Comparison of Failure Modes from Risk Assessment and Historical Data for Bureau of Reclamation Dams

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DAM SAFETY OFFICE

Materials Engineering and Research Laboratory

August 1997

Comparison of Failure Modes from Risk Assessment and Historical Data for Bureau of Reclamation Dams

Dam Safety Research Report

by
Joe Tatalovich
Foreword by
David W. Harris

U.S. Department of the Interior
Bureau of Reclamation
Dam Safety Office

August 1997

Foreword

In the summer of 1997, the Bureau of Reclamation Dam Safety Office funded a student summer sabbatical to review initial studies of Risk Analysis of various dams. Two major questions were addressed:

1. Are risk analyses producing consistent results from the various teams?

2. Can the risk analysis probability results be baselined or calibrated to historical results?

As the work progressed, it became apparent that the work might provide some additional benefits, particularly for initial screening analyses. The Reclamation inventory of dams was classified using the system available at the time of the work. The work in this report could possibly serve as an initial event probability estimate based on historical failure and accident occurrences.

The scope of the work was purposely held to a level achievable by one person over the period of a summer. Additional research is obviously needed and suggested in the report.

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Background and Purpose

To determine which dams need to be renovated because of their risk of failure or accident, the Bureau of Reclamation (Reclamation) has developed a process of calculating that risk. It takes into account the failure possibilities and the number of people who would be affected by certain occurrences. Uncertainties that are inherent in the process make this study of the risk assessment process all the more important.

The purpose of this project was to present findings from various risk assessments of Reclamation dams. The failure modes of these dams were compared to each other as well as to historical failures (Von Thun, 1985). To compare the risk assessment and historical data, it was necessary to put together a comprehensive list of all Reclamation dams classified by their age, height, and type. It was hoped that, through the process of examining the risk assessments and the historical data, Reclamation would learn more about both their dams and how the risk of failure is analyzed. By doing this, the prioritizing of dam servicing in the future may be improved.

Table 1 summarizes dam accidents and failures in the Western United States. Whereas, a failure requires release of the reservoir along with some damage to the structure, an accident is an event (or series of events) that threatens the mechanical, structural, or operational integrity of the dam. The table also indicates trends of the dam inventory such as the abundance of earthfill dams, the rank order of risk, the total number of incidents, etc.

Table 1.—Summary of dam accidents and failures
(Dams in the Western United States)

Fill	Failures	Accidents	Dams	Life years	Risk-this class
Earth	74	100	7812	267039	6.52e-04
Rock	17	14	200	7522	4.12e-03
Concrete					
Arch	4	8	200	9101	1.32e-03
Gravity	4	2	285	13257	4.53e-04
All Dams	99	124		296919	7.51e-04

For comparison, Reclamation dams can be tabulated in a similar manner:

Table 2.—Summary of dam accidents and failures (Reclamation dams)

Fill	Failures	Accidents	Dams	Approximate life years	Risk-this class
Earth	1	39	211	10429	3.83e-03
Rock	0	1	10	507	1.97e-03
Concrete					
Arch	0	8	30	1660	4.82e-03
Gravity	0	10	22	1314	7.61e-03
All Dams	1	58		13910	4.24e-03

According to these figures, Reclamation dams are more risky than the "average" western dam. Even though Reclamation more rigorously documents accidents than what is recorded for other western dams, when one takes into account the recent occurrences at Reclamation dams (which were not figured into the table), the need for effective risk assessment becomes even more apparent. The incident rate for the last three years with seven incidents (see the top of appendix K) is well above the average rate for Reclamation dams.

Historical Inventory

Dams have been constructed with either concrete or some type of fill, e.g., rock and/or earth material. Concrete dams include arch, gravity, and buttress dams. These types were further classified in the inventory by their age (which is represented by the date of final construction) and height. It should be noted that each category contains a number of life years, meaning each dam has been in operation for a number of years and those years are summed. Failure rates are calculated within these categories (i.e., the failure rates are the number of occurrences of failure or accident in the category divided by the number of life years of the same category). The following grid illustrates the breakdown of ages and heights in the data. This grid method was used for each of the types of dams used in historical data: earthfill, rockfill, concrete arch, and concrete gravity/buttress.

	<1930	1930-1960	>1960
<50 feet	Dam A		
50-100 feet		Dam B	
100-300 feet			
>300 feet	Dam C		

The grid shows that there are 12 different categories per dam type. An example of a category would be earthfill dams constructed before 1930 and less than 50 feet high.

Bureau of Reclamation Inventory of Dams

Appendix C contains the major Bureau of Reclamation dams, classified by type, age, and height to correspond to the historical data. A list of diversion dams which are less than 50 feet is included in appendix A. Some dams contain characteristics of more than one type of dam (e.g., Pueblo is a combined buttress and earthfill dam) and were therefore put into the tables under both categories.

Because the 1981 Project Data book was used to compile this inventory, some of the newer dams may be left out (e.g., New Waddell and McGee Creek Dams). Attempts were made to include these dams when the appropriate data were retrievable.

Risk Assessments and Failure Modes

Various teams at Reclamation estimate the risk to which the dams are susceptible along with their modes of failure. Risk assessments define the load probabilities (static, hydrologic, and seismic) and their corresponding consequences. They also seek to ascertain the most risky failure modes that will be contained in the "event trees." Event trees act as visual aides designed to show the path of events from load (static, hydrologic, seismic) to response (failure) to consequence (economic, loss of life). These help determine whether or not the dam needs corrective action.

This study includes everything through the response or failure of the dam. It is imperative to realize that annualized loss of life figures are what Reclamation uses to measure the hazards and this paper seeks to include only the probability of a load and the failure that occurs from that load. The failure probabilities that are seen throughout this report can be multiplied by the number of people at risk from a failure to obtain the annualized loss of life data.

In assessing a dam for risk or modification, a variety of reports are used. Based on existing regulations, a Modification Decision Analysis, or MDA, is completed which determines whether modifications are needed. If there is a decision to take action, a Corrective Action Study, or CAS, is completed. Recently, a risk-based analysis has been added to many of the current studies. A Screening Level Risk Assessment may be done as an initial study to estimate the risk to a dam in a broad scope, whereas the comprehensive Risk Assessment (RA) is more in-depth on the full scope of potential risks. The RA identifies corrective possibilities and determines what effect these corrections would have on the overall safety of the dam. Table 3 shows the level of risk assessments conducted at Reclamation dams.

Table 3.—Dam descriptions and risk assessments

Dam	Type	Date completed	Structural height (ft)	Assessment level
Hungry Horse	Concrete Arch	1953	564	Screening Level[1]
O'Sullivan	Earthfill	1949	200	Screening Level
Willow Creek	Earthfill	1912	93	RA[2]
Whiskeytown	Earthfill	1963	282	RA
Avalon	Earthfill	1907	58	RA during CAS[3]
Deadwood	Concrete Arch	1931	165	RA
Warm Springs	Concrete Arch	1919	106	RA
Elephant Butte	Concrete Gravity	1916	301	Screening Level
East Park	Concrete Arch	1910	139	Screening Level
Nambe Falls	Concrete Arch/Earthfil	1976	150	RA
Spring Creek	Earthfill	1963	196	supplemental MDA[4]
Pueblo	Concrete Buttress/Earthfill	1975	245	RA
Conconully	Earthfill	1910	72	RA
Salmon Lake	Earthfill	1921	54	RA
Lost Creek	Earthfill	1966	248.4	RA
Wasco	Earthfill	1959	59	RA

[1] A Screening Level Risk Assessment may be done as an initial study to estimate the risk to a dam in a broad scope.

[2] An RA covers the full scope of potential risks in more depth than a screening level risk assessment.

[3] If there is a decision to take action, CAS, is completed.

[4] If necessary, after the RA, an MDA, is performed to determine whether modifications are needed.

Because of the individuality of dams and the fact that several different teams are used in this process, there are a wide variety of failure modes used (see "Event Probabilities" in appendix D). Not only do the modes differ from dam to dam, but the event probabilities also tend to vary.

Historical Probability

It needs to be concluded what type of correlation (or lack thereof) the historical data on dam incidents has, or should have, on the risk assessments. By classifying all Reclamation dams into categories by age, height and type and then comparing the number in a category to the probabilities for failure (from the Von Thun study), a sense of priority of what failure modes are important to examine is established. Empirical probabilities provide the basis of what the risk assessment teams should be looking at for a given set of dams. (Once again, an example of a "set," "group," or "category" of dams is earth dams, 100-300 feet high, built between 1930 and 1960.)

To make the risk assessment probabilities correspond to the historic probability, the failure modes listed in "Event Probabilities" (appendix D) were broken down into the seven categories. The historic failure modes were overtopping (OT), foundation (FD), piping (PI), sliding (SL), structural (ST), spillway (SP), and earthquake (EQ).

Conclusions and Recommendations

Failure Modes Not Included in Risk Assessments.—The risk assessments gathered had a variety of failure modes, but those modes did not always correspond with the historical probability for that group. For example, in the earth dams 100 to 300 feet built after 1960 category, the historical probabilities for structural failure and accident are 6e-4 and 1.8e-3, respectively. By comparing these historical probabilities to the list of event probabilities, it is easy to see that there are no structural failures documented in the risk assessments gathered. Looking at this in a simpler context, there might be ways the dam can fail that are not taken into account in the risk assessments. For additional examination of this phenomenon, see appendix E, which compare each risk assessment to the corresponding historical data for its group.

The fact that there are historical probabilities for a category and no risk assessed by the risk assessment teams should not be shocking. Most likely there are clear explanations for why a unique dam does not have, for example, a structural failure probability. What this study has sought to accomplish is to bring these discrepancies to the forefront so that calculations of the risk of Reclamation dams can be more effective.

Policy.—In the *Guidelines For Achieving Public Protection in Dam Safety Decision Making*, various criteria were made for what is acceptable and what is not as far as failure probabilities are concerned. A 10^-4 risk was set as a baseline for a dam needing, at the very least, long-term risk reduction.

The Tier 2 Guidelines schematic (appendix I) is a representation of that policy. There is justification to take corrective action when a probability is above the 10^-4 line. The justification gets even stronger as the risk goes beyond the 10^-3 mark. A few examples from the historical probabilities are plotted on the diagram to give a sense of where some of the higher rates of failure lie. Following the Tier 2 Guidelines is a rank-ordered list of historical failure and accident rates and after that is a list of the Top Twenty rates, eliminating the rates that do not correspond to any Reclamation dams. This will give some idea of the magnitude of the rates.

The most interesting facet of these data is that, according to the *Guidelines For Achieving Public Protection in Dam Safety Decision Making*, the "justification" for correcting many failure possibilities for all types of dams would be strong. Anything above the line drawn on the list of all rates (which occurs on the second page) would require some sort of corrective action, according to the guidelines in place.

The Event Tree.—The manner in which the event tree is done for risk assessments must be carefully considered. The "Event Probabilities" list (appendix D) demonstrates that there is a wide range in potential failure modes. The best explanation for this is the unique nature of dams (i.e., characteristics of each dam that make it susceptible to failure) and the complexity of assessing failure modes.

Historical Probabilities vs. Risk Assessments.—One of the main goals of this study was to compare the historical probability directly with that of the risk assessments. By doing this, risk assessment teams can now see exactly how their numbers correlate (or contrast) with what has actually happened. Table 4 gives a quick synopsis of the findings.

Table 4.—Historical probability vs. risk assessment

Type	Von Thun accident probabilities	Von Thun failure probabilities	Assessment probabilities averages	Number of samples from risk assessments
Overtopping	1.84e-05	1.57e-04	4.70e-05	16
Foundation	9.22e-05	1.88e-05	1.34e-03	17
Piping	9.24e-05	9.51e-05	Risk 3.19e-05	20
Sliding	8.07e-05	6.90e-06	6.38e-07	5
Structural	1.69e-04	3.52e-05	9.71e-05	9
Spillway	2.82e-05	8.86e-06	6.81e-05	12
Earthquake	1.18e-05	6.90e-06	1.85e-04	42

From these numbers, one can see that the risk assessment teams are judging foundation and earthquake failures two orders of magnitude MORE risky than historical data, whereas sliding and overtopping failures have been judged to be an order of magnitude LESS than historical data. Appendix E shows these comparisons risk assessment by risk assessment and appendices G and H show the risk assessment figures next to the historical ones by category in the inventory. (Note: the second set of tables in that group has the historical accident probabilities next to the FAILURE probabilities for the risk assessments.)

Like many sets of data, these figures contain outliers (see Appendix F, Key Parameters & Individual Risks). Risk assessment failure rates were relatively close to historical ones once those outliers were removed. Additional comparison of risk assessment to historical data may shed more light on this phenomenon. If this reveals that continued similarity, *there may be justification for using the historical data for a level of risk assessment* making the process less complex and therefore more economical.

Accidents, Failures, and Modifications in Bureau of Reclamation Dams.—Appendix K shows a list of accidents, failures, and modifications for Bureau of Reclamation dams starting with a list of the most recent. Appendix L contains a list of all Reclamation dams put into their respective categories by type, age, and height (just like the inventory tables) with the Von Thun accident and failure probabilities next to them. The accidents, failures, and modifications were then highlighted (key in top right hand corner).[1] Table 5 shows a few trends pinpointed by this process.

Table 5.—Possible trouble spots

Dam type	Age	Height (ft)	What to look at:
Concrete Arch	1930-60	100-300	Two of the five dams in the category have had problems with erosion below the spillway.
Concrete Arch	1930-60	>300	Two of the five dams in the category have had valve problems.
Concrete Arch	>1960	>300	Two of the five dams in the category have had recent accidents.
Concrete Gravity/ Buttress	1930-60	100-300	Four of the six dams have had accidents, two of which were related to seepage through the construction joints.
Concrete G/B	1930-60	>300	Two of the four dams have had gate troubles.

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[1] For those boxes with no historical data, numbers from appendix M can be used. These *Failure Tomorrow* tables show what the failure or accident rate would be if one more occurrence were added (i.e., as if a failure or accident occurred tomorrow).

This is not a complete list of the trends found in Appendix L, *Dams & Failure / Incident Probabilities By Category*, but should give some indication of what can be found in this very valuable list. Some of the modifications in this list are not classified (i.e., not depicted as a specific type of modification such as overtopping, structural, piping, etc.) but, nonetheless, are highlighted to show that the dam has had some sort of corrective action.

Recent Accidents.—The recent accidents, listed on the first part of appendix K (most likely not a complete list) and in all capital letters in appendix L, may indicate what the future holds as far as dam incidents are concerned. The tables in the introduction to this paper exhibit that there is greater than one failure or accident per 400 life years, and with seven incidences in very recent memory, Reclamation is well above that mark. Learning from these, along with using the historical data effectively, will help in ascertaining what areas need to have priority.

Future Research

More Breakdowns in Classification Cutoff Dates.—To better understand what role the advances in dam construction have played, more dates should be included in the tables. For example, numerous methods and materials have been used to increase the durability and strength of concrete. One logical point for that is in the mid-1940s, when air-entrained concrete was introduced, giving the dams better freeze thaw protection. In the mid-1970s, filters in earth dams were improved. There are many more dates of this type that may shed some light on dam failures and accidents and prevent the need for costly modification.

The Age of the Dam at the Time of Failure, Accident, or Modification (Five year cutoff).— Determining which failures, accidents, and modifications have transpired in the first 5 years of operation (see Appendix H, *Dams & Failure / Accident Probabilities By Category*) can further clarify the prioritization process. Conversely, it would be important to recognize that, if a category of dams is incurring incidents after a certain number of years, other dams in the same category may need remediation.

Incorporation of Loss of Life Figures.—In appendix B, there is a table of annualized loss of life figures for the dams from which risk assessments were gathered. One of the next steps in this research would be to compare those numbers to each other and maybe even come up with a way to quantify a historical annualized loss of life. Since the policy of today is to make decisions based on this factor, this would be extremely useful.

The Risk Assessment Process.—Although dams are unique and therefore have one-of-a-kind problems, their failure mechanisms can be grouped into more concise modes. Additional thought about what these modes would be would make it easier to compare the dams at the response level.

Furthermore, because of the inconsistencies that working in risk assessment teams presents, there is a need to discern *exactly* how historical data reflects the current climate and how something like the Von Thun paper can be used to guide the risk assessments. Since the historical numbers are close to those of the risk assessments, examining additional risk assessments to determine if the correlation continues would be logical. Risk assessments not studied in that report are tabulated in table 6.

Table 6.—Some risk assessments to obtain to continue research

Dam	Obtain from
Reservoir A	Martin Chavira or Bill Engemoen
Wickiup	Mark Barraclough
Bradbury	Mark Bliss
Casitas	John Wilson
Cedar Bluff	Jim Boernge

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Risk Assessment for Warm Springs Dam: Vale Project - Pacific Northwest Region. July 12, 1996.

Screening Level Risk Assessment of East Park Dam: Orland Project, California. January 23, 1997.

Risk Assessment for Deadwood Dam: Payette Division - Boise Project - Pacific Northwest Region. December 11, 1996.

Risk Assessment of Avalon Dam. January 1997.

Risk Assessment for Lost Creek Dam: Weber Basin Project - Upper Colorado Region. Post-January 1997.

Risk Assessment for Wasco Dam: Wapanitia Project - Pacific Northwest Region. Post-October 1996.

Screening Level Risk Assessment for Hungry Horse Dam: Hungry Horse Project, Montana. June 24, 1997.

Acknowledgments

As part of what is hoped to be a continued information exchange between the Northwestern University Advanced Cement-Based Materials Laboratory and the Bureau of Reclamation Materials Engineering and Research Laboratory, the author would like to thank both institutions for their support. In particular, David Harris of Reclamation was the guiding force for this research. Other Reclamation support by means of overall instruction concerning dams and critical comments on this report was given by Chuck Redlinger, John Smart, Dan Mares, and Bill Engemoen as well as many others.

APPENDIX A

Appendix A. - Diversion Dams

Dam	Type	Hydraulic Height (ft)	Date Completed	Extra Notes on Construction
Arnold	Rock/ Gravity	3	1951	
Madera	Gravity/ Earth	13	1947	
Belle Fourche	Gravity/ Earth	18	1907	
Rock Creek	Rock	10.5	1950	timber sheet piling, concrete weir cap
Black Canyon	Gravity	111	1924	Ogee-gated spillway
Boise River	Gravity	39	1908	Concrete and masonry weir, removable crest
Imperial	Buttress	23	1938	
Black River	Gravity		1906	
Fort Thornburgh	Rock/ Earth	9	1961	
Knight	Gravity/ Earth	29	1968	
Water Hollow	Gravity/ Earth	10	1971	
Camp Creek	Gravity	11	1953	
John A. Franchi	Earth	15	1964	also sheet piling
Red Bluff	Gravity/ Earth	20.5	1964	
Toats Coulee	Gravity	5	1970	
East Fork	Gravity/ Earth	8	1962	
Leon Creek	Gravity	10	1960	
Park Creek	Gravity	8	1960	
Big Thompson	Gravity	8	1950	"concrete drop inlet"
East Portal	Rock	10	1947	concrete core wall
Little Hell Creek	Earth/ Rock	33	1952	
North Pourde	Gravity	6	1952	
Pole Hill Afterbay	Earth/ Rock	21	1953	
South Platte Supply Canal	Gravity	5	1956	Stoplogged crest
Willow Creek Forebay	Earth/ Rock	11	1953	
Lytle Creek	Rock/ Earth	4	1962	also timber cutoffs
Little Sandy	Concrete Gate Earth	9	1959	
Swasey	Gravity/ Earth	11	1965	
Florida Farmers	Gravity/ Earth	14	1963	
Fort Sumner	Gravity	11	1951	

Appendix A (cont.).

Dam	Type	Hydraulic Height (ft)	Date Completed	Extra Notes on Construction
Frenchtown	Earth/ Rock	13	1936	nonoverflow
Dry Creek	Gravity	5	1940	
Carter Creek		8	uc	gated structure leading to a vertical shaft
Chapman	Gravity/ Earth	13	1971	
Fryingpan	Gravity/ Earth	14	1971	
Halfmoon Creek	Gravity/ Earth	17	uc	
Hunter Creek		10	uc	gated structure leading to a vertical shaft
Ivanhoe	Gravity	10		
Lily Pad		9	1973	concrete vertical shaft, embankment interceptor
Middle Cunningham Creek		10	uc	gated structure leading to a vertical shaft
Midway Creek		12	uc	gated structure leading to a vertical shaft
Mormon Creek		10	uc	gated structure leading to a vertical shaft
No Name Creek		13	uc	gated structure leading to a vertical shaft
North Cunningham Creek		12	uc	concrete drop inlet with embankment dike
North Fork		13	uc	concrete drop inlet with embankment dike
Sawyer		6	1973	concret drop inlet with dike
South Cunningham Creek		12	uc	concrete drop inlet with embankment dike
South Fork	Gravity/ Earth	13	1971	
Grand Valley	Gravity	14	1916	ogee-gated weir
Savage Rapids	Gravity/ Multiple Arch Weir	30	1955	stoplogged crest
Hammond	Rock/ Earth	12	1962	
Upper Slavin	Slab + Buttress	8	1958	
Yellowstone River	Gravity	8	1957	
Anderson-Rose	R/C Slab + Buttress	12	1921	
Lost River	Arch/ Earth	26	1912	
Malone	Concrete Gate/ Earth	18	1923	
Miller	Gravity/ Earth	5	1924	removable crest
Sweetwater	Rock	8	1948	concrete crest wall
Webb Creek	Rock	10	1948	concrete crest wall
Lower Yellowstone	Rock/Timber-crib/ Earth	4	1910	
Angostura	Gravity	5	1958	
Isleta	Concrete Gate	5	1955	
San Acacia	Concrete Gate	8	1958	
Dodson	Timbercrib/ Concrete weir cap/ Earth	23	1910	movable crest

Appendix A (cont.).

Dam	Type	Hydraulic Height (ft)	Date Completed	Extra Notes on Construction
Paradise	Gravity/ Earth	14	1966	ogee overflow weir
St. Mary	Gravity	6	1915	
Swift Current	Earth/ Rock	13	1915	also timber-crib core; nonoverflow
Vandalia	R/C slab + buttress/ Earth	27	1917	movable crest
Cascade Creek	Rockfilled log-crib weir	6	1937	
Cross Cut	Gravity	10	1938	
Dunlap	Gravity/ Earth	6	1945	
Duchesne Feeder Canal	Gravity/ Earth	6	1939	
Bretch	Gravity/ Earth	35	1978	
Carson River	Concrete Gate	14	1905	
Derby	Concrete Gate/ Earth	15	1905	
Dry Spotted Tail	Steel sheet pile/ Earth	13	1954	
Horse Creek	Gravity/ Earth	6	1923	
Tub Springs Creek	Steel sheet pile/ Earth	9	1954	
Whalen	Gravity/ Earth	11	1909	
Salmon Creek	Gravity/ Earth	5	1906	
Northside	Gravity	3	1913	removable crest
Rainbow	Arch	29	1914	
Palo Verde	Gravity/ Earth	46	1957	
Fire Mountain	Timber sheet piling/ Rock	11	1950	
Superior-Courtland	Gravity/ Earth	8	1950	
Cambridge	Gravity/ Earth	2	1949	
Bartley	Gravity/ Earth	3	1954	
Culbertson	Concrete Gate/ Earth	7	1959	
Red Willow Creek	Baffled Apron Weir/ Earth	11	1963	
James	Gravity/ Earth	20	1964	
Almena	Gravity/ Earth	19	1967	
Arcadia	Concrete Gate/ Earth	8	1962	

Appendix A (cont.).

Dam	Type	Hydraulic Height (ft)	Date Completed	Extra Notes on Construction
Milburn	Gravity/ Earth	13	1956	ogee-gated weir
Woodston	Gravity/ Earth	14	1959	
Barretts	Concrete Gate/ Earth	10	1963	
Wind River	Gravity/ Earth	19	1923	
Duchesne	Rock	17	1952	concrete core wall
Murdock	Gravity/ Earth	19	1950	
Weber-Provo	Gravity/ Earth	19	1930	
Leasburg	Gravity/ Earth	7	1907	
Mesilla	Gravity	10	1916	radial gate structure
Percha	Gravity/ Earth	8	1918	
Riverside	Gravity	8	1928	radial gate structure
Antelope Creek		7	1966	stream drop inlet
Ashland Laterial	Gravity/ Earth Dike	5	1959	
Beaver Dam Creek	Rock	4	1960	concrete core wall
Conde Creek	Gravity/ Rock	4	1958	
Daley Creek	Rock	4	1960	timber core wall
Dead Indian	Gravity/ Rock	4	1958	
Dry Creek	Gravity	9	1967	stoplogged crest
Little Beaver Creek	Rock	9	1959	concrete core wall
Oak Street	Gravity	5	1961	stoplogged crest
Phoenix Canal	Gravity	5	1960	stoplogged crest
Soda Creek	Earth	13	1959	
Little Butte Creek	Rock	4	1960	timber core wall
Blanco	Gravity/ Earth	17.9	1969	
Little Oso	Gravity	14.3	1970	
Oso	Gravity/ Earth	23	1970	
Granite Reef	Gravity/ Earth	18	1908	
Corbett	Slab + Buttress/ Earth	12	1908	
Willwood	Gravity/ Earth	41	1924	
Smith Fork	Gravity/ Earth	10	1962	
Putah	Gravity/ Earth	10	1959	
Indian Creek Crossing	Earth	5	1913	
Spanish Fork	Gravity	13	1908	
Fort Shaw	Rock Overflow	9	1908	

Appendix A (cont.).

Dam	Type	Hydraulic Height (ft)	Date Completed	Extra Notes on Construction
Sun River	Arch	114	1915	
Feed Canal	Concrete, Rock, Timber Weir/ Earth	4	1907	
Maxwell	Concrete, Timber-crib Weir/ Earth	4	1912	
Three Mile Falls	Arch	23	1914	
East Canal	Gravity/ Earth	8	1940	
Garnet	Rock	4	1914	concrete surfaced
Gunnison	Timber-crib/ Concrete	10	1912	
Ironstone	Concrete Gate	13	1962	
Loutzenhizer	Gravity	9	1970	broadcrested, concrete apron
Montrose and Delta		8	1963	gated spillway
Selig	Pile and Timber	10	1914	concrete apron, removable crest
Bully Creek	Rock	4	1964	with timber cutoff
Harper	Concrete Gate/ Earth	12	1929	
Vermejo	Slab + Buttress/ Earth	5	1955	
Robles	Rock	13	1958	timber cutoff wall
Marble Bluff	Earth	22	1975	
Ogden Valley		6	1964	gated spillway
Slaterville	Concrete Gate/ Earth	8	1957	
Stoddard	Concrete Gate	8	1956	
Easton	Gravity	43	1929	movable crest
Prosser	Gravity	7	1933	
Roza	Gravity	34	1939	movable crest
Sunnyside	Gravity/ Earth	6	1907	
Tieton	Gravity/ Earth	3	1908	
Laguna	Rock	10	1909	concrete surfaced

Note: most dams labeled "gravity" were merely called "concrete (weir)" in text
Also: "earth" many times means "embankment wing(s)"
uc=under construction at time "Project Data" book was completed

APPENDIX B

Appendix B. - Annualized Loss of Life For Various Dams

Name of Dam	Dam Type	Status of Analysis	Load Case	Event Probability for Max. Annualized Loss of Life	Minimum (or low end) Annualized Loss of Life	Median Annualized Loss of Life	Maximum (or high end) Annualized Loss of Life	Notes
O'Sullivan	Embankment	screening level	Static	3.30E-05	0	▨	1.07E-03	Hydrologic failures are operational only.
		risk assessment	Hydrologic	▨	▨	▨	▨	
			Seismic	7.01E-05	2.75E-03	▨	2.08E-02	
Whiskeytown	Embankment		Static	n/a	3.80E-04	7.90E-04	1.40E-03	No failure modes for seismic loads.
		risk assessment	Hydrologic	n/a	8.70E-06	1.50E-05	1.50E-05	
			Seismic	▨	▨	▨	▨	
Elephant Butte	Concrete (gravity)	screening level	Static	▨	▨	4.36E-02	▨	One figure given for each failure mode.
		risk assessment	Hydrologic	▨	▨	3.16E-03	▨	
			Seismic	▨	▨	3.23E-02	▨	
East Park	Concrete (arch)	screening level	Static		1.20E-05	▨	5.00E-03	
		risk assessment	Hydrologic		1.76E-03	▨	3.52E-01	
			Seismic		3.31E-07	▨	1.58E-04	
Willow Creek	Embankment		Static	▨	▨	▨	▨	Only seismic modes taken into account.
		risk assessment	Hydrologic	▨	▨	▨	▨	Figures taken from reservoir elevation of
			Seismic	1.10E-04	▨	8.92E-4 (Ave)	1.02E-03	4139 to 4142 feet.
Hungry Horse	Concrete (arch)	screening level	Static	1.00E-04	1.10E-04	2.50E-02	4.90E-02	
		risk assessment	Hydrologic	2.30E-06	4.40E-06	2.10E-05	2.10E-04	May not be complete.
			Seismic	4.80E-05	1.80E-03	3.30E-03	1.40E-02	
Deadwood	Concrete (arch)		Static	1.01E-03	1.00E-02	2.40E-02	8.70E-02	
		risk assessment	Hydrologic	1.84E-05	4.00E-06	3.40E-05	2.60E-04	
			Seismic	7.34E-04	1.10E-02	3.30E-02	7.10E-02	
Warm Springs	Concrete (arch)		Static	5.00E-05	3.74E-05	▨	1.87E-03	<Varying response probability.
		risk assessment	Hydrologic	1.70E-04	1.80E-05	▨	1.46E-03	<Varying load probability.
			Seismic	3.49E-06	2.57E-03	▨	1.03E-04	<Varying failure probability.
Avalon	Embankment	risk assessment	Static	▨	▨	▨	▨	Picked high end and low end of a group
	(zoned earthfill)	during CAS	Hydrologic	5.84E-03	0	▨	5.60E-02	of scenarios.
			Seismic	▨	▨	▨	▨	
Pueblo	Concrete &	risk assessment	Static	2.01E-04	▨	8.30E-02	▨	Event probability is base case referring
	Embankment	DRAFT!!	Hydrologic	2.18E-04	▨	1.20E-01	▨	to the average Loss of Life
			Seismic	2.00E-09	▨	9.10E-07	▨	
Salmon Lake	Earthfill	risk assessment	Static	5.10E-05	2.60E-04	1.10E-03	3.90E-03	Middle figure is considered "best estimate"
			Hydrologic	4.70E-06	0	0	0	
			Seismic	6.70E-05	1.30E-03	5.80E-03	2.25E-02	<Average of given range
Conconully	Earthfill	risk assessment	Static	4.00E-05	1.70E-04	3.40E-04	7.00E-04	Middle figure is considered "best estimate"
			Hydrologic	2.20E-04	3.60E-07	3.20E-06	2.70E-05	
			Seismic	4.10E-05	1.20E-04	5.50E-04	1.60E-03	

APPENDIX C

Appendix C1. - BOR Earth Dams - period of construction v. height

	<1930	1930-1960			1960-	
<50 ft.	Big Meadows	Anita	Picacho South		Arthur V. Watkins	Kitson
	Clear Lake	Carpinteria	Stublefield		Atkinson	Lambert
	Deaver	Crane Prairie	Terminal		Bonham	Little Meadows
	Eden	Crescent Lake	Vermejo Project #13		Cottonwood	Never Sweat
	Lower Lake Alice	Dutch Slough	Vermejo Project #2		Decamp	Silver Lake
	Pilot Butte 1-3	Fish Lake			Forty Acre	Wintering
	Upper Lake Alice	Picacho North			Gray Reef	
50-100 ft.	Avalon	Big Sandy	Keene Creek		Agate	Palmetto Bend
	Bumping Lake	Box Butte	Lovewell		Conconully	Rye Patch
	Deer Flat	Bull Lake	Midview		Forebay	Senator Wash
	Jackson Lake	Como	Olympus		Hollow	South Bottle
	Lake Sherburne	Dickinson	Shadow Mountain		Hollow	Squaw Lake
	McMillan	Flatiron	Unity		Hyatt Prairie	Yellowtail Afterbay
	Minidoka	Fruitgrowers	Wasco		Lewiston	
	Salmon Lake	Helena Valley			Mt. Elbert Forebay	
	Strawberry	Huntington North			North Bottle	
	Willow Creek (MT)	Island Park			O'Neill	
100-300 ft.	American Falls	Agency Valley	Horseshoe	Sly Park	Arbuckle	Meeks Cabin
	Belle Fourche	Alcova	Horsetooth	Sly Park Saddle	Arthur R. Bowman	Merrit
	Cold Springs	Angostura	Howard Prairie	Soldier Canyon	Bully Creek	Nambe Falls
	Guernsey	Boca	Hyrum	Spring Canyon	Calamus	Norman
	Keechslus	Bonny	Jackson Gulch	Sumner	Causey	Norton
	Lahontan	Boysen	Jamestown	Taylor Park	Cheney	Paonia
	McKay	Bradbury	Kachess	Tiber	Choke Canyon	Prosser
	Minatare	Caballo	Keyhole	Trenton	Clark Canyon	Pueblo
		Carter Lake	Keyhole	Twitchell	Contra Loma	Red Willow
		Cascade	Kirwin	Upper Stillwater	Crawford	Redfleet
		Cedar Bluff	Lauro	Vallecito	Currant Creek	Ridgeway
		Cle Elum	Marshall Ford	Vega	Cutter	Rifle Gap
		Davis	Martinez	Wanship	Davis Creek	San Justo
		Deer Creek	Medicine Creek	Webster	Emigrant	Sanford
		Deerfield	Moon Lake	Wickiup	Fontenelle	Scoggins
		Dixon Canyon	Newton	Willow Creek (CO)	Foss	Sherman
		Dry Falls	North		Glen Elder	Silver Jack
		Echo	Ochoco		Heron	Soldier Creek
		El Vado	Ortega		Joes Valley	Spring Creek
		Enders	O'Sullivan		Jordanelle	Stampede
		Fort Cobb	Pactola		Lemon	Starvation
		Fresno	Palisades		Little Panoche	Stateline
		Glen Anne	Pineview		Little Wood River	Steinaker
		Glendo	Pinto		Los Banos	Sugar Loaf
		Granby	Platoro		Lost Creek	Sugar Pine
		Grassy Lake	Rattlesnake		Mann Creek	Twin buttes
		Haystack	Scofield		Mason	Whiskeytown
		Heart Butte	Shadehill			
300 +ft.	Tieton	Anderson Ranch	Folsom		Blue Mesa	Teton
		Casitas	Green Mountain		Navajo	Trinity
					Ruedi	

Appendix C2. - BOR Rockfill Dams - period of construction v. height

	<1930	1930-1960	1960 +
<50 ft.	Clear Lake	Four Mile Lake Fish Lake	none
50-100 ft.	none	none	Hyatt Prairie
100-300 ft.	none	Vega Horseshoe	Heron Meeks Canyon Sugar Pine Mason

Appendix C3. - BOR Arch Dams - period of construction v. height

	< 1930	1930-1960	1960 +
<50 feet	none	none	none
50 -100 ft.	Gerber	none	none
	Clear Creek		
100 -300 ft.	East Park	Bartlett	Anchor
	Gibson	Deadwood	East Canyon
	Pathfinder*	Mormon Flat	Mountain Park
	Sun River Diversion	Seminoe	Nambe Falls
	Theodore Roosevelt**	Stewart Mountain	
	Warm Springs		
300+ ft.	Arrowrock	Hoover	Crystal
	Buffalo Bill	Hungry Horse	Flaming Gorge
	Horse Mesa	Owyhee	Glen Canyon
		Parker	Morrow Point
		Monticello	Yellowtail

* masonry
** Cyclopean

Appendix C4. - BOR Gravity/Buttress Dams - period of construction v. height

	< 1930	1930 -1960	1960 +
<50 ft.	Belle Fourche	none	none
	Lake Tahoe		
50-100 ft.	Jackson Lake	Nimbus	Yellowtail Afterbay
	Minidoka	Thief Valley	
100 - 300 ft.	American Falls	Altus*	Pueblo
	Black Canyon Div.	Angostura	
	Stony Gorge	Canyon Ferry	
		Keswick	
		Kortes	
		Marshall Ford	
300 + ft.	Elephant Butte	Friant	none
		Shasta	
		Grand Coulee	
		Folsom	

* masonry faced

APPENDIX D

Appendix D. - Event Probabilities

Legend:

Names

A=Avalon
C=Conconully
D=Deadwood
EP=East Park
LC=Lost Creek
O=O'Sullivan
SC=Spring Creek
SL=Salmon Lake
Wa=Wasco

EB=Elephant Butte
HH=Hungry Horse
NF=Nambe Falls (arch and earth)
P=Pueblo (buttress and earth)
WC=Willow Creek
Wh=Whiskeytown
WS=Warm Springs
^ --> no event tree present
~ --> figure given in general static

Failure Modes

OT= Overtopping
FD= Foundation
PI= Piping
SL= Sliding
ST= Structural
SP= Spillway
EQ= Earthquake
OP= Operations
▨ Data not available

Load Case	Mode	Dam	Median Event Probabilities (load prob*failure prob)	Average for Failure Mode
STATIC	GENERAL	Wh	6.70E-06	6.70E-06
PI	Piping-Embankment	Wh~	▨	
		NF (earth)	5.00E-06	
		P (earth)	9.97E-07	
		Wa^	▨	
	res<740	SC*	7.60E-07	
		SL	7.80E-06	
		C	1.10E-05	5.11E-06
SL	Instability D/S Slope	Wa^	▨	
		SL	1.10E-06	
		C	1.90E-06	
		NF (earth)	1.00E-07	1.03E-06
FD	Concrete Dam foundation failure	HH	5.10E-05	
		NF (arch)	1.00E-06	
		EP	1.00E-06	1.77E-05
ST	Structural Failure Concrete Dam	HH	5.50E-07	
	general	WS	1.10E-05	
	same as foundation failure	EP	1.00E-06	
		NF (arch)	1.00E-08	3.14E-06
OP	Misoperation	NF	0.00E+00	0.00E+00
SP	Spillway failure (gate or structural)	HH	5.50E-05	
		EP	1.00E-06	2.80E-05
OP	Vandalism	HH	1.00E-05	1.00E-05
PI	Internal Erosion	O	3.30E-05	
	res elevation=4142-4130	WC	1.01E-05	1.44E-05
ST	Arch rupture	D	8.50E-04	8.50E-04
FD	Abutment movement &/or failure	D	2.26E-02	
	uplift	EB	2.00E-05	
PI		P (earth)	9.97E-09	7.54E-03
PI	Outlet Works failure	Wa^	▨	▨
	piping	SL	5.30E-06	
	piping	C	2.90E-06	
	backward erosion and u/s collapse of dam (res<740)	SC*	7.60E-07	
	piping thru d/s and dam collapse (res<740)	SC*	4.00E-08	2.25E-06
PI	Blowout of Downstream Toe	Wa^	▨	▨
PI	Dike failure	EB	5.00E-05	
		EP	1.00E-05	3.00E-05
ST	Dam failure due to high uplift pressures	EB	1.00E-05	1.00E-05
OP	Mechanical	P	0.00E+00	0.00E+00
SL	Embankment foundation sliding	P (earth)	9.97E-09	
	res>780	SC*	8.00E-08	4.50E-08
PI	Seepage in channel plug (spurt)	P (buttress)	9.97E-05	9.97E-05
PI	Bessemer Ditch Piping	P (earth)	9.97E-07	9.97E-07
PI	Embankment contact seepage/piping	P (earth)	9.97E-08	9.97E-08
FD	Shale seam beneath the concrete dam	P (buttress)	9.97E-05	9.97E-05
FD	Foundation Failure	SL	2.90E-06	
		C	4.40E-06	3.65E-06

Appendix D (cont.).

Load Case	Mode	Dam	Median Event Probabilities	Average for Failure Mode
HYDROLOGIC	GENERAL	Wh	2.90E-06	2.90E-06
OT	Wave Erosion failure	NF* (earth)	1.27E-07	1.40E-06
		D	4.08E-06	
		P* (earth)	0.00E+00	
SP	Spillway failure	A	1.60E-06	2.43E-05
		WC*	8.00E-05	
		Wh#	▨	
		EB*	0.00E+00	
	structural	EP*	1.60E-05	
	erosion of foundation	EP*	2.40E-05	
OT	Overtopping of Dikes	Wh#	▨	0.00E+00
		EP*	0.00E+00	
SP	Spillway Erosion & Dike failure	WC*	3.89E-05	3.89E-05
PI	Slope Stability/Seepage/Piping failure of dikes	EP*	0.00E+00	0.00E+00
OT	Spillway & Dam Overtopping failure	WC*	3.40E-10	3.40E-10
OT	Overtopping failure of dam	NF* (earth)	1.27E-05	6.67E-05
		HH*	8.00E-09	
		LC^	▨	
		Wh#	▨	
		A	4.46E-04	
		Wa^	▨	
	December standard	SL	5.10E-07	
	thunderstorm	SL	0	
	December standard	C	3.00E-05	
	thunderstorm	C	3.20E-06	
	camber	SC*	1.09E-04	
		EB*	0.00E+00	
FD	Failure of Abutment	HH*	0.00E+00	5.94E-06
	left abut. failure	D	3.06E-05	
	right abut. failure	D	2.04E-06	
		WS*	0.00E+00	
	uplift	EB*	2.99E-06	
		P* (earth)	0.00E+00	
SP	Rockfall	HH*	1.00E-06	1.00E-06
SP	Spillway Gate/Abutment failure	HH*	0.00E+00	0.00E+00
OT	Overtopping/Abutment failure	HH*	0.00E+00	0.00E+00
PI	Flow through top embankment materials	Wh#	▨	▨
SP	Training Wall failure	A	6.00E-04	6.00E-04
OT	Overtopping of training wall	A	1.48E-04	1.48E-04
ST	Arch ruptures	NF* (arch)	9.42E-09	9.42E-09
PI	Higher heads from increases in seepage and piping	Wa^	▨	▨
SP	Erosion of Concrete due to spillway discharge	WS*	0.00E+00	0.00E+00
PI	Piping failure	A	3.70E-04	3.70E-04
PI	Dike failure	EB*	3.00E-05	3.00E-05
ST	Dam failure due to high uplift pressures	EB*	1.50E-06	1.50E-06
FD	Foundation failure	EP*	0.00E+00	0.00E+00
ST	Structural failure of dam	EP*	0.00E+00	0.00E+00
FD	Erosion of foundation	EP*	0.00E+00	0.00E+00
FD	Buttress foundation	P* (buttress)	1.40E-05	1.40E-05

^ --> no event tree present
* --> least loading condition
# --> figure given in general hydrologic

Appendix D (cont.).

Load Case	Mode	Dam	Median Event Probabilities	Average for Failure Mode
SEISMIC EQ	Dam failure (structural)	HH*	5.50E-07	
		LC^	▨	
		WS*	1.01E-05	
		EB*	1.00E-05	5.16E-06
		EP*	0.00E+00	
	Cracks	NF* (earth)	9.50E-08	
	transverse	SC*	2.00E-09	
		Wa^	▨	4.85E-08
	Cracking & Erosion (Embankment)	LC^	▨	▨
		Wh~	▨	▨
	Gap forms	NF* (arch)	2.53E-08	2.53E-08
	Arch flattens	NF* (arch)	2.53E-08	2.53E-08
	Arch ruptures	D	4.52E-03	4.52E-03
	Arch collapses	NF* (arch)	1.27E-09	1.27E-09
	Spillway failure	NF* (arch)	1.46E-07	
	gate	HH*	5.50E-06	
	rockfall	HH*	3.00E-06	
	cyl. gate	EB*	1.00E-04	
	both structural and foundation	EP*	0.00E+00	2.17E-05
	Liquefaction	LC^	▨	
	res elevation=4139-4142	WC*	1.48E-05	
		Wh~	▨	
		Wa^	▨	1.48E-05
	Liquefaction slump	NF* (earth)	1.90E-08	1.90E-08
	Slumps & overtops	NF* (earth)	0.00E+00	
		WC%	▨	0.00E+00
	Slumping & Cracking	WC%	▨	▨
	Tensile Stresses failure	NF(	▨	▨
	Foundation failure	EP*	1.00E-07	
	spillway intake	HH*	5.50E-06	
	full breach	HH*	1.00E-06	
	left abut.	D	3.00E-03	
	right abut.	D	3.10E-05	
		EB*	4.00E-05	5.13E-04
	Thrust Block failure (sliding)	D	1.34E-06	
	combined with foundation failure	NF* (arch)	1.46E-08	6.77E-07
	Penstock failure	HH*	3.50E-06	
		EB*	1.00E-06	2.25E-06
	Outlet Works Pipe failure	HH*	1.00E-06	1.00E-06
	Rapid Loss of Dam *(res elevation > 1040)*	O*	3.60E-06	3.60E-06
	Slow Loss of Dam *(res elevation > 1040)*	O*	2.16E-06	2.16E-06
	Layers Continuous and Saturated	LC^	▨	▨
	Seepage	Wa^	▨	▨
	Seepage erosion through cracks	SL	8.40E-06	
		C	6.50E-06	7.45E-06
	Overtopping	SL	1.30E-06	
		C	7.20E-06	4.25E-06
	Abutment movement &/or failure	WS*	2.01E-06	2.01E-06
	Landslide	WS*	4.03E-09	4.03E-09
	Dike failure	EP*	0.00E+00	0.00E+00
	Separation between concrete & embankment dams	P	2.00E-13	2.00E-13
	Sliding on shale seam beneath concrete dam	P (buttress)	2.00E-09	2.00E-09
	Embankment slope failure	P (earth)	2.00E-14	2.00E-14
	Flow Failures *(res>780)*	SC*	6.00E-09	6.00E-09

* –> least loading condition (WS-lowest load condition causing nonzero figures)
~ –> possible failure modes given w/o probabilities, because they would have been negligible
(–> is broken down
^ –> no event tree present
% –> WC has potential to liquefy then failure modes from that. Figures were only given for liquefaction.

APPENDIX E

Appendix E. - Historical vs. Risk Assessment Probabilities

Dam	Type	Date Completed	Height (ft)	Failure mode	Von Thun Probability	Risk Assessment Probability
Hungry Horse	Arch	1953	564	OT	0	4.00E-09
				FD	0	2.55E-05
				PI	0	
				SL	0	
				ST	0	5.50E-07
				SP	0	1.87E-05
				EQ	0	2.86E-06
O'Sullivan	Earth	1949	200	OT	0	
				FD	3.00E-04	
				PI	0	3.30E-05
				SL	0	
				ST	0	
				SP	0	
				EQ	0	2.88E-06
Willow Creek	Earth	1912	84	OT	3.80E-04	3.40E-10
				FD	0	
				PI	1.28E-03	1.01E-05
				SL	2.60E-04	
				ST	0	
				SP	0	5.95E-05
				EQ	0	1.48E-05
Whiskeytown	Earth	1963	282	OT	0	
				FD	0	
				PI	0	
				SL	0	
				ST	6.00E-04	
				SP	0	
				EQ	0	
Avalon	Earth	1907	58	OT	3.80E-04	2.97E-04
				FD	0	
				PI	1.28E-03	3.70E-04
				SL	2.60E-04	
				ST	0	
				SP	0	3.01E-04
				EQ	0	
Deadwood	Arch	1931	165	OT	0	4.08E-06
				FD	0	7.54E-03
				PI	0	
				SL	0	
				ST	0	8.50E-04
				SP	6.60E-04	
				EQ	0	1.89E-03

Appendix E (cont.).

Dam	Type	Date Complete	Height (ft)	Failure mode	Von Thun Probability	Risk Assessment Probability
Warm Springs	Arch	1919	106	OT	0	
				FD	0	0
				PI	0	
				SL	0	
				ST	0	1.10E-05
				SP	0	0
				EQ	0	4.04E-06
Elephant Butte	Gravity	1916	301	OT	0	0
				FD	0	1.15E-05
				PI	0	4.00E-05
				SL	0	
				ST	0	5.75E-06
				SP	0	0
				EQ	0	3.78E-05
East Park	Arch	1910	139	OT	0	0
				FD	0	3.33E-07
				PI	0	5.00E-06
				SL	0	
				ST	0	5.00E-07
				SP	0	1.37E-05
				EQ	0	2.50E-08
Nambe Falls	1. Earth	1976	140	OT	0	6.41E-06
				FD	0	
				PI	0	5.00E-06
				SL	0	1.00E-07
				ST	6.00E-04	
				SP	0	
				EQ	0	3.80E-08
	2. Arch	1976	150	OT	0	
				FD	0	1.00E-06
				PI	0	
				SL	0	
				ST	0	9.71E-09
				SP	0	
				EQ	0	4.25E-08
Spring Creek	Earth	1963	196	OT	0	1.09E-04
				FD	0	
				PI	0	5.20E-07
				SL	0	8.00E-08
				ST	6.00E-04	
				SP	0	
				EQ	0	4.00E-09

Appendix E (cont.).

Dam	Type	Date Complete	Height (ft)	Failure mode	Von Thun Probability	Risk Assessment Probability
Pueblo	1. Earth	1975	250	OT	0	0
				FD	0	0
				PI	0	7.72E-07
				SL	0	9.97E-09
				ST	6.00E-04	
				SP	0	
				EQ	0	2.00E-14
	2. Buttres	1975	250	OT	0	
				FD	0	5.68E-05
				PI	0	9.97E-05
				SL	0	
				ST	0	
				SP	0	
				EQ	0	2.00E-09
Conconully	Earth	1910	72	OT	3.80E-04	1.66E-05
				FD		4.40E-06
				PI	1.28E-03	7.00E-06
				SL	2.60E-04	1.90E-06
				ST		
				SP		
				EQ		6.85E-06
Salmon Lake	Earth	1921	54	OT	3.80E-04	2.55E-07
				FD		2.90E-06
				PI	1.28E-03	6.55E-06
				SL	2.60E-04	1.10E-06
				ST		
				SP		
				EQ		4.85E-06

APPENDIX F

Appendix F. - Key Parameters & Individual Risks

Legend

☐ --> outlier

* --> least loading condition

A=Avalon
D=Deadwood
EB=Elephant Butte
EP=East Park
HH=Hungry Horse
LC=Lost Creek
NF=Nambe Falls (arch and earth)
O=O'Sullivan
P=Pueblo (buttress and earth)
SC=Spring Creek
SL=Salmon Lake
Wa=Wasco
WC=Willow Creek
Wh=Whiskeytown
WS=Warm Springs

Failure Mode	Von Thun Failure Probabilities	Risk Assessment Probabilities Averages	Risk Assessment Probabilities	Dam
Overtopping	1.57E-04	4.71E-05	1.27E-07	NF* (earth)
			4.08E-06	D
			0	P* (earth)
			0	EP*
			3.40E-10	WC*
			1.27E-05	NF* (earth)
			8.00E-09	HH*
			4.46E-04	A
			5.10E-07	SL
			0	SL
			3.00E-05	C
			3.20E-06	C
			1.09E-04	SC*
			0	EB*
			0	HH*
			1.48E-04	A
Foundation	1.88E-05	1.42E-03	5.10E-05	HH
			1.00E-06	NF (arch)
			1.00E-06	EP
			$\boxed{\text{2.26E-02}}$	D
			2.00E-05	EB
			2.90E-06	SL
			4.40E-06	C
			0	HH*
			3.06E-05	D
			2.04E-06	D
			0	WS*
			2.99E-06	EB*
			0	P* (earth)
			0	EP*
			0	EP*
			1.40E-05	P* (buttress)

Appendix F (cont.).

Failure Mode	Von Thun Failure Probabilities	Risk Assessment Probabilities Averages	Risk Assessment Probabilities	Dam
Piping	9.51E-05	3.19E-05	5.00E-06	NF (earth)
			9.97E-07	P (earth)
			7.60E-07	SC*
			7.80E-06	SL
			1.10E-05	C
			3.30E-05	O
			1.01E-05	WC
			9.97E-09	P (earth)
			5.30E-06	SL
			2.90E-06	C
			7.60E-07	SC*
			4.00E-08	SC*
			5.00E-05	EB
			1.00E-05	EP
			9.97E-05	P (buttress)
			9.97E-07	P (earth)
			9.97E-08	P (earth)
			0.00E+00	EP*
			3.70E-04	A
			3.00E-05	EB*
Sliding	6.90E-06	6.38E-07	1.10E-06	SL
			1.90E-06	C
			1.00E-07	NF (earth)
			9.97E-09	P (earth)
			8.00E-08	SC*
Structural	3.52E-05	9.71E-05	5.50E-07	HH
			1.10E-05	WS
			1.00E-06	EP
			1.00E-08	NF (arch)
			8.50E-04	D
			1.00E-05	EB
			9.42E-09	NF* (arch)
			1.50E-06	EB*
			0	EP*
Spillway	8.86E-06	6.40E-05	5.50E-06	HH
			1.00E-06	EP
			1.60E-06	A
			8.00E-05	WC*
			0	EB*
			1.60E-05	EP*
			2.40E-05	EP*
			3.89E-05	WC*
			1.00E-06	HH*
			0	HH*
			6.00E-04	A
			0	WS*

Appendix F (cont.).

Failure Mode	Von Thun Failure Probabilities	Risk Assessment Probabilities Averages	Risk Assessment Probabilities	Dam
Earthquake	6.90E-06	1.85E-04	5.50E-07	HH*
			1.01E-05	WS*
			1.00E-05	EB*
			0.00E+00	EP*
			9.50E-08	NF* (earth)
			2.00E-09	SC*
			2.53E-08	NF* (arch)
			2.53E-08	NF* (arch)
			4.52E-03	D
			1.27E-09	NF* (arch)
			1.46E-07	NF* (arch)
			5.50E-06	HH*
			3.00E-06	HH*
			1.00E-04	EB*
			0.00E+00	EP*
			1.48E-05	WC*
			1.90E-08	NF* (earth)
			0.00E+00	NF* (earth)
			1.00E-07	EP*
			5.50E-06	HH*
			1.00E-06	HH*
			3.00E-03	D
			3.10E-05	D
			4.00E-05	EB*
			1.34E-06	D
			1.46E-08	NF* (arch)
			3.50E-06	HH*
			1.00E-06	EB*
			1.00E-06	HH*
			3.60E-06	O*
			2.16E-06	O*
			8.40E-06	SL
			6.50E-06	C
			1.30E-06	SL
			7.20E-06	C
			2.01E-06	WS*
			4.03E-09	WS*
			0.00E+00	EP*
			2.00E-13	P
			2.00E-09	P (buttress)
			2.00E-14	P (earth)
			6.00E-09	SC*

APPENDIX G

Appendix G1. - BOR Earth Dams Failure Probabilities - period of construction v. height

		<1930		1930-1960		1960 +	
	Failure	**Von Thun**	**R.A.**	**Von Thun**	**R.A.**	**Von Thun**	**R.A.**
<50 ft.	OT	1.70E-04		4.00E-05		2.10E-04	
	FD	1.00E-05		1.00E-05			
	PI	7.00E-05		1.00E-05		4.00E-05	
	SL						
	ST	3.00E-05		1.00E-05		8.00E-05	
	SP	1.00E-05					
	EQ	1.00E-05		1.00E-05			
50-100 ft.	OT	3.80E-04	8.97E-05			3.00E-04	
	FD		3.65E-06	1.20E-04			
	PI	1.28E-03	6.79E-05	1.20E-04		6.10E-04	
	SL	2.60E-04	1.50E-06				
	ST						
	SP		1.80E-04				
	EQ		7.64E-06				
100-300 ft	OT	6.80E-04					3.04E-05
	FD			3.00E-04			4.98E-07
	PI	6.80E-04			3.30E-05		1.18E-06
	SL						6.33E-08
	ST					6.00E-04	
	SP						
	EQ				2.88E-06		1.74E-08
300+ ft.	OT						
	FD						
	PI					5.20E-03	
	SL	NO	DAMS				
	ST						
	SP						
	EQ						

NOTE: Data for Whiskey Creek Dam is not included in these tables.

Appendix G2. - BOR Rockfill Dams Failure Probabilities - period of construction v. height

	<1930			1930-1960			1960 +		
	Failure	**Von Thun**	**R.A.**	**Failure**	**Von Thun**	**R.A.**	**Failure**	**Von Thun**	**R.A.**
<50 ft.	OT	2.70E-03		OT			OT		
	FD			FD			FD		
	PI			PI			PI		
	SL			SL			SL		
	ST			ST			ST		
	SP			SP			SP		
	EQ			EQ			EQ		
50-100 ft.	OT			OT			OT		
	FD			FD			FD		
	PI	2.30E-03		PI			PI		
	SL			SL			SL		
	ST	1.10E-03		ST			ST		
	SP			SP			SP		
	EQ			EQ			EQ		
100-300 ft	OT	7.20E-03		OT			OT		
	FD			FD			FD		
	PI			PI			PI		
	SL			SL			SL		
	ST	1.80E-03		ST			ST		
	SP			SP			SP		
	EQ			EQ			EQ		
300+ ft.	OT			OT			OT		
	FD			FD			FD		
	PI			PI			PI		
	SL			SL			SL		
	ST			ST			ST		
	SP			SP			SP		
	EQ			EQ			EQ		

Appendix G3. - BOR Arch Dams Failure Probabilities - period of construction v. height

		<1930			1930-1960			1960 +	
	Failure	**Von Thun**	**R.A.**	**Failure**	**Von Thun**	**R.A.**	**Failure**	**Von Thun**	**R.A.**
<50 feet	OT			OT			OT		
	FD			FD			FD		
	PI			PI			PI		
	SL			SL			SL		
	ST	5.00E-04		ST			ST		
	SP			SP			SP		
	EQ			EQ			EQ		
50-100	OT			OT			OT		
	FD			FD			FD		
	PI			PI			PI		
	SL			SL			SL		
	ST	4.40E-04		ST			ST		
	SP	4.40E-04		SP			SP		
	EQ			EQ			EQ		
100-300	OT		0.00E+00	OT		4.08E-06	OT		
	FD		2.50E-07	FD		7.54E-03	FD		1.00E-06
	PI		5.00E-06	PI			PI		
	SL			SL			SL		
	ST		4.00E-06	ST		8.50E-04	ST		9.71E-09
	SP		1.03E-05	SP	6.60E-04		SP		
	EQ		1.74E-06	EQ		1.89E-03	EQ		4.25E-08
300+	OT			OT		4.00E-09	OT		
	FD			FD		2.55E-05	FD		
	PI			PI			PI		
	SL			SL			SL		
	ST			ST		5.50E-07	ST		
	SP			SP		1.87E-05	SP		
	EQ			EQ		2.86E-06	EQ		
				OP		1.00E-05			

Appendix G4. - BOR Gravity/Buttress Dams Failure Probabilities - period of construction v. height

		<1930			1930-1960			1960 +	
	Failure	**Von Thun**	**R.A.**	**Failure**	**Von Thun**	**R.A.**	**Failure**	**Von Thun**	**R.A.**
<50 ft.	OT	1.80E-04		OT			OT		
	FD			FD			FD		
	PI	1.80E-04		PI			PI		
	SL			SL			SL		
	ST			ST			ST		
	SP			SP			SP		
	EQ			EQ			EQ		
50-100 ft.	OT			OT			OT		
	FD			FD			FD		
	PI			PI			PI		
	SL			SL			SL		
	ST			ST			ST		
	SP			SP			SP		
	EQ			EQ			EQ		
100-300 ft.	OT			OT			OT		
	FD	1.20E-03		FD			FD		5.68E-05
	PI			PI			PI		9.97E-05
	SL			SL			SL		
	ST			ST			ST		
	SP			SP			SP		
	EQ			EQ			EQ		1.00E-09
300+ ft.	OT		0.00E+00	OT			OT		
	FD		1.15E-05	FD			FD		
	PI		4.00E-05	PI			PI		
	SL			SL			SL		
	ST		5.75E-06	ST			ST		
	SP		0.00E+00	SP			SP		
	EQ		3.78E-05	EQ			EQ		

APPENDIX H

Appendix H1. - BOR Earth Dams Accident Probabilities - period of construction v. height

		<1930			1930-1960			1960 +	
	Failure	**Von Thun**	**R.A.**	**Failure**	**Von Thun**	**R.A.**	**Failure**	**Von Thun**	**R.A.**
<50 ft.	OT	3.00E-05		OT	1.00E-05		OT	4.00E-05	
	FD	1.00E-05		FD			FD		
	PI	3.00E-05		PI			PI	1.60E-04	
	SL	1.00E-05		SL	1.00E-05		SL		
	ST	2.00E-05		ST	1.00E-05		ST		
	SP			SP			SP	4.00E-05	
	EQ			EQ			EQ		
50-100 ft.	OT	1.30E-04	8.97E-05	OT			OT		
	FD	7.60E-04	3.65E-06	FD	4.90E-04		FD	1.82E-03	
	PI	2.60E-04	6.79E-05	PI	1.20E-04		PI		
	SL	1.53E-03	1.50E-06	SL	1.20E-04		SL		
	ST	8.90E-04		ST	1.20E-04		ST	3.00E-04	
	SP		1.80E-04	SP	1.20E-04		SP	3.00E-04	
	EQ	1.30E-04	7.64E-06	EQ			EQ		
100-300 ft	OT			OT			OT		3.04E-05
	FD	6.80E-04		FD	3.00E-04		FD	1.20E-03	4.98E-07
	PI	2.70E-03		PI	3.00E-04	3.30E-05	PI	6.00E-04	1.18E-06
	SL	4.70E-03		SL			SL	6.00E-04	6.33E-08
	ST	2.70E-03		ST	2.10E-03		ST	1.80E-03	
	SP	6.80E-04		SP			SP		
	EQ	1.35E-03		EQ		2.88E-06	EQ		1.74E-08
300+ ft.	OT			OT			OT		
	FD			FD			FD	5.20E-03	
	PI			PI			PI		
	SL			SL			SL		
	ST			ST			ST		
	SP			SP			SP		
	EQ			EQ			EQ		

Appendix H2. - BOR Rockfill Dams Accident Probabilities - period of construction v. height

	<1930			1930-1960			1960 +		
	Failure	Von Thun	R.A.	Failure	Von Thun	R.A.	Failure	Von Thun	R.A.
<50 ft.	OT			OT			OT		
	FD			FD			FD		
	PI			PI			PI		
	SL			SL			SL		
	ST			ST			ST		
	SP			SP			SP		
	EQ			EQ			EQ		
50-100 ft.	OT			OT			OT		
	FD	1.10E-03		FD			FD	9.30E-03	
	PI	3.40E-03		PI	6.90E-03		PI		
	SL			SL			SL		
	ST	2.30E-03		ST			ST		
	SP			SP			SP		
	EQ			EQ			EQ		
100-300 ft	OT			OT			OT		
	FD			FD			FD		
	PI			PI			PI		
	SL			SL			SL		
	ST	1.80E-03		ST	8.00E-03		ST		
	SP	1.80E-03		SP			SP		
	EQ			EQ			EQ		
300+ ft.	OT			OT			OT		
	FD			FD			FD		
	PI			PI			PI		
	SL			SL			SL		
	ST			ST	6.70E-03		ST		
	SP			SP			SP		
	EQ			EQ			EQ		

Appendix H3. - BOR Arch Dams Accident Probabilities - period of construction v. height

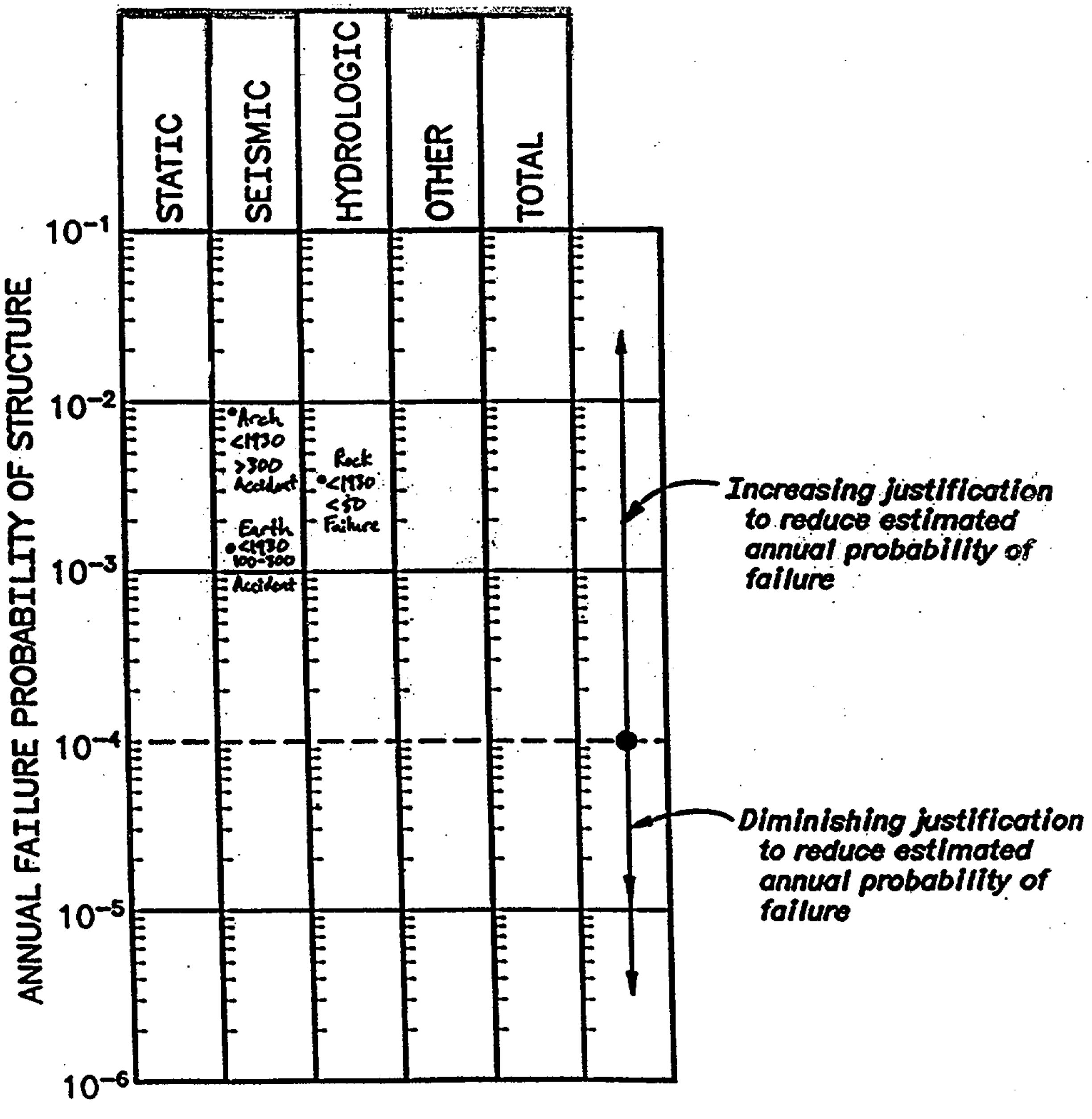
	<1930			1930-1960			1960 +		
	Failure	**Von Thun**	**R.A.**	**Failure**	**Von Thun**	**R.A.**	**Failure**	**Von Thun**	**R.A.**
<50 ft.	OT			OT			OT		
	FD			FD			FD		
	PI			PI			PI		
	SL			SL			SL		
	ST			ST			ST		
	SP			SP			SP		
	EQ			EQ			EQ		
50-100 ft.	OT			OT			OT		
	FD			FD			FD		
	PI			PI			PI		
	SL			SL			SL		
	ST	1.33E-03		ST			ST		
	SP			SP			SP		
	EQ			EQ			EQ		
00-300 ft	OT		0.00E+00	OT		4.08E-06	OT		
	FD		2.50E-07	FD		7.54E-03	FD		1.00E-06
	PI		5.00E-06	PI			PI		
	SL			SL			SL		
	ST		4.00E-06	ST	1.32E-03	8.50E-04	ST		9.71E-09
	SP	5.20E-04	1.03E-05	SP	6.60E-04		SP		
	EQ		1.74E-06	EQ		1.89E-03	EQ		4.25E-08
300+ ft.	OT			OT		4.00E-09	OT		
	FD			FD		2.55E-05	FD		
	PI			PI			PI		
	SL			SL			SL		
	ST			ST		5.50E-07	ST		
	SP			SP		1.87E-05	SP		
	EQ	9.80E-03		EQ		2.86E-06	EQ		
				OP		1.00E-05			

Appendix H4. - BOR Arch Gravity/Buttress Accident Probabilities - period of construction v. height

	<1930			1930-1960			1960 +		
	Failure	**Von Thun**	**R.A.**	**Failure**	**Von Thun**	**R.A.**	**Failure**	**Von Thun**	**R.A.**
<50 ft.	OT			OT			OT		
	FD			FD			FD		
	PI			PI			PI		
	SL	1.80E-04		SL			SL		
	ST			ST			ST		
	SP			SP			SP		
	EQ			EQ			EQ		
50-100 ft.	OT			OT			OT		
	FD			FD			FD		
	PI			PI			PI		
	SL			SL			SL		
	ST			ST			ST		
	SP			SP			SP		
	EQ			EQ			EQ		
100-300 ft	OT			OT			OT		
	FD			FD			FD		5.68E-05
	PI			PI			PI		9.97E-05
	SL			SL			SL		
	ST			ST			ST		
	SP			SP			SP		
	EQ			EQ			EQ		1.00E-09
300+ ft.	OT		0.00E+00	OT			OT		
	FD		1.15E-05	FD			FD		
	PI		4.00E-05	PI			PI		
	SL			SL			SL		
	ST		5.75E-06	ST			ST	2.50E-02	
	SP		0.00E+00	SP			SP		
	EQ		3.78E-05	EQ			EQ		

APPENDIX I

Appendix I. - Tier II Guidelines - Failure Event Probabilites



APPENDIX J

Appendix J1. - Von Thun Failure Rates for Dam failures x 10^{-4}

# of Dams in BOR	Type	Age	Height	Failure	Rate	Mode	Occurrences	# of Dams in category	Life Years
NONE	Conc-Grav	>1960	>300	ST	250	Accident	1	5	40
3	Conc-Arch	<1930	>300	EQ	98	Accident	1	2	102
1	Rock	>1960	50-100	FD	93	Accident	1	8	107
NONE	Rock	1930-1960	100-300	ST	80	Accident	3	13	376
NONE	Rock	<1930	100-300	OT	72	Failure	4	14	557
NONE	Rock	1930-1960	50-100	PI	69	Accident	1	4	145
NONE	Rock	1930-1960	>300	ST	67	Accident	1	5	150
6	Earth	>1960	>300	PI	52	Failure	1	15	193
6	Earth	>1960	>300	FD	52	Accident	1	15	193
8	Earth	<1930	100-300	SL	47	Accident	7	25	1480
NONE	Rock	<1930	50-100	PI	34	Accident	3	15	887
1	Rockfill	<1930	<50	OT	27	Failure	9	57	3347
8	Earth	<1930	100-300	ST	27	Accident	4	25	1480
8	Earth	<1930	100-300	PI	27	Accident	4	25	1480
NONE	Rock	<1930	50-100	ST	23	Accident	2	15	887
NONE	Rock	<1930	50-100	PI	23	Failure	2	15	887
70	Earth	1930-1960	100-300	ST	21	Accident	7	109	3278
14	Earth	>1960	50-100	FD	18.2	Accident	6	273	3295
NONE	Rock	<1930	100-300	ST	18	Failure	1	14	557
NONE	Rock	<1930	100-300	ST	18	Accident	1	14	557
NONE	Rock	<1930	100-300	SP	18	Accident	1	14	557
50	Earth	>1960	100-300	ST	18	Accident	3	140	1666
10	Earth	<1930	50-100	SL	15.3	Accident	12	129	7836
8	Earth	<1930	100-300	EQ	13.5	Accident	2	25	1480
1	Conc-Arch	<1930	50-100	ST	13.3	Accident	3	40	2250
5	Conc-Arch	1930-1960	100-300	ST	13.2	Accident	2	42	1513
10	Earth	<1930	50-100	PI	12.8	Failure	10	129	7836
50	Earth	>1960	100-300	FD	12	Accident	2	140	1666
3	Conc-Grav	<1930	100-300	FD	12	Failure	2	27	1605
NONE	Rock	<1930	50-100	FD	11	Accident	1	15	887
10	Earth	<1930	50-100	ST	8.9	Accident	7	129	7836
10	Earth	<1930	50-100	FD	7.6	Accident	6	129	7836
8	Earth	<1930	100-300	OT	6.8	Failure	1	25	1480
8	Earth	<1930	100-300	PI	6.8	Failure	1	25	1480
8	Earth	<1930	100-300	SP	6.8	Accident	1	25	1480
8	Earth	<1930	100-300	FD	6.8	Accident	1	25	1480
5	Conc-Arch	1930-1960	100-300	SP	6.6	Accident	1	42	1513
5	Conc-Arch	1930-1960	100-300	ST	6.6	Failure	1	42	1513
14	Earth	>1960	50-100	PI	6.1	Failure	2	273	3295
50	Earth	>1960	100-300	SL	6	Accident	1	140	1666
50	Earth	>1960	100-300	PI	6	Accident	1	140	1666
50	Earth	>1960	100-300	ST	6	Failure	1	140	1666
6	Conc-Arch	<1930	100-300	SP	5.2	Accident	1	34	1930
NONE	Conc-Arch	<1930	<50	ST	5	Failure	1	32	1996
17	Earth	1930-1960	50-100	FD	4.9	Accident	4	262	8200
1	Conc-Arch	<1930	50-100	ST	4.4	Failure	1	40	2250
1	Conc-Arch	<1930	50-100	SP	4.4	Failure	1	40	2250
10	Earth	<1930	50-100	OT	3.8	Failure	3	129	7836
14	Earth	>1960	50-100	SP	3	Accident	1	273	3295
14	Earth	>1960	50-100	OT	3	Failure	1	273	3295
14	Earth	>1960	50-100	ST	3	Accident	1	273	3295
70	Earth	1930-1960	100-300	PI	3	Accident	1	109	3278
70	Earth	1930-1960	100-300	FD	3	Accident	1	109	3278

Appendix J1 (cont.).

# of Dams in BOR	Type	Age	Height	Failure	Rate	Mode	Occurrences	# of Dams in category	Life Years
70	Earth	1930-1960	100-300	FD	3	Failure	1	109	3278
10	Earth	<1930	50-100	SL	2.6	Failure	2	129	7836
10	Earth	<1930	50-100	PI	2.6	Accident	2	129	7836
13	Earth	>1960	<50	OT	2.1	Failure	5	1875	24207
2	Conc-Grav	<1930	<50	OT	1.8	Failure	1	85	5467
2	Conc-Grav	<1930	<50	SL	1.8	Accident	1	85	5467
2	Conc-Grav	<1930	<50	PI	1.8	Failure	1	85	5467
7	Earth	<1930	<50	OT	1.7	Failure	19	1649	113556
13	Earth	>1960	<50	PI	1.6	Accident	4	1875	24207
10	Earth	<1930	50-100	EQ	1.3	Accident	1	129	7836
10	Earth	<1930	50-100	OT	1.3	Accident	1	129	7836
17	Earth	1930-1960	50-100	SL	1.2	Accident	1	262	8200
17	Earth	1930-1960	50-100	PI	1.2	Failure	1	262	8200
17	Earth	1930-1960	50-100	PI	1.2	Accident	1	262	8200
17	Earth	1930-1960	50-100	SP	1.2	Accident	1	262	8200
17	Earth	1930-1960	50-100	ST	1.2	Accident	1	262	8200
17	Earth	1930-1960	50-100	FD	1.2	Failure	1	262	8200
13	Earth	>1960	<50	ST	0.8	Failure	2	1875	24207
7	Earth	<1930	<50	PI	0.7	Failure	8	1649	113556
13	Earth	>1960	<50	OT	0.4	Accident	1	1875	24207
13	Earth	>1960	<50	PI	0.4	Failure	1	1875	24207
12	Earth	1930-1960	<50	OT	0.4	Failure	4	3332	103256
13	Earth	>1960	<50	SP	0.4	Accident	1	1875	24207
7	Earth	<1930	<50	ST	0.3	Failure	3	1649	113556
7	Earth	<1930	<50	PI	0.3	Accident	3	1649	113556
7	Earth	<1930	<50	OT	0.3	Accident	3	1649	113556
7	Earth	<1930	<50	ST	0.2	Accident	2	1649	113556
12	Earth	1930-60	<50	ST	0.1	Failure	1	3332	103256
12	Earth	1930-60	<50	PI	0.1	Failure	1	3332	103256
12	Earth	1930-1960	<50	OT	0.1	Accident	1	3332	103256
12	Earth	1930-60	<50	EQ	0.1	Failure	1	3332	103256
12	Earth	1930-60	<50	FD	0.1	Failure	1	3332	103256
12	Earth	1930-1960	<50	SL	0.1	Accident	1	3332	103256
12	Earth	1930-1960	<50	ST	0.1	Accident	1	3332	103256
7	Earth	<1930	<50	SL	0.1	Accident	1	1649	113556
7	Earth	<1930	<50	FD	0.1	Failure	1	1649	113556
7	Earth	<1930	<50	SP	0.1	Failure	1	1649	113556
7	Earth	<1930	<50	EQ	0.1	Failure	1	1649	113556
7	Earth	<1930	<50	FD	0.1	Accident	1	1649	113556

Appendix J2. - Von Thun Failure Rates for Dam failures x 10^{-4} (Top 20 by rate)

DAM Classifications for BOR dams

of Dams in BOR	Type	Age	Height	Failure	Rate	Mode	Occurrences	# of Dams in category	Life Years
3	Conc-Arch	<1930	>300	EQ	98	Accident	1	2	102
1	Rock	>1960	50-100	FD	93	Accident	1	8	107
6	Earth	>1960	>300	PI	52	Failure	1	15	193
6	Earth	>1960	>300	FD	52	Accident	1	15	193
8	Earth	<1930	100-300	SL	47	Accident	7	25	1480
1	Rock	<1930	<50	OT	27	Failure	9	57	3347
8	Earth	<1930	100-300	ST	27	Accident	4	25	1480
8	Earth	<1930	100-300	PI	27	Accident	4	25	1480
70	Earth	1930-1960	100-300	ST	21	Accident	7	109	3278
14	Earth	>1960	50-100	FD	18.2	Accident	6	273	3295
50	Earth	>1960	100-300	ST	18	Accident	3	140	1666
10	Earth	<1930	50-100	SL	15.3	Accident	12	129	7836
8	Earth	<1930	100-300	EQ	13.5	Accident	2	25	1480
1	Conc-Arch	<1930	50-100	ST	13.3	Accident	3	40	2250
5	Conc-Arch	1930-1960	100-300	ST	13.2	Accident	2	42	1513
10	Earth	<1930	50-100	PI	12.8	Failure	10	129	7836
50	Earth	>1960	100-300	FD	12	Accident	2	140	1666
3	Conc-Grav	<1930	100-300	FD	12	Failure	2	27	1605
10	Earth	<1930	50-100	ST	8.9	Accident	7	129	7836
10	Earth	<1930	50-100	FD	7.6	Accident	6	129	7836

APPENDIX K

Appendix K. - Table of Dam Failures/Accidents & Modifications

Information obtained from Case Studies and Safety Evaluation

note: 1. spillway gate failure was classified as SP
2. risk assessments do not include failures/accidents in the first 5 years of the dam

Dam	Failure/Accident or Modification	Type of Accident/ Failure or Modification	Accident, Failure or Modification	Year(s) of Problem or Detection	Consequences/ Notes
Most Recent:					
Flaming Gorge	Burst pipe	ST	acc		
Folsom	Spillway gate failure	ST	acc		
Como	D/s sandboil, observed whirlpool	PI	acc/mod		
Pishkun	Sinkhole vent pipe	PI	acc		not included in Dams & Failure/ Accidents...
Willow Creek (MT)	Sinkhole piping into outlet works	PI	acc/mod		
Ochoco	Seepage along outlet works; whirlpools observed	PI	acc/mod		
Flatiron	Powerhouse fire	ST	acc		
From Case Studies:					
Agate	Sleeve valve packing and lubrication	ST	acc/mod	1970	adversely affected operations
Agency Valley	Malfunctioning needle valves	ST	acc	1965-1984	
	Radial gate deterioration	ST	acc	1984	
Altus	Spillway gate problem	SP	mod	1980-83;1984-85	
	Masonry dam seepage	ST	acc/mod	1977	serious
American Falls	Defective seals on radial spillway gates	SP	acc/mod	1978	
	Overloaded low-level outlet gates	ST	mod	1979-1981	
	Abrasion and cavitation erosion in stilling basin	SP	acc/mod	1927-;1979+1982 repairs	
	Alkali-aggregate reaction of concrete	ST	mod	1927-78;Dam replaced in 1978	entire dam replaced
Bartlett	Needle valve failure	ST	acc/mod	1984	1 fatality
	Erosion below spillway	SP	acc/mod	1965-68;1978-79	high criticality in 1966 leading to shotcrete repair
	Dam raise; aux. spillway added	OT/SP	mod	1994-97	
Bradbury	Leakage of hollow-jet valves in OW	ST	acc/mod	1971	operations restricted during rehab
	Spillway gate automatic float problem	SP	mod	1976-1981	
Buffalo Bill	Replacement of OW (due to high S)	ST	acc/mod	1959	situation began to affect operations
	Aux. spillway incorporated; dam raise	SP/OT	mod	1990	
Bumping Lake	Gatehouse fire	ST	acc/mod	1976	$120,000
Crane Prairie	Concrete deck-pedestal failure	ST	mod	before 1981	
Currant Creek	Flooding of control house	ST	acc/mod	1985	
Friant	Unexpected lowering of spillway drum gate	SP	mod	1986	
Gibson	Poorly casted needle valve	ST	mod	1956;1969	
	Overtopping of dam	OT	fail/mod	1964;1981	Failure;Modification
Hoover	Costly needle valve replacement	ST	mod	1975-76;1985-86	
Trenton	Wire rope replacement	SP	mod	1980	
Whiskeytown	Gate valve failure	ST	acc/mod	1983	
Willow Creek (CO)	Undersized hydraulic control system	ST	mod	1983	
Anchor	Sinkhole seepage	PI	acc/mod	1960-1985	high criticality; consv. storage functions lost
Angostura	Seepage through construction joints	PI	mod	1949-	
Auburn Cofferdam	Cofferdam overtopping & failure	OT	fail	1986	Failure
Canyon Ferry	Seepage through construction joints	PI	acc/mod	1954-1965	operations marginally affected

Appendix K (cont).

Dam	Failure/Accident or Modification	Type of Accident/ Failure or Modification	Accident, Failure or Modification	Year(s) of Problem or Detection	Consequences/ Notes
Carpinteria	Seepage through reservoir floor	PI	acc/mod	1975	operations restricted during repair
Causey	Abutment seepage	FD	acc/mod	1965-67;1974	serious
	Erosion of stilling basin	SP	acc/mod	1976; damage found in 1987	serious effect on operations
Cold Springs	Toe drain failure	PI	acc/mod	1967-1980	safety of dam threatened by uncontrolled seepage
Conconully	Safety of dams modification	SP	mod	1968-69	New spillway
Deer Flat	Excessive seepage	PI	acc/mod	1983	additional monitoring necessary
Fontenelle	Excessive abutment seepage	PI	acc/mod	1965-67;1985-86	
Helena Valley	Uplift pressure and seepage problems	PI	acc/mod	1961;1963-64;1977	high criticality
Lake Alice No. 1	Foundation seepage	FD	acc/mod	1980	serious b/c struct. in danger
McKay	Excessive seepage	PI	acc/mod	1927-	increased monitoring
Mt. Elbert Forebay	Seepage through potential slide area	PI	mod	1979	high criticality before membrane added
Palmetto Bend	Sinkhole adjacent to east drain drop structure	PI	acc/mod	1985-86	
Pueblo	Plugged formed drains	ST	acc/mod	1983	
San Luis	Seepage through sedimentary rock	PI	acc/mod	1967	
	Embankment u/s slope failure	SL	acc/mod	1981	critical to dam stability
Senator Wash	Seepage through reservoir floor	PI	acc/mod	1966	repairs considered urgent; happened on initial filling
Teton	Dam Failure	PI	fail	1976	Failure (11 fatalities)
Twin Buttes	Foundation seepage	FD	acc/mod	1971;1981 repair	high criticality
Wickiup	Seepage through sinkholes	PI	acc/mod	1940-	
Anita	Inadequate u/s face riprap	ST	acc	1937-	
Arthur R. Bowman	Outlet tunnel cavitation/erosion	ST	mod	built 1961;1963 repair	another year w/o repair--> big struct. damage
	OW-spillway stilling basin damage	SP	acc	1969;1979;1984	$20,000;$32,000;$50,000
Belle Fourche	U/s dam face protection	ST	acc/mod	1931;1939;1976-77;1984	Failure in 1931
Glen Canyon	Cavitation in spillway elbows	SP	acc/mod	1983	
Horseshoe	Erosion of toe of embankment	SP	acc/mod	1975;1976;1978	
Kortes	Hydraulic erosion of spillway tunnels	SP	acc/mod	1983	freeze-thaw protection was inadequate
Monticello	Hollow-jet valve and pivot valve cavitation	ST	mod	1982	
Palisades	Cavitation d/s of OW gates	ST	acc/mod	1957-;1972;1981	operations marginally affected
Platoro	Vibrating outlet	ST	mod	built 1951;high water levels	
Ruedi	Cavitation of OW concrete	ST	mod	repairs required every 2 years;1975	
Stampede	Cavitation of concrete below OW gates	ST	acc/mod	1982	
Stewart Mountain	Erosion below spillway with an unlined plunge pool	SP	acc/mod	1966;1975-77;1979	
	Alkali-aggregate concrete problem	ST	acc/mod	1937-	
	Instability from seismic conditions; spillway capacity	EQ/SP	mod	1988-90;1991-92	
Big Sandy	Spillway floor deterioration and failure	SP	acc/mod	1985	spillway unsafe to operate
Bumping Lake	Gatehouse tower concrete deterioration	ST	mod	1949-;1951+64 repairs	reservoir had to be drained twice
	Spillway deterioration	SP	acc	since early 1950s	
Deerfield	Deterioration of spillway concrete	SP	mod	1971;1984 rehab	
Eden	Potential failure of OW tunnel	ST	mod	1959 rehab	high criticality for crop production
Fruitgrowers	Settlement of spillway crest structure	SP	acc/mod	built 1939	high criticality developed "over a period of years"
Grassy Lake	Deflection and severe cracking of chute walls	SP	acc/mod	1983	severe problem, failure of spillway anticipated
Island Park	Spillway replacement	SP	mod	1948-79; 1979-80	
Lake Sherburne	Spillway replacement	SP	mod	1960	some reduction in consv. storage
Lemon	Spillway entrance concrete wall failure	SP	acc/mod	1966-;wall failed 1973	
Milburn Diversion	Sluiceway deterioration by sand and water	ST	acc/mod	1965-	
Vallecito	Stilling basin counterfort wall failure	SP	acc/mod	1973	
Webster	Deterioration of spillway chute concrete floor	SP	acc/mod	1962-	
Coolidge	Overtopping protection	OT	mod	1994	
McPhee	Cavitation mitigation	SP	mod	1986	
Clear Creek	Conversion from thin arch to gravity arch	ST	mod	1992	

APPENDIX L

Appendix L. - Dams & Failure/Incident Probabilities By Category

Legend:
Boldface = incident
BOLDFACE & CAPS = most recent accidents
Underlin = modifications & restrictions
▨ = failure
Italics = Risk assessments used in this study.

Earth Dams

		Von Thun Probabilities					
		Failure	Accident	Mode			
Age:	<1930	1.70E-04	3.00E-05	OT	Big Meadows		
Height:	<50 ft.	1.00E-05	1.00E-05	FD	Eden ST		
		7.00E-05	3.00E-05	PI	Lower Lake Alice		
	7 dams		1.00E-05	SL	**Upper Lake Alice (No. 1)** FD		
		3.00E-05	2.00E-05	ST	Pilot Butte 1-3		
		1.00E-05		SP	Deaver		
		1.00E-05		EQ	Clear Lake		
Age:	1930-1960	4.00E-05	1.00E-05	OT	**Carpinteria** PI	Terminal	
Height:	<50 ft.	1.00E-05		FD	Dutch Slough	Vermejo Project #2	
		1.00E-05		PI	Crescent Lake	Vermejo Project #13	
	12 dams		1.00E-05	SL	Crane Prairie ST	Stublefield	
		1.00E-05	1.00E-05	ST	**Anita** ST	Fish Lake	
				SP	Picacho North		
		1.00E-05		EQ	Picacho South		
Age:	>1960	2.10E-04	4.00E-05	OT	Atkinson	Little Meadows	
Height:	<50 ft.			FD	Bonham	Neversweat	
		4.00E-05	1.60E-04	PI	Cottonwood	Silver Lake	
	13 dams			SL	Decamp	Wintering	
		8.00E-05		ST	Forty Acre	Gray Reef	
			4.00E-05	SP	Kitson	Arthur V. Watkins	
				EQ	Lambert		
Age:	<1930	3.80E-04	1.30E-04	OT	**Deer Flat** PI	**Bumping Lake** ST	
Height:	50-100 ft.		7.60E-04	FD	*Avalon*	Minidoka	
		1.28E-03	2.60E-04	PI	McMillan	Jackson Lake EQ	
	10 dams	2.60E-04	1.53E-03	SL	Lake Sherburne SP		
			8.90E-04	ST	*Salmon Lake* EQ		
				SP	Strawberry		
			1.30E-04	EQ	***WILLOW CREEK (MT)*** PI		
Age:	1930-1960			OT	**COMO** PI	**Fruitgrowers** SP	Bull Lake
Height:	50-100 ft.	1.20E-04	4.90E-04	FD	Unity	Island Park SP	Keene Creek
		1.20E-04	1.20E-04	PI	Flatiron	Box Butte	Wasco PI
	17 dams		1.20E-04	SL	Olympus	Midview	
			1.20E-04	ST	Shadow Mountain	Lovewell	
			1.20E-04	SP	**Big Sandy** SP	Dickinson	
				EQ	Huntington North	**Helena Valley** PI	

Appendix L (cont).

Age: >1960
Height: 50-100 ft.
14 dams

	Failure	Accident	Mode
	3.00E-04		OT
		1.82E-03	FD
	6.10E-04		PI
			SL
		3.00E-04	ST
		3.00E-04	SP
			EQ

Lewiston
North Bottle Hollow
South Bottle Hollow
O'Neill EQ
Squaw Lake PI
Rye Patch EQ
Senator Wash PI
Conconully SP
Palmetto Bend PI
Hyatt Prairie
Yellowtail Afterbay
Agate ST
Mt. Elbert Forebay PI

Age: <1930
Height: 100-300 ft.
8 dams

	Failure	Accident	Mode
	6.80E-04		OT
		6.80E-04	FD
	6.80E-04	2.70E-03	PI
		4.70E-03	SL
		2.70E-03	ST
		6.80E-04	SP
		1.35E-03	EQ

Belle Fourche ST
American Falls SP,SP,ST,ST
Guernsey
Cold Springs PI
Keechelus
McKay PI
Minatare
Lahontan

Age: 1930-1960
Height: 100-300 ft.
71 dams

	Failure	Accident	Mode
			OT
	3.00E-04	3.00E-04	FD
		3.00E-04	PI
			SL
		2.10E-03	ST
			SP
			EQ

Cascade
Bradbury SP
Glen Anne
Lauro
Ortega
Sumner
Martinez
Grassy Lake SP
Moon Lake
Newton
Pineview
Palisades ST
Boysen
Keyhole
Pactola
Medicine Creek
Enders
Trenton SP
Alcova
Jackson Gulch
Fresno
Fort Cobb
Wanship
Hyrum
Sly Park
Sly Park Saddle
Carter Lake
Granby
Horsetooth
Dixon Canyon
Soldier Canyon
Jamestown
Shadehill
Heart Butte
Tiber
Glendo
Cedar Bluff
Kirwin
Webster SP
Bonny
Vallecito SP
Upper Stillwater
Echo
Cle Elum
Kachess
Angostura PI
Davis
Wickiup PI
Spring Canyon
Rattlesnake
Willow Creek (CO) ST
Dry Falls
North
Pinto
O'Sullivan
Deer Creek
Deerfield SP
Caballo
Howard Prairie
Platoro ST
Twitchell
Scofield EQ
Boca EQ
Taylor Park
Agency Valley ST,ST
Morman Island Aux. EQ
El Vado
Marshall Ford
Vega
Horseshoe SP
OCHOCO PI
Haystack

Age: >1960
Height: 100-300 ft.
55 dams

	Failure	Accident	Mode
			OT
		1.20E-03	FD
		6.00E-04	PI
		6.00E-04	SL
	6.00E-04	1.80E-03	ST
			SP
			EQ

Arbuckle
Silver Jack
Sanford
Currant Creek ST
Redfleet
Soldier Creek
Starvation
Steinaker EQ
Contra Loma
Little Panoche
Los Banos
Spring Creek
Prosser
Heron
Meeks Cabin EQ
Sugar Pine
Mason
Whiskeytown ST
Joes Valley
Lemon SP
Sugar Loaf
Little Wood River
Stateline
Mann Creek
Cutter
Norman
Choke Canyon
Paonia
Red Willow
Cheney
Nambe Falls
Pueblo ST
Scoggins
Norton
Sherman
Merritt
Glen Elder
Clark Canyon
Emigrant
Twin Buttes FD
FONTENELLE PI,PI
Rifle Gap
Crawford
Bully Creek
Foss
Arthur R. Bowman ST,SP
Auburn Cofferdam OT
Stampede ST
Causey FD,SP
Lost Creek EQ

Appendix L (cont).

		Failure	Accident	Mode	
Age:	<1930			OT	Tieton
Height:	>300 ft.			FD	
				PI	
	1 dam			SL	
				ST	
				SP	
				EQ	
Age:	1930-1960			OT	Anderson Ranch
Height:	>300 ft.			FD	Green Mountain
				PI	Casitas
	4 dams			SL	**FOLSOM** ST
				ST	
				SP	
				EQ	
Age:	>1960			OT	**San Luis** PI,SL
Height:	>300 ft.		5.20E-03	FD	Trinity
		5.20E-03		PI	Blue Mesa
	6 dams			SL	Navajo PI
				ST	Ruedi ST
				SP	Teton PI
				EQ	

Appendix L (cont.)

Rock Dams

		Von Thun Probabilities			
		Failure	Accident	Mode	
Age:	<1930	2.70E-03		OT	Clear Lake
Height:	<50 ft.			FD	
				PI	
	1 dam			SL	
				ST	
				SP	
				EQ	
Age:	1930-1960			OT	Fourmile Lake
Height:	<50 ft.			FD	Fish Lake
				PI	
	2 dams			SL	
				ST	
				SP	
				EQ	
Age:	>1960			OT	
Height:	<50 ft.			FD	
				PI	
	0 dams			SL	
				ST	
				SP	
				EQ	
Age:	<1930			OT	
Height:	50-100 ft.		1.10E-03	FD	
		2.30E-03	3.40E-03	PI	
	0 dams			SL	
		1.10E-03	2.30E-03	ST	
				SP	
				EQ	
Age:	1930-1960			OT	
Height:	50-100 ft.			FD	
			6.90E-03	PI	
	0 dams			SL	
				ST	
				SP	
				EQ	
Age:	>1960			OT	Hyatt Prairie
Height:	50-100 ft.		9.30E-03	FD	
				PI	
	1 dam			SL	
				ST	
				SP	
				EQ	

Appendix L (cont.).

Rock Dams (Cont.)

Age: <1930
Height: 100-300 ft.

0 dams

Von Thun Probabilities		
Failure	Accident	Mode
7.20E-03		OT
		FD
		PI
		SL
1.80E-03	1.80E-03	ST
	1.80E-03	SP
		EQ

Age: 1930-1960
Height: 100-300 ft.

3 dams

		OT	Vega
		FD	**Horseshoe** SP
		PI	Upper Stillwater
		SL	
	8.00E-03	ST	
		SP	
		EQ	

Age: >1960
Height: 100-300 ft.

4 dams

		OT	Heron
		FD	Meeks Cabin
		PI	Sugar Pine
		SL	Mason
		ST	Auburn Cofferdam OT
		SP	
		EQ	

Age: <1930
Height: >300 ft.

0 dams

		OT
		FD
		PI
		SL
		ST
		SP
		EQ

Age: 1930-1960
Height: >300 ft.

0 dams

		OT
		FD
		PI
		SL
	6.70E-03	ST
		SP
		EQ

Age: >1960
Height: >300 ft.

0 dams

		OT
		FD
		PI
		SL
		ST
		SP
		EQ

Appendix L (cont.).

Arch Dams

Age: <1930
Height: <50 ft.

0 dams

Von Thun Probabilities		
Failure	Accident	Mode
		OT
		FD
		PI
		SL
5.00E-04		ST
		SP
		EQ

Age: 1930-1960
Height: <50 ft.

0 dams

		OT
		FD
		PI
		SL
		ST
		SP
		EQ

Age: >1960
Height: <50 ft.

0 dams

		OT
		FD
		PI
		SL
		ST
		SP
		EQ

Age: <1930
Height: 50-100 ft.

2 dams

		OT	Gerber
		FD	
		PI	
		SL	
4.40E-04	1.33E-03	ST	
4.40E-04		SP	
		EQ	

Age: 1930-1960
Height: 50-100 ft.

0 dams

		OT
		FD
		PI
		SL
		ST
		SP
		EQ

Age: >1960
Height: 50-100 ft.

0 dams

		OT
		FD
		PI
		SL
		ST
		SP
		EQ

Appendix L (cont.).

Arch Dams (cont.)

		Von Thun Probabilities			
		Failure	Accident	Mode	
Age:	<1930			OT	Pathfinder
Height:	100-300 ft.			FD	Theodore Roosevelt OT
				PI	*East Park*
	6 dams			SL	Sun River Diversion
				ST	*Warm Springs*
			5.20E-04	SP	**Gibson** ST,OT
				EQ	
Age:	1930-1960			OT	Seminoe
Height:	100-300 ft.			FD	*Deadwood*
				PI	**Bartlett** ST,SP,OT/SP
	5 dams			SL	Mormon Flat
			1.32E-03	ST	**Stewart Mountain** ST,SP,SP/EQ
		6.60E-04	6.60E-04	SP	
				EQ	
Age:	>1960			OT	Mountain Park
Height:	100-300 ft.			FD	**Anchor** PI
				PI	East Canyon
	4 dams			SL	*Nambe Falls*
				ST	
				SP	
				EQ	
Age:	<1930			OT	Arrowrock
Height:	>300 ft.			FD	Horse Mesa
				PI	**Buffalo Bill** ST,SP/OT
	3 dams			SL	
				ST	
				SP	
			9.80E-03	EQ	
Age:	1930-1960			OT	Hoover ST
Height:	>300 ft.			FD	*Hungry Horse*
				PI	Owyhee
	5 dams			SL	Parker
				ST	Monticello ST
				SP	
				EQ	
Age:	>1960			OT	Crystal
Height:	>300 ft.			FD	**FLAMING GORGE** ST
				PI	**GLEN CANYON** SP,SP
	5 dams			SL	Morrow Point
				ST	Yellowtail
				SP	
				EQ	

Note: By some definitions, the incident at Gibson was a failure.

Appendix L (cont.).

Gravity/
Buttress Dams

Age: <1930
Height: <50 ft.
2 dams

Von Thun Probabilities		
Failure	Accident	Mode
1.80E-04		OT
		FD
1.80E-04		PI
	1.80E-04	SL
		ST
		SP
		EQ

Lake Tahoe EQ
Belle Fourche ST

**Milburn Diversion (ST) is on the Table of Dam Failures/Accidents, but is not included here because it is a diversion dam less than 50 feet high.

Age: 1930-1960
Height: <50 ft.
0 dams

		OT
		FD
		PI
		SL
		ST
		SP
		EQ

Age: >1960
Height: <50 ft.
0 dams

		OT
		FD
		PI
		SL
		ST
		SP
		EQ

Age: <1930
Height: 50-100 ft.
2 dams

		OT
		FD
		PI
		SL
		ST
		SP
		EQ

Minidoka (spillway)
Jackson Lake EQ

Age: 1930-1960
Height: 50-100 ft.
2 dams

		OT
		FD
		PI
		SL
		ST
		SP
		EQ

Thief Valley
Nimbus

Age: >1960
Height: 50-100 ft.
1 dam

		OT
		FD
		PI
		SL
		ST
		SP
		EQ

Yellowtail Afterbay

Appendix L (cont.).

Gravity/ Buttress Dams (cont.)

		Von Thun Probabilities			
		Failure	Accident	Mode	
Age:	<1930			OT	Stony Gorge OT
Height:	100-300 ft	1.20E-03		FD	Black Canyon Div.
				PI	**American Falls** SP,SP,ST,ST
	4 dams			SL	Coolidge OT
				ST	
				SP	
				EQ	
Age:	1930-1960			OT	Keswick
Height:	100-300 ft.			FD	**Canyon Ferry** PI
				PI	**Kortes** SP
	6 dams			SL	**Altus** SP,ST
				ST	Angostura PI
				SP	Marshall Ford
				EQ	
Age:	>1960			OT	***Pueblo*** ST, FD
Height:	100-300 ft.			FD	
				PI	
	1 dam			SL	
				ST	
				SP	
				EQ	
Age:	<1930			OT	*Elephant Butte*
Height:	>300 ft.			FD	
				PI	
	1 dam			SL	
				ST	
				SP	
				EQ	
Age:	1930-1960			OT	Friant SP
Height:	>300 ft.			FD	Shasta
				PI	Grand Coulee
	4 dams			SL	**FOLSOM** ST
				ST	
				SP	
				EQ	
Age:	>1960			OT	
Height:	>300 ft.			FD	
				PI	
	0 dams			SL	
			2.50E-02	ST	
				SP	
				EQ	

APPENDIX M

Appendix M1. - "Failure/Accident Tomorrow"

For modes in categories that have no failures or accidents so far.

Von Thun Failure Rates for Dam failures x 10^{-4}

of Dams in BOR	Type	Age	Height (ft)	Life Years	Rate x 10^{-4} (1/Life Years)	Associated Failure Types*
7	Earth	<1930	<50	113556	0.1	SL
12		1930-1960		103256	0.1	SL, SP
13		1960-		24207	0.4	FD,SL,SP,EQ
10		<1930	50-100	7836	1.3	FD,ST,SP,EQ
17		1930-1960		8200	1.2	All but FD + PI
14		1960-		3295	3.0	All but OT + PI
8		<1930	100-300	1480	6.8	All but OT + PI
70		1930-1960		3278	3.1	All but FD
50		1960-		1666	6.0	All but ST
1		<1930	300-	0		All
4		1930-1960		72	138.9	All
6		1960-		193	51.8	All but PI
1	Rock	<1930	<50	3347	3.0	All but OT
2		1930-1960		1401	7.1	All
0		1960-		257	38.9	All
0		<1930	50-100	887	11.3	All but PI + ST
0		1930-1960		145	69.0	All
1		1960-		107	93.5	All
0		<1930	100-300	557	18.0	All but OT + ST
2		1930-1960		376	26.6	All
4		1960-		199	50.3	All
0		<1930	300-	54	185.2	All
0		1930-1960		150	66.7	All
0		1960-		42	238.1	All
0	Arch	<1930	<50	1996	5.0	All but ST
0		1930-1960		440	22.7	All
0		1960-		43	232.6	All
1		<1930	50-100	2250	4.4	All but ST + SP
0		1930-1960		356	28.1	All
1		1960-		70	142.9	All
6		<1930	100-300	1930	5.2	All
5		1930-1960		1513	6.6	All but SP
4		1960-		179	55.9	All
3		<1930	300-	102	98.0	All
5		1930-1960		129	77.5	All
5		1960-		93	107.5	All
2	Gravity/	<1930	<50	5467	1.8	All but OT + PI
0	uttress	1930-1960		2675	3.7	All
0		1960-		247	40.5	All
2		<1930	50-100	1639	6.1	All
2		1930-1960		662	15.1	All

Appendix M1 (cont.).

Von Thun Failure Rates for Dam failures x 10^{-4}

of Dams in BOR	Type	Age	Height (ft)	Life Years	Rate x 10^-4 (1/Life Years)	Associated Failure Types
1		1960-		61	163.9	All
3		<1930	100-300	1605	6.2	All but FD
6		1930-1960		518	19.3	All
1		1960-		166	60.2	All
1		<1930	300-	51	196.1	All
4		1930-1960		126	79.4	All
0		1960-		250	40.0	All

Key*

EQ: earthquake
FD: foundation
OT: overtopping
PI: piping
SL: sliding
SP: spillway
ST: structural

Appendix M2. - "Failure/Accident Tomorrow"

For modes in categories that have already had at least one occurrence.

Von Thun Failure Rates for Dam failures x 10^{-4}

# of Dams in BOR	Type	Age	Height	Failure	New Rate	Mode	Occurrences	Occurrences plus one	Life Years
NONE	Conc-Grav	>1960	>300	ST	500.0	Accident	1	2	40
3	Conc-Arch	<1930	>300	EQ	196.1	Accident	1	2	102
1	Rock	>1960	50-100	FD	186.9	Accident	1	2	107
NONE	Rock	1930-1960	100-300	ST	106.4	Accident	3	4	376
NONE	Rock	<1930	100-300	OT	89.8	Failure	4	5	557
NONE	Rock	1930-1960	50-100	PI	137.9	Accident	1	2	145
NONE	Rock	1930-1960	>300	ST	133.3	Accident	1	2	150
6	Earth	>1960	>300	PI	103.6	Failure	1	2	193
6	Earth	>1960	>300	FD	103.6	Accident	1	2	193
8	Earth	<1930	100-300	SL	54.1	Accident	7	8	1480
NONE	Rock	<1930	50-100	PI	45.1	Accident	3	4	887
1	Rockfill	<1930	<50	OT	29.9	Failure	9	10	3347
8	Earth	<1930	100-300	ST	33.8	Accident	4	5	1480
8	Earth	<1930	100-300	PI	33.8	Accident	4	5	1480
NONE	Rock	<1930	50-100	ST	33.8	Accident	2	3	887
NONE	Rock	<1930	50-100	PI	33.8	Failure	2	3	887
70	Earth	1930-1960	100-300	ST	24.4	Accident	7	8	3278
14	Earth	>1960	50-100	FD	21.2	Accident	6	7	3295
NONE	Rock	<1930	100-300	ST	35.9	Failure	1	2	557
NONE	Rock	<1930	100-300	ST	35.9	Accident	1	2	557
NONE	Rock	<1930	100-300	SP	35.9	Accident	1	2	557
50	Earth	>1960	100-300	ST	24.0	Accident	3	4	1666
10	Earth	<1930	50-100	SL	16.6	Accident	12	13	7836
8	Earth	<1930	100-300	EQ	20.3	Accident	2	3	1480
1	Conc-Arch	<1930	50-100	ST	17.8	Accident	3	4	2250
5	Conc-Arch	1930-1960	100-300	ST	19.8	Accident	2	3	1513
10	Earth	<1930	50-100	PI	14.0	Failure	10	11	7836
50	Earth	>1960	100-300	FD	18.0	Accident	2	3	1666
3	Conc-Grav	<1930	100-300	FD	18.7	Failure	2	3	1605
NONE	Rock	<1930	50-100	FD	22.5	Accident	1	2	887
10	Earth	<1930	50-100	ST	10.2	Accident	7	8	7836
10	Earth	<1930	50-100	FD	8.9	Accident	6	7	7836
8	Earth	<1930	100-300	OT	13.5	Failure	1	2	1480
8	Earth	<1930	100-300	PI	13.5	Failure	1	2	1480
8	Earth	<1930	100-300	SP	13.5	Accident	1	2	1480
8	Earth	<1930	100-300	FD	13.5	Accident	1	2	1480
5	Conc-Arch	1930-1960	100-300	SP	13.2	Accident	1	2	1513
5	Conc-Arch	1930-1960	100-300	ST	13.2	Failure	1	2	1513
14	Earth	>1960	50-100	PI	9.1	Failure	2	3	3295
50	Earth	>1960	100-300	SL	12.0	Accident	1	2	1666
50	Earth	>1960	100-300	PI	12.0	Accident	1	2	1666
50	Earth	>1960	100-300	ST	12.0	Failure	1	2	1666
6	Conc-Arch	<1930	100-300	SP	10.4	Accident	1	2	1930
NONE	Conc-Arch	<1930	<50	ST	10.0	Failure	1	2	1996
17	Earth	1930-1960	50-100	FD	6.1	Accident	4	5	8200
1	Conc-Arch	<1930	50-100	ST	8.9	Failure	1	2	2250
1	Conc-Arch	<1930	50-100	SP	8.9	Failure	1	2	2250
10	Earth	<1930	50-100	OT	5.1	Failure	3	4	7836

Appendix M2 (cont.).

# of Dams in BOR	Type	Age	Height	Failure	New Rate	Mode	Occurrences	Occurrences plus one	Life Years
14	Earth	>1960	50-100	SP	6.1	Accident	1	2	3295
14	Earth	>1960	50-100	OT	6.1	Failure	1	2	3295
14	Earth	>1960	50-100	ST	6.1	Accident	1	2	3295
70	Earth	1930-1960	100-300	PI	6.1	Accident	1	2	3278
70	Earth	1930-1960	100-300	FD	6.1	Accident	1	2	3278
70	Earth	1930-1960	100-300	FD	6.1	Failure	1	2	3278
10	Earth	<1930	50-100	SL	3.8	Failure	2	3	7836
10	Earth	<1930	50-100	PI	3.8	Accident	2	3	7836
13	Earth	>1960	<50	OT	2.5	Failure	5	6	24207
2	Conc-Grav	<1930	<50	OT	3.7	Failure	1	2	5467
2	Conc-Grav	<1930	<50	SL	3.7	Accident	1	2	5467
2	Conc-Grav	<1930	<50	PI	3.7	Failure	1	2	5467
7	Earth	<1930	<50	OT	1.8	Failure	19	20	113556
13	Earth	>1960	<50	PI	2.1	Accident	4	5	24207
10	Earth	<1930	50-100	EQ	2.6	Accident	1	2	7836
10	Earth	<1930	50-100	OT	2.6	Accident	1	2	7836
17	Earth	1930-1960	50-100	SL	2.4	Accident	1	2	8200
17	Earth	1930-1960	50-100	PI	2.4	Failure	1	2	8200
17	Earth	1930-1960	50-100	PI	2.4	Accident	1	2	8200
17	Earth	1930-1960	50-100	SP	2.4	Accident	1	2	8200
17	Earth	1930-1960	50-100	ST	2.4	Accident	1	2	8200
17	Earth	1930-1960	50-100	FD	2.4	Failure	1	2	8200
13	Earth	>1960	<50	ST	1.2	Failure	2	3	24207
7	Earth	<1930	<50	PI	0.8	Failure	8	9	113556
13	Earth	>1960	<50	OT	0.8	Accident	1	2	24207
13	Earth	>1960	<50	PI	0.8	Failure	1	2	24207
12	Earth	1930-1960	<50	OT	0.5	Failure	4	5	103256
13	Earth	>1960	<50	SP	0.8	Accident	1	2	24207
7	Earth	<1930	<50	ST	0.4	Failure	3	4	113556
7	Earth	<1930	<50	PI	0.4	Accident	3	4	113556
7	Earth	<1930	<50	OT	0.4	Accident	3	4	113556
7	Earth	<1930	<50	ST	0.3	Accident	2	3	113556
12	Earth	1930-60	<50	ST	0.2	Failure	1	2	103256
12	Earth	1930-60	<50	PI	0.2	Failure	1	2	103256
12	Earth	1930-1960	<50	OT	0.2	Accident	1	2	103256
12	Earth	1930-60	<50	EQ	0.2	Failure	1	2	103256
12	Earth	1930-60	<50	FD	0.2	Failure	1	2	103256
12	Earth	1930-1960	<50	SL	0.2	Accident	1	2	103256
12	Earth	1930-1960	<50	ST	0.2	Accident	1	2	103256
7	Earth	<1930	<50	SL	0.2	Accident	1	2	113556
7	Earth	<1930	<50	FD	0.2	Failure	1	2	113556
7	Earth	<1930	<50	SP	0.2	Failure	1	2	113556
7	Earth	<1930	<50	EQ	0.2	Failure	1	2	113556
7	Earth	<1930	<50	FD	0.2	Accident	1	2	113556

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave Blank)*

2. REPORT DATE
August 1997

3. REPORT TYPE AND DATES COVERED
Final

4. TITLE AND SUBTITLE
Comparison of Failure Modes from Risk Assessment & Historical Data for Bureau of Reclamation Dams

5. FUNDING NUMBERS

6. AUTHOR(S)
Joe Tatalovich

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Bureau of Reclamation
Materials Engineering and Research Laboratory
Denver Federal Center
PO Box 25007
Denver CO 80225-0007

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Same

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The Bureau of Reclamation (Reclamation) has developed a process to determine which dams need to be renovated because of their risk of failure or accident. It takes into account the failure possibilities and the number of people who would be affected by certain occurrences.

This project assessed risk of failure and accident at Reclamation dams. The failure modes of these dams were compared to each other as well as to historical failures. A comprehensive list of all Reclamation dams classified by age, height, and type was compiled. It was hoped that, through the process of examining the risk assessments and the historical data, Reclamation will learn more about both its dams and how the risk of failure is analyzed. This may improve dam servicing in the future.

The study showed that Reclamation dams are more risky than the "average" western dam. Even though accidents are more rigorously documented at Reclamation dams than at other western dams, the need for effective risk assessment is apparent. The incident rate for the last three years with seven incidents is well above the average rate for Reclamation dams.

14. SUBJECT TERMS-- event trees, dam accidents and failures in the Western United States, incident rate, modes of failure, annualized loss of life figures, screening level risk assessment, comprehensive risk assessment, modification decision analysis, corrective action study

15. NUMBER OF PAGES
13

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
UL

18. SECURITY CLASSIFICATION OF THIS PAGE
UL

19. SECURITY CLASSIFICATION OF ABSTRACT
UL

20. LIMITATION OF ABSTRACT
UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18
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