WASHINGTON STATE DEPARTMENT OF ECOLOGY

DAM SAFETY GUIDELINES

Technical Note 2:

Selection of Design/Performance Goals for Critical Project Elements

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SELECTION OF DESIGN/PERFORMANCE GOALS FOR CRITICAL PROJECT ELEMENTS

OVERVIEW

Critical project elements are those elements of a project whose failure could result in dam failure and an uncontrolled release of the reservoir. This technical note provides guidance in selecting design/performance goals for critical project elements. It has application in design of proposed dams and in evaluating the adequacy of existing dams.

A decision making framework is presented which aids in the selection of appropriate design/performance goals and which incorporates the concepts of *Consequence Dependent Design Levels* and *Balanced Protection*. A Design Step Format with 8 design steps is used wherein design/performance goals range from an annual exceedance probability of 1 in 500 at Design Step 1 to an annual exceedance probability of 10^{-6} at Design Step 8. In the latter case, Design Step 8 corresponds to theoretical maximum events/loading conditions for critical project elements.

Subjects considered in the decision framework are similar to those considered in assessing the Downstream Hazard Classification[32] for a project. Thus, the design step for a project can be generally related to the Downstream Hazard Classification as shown in Table 1. This Table may be used in the planning stages of a project to make an initial assessment of the design step.

The design step determined from procedures in this Technical Note has application in the following subject areas in *Dam Design and Construction*, *Part IV* of the *Dam Safety Guidelines*:

- Computation of Inflow Design Floods
- Assessing the Seismic Stability of Embankments
- Design of Outlet Conduits
- Reliability Levels for Critical Electrical and Mechanical Systems

A Worksheet is included in Appendix B to assist in the computational procedures for determining an appropriate design step and design/performance goal. After the reader becomes familiar with the contents of this technical note, this Worksheet will be the primary tool used to determine/select an appropriate design step.

TABLE 1. GENERAL RELATIONSHIP OF DESIGN STEP TO DOWNSTREAM HAZARD CLASSIFICATION

DOWNSTREAM HAZARD POTENTIAL	DOWNSTREAM HAZARD CLASSIFICATION	POPULATION AT RISK	ECONOMIC LOSS GENERIC DESCRIPTIONS	ENVIRONMENTAL DAMAGES	TYPICAL DESIGN STEP
LOW	3	0	Minimal. No inhabited structures. Limited agriculture development.	No deleterious materials in reservoir	1 - 2
SIGNIFICANT	2	1 to 6	Appreciable. 1 or 2 inhabited structures. Notable agriculture or work sites. Secondary highway and/or rail lines.	Limited water quality degradation from reservoir contents and only short term consequences	3 - 4
HIGH	1C	7 to 30	Major. 3 to 10 inhabited structures. Low density suburban area with some industry and work sites. Primary highways and rail lines.	Severe water quality degradation potential from reservoir contents and long term effects on aquatic and human life	3 - 6
HIGH	1B	31-300	Extreme. 11 to 100 inhabited structures. Medium density suburban or urban area with associated industry, property and transportation features.		4 - 8
HIGH	1A	More than 300	Extreme. More than 100 inhabited structures. Highly developed, densely populated suburban or urban area with associated industry, property, transportation and community life line features.		8

SELECTION OF DESIGN/PERFORMANCE GOALS FOR CRITICAL PROJECT ELEMENTS

1. INTRODUCTION

The selection of the design level and corresponding design event/load for each element of a project is an important step in the design process. Traditionally, it has been common practice in the engineering community that the degree of conservatism in design be commensurate with the intended use and the consequences of failure of a given system element. If the failure of a given system element does not pose a public safety concern, then the design level is usually based on economic considerations and the effects of a disruption of system operation.

A contrasting situation is where the failure of a given element could pose a threat of loss of life. In these cases, the design levels are typically very conservative to provide protection from the consequences of a failure. And, as the potential magnitude for loss of life and property damage resulting from a failure increases, the design levels become increasingly more stringent. This concept is termed *Consequence Dependent Design Levels* and is a standard consideration within some engineering disciplines. For example, in hydrologic engineering, the magnitude of the flood used in the design of dams has historically been dependent on the downstream consequences of dam failure[1]. Likewise, in structural engineering, the American Society of Civil Engineers[2] requires the magnitude of design loads used for buildings of critical importance such as hospitals, schools and power stations be increased over that used for general purpose structures.

While the use of consequence dependent design levels is common within some engineering disciplines, it has not been common practice to endeavor to provide similar levels of conservatism in the design of the various components of a system. This lack of coordination between engineering disciplines can result in the various elements of a project or system being designed to widely different standards - often affording quite dissimilar levels of protection from failure. This situation can exist in dam engineering where a variety of disciplines are represented by engineering geologists, geotechnical engineers, hydrologists, structural, mechanical and electrical engineers who may be involved in the design of various critical project elements.

A lack of coordination can be a serious shortcoming when the failure of one element of a system or project could pose a threat of loss of life - as is the case with dams. This shortcoming points out the need for a systems approach to design and the use of *Balanced Protection* concepts. It should be remembered that the reliability of the system is often governed by the strength of the weakest element.

In particular, experience[3] has shown that common causes of dam failure include: overtopping by floodwaters; internal erosion of foundations and embankments caused by seepage; seepage along outlet conduits; and deterioration of outlet conduits and other man-made materials used in construction. These are logical areas which should receive increased attention and where a balanced approach is needed to protect against a variety of failure modes.

Thus, a commitment is needed during the design and construction phases of a project to achieve a balance by providing reasonably similar levels of conservatism in design and construction of the various critical project elements. Likewise, when an existing project is evaluated, a balanced approach is needed to assess the relative levels of actual performance attained by the critical project elements and to allow identification of weak elements.

At the same time, it is recognized that the various engineering disciplines involved in dam design/evaluation currently utilize methodologies which do not readily lend themselves to direct comparison. A variety of methodologies are currently used in dam design/evaluation which span the range from deterministic, to combined deterministic-probabilistic, to probabilistic approaches. In many disciplines, technologies are not sufficiently advanced to quantitatively assess the reliability afforded by the extreme loading conditions used in project design/evaluation.

Nonetheless, there is great value in incorporating a systems approach and *Balanced Protection* concepts in the design philosophy for the project. For the time being, many of the comparisons between multi-disciplinary design levels are necessarily qualitative rather than quantitative. However, qualitative assessments are still quite valuable and have been incorporated into *Part IV of the Dam Safety Guidelines*. In the future, studies and advances in technology will continue to be made under the names of reliability engineering, risk assessment and probabilistic based design which will improve the ability to quantify the protection afforded by a given design level. Ultimately, the goal of providing balanced protection in design and actual performance will come within reach.

Toward that end, a decision framework is presented here for selection of design/performance goals which incorporates the concepts of *Consequence Dependent Design Levels* and *Balanced Protection* and clearly identifies the reliability goals for the performance of critical project elements.

1.1 TERMINOLOGY

This technical note utilizes a number of terms, some of which are not in common usage and may be unfamiliar to the user. In particular, definitions for the terms *design/performance goal, reliability and design level* are important to the application of this technical note. The relationship between these terms is discussed in Section A1.2 of the Commentary in Appendix A.

The following selected terms are defined to clarify their meaning and to provide a common definition for *Part IV* of the *Dam Safety Guidelines* regarding *Dam Design and Construction.*

Advanced Warning Time - The amount of time available for evacuation after notification of a dangerous situation or after self-recognition of a dangerous situation.

Annual Exceedance Probability (AEP) - The chance that a specified magnitude of some phenomenon of interest is equaled or exceeded during a given year.

> For example, in Olympia WA, a 24 hour precipitation depth of 5.5 inches has an AEP of 0.01. Stated another way, there is one chance in one hundred that 5.5 inches of precipitation or more will fall in Olympia in some 24 hour period in any given year.

Critical Project Element - An element of a project whose failure could result in dam failure and/or an uncontrolled release of the reservoir.

Design Level - In general usage, design level is a generic term used to describe the relative conservatism of a particular design event or design load. The design level may be expressed in terms of the annual exceedance probability of the design event, or correspond to a deterministic design event or design load.

In many engineering applications, the actual level of protection provided by a specified design level/event/load may not be known with accuracy. (See also Section A1.2 of Appendix A)

Design/Performance Goal - A goal for the performance of critical project elements which may be used in design or evaluation. It is expressed as an annual exceedance probability and is a measure of the chance of adverse behavior, or failure of a critical project element.

Design Step - An integer value from one through eight which is used as an index for increasingly stringent design/performance goals (Figure 1). The design step is used in Part IV of the *Dam Safety Guidelines* to set design events and design loads for design or evaluation of critical project elements.

Hazard - A condition or situation which is a potential source of danger.

Level of Protection - A term which is equivalent to reliability and is often used in the context of the protection afforded by a given design level.

Performance Level - Similar to the definition for the design/performance goal, except that it refers to the actual performance achieved by the in-place project element.

Reliability - The likelihood of successful performance of a given project element. It may be measured on an annualized basis or for some specified time period of interest, such as the project life. Mathematically, reliability is expressed as:

$$\text{RELIABILITY} = 1 - \text{PROBABILITY}\ [\textit{Adverse Behavior or Failure}] \qquad (1)$$

Risk - A measure of the exposure to, or consequences of, an adverse outcome.

2. DESIGN STEP FORMAT

The Design Step Format utilizes 8 steps where design/performance goals become increasingly more stringent in progressing from Step 1 through Step 8 (Figure 1). Design Step 1 is applicable where the downstream consequences of failure would be minimal and there would be no potential for loss of life. The design/performance goal at Step 1 has an Annual Exceedance Probability (AEP) of 1 in 500, one chance in 500 of being exceeded in any given year. This design/performance goal is consistent with engineering design practice for dams in similar low hazard settings (National Research Council[1,7], ICE[5], ICOLD[6], BC Hydro[33]).

Design Step 8 is applicable where the consequences of dam failure could be catastrophic with hundreds of lives at risk. In this situation, extreme design events and design loads are appropriate to provide the extremely high levels of reliability needed to properly protect the public. For Design Step 8, the maximum design/performance goal is set at an AEP of 10^{-6} (1 chance in 1 million). This corresponds to theoretical maximum design events and loading conditions for some project elements. The use of a design/performance goal with an AEP of 10^{-6} is based on existing design standards (EPRI[25]) and review of recommendations for engineered structures with similar extremely serious consequences of failure (CSS[10], Kennedy[23], BC Hydro[33], Nuclear Regulatory Commission[8], Newton[9]).

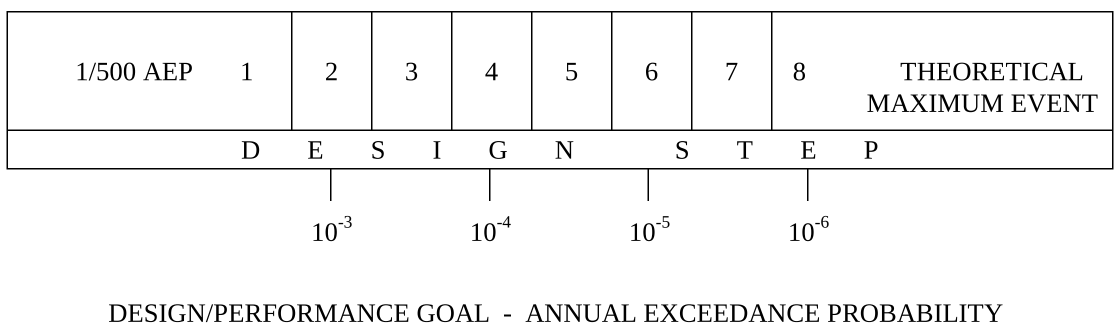


FIGURE 1. DESIGN STEP FORMAT FOR DESIGN/PERFORMANCE GOALS

To complete the 8 step format, design/performance goals should consistently and progressively increase between steps 1 and 8. This is accomplished by providing uniform performance increments between the design steps. A review of Figure 1 shows the annual exceedance probability of the design/performance goals decrease tenfold for every two design steps. Thus, this format strives to provide a reliability of design/evaluation with a tenfold increase in protection from failure for every two step increase.

3. DECISION FRAMEWORK

A decision framework for selection of appropriate design/performance goals was developed using an additive weighting scheme[11,12,29] to incorporate numerical indicators of the consequences of a dam failure into the design step format. The numerical methods for assessing the consequences of a dam failure and for calibrating the additive weighting scheme are discussed in following sections.

3.1 ASSESSMENT OF CONSEQUENCES OF DAM FAILURE

The first component of the decision framework is the assessment of the consequences of dam failure. In order to assess the consequences of failure, information is needed on the magnitude of the dam break flood which could occur from a given failure mode and the resultant inundation in downstream areas.

Information and technical references are contained in Technical Note 1, entitled *Dam Break Inundation Analysis and Downstream Hazard Assessment*[32], to assist engineers in conducting dam break analyses and downstream inundation mapping. In particular, simplified procedures are identified in Technical Note 1 which are appropriate for small projects in undeveloped settings. After the dam break inundation analyses are complete, an assessment of the consequences of dam failure can be made.

There are a number of considerations in assessing the consequences of dam failure. These considerations can be grouped into three general categories.

Capital Value of Project - This category would include the capital value of the project elements which would be destroyed or damaged, and the loss of the benefits, services, revenues, or aesthetics provided by the project.

Potential for Loss of Life - This category would include considerations for: the population at risk in downstream areas; the catastrophic nature of the dam breach flood; the adequacy of warning to downstream inhabitants; and the potential for future downstream development.

Potential for Property Damage - This category would include the amount of damage to: residential and commercial property; transportation facilities such as roads and bridges; damage and disruption of lifeline and community service facilities; and environmental degradation from projects with deleterious reservoir contents.

3.2 ADDITIVE WEIGHTING SCHEME

A review of the three categories of consequences reveals that some consequences are primarily economic and directly affect the owner, such as the loss of the dam and the benefits it provides. Other consequences may be economic, aesthetic or environmental and affect downstream property or cause disruption of community services. Still other consequences such as loss of human life are not easily amenable to economic or value analysis. In the past, methodologies proposed for selection of design levels which were based primarily on economic considerations (Buehler[13], ASCE[14], ASCE[15]) have been met with limited acceptance.

This variety of potential consequences makes attempts at using direct analytical methods for decision making a very difficult task - because there is no common ground of comparison among the various consequences.

An alternative is to use the principles of decision theory to develop a procedure for decision making. An additive weighting scheme is a simple tool from decision theory which is particularly suited to choosing among a set of alternatives (in this case, choosing design/performance goals as represented by 1 of 8 design steps) when the factors to be considered (the consequences) are many and varied.

The additive weighting scheme employs numerical ratings of the consequences which reflect the relative importance of each consequence and the range of severity of the impacts possible for each consequence. The summation of the rating points from each consequence is then used to establish the characteristics of the consequences of failure of a given project as measured against a scale reflecting the possible range of consequence rating points.

Cumulative consequence rating points with values between 200 and 600 points were used to define the working range for the 8 step format (Figure 2). Each design step increase corresponds to an increase of 50 consequence rating points over the previous step. An increase of 100 rating points corresponds to a two step increase and a tenfold increase in the reliability afforded at the higher design/performance goal.

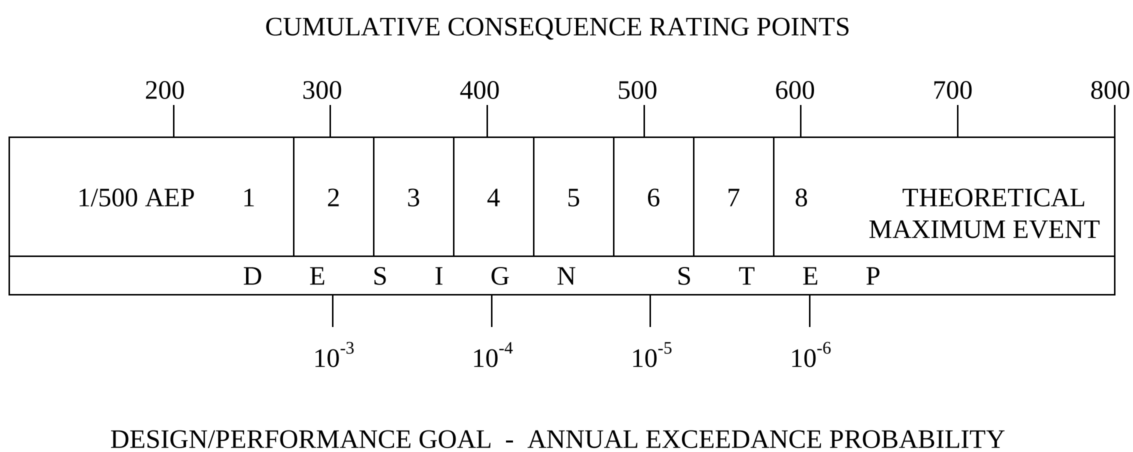


FIGURE 2. DESIGN STEP FORMAT AND CONSEQUENCE RATING POINTS

Final selection of the weighting factors for each consequence (the consequence rating points) was based on calibration of the additive weighting scheme (Section 4) against a preselected set of idealized project types. These idealized project types and their associated consequence "settings" were used to establish benchmarks or calibration.

3.3 NUMERICAL RATING OF CONSEQUENCES

Factors were identified within each of the three general categories of consequences, which were descriptive of the nature of the consequences within that category. These factors were selected because they are indicator parameters for the consequences and because they are amenable to quantification. As a broad reference, the three general consequence categories, indicator parameters and range of rating points are summarized in Table 2.

TABLE 2. NUMERICAL RATING FORMAT FOR ADDITIVE WEIGHTING SCHEME FOR ASSESSING CONSEQUENCES OF DAM FAILURE

CONSEQUENCE CATEGORIES	CONSEQUENCE RATING POINTS	INDICATOR PARAMETER	CONSIDERATIONS
CAPITAL VALUE OF PROJECT	0 - 150	DAM HEIGHT	Capital Value of Dam
	0 - 75	PROJECT BENEFITS	Revenue Generation or Value of Reservoir Contents
POTENTIAL FOR LOSS OF LIFE	0 - 75	CATASTROPHIC INDEX	Ratio of Dam Breach Peak Discharge to 100 Year Flood
	0 - 300	POPULATION AT RISK	Population at Risk Potential for Future Development
	0 - 100	ADEQUACY OF WARNING	Likely Adequacy of Warning in Event of Dam Failure
POTENTIAL FOR PROPERTY DAMAGE	0 - 250	ITEMS DAMAGED OR SERVICES DISRUPTED	Residential and Commercial Property Roads, Bridges, Transportation Facilities Lifeline Facilities Community Services Environmental Degradation from Reservoir Contents (Tailings, Wastes, etc.)

A complete description of the procedures for determining the consequence rating points for each of the indicator parameters is presented in the following sections. A Worksheet is contained in Appendix B for compiling the rating points and selecting an appropriate design Step.

3.3.1 Capital Value of Project

Two indicator parameters are used to describe the capital value of the project, Dam Height and Project Benefits.

3.3.1.1 Dam Height Index - Dam height is readily seen as indicative of the capital value of a dam. Large dams cost more to construct or replace than small dams. However, there are economy of scale effects, as measured by unit costs, which make small dams disproportionately more expensive to construct than large dams. There are also some engineering planning and design costs which do not change significantly with the scale of a project. These factors result in a non-linear type of utility curve (Figure 3) and give heavier marginal weights to the smaller dams. The appropriateness of the general shape of this curve for relating the rating points to dam height was confirmed during calibration of the additive weighting scheme.

3.3.1.2 Project Benefits - Another indicator of the capital value of the project is the benefits provided by the project. These benefits may be lost entirely or disrupted for some period of time following a dam failure. Project benefits may be separated into two sub-categories.

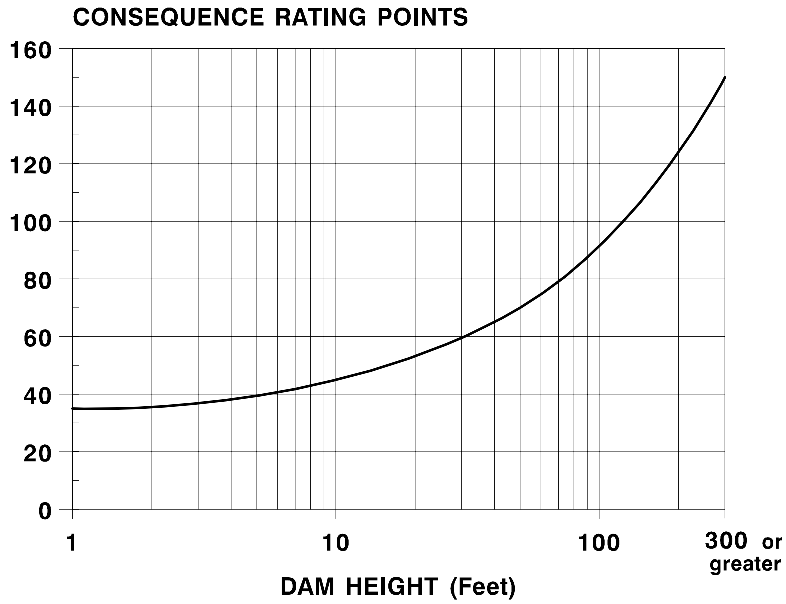


FIGURE 3. CONSEQUENCE RATING POINTS FOR DAM HEIGHT INDEX

One sub-category would include those project benefits whose loss would be a loss of a limited resource and the general public would be directly and adversely affected. Loss of project benefits of this type are a mandatory consideration in assessing the consequences of dam failure.

The second sub-category would include those project benefits whose loss would primarily affect the project owner and private enterprise. Discretion may be used in including or excluding these items in assessing the consequences of dam failure. Table 2 lists the range of consequence rating points applicable to common project types.

A review of Table 2 shows a wide range of consequence rating points are possible. Selection of an appropriate value should be based on the size and importance of the project under consideration relative to the broad range of projects of that type. In addition, a larger or smaller value may be selected depending on the need for conservatism in protecting that project benefit.

3.3.2 Potential for Loss of Life

Determining the consequence rating points for the Loss of Life Category involves assessing three indicator parameters: the *Catastrophic Potential Index*; the *Population at Risk* in downstream areas, including the potential for future development; and the *Adequacy of Warning* to downstream residents.

3.3.2.1 Catastrophic Potential Index - The Catastrophic Potential Index serves as a measure of the catastrophic damage potential of the dam break flood. Numerically, it is the ratio of the estimated dam break flood peak discharge at the dam site to the magnitude of the 100 year flood peak discharge. It gives a simple indication of the magnitude of the dam break flood relative to large floods for the receiving stream and valley configuration. It is to be evaluated and used for all dams regardless of the downstream hazard setting.

TABLE 2. CONSEQUENCE RATING POINTS FOR LOSS OF PROJECT BENEFITS

CONSEQUENCE SUB CATEGORY	CONSIDERATION	TYPICAL EXAMPLES	RATING POINTS
LIMITED RESOURCE LOSS WOULD AFFECT GENERAL PUBLIC	MANDATORY	PUBLIC WATER SUPPLY RESERVOIR	25 - 75
PRIVATE ENTERPRISE LOSS WOULD NOT AFFECT GENERAL PUBLIC	DISCRETIONARY	IRRIGATION OR INDUSTRIAL WATER SUPPLY	10 - 75
		HYDROPOWER GENERATION	10 - 75
		MINING OR MANUFACTURING	10 - 75
		AESTHETICS, RECREATION OR WILDLIFE HABITAT	10 - 25

The 100 year flood should be computed for the natural watercourse downstream of the dam at a point where the first residence would be affected by flooding from a dam failure. If there are no permanent dwellings downstream, the 100 year flood should be evaluated at a point on a natural watercourse 1 mile downstream of the dam.

The utility curves for the Catastrophic Potential Index are shown in Figure 4. There are three curves, one each for small, intermediate and large dams to reflect the differing potential for catastrophic damage from a dam break flood.

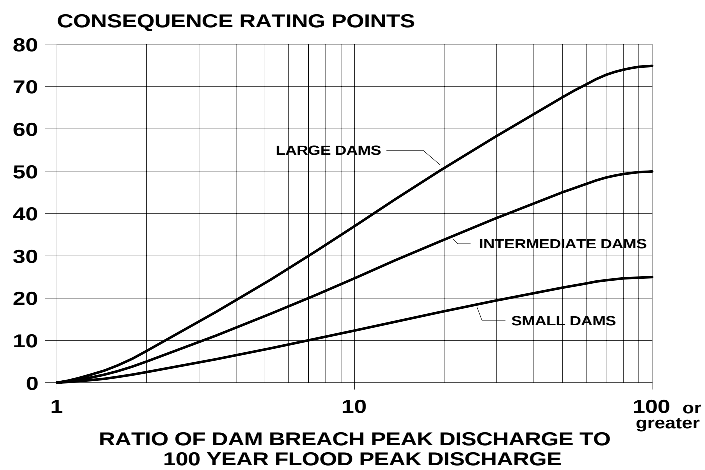


FIGURE 4. CONSEQUENCE RATING POINTS FOR CATASTROPHIC POTENTIAL INDEX

Estimation of the 100 year flood for locations on ungaged streams within Washington may be made using regression equations developed by the U.S. Geological Survey (USGS)[16,17]. These equations were developed using flood frequency analysis methods for floods recorded at streamflow gaging stations throughout the state.

3.3.2.2 Population at Risk - The Population at Risk is used as an indicator for the potential for loss of life from flooding produced by a dam failure. Population at Risk essentially corresponds to the number of people who would have to evacuate from downstream areas in the event of a dam failure. Population at Risk is defined in WAC 173-175-030 as - "the number of people who may be present in areas downstream of a dam and could be in danger in the event of a dam failure". This definition includes persons at permanent dwellings, worksites and at temporary use areas.

Estimation of the Population at Risk (PAR) can be made based on information and technical references contained in Technical Note 1, entitled *Dam Break Inundation Analysis and Downstream Hazard Assessment*[32]. It is common practice to use a value of 3 persons per inhabited dwelling[18] if no other specific information is known.

Site specific information about the likely occupancy should be used at worksites such as water or wastewater treatment facilities, manufacturing or production facilities, farming operations, fish hatcheries, etc. Seasonal use information should be used in addition to inundation mapping at temporary use facilities such as resorts, campgrounds and recreational areas to assess the likely PAR. In all cases, conservative judgement should be exercised in estimating the areas that would be inundated and the population at risk.

A comparison of the magnitude of the consequence rating points for the various consequence categories reveals that the PAR is a dominant factor in determining the design step. Development of the utility curve for PAR was based on information collected by the Bureau of Reclamation[19] concerning loss of life resulting from dam failures and other natural hazards. In their studies it was found that the actual loss of life relative to the population at risk dropped dramatically when there is adequate warning of danger. In particular, there was a significant reduction in fatalities when 5 minutes to 90 minutes of warning was available. An envelope curve for estimating the Loss of Life (LOL) when there is greater than 5 minutes of warning can be expressed as a function of the PAR as:

$$LOL = (PAR)^{.6} \qquad (2)$$

It was further found[19] that with 90 minutes or more of warning time, there were few lives lost even in cases where thousands had to be evacuated. An envelope curve for estimating the loss of life when there is 90 minutes or more of warning can be expressed as:

$$LOL = (PAR)/5000 \qquad (3)$$

Based on this information, Equation 2 was used to establish the general shape of the utility curve for the PAR (Figure 5). The assignment of the consequence points was based on the results of calibration of the additive weighting scheme as measured against a number of selected benchmarks (see Section 4, *Calibration*).

<u>Potential for Future Development</u> - It should be recognized that future downstream development may increase the population at risk during the life of the project. At some time in the future, increased development could be cause for a reassessment of the Downstream Hazard

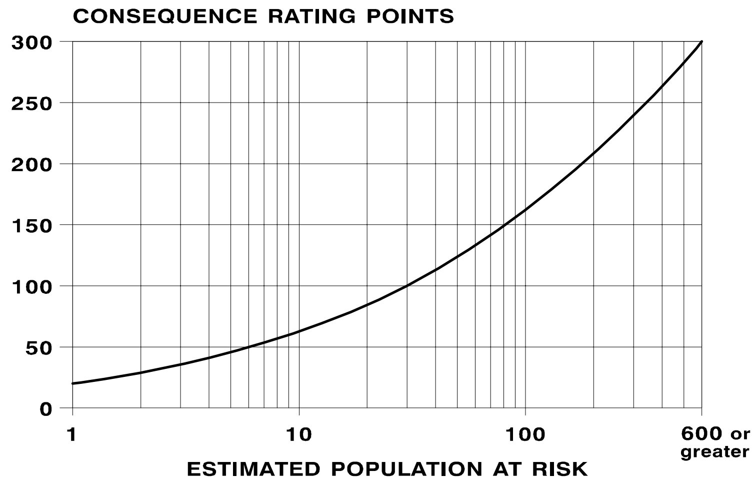


FIGURE 5. CONSEQUENCE RATING POINTS FOR POPULATION AT RISK

Classification and the corresponding design step which is needed to provide adequate protection for those living downstream of the dam.

To reduce the need for some future upgrade of a project as a result of increased downstream development, an estimate of likely future development should be made and incorporated into the current estimate of the population at risk. It is recommended that a period of 15 to 20 years be considered when assessing future development. Forecasting of future development will undoubtedly be subject to much speculation. Nonetheless, it is important that this aspect of the problem be consciously addressed during the planning and design stage of a project.

3.3.2.3 Adequacy of Warning - The adequacy of warning is a key factor in determining the threat to loss of life from a dam failure. Studies by the Bureau of Reclamation[19] have shown that advanced warning of danger of as little as 5 minutes can significantly reduce the potential for loss of life. When a warning time of 90 minutes or more has been available, very few fatalities have occurred. Warning to the downstream residents may occur as a result of an official alert by: local emergency authorities; radio, telephone or on-site notification; or by recognition of the unusual flood conditions by the persons at risk.

Advanced Warning Time as used in this technical note is defined as the amount of time available for evacuation *after notification* of a dangerous situation or *after self-recognition* of a dangerous situation.

Estimation of advanced warning time should consider the characteristics of the failure mode for the critical project element under consideration and the time required for a responsible party to observe and recognize the dangerous situation and to initiate the procedures for alerting the downstream residents. Adverse factors such as the possibility of the event occurring at night and the disruption of normal communications should also be considered.

In those cases where no outside source initiates a warning, self-recognition of the onset of unusual flooding may be the only way in which downstream residents would be alerted. The advanced warning time for cases of self-recognition would depend primarily on the quickness with which the dangerous flood levels could occur at a given location.

Warning times for failures initiated by natural flooding are generally greater than from other causes because the unusual meteorological conditions can provide significant advance notice of potential problems. In addition, the ongoing natural flood in advance of a failure oftentimes alerts downstream residents of the potential danger. Warning times for other critical failure modes, such as earthquakes, are often shorter because the problem may develop quickly following the triggering event.

Characteristics of inadequate warning situations would include: projects which are located in remote areas and not subject to observation by the dam owner, dam tender or the public; narrow confining valleys where evacuation routes are aligned along the valley floor and there is limited access to high ground; and dam failure causes, such as earthquakes, which may catch the downstream inhabitants by surprise.

Guidance in determining the adequacy of warning is provide in Table 4. The cumulative Warning Index Points from Table 4 are to be used in conjunction with Figure 6 in determining the consequence rating points and in classifying the adequacy of warning. Site specific information and sound judgement should be used to assess the characteristics of: the causative event; the likelihood that the dangerous situation would be observed and recognized; and the ease of evacuation based on the setting in the downstream valley.

3.3.3 Potential for Property Damage

3.3.3.1 Property Damage - Property damages would include damage to inhabited dwellings, commercial and production buildings, loss of livestock, agricultural lands and crops, roads, highways and utilities and the associated economic losses both permanent and temporary. This would also include damages to lifeline facilities and economic disruption. The intent, in considering the potential property damage and economic loss, is to identify the relative magnitude of losses against a broad scale of values. No attempt is made to assess actual fair market value or actual dollar losses.

Assignment of consequence rating points for property damage to residential development is shown in Figure 7. The shape of the utility curve and the assignment of consequence points for residential property damage was based on calibration of the additive weighting scheme.

General guidance in assignment of consequence rating points for a variety of types of property damages and economic losses is contained in Table 5. More specific information is listed in the Worksheet in Appendix B.

TABLE 4. CHARACTERISTICS OF ADEQUATE, MARGINAL AND INADEQUATE WARNING

FACTOR	ADEQUATE WARNING	MARGINAL WARNING	INADEQUATE WARNING
ADVANCED WARNING TIME	More than 30 minutes *0 Warning Index Points*	More Than 10 Minutes but Less Than 30 Minutes *25 Warning Index Points*	Less Than 10 Minutes *50 Warning Index Points*
LIKELIHOOD OF DANGEROUS SITUATION TO BE OBSERVED AND NOTIFICATION GIVEN TO GENERAL PUBLIC	Dam Owner Resides near Dam Site, or Designated Responsible Party Has Reasonably Short Access Time to Dam Site and has Duty of Initiating Warning *0 Warning Index Points*	Designated Responsible Party not Located near Dam Site, but Dam Site is Visible to General Public. There is Reasonably Good Vehicular Access near Dam Site and Intermittent Vehicular Traffic. *15 Warning Index Points*	No Designated Responsible Party near Dam Site. Dam in Remote Location. Poor Vehicular Access to Dam Site. *30 Warning Index Points*
DOWNSTREAM VALLEY SETTING AND EASE OF EVACUATION	Valleys with Good Access to High Ground and Good Roadway Systems for Escape Routes *0 Warning Index Points*	Valleys with Limited Access to High Ground and Limited Roadway Systems *10 Warning Index Points*	Narrow Confining Valley with Roadways near the Stream Bank or Along Valley Floor and Poor Access to High Ground *20 Warning Index Points*

The adequacy of warning is only considered in those cases where there is a potential for loss of life.

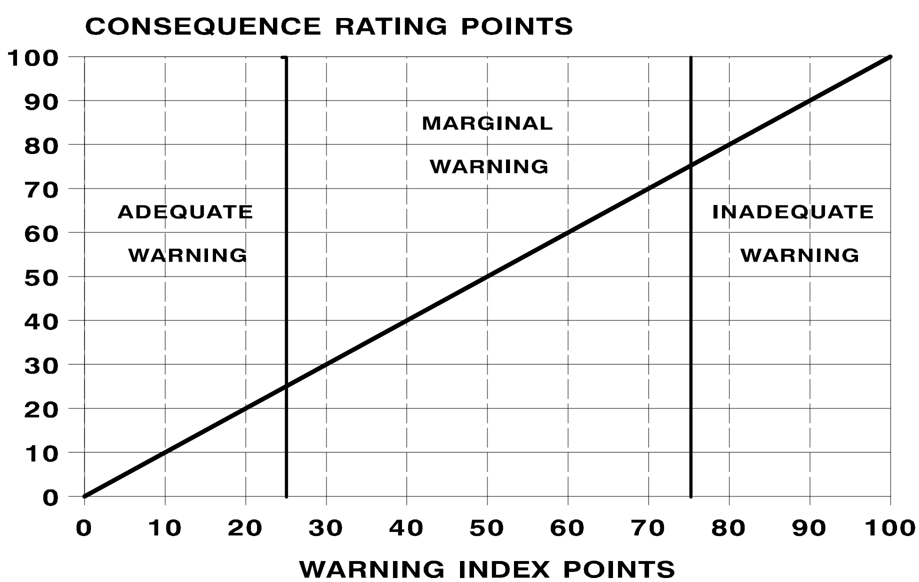


FIGURE 6. CONSEQUENCE RATING POINTS FOR ADEQUACY OF WARNING

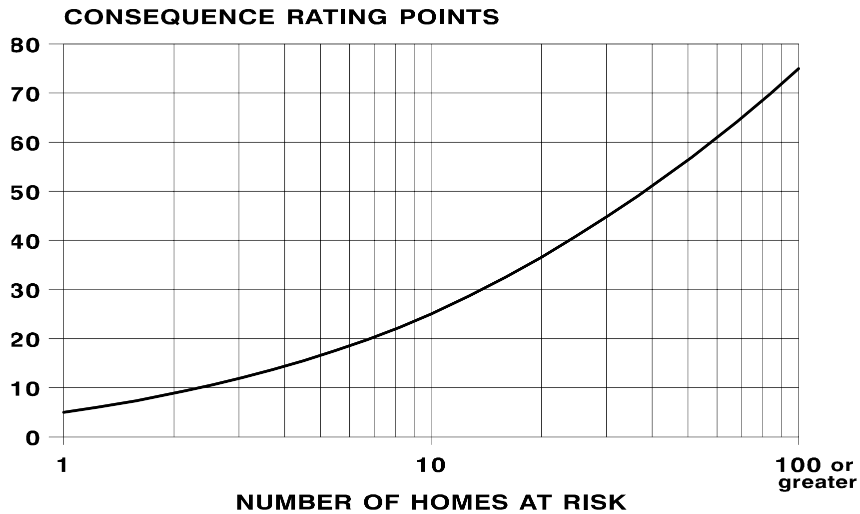


FIGURE 7. CONSEQUENCE RATING POINTS FOR PROPERTY DAMAGE TO RESIDENCES

TABLE 5. CHARACTERISTIC VALUES OF CONSEQUENCE RATING POINTS FOR PROPERTY DAMAGES, ECONOMIC DISRUPTION AND ENVIRONMENTAL DAMAGES

ITEMS DAMAGED	CONSEQUENCE POINTS
INTERSTATE HIGHWAYS	25
STATE HIGHWAYS	10
WATER SUPPLY TREATMENT FACILITIES	10 - 25
POLICE, FIRE OR EMERGENCY RESPONSE UNITS	10 - 75
INDUSTRIAL AND COMMERCIAL DEVELOPMENTS	5 - 75
FISH HATCHERIES	5 - 25
LONG TERM ENVIRONMENTAL DAMAGE FROM DELETERIOUS RESERVOIR CONTENTS	10 - 75

The range of consequence rating points listed in Table 5 and in the Worksheet reflect both the importance of a facility and the relative magnitude of expected damages based on the depth of flooding. General guidance in selecting an appropriate value may be obtained by comparison of the size and importance of the item of interest relative to the broad range of features of that type.

In addition, a larger or smaller value may be selected depending on the need for conservatism in protecting the item that could be damaged.

3.3.3.2 Environmental Damages - Consideration of environmental damages would address situations where the reservoir contains materials which may be deleterious to human or aquatic life or stream habitat. This applies to projects such as: domestic and agricultural waste lagoons; industrial waste lagoons; and mine tailings dams where the reservoir may contain trace amounts of heavy metals, chemical residues from ore processing, or large volumes of sediment in a loose or slurry condition.

Temporary damages to stream habitat are also to be considered. This would apply to streams with fisheries of regional significance where large scale channel scour and sediment deposition are likely to be caused by a dam break flood. General guidance in assignment of consequence rating points for environmental damages is contained in Table 5 and more specific information is listed in the Worksheet in Appendix B.

4. CALIBRATION OF ADDITIVE WEIGHTING SCHEME

Calibration of the additive weighting scheme was essential for ensuring the useability and consistency of the decision framework across the range of design steps. The calibration procedure was comprised of several components. First, idealized project types were used to create several benchmarks for establishing a fixed relationship between the idealized project types, downstream hazard settings, consequence rating points and the Annual Exceedance Probabilities (AEPs) of the design/performance goals for the design steps (Figure 2, Table 6).

TABLE 6. BENCHMARKS FOR CALIBRATING POINT RATING ALGORITHM FOR USE IN DECISION FRAMEWORK

BENCHMARK	CHARACTERISTICS OF IDEALIZED PROJECTS	MINIMUM DESIGN STEP	DESIGN LEVEL AEP
1	1 or More Lives at Risk	3	3×10^{-4}
2	Large Dam, over 50 feet High No Downstream Hazard	3	3×10^{-4}
3	Intermediate Dam No Commercial Development 10 Residences at Risk	4	10^{-4}
4	Large Dam Limited Commercial Development 34 Residences at Risk	6	10^{-5}
5	Large Dam Significant Commercial Development 100 Residences at Risk	8	10^{-6}

The basic concept in setting these benchmarks was to use the broad spectrum of engineering design practice as a reference for establishing design/performance goals. While direct situational comparisons are few, there are enough similarities to provide sound guidance (Foster[20]). This approach provides a means of setting design/performance goals which are consistent with levels of safety provided by other engineering disciplines and by existing government regulation in other engineering and product safety areas. This aspect of the decision framework is explained in more detail in the *Commentary* section, Appendix A.

Second, a representative sample of 15 existing projects in Washington was assembled. This representative sample was used to check the results of the additive weighting scheme against the desired total of consequence rating points for preselected benchmarks. Third, adjustments were made to the utility curves to calibrate the additive weighting scheme to meet the constraints posed by the benchmarks.

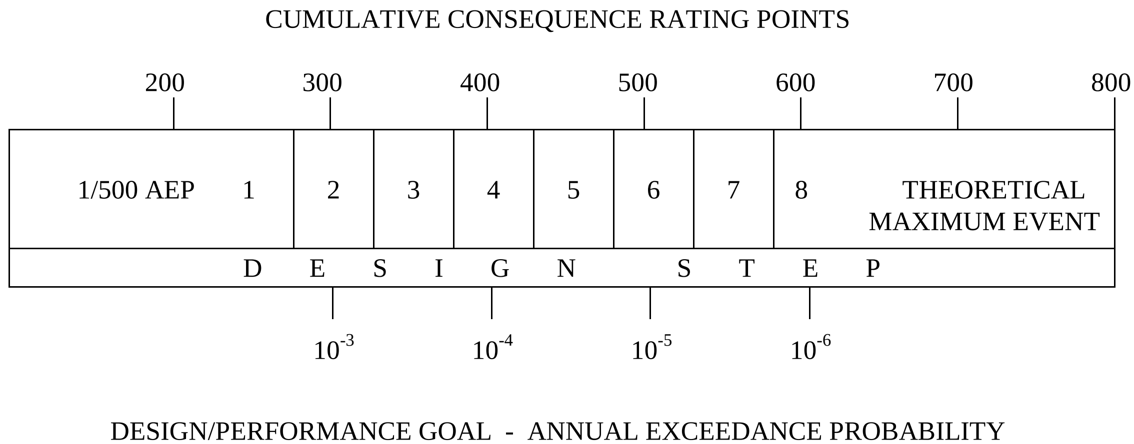
The utility curves and tables for consequence rating points presented previously incorporate adjustments made during calibration. In particular, during the calibration process it was determined that 150 Base

Points need to be added to properly adjust the cumulative consequence rating points within the working range of the 8 step format.

It should be recognized that the magnitude of consequence points for various factors do not necessarily reflect the relative importance of those factors. Rather, they are the end product of the calibration process and must account for the resultant total of consequence points for the numerous combinations of factors which occur in normal usage of the additive weighting scheme.

5. APPLICATION OF DECISION FRAMEWORK

Application of the additive weighting scheme to a given project proceeds by assessing the consequence rating points for each of the indicator parameters discussed in Section 3, *Decision Framework*. For ease of application, a copyable Worksheet is contained in Appendix B for tabulating the rating points. The cumulative consequence rating points are then used in conjunction with the design step format (originally shown in Figure 2) to select the appropriate design step.



5.1 <u>SELECTION OF THE DESIGN STEP</u>

There are a number of issues which should be considered when applying this decision framework to selection of a design step. Issues regarding multiple modes of failure, projects with multiple dams, the use of engineering judgement, and design minimums are discussed in the following sections.

5.1.1 Modes of Failure for Various Critical Project Elements

When these procedures are applied to the selection of a design step for each critical element of a project, it is possible that different design steps may be indicated for each element. This can occur because different reservoir levels, dam break floods, downstream damages and warning situations may be present for different failure modes.

However, it has been our experience that in most cases the design steps selected for the various critical elements differ by only one step. It has been found that a reasonable approach for applying the decision framework is to evaluate the consequences for the failure mode that would produce the most severe consequences and then to use that design step and design/performance goal for the design of all critical project elements. This is in keeping with the concept of *Balanced Protection* and striving to achieve reasonably similar levels of conservatism and reliability in the performance of all critical project elements.

Under most circumstances, a dam failure produced by overtopping by floodwaters would produce the greater depth of inundation and the more severe consequences. This failure mode should normally be examined first in determining the design step and design/performance goal to be used in the design of all critical project elements.

5.1.2 Projects with Multiple Dams

Complications may arise when applying the decision framework to projects where a reservoir is impounded by two or more dams. In these situations, it is common that the dams are of different sizes and have different consequences if they were to fail. Thus, it is reasonable that the design levels and loadings for each dam may be different. In simple terms, the design levels and protection afforded for the larger dam(s) should be greater because of the more severe consequences of failure.

5.1.3 Dams in Series

When several dams are situated on a watercourse, the failure of an upstream dam may cause failure of one or more downstream dams. In these cases, the assessment of the consequences of failure of an upstream dam must include the additional consequences of failure of any downstream dam. Specifically, the design step for any upstream dam which can cause failure of a downstream dam(s) must be equal to or greater than the design step for the downstream dam(s).

5.1.4 Engineering Judgement

It should be recognized that this Decision Framework is an aid to decision making and is not intended to replace sound engineering judgement. It is possible that situations will arise where prudent reasoning will indicate that a higher, or lower, Design Step is appropriate for a given project. Owners and their engineering consultants are encouraged to use this decision framework in a conservative manner and to provide as much design protection as practicable.

5.1.5 Design Step Minimums

As discussed previously, the Decision Framework provides the numerical basis for selection of a design step. However, there are situations, particularly for small dams with limited downstream hazard potential, where the numerical value of the consequence rating points may not correspond to an adequate design step. To preclude this situation, ***Design Step 3 is the minimum design step when any lives are at risk*.**

In addition, it is recommended that the user compare the magnitude of the design step and the individual consequence rating points with the calibration benchmarks in Table 6. If the design step differs significantly from that indicated by the generic benchmarks, the consequence rating points should be carefully reviewed to determine the reasonableness of the selected design step.

5.2 RELATIONSHIP OF DESIGN STEP TO DOWNSTREAM HAZARD CLASSIFICATION

Oftentimes during the planning stage of a project there is a need to make a quick assessment of the value of the design step. This can be accomplished by utilizing the Downstream Hazard Classification for the project as a rough indicator for the design step. Experience has shown that the value of the design step typically falls within a small range for each of the Downstream Hazard Classes as shown in Table 7.

TABLE 7. RELATIONSHIP OF DESIGN STEP TO DOWNSTREAM HAZARD CLASSIFICATION

DOWNSTREAM HAZARD POTENTIAL	DOWNSTREAM HAZARD CLASSIFICATION	POPULATION AT RISK	ECONOMIC LOSS GENERIC DESCRIPTIONS	ENVIRONMENTAL DAMAGES	TYPICAL DESIGN STEP
LOW	3	0	Minimal. No inhabited structures. Limited agriculture development.	No deleterious materials in reservoir	1 - 2
SIGNIFICANT	2	1 to 6	Appreciable. 1 or 2 inhabited structures. Notable agriculture or work sites. Secondary highway and/or rail lines.	Limited water quality degradation from reservoir contents and only short term consequences	3 - 4
HIGH	1C	7 to 30	Major. 3 to 10 inhabited structures. Low density suburban area with some industry and work sites. Primary highways and rail lines.	Severe water quality degradation potential from reservoir contents and long term effects on aquatic and human life	3 - 6
HIGH	1B	31-300	Extreme. 11 to 100 inhabited structures. Medium density suburban or urban area with associated industry, property and transportation features.		4 - 8
HIGH	1A	More than 300	Extreme. More than 100 inhabited structures. Highly developed, densely populated suburban or urban area with associated industry, property, transportation and community life line features.		8

6. SUMMARY

The concepts of *Consequence Dependent Design Levels* and *Balanced Protection* are the cornerstones of the decision framework employed here. The decision methodologies utilize probabilistic concepts for establishing the format for the design/performance goals to be used for the various critical project elements. Probabilistic methods were chosen because they offered the capability of implementing a balanced protection approach for selecting design/performance goals across a range of engineering disciplines. This decision framework is intended to provide a consistent and rational approach to the selection of design/performance goals for the design and evaluation of critical project elements.

7. REFERENCES

1. National Research Council, Safety of Dams, Flood and Earthquake Criteria, Committee on Safety Criteria for Dams, Water Science Technology Board, Commission on Engineering and Technical Systems, National Science Council, National Academy Press, Washington, DC, 1985.

2. ASCE, Minimum Design Loads for Buildings and Other Structures, American Society of Civil Engineers, ASCE 7-88, July, 1990.

3. Middlebrooks, T.A., Earth Dam Practice in the United States, Centennial Transactions paper 2620, 1952, pp. 697-722.

4. Kennedy, R.P., Short, S.A., McDonald, M.W., McCann Jr., M.W., and Reed, J.W., Progress Towards Developing Consistent Design and Evaluation Guidelines for Department of Energy Facilities Subjected to Natural Phenomena Hazards, Proceedings DOE Natural Phenomena Hazards Mitigation Conference, Las Vegas, Nevada, 1985.

5. Institute of Civil Engineers (ICE), Reservoir Flood Standards, Institute of Hydrology, Wallingford, Great Britain, 1975.

6. Brouvard, M., Reporting for International Committee on Large Dams (ICOLD), 16^{th} Congress of ICOLD - IV, Water Power and Dam Construction, January, 1989.

7. California Dam Safety Program, Engineering Memorandum No. 49, Hydrology Design Criteria, April, 1976.

8. Nuclear Regulatory Commission (NRC), Standard Review Plan, NUREG-0800, Office of Nuclear Reactor Regulation, Section 2.2.3, Washington D.C., 1975, 1981.

9. Newton, D.M., Realistic Assessment of Maximum Flood Potentials, ASCE Hydraulics Journal, Vol. 9, June 1983, pp. 905-918.

10. Council for Science and Society (CSS), The Acceptability of Risks, Barry Rose Publishers Ltd., 1977, Great Britain, pp. 102.

11. Hayes, J.B., The Complete Problem Solver, Lawrence Erlbaum Associates Publishers, Hillsdale, N.N., 1989.

12. Keeney, R.L., Raiffa, H., Decisions with Multiple ObjectivesÑ Preferences and Value Tradeoffs, John Wiley and Sons, 1976.

13. Buehler, R., Monetary Value of Life and Health, ASCE Hydraulics Journal, January 1975, pp. 29-46.

14. ASCE Task Committee, Reevaluating Spillway Adequacy of Existing Dams, ASCE Hydraulics Journal, Feb. 1973, pp. 337-372 and discussion comments.

15. ASCE Task Committee, Evaluation Procedures for Hydrologic Safety of Dams, Report prepared by the ASCE Task Committee on Spillway Design Flood Selection of the Committee on Surface Water Hydrology of the Dydraulics Division, 1988.

16. Cummans, J.E., Collings, M.R. and Nassar, E.G., Magnitude and Frequency of Floods in Washington, USGS Open File Report 74-336, 1975.

17. Haushild, W.L., Estimation of Floods of Various Frequencies for the Small Ephemeral Streams in Eastern Washington, USGS Open File Report 79-81, 1979.

18. USBR, Downstream Hazard Classification Guidelines, ACER Technical Memorandum No. 11, Bureau of Reclamation, Denver, CO, December, 1988.

19. USBR, Guidelines to Decision Analysis, ACER Technical Memorandum No. 7, Bureau of Reclamation, Denver, CO, March, 1986, pp. C13-C23.

20. Foster, H.D., Disaster Planning, The Preservation of Life and Property, Springer-Verlag Publishers, 1980.

21. Starr, C., Social Benefit Versus Technological Risk, What is our Society Willing to Pay for Safety, Science, Vol. 165, Sept. 1969, pp. 1232-1238.

22. Okrent, D., Comment on Societal Risk, Science, Vol. 208, April 1980, pp. 1232-1238.

23. Kennedy, R.P., Short, S.A., McDonald, J.R. McCann, M.W. Jr., Murray, R.C. and Hill, J.R., Design and Evaluation Guidelines for Department of Energy Facilities Subjected to Natural Phenomena Hazards, United States Department of Energy, Office of the Assistant Secretary for Environment, Safety and Health, Report UCRL-15910, June 1990.

24. National Safety Council, Accident Facts, 1975, Chicago, Illinois.

25. Electric Power Research Institute (EPRI), Advanced Light Water Reactor Requirements Document, Appendix A, Probabilistic Risk Assessments Key Assumptions and Groundrules, EPRI, June, 1989.

26. Schaefer, M.G., Extreme Storm Characteristics - Application to Computing Inflow Design Floods in Washington State, Presented at Climatology and Flood Hydrology of the Rocky Mountains, October, 1990.

27. International Conference of Building Officials, Uniform Building Code, 1988 Edition, Whittier, California, 1988.

28. Graham, J.D., and Vaupel, J.W., The Value of Life: What Difference Does it Make, Risk/Benefit Analysis in Water Resources Planning and Management, Plenum Press, N.Y., 1981, pp. 223-243.

29. Keeney, R.L., Sitting of Energy Facilities, Academic Press, N.Y., 1980.

30. Iwan, W.D., Thiel, C.C., Housner, G.W., and Cornell, C.A., Seismic Safety Requalification of Offshore Plataforms, American Petroleum Institute, In Draft, March, 1992.

31. Cornell, C.A., Personal Communication, March 1992.

32. Schaefer, M.G., Dam Break Inundation Analysis and Downstream Hazard Classification, Technical Note 1, Dam Safety Guidelines, Washington State Dept. of Ecology, Olympia, WA, Repport 92-55E,

July 1992.

33. BC Hydro, Guidelines for Consequence Based Dam Safety Evaluations and Improvements, B.C. Hydro, Vancouver, B.C., Draft February, 1993.

ADDITIONAL REFERENCES

Covello, V.T. et al, The Analysis of Actual Versus Perceived Risks, Plenum Press, N.Y., 1983.

Mark, R.K., and Stuart-Alexander, D.E., Disasters as a Necessary Part of Benefit-Cost Analysis, Science, Vol. 197, pp. 1160-1162.

Puget Sound Council of Governments, Regional Disaster Mitigation Plan for the Central Puget Sound Region, 2 Volumes, 1975.

Royal Society of London, The Assessment and Perception of Risk, Royal Society, 1980.

Waller, R.A., and Covello, V.T., Low-Probability High Consequence Risk Analysis, Plenum Press, N.Y., 1984.

Wiggins, J.H., Generalized Description of the Concept of Risk, Acceptable Risk/Balanced Risk, Socio-Economic Aspect of Risk Taking/Decision Making, Conference on Seismic Risk Analysis Sponsored by Earthquake Engineering Research Institute, Feb. 1978.

Zeckhauser, R.J., and Viscusi, W.K., Risk Within Reason, Science, Vol. 248, May 1990, pp. 559-564.

APPENDIX A

A1. COMMENTARY ON SELECTION OF DESIGN/PERFORMANCE GOALS

One of the key decisions in the design of any engineered system is the selection of appropriate design events and design loads for the elements of the system. This technical note has presented the decision framework that was developed to aid in the selection of design/performance goals for use in establishing the magnitude of design events and design loads for design/evaluation of critical project elements. The approach taken herein was to use the broad spectrum of engineering design practice as a reference for setting benchmarks for design/performance goals. While direct situational comparisons are few, there are enough similarities between factors consider in dam design and those factors considered in the design of other engineered systems, to provide sound guidance. This approach has provided a means of setting design/performance goals which are consistent with levels of safety provided by other engineering disciplines and by existing governmental regulation in other engineering and product safety areas.

A1.1 SETTING BENCHMARKS FOR DESIGN/PERFORMANCE GOALS

In many engineering applications, the design levels and corresponding design events and design loads are set by industry standards or codes which provide either guidance or set design minimums. Unfortunately, the embodiment of the design levels into standards/codes usually obfuscates the actual levels of protection afforded by the standards. This result is not entirely unintentional. Governing bodies and standards boards are often hesitant to openly discuss issues of system reliability, acceptable levels of risk and probabilities of failure for those cases where a system failure could pose a threat to life. These issues are very sensitive, often controversial, and are not easily explained in a public forum.

This situation requires that many of the standards and codes be examined and the design levels and associated probabilities of failure or adverse performance be back-calculated. This type of back-calculation was used by Kennedy et al[4,23] in examining building codes to estimate the performance levels achieved by most building codes. These values helped form the basis for establishing design/performance goals for use in design and evaluation of Department of Energy facilities[23]. That information, as well as other sources provided the background data necessary for setting the benchmarks (Table A1) for the design/performance goals presented in this technical note.

Additional guidance in setting design/performance goals was obtained by examining the levels of risk to which the public is exposed in ordinary life. Several of these types of risks, such as risk of fatalities from disease and accidental death are shown in Table A2. These types of comparisons helped give some perspective between the broad spectrum of life risks[28] and risk/protection levels employed in engineering design.

A review of the data in Table A2 reveals a basic trend. In those activities where few lives are at risk and the activity is voluntary in nature, nominal levels of protection are accepted by the general public (Starr[21]). Conversely, as the number of persons at risk and the level of hazard to the public from a certain activity increases - the level of protection expected by society and the engineering professions increases significantly. This viewpoint is called "risk averse" with regard to the loss of life. The Decision Framework presented here reflects a risk averse position in utilizing the concepts of *Consequent Dependent Design Levels*.

TABLE A1 - BENCHMARKS FOR CALIBRATING POINT RATING ALGORITHM FOR USE IN DECISION FRAMEWORK

BENCHMARK	CHARACTERISTICS OF IDEALIZED PROJECTS	MINIMUM DESIGN STEP	DESIGN/PERFORMANCE GOAL AEP
1	1 or More Lives at Risk	3	3×10^{-4}
2	Large Dam, over 50 feet High No Downstream Hazard	3	3×10^{-4}
3	Intermediate Dam No Commercial Development 10 Residences at Risk	4	10^{-4}
4	Large Dam Limited Commercial Development 34 Residences at Risk	6	10^{-5}
5	Large Dam Significant Commercial Development 100 Residences at Risk	8	10^{-6}

Note: AEP - Annual Exceedance Probability

A1.1.1 Calibration Benchmarks

Several idealized dam project types were used to establish the benchmarks used for calibration of the additive weighting scheme. As an example, the performance level for ordinary structures achieved by most building codes[23,27] for the protection of building occupants, and the levels of risk for accidental death were used to conservatively set the minimum level of protection acceptable for use in dam design and construction for the case where one life could be at risk from a dam failure. This situation is represented by Benchmark 1, originally shown in Table 5 and repeated here for reference.

Benchmark 2 represents the case where there would be a significant capital investment in the structure but no lives would be at risk. This situation compares well to that of any substantial building and thus the performance level reflected in the uniform building code was used to set the design/performance goal.

The situation for Benchmark 3 compares well with that for the British Spillway Design Standard[5] and is also consistent with the performance level for important facilities as designated in the ASCE - *Minimum Design Loads for Buildings and Other Structures*[23].

TABLE A2 - LISTING OF RISKS FOR VARIOUS ACTIVITIES AND PERFORMANCE LEVELS FOR VARIOUS ENGINEERED SYSTEMS

ACTIVITY/ITEM	TYPICAL NUMBER OF PERSONS AT RISK	RISK LEVEL	PERFORMANCE LEVEL
NATIONAL FLOOD INSURANCE PROGRAM • Risk from Natural Flooding	Varies Widely		1/100 AEP 100 Year Flood
FATAL DISEASE[21] • All Causes	1	1/120 AC	
ASCE STRUCTURAL CODE[2] • Performance of Individual Structural Members for Ordinary Buildings Subject to Natural Hazards due to Wind and Earthquake Loads	Typically 1-20		1/1000 AEP
EXISTING OFFSHORE DRILLING PLATFORMS[30] • Performance Subject to Wind, Wave and Earthquake Loads	Varies 0 - 25		1/1000 AEP
ACCIDENTAL DEATH[24] • All Causes	Few 1-3	1/2000 AC	
ACCIDENTAL DEATH[24] • Motor Vehicles	1-6	1/3000 AC	
ACCIDENTAL DEATH[24] • Non-Motor Vehicles	Few 1-3	1/6000 AC	
UNIFORM BUILDING CODE[23,27] • Performance of Essential Buildings such as Hospitals and Emergency Response Facilities to Maintain Building Functionality and Protect Occupants for Buildings Subjected to Wind and Earthquake Loads	Typically 50-200		1/5,000 AEP
BRITISH SPILLWAY DESIGN[5]	Small Community More than 30		1/10,000 AEP 10,000 Year Flood
DEPT. OF ENERGY BUILDINGS[4,23] • Performance of Building to Contain Radioactive or Toxic Materials and Protect Occupants for Buildings Subjected to Wind, Flood or Earthquake Loads	Varies - Often Large Numbers of People at Risk		1/10,000 AEP
DEPT. OF ENERGY BUILDINGS[4,23] • Very High Confidence of Containment of Radioactive and Toxic Materials and Protection to Occupants for Buildings Subjected to Wind, Flood or Earthquake Loads	Varies - Often Large Numbers of People at Risk Both Onsite and Offsite		1/100,000 AEP
NUCLEAR POWERPLANTS[25] • Damage to Core of Nuclear Powerplant from Earthquakes	Varies Potentially Very Large Numbers of People		1/100,000 AEP
AIR TRANSPORTATION[21,24] • Fatalities - All Aircraft	Varies 1-300	1/150,000 AC**	
AIR TRANSPORTATION[21,24] • Fatalities - Commercial Airlines	Varies 50-350	1/700,000 AC**	
NUCLEAR POWERPLANTS[25] • Performance Goal for Radioactive Releases Greater than 25 REM	Varies Potentially Very Large Numbers of People at Risk		1/1,000,000 AEP

Note: AC - Annual Chance of Occurrence
AEP - Annual Exceedance Probability
** - Based on an "Average Traveller"

Benchmark 4 was set to provide similar levels of public protection as afforded: in the design of Department of Energy Buildings[23] which store radioactive and toxic materials; in the design and operation of nuclear powerplants[25] in protecting the reactor core from damage by earthquake; and in the operation of commercial airlines[24].

Benchmark 5 was set with guidance primarily from: the performance goal for protection from radioactive releases at nuclear powerplants[25]; and findings by Schaefer[26] that estimates of Probable Maximum Precipitation (PMP) in Washington have Annual Exceedance Probabilities (AEPs) which range from about 10^{-5} to 10^{-8}. Also considered were discussions by the Council for Science and Society (CSS)[10] which characterized common practice in risk assessment as not considering causal events for failure with AEPs smaller than about 10^{-7} and Newton[9] who used a generic 10^{-7} for assessing the adequacy of spillway design for very large high hazard dams.

In summary, these selected benchmarks for idealized dam projects were chosen to be consistent with or somewhat more conservative than the performance levels/goals shown in Table A2. These benchmarks provided the basis for calibrating the additive weighting scheme used in the decision framework.

A1.2 DISTINCTION BETWEEN DESIGN LEVEL AND PERFORMANCE LEVEL

In applying the decision framework, it is important to understand the distinction between design level and performance level. In most engineering applications, there are numerous computational procedures employed between the point where the design level/design event/design load is selected and the point where the design/evaluation of the project element is completed. These computational procedures usually involve engineering assumptions and approximations which normally increase the conservatism and reliability of the project element beyond that indicated by the design level.

Thus, the performance goal/level of the completed and in-place project element generally has a higher reliability than that indicated by the AEP of the design level. For example, the design level for the flood to be passed by a simple roadway culvert may be a 25 year flood event (0.04 AEP). Oftentimes, the flood is estimated by rainfall-runoff modeling. If, in addition to the 25 year rainfall amount, sufficiently conservative values are used for the rainfall time distribution, antecedent soil moisture conditions, and the rainfall-runoff model parameters - then a much rarer flood, perhaps a 100 year flood (0.01 AEP) may result. Thus, the conservatisms in analysis would have produced a fourfold increase in protection as represented by a performance level of 0.01 AEP. This distinction between the design level and performance level is important because, it is often incorrectly assumed that the magnitude of the design level reflects the reliability of the in-place project element. As another example, most building codes[2,23,27] employ a design wind speed with a magnitude corresponding to a 50 year event (0.02 AEP). Because of the conservatisms incorporated into various design and construction standards and minimums in building codes, the actual performance level achieved is about 0.001 AEP[23]. This is a twentyfold increase in design protection and reliability of the project element.

This increase in design protection produced by the conservatisms in analysis is termed the "knockdown factor". As it happens, the conservatisms employed in design/analysis in many of the engineering disciplines often result in knockdown factors of from 2 to 10 or greater (Cornell[31]).

Numerically, the Knockdown Factor (K_f) is:

$$K_f = \frac{\text{Design Level (AEP)}}{\text{Performance Level (AEP)}} \quad \text{(A1)}$$

The relationship between design level, the conservatisms in design/analysis as expressed by the knockdown factor, and the resultant performance level must be recognized when establishing design levels as a means of achieving performance goals. To the extent practicable, these considerations have been incorporated into the design criteria, requirements and procedures presented in *Part IV of the Dam Safety Guidelines* entitled *Dam Design and Construction*.

A1.3 RELATIONSHIP OF THE PERFORMANCE LEVEL FOR A PROJECT ELEMENT TO THE PERFORMANCE LEVEL FOR THE ENTIRE PROJECT

The reliability of a given project is dependent upon the actual performance levels of the individual critical project elements. Most of the phenomenon which could produce dam failure such as floods, earthquakes, internal erosion of embankment or foundation materials, conduit failures, etc, represent independent failure mechanisms. Because of this independence, the Performance Level (PL) for the entire project can be computed as the summation of the performance levels for the critical project elements which could fail as a result of the various failure mechanisms.

In actual practice, the simple enumeration of the performance level for each critical element is complicated further because a critical project element can have multiple failure modes and causative mechanisms. However, the performance level for the project can be generally expressed in terms of the critical elements as:

Project PL = Spillway PL + Barrier PL + Foundation PL + Conduit PL + Etc. (A2)

A review of equation A2 also reveals that the performance level for the project may be governed by the performance level of the weakest element(s). Excessive design conservatism applied to only one or two failure modes may significantly reduce the chance of failure for those modes but may not significantly alter the chance of failure for the project. This situation points out the importance of *Balanced Protection* in design and underscores the necessity for maintaining a reasonable balance in the relative conservatism applied to the design of the various critical project elements.

A1.3.1 Current and Future Applications of this Technical Note

A desirable long term goal is to be capable of making a reasonable assessment of the reliability of a given project. At the present time, quantitative methods for computing performance levels are technically feasible only for causative mechanisms such as floods and earthquakes. These are two of the more significant considerations affecting the reliability of the project. However, the inability to reasonably quantify the performance levels achieved for other causative mechanisms and critical project elements makes a realistic assessment of the actual performance level for an entire project unattainable at this time.

In the future, studies and advances in technology will continue to be made under the names of reliability engineering, risk assessment and probabilistic based design which will improve the ability to quantify the protection afforded by a given critical project element. At that time, procedures in this Technical Note and in *Dam Design and Construction, Part IV of the Dam Safety Guidelines*, will need to be modified to incorporate a more comprehensive approach. That approach would place greater emphasis on evaluating the performance level for the entire project in addition to selecting/evaluating the performance levels for the various critical project elements.

APPENDIX B

WORKSHEET

DAM SAFETY GUIDELINES

TECHNICAL NOTE 2

SELECTION OF DESIGN/PERFORMANCE GOALS

FOR CRITICAL PROJECT ELEMENTS

WORKSHEET
DAM SAFETY GUIDELINES

SELECTION OF DESIGN/PERFORMANCE GOALS
FOR CRITICAL PROJECT ELEMENTS

PROJECT NAME: ______________________________

DAM NAME: ______________________________

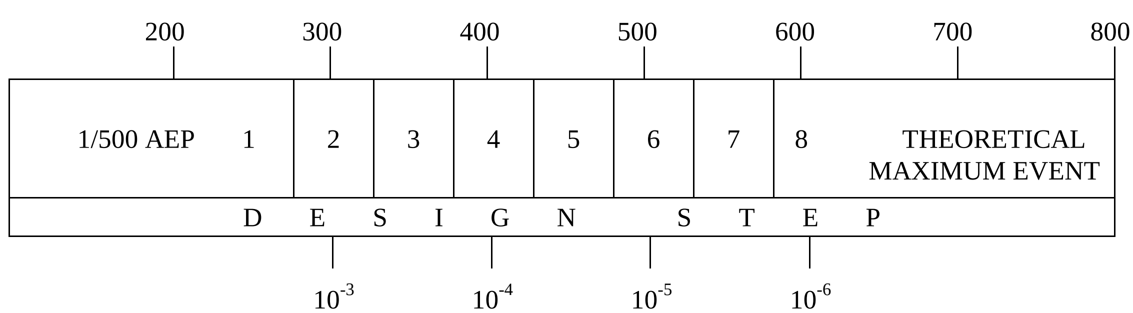
CONSEQUENCES EVALUATED FOR FAILURE OF ______________________________

AT RESERVOIR LEVEL OF ______________________________

SUMMARY SHEET

		CONSEQUENCE RATING POINTS
I.	**CAPITAL VALUE OF PROJECT**	________
II.	**POPULATION AT RISK**	________
III.	**DOWNSTREAM PROPERTY AT RISK**	________
	BASE POINTS	**150**
	CUMULATIVE CONSEQUENCE RATING POINTS	________

CUMULATIVE CONSEQUENCE RATING POINTS



DESIGN/PERFORMANCE GOAL - ANNUAL EXCEEDANCE PROBABILITY

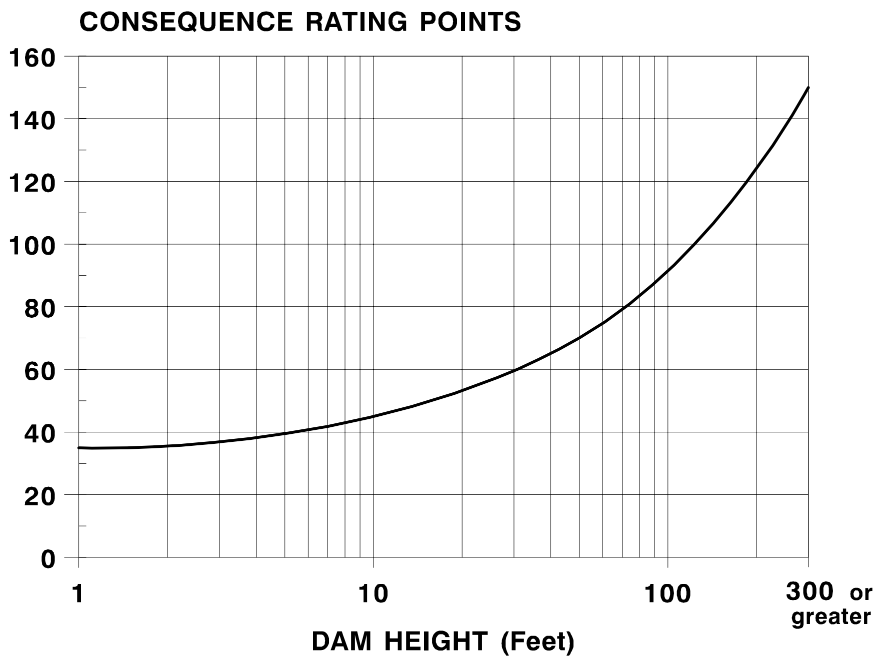
DESIGN STEP NUMBER ________

PROJECT ENGINEER ______________________________ **DATE** ____________

I. CAPITAL VALUE OF PROJECT

A. DAM HEIGHT INDEX

	Dam Height (feet)	Consequence Rating Points
Maximum Dam Height	____________	____________



I. CAPITAL VALUE OF PROJECT - Continued

B. VALUE OF RESERVOIR CONTENTS/PROJECT BENEFITS

Mandatory Consideration for Some Projects		Points Per Item	Consequence Rating Points
1.	Public Water Supply Storage	25 - 75	____________
Discretionary Considerations			
2.	Irrigation Water Supply Storage	10 - 75	____________
3.	Industrial Water Supply Storage	10 - 75	____________
4.	Hydropower Generation Facilities	10 - 75	____________
5.	Mining or Manufacturing Process Water	10 - 75	____________
6.	Aesthetics, Recreation or Wildlife Habitat	10 - 25	____________
7.	Other ________________________________		____________

Describe: ____
____
____
____
____
____
____
____
____
____
____

Assignment of consequence rating points to dams which provide a community with a limited resource, such as a public water supply, is mandatory.

Assignment of consequence rating points to dams which provide benefits primarily to the owner, is at the discretion of the owner and/or project engineer.

A wide range of consequence rating points are possible for the various project benefits. Selection of an appropriate value should be based on the size and importance of the project benefit under consideration relative to the broad range of projects of that type. In addition, a larger or smaller value may be selected depending on the owner's and/or project engineer's perceived need for conservatism in protecting project benefits.

SUBSECTION I - SUBTOTAL OF CONSEQUENCE RATING POINTS __________________

II. POPULATION AT RISK

A. CATASTROPHIC POTENTIAL INDEX

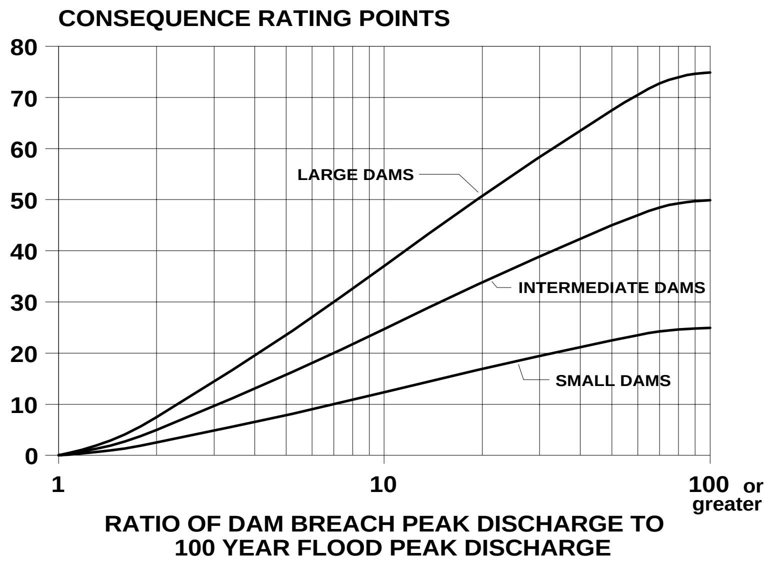
1. Estimated Dam Breach Peak Discharge at Dam Site due to Failure of Critical Project Element __________________ cfs

2. Estimated 100 year Flood Peak Discharge __________________ cfs

   Taken on a Natural Watercourse at First Location Downstream of the Dam Where There is a Potential for Loss of Life or

   If There is No Downstream Development, It is Taken on the Natural Watercourse at a Point 1 Mile Downstream of Dam

	Index	Consequence Rating Points
3. Ratio of Dam Breach Peak Discharge to 100 Year Flood Peak Discharge	______________	________________



II. POPULATION AT RISK - Continued

B. POPULATION AT RISK INDEX

		No. of Persons	Consequence Rating Points
1.	Estimated Current Population at Risk (PAR)	____________	
2.	Increase in Population Due to Development	____________	
3.	TOTAL - Future Population at Risk	____________	___________

Describe: ____
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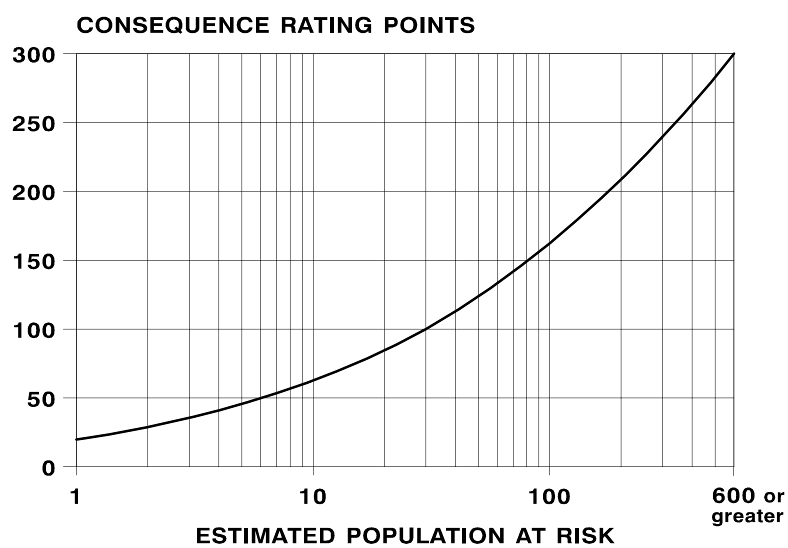


II. POPULATION AT RISK - Continued

C. ADEQUACY OF WARNING

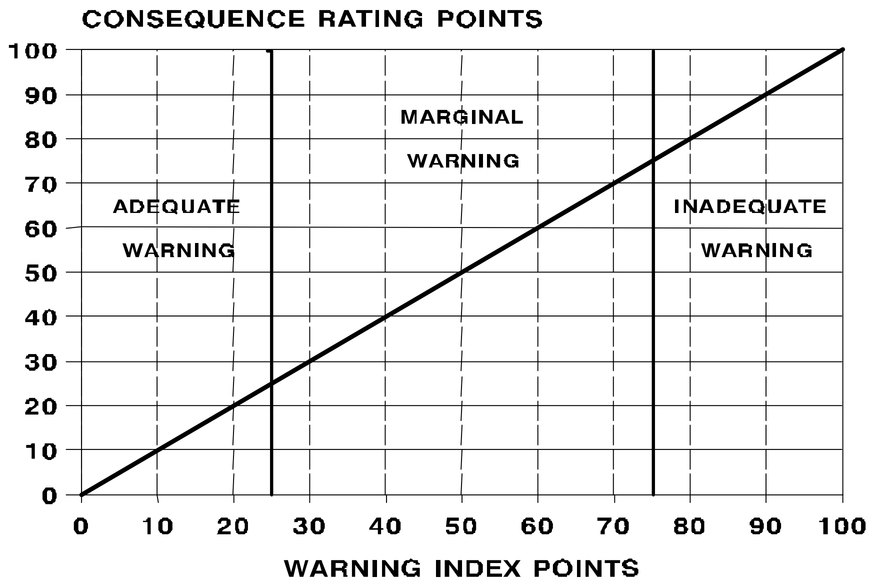
To be used when there is Population at Risk

FACTOR	ADEQUATE WARNING	MARGINAL WARNING	INADEQUATE WARNING
ADVANCED WARNING TIME	More than 30 minutes *0 Warning Index Points*	More Than 10 Minutes but Less Than 30 Minutes *25 Warning Index Points*	Less Than 10 Minutes *50 Warning Index Points*
LIKELIHOOD OF DANGEROUS SITUATION TO BE OBSERVED AND NOTIFICATION GIVEN TO GENERAL PUBLIC	Dam Owner Resides near Dam Site, or Designated Responsible Party Has Reasonably Short Access Time to Dam Site and has Duty of Initiating Warning *0 Warning Index Points*	Designated Responsible Party not Located near Dam Site, but Dam Site is Visible to General Public. There is Reasonably Good Vehicular Access near Dam Site and Intermittent Vehicular Traffic. *15 Warning Index Points*	No Designated Responsible Party near Dam Site. Dam in Remote Location. Poor Vehicular Access to Dam Site. *30 Warning Index Points*
DOWNSTREAM VALLEY SETTING AND EASE OF EVACUATION	Valleys with Good Access to High Ground and Good Roadway Systems for Escape Routes *0 Warning Index Points*	Valleys with Limited Access to High Ground and Limited Roadway Systems *10 Warning Index Points*	Narrow Confining Valley with Roadways near the Stream Bank or Along Valley Floor and Poor Access to High Ground *20 Warning Index Points*

	Item	Warning Index Points	Consequence Rating Points
1.	Advanced Warning Time	_____________	
2.	Likelihood of Dangerous Situations to be Observed and Notification Give to Public	_____________	
3.	Downstream Valley Setting and Ease of Evacuation	_____________	
	TOTAL WARNING INDEX POINTS	_____________	

WARNING RATED AS ___________________ _____________

II. POPULATION AT RISK - Continued



Describe: ____
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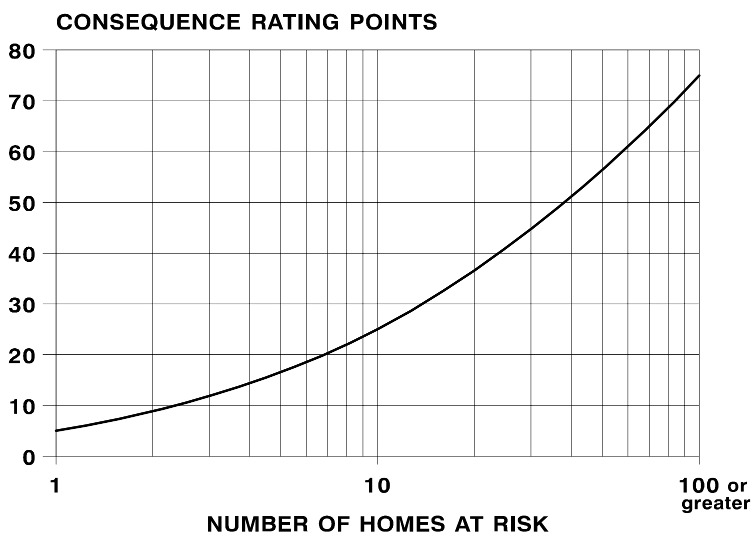
SUBSECTION II - SUBTOTAL OF CONSEQUENCE RATING POINTS ________________

III. DOWNSTREAM PROPERTY AT RISK

A. RESIDENTIAL UNITS	No. of Items	Consequence Rating Points
1. Equivalent Single Family Dwelling Units	____________	____________



B. LIFELINE FACILITIES	Points Per Item	No. of Items	Consequence Rating Points
1. Transportation Links - Bridges and Stream Crossings			
a. Freeways/interstate highways Railway main lines	25	______	___________
b. State highways	10	______	___________
c. Other public roads Railway spur lines	2 - 5	______	___________

III. DOWNSTREAM PROPERTY AT RISK - Continued

	Points Per Item	No. of Items	Consequence Rating Points
2. Water Supply Systems			
a. Storage Reservoirs (Downstream)	10 - 75	______	___________
b. Treatment Facilities	10 - 25	______	___________
c. Delivery Systems	5 - 25	______	___________
3. Domestic Waste Treatment Systems			
a. Treatment Facilities	5 - 25	______	___________
4. Electric Power Facilities			
a. Electric power plant or Appurtenant works	5 - 75	______	___________
5. Emergency Response Facilities			
a. Hospitals, Police, Fire, Paramedical Units	10 - 75	______	___________

C. OTHER IMPORTANT FACILITIES

1. Public Buildings, Schools, Libraries	10 - 75	______	___________
2. Fish Hatcheries	5 - 25	______	___________
3. Industrial, Commercial and Agricultural Developments	5 - 75	______	___________
4. Other Facilities or Considerations		______	___________

A wide range of consequence rating points are possible for the damages that could occur to property and lifeline facilities. Selection of an appropriate value should be based on the size and importance of the features under consideration relative to the broad range of features of that type. In addition, a larger or smaller value may be selected depending on the owner's and/or project engineer's perceived need for the protection against property damages.

III. DOWNSTREAM PROPERTY AT RISK - Continued

D. ENVIRONMENTAL DEGRADATION

	Points Per Item	No. of Items	Consequence Rating Points
1. Deleterious contents in proposed reservoir			
a. Release of reservoir contents will result in long term environmental degradation	10 - 75	_____	_________
b. Release of reservoir contents will result in temporary, minor environmental degradation	5 - 20	_____	_________
2. Damage to downstream facilities could result in release of deleterious materials stored on-site			
a. Release of deleterious materials will result in long term environmental degradation	10 - 75	_____	_________
b. Release of deleterious materials will result in temporary, minor environmental degradation	5 - 20	_____	_________

Description of damages to property, lifeline facilities, and environmental degradation: _________
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SUBSECTION III - SUBTOTAL OF CONSEQUENCE RATING POINTS _____________

GENERAL NOTES AND COMMENTS:

APPENDIX C

RISK MEASURES

The Decision Framework can also be described in terms of risk. Herein, risk can be expressed as a statistical expectation concerning loss of life. Specifically, the AEPs for the various design steps can be used in conjunction with equations 2 and 3 for loss of life to make expectations of loss of life for the cases of earthquakes and floods. This produces expectations expressed as loss of life per year which vary from $3x10^{-4}$ at Design Step 3 to $1x10^{-4}$ at Design Step 8. This progression holds for each of the cases of adequate, marginal and inadequate warning. This is a risk averse position concerning loss of life and is similar, although somewhat more conservative, than the risk based criteria used by BC Hydro[33].

In summary, the Decision Framework is consistent with existing probabilistic criteria for design/performance goals and with risk based criteria commonly used in probabilistic risk assessments.

EXTRA

In summary, the decision framework and methodologies presented here utilize probabilistic concepts for establishing the format for the design levels to be used for the various project elements. Probabilistic methods were chosen because they offered the capability of implementing a balanced protection approach for selecting design levels across a range of engineering disciplines. The concepts of *Balanced Protection* and *Consequence Dependent Design Levels* are the cornerstones of the decision framework employed here.

One such example is the case of the building standards recently adopted by the American Society of Civil Engineers (ASCE) entitled Minimum Design Loads for Buildings and Other Structures. These standards are probabilistic based and employ the concept of *Consequent Dependent Design Levels*, yet little quantitative background is written on the levels of protection afforded by the standards.

In many respects, this lack of open discourse has hampered progress in engineering bodies to directly address the safety implications of design standards. Thus, while great strides have been made in the past decades in the ability to numerically model or otherwise analyze engineered systems, there often remains unanswered questions regarding appropriate design targets, acceptable levels of risk and conversely acceptable levels of protection/reliability. Thus, many practicing engineers are misfocused on the question - does it meet code? And never recognizing that there is a chance that the design levels or assumptions of analysis may be exceeded and there is a probability of failure associated with the design.

The use of deterministic design methods employing such design events as: Probable Maximum Precipitation (PMP), Maximum Credible Earthquake (MCE) and Probable Maximum Wind (PMW) have fostered the misconception that use of these events provides for zero risk of failure.

In utilizing this methodology, it is recognized that the various engineering disciplines involved in dam design currently utilize design approaches which do not readily lend themselves to direct comparison. A variety of design levels and loadings are currently used which span the range from deterministic, to combined deterministic-probabilistic to probabilistic approaches. In many disciplines, technologies are not sufficiently advanced to quantitatively assess the protection afforded by the extreme loading conditions used in design.

Nonetheless, there is great value in incorporating a systems approach and *Balanced Protection* concepts in the design philosophy for the project. For the time being, quantitative assessments of performance levels for some project elements are limited by technological capability to use with the lower design steps. Assessments at the higher design steps must proceed in a more qualitative and deterministic fashion as has been standard practice in many disciplines for decades. Likewise, many of the comparisons between multi-disciplinary design levels are necessarily qualitative rather than quantitative. However, qualitative procedures and assessments are still quite valuable and have been used throughout *Part IV of the Dam Safety Guidelines*.