ALARP EVALUATION: USING COST EFFECTIVENESS AND DISPROPORTIONALITY TO JUSTIFY RISK REDUCTION

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"One accepts options, not risks." Fischhoff et al. (1981)

ABSTRACT

A key principle in achieving Tolerable Risk under ANCOLD (2001) Guidelines is "reducing risks as low as reasonably practicable" (ALARP). The ALARP Principle is founded on the legal obligation of dam owners as duty holders to reduce risks to the point that additional risk reduction would "cost" "disproportionally" more than the risk reduction (benefit) achieved. To make this evaluation, there must be an option for risk reduction that can be identified. The Cost Effectiveness and Disproportionality Ratio approaches, which can be used in ALARP Evaluation, are presented and illustrated in this paper. While the Cost Effectiveness or cost per statistical life saved approach has been used in Australia for almost a decade, the explicit estimation of the degree of disproportionality associated with a potential risk reduction measure, as proposed by the UK HSE, is new to Australian practice. The "Disproportionality Ratio" is a Cost/Benefit ratio that includes both economic and life safety benefits. Example guidelines are offered for using the Disproportionality Ratio in decision making.

1. INTRODUCTION

A key principle for achieving Tolerable Risk under ANCOLD (2001) interim guidelines is "reducing risks as low as reasonably practicable" or the ALARP Principle. This principle is founded on the legal obligation of dam owners as duty holders to reduce risks to a point of diminishing returns where additional risk reduction would "cost" "disproportionally" more than the risk reduction benefit achieved. A prerequisite for estimating and evaluating whether or not ALARP has been met is the identification of any "physically possible"[2] structural or non-structural options for further risk reduction. Hence, Fischhoff et al. (1981) state, "*One accepts options, not risks.*" The identification of such options requires the creative skills of experienced dams engineers and others and is aided by the application of a systematic failure modes analysis for the existing dam and each possible risk reduction option. In addition to providing assurance that ALARP is met, such an approach has the following benefits:

- An improved assurance that all reasonably foreseeable failure modes have been identified and adequately addressed
- A stronger Safety Case (HSE 1992, HSE 2002a) for the risk reduction decision
- A stronger Business Case (Bowles 2000) for the risk reduction decision
- A greater degree of defensibility for the risk reduction decision.

A thorough ALARP Evaluation is an important step in answering the question, "How safe is safe enough?" However, there is no objective or universal answer to this question; so, how should ALARP Evaluation be approached?

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[2] HSE (2002b) states that "Reasonable practicable" is a narrower term than "physically possible."

Bowles (1987, 2001) and Bowles et al (2003) have shown how estimates of cost per statistical life saved (CSLS)[3] for risk reduction options, obtained from a risk analysis, can be used to evaluate the strength of justification for further risk reduction as part of an ALARP Evaluation. The approach uses comparisons of CSLS estimates with CSLS (Cost Effectiveness) values used by regulators, or achieved by other dam owners or in other industries, which are responsible for managing risks that are similar in nature to those in dam safety. Chauhan and Bowles (2001 and 2003) have extended the approach to include the degree of confidence in the estimated values of CSLS.

The UK Health and Safety Executive's (HSE) approach of estimating the degree of disproportionality between the cost and benefits associated with a potential risk reduction measure is a variation of the Cost Effectiveness approach to ALARP Evaluation. The Disproportionality approach involves the calculation of a "Disproportionality Ratio" to assess the strength of justification for each risk reduction option. This ratio is a form of Cost/Benefit ratio that incorporates CSLS as a measure of unit cost in the numerator, while the unit benefit in the denominator is "valued" using an estimate of society's willingness to pay for preventing a fatality. Cost Effectiveness and Disproportionality between the risk reduction costs and benefits are therefore closely related concepts.

In this paper, tolerable risk and ALARP concepts are discussed in Section 2. The Cost Effectiveness and Disproportionality Approaches and examples of guidelines for their evaluation are presented in Section 3. An example of some simplified calculations and interpretations of results for both approaches is given in Section 4. The paper finishes with a Summary and Conclusions in Section 5, which includes a caution that the Cost Effectiveness and Disproportionality Approaches are intended to be aides to dam safety decision making in general and ALARP Evaluation in particular. They should not be the sole factor that determines either the decision outcome or whether or not ALARP is considered to be met. Simplified definitions for various risk variables that are used in this paper are presented in Appendix A.

2. TOLERABLE RISK AND ALARP PRINCIPLE

2.1 Tolerable Risk

Risk evaluation is defined by ICOLD (2002) as *"the process of examining and judging the significance of risk."*

Tolerable risk is defined by ICOLD (2002) as *"a risk within a range that society can live with so as to secure certain net benefits. It is a range of risk that we do not regard as negligible or as something we might ignore, but rather as something we need to keep under review and reduce it still further if and as we can."*

An essential attribute of the concept of Tolerable Risk is that it cannot be defined in general terms for all dams. It must be based on a case-specific evaluation of all possible risk reduction measures, both structural and non-structural, and including management processes[4]. This is consistent with the common law legal system, which does not prescribe reasonable practice in any field. Rather, the common law legal system provides a broad framework that is applied (retroactively) to a specific situation, with all its peculiarities and special considerations that could never be fairly and adequately covered in a prescriptive approach. In this sense an evaluation of whether or not the conditions for Tolerable Risk (including ALARP) would be met for a dam can be considered to be a "pre-posterior" (Benjamin and Cornell 1970) (or "pre-retroactive") analysis based on identified failure modes. This is a simple legal reality

[3] CSLS is not a value placed on a human life and neither is it the amount of compensation for an accidental loss of life paid by insurance or as the result of legal proceedings. Rather, CSLS is the cost of achieving an increment of life safety risk reduction. For example, the CSLS for reducing the risk to an individual by 1 in 10 000 per year at an annualised cost of $1 000 per year is $10M = $1 000/(1/10 000).

[4] Again, the quotation, "One accepts options, not risks." (Fischhoff et al. 1981) from the beginning of this paper applies to this consideration; although one might wish to substitute the word "tolerates" for "accepts".

that cannot be changed by the whim of any body that seeks to define a procedure for assessing Tolerability of Risk including the edict of a regulator, unless it is supported by the necessary legislative changes. It also follows from the principle of Equity upon which Tolerable Risk guidelines are defined (ICOLD 2003).

2.2 ALARP Principle

A key principle in achieving Tolerable Risk under most risk evaluation guidelines is "reducing risks as low as reasonably practicable" (ALARP). The IAEA (1992) states that risks are *"acceptable only if reasonable practical measures have been taken to reduce risks"*. ALARP is implied in the ICOLD (2002) definition of Tolerable Risk given in preceding subsection. ALARP is an integral part of the interim ANCOLD (2001) individual and societal risk guidelines. Although the term is not explicitly used, the ALARP Principle is an important consideration in the USBR (2003) Public Protection Guidelines. The ALARP Principle is also an important factor in HSE's decision-making process" (HSE 2001). The HSE consider that the regulation of Reservoir Safety in the UK comes under its purview, although currently they defer to the Panel Engineer system except for those reservoirs whose safety does not fall under the Reservoirs Act 1975 (Personnel Communication, L. Golob, 21 February 2003).

An important UK legal finding that enunciates the ALARP Principle is Edwards v. The National Coal Board (1949 1 All ER 743):

> *"established that a computation must be made in which the quantum of risk is placed on one scale and the sacrifice, whether in money, time or trouble, involved in the measures necessary to avert the risk is placed in the other; and that, if it be shown that there is a gross disproportion between them, the risk being significant in relation to the sacrifice, the person upon whom the duty (of care) is laid discharges the burden by proving that compliance was not reasonably practicable"*

Therefore, HSE (2001) refers to the satisfaction of the ALARP Principle as requiring a *"gross disproportion"* test applied to individual risks and societal concerns, including societal risks. The gross disproportion, which should be sought in deciding how far to pursue risk reduction, is between the cost[5] of an additional risk reduction measure (fix) and the estimated risk reduction benefit estimated for that measure. HSE (2002b) refers to this disproportion as "*the bias on the side of safety*", "*erring on the side of safety"*, and "*compensating to some extent for imprecision in the comparison of costs and the benefits*"

Rowe (1977) proposed that Cost Effectiveness measures, such as cost per statistical life saved (CSLS), be used to assist in implementing an ALARP Evaluation. In practice, this is commonly interpreted that risks should be to a point of diminishing returns, where practicable measures for achieving such risk reductions can be identified.

Earlier versions of the ANCOLD interim tolerable risk guidelines (e.g. ANCOLD 1994) incorporated an objective at a lower level of probability of life loss than the "limit of tolerability"[6]. Under these versions, ALARP

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5 Where HSE considers cost in broad terms that may include "time, trouble and effort" and not just monetary aspects.

6 In the ANCOLD (2001) draft guidelines, risks higher than the "limit of tolerability" are defined as "intolerable risk". This terminology is inconsistent with the HSE (2001) and ICOLD (2002) definitions of Tolerable Risk. Bowles (2002) suggested that the term, "limit of acceptability" would be more appropriate than "limit of tolerability" and that the region above this line would be more accurately referred to as "unacceptable risk" rather than "intolerable risk". Upon further reflection, the most accurate term to replace "limit of tolerability" would appear to be "limit of unacceptability." The key points being that, a) the region above this limit line is a region of unacceptable risk but the region below is not necessarily a region of acceptable risk; and b) the region that meets all conditions for tolerable risk, including ALARP, would not begin above this limit line and in many cases it would not begin until probability levels that are lower than this limit line. Therefore, the "true" limit of tolerability would generally be below the limit line proposed in ANCOLD (2001). Furthermore, this "true" limit of tolerability cannot be generally

was only applied between the limit and the objective. However, there is no legal basis, which the author is aware of, that ALARP and Disproportionality Principles cease to apply below some low level of probability. The objective has now been dropped from ANCOLD guidelines, so that ALARP applies without restriction below the "limit of tolerability".

2.3 Existing Good Practice

HSE (2001) state that a comparison against "existing good practice"[7] could be used as an ALARP Evaluation test if such practice is known to be ALARP (HSE 2002c). It is the author's opinion that at this time, it is not clearly established for all aspects of existing good dam safety practice which would be ALARP, and which might fall short or go beyond satisfying ALARP. For example, a costly spillway modification for a dam in a remote location that already has 95% PMF capacity may be argued to be "good practice" but it unlikely to be justified under an ALARP Evaluation.

3. ALARP EVALUATION APPROACHES

The Cost Effectiveness and Disproportionality Approaches are presented in this Section. Examples of guidelines for ALARP Evaluation are given, but these should not be used without careful consideration as to their applicability in a particular decision context. In any case, no such guidelines can provide absolute defensibility for a specific dam safety decision. In addition, as mentioned in a Footnote 5 in Section 2.2, is not just the monetary "cost" that should be considered in an ALARP Evaluation but any type of effort that could lead to risk reduction, including, for example improved management processes.

Appendix A contains simplified formulae[8] and their units for various risk variables used in this paper. It would be useful for the reader to review them before reading this section.

3.1 Cost Effectiveness (CSLS)

The CSLS is a measure of the Cost Effectiveness (or unit cost) of life safety risk reduction. The Adjusted CSLS[9] is calculated as follows [see definition h) in Appendix A]:

ACSLS =
[Annualised Cost of Risk Reduction Measure - Annualised Economic Benefit of Risk Reduction Measure]/Annualised Life Safety Risk Reduction for Risk Reduction Measure]

in which:

Annualised Economic Benefit of Risk Reduction Measure = Economic Loss * Reduction in Probability of Dam Failure Life Loss for Risk Reduction Measure

Annualised Life Safety Risk Reduction for Risk Reduction Measure = Estimated

defined, but must be based on an ALARP Evaluation of specific risk reduction options (see discussion in Section 2.1).

[7] HSE (2002c) distinguishes "good practice" from "*best practice, which usually means a standard of risk control above the legal minimum.*"

[8] All formulae presented in this paper are simplifications in that they do not account for the such factors as the following: variation in consequences over the range of loading; differences between dam failure and life loss probabilities; obtaining the products of probabilities and consequences using numerical (convolution) integration procedures incorporating small increments of Flood or Earthquake loading and summing over all failure modes for a reservoir; incremental consequences for flood failures; and differences in consequences associated with performance of existing dam and risk reduction measures. These simplifications are made to assist in communicating the underlying concepts. The reader is cautioned against using these formulae exactly as presented in this paper without accounting for the above-mentioned and other considerations that are important for accurately estimating these variables.

[9] The adjusted cost per statistical life saved (ACSLS) is the focus of discussion in this paper on ALARP Evaluation. The unadjusted CSLS [UCSLS, see definition g) in Appendix A] is used in prioritisation of risk reduction measures. It is not used for ALARP Evaluation because it does not account for the part of the annualised cost that is justified by economic benefits (Bowles 2000).

Number of Fatalities * Reduction in Probability of Dam Failure Life Loss for Risk Reduction Measure

ACSLS estimates can be useful for selecting amongst risk reduction alternatives. Smaller values of ACSLS indicate that a risk reduction alternative is "better value for the money".

It is sometimes useful to assess if a point of diminishing returns has been reached by examining the variation of ACSLS with project scale, such as spillway capacity in terms of design flood annual exceedance probability (AEP). In this case, ACSLS should be calculated and evaluated for each increment of additional capacity[10] and not for the successively increasing total capacities.

Similarly to the approach described in the previous paragraph for incrementally considering different capacities for a dam safety fix, it is appropriate to evaluate each component a multi-purpose or multi-component fix incrementally. For example, at the planning stage, consider the following multi-purpose fix which comprises raising an embankment dam and adding a berm to improve its stability under earthquake loading, to reduce the risk of a piping/seepage failure, and to provide additional flood capacity in conjunction with a new auxiliary spillway. The modifications to the embankment and the auxiliary spillway could be considered separately in an ALARP Evaluation since they are separable construction upgrade projects (SCUPS) (Bowles 2000). In addition, alternative embankment modifications, which consider different combinations of the three risk reduction purposes listed above, or design details for the embankment, could be considered incrementally in an ALARP Evaluation, similarly to the incremental approach described above for project scale. If any aspects of the proposed modifications are judged to be existing good practice that is considered to be ALARP (see discussion in Section 2.3), then there is no need to consider its possible exclusion in the ALARP Evaluation.

[10] Practical considerations that affect incremental sizing should be factored into the process.

The ratio of the second to the first term in the numerator of the above equation for calculating ACSLS is equal to the Economic Benefit/Cost ratio [see definition e) in Appendix A]. For a risk reduction measure with a Economic Benefit/Cost ratio of less than 1.0, as is common for dam safety risk reduction works, the amount by which annualised costs exceed annualised benefits is, in effect, allocated by the numerator of the above equation for ACSLS as a cost of improving life safety. In principle, other allocations could be made to types of benefits other than life safety and the economy, such as protection of community structure, the environment, or the owner's reputation.

If the Economic Benefit/Cost ratio exceeds 1.0, the numerator in the above equation for ACSLS would be negative. However, it is set to zero to avoid negative values of ACSLS [see definition h) in Appendix A]. In this case, the risk reduction measure is justified completely by its economic benefits, and the reduction in life safety risk can be considered to be at a zero cost (i.e. it is "free") and thus ACSLS = $0/life.

Comparing ACSLS estimates for dam safety risk reduction measures with CSLS estimates from other fields can provide a basis for evaluating whether or not a risk reduction measure meets ALARP. The fields selected for such comparisons must involve management of risks that are similar in character to those in dam safety. Table 1 lists CSLS estimates for various activities in the USA, many of which could be considered similar to dam safety in that the population at risk is dependent on a duty holder and has essentially no control over management of the hazard.

Rather than use a single threshold value of ACSLS for comparison with values estimated for dam safety risk reduction measures in the ALARP Evaluation, it would appear to be preferable to associate ranges of values of ACSLS with ranges of the strength of "ALARP justification" to proceed with a measure. The use of only a single value appears to be inconsistent with the common law legal framework, which provides for no such prescriptions or "bright lines" above which ALARP is clearly met. Rather, the confidence and degree of defensibility with which one can conclude that ALARP has been met can be considered to increase as ACSLS increases.

Table 2 is an example of ALARP ratings for the "strength of justification to proceed with risk reduction" assigned for ranges of increasing magnitudes of the Cost Effectiveness of improving life safety expressed as ACSLS. Four illustrative ALARP Justification Ratings are illustrated: "Very Strong", "Strong", "Moderate", and "Poor".

The illustrative example given in Table 2 is based on U.S. Federal Government practice. According to Kniesner (1997) *"The executive branch of the federal government has accepted regulations with a cost per life saved of up to $140 million* (used as "Moderate" – "Poor" ALARP Justification Rating boundary, which is approximated in Table 2 as AU$200M) *even though there are programs I will soon mention that can save lives for under $10 apiece."* Kniesner (1997) also states that *"The EPA has used a ceiling of $12 billion per case of cancer prevented to allocate Superfund cleanup efforts while the U.S. Department of Transportation has refused regulations costing more than $3 million per life saved* (used as "Very Strong" – "Strong" ALARP Justification Rating boundary, which is approximated in Table 2 as AU$5M)."

To the author's knowledge, many, although not all, dam safety risk reduction measures that are currently being implemented in Australia are rated "Very Strong" and "Strong". It is possible that as measures with these higher ALARP Justification Ratings are completed, then more measures with lower ratings, such as "Moderate" will be committed to. Based on the author's experience with estimating ACSLS for approximately 400 dams, values have varied from $0 to in excess of US$10 trillion per life saved.

The ALARP Justification Ratings presented in Table 2 are illustrative examples only. Each dam owner should develop their own position on the definition and interpretation of such ratings.

3.2 Disproportionality

The HSE (2001) proposes a way to make a quantitative estimate of the degree of disproportionality for a risk reduction measure as an input to an ALARP Evaluation. The degree of disproportionality is represented by a "Disproportionality Ratio"[11]. This ratio incorporates ACSLS as a measure of net unit cost in the numerator, and the unit (health and) safety benefits of risk reduction in the denominator (HSE 2001). Life safety benefits are valued using an estimated "value of preventing a fatality" (VPF), based on willingness to pay for preventing a fatality (HSE 2001). Based on 2001 prices the HSE has estimated a value of £1M per fatality for VPF (Appendix 3, HSE 2001). Although this estimate was based specifically on preventing road fatalities, it is used widely for other hazards by the HSE. However, the cases in death is caused by cancer, such as for nuclear plants, the HSE uses twice this value on the basis that they believe that people are wiling to pay premium for preventing this type of fatality. The HSE plans to conduct further research in this area.

The Disproportionality Ratio, R, is calculated as follows [see definition i) in Appendix A]:

Disproportionality Ratio, R =

> [Annualised Cost of Risk Reduction Measure - Annualised Economic Benefit of Risk Reduction Measure]/Annualised Life Safety Benefit of Risk Reduction Measure]

in which:

> Annualised Economic Benefit of Risk Reduction Measure = Economic Loss * Reduction in Probability of Dam Failure estimated for Risk Reduction Measure

> Annualised Life Safety Benefit of Risk Reduction Measure = Value of Preventing a Fatality * Estimated Number of Fatalities * Reduction in Probability of Dam Failure estimated for Risk Reduction Measure

[11] Referred to in HSE (2002b) as a "proportion factor".

The Disproportionality Ratio is related to ACSLS as follows [see definition j) in Appendix A]:

Disproportionality Ratio, R = ACSLS/VPF

Similar to ACSLS (see Section 3.1), a risk reduction measure with a Economic Benefit/Cost ratio greater than 1.0, will have a Disproportionality Ratio of zero because the numerator in the above equation for R is set to zero when the annualised economic benefit of the risk reduction measure exceeds its annualised cost [see definition i) in Appendix A]. In this case, the annualised cost of the risk reduction measure is completely justified by the annualised economic benefits.

When annualised costs and life safety benefits, valued using VPF, for a risk reduction measure are equal, R is exactly 1.0, and the ACSLS for the risk reduction measures is equal to the VPF. This indicates that there is no disproportionality between the annualised costs and benefits. High degrees of disproportionality result in high values of R, indicating that the annualised cost of the risk reduction measure significantly exceeds its annualised life safety benefits, valued using VPF. The question is how large should R be for "gross disproportionality to be achieved?

Viscusi (1998) documents that implicit value of preventing a fatality in the US industry are US$3M - US$7M with a midpoint value of US$5M. He states that this is at least an order of magnitude more than the amount of compensation paid in court cases after a fatality. He also refers to the "deterrent" role that these higher VPF values play.

Viscusi (1998) also reviews the decision by Ford Motor Company not to incur an additional cost of US$11 per vehicle to move the petrol tank forward into a safer position in the Ford Pinto. Their decision was based on a risk assessment in which Ford estimated the compensation that would be paid in the case of fatalities and burn victims. This calculation leads to an estimated R value of more than 2. Viscusi (1998) points out that if they had used a more realistic VPF estimate of US$5M, they would have estimated R to be about 0.1. This smaller value of R would have provided very strong justification to proceed with a safer location for the petrol tank.

In the UK, a former Director General of the HSE is quoted (Personnel Communication, L. Golob, 21 February 2003) as providing the following oral guidance on Disproportionality Ratios:

- Disproportionality Ratio of at least 10 for a probability of life loss of 1 in 10 000/year
- Disproportionality Ratio of at least 3 for a probability of life loss of 1 in 1 000 000/year

In addition, HSE (2001) provides the following guidance:

- Individual risk limit of 1 in 10 000/year[12]
- Value of preventing a fatality (VPF) based on a willingness to pay for risk reduction = £1M per fatality (2001 prices)

Figure 1 is a graphical representation of the HSE guidance, which was prepared by the author based on the four dot points above. Disproportionality Ratio is plotted on the vertical axis and the probability of life loss from dam failure before implementation of the risk reduction measure is plotted on the horizontal axis. A risk reduction measure is thus represented as a point on Figure 1 or as a scattergram if uncertainty is shown (Chauhan and Bowles 2003). The "gross disproportionality" test outcome is interpreted according to which of the following three regions in Figure 1 the risk reduction measure plots in:

1) Unacceptable Risk – risk reduction required
2) Intolerable Risk - risk reduction option is justified to proceed
3) Tolerable Risk – risk reduction option may not be justified to proceed

In developing Figure 1 as a semi-logarithmic plot, a straight line was drawn between the two plotted points that correspond to the first two dot points of HSE guidance. The line is a boundary between the Tolerable and

[12] This individual risk limit matches ANCOLD's Individual Risk limit for the person or group most at risk.

Intolerable Risk regions based on the HSE guidance. It is labelled the "HSE Strength of Tolerability Boundary." The boundary is extended down to R = 1.0 and from there it is continued horizontally to the left at a constant R value of 1.0. The basis for this is that a fix with a Disproportionality Ratio of less than R = 1.0 is always justified to proceed regardless of how low the probability of failure is estimated to be before the fix. Below R = 1.0, life loss risk reduction has a zero marginal cost and is therefore fully justified by the economic benefits alone.

R has a built-in characteristic that, the smaller the values of the probability of life loss prior to risk reduction, the larger the value of R [see Definition i) in Appendix A] and hence further risk reduction is less well justified. This is illustrated in the sensitivity plot in Figure 2. In this plot, the Disproportionality Ratio (R) is calculated for various probabilities of life loss prior to a fix for the example presented in the Section 4. The plot clearly shows that R becomes very large as the probability decreases[13]. Thus, there is no need to use a low end probability limit, such as 1×10^{-6} per year[14], which would limit the range of applicability of the ALARP Principle, because R "naturally" indicates the poor strength of justification for risk reduction measures associated with very low probabilities that have a gross disproportionality between cost and benefit. The advantages of not using a low end probability limit include the following:

a) the ALARP or Disproportionality Principle is applied without a restriction for which no legal basis is apparent; and
b) in the case of a very high consequence dam, the estimated value of R will indicate when a justification for risk reduction exists even at very low probability levels.

[13] In reality, it would likely reach even larger values because if practical risk reduction measures existed to achieve risk reduction below these low initial probabilities (a questionable assumption) it is likely that the capital cost would increase, rather than remain constant as is the case in the example calculations in Section 4.

[14] I.e., the objective concept from earlier versions of ANCOLD tolerable risk guidelines (ANCOLD 1994). See discussion at the end of Section 2.3.

The effect of uncertainties associated with low probability estimates of life loss should be considered.

Additional regions could be defined in Figure 1 using lines parallel to the existing sloping line but at higher R values, these regions would correspond to regions of decreasing strengths of justification to proceed with risk reduction measures and could be labelled similarly to the Cost Effectiveness (ACSLS) regions defined in Table 2 (e.g. "Very Strong", "Strong", "Moderate", and "Poor").

The existing regions in Figure 1, or the additional regions suggested in the previous paragraph, could be used as an additional factor in classifying risk reduction measures for prioritisation. However, the resulting rate of risk reduction would be less than for a prioritisation based on increasing values of (unadjusted) CSLS or Cost Effectiveness alone (Bowles 1998).

As with the Cost Effectiveness approach presented in Section 3.1, the use of estimated Disproportionality Ratios should be to inform and not to prescribe the outcomes of an ALARP Evaluation and related dam safety decisions.

4. AN EXAMPLE

Example calculations for the Cost Effectiveness and Disproportionality Ratio approaches are provided in this section. Interpretations of the resulting numerical estimates are given based on the examples of guidance presented in Sections 3.1 and 3.2.

4.1 Cost Effectiveness (ACSLS)

The example calculation of the adjusted cost per statistical life saved (ACSLS) is based on the following values of each of the inputs, which are defined in Appendix A:

r = 6.75%/year or 0.067 5/year
C = \$3 000 000
E = \$300 000 000
P_b = 1 in 10 000/year or $1\text{x}10^{-4}$/year or 0.000 1/year
P_a = 1 in 200 000/year or $5\text{x}10^{-6}$/ year or 0.000 005/year
N = 100 fatalities

Using the formula h) from Appendix A, we first obtain ?P [see definition in b) in Appendix A] and then ACSLS as follows:

?P = P_b - P_a
= (0.000 1 - 0.000 005)/year
= 0.000 095/year

ACSLS = {(r * C) - [E * ?P]}/(N * ?P)
= {(0.067 5 * 3 000 000) - [300 000 000 * 0.000 095]}/(100 * 0.000 095)
= $18.3M

This value of ACSLS would be given a "Strong" ALARP Justification Rating based on the example ratings in Table 2.

4.2 Disproportionality Ratio

The example calculation of the Disproportionality Ratio is presented for the same values of each of the inputs used in Section 4.1 plus the following additional input:

VPF = $3 000 000 per fatality[15]

Using the relationship j) between ACSLS and R from Appendix A, we obtain R as follows:

R = ACSLS/VPF
= $18.3M/$3M
= 6.1

Using the detailed formula i) from Appendix A, we obtain R as follows:

R = {(r * C) - [E * ?P]}/[VPF * N * ?P]
= {(0.067 5 * 3 000 000) - [300 000 000 * 0.000 095]}/[3 000 000 * 100 * 0.000 095]
= 6.1

This result would be plotted in the Intolerable Risk region on Figure 1 at R = 6.1 and P_b = $1x10^{-4}$/year. This position indicates that the risk reduction measure is justified because R is below the "HSE Strength of Tolerability Boundary"[16]. It is possible that additional measures, if practically available, would also be justified. Such measures might be non-structural in nature, such as more effective approaches for detection of a developing failure mode or improved emergency planning and management.

Figure 3 is a version of Figure 1 in which the example ALARP Justification Ratings presented in Table 2 are displayed for comparison purposes. The example ratings are represented in Figure 3 by regions, which are separated by horizontal lines corresponding to constant R values. Based on VPF = AU$3M as used in the above example, the boundaries between the example ALARP Justification Ratings are calculated as follows:

- R = 1.7 (AU$5M) "Very Strong"/"Strong"
- R = 17 (AU$50M) "Strong"/"Moderate"
- R = 66 (AU$200M) "Moderate"/"Poor"

Thus, it can be seen that the ALARP Justification Ratings and corresponding ACSLS values in Table 2 cover a much larger range of R values than the range of R values used to define the Tolerable/Intolerable Risk regions in Figure 1. This comparison should be qualified, however, in that the ALARP Justification Ratings are referenced to US Federal Government practice, whereas the regions in Figure 1 are referenced to UK HSE practice in evaluating ALARP using a UK estimate willingness to pay for preventing a fatality.

5. SUMMARY AND CONCLUSIONS

A thorough ALARP Evaluation is an important step in answering the question, "How safe is safe enough?" A prerequisite for conducting an ALARP Evaluation is the identification of a potential risk reduction measures. In addition to considering structural measures, non-structural measures, including improved management systems should be considered. This suggests that management as well as technical and operations personnel should be

[15] A VPF of AU$3M is used in this example for the illustrative purposes only. This should not be taken as a recommended value for VPF at this time.

[16] This result can also be found on the sensitivity plot in Figure 2 plotted at R = 6.1 and P_b = 1×10^{-4} per year.

involved in the ALARP Evaluation process. The process of identifying and evaluating (including documenting) risk reduction options is referred to by HSE (2002d) as "optioneering". If no further risk reduction measures can be conceived, and the risk is not unacceptably high, then ALARP is considered to be met, provided that the proper monitoring, surveillance and other dam safety management processes are in effect, at least for the time being. A "Technology Watch" should be undertaken to identify any new cost effective risk reduction options in the future. ALARP should be reevaluated as part of periodic dam safety reviews.

If a dam meets all risk evaluation guidelines, including ALARP, with adequate confidence, the risk assessment can be said to provide a justification for no further risk reduction measures[17] . Alternatively, if a dam does not meet all risk guidelines, including ALARP, with adequate confidence, the risk assessment can be said to provide a justification for risk reduction, or at least for further investigations to improve the confidence in the risk evaluations. As higher levels of safety are achieved, the number and strength of engineering and risk-based justifications for further risk reduction are typically reduced.

This paper presents two approaches for use in ALARP Evaluation. The Cost Effectiveness and Disproportionality Ratio approaches are intended to "inform" but not necessarily to "determine" risk reduction decisions. The level of uncertainty in estimates of the risks should be considered. For example, most initial portfolio risk assessments (PRA) would yield ALARP Evaluations that should be considered indicative in nature rather than definite enough for final "sign-off" level decisions on risk reduction. Such decisions would normally require more in-depth identification, estimation and evaluation of each risk reduction option.

ALARP Evaluation is a process which can be greatly strengthened through reference to the practice of other dam owners, giving allowances for differences in their decision contexts and risk analysis approaches. Such comparisons can be made through experts who are involved with risk assessments for a broad range of dam owners and through sharing information amongst dam owners. However, at the end of the day, it is for the courts to decide retroactively if ALARP has been adequately met in any particular situation.

[17] This does not preclude other considerations from justifying the risk reduction.

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APPENDIX A – SOME RISK VARIABLE DEFINITIONS

Simplified formulae and their units for various risk variables calculated in dam safety risk analysis and used in this paper are defined in this Appendix. Examples of these simplifications are given in a Footnote 8 at the beginning of Section 3. These simplifications are made to assist with conceptual understanding free from mathematical complexity. As mentioned in the footnote, the reader is cautioned against using these formulae exactly as presented in this paper. Each definition utilizes preceding definitions and so it may be necessary to refer to other definitions to understand all terms that are used.

a) Annualised life loss, L_L, in lives per year is obtained by multiplying the estimated probability of life loss[18] (per year) by the estimated life loss (lives or fatalities) associated with dam failure, as follows with units shown in italics:

L_L = Annualised life loss *[fatalities/year]*
= N * P
[fatalities/year]= [fatalities][/year]*

in which:

N = Number of fatalities *[fatalities]*
P = Probability of life loss associated with dam failure *[/year]*

b) Annualised life loss reduction, r_L, in lives per year is the annualised life loss after a fix subtracted from the annualised life loss before the fix, as follows:

r_L = L_{Lb} - L_{La}
= N * (P_b - P_a)
= N * ?P
[fatalities/year]= [fatalities][/year]*

in which:

L_{La} = Annualised life loss before fix *[fatalities/year]*
L_{Lb} = Annualised life loss after fix *[$/year]*
P_b = Probability of dam failure life loss before fix *[/year]*
P_a = Probability of dam failure life loss after fix *[/year]*
?P = Reduction in probability of life loss for fix *[/year]*
= P_b - P_a

c) Risk cost, c_E, in $ per year is obtained by multiplying the estimated probability of life loss (per year) by the estimated economic losses ($) associated with dam failure, as follows:

c_E = Risk cost *[$/year]*
= E * P
[$/year]= [$][/year]*

in which:

E = Economic loss associated with dam failure *[$]*

Risk cost is thus an annualised economic loss.

d) Economic benefit, b_E, for a fix in $ per year is the risk cost after a fix subtracted from the risk cost before the fix, as follows:

b_E = $c_{Eb} - c_{Ea}$
= E * (P_b - P_a)
= E * ?P
[$/year]= [$][/year]*

in which:

c_{Eb} = Risk cost before fix *[$/year]*
c_{Ea} = Risk cost after fix *[$/year]*

e) Economic Benefit/Cost Ratio, B/C, is calculated as the economic benefit divided by the annualised cost of the risk reduction measure, as follows:

18 In general, probability of life loss may differ from probability of dam failure because not all failure modes and exposure cases may lead to life loss.

$B/C = b_E / c$
[-]=[$/year]/[$/year]

in which:

c = Annualised cost of risk reduction measure based on an infinite asset life[19] *[$/year]*
$= r * C$
[$/year]= [/year]*[$]
r = Discount rate *[/ year]*
C = Capital cost of risk reduction measure *[$]*

f) Net present value, NPV, is calculated as the economic benefit minus the **a**nnualised cost of the risk reduction measure, as follows:

$NPV = (b_E – c)$
[$/year]= [$/year]

g) Unadjusted cost per statistical life saved (UCSLS) in $ per (statistical) life is estimated by dividing the annualised cost of a fix by the annualised life loss reduction estimated for the fix, as follows:

$UCSLS = c / r_L$
[$/life] = [$/year]/ [fatalities/year]

UCSLS is used in prioritisation of risk reduction measures to provide a monotonic reduction in cost effectiveness with increasing investment in risk reduction (Bowles 2000)

h) Adjusted cost per statistical life saved, ACSLS, in $ per (statistical) life is obtained by dividing the annualised cost of a fix ($ per year) minus the economic benefit of the fix ($ per year) by the annualised life loss reduction estimated for the fix (lives per year), as follows:

$ACSLS = (c - b_E)/r_L, \quad c > b_E$
$= 0, \quad c = b_E$
[$/life]= {[$/year]-[$/year]}/ [fatalities/year]

ACSLS is used in ALARP Evaluation because considers the annualised cost reduced by the economic benefits (Bowles 2000).

i) Disproportionality Ratio, R, in $ per (statistical) life is obtained by dividing the annualised cost of a fix ($ per year) minus the economic benefit of the fix ($ per year) by the annualised benefit estimated for the fix ($ per year), as follows:

$R = [c - b_E) / b_L, \quad c > b_E$
$= 0, \quad c = b_E$

[-] = {[$/year]-[$/year]}/[$/year]

in which:

b_L = Annualised Life Safety Benefit of Risk Reduction Measure *[$/year]*
$= VPF * N * (P_b - P_a)$
= VPF * N * ?P
[$/year] = [$/fatality][fatalities]* [/year]*
VPF = Value of preventing a fatality *[$/fatality]*

Thus, the expanded equation and units based on substitution of the formulas for each term is as follows:

$R = (c - b_E)/b_L$
$= \{(r * C) - [E * (P_b - P_a)]\} / [VPF * N * (P_b - P_a)]$
= {(r * C) - [E * ?P]} / [VPF * N * ?P]
[-] ={[/year][$]-[$]*[/year]}/ {[$/fatality] *[fatalities]*[/year]}*

j) Relationship between R and ACSLS:

$R = ACSLS/VPF$

k) Relationship between R and NPV:

$R = -NPV/ b_L$

l) Relationship between ACSLS and NPV:

$ACSLS = -NPV/ r_L$

[19] For finite asset lives, an alternative approach should be used to obtaining the annualised cost of the fix.

Table 1. US CSLS Estimates (Based on OMB 1992)

Regulation [a)]	Year Issued	Health or Safety?	Agency	Baseline Mortality Risk per Million Exposed	Cost per Premature Death Averted ($US Millions 1990)
Aircraft Cabin Fire Protection Standard	1985	S	FAA	5	0.1
Steering Column Protection Standard [b)]	1967	S	NHTSA	385	0.1
Trihalomethane Drinking Water Standards	1979	H	EPA	420	0.2
Aircraft Seat Cushion Flammability Standard	1984	S	FAA	11	0.4
Auto Fuel-System Integrity Standard	1975	S	NHTSA	343	0.4
Aircraft Floor Emergency Lighting Standard	1984	S	FAA	2	0.6
Side-Impact Standards for Autos (Dynamic)	1990	S	NHTSA	NA	0.8
Auto Side Door Support Standards	1970	S	NHTSA	2,520	0.8
Low-Altitude Windshear Equipment & Training Standards	1988	S	FAA	NA	1.3
Side-Impact Standards for Trucks, Buses, and MPVs	1989 (Proposed)	S	NHTSA	NA	2.2
Rear Lap/Shoulder Belts for Autos	1989	S	NHTSA	NA	3.2
Benzene NESHAP (Original: Fugitive Emissions)	1984	H	EPA	1,470	3.4
Ethylene Dibromide Drinking Water Standard	1991	H	EPA	NA	5.7
Benzene NESHAP (Revised: Coke By-Products) [c)]	1988	H	EPA	NA	6.1
Arsenic Emission Standards for Glass Plants	1986	H	EPA	2,660	13.5
Haz Waste Listing for Petroleum Refining Sludge	1990	H	EPA	210	27.6

Table 1. US CSLS Estimates (Based on OMB 1992) (Continued)

Regulation [a)]	Year Issued	Health or Safety?	Agency	Baseline Mortality Risk per Million Exposed	Cost per Premature Death Averted ($US Millions 1990)
Cover/Move Uranium Mill Tailings (Inactive Sites)	1983	H	EPA	30,100	31.7
Benzene NESHAP (Revised: Transfer Operations)	1990	H	EPA	NA	32.9
Cover/Move Uranium Mill Tailings (Active Sites)	1983	H	EPA	30,100	45.0
Asbestos Ban	1989	H	EPA	NA	110.7
Diethylstilbestrol (DES) Cattlefeed Ban	1979	H	EPA	22	124.8
1,2-Dichloropropane Drinking Water Standard	1991	H	EPA	NA	653.0
Haz Waste Land Disposal Ban (1st 3rd)	1988	H	EPA	2	4,190.4
Municipal Solid Waste Landfill Standards (Proposed)	1988	H	EPA	<1	19,107.0
Atrazine/Alaclor Drinking Water Standard	1991	H	EPA	NA	92,069.7
Haz Waste Listing for Wood Preserving Chem.	1990	H	EPA	<1	5,700,000.0

a) 70-year lifetime exposure assumed unless otherwise specified
b) 50-year lifetime exposure
c) 45-year lifetime exposure
NA = Not available
Agency Abbreviations-EPA: Environmental Protection Agency; NHTSA: National Highway Traffic Safety Administration; FAA: Federal Aviation Administration; FDA: Food and Drug Administration; OSHA-S: Occupational Safety and Health Administration, Safety Standards.
Source: John F. Morrill, III, “A Review of the Record.” *Regulation*, Vol. 10, No. 2 (1986), p. 30. Updated by the Author, et al.

Table 2. ALARP Justification Ratings (Illustrative Example Only) (Bowles and Anderson 2003)

ALARP Justification Rating	Range of Cost-per-statistical-life saved (AU$M/life)	
	Greater than or equal to	Less than
Very Strong		5
Strong	5	50
Moderate	50	200
Poor	200	

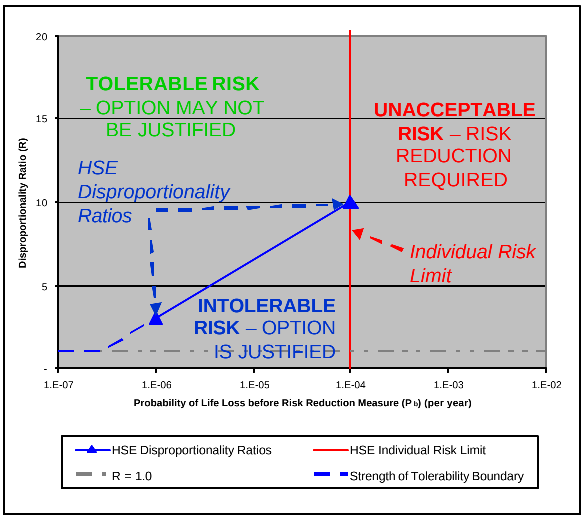

Figure 1. Plot of HSE Guidance for Evaluation of Disproportionality Ratio

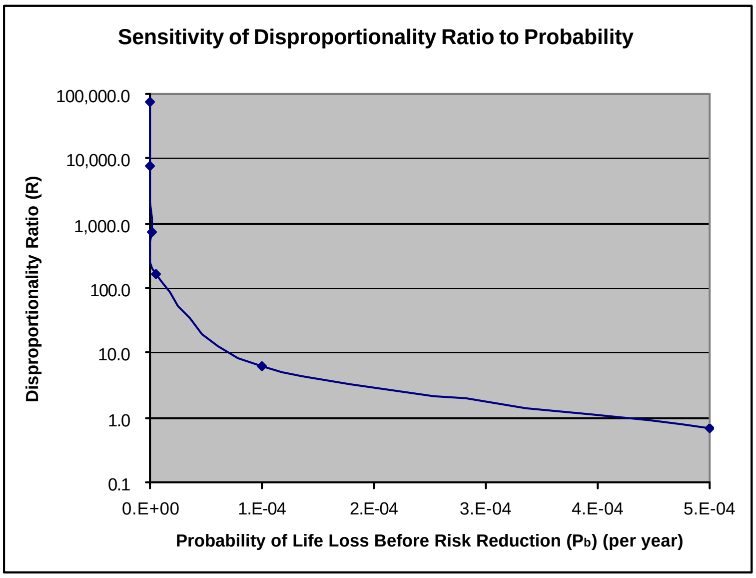

Figure 2. Example of the Sensitivity of Disproportionality Ratio (R) to Probability of Life Loss Before Risk Reduction (P_b) (per year)

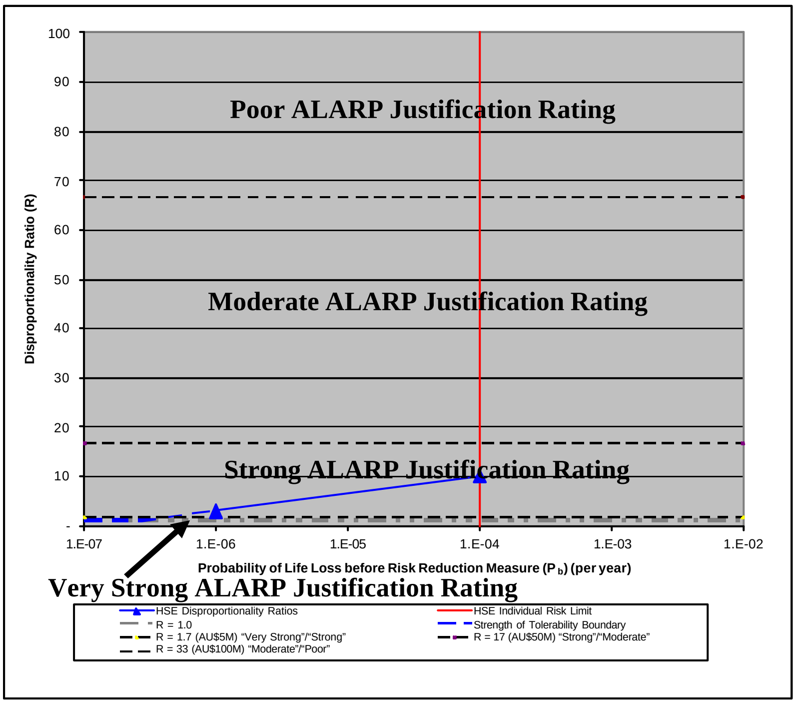

Figure 3. Comparison of ALARP Justification Ratings and HSE Disproportionality Ratios