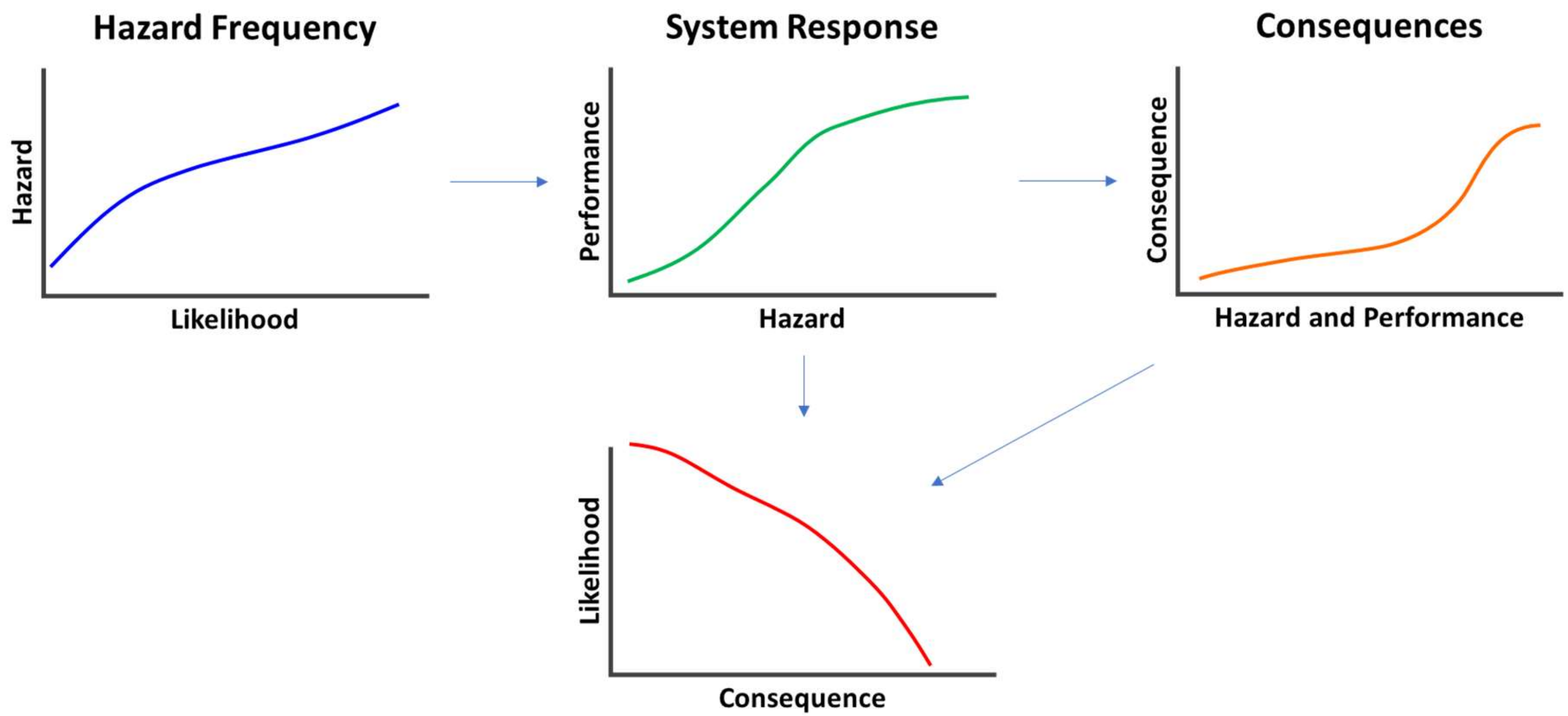
Description of Condition or Event	Order of Magnitude of Probability Assigned
Occurrence is virtually certain	1
Occurrence of the condition or event are observed in the available database	10^{-1}
The occurrence of the condition or event is not observed, or is observed in one isolated instance, in the available database; several potential failure scenarios can be identified.	10^{-2}
The occurrence of the condition or event is not observed in the available database. It is difficult to think about any plausible failure scenario; however, a single scenario could be identified after considerable effort.	10^{-3}
The condition or event has not been observed, and no plausible scenario could be identified, even after considerable effort.	10^{-4}


Perceptions of Probability
Almost Certainly
Highly Likely
Very Good Chance
Probable
Likely
We Believe
Probably
Better Than Even
About Even
We Doubt
Improbable
Unlikely
Probably Not
Little Chance
Almost No Chance
Highly Unlikely
Chances Are Slight
0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%
Assigned Probability
created by /u/zonination

An Introduction to Risk Assessment

- Identification and Assembly of all relevant data,
- Hazard and Failure Mode Identification,
  - Failure Mode Development (Event Tree),
  - Failure Mode Analysis,
- Introduce Risk Plots,
- Total Risk (RMC-USACE)

Risk Plots



Hazard Frequency
Hazard
Likelihood
System Response
Performance
Hazard
Consequences
Consequence
Hazard and Performance
Likelihood
Consequence

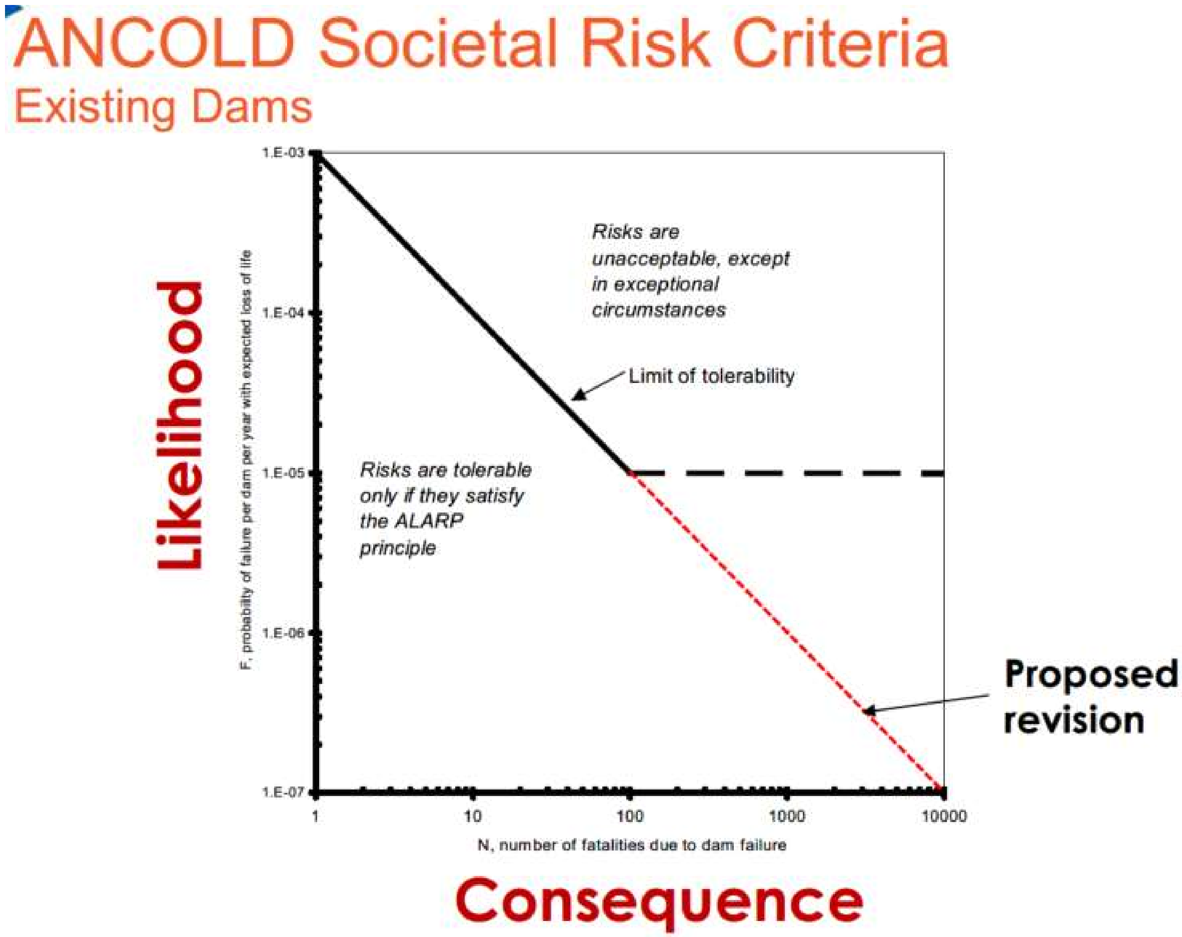
Risk Plots

Calculate the breach life loss at the mid-point of each loading range by interpolating

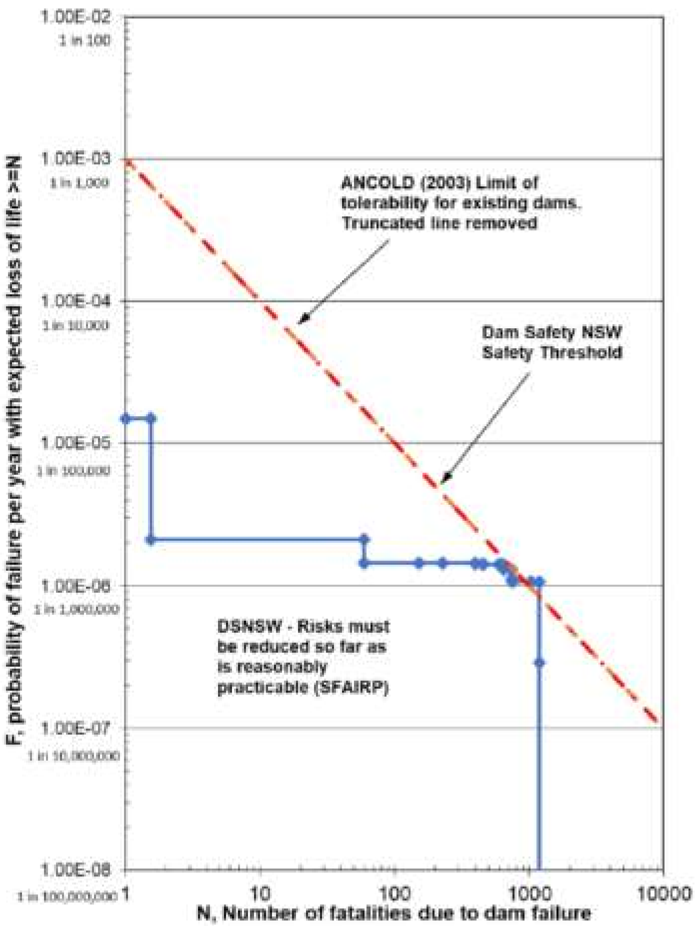
Loading Range	Mid-Point	Breach Life Loss
EL 816.9 to EL 827.4	822.2	0
EL 827.4 to EL 838.0	832.7	0
EL 838.0 to EL 848.5	843.3	0
EL 848.5 to EL 859.1	853.8	7
EL 859.1 to EL 869.6	864.4	26
EL 869.6 to EL 880.2	874.9	46
EL 880.2 to EL 890.7	885.4	93
EL 890.7 to EL 901.3	896.0	202
EL 901.3 to EL 911.8	906.5	495
> EL 911.8	911.8	570

Peak Stage	Breach Life Loss
850.0	0
875.0	46
889.3	110
900.0	257
905.0	473
913.8	598

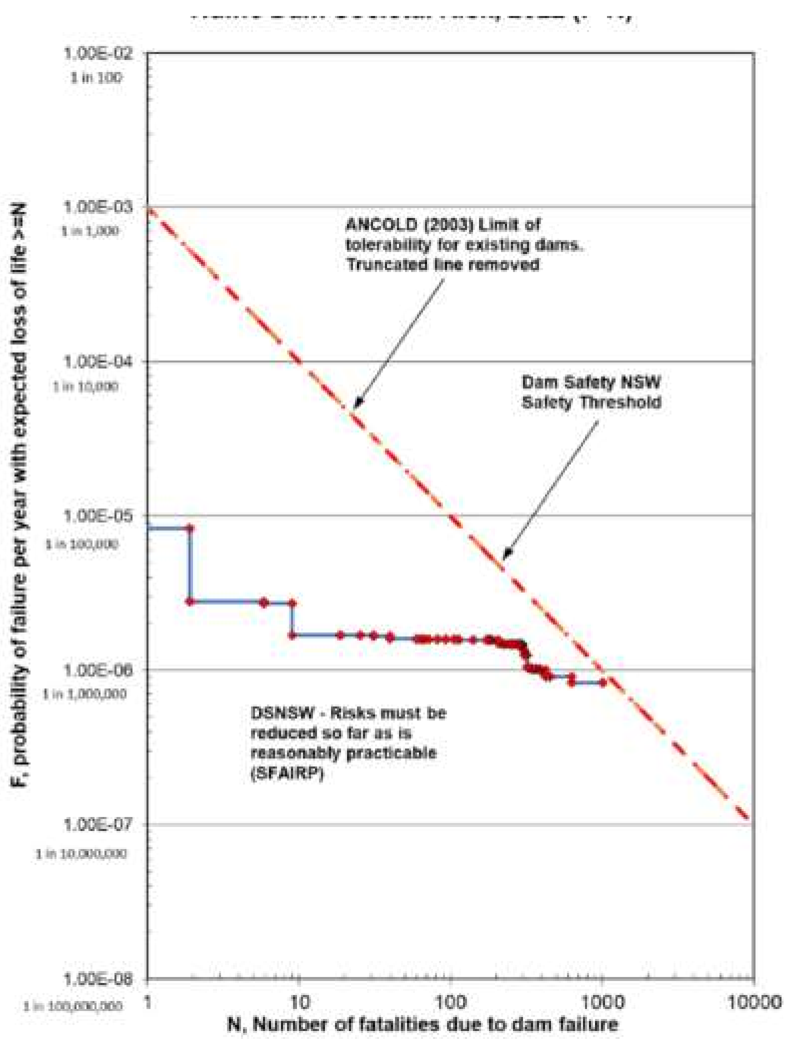
Risk Plots


ANCOLD Societal Risk Criteria
Existing Dams
Likelihood
F, probability of failure per dam per year with expected loss of life
1.E-03
1.E-04
1.E-05
1.E-06
1.E-07
Risks are unacceptable, except in exceptional circumstances
Limit of tolerability
Risks are tolerable only if they satisfy the ALARP principle
Proposed revision
1
10
100
1000
10000
N, number of fatalities due to dam failure
Consequence

Risk Plots

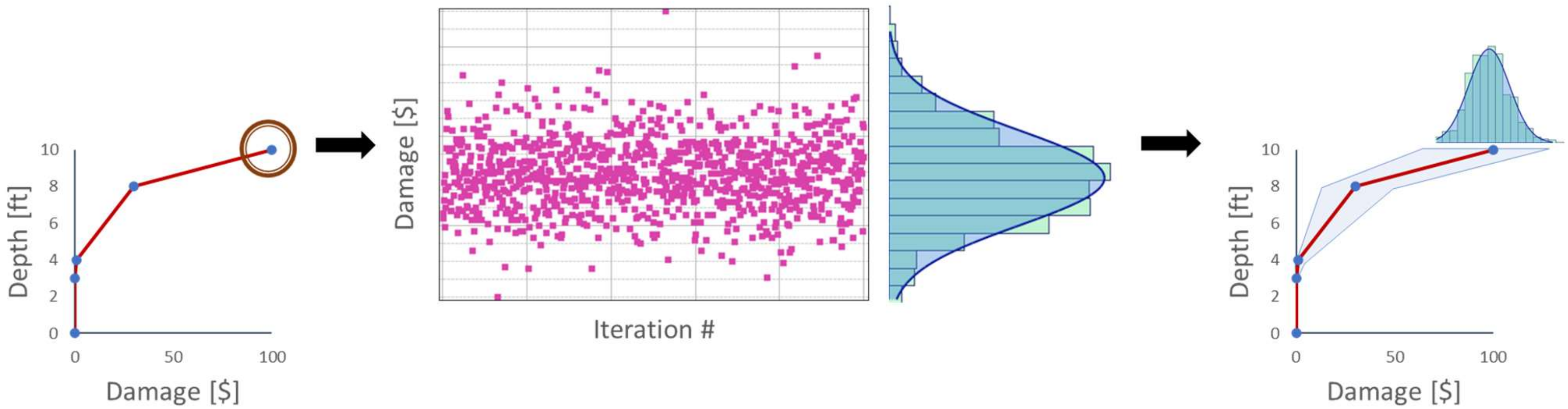


1.00E-02
1 in 100
1.00E-03
1 in 1,000
1.00E-04
1 in 10,000
1.00E-05
1 in 100,000
1.00E-06
1 in 1,000,000
1.00E-07
1 in 10,000,000
1.00E-08
1 in 100,000,000
1
10
100
1000
10000
F, probability of failure per year with expected loss of life >=N
N, Number of fatalities due to dam failure
ANCOLD (2003) Limit of tolerability for existing dams. Truncated line removed
Dam Safety NSW Safety Threshold
DSNSW - Risks must be reduced so far as is reasonably practicable (SFAIRP)



1.00E-02
1 in 100
1.00E-03
1 in 1,000
1.00E-04
1 in 10,000
1.00E-05
1 in 100,000
1.00E-06
1 in 1,000,000
1.00E-07
1 in 10,000,000
1.00E-08
1 in 100,000,000
1
10
100
1000
10000
F, probability of failure per year with expected loss of life >=N
N, Number of fatalities due to dam failure
ANCOLD (2003) Limit of tolerability for existing dams. Truncated line removed
Dam Safety NSW Safety Threshold
DSNSW - Risks must be reduced so far as is reasonably practicable (SFAIRP)

Risk Plots



10
8
6
4
2
0
Depth [ft]
0
50
100
Damage [$]
Damage [$]
Iteration #
10
8
6
4
2
0
Depth [ft]
0
50
100
Damage [$]

Risk Plots

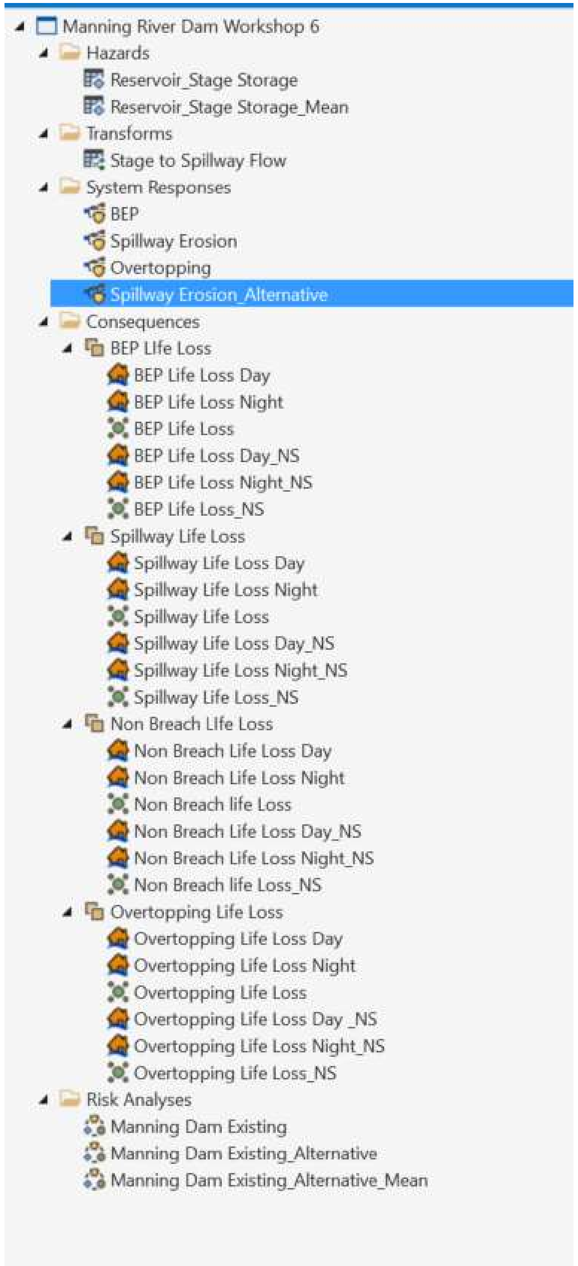
Further Reading

- ANCOLD (2003) Guidelines on Risk Assessment
- ANCOLD (2020) Draft Guidelines on Risk Assessment (coming soon!)

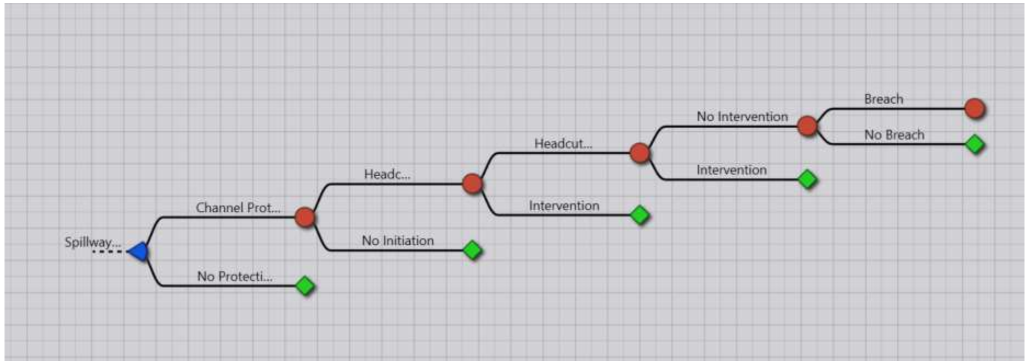
An Introduction to Risk Assessment

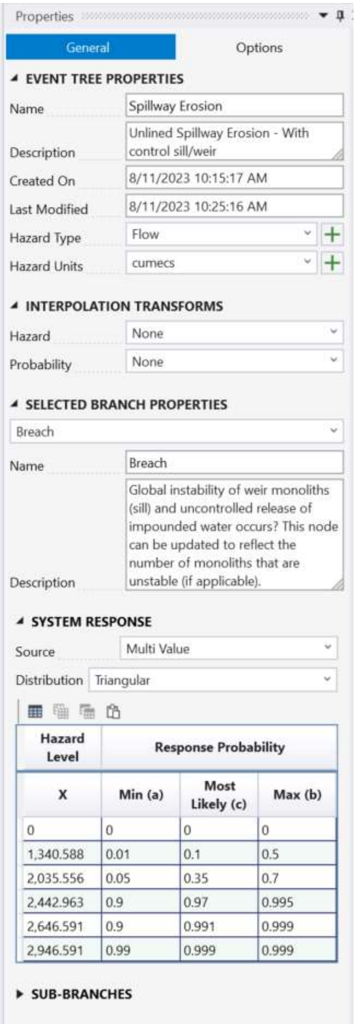
- Identification and Assembly of all relevant data,
- Hazard and Failure Mode Identification,
- Failure Mode Development (Event Tree),
- Failure Mode Analysis,
- Introduce Risk Plots,
- Total Risk (RMC-USACE)

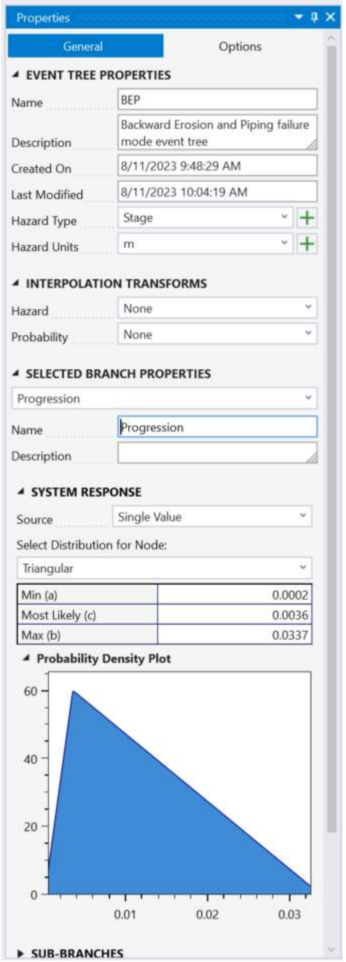
Total Risk (RMC-USACE)

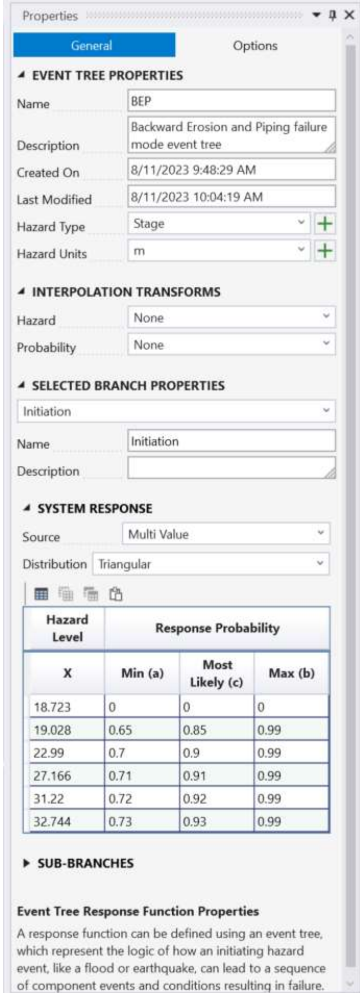


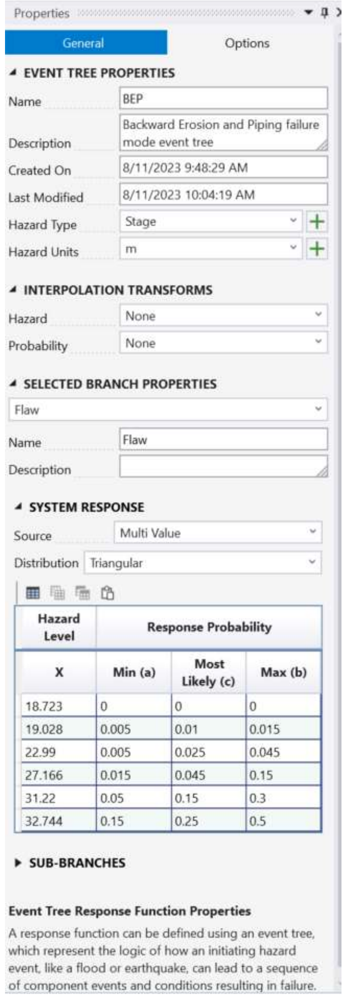
Total Risk (RMC-USACE)



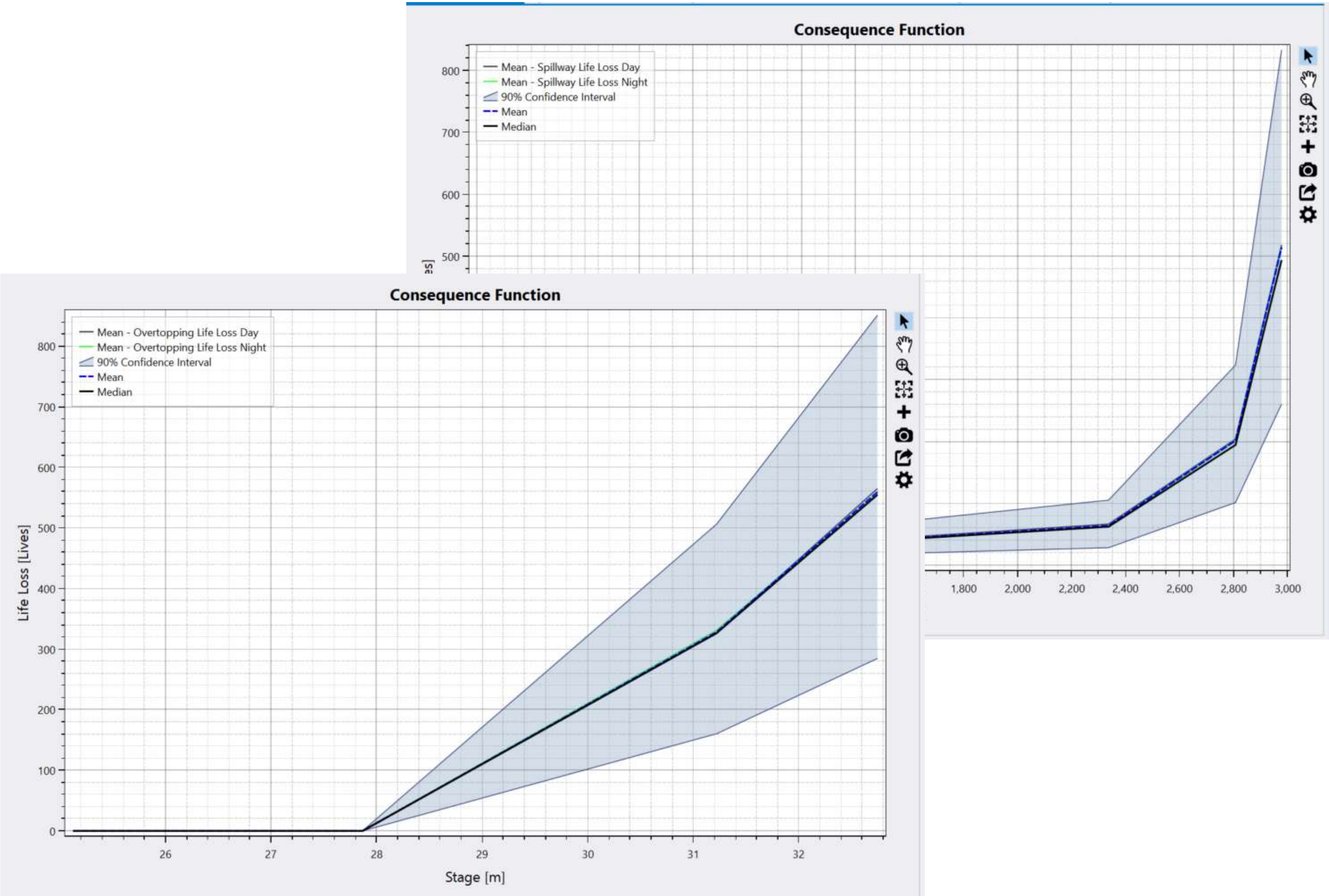




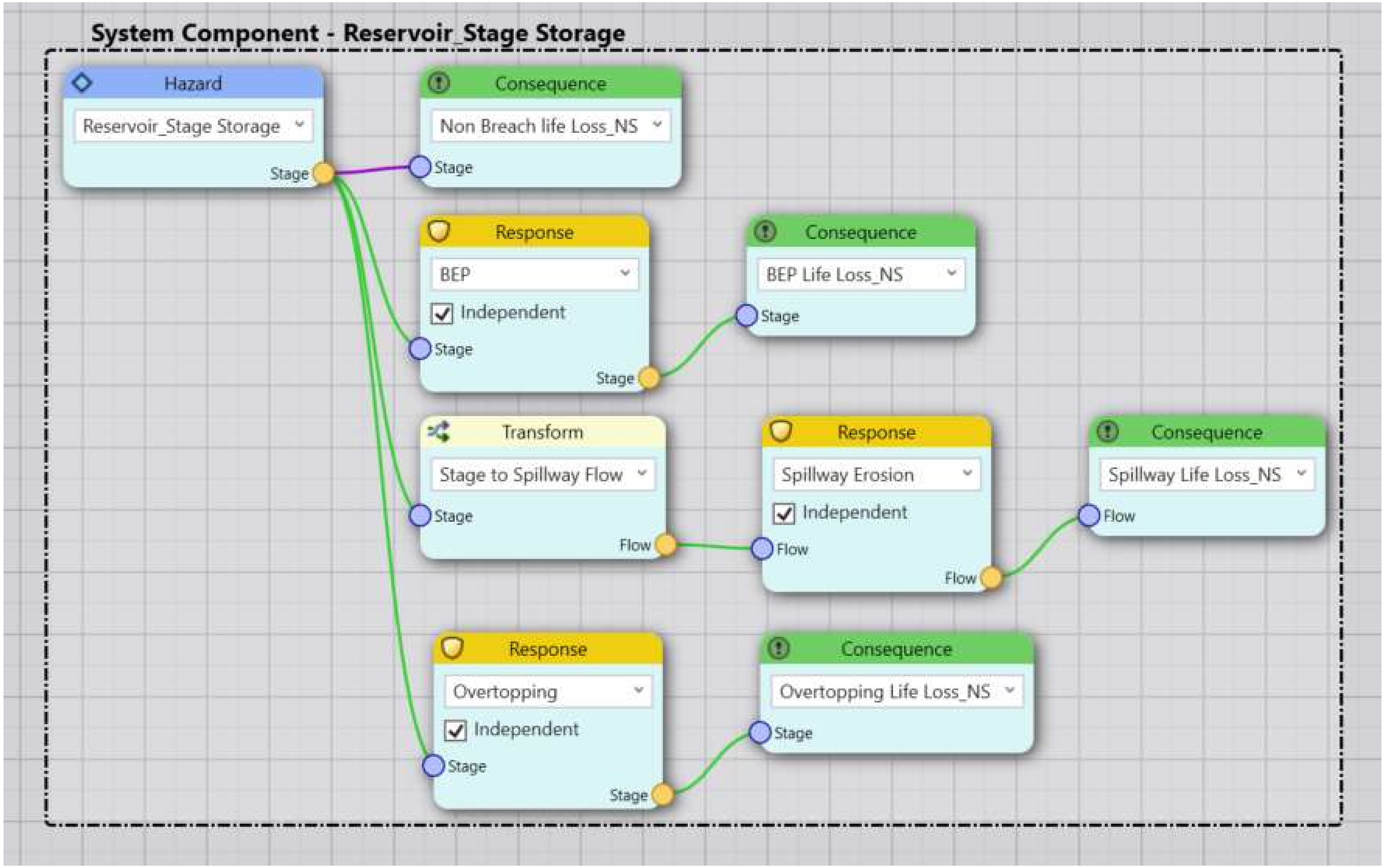




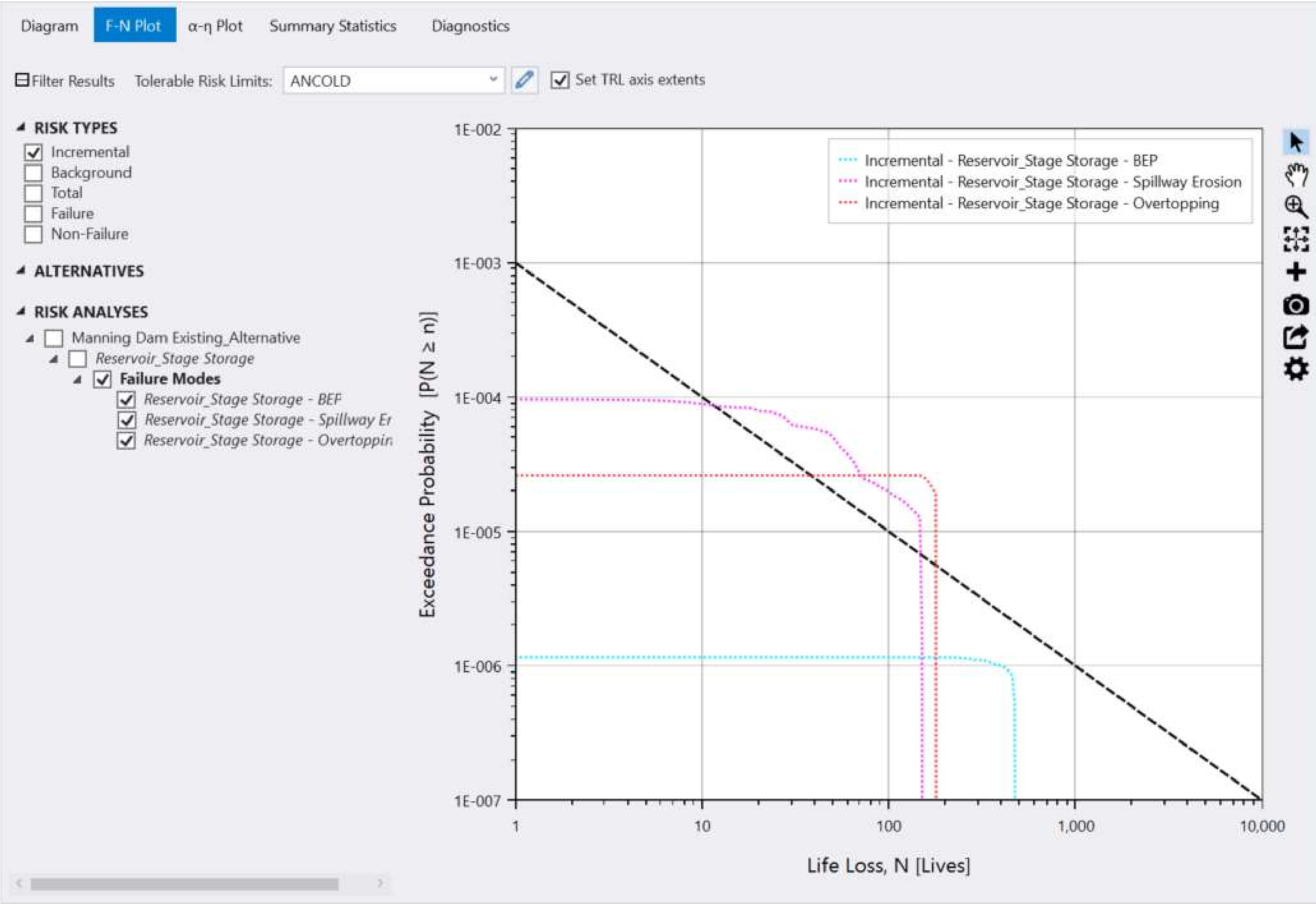
Total Risk (RMC-USACE)



Total Risk (RMC-USACE)

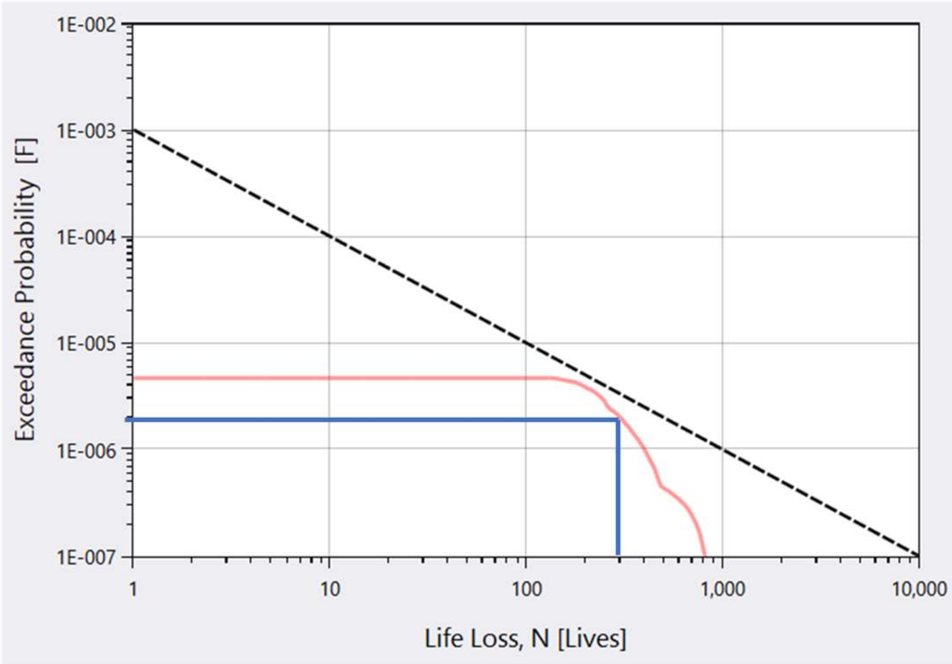


Total Risk (RMC-USACE)



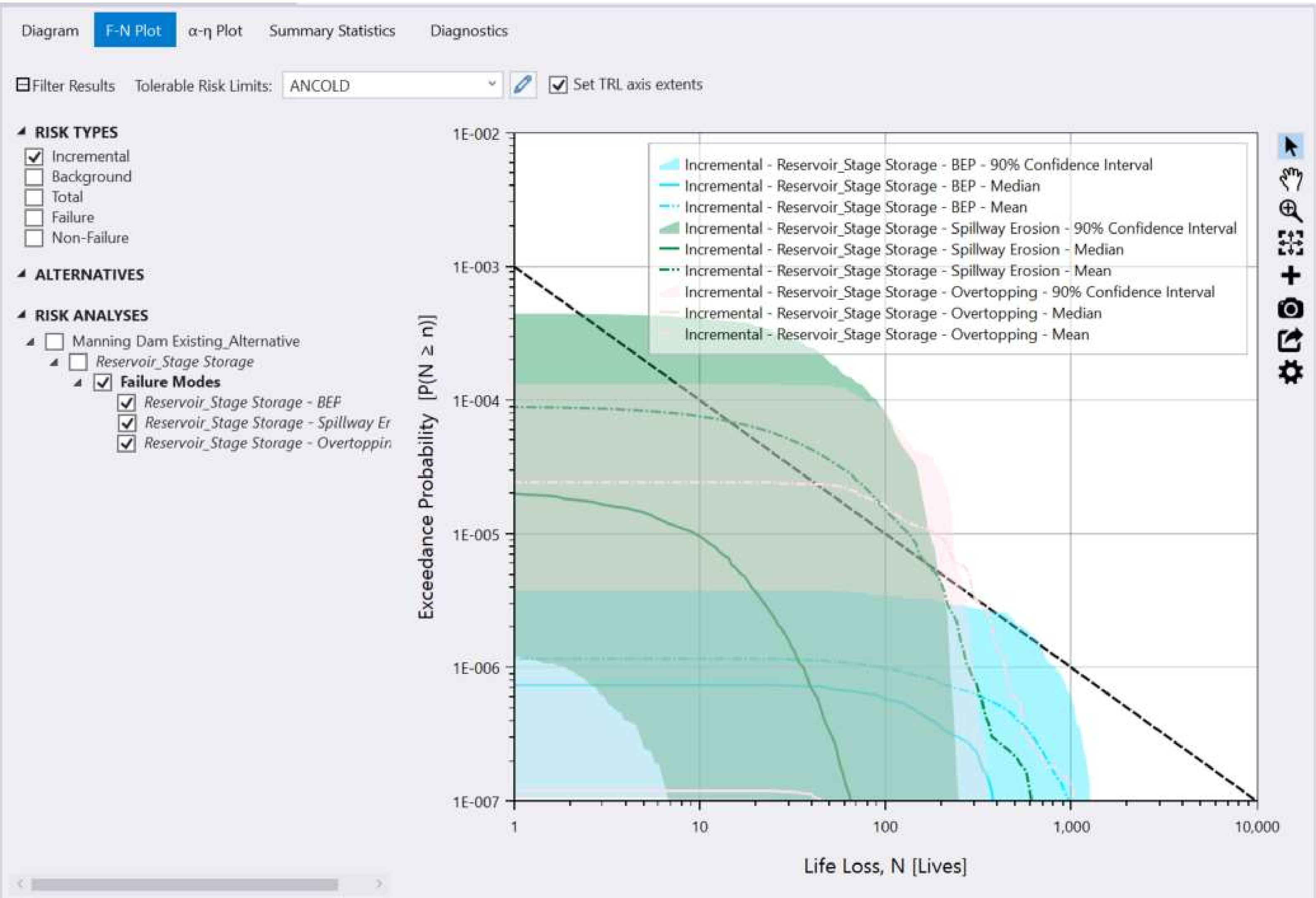
Total Risk (RMC-USACE)

- "What is the annual probability (F) of incremental life loss greater than or equal to N?"
- In this example, there is about a 2E-06 probability per year of a dam failure leading to incremental life loss of 300 or more.



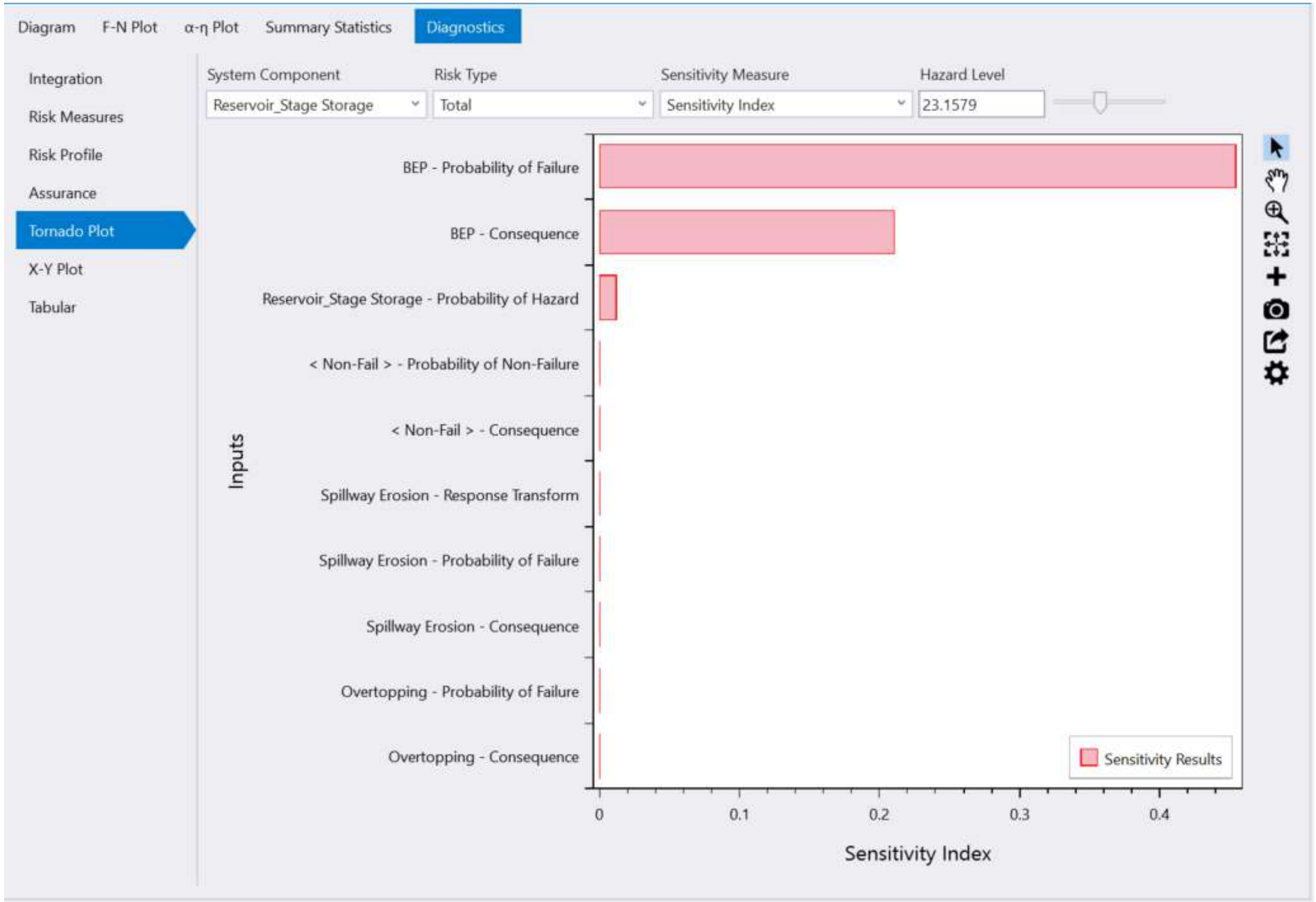
Total Risk (RMC-USACE)

Interpretation is the key!



Total Risk (RMC-USACE)

Interpretation is the key!



Summary

&

Conclusion

Thank You!