Applying the Rational Quantitative Optimal risk approach to optimize rehabilitation for a portfolio of dams

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Abstract

The Rational Quantitative Optimal (RQO) approach to risk based dam safety produces a definitive result for an assessment of the reduction of risk from the overtopping of embankment dams. The model is applied to 3 embankment dams in Namibia.

The model is based on principles of risk, but an assessment of a portfolio of dams provides discrete optimal results, not expressed in terms of probability. The model provides a transparent framework for decision making related to public safety, which will also appeal to the technically minded portfolio manager looking for a purely quantitative procedure.

The RQO approach relates the probability of occurrence of a flood, which exceeds the spillway capacity, to the cost of fractionally raising the non-overspill crest to accommodate the flood. By applying this relationship to a range of raised levels, the risk characteristics of a dam can be obtained as a technology curve. A portfolio of technology curves for several dams provides a tool for decision makers regarding priority and extent of rehabilitation.

1. Introduction

Dam safety is not an absolute condition, but it is a tolerated situation, with low levels of residual risk ever present (ICOLD 2005, Charlwood et al. 2007). The practice of dam safety aims at reducing the risk of failure of new and existing dams to acceptable levels; as discussed in the International Commission on Large Dams (ICOLD) Bulletin 99 (ICOLD 1995), dam failure means the ‘Collapse or movement of a part of the dam or its foundation, so that the dam cannot retain water. In general a failure results in the release of large quantities of water, imposing risks on the people or property downstream’.

Dam failure due to overtopping of the Non-Overspill Crest (NOC) is the single largest cause of embankment dams failing internationally (ICOLD 1995). This is even more so in Namibia, where the larger embankment dams are constructed in a way which gives them an inherent resistance against internal erosion; the second highest cause of dam failure, according to ICOLD.

Overtopping of the embankment is usually due to insufficient spillway capacity; a product of the short hydrological records available and flood models at the time of design. This is a global problem, especially with the older dams which were built early in the 20th century, or even earlier. As new flood data becomes available, current flood models are updated to incorporate the newer information, and in many cases the probability of the previous extreme floods increase

1.1. Flood hydrology in Namibia

Overtopping of the NOC of an embankment is usually due to insufficient spillway capacity; a product of the short hydrological records available and flood models at the time of design. This is a global problem, especially with the older dams which were built early in the 20th century, or even earlier. As new flood data becomes available, current flood models are updated to incorporate the newer information, and in many cases the probability of the previous extreme floods increase.

The flood hydrology of Namibia was recently updated to incorporate the past 30 years of recorded flood peak data, as well as palaeoflood data which extended flood records to several thousand years (Cloete et al. 2014).

1.2. Dam safety in general

According to ICOLD (1995) the failure of embankment dams contributes to 80% of all dam failures. Of this 80%, the largest mode of failure is overtopping of the embankment which leads to subsequent external erosion and failure. ICOLD (1995) provides the figure of overtopping as the primary cause of failure at 32%. The second largest mode of embankment dam failure is internal erosion, at 16%. However the three dams evaluated in this paper are concrete faced rock fill dams (CFRD). These dams have an inherent resistance against internal erosion. They are, however, still prone to failure during overtopping. For various historical reasons and some technical reasons, the safety of dams has been controlled by an engineering Standards-based Approach.

This paper investigates an approach to dam safety which addresses risk quantitatively and optimally reduces risk over a portfolio of dams without or complementary to employing design standards.

2. Risk in dam safety

By trial and error, over many years, design standards have developed into the standards-based approach to dam design and dam safety which is applied today. The standards-based approach to risk management has served dam safety well, reducing the rate of dam failures from 2.5% in the early part of the 20th century to less than 0.5% in the second half (ICOLD 1995). However the Standards-based Approach does not differentiate between high or low risk; either the dam complies with the standard or it does not.

The main purpose of risk analysis is the transparent treatment of uncertainty of causes and consequences of dam failure (ANCOLD 2003b), which is required by society, and also to provide support for decision making regarding the management and rehabilitation of a portfolio of dams (Hartford & Baecher 2004).

Risk based dam safety is gaining popularity, specifically where a portfolio of dams requires the owner to prioritise rehabilitation activities. This approach is being applied in Australia and also by the United States Bureau of Reclamation (ANCOLD 2003b, Charlwood et al. 2007). However in these cases the standards-based approach is still used as a guide for the extent of rehabilitation required at each dam (ICOLD 2005).

3. The problem statement

The problem faced in general by dam owners is that the current Standards Based Approach (SBA) to dam safety is a blunt instrument which does not evaluate risk, but only indicates whether a dam complies with pre-set standards. Irrespective of whether an investment is disproportionate to the reduction in risk, the SBA requires that all standards be met.

Society has become more aware of risk and therefore requires transparency in the process of risk estimation. A problem raised by some dam owners and regulators, however, is that there is insufficient confidence in the scientific validity, or robustness, of judgmental quantified probabilities to make life safety decisions using these techniques (ICOLD 2005). Also, in the absence of a suitable risk analyses, the decision maker may subjectively undertake actions which do not optimally utilize societal resources.

4. The rational quantitative optimal risk model

The main purpose of risk analysis is the transparent treatment of the uncertainty of the causes and consequences of dam failure (ANCOLD 2003b). Cloete et al. (2016) presents the Rational Quantitative Optimal (RQO) risk model which establishes the characteristics of the marginal cost of life saving, based on the increased flood handling capacity of a dam, against the probability of the flood required to overtop the dam.

The components which form the structure of the RQO approach are discussed below (Cloete 2015, Cloete et al. 2016). The process development is discussed in detail in the aforementioned papers. The approach culminates in the development of a technology curve: a curve representing risk reduction gained through applied technology. The basic components follow:

- Determine the probability of extreme flood events as a function of the flood discharge capacity of a particular dam.
- The probability of dam failure is associated with the flood which overtops the embankment NOC: incipient motion commences once water spills over the NOC.

- Investment in life-saving activities: by raising the NOC level of an embankment, the freeboard is increased and, hence, the flood discharge capacity also. In so doing the probability of overtopping is reduced.
- Determine the likely loss of life (LOL) in case of dam failure due to overtopping.
- Determine the risk to life, due to dam failure, as a product of the likely loss of life and probability of dam failure.
- Compile the technology curve, expressed as a function of risk vs the cost of risk reduction.
- Compare the Invert Technology Curve (ITC) of several dams in a portfolio, to determine the sequence of rehabilitation, and the extent of rehabilitation required per dam, to optimise resources.

4.1. The technology curve

In the context of risk and civil engineering structures, such as dams, the technology curve represents a "curve showing the available technology or best praxis for risk reduction" (Schubert 2009).

The technology curve indicates the extent that risk to life can be reduced by investing an amount of money on life saving measures. Societal resources for life saving activities are limited and need to be invested in the most efficient manner (Kraemer et al. 2010). A typical technology curve as per Fischer (2012) is shown in **Figure 1.**

4.2. The invert technology curve

The technology curve displayed in Figure 1 starts at some random risk value, representing the current status of the dam: if zero money is spent on rehabilitation work (the "do nothing" option), then the risk associated with external erosion will be at its highest. However, as funds are invested in raising the dam to increase freeboard, the risk reduces.

Since risk is expressed in terms of lives lost, it can be normalised by considering the change in risk as the marginal lives saved by the safety investment. In so doing, an Inverted Technology Curve (ITC) is obtained, expressing the "Marginal Lives Saved" as a function of the "Investment in Life Safety". Refer to **Figure 2**. The slope of the graph provides an indication of the gain in lives saved per incremental investment in safety. Notably the initial investment achieves the highest gain, with asymptotic decrease in effectiveness with increasing investment. It is shown that initial establishment costs can be neglected (Cloete 2015).

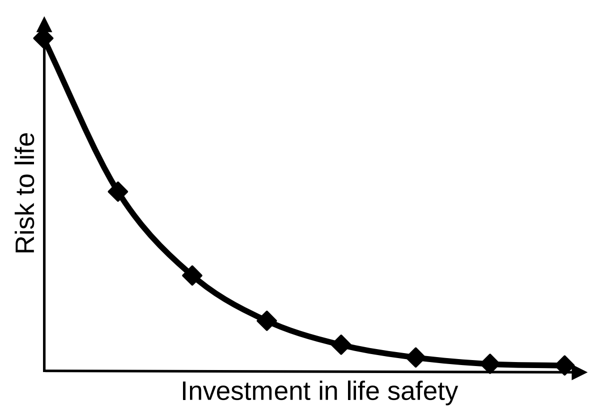

Figure 1. The typical technology curve; investment in life saving activities brings about a reduction in risk to life

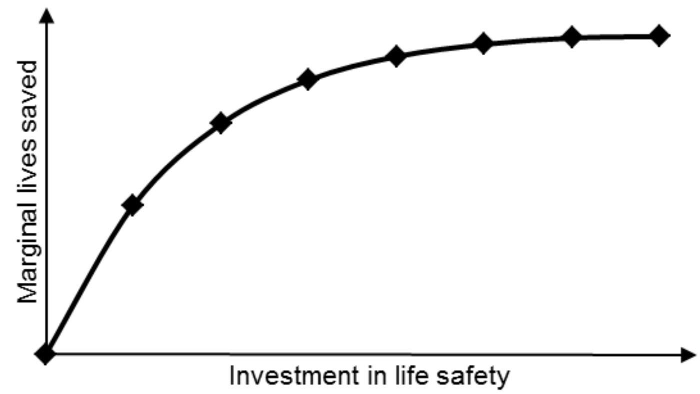

Figure 2. The Invert Technology Curve (ITC) for a dam

4.3. Reducing risk over a portfolio of dams

An objective of risk reduction over a portfolio of dams is to identify and rehabilitate the highest risk dams first, and thereafter direct rehabilitation activities on the next highest risk dams, as far as resources permit. A portfolio of dams can be ranked in terms of the initial slope of their respective ITC graphs to indicate the order in which the dams are selected for rehabilitation. As the first matter for decision, the steepest ITC slope produces the most gain in lives saved for the initial investment.

The next class of decision is when to change over investment from the first to the second dam, and the next, etc. Firstly, determine a function representing each of the ITC curves in the portfolio. From the first derivative of the curve functions, at the point where the initial slope of the second ranked dam is equal to the slope of the first ranked dam, there the investment is transferred from the first to the second dam (Cloete et al. in press). This process optimises the investment available for risk reduction. Refer to **Figure 3**.

The RQO process is applied mechanistically, not requiring judgement from the decision maker. In so doing it addresses the concern raised by dam owners regarding the judgmental probability of risk assessment

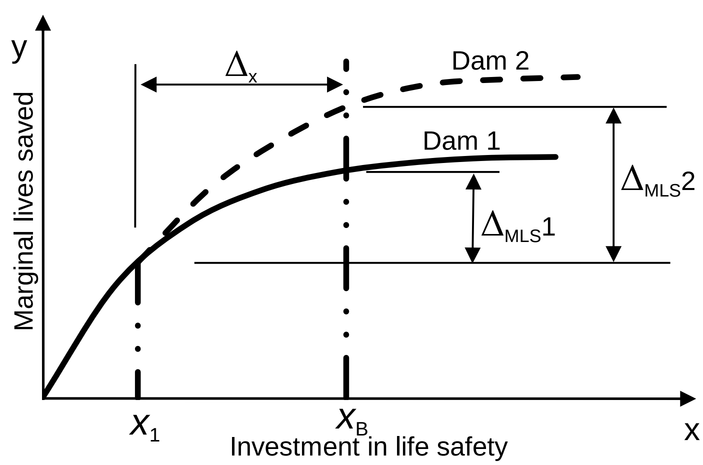

Figure 3. Optimising risk reduction by applying the RQO process. Where X = XD2, investment in rehabilitation is shifted from Dam 1 to Dam 2. Therefore at XB, the budget limit, more marginal lives have been saved through the optimising process than having the investment remain with Dam 1

5. Applying the RQO model to three dams in Namibia

Having developed a quantitative risk approach, the process is applied to three real dams in Namibia. The RQO process for one of the dams is explained within the body of the text below, while only the results of the other two are included at the end to complete the process.

5.1. The selected dams

Typically, the large embankment dams in Namibia are constructed as concrete faced rockfill dams (CFRD). This is due to the coarse nature of material found in the mechanically eroded landscape of arid regions. The three dams used in the RQO portfolio assessment are the Avis Dam on the outskirts of Windhoek in central Namibia, the Hardap Dam near the town Mariental in the south, and the Von Bach Dam near the town Okahandja, also in central Namibia. The construction work on the dams was completed in 1932, 1962 and 1970 respectively. The Hardap Dam has an embankment height of 35.9 m above riverbed, and a crest length of 865 m. The Von Bach dam has an embankment height of 35 m and a crest length of 230 m. The Avis dam has an embankment height of 12.8 m and a crest length of 300 m. Information on the population at risk for the Hardap Dam break is included in the Hardap Dam safety evaluation by Hattingh (2007), and for the Von Bach Dam, an estimate was used.

5.2. Constructing the Avis Dam technology curves

In the construction of an ITC for the Avis dam, consider the following (Cloete 2015):

- Based on the new Regional Maximum Flood (RMF) model for Namibia (Cloete et al. 2014), the 1:10 000 year flood is estimated at 1 025 m3/s, generated in the 105 km2 catchment area.
- The maximum spillway discharge capacity at NOC level of 1723.1 mAMSL is 943 m3/s. Hence the flood fraction (FQ) of the spillway flood over the RMF flood is 0.92.
- Applying the Flood Fraction (FQ) in the RMF function, from Figure 4, the Annual Recurrence Interval (IR) of maximum spillway discharge, at NOC level, is 4 163 years. This produces an annual exceedance probability (AEP) of 0.00024.

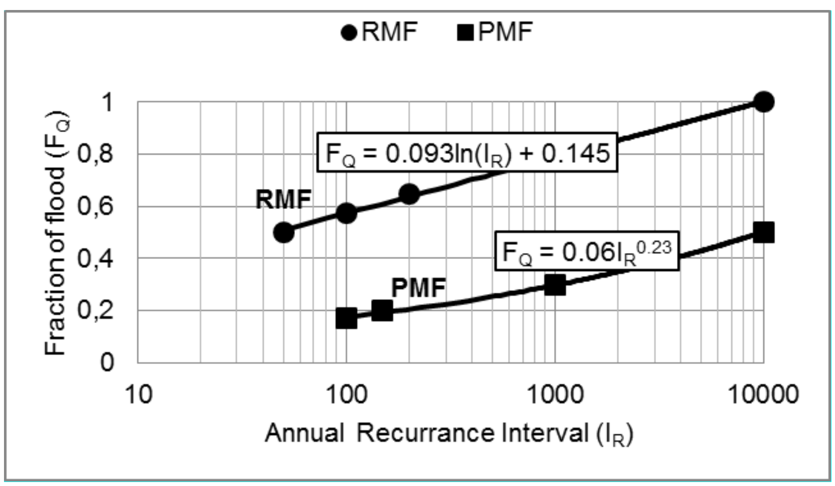

Figure 3. The functions representing the fractions of the RMF and PMF against annual recurrence interval (I_R). Functions representing the RMF and PMF fraction-curves are indicated by F_Q

- Repeat the steps above for several height increments and determine the AEP for each, as presented in **Table 1**.
- Determine the cost for each incremental increase in the NOC height; earthworks in this case. Also determine the likely loss of life (LOL) for a dam break scenario. Dekay and McClelland (1993) was used in this case.
- From the consequences (LOL) and the AEP, risk is determined. Refer to **Table 2**.
- From the data provided in **Table 2**, plot a technology curve, Refer to **Figure 5**.

- By inverting the risk, the resultant curve displays marginal lives saved per incremental investment. Refer to **Figure 6**.

Table 1. Avis Dam AEP for various height increments above the NOC

mAMSL	Discharge	F_Q	I_R	AEP
(m)	(m^3/s)		(years)	
1723.1	943	0.92	4 163	0.00024
1723.2	1001	0.98	7 675	0.00013
1723.3	1061	1.04	14 344	0.00007
1723.4	1122	1.09	27 164	0.000037
1723.5	1184	1.16	52 123	0.000019
1723.6	1247	1.22	101 317	0.000010

Table 2. Avis Dam risk associated with the probability of failure for each increment with which the dam is raised

mAMSL	Cumulative Cost of earthworks	AEP	Loss of Life (LOL)	Risk
(m)	(Million N$)			
1723.1	0	0.000240	620	0.148928
1723.2	3.38	0.000130	620	0.080778
1723.3	6.76	0.000070	620	0.043225
1723.4	10.13	0.000037	620	0.022824
1723.5	13.51	0.000019	620	0.011895
1723.6	16.89	0.000010	620	0.006119

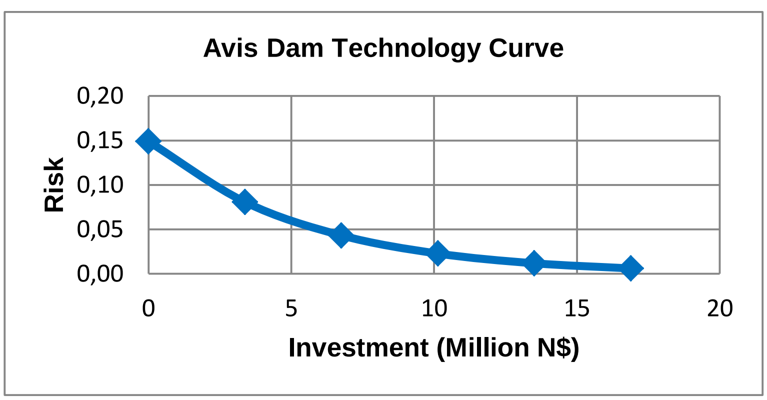

Figure 4. The technology curve for the Avis Dam

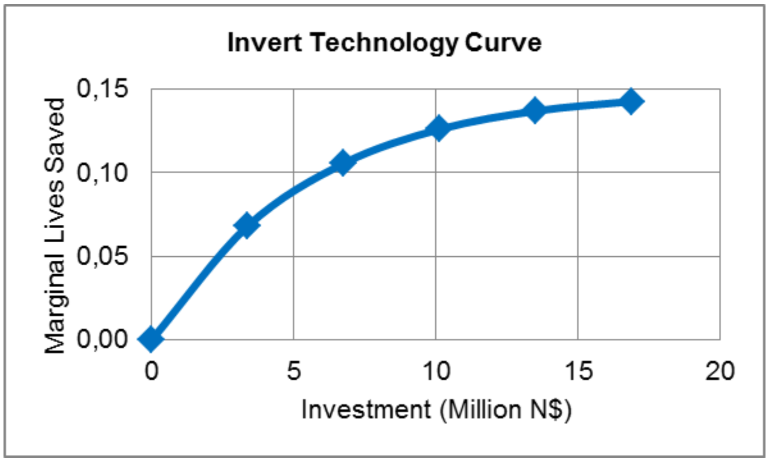

Figure 5. The inverted Technology Curve for the Avis Dam

5.3. Constructing the combined inverted technology curve for the three dams

Following the construction of ITC curves, the following steps are to rank the dams from highest initial risk to the lowest. Next the point of transition of investment from one dam to the next is determined, to optimise the investment by saving the greatest number of marginal lives within the available budget. The first step would be to determine functions fitting the technology curves, as discussed in Section 4.3. Then determine the first derivative of each function. The initial slope (where x = 0), would then be the first constant of the first derivative.

Due to the size differences in the three dams, the Hardap Dam has the largest rehabilitation cost and the Avis dam the highest risk in loss of life. The Von Bach Dam, in comparison, has a low risk and low rehabilitation cost associated with it. Refer the Figure 7 for the ITC curves of the three dams.

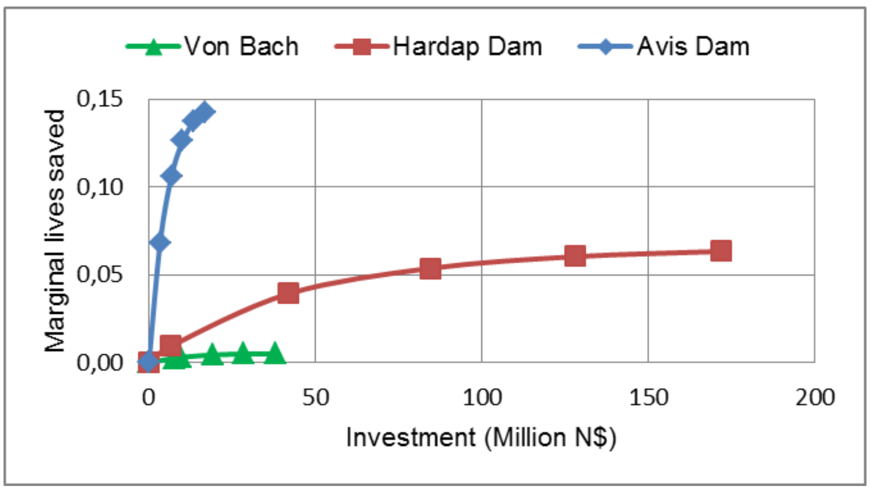

Figure 6. The inverted technology curves for the Von Bach, Hardap, and Avis Dams

From CurveExpert software version 1.3, 4th Degree Polynomial equations were determined for each of the ITC's. As follows:

The general expression for the polynomial equation is:

$f(x) = a + bx + cx^2 + dx^3 + ex^4 + \ldots$

where $f(x)$ represents marginal lives saved

x represents investment value

The coefficient data are presented in **Table 3**.

Table 3. Coefficients for the polynomial equations

Coefficients	Avis	Hardap	Von Bach
a	0	0	0
b	0.0263	0.00146	0.00047
c	-0.00208	-1.58E-05	-1.77E-05
d	8.55E-05	8.70E-08	3.26E-07
e	-1.46E-06	-1.86E-10	-2.42E-09

The first derivative is:

f ´(x) = b + 2cx + 3dx2 + 4ex3

Therefore the initial slope, where x = 0, then f´(x) = b

from the polynomial coefficients in Table 3, the initial slopes for each of the dams is as follows, starting with the steepest:

Avis Dam: f ´(x) = 0.0263

Hardap Dam: f ´(x) = 0.00146

Von Bach Dam f ´(x) = 0.00047

From the above it can be seen that the Avis Dam takes first priority regarding investment, since the most lives will be saved for the initial investment. Thereafter follows the Hardap Dam and last the Von Bach Dam.

To determine the transfer of investment from the Avis- to the Hardap Dam, determine at which point the slope of the Avis Dam curve is equal to the initial slope of the Hardap Dam. At this point the Hardap Dam will begin to show a greater gain in marginal lives saved than the Avis Dam. At this point, further investment in the Avis Dam should cease and investment in the rehabilitation of the Hardap Dam should start.

The first change over from Avis to Hardap Dam takes place where the Avis Dam f ´(x) = 0.00146 (the starting slope of Hardap Dam). At this point the 'Investment Value' stands at N$ 15.76 million. The second change over, from the Hardap to the Von Bach Dam, takes place where the slope of the Hardap Dam, f ´(x) = 0.00047, is also the initial slope of the Von Bach Dam.

At this point the investment value of the Hardap Dam will stand at = N$ 47.20 million. However, this N$ 47.20 million accumulates on top of the N$ 15.76 million invested in the Avis Dam; since one dam follows on the next, the cost of investment will be accumulative.

The starting point for investment on each of the dams is as follows:

Avis Dam N$ 0.00 (the initial expenditure due to steepest initial slope)

Hardap Dam N$ 15.76 million

Von Bach Dam N$ 15.76 + N$ 47.20 = N$ 62.96 million

Refer to **Figure 8** for the RQO sequence and extent of dam rehabilitation.

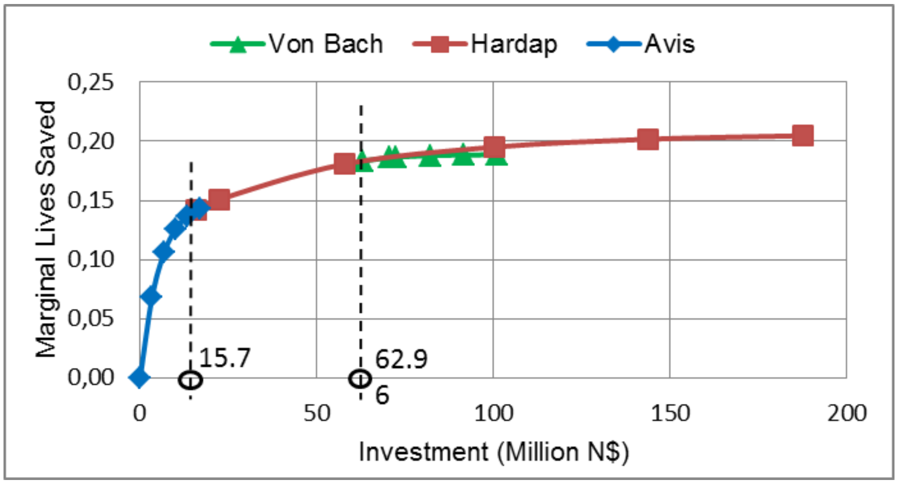

Figure 7. The combined ITC's for the Hardap, Von Bach and Avis Dams. Indicated are the transition points for investment from one dam to the next to optimise expenditure

6. decision making after applying the RQO

Nathwani et al. (1997) suggest that quantitative risk methods are a hallmark of professional quality in risk management; however it should not replace judgement in management. Quantitative risk analysis will aid the judgement of a decision maker faced with complex issues, to foster consistency among risk management decisions, and to support accountability

Until this stage, very little decision making has been required from the analyst. However, now that the portfolio of dams has been ranked in order of the highest to lowest risk, and the changeover from one dam to the next has been established, so as to optimise the investment, the analyst will be required to evaluate the outcome and its practicality.

With specific reference to the change-over in investment from the Hardap to the Von Bach Dam, the initial rate of marginal lives saved for the Von Bach Dam equals that of the Hardap Dam but it does not exceed it. The Von Bach Dam curve flattens off much more quickly than the Hardap Dam. Therefore it remains more beneficial regarding marginal lives saved rather to continue investing in the Hardap Dam than to change over to the Von Bach Dam.

7. Conclusions

The RQO process provides a quantitative approach to risk based dam safety in Namibia which can be used by dam portfolio managers to compare risks, prioritise rehabilitation activities and propose the extent of rehabilitation required at each dam to optimize the resources.

The RQO relates the probability of occurrence of the flood magnitude equal to the spillway capacity and the associated lives lost expressed in risk terms as the expected lives lost, to the cost of raising the non-overspill crest to the flood magnitude. By applying this relationship to a range of raised levels the risk characteristics of a dam can be obtained as a technology curve. Rehabilitation of a portfolio of dams can be prioritised in terms of their respective technology curves.

Risks in the RQO model are dominated by flood events with recurrence intervals spanning thousands of years.

The RQO process is applied mechanistically, not requiring judgement from the decision maker. In so doing it addresses the concern raised by dam owners regarding the judgmental characteristics of risk assessment. However, applying the RQO model to three real dams revealed that judgement is still required to evaluate the results.

8. Acknowledgements

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