IV-2 Flood Overtopping Failure

Best Practices

Last Modified November 2012

RECLAMATION
Managing Water in the West

US Army Corps of Engineers
BUILDING STRONG®

Auburn Cofferdam

Taum Sauk Dam

Rainbow Dam, Michigan 1986

Rainbow Dam, Michigan 1986

Gibson Dam, MT

Gibson Dam Overtopping Case Study

- June 6-8, 1964 record regional rainstorm in northern Montana
- Spillway radial gates not fully open
  - controls inaccessible
  - 2 gates completely open
  - 2 gates completely closed
  - 2 gates partially open
- Overtopping about 3 feet over parapet for 20 hours
- Modified in 1981 to allow overtopping

ICOLD Bulletin 82 (1992)

Gibson Dam, MT June 1964

Gibson Dam, MT June 1964

Dam Overtopping Failure Mode

- Failure of dams due to overtopping is a common failure mode, accounting for 30 percent of the failures in the U.S. over the last 75 years
- Many older dams may have been designed for floods that no longer represent a remote flood event
- Many dams can not pass the current Probable Maximum Flood without overtopping

Dam and Levee Overtopping Failure Mode

- Two ways for the dam or levee to overtop
  - Continuous flow as the water surface elevation exceeds the elevation profile of the structure
  - Overwash from waves when the water surface stays below the structure elevation profile

Dam Overtopping Failure Mode

- Most embankment dams would likely not withstand sustained overtopping of a foot or more without a high probability of failure
- While most concrete dams can likely withstand a certain level of overtopping due to their rock foundations, some may be vulnerable due to the jointing and fracturing in the rock mass

Erosion Process

- Removable of vegetation or protection
- Soil is eroded until a headcut forms or is initiated
- Headcut advances (and can deepen and widen at the same time) to the upstream side of the crest
- Embankment Breach initiates

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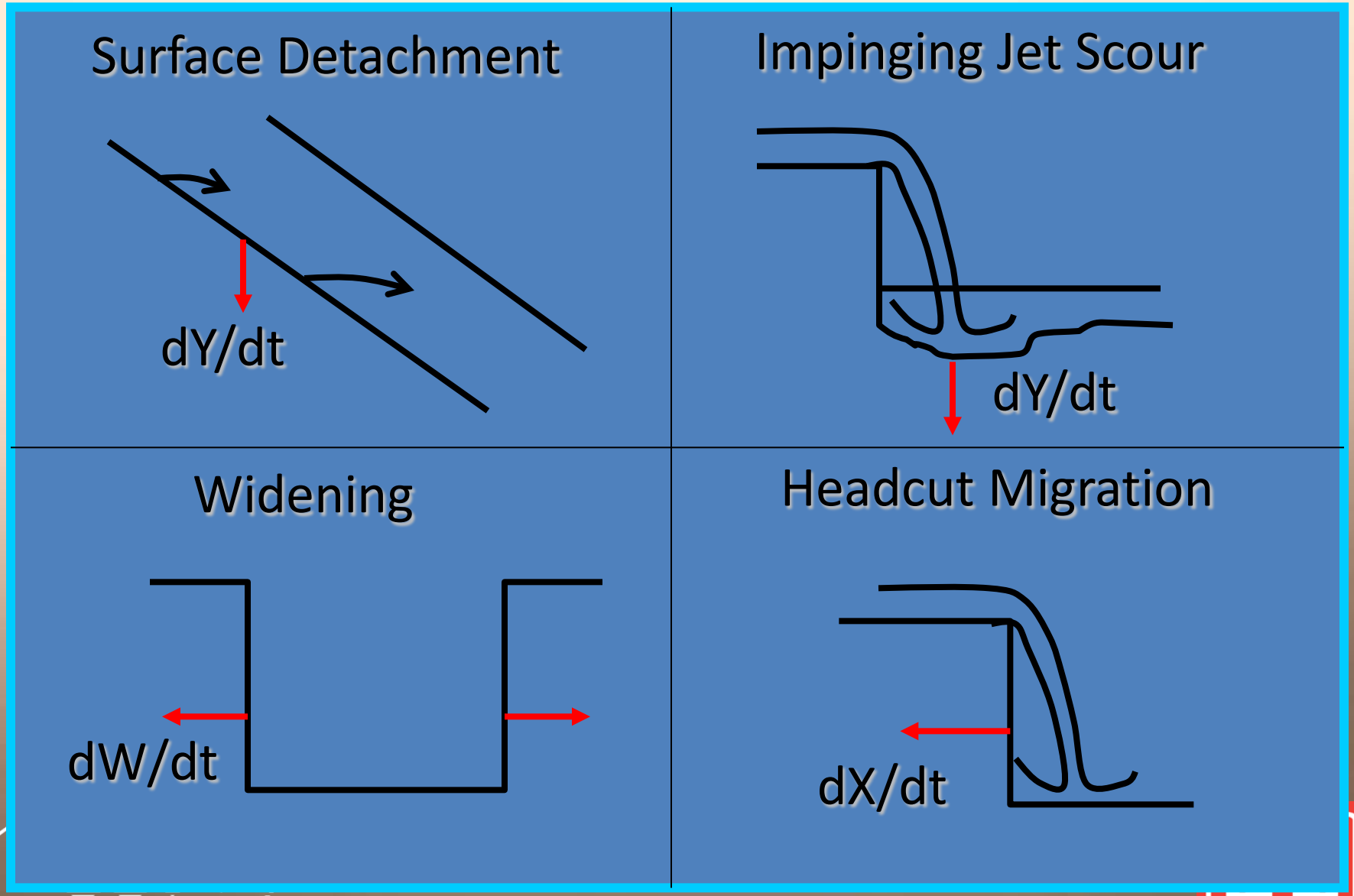
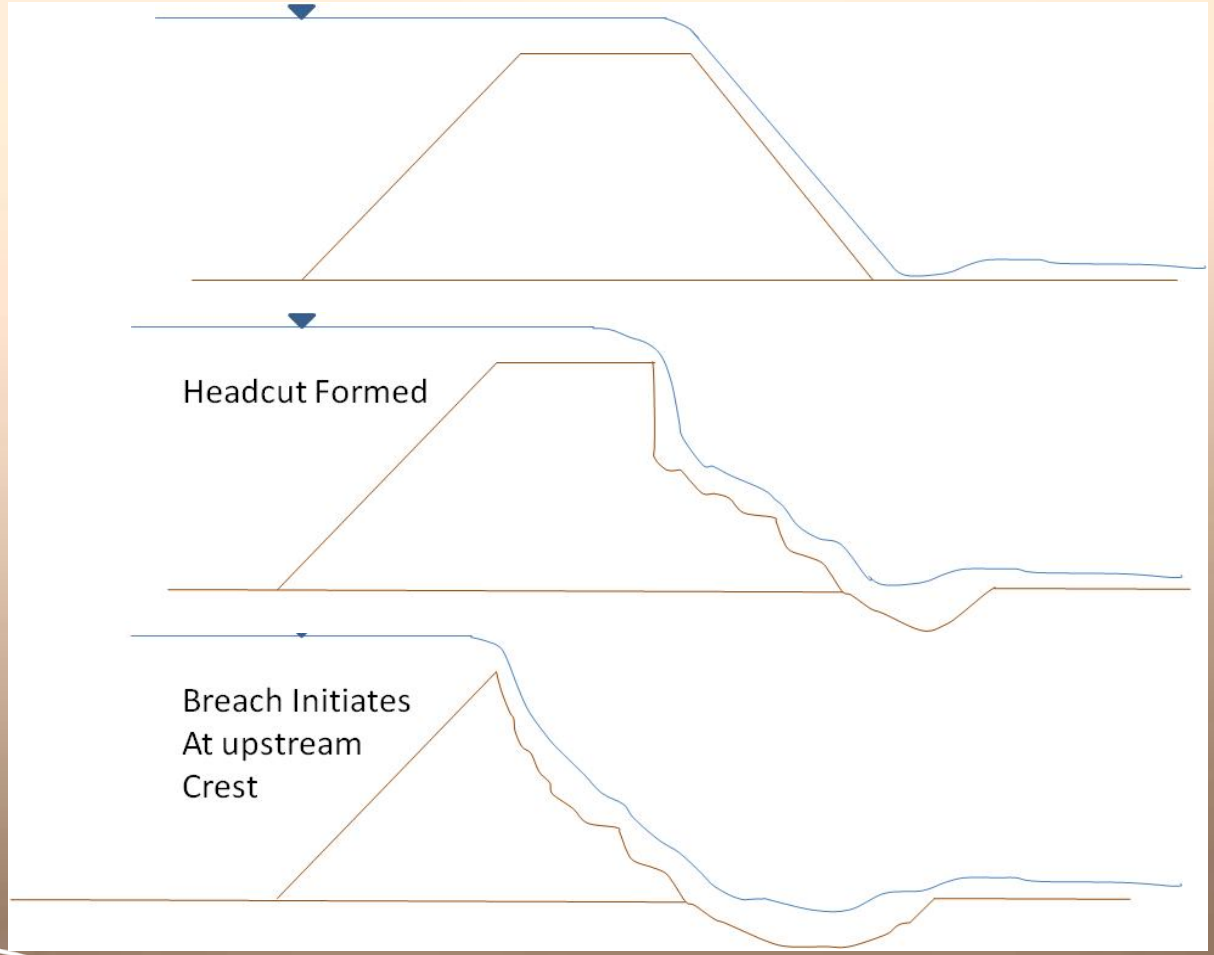
Taken from October 2011 WinDAM Training by ARS

Key Embankment Erosion Processes



Taken from October 2011 WinDAM Training by ARS

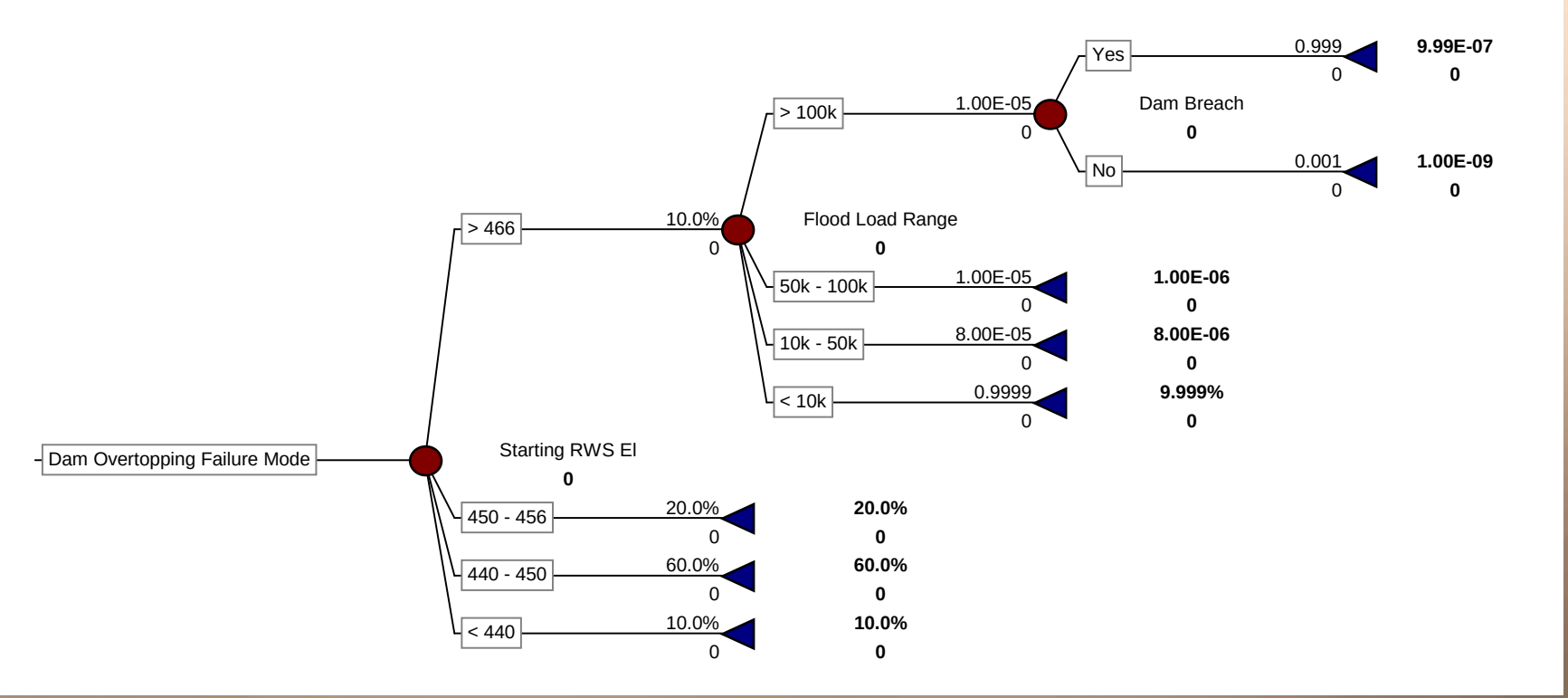
Embankment Dam Overtopping Failure



Embankment Dam Overtopping Event Tree

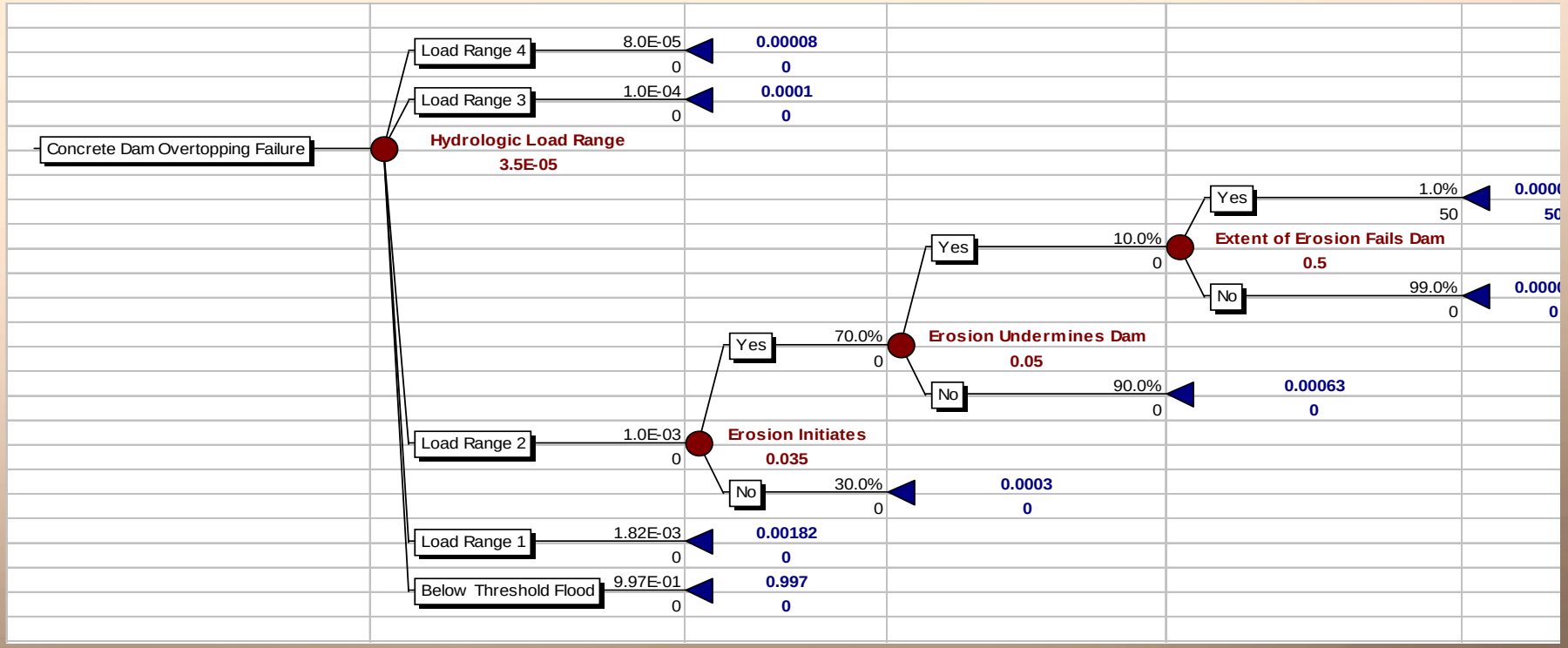
- Erosion of the surface of the downstream slope, which may consist of vegetation, riprap, or bare soil.
  - Concentrated erosion on the downstream slope causing a deepening of the erosion channel until one or more headcuts are formed on the downstream slope (for conservatism, physically-based dam breach models such as WinDAM B assume that a headcut is formed at the top of the slope / downstream edge of the dam crest; see chapter 15 Modeling Erosion of Rock and Soil for details).
    - Advancement of headcuts upstream, usually accompanied by consolidation of multiple headcuts.
      - When the most upstream headcut advances through the upstream edge of the dam crest, **breach is initiated** and the breach opening begins to enlarge. (After this point, intervention to save the dam is no longer possible).
        - Headcuts continue to advance upstream, enlarging the breach and releasing reservoir storage.
          - The breach widens as long as hydraulic stresses at the sides of the breach opening are sufficient to exceed the erosion threshold of the soil

Embankment Dam Overtopping Event Tree (Reclamation)



Conditional failure probabilities often simplified

Concrete Dam Overtopping Event Tree



Overtopping

- Recommend using a surveyed top of embankment (levee or dam) to determine the low spots
  - Incorporates overbuild and settlement when survey is used
  - Helps identify where overtopping occurs first
  - May identify where flow concentrations may occur

Breach Prediction

- Empirical Equations – assume dam has failed
- NWS-Breach – mainly for cohesionless materials
  - Uses sediment transport equation
- WinDAM – may help frame the discussion on the speed of breaching and impacts vegetation and material type have on breaching
  - Only works for homogenous embankments
  - Empirical basis
- HR-Breach or other breaching models
- Combining some of these methods will likely yield better results

Probable Maximum Flood (PMF)

- Reclamation currently recognizes the PMF as the upper limit of flood potential at a site, for storm duration and magnitude defined by the Probable Maximum Precipitation (PMP)
- Reclamation uses the PMF, calculated using current procedures and policy, as the upper limit of extreme floods for risk analysis, corrective action decisions, and dam safety modifications
- This is consistent with Federal guidelines for selecting and accommodating inflow design floods (FEMA, 1998)

Probable Maximum Flood (PMF)

- If the dam can safely pass a PMF using current HMR report with sufficient freeboard, it is termed hydrologically adequate (USACE) and overtopping should not be considered a failure mode
- If it dam passes the PMF but insufficient freeboard, wave overwash may be a concern
  - Need a high pool for an extended time
  - Need to consider the duration needed for wind speed to occur for the waves
  - Consult Coastal Engineering Manual for more information http://140.194.76.129/publications/eng-manuals/EM_1110-2-1100_vol/PartI/PartI.htm

Reasons Overtopping may be a concern

- Exceptions to screening out failure mode if no overtopping
  - PMF is not current and is expected to increase
  - PMF is for a certain storm event and a more critical storm event may exist
  - The spillway is gated and there are concerns that the spillway may not be operated as intended
  - Reasons to believe assumptions made in flood routing may not be achieved during an actual flood

Risk of Dam Overtopping Based on Peak Inflows (Reclamation)

- Flood frequency curve is generated which relates peak inflows (or volumes) to a return period
- Reservoir elevation ranges are set up and spillway discharges are matched to reservoir elevations; spillway discharges are equated to peak flood inflows
- Based on the conservative assumptions that inflow equals outflow and that there is no benefit from reservoir surcharge space
- Risks are generated from the above process and compared to Reclamation's Public Protection Guidelines
- If a threshold flood has been estimated as a percentage of the PMF, the flood frequency curves can be used to estimate the return period of the threshold flood

Table 16-1 - Summary of Risk Estimates for Dam Overtopping							
Evaluation Based on Comparison of Spillway Discharge Capacity to							
Reservoir Water Surface El Range, ft	Spillway Discharge Capacity, ft^3/s	Corresponding Frequency Flood, year	Probability of	Freeboard (+) Overtopping (-) Depth, ft	Estimated Probability of Failure	Annual Probability of Failure	Annualized Loss of Life[1]
740 – 749	0 – 7400	100–10,000	.0099	9 to 2	0	0	0
749 – 750	7400 – 8670	10,000–50,000	.00008	2 to 1	0 to 0.1	4 E-06	4 E-04
750 – 751	8670 – 10,000	50,000–100,000	.00001	1 to 0	0.1 to 0.3	2 E-06	2 E-04
751 – 752	10,000 – 11,390	100,000-120,000	.00000167	0 to -1	0.3 to 0.999	1 E-06	1 E-04
> 752	11,390 – 12,848	> 120,000	.00000833	> -1	1	8 E-06	8 E-04
Totals						1.5 E-05	1.5 E-03

Risk of Dam Overtopping Based on Flood Routings (Reclamation)

- If an evaluation of risk based on a comparison of flood peaks to spillway discharge capacity indicates overtopping may still be a viable failure mode, additional studies are conducted
- Flood frequency hydrographs are developed and routed through the reservoir
- This provides more accurate information on the potential for dam overtopping
- Routing results are used to determine flood frequencies for reservoir elevation ranges
- Risk results are compared to Reclamation's Public Protection Guidelines

Table 16-2 - Summary of Risk Estimates for Dam Overtopping							
Evaluation Based on Flood Routing Results of Frequency Floods							
Reservoir Water Surface El Range, ft	Corresponding Frequency Flood from Flood Routings	Spillway Discharge Capacity, ft^3/s	Probability of	Freeboard (+) Overtopping (-) Depth, ft	Estimated Probability of Failure	Annual Probability of Failure	Annualized Loss of Life[1]
740 – 749	200-50,000	0 – 7400	.00498	9 to 2	0	0	0
749 – 750	50,000-300,000	7400 – 8670	.0000167	2 to 1	0 to 0.1	8 E-07	8 E-05
750 – 751	300,000-700,000	8670 – 10,000	.0000019	1 to 0	0.1 to 0.3	4 E-07	4 E-05
751 – 752	700,000-900,000	10,000 – 11,390	.00000032	0 to -1	0.3 to 0.999	2 E-07	2 E-05
752 – 753	> 900,000	11,390 – 12,848	.0000011	> -1	1	1 E-06	1 E-04
Totals						2.4 E-06	2.4 E-04

[1] Loss of life of 100 people estimated for all cases.

Uncertainties in Flood Routings

- Flood Events
- Starting Reservoir Water Surface Elevation
- Reservoir Operations/Misoperations
- Spillway Discharge
- Modifications to the spillway approach

Uncertainties with Flood Events

- The size and shape of a given frequency flood may vary, depending on the peak and volume considerations and variations and the type of flood (thunderstorm or rain-on-snow flood)
- The PMF for a given dam may change in the future if the hydrometeorological report for the site changes

Uncertainties with Starting Reservoir Water Surface Elevation (Reclamation)

- The starting reservoir water surface elevation can be a critical input for flood routings
- The default elevation may be the top of active conservation storage or normal pool, but historical reservoir level data may indicate the reservoir is at this level a small percentage of the time
- If starting reservoir water surface elevation is significant, flood routings should consider this variable and results incorporated into the event trees
- Consideration for starting reservoir water surface elevations should also include the time of the year the flood is likely to occur

Uncertainties with Reservoir Operations/Misoperations

- The assumptions regarding reservoir operations for flood routings should be evaluated for reasonableness
- If gated spillway operations will exceed downstream safe channel capacity, operators may be reluctant to follow SOP (Reclamation) or Water Control Manual (USACE)
- Gated spillways may be vulnerable to one or more gates failing during a flood, due to mechanical failures, loss of power or gate binding
- Sensitivity routings can evaluate variable assumptions

Uncertainties with Spillway Discharge

- Spillway discharge curves used in flood routings are often based on idealized discharge curves
- Approach conditions that are less than ideal may reduce the discharge from what was assumed
- Debris may block spillway openings and significantly lower the discharge
- For gated spillways, flow will vary at a given water surface elevation depending on whether free flow or orifice conditions exists

Levee Overtopping

- Overtopping will occur for flows greater than the design discharge
- Modifications from:
  - Addition from Bridges or other encroachments
  - Debris blockage
  - Channel Roughness changes
  - Original modeling technique
  - Change in the frequency of the design discharge

Embankment Overtopping – Key Factors

- Depth and duration of overtopping
- Camber or low spots on dam crest may concentrate overtopping flows
- Downstream zoning/slope protection
- Dam crest
- Wave set-up and run-up
- Should initially assume that any overtopping leads to dam breach
- If further refinement is needed, system response curves can be developed

System Response Curves – Embankment Dam or Levee Overtopping

- Team should consider carefully and document reasoning behind curves
- For a given depth of overtopping, a range of values and a best estimate should be developed
- Considerations include:
  - Depth of overtopping
  - Duration of overtopping
  - Potential concentration of overtopping flows at dam crest due to camber or low spots
  - Potential concentration of overtopping flows on the dam face, along the groins or at the toe of the dam
  - Erosional resistance of materials on the downstream face and in the downstream zones of the embankment
  - Whether the dam crest is paved
  - Whether a parapet wall is provided and the potential for the wall to fail before or after its overtopped
  - Change in geometry or topography on d/s face that could initiate erosion

Concrete Dam Overtopping – Key Factors

- Depth and duration of overtopping
- Foundation conditions
- Tailwater elevations

Consequences

- Inundated area will generally increase over sunny day failure
- Warning time may be substantial due to monitoring during a large flood
- Population at risk may be reduced due to spillway releases prior to dam failure, but need to consider if evacuated populations remain in dam breach flood plain
- Loss of life may be less than for sunny day failure
- Thunderstorm events may reduce reaction and warning time as compared to rain on snow flood events

Conclusions

- Overtopping flow and wave overwash could be potential failure modes for dams and levees
- Depth and duration of overtopping are key factors
- Erodibility of earthen embankments material is key factor
- Erodibility of the rock foundation is a key factor for concrete dams

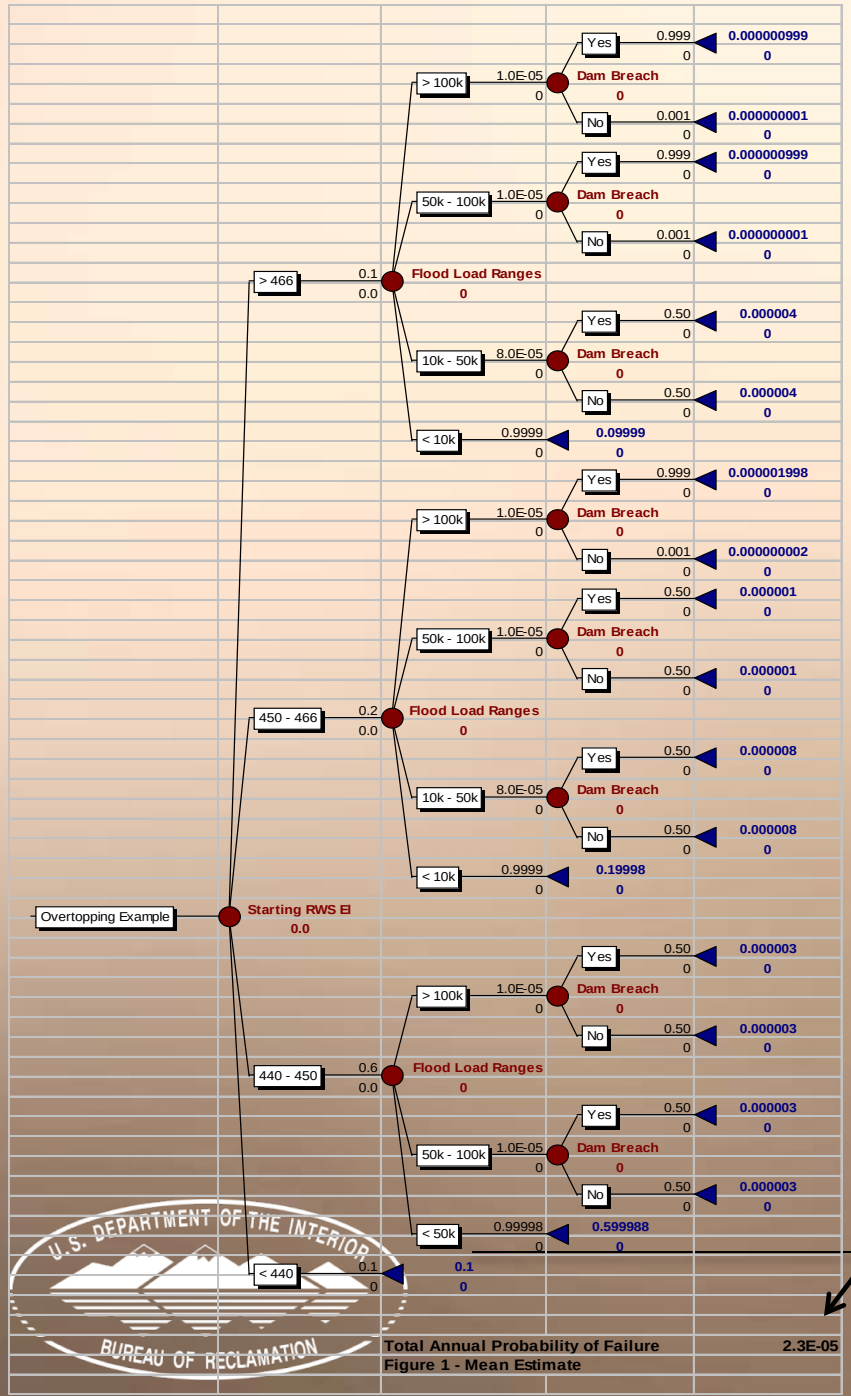
Dam Exercise

- Consider a 90 foot high embankment dam with the dam crest at elevation 480.5. The crest of the dam is surfaced with gravel and recent surveys indicate that the crest elevation is uniform, with no low spots or depressions along the crest. The downstream shell of the dam consists of a well graded mix of compacted sand and gravel. The critical floods for the dam are spring rain-on-snow events, which have long durations. The reservoir water surface typically varies between elevations 440 and 466 during flood season each year. At this time of year, historical reservoir water surface elevations indicate that the reservoir is above elevations 440, 450 and 466, 90 percent, 30 percent and 10 percent of the time, respectively. Frequency floods for the dam were developed and a flood routing study produced the results in Table 11-3. Additional analysis has shown the embankment is highly likely to fail from 1 foot or more of overtopping given the duration of overtopping and type of embankment material. Estimate the expected value annual dam failure probability due to overtopping.

Dam Exercise

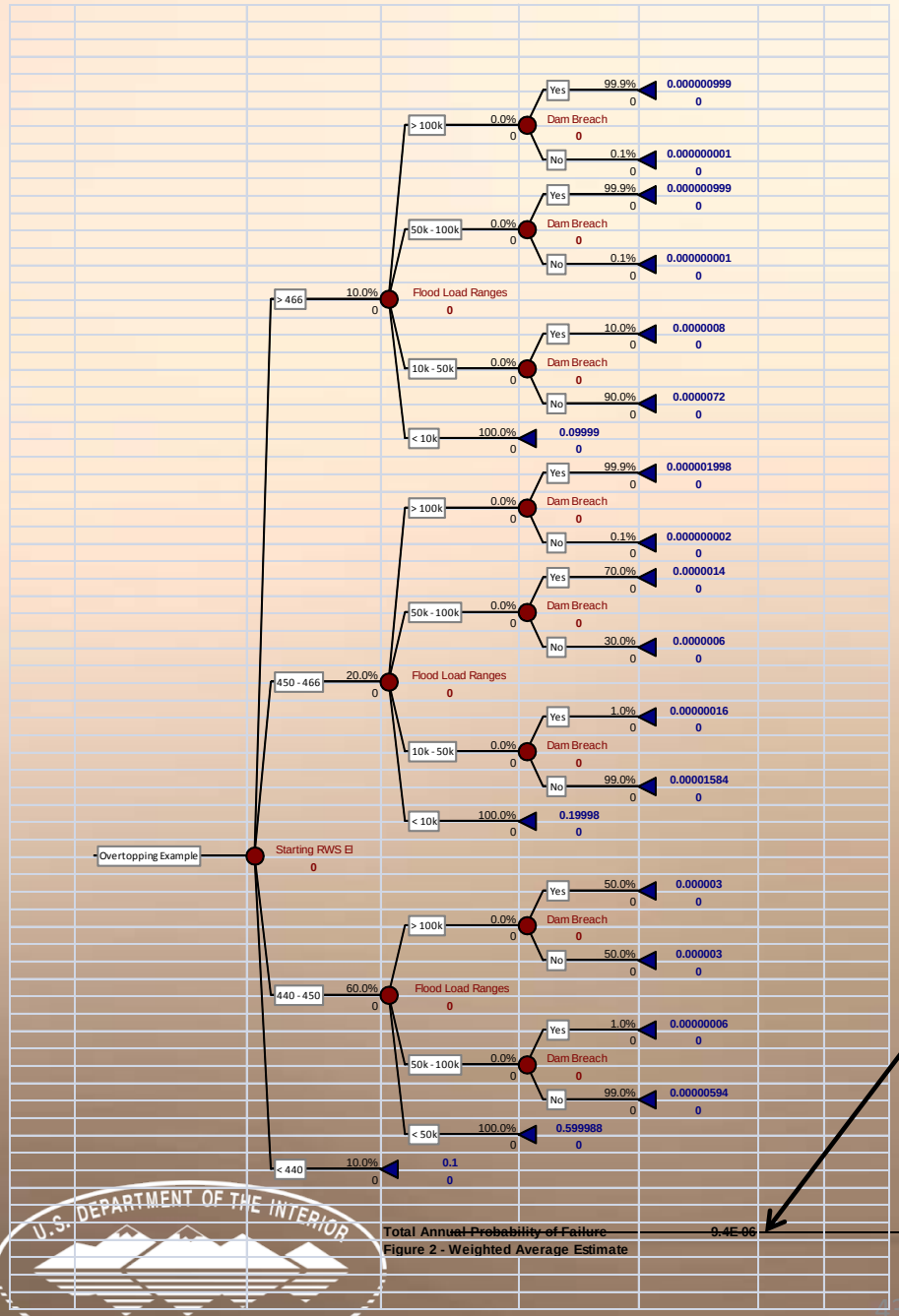
Table 16-3 - Flood Routing Results, Maximum Water Surface Elevation (feet)				
Starting Reservoir Water Surface Elevation, feet	Flood Return Period, years			
	5000	10,000	50,000	100,000
466	468.2	475.1	480.9	484.0
450	467.4	473.4	480.0	482.3
440	466.0	471.2	475.6	479.7

Mean Estimate



Total Annual Probability of Failure = 2.3 E-05

Similar to 1.5 E-05



Weighted Ave Estimate

Total Annual Probability of Failure = 9.4 E-06

Similar to 2.4 E-06

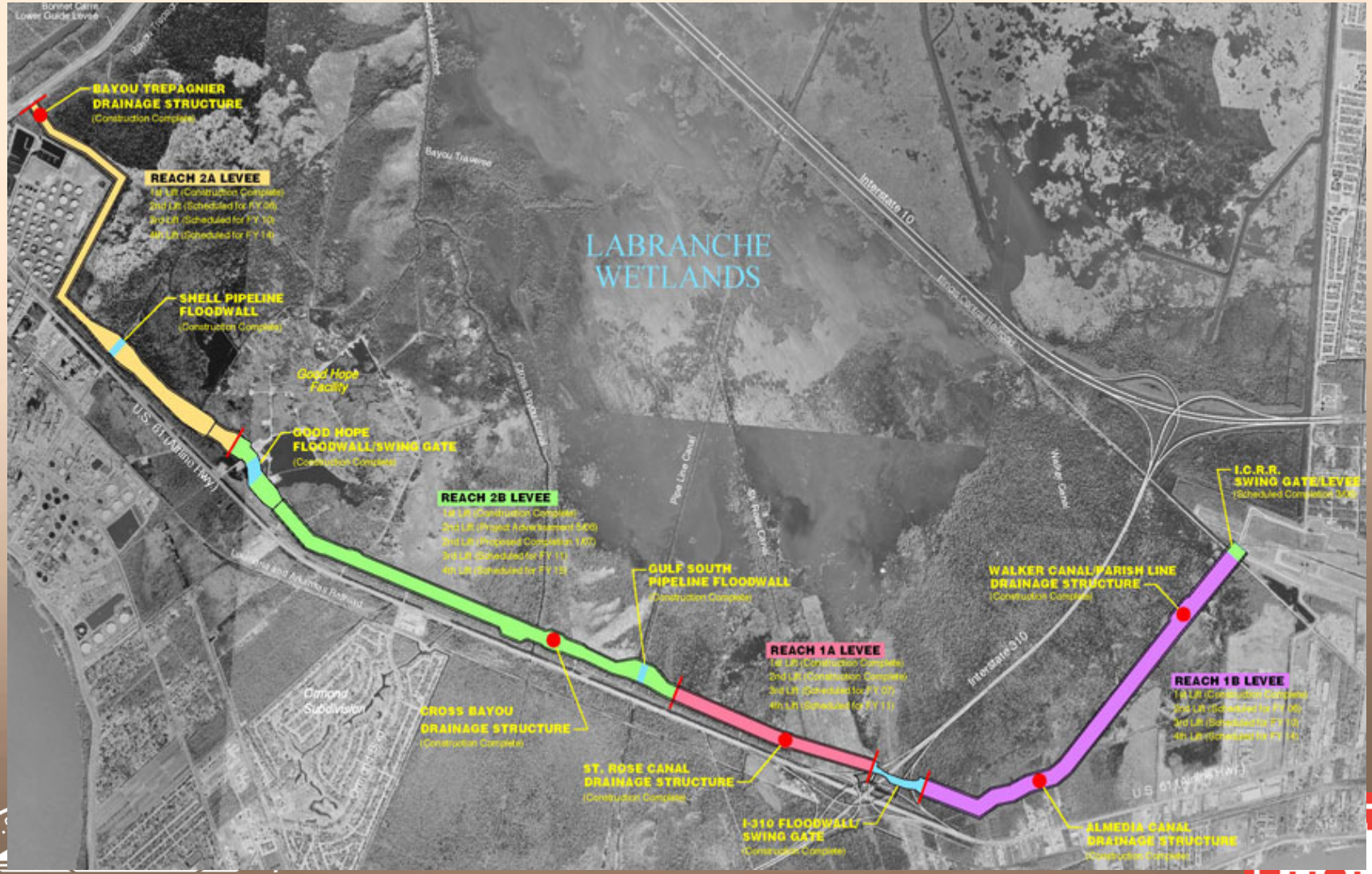
Levee Exercise

List factors that affect the overtopping erosion for a riverine levee, a hurricane (coastal) levee, a water conservation area levee (Florida):

Riverine levee crest near transition to floodwall , which is visible below bridge. The river under normal flow conditions is located about 300 feet to the right of the embankment.

Levee Exercise

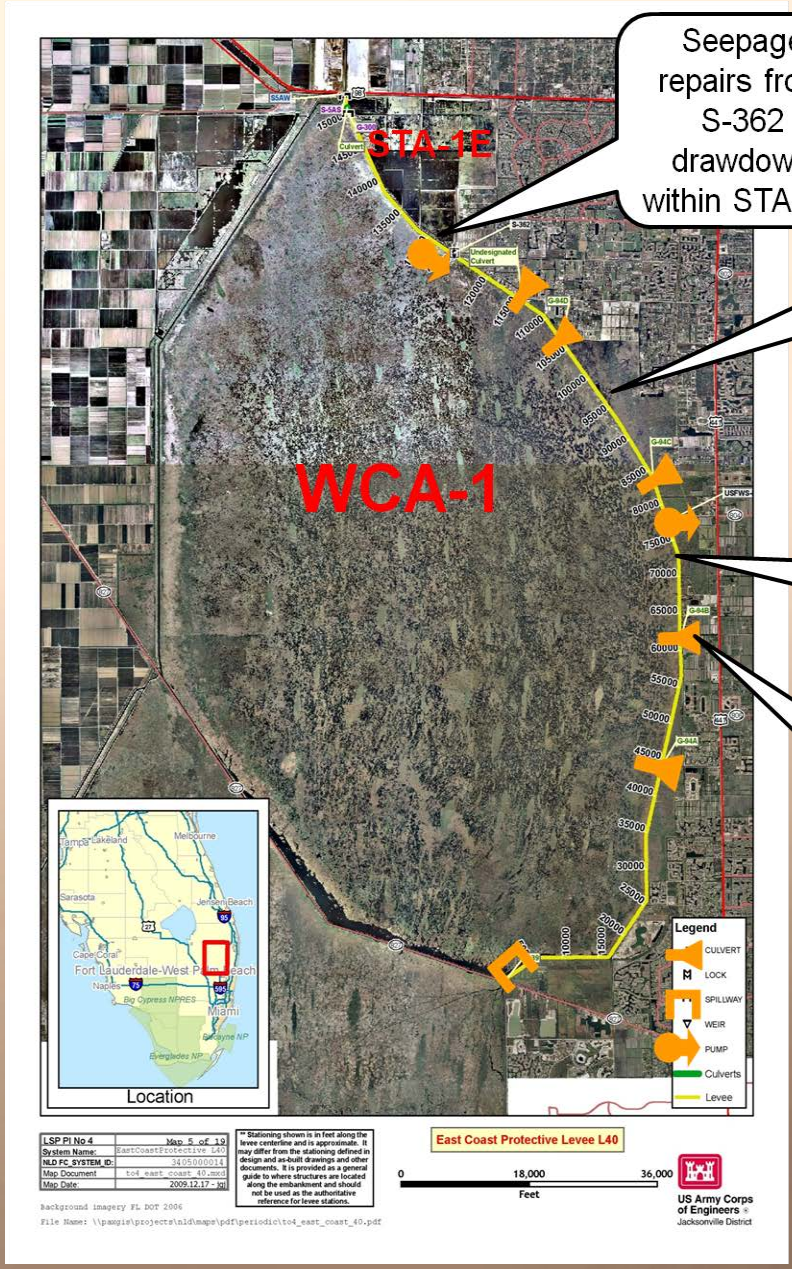
Coastal Levee along Lake Pontchartrain



Levee Exercise

Coastal Levee along Lake Ponchatrain (pull view from Orleans hurricane)

Annotated satellite image of water conservation area levee (yellow line shows levee alignment) is southern Florida.



The following are partial lists

Riverine	Hurricane	WCA
• Slope protection	• Slope protection	• Slope protection
• Type of grass	• Type of grass	• Type of grass
• Grass coverage	• Grass coverage	• Grass coverage
• Depth of flow	• Wave height	• Depth of flow
• Duration of flow	• Wave frequency	• Duration of flow
• Low spots	• Duration of storm	• Wave height
• Variation in vegetation	• Slope of levee	• Wave frequency
• Bare spots	• Slope of foreshore	• Duration of storm
• Gullies	• Wind speed	• Slope of levee
• Water craft induced waves	• Wind direction	• Slope of foreshore
• HPTRM use	• Low spots	• Wind speed
	• Variation in vegetation	• Wind direction
	• Bare spots	• Vegetation within the WCA
	• Gullies	• Low spots
	• Water craft induced waves	• Variation in vegetation
	• HPTRM use	• Bare spots
		• Gullies
		• Water craft induced waves
		• HPTRM use

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