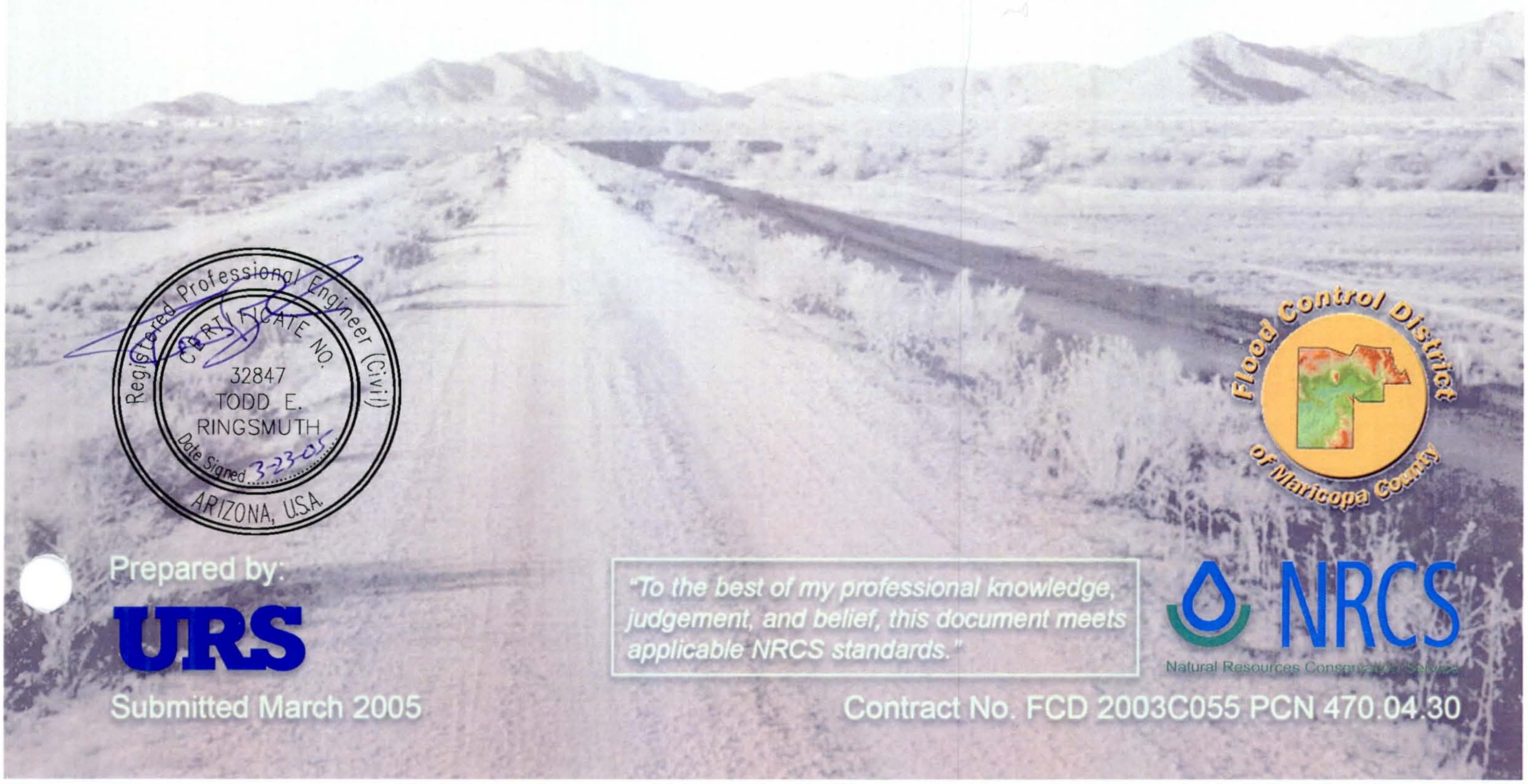
WHITE TANKS
FRS #3

RISK ASSESSMENT

WHITE TANKS FRS NO. 3
REMEDIATION PROJECT - PHASE 1



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"To the best of my professional knowledge, judgement, and belief, this document meets applicable NRCS standards."

NRCS
Natural Resources Conservation Service

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URS

Memorandum

To:	Larry Lambert Maricopa County Flood Control District	From:	Dick Davidson and Todd Ringsmuth
		Offices:	Denver and Phoenix
		Date:	March 23, 2005

Subject: White Tanks FRS #3 Risk Assessment

1. Introduction

A detailed risk assessment for the final design of the Fissure Risk Zone (FRZ) embankment reconstruction of White Tanks Flood Retention Structure (FRS) No. 3 was conducted by URS on behalf of the Flood Control District of Maricopa County. The risk assessment was initiated in a workshop convened on 1 October 2004 with an Expert Panel comprised of the following:

- Flood Control District of Maricopa County – Larry Lambert, Tom Renckly, Dennis Duffy
- Arizona Department of Natural Resources – Jon Benoist, Ravi Murthy
- USDA NRCS – Danny McCook, Ilde Chavez
- AMEC – Ralph Weeks, Ken Fergason,
- Geological Consultants, Inc. (GCI) – Ken Euge
- URS Corporation – Rich Millet, Ed Villano, Todd Ringsmuth, Dick Davidson (Facilitator).
- Engineering & Hydrosystems – George Annandale

The structure of the event trees and the most important probability judgments were completed by consensus in the workshop. The following text discusses the technical presentations and open discussions that occurred on the key technical issues. The event trees were completed subsequently by checking for internal consistency and using additional analysis results, as appropriate.

2. Methodology of Risk Based Analysis

The approach that was used is based on the concept that the risk posed by a given event is equal to the probability of the event occurring multiplied by the consequences if the event occurs. In quantitative terms, "risk" is defined by:

$$\text{Risk} = \text{Likelihood} \times \text{Consequence}$$

For this project, the consequences have been explicitly defined for each failure mode in quantitative terms based on the consensus of a panel of technical experts reflecting specific knowledge of the dam, the surrounding environment, earth fissures and subsidence in the Phoenix region, and the expected behavior of dams under flood loading. Consequences were considered in terms of life loss potential (LLP). Not considered were other consequences such as environmental/social/business impacts. Eventually, all of these various consequences could be quantified in financial terms.

Likelihoods (probabilities) were derived using best-practice event tree methods. Event trees begin with an initiating event, which in this case is a flood, and then systematically develop the logical sequence of events required for a failure of the dam that leads to defined consequences. Each branch of the tree requires a judgment of the probability or likelihood of that event occurring, which is done by consensus of the expert panel in the workshop. Multiplying all probabilities on each branch provides the total probability or likelihood of that particular failure scenario.

URS applied the RISQUE method (Bowden, et al., 2001), which is a systematic, quantitative process that uses expert panel knowledge to provide judgments that are incorporated into a quantitative risk analysis and management framework. The method offers a systematic methodology that is defensible with respect to current world best practice. The RISQUE method can be broken down into five stages, as follows:

1. Establish the context.
2. Identify the risk.
3. Analyze the risk.
4. Formulate a risk treatment strategy.
5. Implement the risk treatment strategy.

Some advantages of using a quantitative risk assessment approach are:

- Can provide a clear understanding of comparative risk.
- Provides good differentiation between events. Risk profiles generated from quantitative analysis differentiate on the basis of real numbers.
- No use of emotive terms to describe classes of risk.
- Precise definition of risk events. Events are presented as true values of risk.
- Easy to compare events on the same basis.

- Can include complex events through event tree analysis by combining several consequences that may arise from a single event.
- Can include usually "unquantifiable" events.

The process undertaken for the assessment of flood-related risks associated with White Tanks FRS # 3 consisted of the following key steps:

1. Defining failure as release of water in excess of the quantity handled by downstream flood control measures.
2. Identification of flood-related failure modes and their likelihoods of occurrence for various earth fissure scenarios.
3. Identification of the consequences of dam release failure for each flood case.
4. Analysis of risk for Phase1 FRZ embankment only. Transition section and Phase 2 embankments could be included in the risk analysis at a later time.
5. Comparison of risk with established national and international dam risk guidelines.

For the final FRZ embankment, the expert panel addressed topics such as potential frequency, severity, impact of failure, detection, and potential mitigation. The expert panel relied on the information provided by specialists working on various elements of the project such as the modeling of the subsidence and the earth fissure development / erosion process, geologic conditions, groundwater conditions, flood hydrology and spillway design, and the embankment design issues such as the ability of the soil cement section to bridge over an eroded fissure and the effectiveness of the soil cement bentonite cutoff walls. Discussions were held to facilitate understanding and evaluation of these key elements.

3. Fissure Risk Zone Embankment Failure Modes Under Flood Loading and Risk Event Trees

3.1 General

One of the fundamental tools of detailed quantitative risk assessment is the event tree. An event tree is a hazard identification and frequency analysis technique that employs inductive reasoning to describe the potential outcomes that may arise from an initiating event. The fundamental principle of the event tree process is to unravel a relatively complex event, in this case a flood failure mode, to derive a sequence of simpler component events, whose probabilities and consequences have a better prospect of estimation using available data or judgment.

A risk or failure event is an environmental, statutory, engineering, or other event that has been identified during the risk assessment as having some likelihood of occurrence and that could have some potential detrimental effect should it occur.

The risk model was developed in Microsoft Excel V5.0 with an add-in called Precision Tree (Professional Version).

Each of the event trees was created to focus on the consequential failure modes of various ranges of flood loading:

- Floods equal to the 200 year Annual Exceedence Probability (AEP) Storm; this storm is fully contained by the reservoir;
- Floods causing flow over the spillway at Elevation 1212 ranging from the 500 year AEP (Outflow Q = 900 cfs) to Half PMF event (Q = 9,000 cfs); and
- Probable Maximum Flood (PMF) from the Probable Maximum Precipitation (PMP) event with an outflow of Q = 26,000 cfs over the spillway.

We have utilized a 200 year probability for the first partition with this flood reaching an elevation of 1212. For the second partition, we selected a flood return period of 1 in 500 years or an annualized probability of 2×10^{-3}. The 72-hour PMP storm flood has an occurrence probability of 4×10^{-8}.

A full suite of outcomes for each failure mode was considered. Failure not only means catastrophic structural failure of the dam and breach release of the water contained in the reservoir, but also includes fissure flows which exceed the capacity of the downstream flood control measures, which is a discharge flow of about 560 cfs.

Risks associated with spillway discharges from the flood events, were not included in these calculations, but are discussed in Section 5.0.

Each outcome for a failure mode was assigned a probability of occurrence based on statistical data, historical precedent, or the subjective probability guidelines in Table 3.1. For events with known statistics, these are used directly in the event tree to assign probabilities. The subjective probability guidelines were first published by Barneich et al. (1996) and have been used extensively for detailed risk assessments of many types of engineering structures and natural events. They were originally developed for the nuclear power industry and have been tested extensively and found to provide a reasonable basis for making subjective judgments. These guidelines have been adopted for dams in Australia (ANCOLD, 2003).

Table 3.1
Guidelines for Subjective Probabilities

Description	Annual Probability
Occurrence is virtually certain.	1
Occurrence of the condition or event is observed in the available database.	10^{-1}
The occurrence of the condition or event is not observed, or is observed in one 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}

Each failure mode event tree starts with one of the three flood initiating events with three branches based on the ranges of subsidence.

The range of subsidence events was established from guidance provided by Ralph Weeks and Ken Fergason of AMEC and Ken Euge of GCI. This range considered three different settlement subsections models with the predicted additional subsidence from 150 ft of additional future drawdown ranging from 0.7 ft to 4 ft. In all cases the branches' cumulative probability at each node must add up to 1.

The three subsidence branches for each failure mode, focusing on differential subsidence over the 1000 ft length of the fissure risk zone were:

- Greater than 2 ft reflecting,
  - Upper bound of predicted total subsidence from ground water drawdown;
  - Actual differential subsidence is more abrupt than expected; and
  - Probability of Occurrence of 1 in 20 or 5×10^{-2}.
- Between 0.5 and 2 ft reflecting,
  - Best estimate of total subsidence and distribution along length of embankment; and
  - Probability of Occurrence of 8 in 10 or 8×10^{-1}.

- Less than 0.5 ft reflecting,
  - Actual subsidence is at the lower bound of what was predicted, perhaps because of less drawdown over the design life or stiffer soil behavior;
  - Differential subsidence profile is more uniform than expected; and
  - Probability of Occurrence, 1.5×10^{-1}.

The next stage of the event trees considers the potential size of an earth fissure that could develop as a result of the predicted subsidence. Based on the experience of the Expert Panel, the fissures, which are induced by ground subsidence caused by groundwater withdrawal in the alluvium basin forming the foundation of White Tank FRS, could range from none to 0.5 inch to 1 inch to 2 inches in width. Observations of other earth fissures reveal that they can extend for miles and remain open to the full depth of the water table.

Given the initial size of the earth fissure, the next node evaluates whether the fissure is observed prior to flood event either by visual inspection, GPS survey, tape extensometer measurement, or tension on the TDR cables. The Expert Panel had an extensive discussion on monitoring based on past experience and the instrumentation program planned for McMicken Dam. In the case of an observed fissure, various treatment strategies were identified by the Expert Panel, including excavation and sealing, blanketing and grout injection. The panel then judged whether the treatment would be effective or partially effective.

Given that the fissure was not observed or the treatment was not fully effective, then the next node assessed the enlargement of the fissure. The basis for the eroded fissure width was the range in the Annadale erosion model results (E&H, 2005) for that flood hydrograph using the range of erosion rates developed from the various erosion tests and geotechnical characterization of the soils beneath the proposed Phase 1 embankment structure. The erosion model also produced peak fissure flow rates from which downstream consequences could be judged.

Given that the fissure erodes under the specific flood scenario, the final node judges the probability that the soil cement embankment collapses into the fissure creating a breach that releases the reservoir, or alternatively the embankment bridges over the fissure allowing the peak fissure flows to be released downstream. A separate event tree was prepared to examine whether the soil cement embankment could collapse into various size fissures ranging from:

- Less than 1 ft;
- Between 2 to 4 ft; and
- Greater than 4 ft, typically 5 to 7 ft, which is the largest eroded fissure predicted.

So the failure scenario outcome at the end of each event tree is the probability of catastrophic breach, the probability of high fissure flow exceeding Q = 560 cfs, and the probability of low fissure flow less then Q = 560 cfs which can be contained within the downstream flood control works.

In order to calculate the overall probability of failure for a selected failure mode scenario, the probabilities of each outcome are multiplied across each branch of the tree. Next, the total outcome probabilities are summed over the entire tree to give the overall probability of a specific failure mode and consequence. By taking the inverse of the annualized probability of failure, the recurrence of the failure mode can be expressed in years.

Figure 1 presents an example of the event tree starting with the 2004 flood event. The complete failure mode event trees for the three flood levels are described in the following sections and presented in Appendix A.

3.2 Small Flood (200 Year Event)

The small flood case is stored in the reservoir without flow over the spillway. The Annadale erosion model indicates that under a 200-year flood event the low erosion rate enlarges fissures from starting widths of 0.5 to 2 inches to final widths of 0.1 to 0.3 ft, respectively, with peak flows ranging from 35 to 247 cfs. With the high erosion rate, the starting fissure width of 0.5 to 2 inch erodes to final widths of 3.6 to 3.8 ft, respectively, with peak flows of 1,300 to 1,550 cfs.

The results indicate the probability of fissure flow greater than 560 cfs is equal to 1.50×10^{-5}. Additionally, the probability of an embankment breach is 2.29×10^{-12}, which is a diminimus contribution to risk.

3.3 Intermediate Flood Between 500 Year Event and Half PMF

Under intermediate floods, which cause flow over the spillway, the Annadale erosion model predicts that for low erosion rates the fissure erodes to final widths of 0.1 to 0.3 ft with corresponding flows of 35 to 250 cfs. For the high erosion rate the fissure erodes to final widths of 3.9 to 4.1 ft with corresponding flows of 1,350 to 1,800 cfs.

For this event tree the probability of a fissure flow greater than 560 cfs is 6.0×10^{-6}. It should be noted that the 500 year spillway discharge (900 cfs) exceeds current downstream capacity (560 cfs) and has a probability of occurrence of 2×10^{-3}.

3.4 Extreme PMF Event

The most extreme flood event corresponds to the probable maximum flood, which in this case corresponds to the 72-hour probable maximum precipitation event with a probability of occurrence of 4 x 10^{-8}. For the low erosion rate, the fissure erodes to final widths of 0.1 to 0.4 ft with corresponding peak flows of 35 to 283 cfs. For the high erosion rate the fissure erodes to final widths of 5.4 to 6.6 ft with corresponding flows ranging from 2,260 to 3,461 cfs. The PMF spillway flows of 26,000 cfs greatly overshadow these fissure flows. Therefore, no matter what fissure flows occurs the downstream flood failure criteria are exceeded.

The probability of catastrophic breach from the PMF was computed to be 1.92 x 10^{-14}. The probability of a fissure flow greater than 560 cfs is equal to 1.20 x 10^{-10}. PMF spillway discharge (26,000 cfs) overwhelms any fissure flow discharge and the current downstream channel capacity and has a probability of occurrence of 4 x 10^{-8}.

3.5 Summary

The probability of failure for each flood failure mode event tree has been summarized in Table 3.2.

Table 3.2
Probability of Failure Due to Fissure Flow of FRZ Embankment

Failure Mode	Catastrophic Breach	Fissure Flows Exceed Q = 560 cfs
200 year	2.3 x 10^{-12}	1.5 x 10^{-5}
500 year to ½ PMF	2.2 x 10^{-10}	6.0 x 10^{-6}
PMF	1.9 x 10^{-14}	1.2 x 10^{-10}
Total Probability	2.2 x 10^{-10}	2.1 x 10^{-5}

These probabilities are now used with the associated consequences presented in the next section to compute risk.

4. Consequences of Each Failure Mode Due to Fissure Flow

The life loss potential (LLP) consequences of the three flood failure modes have been grouped into three main potential outcomes:

- Catastrophic embankment breach;
- Fissure flow exceeding downstream channel Q = 560 cfs; and
- Fissure flow staying within downstream channel.

The LLP has been computed using the Graham (2004) simplified method utilizing population at risk PAR numbers estimated from current maps and future planning documents for the region. The following LLP estimates in Table 4.1 have been utilized:

Table 4.1
Life Loss Potential (LLP) Consequences

Flood Scenario	Current LLP
Catastrophic Breach	2160
200 year	20
500 year to ½ PMF	20
PFM	40

5. Risk Results

Risk has been computed as the product of the probability of each failure mode and the associated current LLP consequences.

Table 5.1
Fissure Flow Failure Risk of FRZ Embankment

Failure Mode	Catastrophic Breach	Fissure Flows Exceed Q = 560 cfs
200 year	4.9×10^{-9}	3.0×10^{-4}
500 year to ½ PMF	4.8×10^{-7}	1.2×10^{-4}
PMF	4.1×10^{-11}	2.4×10^{-9}
TOTAL RISK	4.8×10^{-7}	4.2×10^{-4}

The fissure flow risks can now be compared to international tolerability criteria established by ANCOLD (2003) for a new dam of 1×10^{-4} and to risk criteria established by the Bureau of Reclamation (2003) as plotted in Figure 2. The F-N curve representation of risk was originally established by Baecher and Whitman, and then directly applied to dams by ANCOLD. Christian (2004) in his Terzaghi lecture discussed F-N curves. The representation shown in Figure 2 is now being used in the newly developed FEMA / ASDSO risk prioritization process.

Downstream risks generated by catastrophic breach and flows generated by fissure erosion are within the acceptable range as shown in Figure 2, the "green zone". It should be noted, these risks are significantly lower than that calculated for spillway discharge produced by floods with occurrence intervals of 500 year (2×10^{-3}) and greater.

6. References

Australian National Committee on Large Dams (2003), *Guidelines on Risk Assessment*, October.

Barneich J, Majors D, Moriwaki Y, Kulkarni R, and Davidson R, (1996), *Application of Reliability Analysis in the Environmental Impact Report (EIR) and Design of a Major Dam Project*, Uncertainty '96, ASCE, 1996.

Bowden, A., Lane, M. and Martin, J. (2001), "*Triple Bottom Line Risk Management Enhancing Profit, Environmental Performance, and Community Benefits*." John Wiley & Sons, Inc. 2001.

Bureau of Reclamation (2003), *Guidelines for Achieving Public Protection in Dam Safety Decisionmaking*, June 15.

Christian, JT (2004), *Geotechnical Engineering Reliability: How Well do We Know What We are Doing?* Terzaghi Lecture, ASCE Journal of Geotechnical GeoEnvironmental Engineering, Vol. 130, No. 10 October.

Engineering & Hydrosystems, Inc. (2005), *White Tanks FRS No. 3 Foundation Fissure Modeling*, Report.

Graham, W (2004), *Risk-Based Dam Safety Prioritization, A Project Sponsored by ASDSO and FEMA, A Method for Easily Estimating the Loss of Life from Dam Failure*, Draft, June 18, 2004.

Figure 1 - Example White Tanks F.... for 200 year Flood Event Tree

LOADING: Up to 200 Year Flood

Probability of Flood Loading = 5.00E-03
Flood Loading = Flood Level Equal to 1212

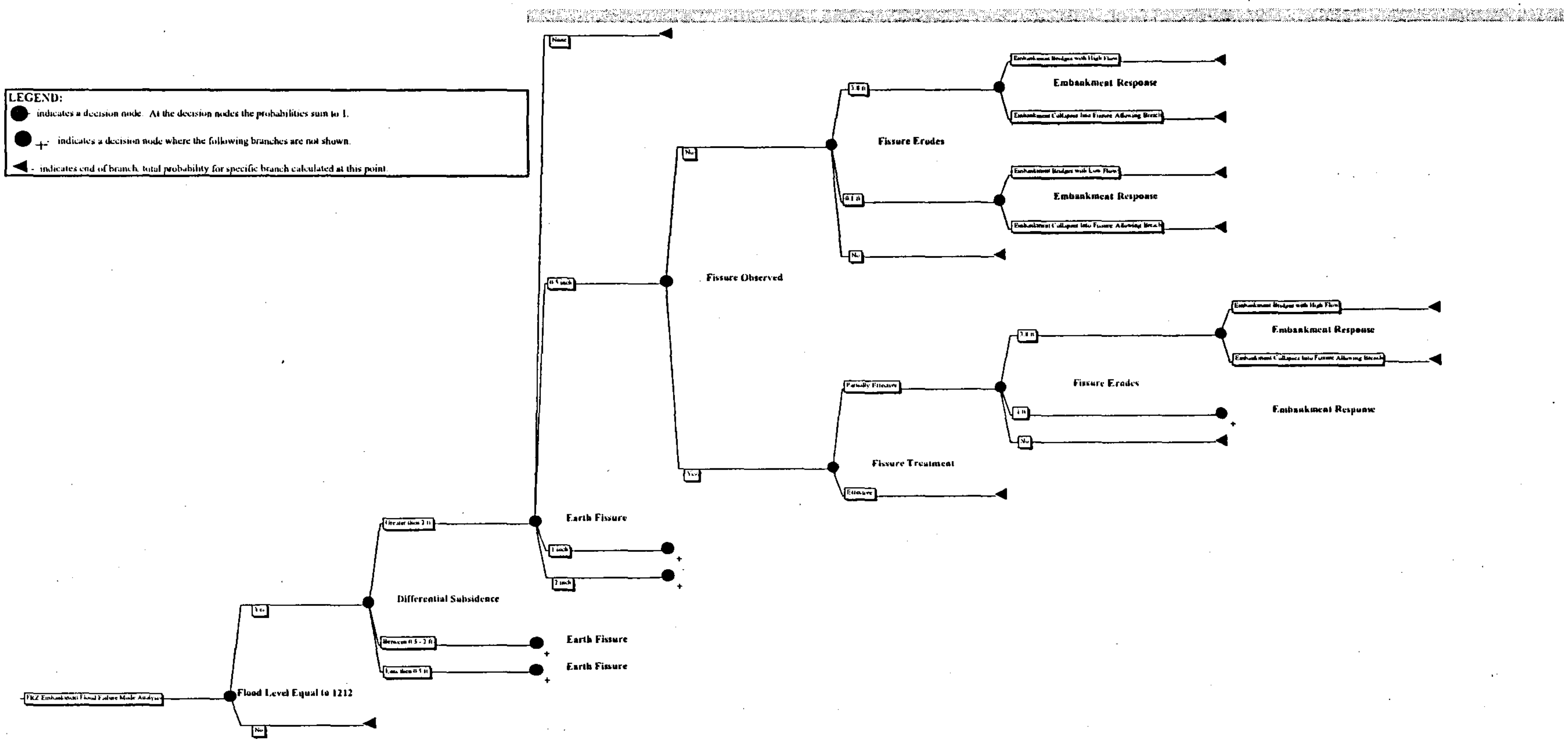
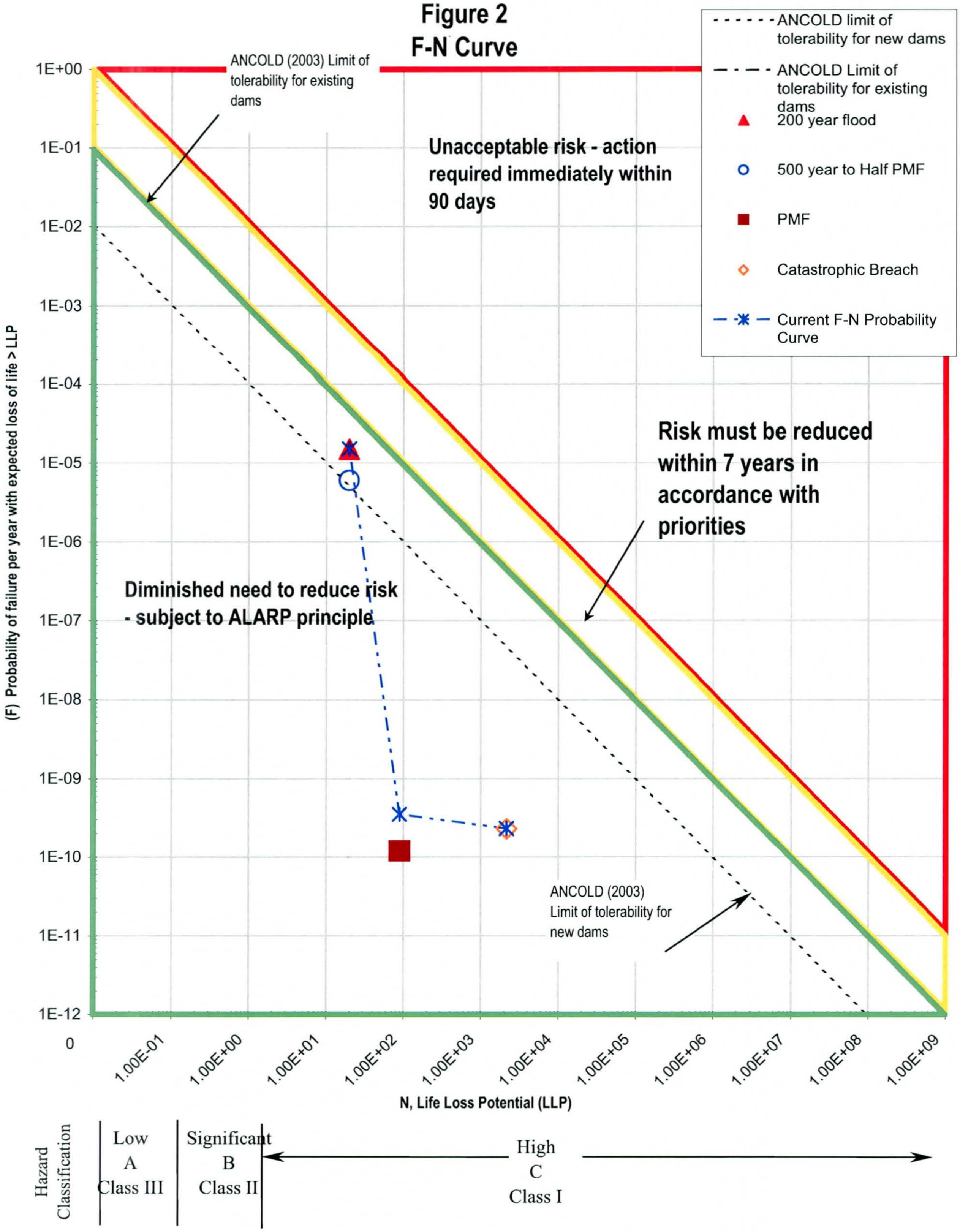


Figure 2
F-N Curve

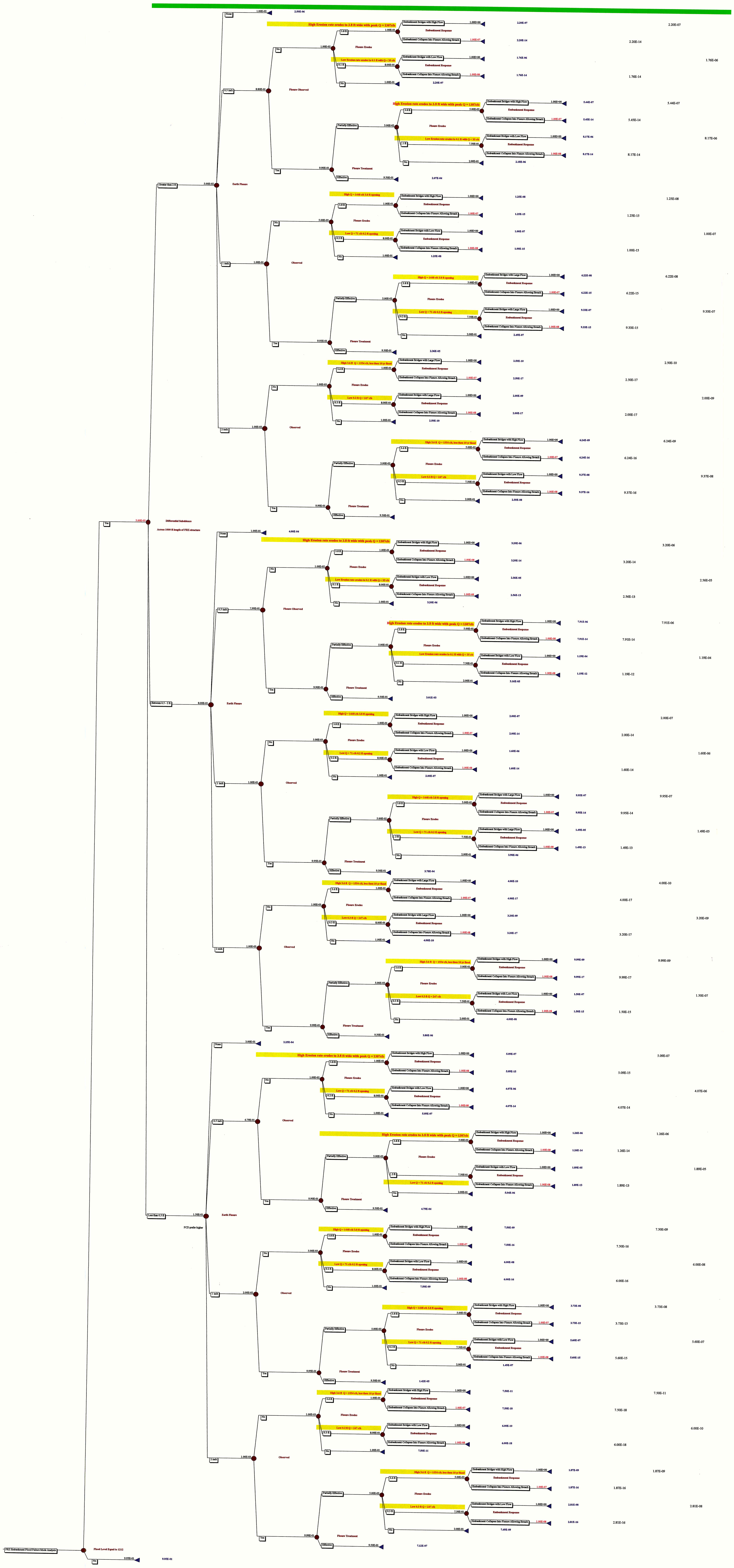


WHITE TANKS FRS#3 EVENT TREE - FLOODING

LOADING: 200 Year Flood

Probability of Flood Loading = **5.00E-03**
Flood Loading = **Flood Level Equal to 1212**

Failure Probability of Embankment Breach	Probability of Fissure Flow Q > 560 cfs	Probability of Low Fissure Flow Q< 560 cfs



Cumulative Probability	2.29E-12	1.50E-05	1.96E-04

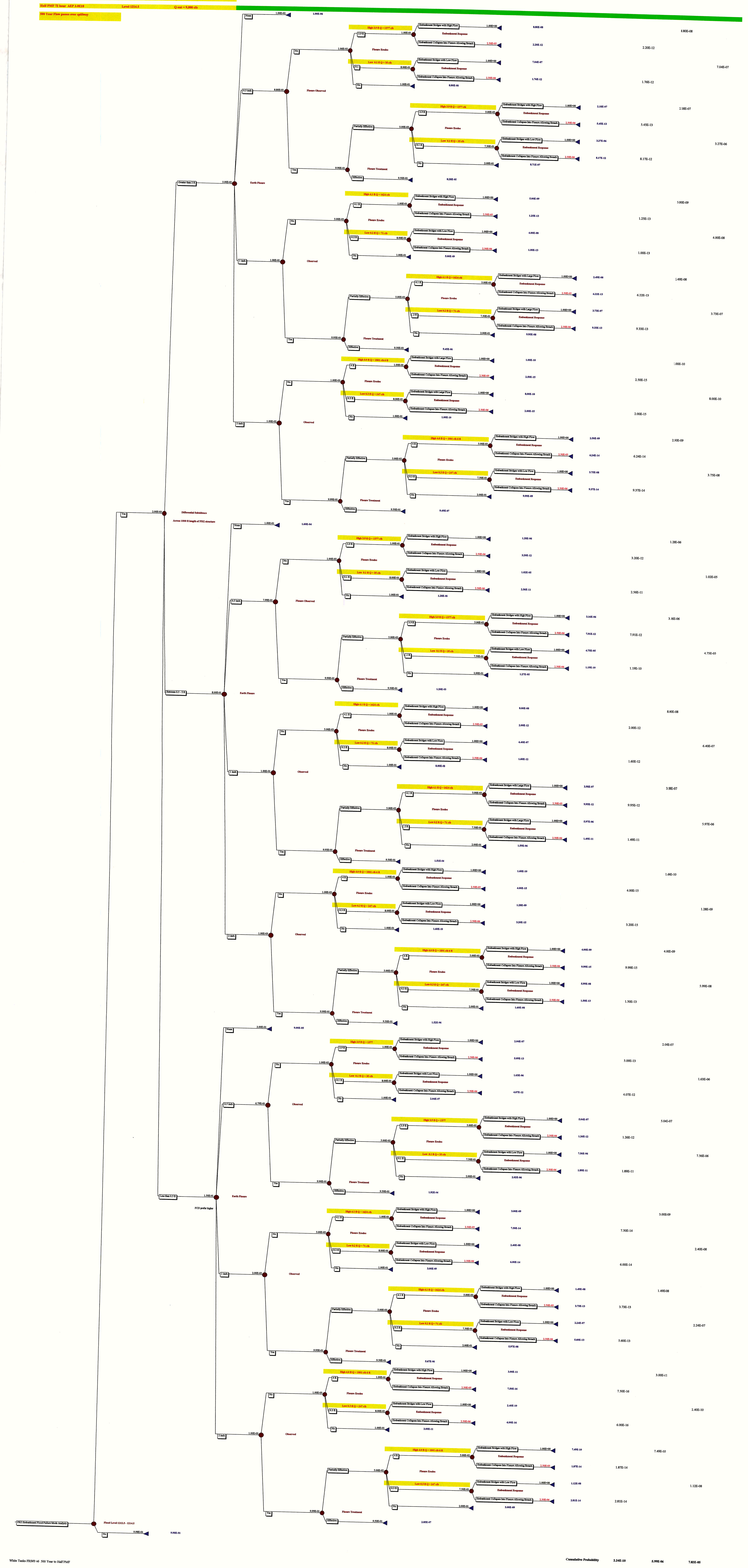
WHITE TANKS FRS#3 EVENT TREE - FLOODING

LOADING: 500 Year to Half PMF

Probability of Flood Loading = 2.0E-03
Flood Loading = Flood Level 1212.5 - 1214.5

		Spillway Flow
500 Year 24 hr	Level 1212.5	Q out = 900 cfs
Half PMF 72 hour AEP 3.0E10	Level 1214.5	Q out = 9,000 cfs

500 Year Flow passes over spillway



White Tanks FRS#3 v6 500 Year to Half PMF

WHITE TANKS FRS#3 EVENT TREE - FLOODING

LOADING: PMF

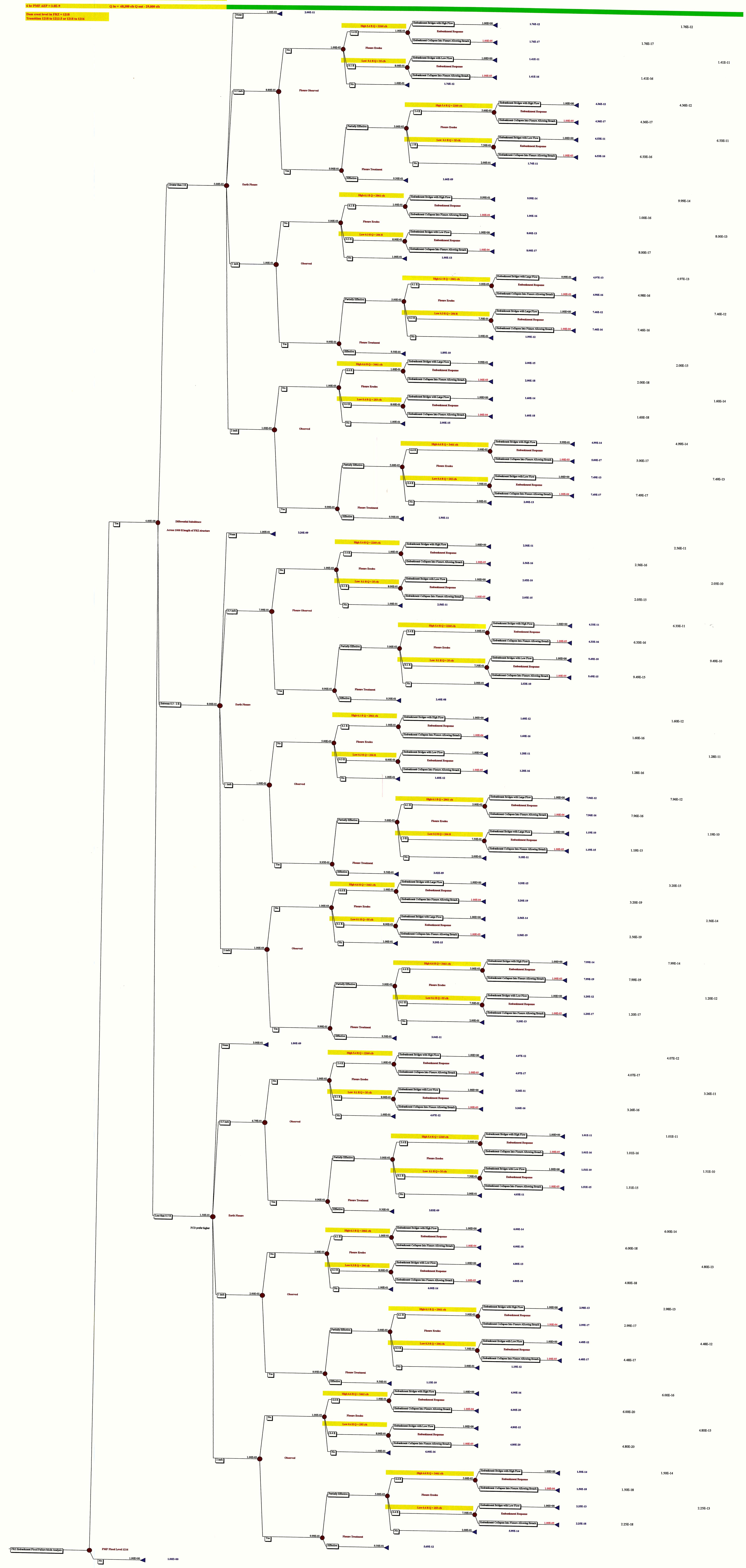
Probability of Flood Loading = 4.00E-08
Flood Loading = PMF Flood Level 1216

72 hr PMF AEP = 4.0E-8 — Q in = 32,700 cfs Q out = 26,000 cfs

6 hr PMF AEP = 3.0E-9 — Q in = 68,300 cfs Q out - 29,000 cfs

Dam crest level in FRZ = 1218
Transition 1218 to 1213.5 or 1218 to 1216

Failure Probability of Embankment Breach	Probability of High Fissure Flow Q > 560 cfs	Probability of Low Fissure Flow Q <560 cfs



Cumulative Probability 1.92E-14 1.20E-10 1.56E-09