Evaluating the decision criteria for the prioritisation of South African dams for rehabilitation in terms of risk to human lives

by

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Abstract

Evaluating the decision criteria for the prioritisation of South African dams for rehabilitation in terms of risk to human lives.

In South Africa a large number of dams owned by the Department of Water Affairs (DWA) need to be rehabilitated. This study investigated the decision process involved in the prioritisation of dams for rehabilitation. DWA developed a risk analysis methodology for defining the risks associated with dam safety, expressed as the combination of the probability and consequences of dam failure. These risks are evaluated using multiple acceptability criteria to assess risk to human life and the economic, social, socio-economic and environmental impacts of dam failure. In this study, the criteria used in the decision process to evaluate the acceptability of life safety risks were evaluated by comparing to international best practice methods, where the acceptability of risk to human life is commonly assessed as the expected number of fatalities against life safety criteria presented as FN-criteria on an FN-diagram.

Dam rehabilitation should reduce the probability of dam failure, thereby reducing the risk to society in terms of the expected lives lost. However, the rehabilitation works come at a cost and the level of these investments are usually large. In addition, the rehabilitation of South African government owned dams are financed by society and these financial resources are limited. Thus investments into dam rehabilitation works should be worthwhile for society. Society's Willingness to Pay (SWTP) for safety was applied to South African dam safety to determine the acceptable level of expenditure into life safety that is required by society.

Investments into improved safety levels are not always dictated by society, but could also be driven by the decision maker or owner requiring an economically optimal solution for the rehabilitation. Economic optimisation accounts for considerations additional to life safety, including economic motivations, damage costs of dam failure as well as compensation costs for lives lost. Often economic optimisation would govern the decision problem. Also, the DWA current evaluation does not take the cost of rehabilitation into account in any way. Thus, FN-criteria that primarily evaluates life safety, but also incorporates a measure of economic efficiency, were suggested in this study.

Uittreksel

Evaluering van die besluitnemingskriteria vir die prioritisering van Suid-Afrikaanse damme vir rehabilitasie in terme van risiko teenoor menselewens.

In Suid-Afrika moet ’n groot aantal damme wat deur die Departement van Waterwese (DWA) besit word gerehabiliteer word. Hierdie studie het die besluitnemingsproses ondersoek wat toegepas word om damme te prioritiseer vir rehabilitasiewerke. DWA het ’n bestaande metodologie wat gebaseer is op risiko-analise. Die risikos wat verband hou met damveiligheid word deur die metode bepaal en word uitgedruk as die kombinasie van waarskynlikheid en die beraamde gevolge van damfaling. Hierdie risikos word geëvalueer teenoor verskeie kriteria wat die aanvaarbaarheid van risikos teenoor menselewens en die ekonomiese, sosiale, sosio-ekonomiese en omgewingsimpakte van damfalings assesseer. In hierdie studie word die kriteria wat gebruik word in die besluitnemingsproses om die aanvaarbaarheid van risikos teenoor menselewens te bepaal geëvalueer deur die kriteria te vergelyk met metodes wat internasionaal as beste praktyk beskou word. Internasionaal word die aanvaarbaarheid van risikos teenoor menselewens oor die algemeen as die verwagte aantal sterftes teenoor lewensveiligheidskriteria FN-kriteria op ’n FN-diagram geassesseer.

Dam rehabilitasiewerke behoort die waarskynlikheid van damfaling te verminder, sodoende verminder die risiko teenoor die samelewing in terme van verwagte sterftes. Die rehabilitasiewerke vereis finansiële beleggings, en hierdie beleggings is gewoonlik groot. Verder word die rehabilitasie van Suid-Afrikaanse damme wat deur DWA besit word deur samelewing gefinansier en hierdie finasiële hulpbronne is beperk. Dus moet hierdie beleggings die moeite werd wees vir die samelewing. Die samelewing se bereidwilligheid om te betaal (*"SWTP"*) vir veiligheid word toegepas in Suid-Afrikaanse damveiligheid om die aanvaarbare vlak van beleggings vir ’n verbeterde veiligheid teenoor menselewens wat deur die samelewing vereis word te bepaal.

Beleggings in verbeterde damveiligheidsvlakke word egter nie altyd bepaal deur die samelewing nie, maar kan ook gedryf word deur die besluitnemer of eienaar wat ’n ekonomies optimale oplossing vir die rehabilitatiesewerke vereis. Ekonomiese optimering neem oorwegings addisioneel tot

lewensveiligheid in ag, insluitend ekonomiese motiverings, skade kostes as die dam faal, sowel as vergoedingskostes vir die verwagte sterftes. Ekonomiese optimering beheer dikwels die besluitnemingsprobleem. Verder neem die huidige DWA besluitnemingssproses in geen manier die kostes van rehabilitasie in ag nie. Dus word FN-kriteria wat hoofsaaklik veiligheid teenoor menselewens evalueer, maar wat ook ’n mate van ekonomiese doeltreffendheid insluit, voorgestel in hierdie studie.

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List of Acronyms

ACDS	Advisory Committee on Dangerous Substances (in the United Kingdom)
ACMH	Advisory Committee on Major Hazards (in the United Kingdom
ALARA	As Low As Reasonably Achievable
ALARP	As Low As Reasonably Practicable
ANCOLD	Australian National Committee On Large Dams
AW	Annual Worth (In economics)
CHINCOLD	Chinese National Committee on Large Dams
COMAH	Control Of Major Accident Hazards
DSO	Dam Safety Office (of Department of Water Affairs of South Africa)
DSRP	Dam Safety Rehabilitation Project (of Department of Water Affairs of South Africa)
DWA	Department of Water Affairs (governmental department of Republic of South Africa)
ECSA	Engineering Council of South Africa
ESVSL	Earth value for Societal Value of a Statistical Life
ESWTP	Earth value for Societal Willingness To Pay
FN-criteria	FN-curves are evaluated against FN-criteria on an FN-diagram (see *FN-curves* and *FN-diagrams*)
FN-curves	Form of presentation of risk to human life on FN-diagrams as the combination of the predicted number of fatalities (N) and the frequency (F) of N or more fatalities occurring (see *FN-diagrams*)
FN-diagrams	FN-curves are presented on FN-diagrams with the x-axis presenting the number of fatalities (N) and the y-axis representing the frequency (F) of N or more fatalities occurring
FW	Future Worth (In economics)
GDP	Gross Domestic Product
GIS	Geographical Information System

HF	- High Force (condition used in DeKay and McClelland (1993) method)
HSE	- Health and Safety Executive (of the United Kingdom)
IALAD	- Integrity Assessment of Large Dam)
ICOLD	- International Commission on Large Dams (ICOLD)
JCSS	- Joint Committee of Structural Safety
LF	- Low Force (condition used in DeKay and McClelland (1993) method)
LOL	- Loss Of Life
LQI	- Life Quality Index
NSW-DCS	- New South Wales Dam Safety Committee
OLF	- Object Loss Frequency approach
PAR	- Population At Risk
PEL	- Potential Economic Loss
PFRA	- PortFolio Risk Assessment
PLL	- Potential Loss of Life
R2P2	- HSE document: *"Reducing risk, protecting people"* (2001)
SANCOLD	- South African National Committee on Large Dams
SBA	- Standards Based Approach
SVSL	- Societal Value of a Statistical Life
SWTP	- Societal Willingness To Pay
UKAEA	- United Kingdom Atomic Energy Authority
USA	- United States of America (or U.S.)
USACE	- United States Army Corps of Engineers
USBR	- United States Bureau of Reclamation
USCOLD	- United States Committee on Large Dams
UDHR	- Universal Declaration of Human Rights
UK	- United Kingdom
WT	- Warning Time

Chapter 1

Introduction

1.1 Background to the study

The Department of Water Affairs (DWA) is a national governmental department who currently owns 314 dams across South Africa (Segers, 2012). According to Oosthuizen *et al.* (2010), most of the dams were designed and constructed many years ago by DWA itself, with dam building reaching its peak in the 1980's. Since then there has been a shift in dam engineering from the design of dams to the maintenance and rehabilitation of dams in terms of their safety.

To endorse dam safety in South Africa the dam safety legislation was implemented in 1987. The purpose of the legislation, according to the National Water Act, Act No. 36 of 1998 (DWA, 1998):

"...is to improve the safety of new and existing dams with a safety risk to reduce the potential harm to the public, damage to property or to resource quality..."

The legislation requires evaluations to take place at regular intervals to assess the current state of a dam in terms of its purpose and safety. In addition, it has become standard to perform a risk analysis as part of the regular dam safety evaluations completed in accordance with the legislation.

The risk analysis methodology developed by DWA combines the probability of dam failure and the associated consequences to define the risks. These risks are evaluated using multiple acceptability criteria to assess risk to human life and the economic, social, socio-economic and environmental impacts in case of dam failure. If the risks do not comply with the criteria, the rehabilitation of the dam may be recommended to improve its safety.

According to a report compiled by DWA, in the years 2004/2005, 166 of the 314 government owned dams were identified to be in need of rehabilitation works (Segers, 2012). The report further stated that of the 166 dams; 20 dams were removed from the list since the initial deficiencies were found to not warrant any action and 25 dams were identified to be of low importance to society and it was therefore not justified to invest into dam safety rehabilitation works.

Since the years 2005/2006 a dam safety rehabilitation programme was initiated by DWA and 19 of the dams in need of rehabilitation works have been rehabilitated in full. For an additional 9 dams, the civil works of rehabilitation works were completed, but the mechanical refurbishment works are still outstanding. The remaining 94 dams in need of rehabilitation works are in different stages of design, construction, planning or requires further assessments before action could be taken. In Table 1.1, a summary of the expenditure for the rehabilitation works conducted by DWA is provided. The total expenditure up until the 2011-2012 financial year is estimated to be more than R 1.5 billion.

Table 1.1: Summary of expenditure of dam rehabilitation works performed by DWA (Segers, 2012)

Financial Year	Total Expenditure
2005-2006	R 2,171,229
2006-2007	R 56,484,041
2007-2008	R 240,956,004
2008-2009	R 383,597,900
2009-2010	R 365,667,000
2010-2011	R 300,805,613
2011-2012 (estimated)	R 161,804,000
TOTAL	**R 1,511,485,787**

1.2 Research problem

The Department of Water Affairs (DWA) recently identified the need for reviewing the acceptability criteria used to evaluate dams for rehabilitation works. DWA specifically required the criteria used in the decision process to establish acceptability of assessed risk to human life to be evaluated.

When a dam is rehabilitated, it is expected for the probability of dam failure to be reduced and consequently the risk to human life should be reduced. However, these rehabilitation works come at a cost. The South African government finances rehabilitation works via public taxes or public charges and the level of these investments are large. Since it is society who essentially finance the rehabilitation of dams, it should be ensured that these investments into life safety are actually worthwhile for society. In this sense it must be noted that the societal resources that can be allocated to improving life safety through dam rehabilitation works are limited. If the cost of reducing the risk to human life through the dam rehabilitation works is disproportionate to the actual reduction in risk to life, these resources may need to be redirected in other sectors, for example into health care, transportation services or education, to improve the quality of life of society.

However, investments into dam rehabilitation works are not always driven by society's preferences for life safety, but are often dictated by the decision maker or owner's preferences taking other considerations in addition to life safety into account. These additional considerations may account for the profitability of the project or the economic, environmental or other impacts in case of dam failure.

In light of evaluating South African dams for rehabilitation works, the following research questions were developed:

1. What should the acceptability criteria for risk to human life be?
2. What is the acceptable level for investments into life safety required by society?
3. Are further investments into rehabilitation works, in addition to investments for life safety, justified based on the preferences of the decision maker or owner?

1.3 Existing approaches

Three major existing approaches may be used to assess the acceptability of risk to human life, if the investment into reducing risk to human life is required by society, and if further investments is justified on behalf of the decision maker or owner's preferences. These approaches include:

- **Conventional criteria for human safety**
  Conventional criteria for human safety assess the risk to human life without explicitly evaluating the costs of the safety measure. The risk to human life is commonly expressed as the expected fatalities per year. This is the most commonly applied criteria and are generally calibrated by analysing safety levels of previous projects (Lentz, 2007).
- **Utility-based criteria for human safety**
  Instead of independently evaluating the risk to life imposed by a dam and the investment cost into reducing the risk to life, a joint indicator may be used which unites both aspects. This may be achieved through socio-economic utility theory where utility is a measure of its own, but can equally be transformed into other units, such as life expectancy or income.

  Societal Willingness To Pay (SWTP) is a utility function which may be used as an effective tool to determine the acceptable level of expenditure that is required by society in exchange for a reduction in risk to human life (Pandey *et al.*, 2006). It determines a lower boundary for investments into risk reduction measures, by considering society's preference for exchanging money for life years.

- **Economic optimisation**

  Investments are not only driven by life safety concerns, but are often driven by economic considerations.

  Economic optimisation primarily considers the interests of the decision maker or owner and is of little interest to society. It evaluates the costs of a safety measure, requiring a maximised monetary net benefit at the lowest cost. This may be achieved by economically optimising the profitability of a project, where the profitability of a project is determined by subtracting the investment cost for the safety measure and the damage costs in case of failure from the benefit of the safety measure. Although it does not evaluate the acceptability of risk to human life, the damage costs in case of failure include compensation costs for loss of human life.

1.4 Aim of the study

This study will aim at evaluating the decision criteria for the prioritisation of South African dams for rehabilitation works in terms of risk to human lives. In addition, this study will propose additional decision tools regarding the level of investments into dam rehabilitation works. This will be done by applying the three major existing approaches discussed in section 1.3. The research methodology will be as follows:

- The current acceptability criteria for risk to human life used in South African dam safety will be evaluated by comparing to conventional criteria used internationally.

- The SWTP utility function is proposed to determine the lower bound for acceptable investments into life safety through dam rehabilitation works required by society.

- Economic optimisation is proposed as an additional decision tool to evaluate if investments into dam rehabilitation works, above and beyond the SWTP threshold, are justified according to the decision maker or owner's preferences.

- Conventional acceptability criteria for life safety do not incorporate the investment costs for rehabilitation works. Considering the recommendations for investments through SWTP and economic optimisation, it is proposed to develop a single-evaluation criteria to primarily evaluate life safety risks, but also with some measure of economic efficiency incorporated.

1.5 Outline of the study

The chapter outline is as follows:

Chapter 2 - Risk-based decision making in dam safety management
In Chapter 2 existing literature regarding the topic of this study are reviewed. A brief overview of the importance of dams and dam safety are provided. The management of dam safety, both internationally and in South Africa, are discussed. The use of risk-based tools to aid decisions regarding the adequacy of dam safety levels are considered. Finally, the main principles and preferences which should be considered when evaluating risks to human life are reviewed.

Chapter 3 - Development and application of conventional acceptability criteria for risk to human life
In Chapter 3 a theoretical background of conventional acceptability criteria for risk to human life are provided. Thereafter, the development and application of conventional acceptability criteria for risk to human life on an international level in different industries and also specifically in dam safety are discussed.

Chapter 4 - Evaluation of South African dam safety acceptability criteria to assess risk to human life
In Chapter 4 the current acceptability criteria used in South African dam safety for life safety risks are evaluated by comparing to international best practice criteria identified in Chapter 3. South African case studies of government owned dams which were recommended for rehabilitation works by DWA are evaluated in terms of the acceptability criteria proposed in this chapter to assess if the original decision to rehabilitate was justified.

Chapter 5 - SWTP as a lower bound constraint on dam safety levels
In Chapter 5, Societal Willingness To Pay (SWTP) is suggested as an additional tool to evaluate if a investment into life safety through dam rehabilitation works is required by society. Firstly, a theoretical background on SWTP as a utility function is provided. Thereafter, the SWTP concept is applied to South African dam study and SWTP criteria are developed for evaluating dams for rehabilitation works. The same case studies that were evaluated in terms of conventional acceptability criteria for

risk to human life in Chapter 4, are evaluated in terms of SWTP criteria to identify if rehabilitation was required by society.

Chapter 6 - Economic optimisation as a decision tool for the evaluation of South African dam rehabilitation works

Lastly, economic optimisation is applied as an additional decision tool to evaluate if further investments into dam rehabilitation works, in addition to SWTP requirements for life safety, is justified. Firstly, a theoretical background on economic optimisation is reviewed. Thereafter, economic optimisation criteria relevant to this study is developed. The South African case studies of government owned dams are assessed in terms of the proposed criteria to evaluate if the investment is economically beneficial. The economic optimisation results are compared to the recommendations for rehabilitation works through conventional acceptability criteria for risk to life and SWTP criteria.

Finally, a single-evaluation criteria is proposed to primarily evaluate life safety risks, but also with some measure of economic efficiency incorporated.

Chapter 7 - Conclusions and recommendations

An overview of the main findings when developing the decision tools proposed in this study is presented. In addition, the results obtained when evaluating the South African case studies in terms of the proposed decision tools are discussed. Finally, a summary of the main conclusions and recommendations regarding evaluating South African dams for rehabilitation works is presented.

Chapter 2

Risk-based decision making in dam safety management

2.1 Introduction

The purpose of this chapter is to give an overview of the importance of dams and the management of dam safety. Existing knowledge on the use of risk analysis methods to aid decision making with regards to dam safety are presented. Additionally, factors which need to be considered when evaluating life safety risks are investigated.

The chapter is structured as follows:

- A brief overview of the importance of dams, dam safety and the management of dam safety is provided.
    - A background of dams, the elements of a dam, the types of dams encountered and the purposes of a dam are presented to outline the importance of dams in general.
    - Dam safety and dam failure are defined. Typical causes and examples of dam safety related incidents which have occurred in South Africa and internationally are presented.
    - The importance of dams and dam safety stresses the need for managing dam safety. Some international dam safety organisations are listed. The management of dam safety in South Africa, with specific reference to the development of the dam safety legislation, is discussed.
- The management of dam safety includes evaluating and making decisions regarding the safety levels of a dam. Risk analysis methods are useful in guiding the decision making process.

  - The concept of engineering decision making and the use of risk-based decision tools to aid decisions regarding dam safety are discussed.
  - A generic framework for making decisions based on risk is presented.
  - The application of risk-based decision making methods in international and South African dam safety are discussed.

- Dam safety risks which are estimated through risk analysis methods should be evaluated against decision criteria to determine the acceptability of the risk. In this study, decision criteria for evaluating the acceptability of assessed risk to human life imposed by dams are investigated. In establishing life safety criteria, some important aspects need to be considered:
  - The difference between assessing life safety on an individual or societal level is discussed.
  - The fundamental and ethical principles that need to be taken into account when evaluating risk to human life are presented.
  - Preferences that may influence decisions regarding life safety are discussed.
- A concluding summary is provided.

2.2 Importance of dams, dam safety and management of dam safety

In the following section the importance of dams to society are highlighted. Examples of dam safety related incidents are presented to stress the need for the proper management and control of dams in terms of their safety.

2.2.1 Background of dams

A dam is a man-made barrier which is built in order to hold back water and form an artificial lake or reservoir behind it (Tancev, 2005). The barrier has an upstream and downstream face with the upstream face the side where the water is retained and the downstream face the opposite side situated in the direction in which a river flows.

As an example, a photograph of Hoover Dam is shown in Fig. 2.1. It is located in the Black Canyon of the Colorado River in the United States of America (USA) and was constructed between the years 1931 and 1936 by the United States Bureau of Reclamation (USBR, 2012). It is a 221.4 meters high concrete dam in the form of an arch and can hold up to 35 billion cubic meters of water in Lake Mead behind it (Vilander, 1999).

Figure 2.1: Hoover dam constructed by the Bureau of Reclamation in the USA (WePhotographer, 2004)

The barrier is the main element of a dam, but additional structures or facilities, also called appurtenances, are incorporated to control the discharge of water and to ensure the dam operates safely. The additional structures or facilities could include; spillways, outlet works, internal drainage systems to control seepage and internal galleries and shafts (Novak *et al.*, 2007).

Dams can be classified into two general groups based on the principal construction material used; embankment dams, constructed from natural materials such as earth and rock, and concrete dams, constructed from concrete but could also be constructed from masonry or stone. Embankment dams most commonly have a trapezoidal cross-sectional shape and are constructed by means of dump filling the earth and/or rock which may be obtained locally (Tancev, 2005). In Fig. 2.2, Sterkfontein Dam, situated in the Free State province of South Africa, is shown as an example of an embankment dam. In contrast to embankment dams, concrete dams typically have different face slopes, with generally a steep downstream side and an almost vertical upstream side (Novak *et al.*, 2007). Less construction material is needed for concrete dams since the horizontal force can be resisted by the self-weight of the concrete, i.e. gravity holds it down to the ground and stops the water from pushing it over. The main types of concrete dams are; gravity dams, typically having a triangular cross-section, buttress dams, consisting of a thin slab and a series of supports on the downstream side of the dam, and arch dams, curved in shape with the top point of the arch pointing back into water and resisting the pushing force of the water (Tancev, 2005). Hoover dam, illustrated in Fig. 2.1

is an example of an arched concrete dam. It must be noted that dams may also be constructed as composite dams, utilising a combination of embankment and concrete dams.

Figure 2.2: Example of an embankment dam, Sterkfontein Dam in South Africa (DWA, 2012)

According to Novak *et al.* (2007), embankment dams are mostly encountered, since mainly local materials are used to construct the dam and it is more economical and technologically sufficient. Embankment dams also prove to be more adaptable to site conditions, whereas concrete dams may require very specific conditions for the foundation.

Novak *et al.* (2007) further states that each dam is a unique structure which is not only dependent on site specific conditions for the foundation but also depends on the geology, material characteristics, catchment flood hydrology and much more. Therefore, in selecting an appropriate site for designing and constructing a dam, expertise from many different disciplines, for example structural and fluid mechanics, geology, flood hydrology and hydraulics, are needed.

Dams are useful in serving a number of purposes. Through storing water from a river behind a dam, the water could become available for use in dry periods. Historically, through the increased reliability of water available for the growth of agriculture, more irrigation systems were implemented. The continuous availability of water therefore allows for an increase in wealth of a society which in turn results in human development (ICOLD, 2005). In addition, a dam may reduce the severity of flooding downstream of the dam. This allows for increased living space downstream of the dam as shown in Fig. 2.3. Also, the recreational possibilities of a dam may attract people to live nearby the dam.

The main purposes of a dam, as outlined by the International Commission on Large Dams (ICOLD, 2012), are listed:

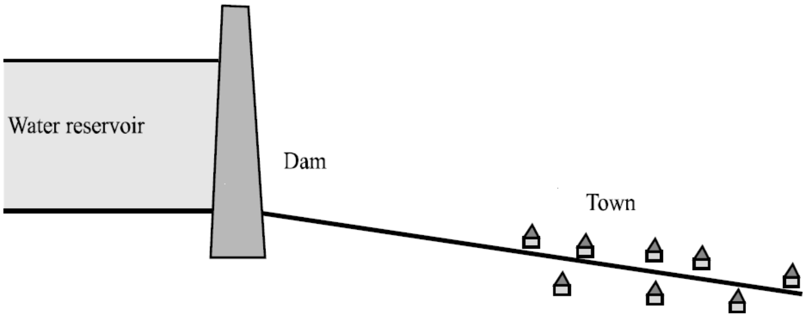

Figure 2.3: Town situated downstream of a dam

- **Irrigation:**
  Dams could supply water for agriculture and as the world's population is growing an increased food demand stresses the need for water supply for irrigation purposes .
- **Hydropower:**
  Dams may be constructed to generate electricity, which may be a sufficient renewable energy resource for society.
- **Water supply:**
  Dams may be needed to supply water for both domestic and industrial use. Since hydrological cycles may be unpredictable, water storage in dams are essential for providing a consistent supply of water during water shortages.
- **Flood control:**
  Dams regulate river levels and control flooding downstream of a dam and in the case of flooding, dams can store the flood volume and release it in a controlled manner.
- **Inland navigation:**
  Inland navigation includes rivers that have been developed with dams and reservoirs to transport goods. In comparison to highway and rail, inland navigation allows for large loads to be transported at a fuel efficient manner.
- **Recreation, fish farming and other purposes**

In summary, dam engineering relies upon many different scientific principles as well as informed engineering judgement and therefore it is a unique specialized field with a broad basis (Novak *et al.*, 2007). Also, in addition to the number of roles dams play in a society, the main purpose of developing a large dam is to enhance the welfare of society. As populations grow economic development increases the demand for the consumption of water and consequently the need for storing water in dams is becoming more important.

2.2.2 Dam safety and incidents relating to dam safety

Dams play an important role in enhancing the quality of life of society, but the safety of dams is also important as dam failure may lead to disastrous consequences, such as the loss of human lives and significant financial losses.

Defining dam safety and dam failure

Dam safety cannot be defined explicitly and consequently many variations of definitions for dam safety may exist. The International Commission on Large Dams (ICOLD) is an international non-governmental organisation which allows the exchange of knowledge and experience in dam engineering between nations (ICOLD, 2012). ICOLD describes "dam safety" in Bulletin 59 on *"Dam Safety - Guidelines"* (1987) as follows:

"the safety of a dam manifests itself in being free of any conditions and developments that could lead to its deterioration or destruction. The margins which separate the actual condition of a dam, or the conditions it is designed for, from those leading to its damage or destruction is a measure of its safety"

Another example of a definition of dam safety is provided by the Water Management Branch of the Province of British Columbia in Canada in their dam safety guidelines for inspection and maintenance of dams (2011). According to the guidelines a "safe dam" is a:

"Dam which does not impose an unacceptable risk to people or property, and which meets safety criteria that are acceptable to the government, the engineering profession and the public."

Alternatively, dam failure can also be defined, but the definitions for dam failure could also vary. ICOLD defines "dam failure" in Bulletin 99 on *"Dam Failures - Statistical Analysis"* (1995) as follows:

"Collapse or movement of part of a 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."

Typical causes of dam failure

ICOLD has compiled a list of causes of dam failures. The list is extensive, but some failure types as obtained from Bulletin 99 (ICOLD, 1995) include:

- Inadequate design
- Failure due to the dam foundation due to the following factors; inadequate site investigation, seepage, internal erosion, sliding and shear strength.
- Failure due to the dam materials including the following contributing factors; permeability, ageing and compaction.
- Failure due to the unforeseen actions of exceptional magnitude such as; precipitation, waves on the reservoir, earthquakes, uplift, overtopping or strong blasting nearby.
- Failure due to the structural behaviour of the body including; insufficient slope protection, seepage and internal erosion.
- Failure due to the appurtenant works such as; insufficient spillway capacity, internal erosion, mechanical strength or excessive flow rates.

In South Africa, Nortje (2002) has compiled statistics on the causes of dam failures or severe damage as recorded by the Department of Water Affairs (DWA) from 1987 to 2001. According to Nortje (2002), inadequate spillway capacity is the major cause of dam failure in South Africa. Another important cause of failure or severe damage is due to erosion/undermining of spillways during floods.

Some case studies of dam safety related incidents in South Africa resulting in either loss of life or narrow escapes of human beings are presented in Table 2.1 as obtained from Nortje (2002):

Table 2.1: Examples of dam safety related incidents in South Africa (Nortje, 2002)

Location	Incident	Year	No. of lives lost
Lydenburg Flooding	Partial failure of Lydenburg Town Dam due to high intensity rainfall	2001	**6 lives lost**
Lake Mzingazi Flooding near Richards bay	Breach of dam wall due to high intensity rainfall	2000	**3 lives lost**
Boomryk Dam near Levubu	Breach of dam wall due to high intensity rainfall	2000	**2 lives lost**
Windsor Dam near Ladysmith	Unauthorised opening of sluice gate	1998	**4 lives lost (children playing downstream)**
Klein Kariba near Warmbath	Upstream dam failed due to piping	1996	No lives lost (30 people swiftly evacuated)
Kruin Dam near Grabouw	Dam failed due to piping	1994	No lives lost (60 people evacuated)

Some examples of dam failures that occurred internationally are presented:

1. South Fork Dam in Pennsylvania: Failed 31 May 1889

   The failure of this earthfill dam resulted in **2209 human fatalities** and the damage was estimated to be 17 million U.S. Dollars. It is believed that the dam failed due to bad maintenance, a clogged spillway and heavy rainfall (ASDSO, 2012).

2. Banqiao Reservoir Dam in China: Failed in 1975

   The dam failure was preceded by heavy rainfalls due to a typhoon. The dam was 118m high and had a storage capacity of 492 million cubic meters. It is estimated that there was more than **150 000 human fatalities**, 26 000 fatalities were directly related to the flooding, and the other fatalities were due to related causes, such as health epidemics due to contaminated water (Britannica, 2012).

3. St. Francis Dam, California: Failed on 12 March 1928

   St. Francis Dam collapsed, with the left side giving way first. This dam failure resulted in more than **600 fatalities** and more than 5.5 million U.S. Dollars in damages (ASDSO, 2012). In Fig. 2.4 a photo of the failed dam is shown.

Figure 2.4: Photo of failed St. Francis Dam, California (Cervin, 2008)

4. Malpasset Dam in France: Failed on 2 December 1959

   Malpasset dam was an arch dam which failed due to foundation failure. The geological study of the region was not thorough. A tectonic fault was later found as the most likely cause for the disaster. The dam failure resulted in **421 fatalities** and the damage was estimated to be 68 million U.S. Dollars (Reporter, 2012).

5. Vaiont Dam in Italy: Failed on 9 October 1963

   This double curvature arch dam failed due to a landslide in the dam basin, leading to **almost 2000 human fatalities** (Genevois and Ghirotti, 2005).

6. Camara Dam in Brazil: Failed on 21 June 2004

   Heavy rain preceded the failure of Camara Dam, which resulted in **5 fatalities** (Charles *et al.*, 2011).

In summary, dam safety related incidents are a reality and by studying previous case studies, internationally and in South Africa, it is observed that there are serious cases of human fatalities and loss of downstream property caused by dam failures. This necessitates the need for the proper management and control of dam safety.

2.2.3 Management of dam safety internationally and in South Africa

In this section an overview of how dam safety is managed internationally and in South Africa is provided.

Overview of dam safety management internationally

On an international level dam safety is strongly influenced by the standards provided by the International Commission on Large Dams (ICOLD), where as aforementioned, ICOLD is a non-governmental organisation allowing the exchange of knowledge and experience in dam engineering between different countries (ICOLD, 2012). Another international organisation, the World Commission on Dams was established in 1998. Their purpose is to research the environmental, social and economic impacts of the development of dams.

Some dam safety organisations, specific to certain countries, are listed:

- IALAD (Integrity Assessment of Large Dams) - an European dam safety group representing the following countries: Austria, Bulgaria, France, Germany, Greece, Italy, Romania, Slovenia, Spain, Switzerland and Turkey.
- ANCOLD (Australian National Committee on Large Dams) - representing Australia
- B.C. Hydro and Water Management Branch, in province of British Columbia - representing Canada
- SANCOLD (South African National Committee on Large Dams) - representing South Africa
- CHINCOLD (Chinese National Committee on Large Dams) - representing China
- USCOLD (United States Committee on Large Dams)- representing the USA

- USBR (United States Bureau of Reclamation)

In addition to the international dam safety organisations providing dam safety standards, each country may have further authorities which manage the safety of dams. These may include the government, regulators or dam owners. Therefore, each country have their own dam safety standards specific to their own circumstances.

Overview of South African dam safety management

In South Africa, the Department of Water Affairs (DWA) is a national governmental department which is the custodian of and is responsible for all aspects of law regarding water resources. According to a DWA progress report, the Department currently owns 314 dams and weirs across South Africa (Segers, 2012). Before the 1970's there was no official dam safety program in South Africa. During this period only the odd dam safety inspection took place (Oosthuizen *et al.*, 2010).

Two major dam accidents in Europe in the 1950's and 1960's drew more attention to dam safety in South Africa, including the failure of the Malpasset Dam in France in 1959 and the slope failure of Vaiont Dam in Italy 1963. Both dam failures resulted in large numbers of human lives lost and considerable financial losses. In consequence, it was decided by DWA to establish a dam safety programme, which included the promulgation of the dam safety legislation in South Africa (Oosthuizen *et al.*, 2010).

South African dam safety legislation

The South African dam safety legislation was implemented in 1987, following the insertion of Section 9(C) relating to dams with a safety risk in the National Water Act, 1956 (Act 54 of 1956) in 1984 and also after the publication of Dam Safety Regulations in Government Notice R.1560 on 25 July 1986. The Dam Safety Office (DSO) was established as part of DWA in the years 1985/86 to ensure the implementation of the dam safety legislation. The previous Water Act, 1956 (Act 54 of 1956) was replaced by the National Water Act, 1998 (Act 36 of 1998) and a whole chapter of this act is dedicated to the "Safety of Dams". In summary, the dam safety programme in South Africa is enforced by the following legislation:

- Sections 117 to 123 (Chapter 12) of the National Water Act, 1998 (Act 36 of 1998). Hereafter referred to as the Act.

  The seven sections of Chapter 12 of the Act regarding the "Safety of dams" consist of; definitions, control measures for dams with a safety risk, responsibilities of approved professional persons, registration and factors to be considered when declaring a dam with a safety risk, exemptions and regulations regarding dam safety.

- The Dam Safety Regulations as published in Government Notice R.1560 of July 1986. Hereafter referred to as the Regulations.

  The general requirements of the Regulations are summarised:

  - Classification and registration of dams
  - Procedures for construction, enlargement, alterations or repair of dams with a safety risk
  - Procedures for first filling of dams
  - Requirements regarding operation and maintenance of dams
  - Dam safety evaluation of dams with a safety risk
  - Decommissioning of dams with a safety risk
  - Approval of professional persons and professional teams including register

Purpose of South African dam safety legislation

The purpose of the South African dam safety legislation, according to the Act (DWA, 1998):

"...is to improve the safety of new and existing dams with a safety risk to reduce the potential harm to the public, damage to property or to resource quality..."

A "dam with a safety risk" is defined by the Act and depends on how much water the dam can contain and the wall height. The definition therefore acts as a first sieve, excluding smaller dams with a low hazard potential of lesser importance.

The Act further requires that dams with a safety risk should be registered and classified. A dam is classified in accordance with the Regulations based on the combination of the size class and the hazard potential rating of the dam as shown in Table 2.2.

Table 2.2: Category classification of dams with a safety risk in South Africa according to Dam Safety Regulations as published in Government Notice R.1560 of July 1986 (DWA, 1986)

Size class	**Hazard potential rating**		
H = maximum wall height(m)	Low PLL=0 PEL: minimal	Significant PLL≤10 PEL: significant	High PLL>10 PEL: great
Small (5<H<12)	Category I	Category II	Category II
Medium (12≤H<30)	Category II	Category II	Category III
Large (H≥30)	Category III	Category III	Category III

The size classification is based on the maximum wall height with the limits shown in Table 2.2. The hazard potential is based on the potential loss of life (PLL) and potential economic loss (PEL) in case of dam failure, where the PLL and PEL are considered independently and the highest of the two determines the hazard potential rating. The limits for hazard potential classification are also shown in Table 2.2.

The limits for the PEL are not defined explicitly in the Regulations and the typical values used by Chemaly, 1997 cited in Nortje (2002) are shown:

Minimal	0 to 2 million Rand
Significant	2 to 20 million Rand
Great	More than 20 million Rand

It must be noted that only the size and hazard potential influence the classification of dams and not the present structural condition of the dam. This category classification determines the level of control over dams with a safety risk. For example, in the case of Category II and III dams, the involvement of an approved professional person (APP) is required when a dam is being evaluated for safety, designed or constructed, where an APP is a person registered with the Engineering Council of South Africa (ECSA).

Dam safety evaluations according to the Regulations

The Regulations require regular inspections or evaluations of a dam with a safety risk. These evaluations are required at 5 yearly intervals to check whether the dam is still in a serviceable condition and if it still is capable to perform the function for which it is intended.

For a dam safety inspection/evaluation; the adequacy of the spillway capacity and the stability of the dam is evaluated, the maintenance and operation of the dam is assessed, the consequences of overtopping, including the estimated loss of life, economic losses and other impacts in case of dam failure are assessed, the corrective measures needed and the urgency of these measures are provided in the dam safety evaluation report. Further requirements regarding the dam safety evaluations are provided in the Regulations.

Revised dam safety regulations

According to Nortje (2010), revised dam safety regulations are in the process of being published by DWA. A draft for the new regulations were published on 1 September 2009 and were open to public comment, where comments were received and incorporated.

In summary, in South Africa the dam safety legislation is responsible for improving the safety of new and existing dams with a safety risk by determining the level of control over these dams. In addition, regular dam safety evaluations are required by the legislation and these evaluations could stress the need for rehabilitation works at a dam to improve its safety.

2.3 Risk analysis to aid decision-making regarding dam safety

The management of dam safety includes evaluating and making decisions regarding the adequacy of dam safety levels. To guide the decision-making process, risk analysis methods may be used.

In this section the concept of engineering decision making and the use of risk-based tools to aid the decision problem are discussed. The term "risk" is formally defined and the framework for decision making based on risk is presented. Lastly the application of risk-based decision making methods in international and in South African dam safety are discussed.

2.3.1 Risk-based decision making

Objective of engineering decision-making

In section 2.2.3 it is highlighted that internationally there are organisations responsible for setting standards and for evaluating existing dams regarding its safety. If a dam is found to be inadequate in terms of safety, the decision to rehabilitate the dam may be recommended. However, this decision problem may be more complex than anticipated. The following questions may arise: "At what level is a dam considered to be 'unsafe' and should it be rehabilitated?", "What is an acceptable amount to invest into rehabilitation works, especially if dam is a government owned dam and investments into safety works are made on behalf of the public?". To provide some answer to these questions, the main requirements of an engineering facility should be considered.

From the perspective of the owner (private or public) the optimal decision regarding an engineering facility would be one which produces the highest economic benefit. From a societal perspective, the facility should intend to benefit the quality of life of the individuals of society. On a societal level, a beneficial engineering facility is a facility which is (Faber, 2009):

- economically efficient in serving a purpose,
- safe for individuals of society, and
- does not have adverse effects on the environment.

These requirements are set by the principle of sustainable development which requires decision-making to involve the joint consideration of society, economy and environment (Brundtland *et al.*, 1987). The principle was influenced by the realisation that our world's current population is growing and the consumption of resources are becoming more and more stressed (Mihelcic and Zimmerman, 2010).

Sustainable development is also defined as development "that meets the needs of the present without comprising the ability of future generations to meet their own needs" (Brundtland *et al.*, 1987). Therefore, in making decisions regarding engineering facilities it should be kept in mind that our generation should not leave the burden of too short-lived structures to future generations. In addition, our generation should ensure that financial resources are allocated optimally and not more is used than is really available (Faber, 2009).

Another factor which should be considered when making decisions regarding engineering facilities, is the case where an engineering facility is financed by the public via taxes or public charges. Since it is society who pays, they should enjoy the benefit received from the facility (Faber, 2009).

In summary, it must be noted that when decisions regarding an engineering facility are made, the decision problem may be very complex and may involve prerequisites set by the owner or by society.

Risk-based decision-making

As aforementioned, from a societal perspective engineering facilities should intend to benefit the quality of life of individuals of society, jointly considering the society, economy and the environment. From the owner's perspective decisions regarding investments into engineering facilities should be made in order to provide the largest possible economic benefit. If the facility provides no benefit it should not be realised at all (Faber, 2009). In order to evaluate the benefits received from an engineering facility, the decision problem may be considered from a risk management point of view, where risk management is the process of making decisions based on risks. Risks are the consequences if an event at a facility occurs combined with the probability or likelihood of the event occurring. The term "risk" indicates that there is uncertainty or lack of knowledge associated with an event, its consequences, or likelihood (Faber, 2009).

Risk (R) is often expressed as the product of the probability that the event will occur (P) and the consequences (C) if the event occurs, as shown in Eq. 2.3.1:

$$R = P \cdot C \tag{2.3.1}$$

As an example, the decision problem of rehabilitating a dam, consisting of two decision alternatives, is considered: the decision to rehabilitate the dam, or the decision to do-nothing and thereby not rehabilitate the dam.

For the "rehabilitate" option, the probability of the dam failing should be lowered. The consequences in case of dam failure most likely would remain the same as before the rehabilitation works were implemented, or possibly might be lowered. In effect, the risk as the combined probability and consequence is reduced. This decision alternative benefits society in that the safety of the dam is improved. Considering the owner's perspectives, the risk of economic losses is also reduced. However, to rehabilitate a dam comes at a cost. If the probability of failure is not reduced adequately enough in comparison with the cost, the alternative may not be justifiable.

If the "do-nothing" alternative is chosen there is no benefit in terms of safety since the probability of dam failure remains the same. However, there are no costs associated with this alternative.

In effect, the advantages of each decision alternative should be weighed against each other and the most beneficial option should be preferred. The decision problem with the two decision alternatives is summarised in Table 2.3.

In the following section, a generic framework for decision-making based on risk is presented.

Table 2.3: Interrelation of cost and safety associated with two different decision alternatives when considering a dam for rehabilitation works

Decision Alternative	Probability of Failure	Consequence of dam failure	Safety risk	Costs of Decision Alternative
No Rehabilitation	High	High	High	No costs
Rehabilitation	Lowered	High, Or possibly lowered	Lowered	Costs of rehabilitation

2.3.2 Framework for risk-based decision making

A framework for risk management as obtained from Holický (2009*b*) is shown in Fig. 2.5. Risk management consists of risk assessment and risk control. Risk assessment consists of performing a risk analysis, where the risks are estimated from identified hazards, and the evaluation of the risks in terms of acceptance criteria to decide which risks need treatment. Risk control involves decision making with regards to the treatment of the evaluated risks. In addition this step also involves consistently monitoring the risks for continuous improvements.

Hazard identification involves determining the sources of risk and the events which may have an impact on the facility. A hazard is defined by the ISO/IEC (1999) Guide 51 regarding safety aspects as

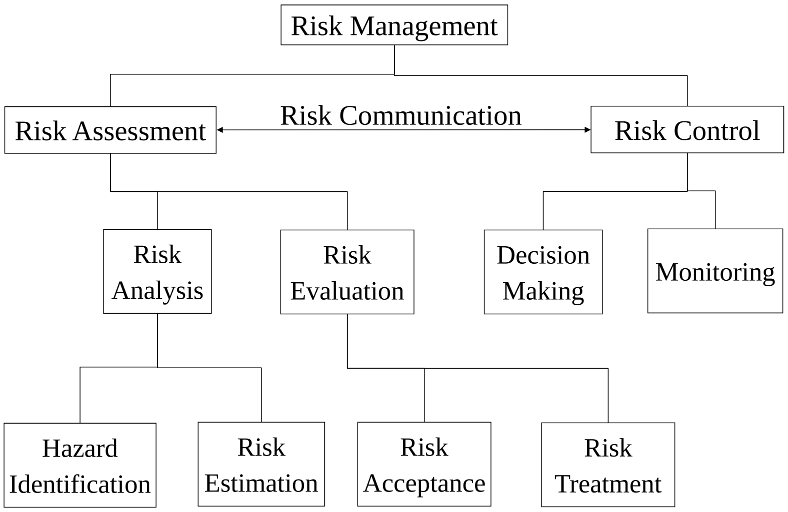

Figure 2.5: A framework for risk management (Holický, 2009*a*)

a: *"potential source of harm"*, where harm could include: *"physical injury or damage to the health of people, or damage to property or the environment"*. This step also includes **modelling of the relevant hazard scenarios**, where hazard scenarios are a sequence of events for a given hazard which may lead to the undesirable consequences (Holický, 2009*b*).

Next, the **risk is estimated** by determining the consequences and the probability of a hazardous event occurring. The probability analysis includes determining the chance or likelihood for a particular event to occur within a certain period of time (e.g. in one year). Through a consequence analysis the possible outcomes of an undesired event are determined. These may include human fatalities or injuries, financial losses or environmental damages (Holický, 2009*b*). The risk is expressed as an expected value, being the product of the probability and the consequences as shown in Eq. 2.3.1. Risk is thus a measure of the danger that the undesired events present to humans, the environment or economic values (Holický, 2009*b*).

Different levels of risk analyses may be conducted; the study may be qualitative or quantitative in nature. For a qualitative risk analysis, the magnitude of the potential consequences and the likelihood that the consequences will occur are expressed using words, while for a quantitative risk analysis numerical values are used.

Next in the risk management process the risks that were estimated are **evaluated** to make decisions on what risks need treatment, and what the extent and nature of the treatment should be. This step involves comparing the risks estimated through the risk analysis against **acceptance criteria**.

Multiple criteria may be used to evaluate the acceptability of different risks, for example risk to human life (expected fatalities or injuries), financial impacts (expected economic losses), environmental impacts (expected environmental damages), obtained from the risk analysis. Risk acceptance criteria are generally based on regulations, standards, experience and theoretical knowledge (Holický, 2009*b*).

The following **risk treatment** options for risks with negative outcomes, as obtained from the Australian and New Zealand Standard, AS/NZS 4360:2004 (2004) on *"Risk Management"*, should be considered:

- **Avoid the risk** by deciding not to start or continue with the activity that gives rise to the risk, for example by decommissioning an existing dam.
- **Reduce (prevent) the probability of occurrence** which would reduce the likelihood of negative outcomes. As an example, in dam safety this could be done through structural measures or dam safety management activities such as monitoring, surveillance and periodic inspections.
- **Reduce (mitigate) the consequences** which would reduce the extent of the losses. For example, in dam safety this could be done through emergency evacuation planning or by relocating the population at risk.
- **Transfer the risk**. This involves sharing the risk with another party, for example by contractual arrangements.
- **Retain (accept) the risk**. After all the different risk treatments are applied, there will be residual risks that are retained and may require risk financing (e.g. insurance).

According to the Australian and New Zealand Standard, AS/NZS 4360:2004 (2004) on *"Risk Management"*, it is essential to **communicate and consult** the basis on which decisions are made to the stakeholders throughout the risk management process, where the stakeholders may include the owner (private or public) or society. Stakeholders make judgements on risks based on different perceptions such as values, needs, assumptions, concepts and concerns. Since these views can impact the decisions made in the risk management process, it is important to integrate these perceptions into the process.

In the following section the application of risk-based decision making methods in international and in South African dam safety are discussed.

2.3.3 Use of risk assessment in international dam safety

The ICOLD Bulletin 130 on *"Risk Assessment in Dam Safety Management"* (2005) outlines the current international application of risk assessment in the management of dam safety. It is based on responses to a survey by respective ICOLD member countries. Information was collected for 24 countries, where the collected information was divided into two broad categories as shown:

- information related directly to **risk management** (analysis, evaluation, assessment)
- **related information** like legislation, guidelines, references etc.

The application of **risk management** in dam safety was further subdivided into the following categories:

- **Risk analysis** (the generation of information on risks)
  - Standards Based Approach (SBA)
  - Qualitative risk analysis
  - Quantitative risk analysis
- **Risk evaluation** (principles for deciding the significance of risks)
- **Applications of risk assessment to decision recommendations**

Standards Based Approach (SBA) is the traditional approach in dam engineering where risks are controlled using established standard engineering practice and safety coefficients. Risk analysis are not used explicitly through SBA, but risk and safety are considered implicitly in developing design loads and coefficients used in standards. All of the 24 member countries which responded to the ICOLD survey use this method. Also, 12 of the countries only use SBA and do not use qualitative and quantitative risk analysis in dam safety management. Some countries using only SBA, classify dams according to the hazardous nature of the dam and the potential consequences in case of dam failure without performing a further risk analysis (ICOLD, 2005).

Qualitative risk analysis does not use absolute values to describe the magnitude of the probability of an event and the associated consequences, but instead word form, descriptive or numeric rating scales are used (ICOLD, 2005). The most simple form of qualitative risk analysis used by responding member countries is the "ranking" technique, where dams are ranked and prioritised for risk reduction measures. In addition, other qualitative risk analysis methods, such as the Failure Modes and Effects Analysis (FMEA) and Failure Modes and Effects Criticality Analysis (FMECA), have been used by less than half of the responding countries. These methods are formal qualitative risk analysis techniques which are widely used in other industries with the application to dams slowly increasing.

Quantitative risk analysis uses numerical values as a representation of the actual magnitude of the probability of an event occurring and its associated consequences. According to the ICOLD Bulletin 130 (2005), only a limited number of responding countries use quantitative risk analysis techniques in dam safety management. Formal methods which include the First Order Second Moment (FOSM), Monte Carlo Simulation and full mathematical integration, where all variables are integrated over their full ranges. Other formal methods include the quantitative event tree or fault tree which may also give a mathematical representation of risk. These techniques are used in a varying or limited degree amongst the countries, mostly by a small group of specialists or consultants within the country.

Risk evaluation considers acceptability criteria for risk to life for individuals and society, it also considers criteria for other risks such as financial or environmental risks. According to the ICOLD Bulletin 130 (2005), acceptable or tolerable risk should be determined through a political process based on societal values. From the responding countries, some legislators (e.g. Netherlands) establish risk criteria. In other countries the regulators (e.g. UK HSE), professional bodies (e.g. ANCOLD) and dam owners (e.g. US Bureau of Reclamation) establish risk criteria for dam safety. From the 24 responding countries, 11 show a view on risk evaluation, where these countries include: Australia, Canada, Czech Republic, Germany, the Netherlands, New Zealand, South Africa, United Kingdom, the USA, Norway and Sweden (ICOLD, 2005).

The **applications of risk assessment to decision recommendations** is where the the complete risk assessment framework is considered and consequently dam safety decisions are made. Of the responding countries, half rely completely on the Standards Based Approach for risk management and control.

One method which considers the complete risk assessment framework is PortFolio Risk Assessment (PFRA), which considers a group of dams for dam safety risk management where a single owner or regulator is responsible. According to the Glossary of the ICOLD Bulletin 130 (2005), "portfolio risk assessment" is defined as follows:

> *"A particular form of risk assessment or analysis, which aims to make a comparative estimation of risks over all of, or many of, the dams of a single owner or single regulatory or other jurisdiction..."*

Of the responding countries, the following countries use PFRA: Australia, Canada, Czech Republic, South Africa and the USA.

The information collected from the ICOLD member countries regarding risk management are provided in the ICOLD Bulletin 130 (ICOLD, 2005). In addition, an overview of **related information** regarding guidelines, legislation and research in progress on risk assessment in dam safety management as obtained from the responses from the countries is also presented in the Bulletin.

2.3.4 Use of risk assessment in South African dam safety

As discussed in section 2.2.3, an official dam safety programme was implemented with regards to regulating the safety of the South African dams in 1986. According to Oosthuizen *et al.* (2010), in addition to the establishment of the dam safety legislation, a risk-based decision model for evaluating the safety of government owned dams was developed by the Department of Water Affairs (DWA). Although it is not currently required by the dam safety legislation, it has become standard to perform a risk analysis as part of the regular dam safety evaluations completed in accordance with the legislation. However, as discussed in section 2.2.3, the dam safety regulations were revised and are in the process of being published and a significant change in the revised dam safety regulations include that a risk analysis and/or risk assessment may be required to be carried out in case of applications for licence to construct and in the case of dam safety evaluations for Category II and III dams (Nortje, 2010).

Through the risk analysis the expected probability of dam failure and the consequences in case of dam failure are combined to define the risks which are evaluated in terms of acceptability criteria. The basic steps of the risk analysis methodology are as follow (Oosthuizen *et al.*, 2010):

- Determine the probability of dam failure.
- Perform a dam break analysis.
- Determine the consequences in case of dam failure.
- Evaluate the estimated risks against multiple acceptability criteria.
- Determine priorities using the multi-criteria decision model.

The estimated risks are presented on five impact diagrams (as shown in Fig. 2.6), with the x-axis representing the consequence in case of dam failure and the y-axis the annual probability of occurrence. A sixth diagram is used by DWA to represent the risk level. The risks are evaluated as unacceptable or acceptable in terms of acceptability criteria, which are presented as a dividing line on the diagrams.

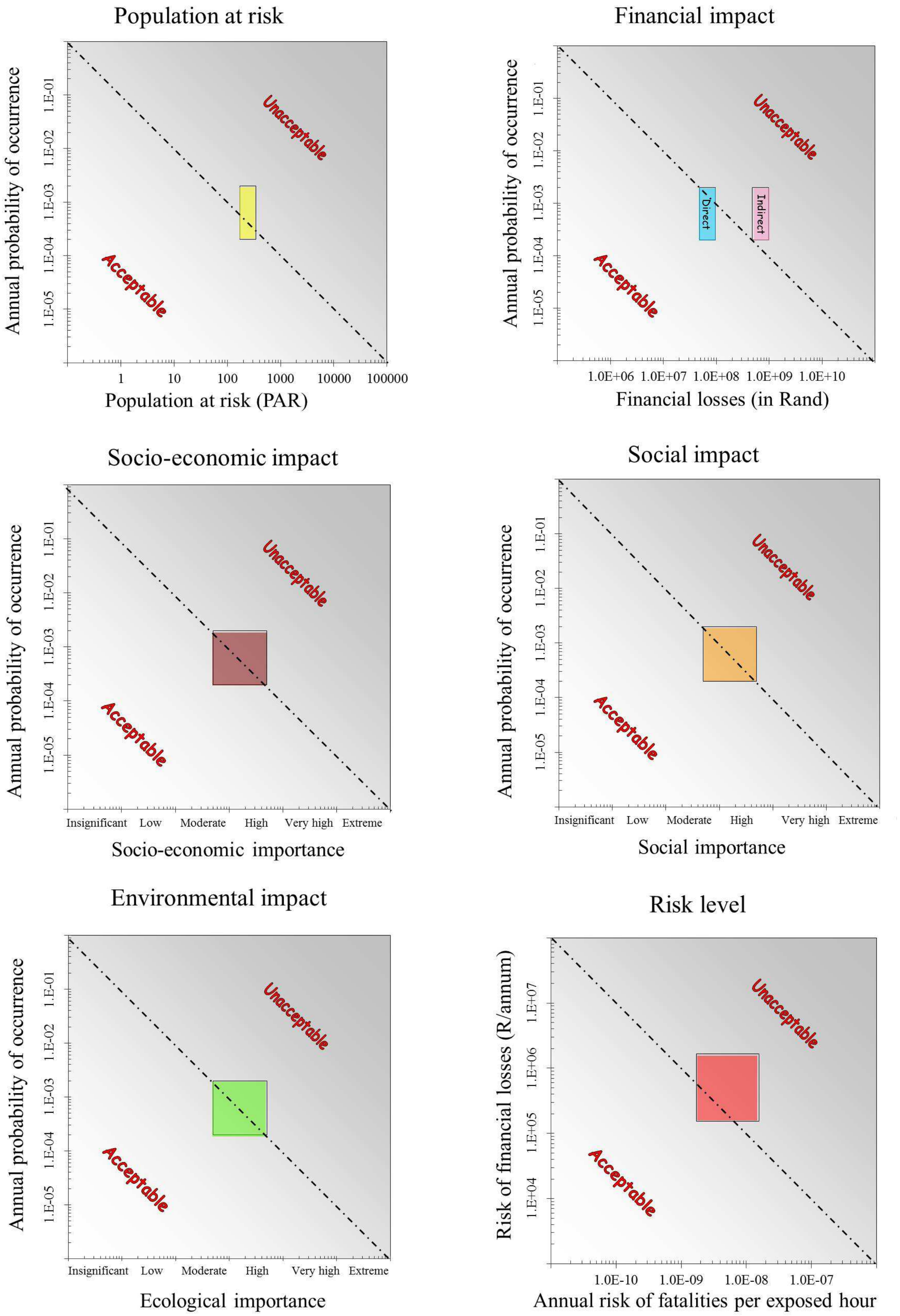

Figure 2.6: Impact and risk level diagrams used by Department of Water Affairs (DWA) (Hattingh and Oosthuizen, 2009)

Note that DWA estimates an interval for the probability and the consequences in case of dam failure, representing the level of confidence of the data. The maximum and minimum value of the interval is used to plot the risks in the form of a block on the impact and risk level diagrams as shown in Fig. 2.6.

The following expected risks are assessed against the multiple acceptance criteria as obtained from Oosthuizen *et al.* (2010), Hattingh and Oosthuizen (2009), Oosthuizen (2002) and Oosthuizen *et al.* (1991):

- **Population at risk**

  The number of people exposed to a dambreak flood and the probability of dam failure is expressed as the expected risk to human life on a population at risk diagram.

- **Financial impact**

  The financial losses due to a dam failure include both direct and indirect financial losses. Both the direct and indirect financial losses and the associated probability of dam failure are presented on a financial impact diagram.

  Direct financial losses may include the damage to the infrastructure, loss of agriculture and costs of emergency relief. The **indirect financial losses** are not only applicable to the flooded area downstream of the dambreak. This may include loss of future benefits from the dam and the loss of future earnings for humans.

  Certain financial losses may be wrongly interpreted, for example, the loss of future benefits and the replacement costs of the dam. When a dam breaks, the future benefits of the dam is lost and the value of these benefits is equivalent to the "value of the dam". If a dam is being rebuilt or replaced, the costs and benefits should be evaluated as a new project on its own. It is recommended by DWA that either the loss of future benefits or the replacement costs of a dam should be included in the financial losses.

- **Social impact**

  For the social impact the importance of the water provided by the dam for the society is judged subjectively. The relevant population density, the available water per capita and alternative sources of water guide the decision regarding social impact.

- **Socio-economic impact**

  The socio-economic impact is quantified subjectively. The gross geographical product of the relevant area, i.e. the income or payment received from agriculture, mining and manufacturing through the dams' existence, and the gross geographic product per capita are used to quantify the socio-economic importance of the dam.

- **Ecological impact**

  The ecological impact of a dam failure is also quantified subjectively. Environmental studies conducted by DWA assisted in defining categories for the ecological impact depending on the influence on the river and the loss of bio mass in case of dam failure.

- **Risk level**

  The risk level diagram is used in combination with the impact diagrams created for the population at risk, financial losses and social, socio-economic and ecological impacts in case of dam failure. The x-axis represents the expected loss of life per exposed hour. This therefore only applies to humans directly exposed to the hazard and may include fishermen, motorists and workers in the downstream area of the dambreak. Using actual historical data, the loss of life is predicted from the population at risk and assumptions related to the warning time available to the population at risk in case of a dam failure. The y-axis of the risk level graph represents the annual risk of both direct and indirect financial losses.

The risk analysis methodology have been updated and refined continuously by DWA as discussed in Oosthuizen *et al.* (1991), Oosthuizen and Elges (1998), Oosthuizen (2000), Oosthuizen *et al.* (2002), Oosthuizen and Hattingh (June 2007) and Oosthuizen (2009).

In summary, when dams are evaluated in terms of their safety the decision problem may be considered from a risk management point of view. If risks are evaluated as unacceptable in terms of risk acceptance criteria, treatment measures such as rehabilitation works may be recommended to reduce the level of risk imposed by the dam and improve the safety of the dam.

In this study, in light of evaluating South African dams for rehabilitation works, the criteria against which the acceptability of risk to human life are evaluated (i.e. the population at risk diagram in Fig. 2.6) are investigated. In the following section the underlying principles of risk evaluation and decision making specifically with respect to risk to human life are discussed.

2.4 Risk evaluation and decision making with regards to life safety

When establishing acceptability criteria for risk to human life, the preferences of the relevant stakeholder, either the owner or society, should be considered. If a facility fails, the owner (public or private) faces the consequences of financial losses. From a societal point of view, the most serious consequence of failure is fatalities (Lentz, 2007). Thus, when decisions regarding risk to human life is of concern, the values, needs, concepts and concerns of society need to be incorporated. In this section, the main aspects of defining life safety criteria are discussed.

2.4.1 Individual versus societal risk

From an engineering perspective, societal risk is purely the relationship between the probability of occurrence and the the number of people suffering a level of harm from a specific hazard (Ball and Floyd, 1998). However, there should be a distinction between risk to an individual (termed "individual risk") and risk to a group of people (termed "societal risk"). Formal definitions for individual and societal risk are provided as obtained from the Institution of Chemical Engineers (1992) cited in Ball and Floyd (1998):

- ***"Individual risk** is the frequency at which an individual may expect to sustain a given level of harm from the realisation of specified hazards."*
- ***"Societal risk** is the relationship between the frequency and the number of people suffering from a specified level of harm in a given population from the realisation of specified hazards."*

The difference between individual and societal risk is demonstrated by considering an example of risk to residents close to a hazardous facility:

- **Individual risk** - For a person close to a hazardous facility the chance of 1 fatality may be 1 in 100 000 per year due to an incident at the facility.
- **Societal risk** - For residents close to a hazardous facility the chance of 1 fatality **or more** may be 1 in 100 000 per year due to an incident at the facility.

When considering dam safety, the International Commission on Large Dams (ICOLD) defines individual and societal risk in Bulletin 130 on *"Risk Assessment in Dam Safety Management"* (2005) as follow:

- **Individual risk:**

  "Individual risk is the increment of risk imposed on a particular individual by the existence of a hazardous facility. This increment of risk is in addition to the background risk to life, which the person would live with on a daily basis if the facility did not exist or, in the context of dam safety, if the dam did not fail."

- **Societal risk:**

  "The risk of widespread or large scale detriment from the realisation of a defined hazard, the implication being that the consequence would be on such a scale as to provoke a socio/political response, and/or that the risk (i.e. the chance combined with the consequence) provokes public discussion and is effectively regulated by society as a whole through political processes and regulatory mechanisms.

  Such large risks are typically unevenly distributed, as are their attendant benefits. Thus the construction of a dam represents risk to those close by and a benefit to those further off, or a process may harm some future generation more than the present one. The distribution and balancing such major costs and benefits is a classic function of Government, subject to public discussion and debate."

According to Ball and Floyd (1998), in the past, societal risks have only been related to the people directly associated with the accident. However, over the years societal risk is considered in a broader framework, and is defined as the total harm to the population as described by the ICOLD definition for "societal risk" above. Therefore, societal risk is most commonly judged at a national level.

In this study, the need for rehabilitation works to reduce the risk to human life imposed by South African government owned dams are considered. Since the dams are owned by the government, the rehabilitation of these dams are funded by society by means of public taxes or charges. Further, the loss of life in case of dam failure would provoke a socio/political response and public discussion. Hence, when establishing acceptability criteria for evaluating risk to human life imposed by South African government owned dams societal risk should be considered.

2.4.2 Fundamental and ethical principles of life safety

The fundamental importance of ensuring life safety to society may be highlighted by considering the rights of humans. The Universal Declaration of Human Rights (UDHR) is a declaration adopted by the United Nations General Assembly and is the foundation of the international human rights law. In the Declaration the moral obligation to treat all human beings as equal are highlighted. In addition, the right of safety to human beings are highlighted. To demonstrate these requirements, article 1, 3 and 7 of the Declaration are quoted (the full text of the declaration may be obtained from: http://www.un.org/en/documents/udhr/index.shtml, 2012).

Article 1

"All human beings are born free and equal in dignity and rights. They are endowed with reason and conscience and should act towards one another in a spirit of brotherhood."

Article 3

"Everyone has the right to life, liberty and security of person"

Article 7

"All are equal before the law and are entitled without any discrimination to equal protection of the law. All are entitled to equal protection against any discrimination in violation of this Declaration and against any incitement to such discrimination."

The fundamental principles of human rights highlighted by the UDHR should always be abided when formulating life safety criteria. In addition, the value of human life could be considered from a philosophical point of view. There are a number of ethical principles which influence decisions regarding life safety and three principles as obtained from Lentz (2007) are outlined. These principles include: Kant's categorical imperative, the concept of intangibility of human life and the concept of utilitarianism.

Categorical Imperative

The categorical imperative was formulated by Immanual Kant's (1724-1804) argument that the fundamental principle of morality is based on a standard of rationality (Johnson, 2012). Thereby, the foundational moral principle is the demands of each person's own will. Among his formulations the following two formulations as obtained from Lentz (2007) are shown:

1. *"Act only according to that maxim whereby you can at the same time will that it become a universal law."*

   In other words, always act in such a way that you will be willing for it to become a general law that everyone else should do the same in the same situation.

2. *"Act so as to use humanity, whether in your own person or in others, always as an end, and never merely as a means."*

In other words, people should always be treated as valuable - as an end in themselves - and should not just be used in order to achieve something else.

Intangibility of human life

The intangibility of human life principle is derived from the Judeo-Christian tradition where man is understood to be the counterpart of God and human life is seen as holy. The intangibility principle stresses the infinite value of life:

"The value of any human life is higher than that of a non-human life or that of an unenlivened object."

"When each life is of infinite value, each fraction of life must equally be of infinite value. In consequence, the value of each human life is equal, regardless of age, health or remaining life expectancy."

Utilitarianism

The ethical theory known as utilitarianism was established in the 18^{th} century by the philosopher and reformer, Jeremy Bentham (Lentz, 2007). His principle of happiness interprets pain and pleasure as the only absolutes in the world. This lead to the central principle of utilitarianism:

"the greatest good for the greatest number"

In order to prevent that society benefits on the expenses of others, the utilitarianism principle is subject to a major constraint . This constraint is implemented by means of the Kaldor-Hicks Principle which states that:

"A policy is to be judged socially beneficial if the gainers receive enough benefits that they can compensate the losers fully and still have some net gain left over."

From an engineering perspective, the utilitarianism principle is implicitly taken into account by using quantitative risk analysis as the basis of their decisions. Such processes of decision making implies using numerical values and ultimately prices with respect to human life. This stands in contradiction with the principle of intangibility where human life is considered to be of infinite value. However, despite the fact that each human life should be considered to be of infinite value, societal resources are limited and should be prioritised (Faber, 2009).

2.4.3 Preferences in life safety decision making

In addition to decisions regarding life safety being subjected to fundamental and ethical principles, preferences of the individual and society may affect the decision. These preferences are outlined.

Individual and societal preferences

When establishing acceptability criteria for risk to human life, it must be noted that the viewpoint of what is acceptable risk for an individual may differ greatly from what is acceptable for society (Faber, 2009). Each individual has their own perception of risk, or in other terms, their own preferences. An individual decides to undertake an activity, weighing the risks against the direct and indirect personal benefits (Vrijling *et al.*, 1998). Individual preferences depends on each individual's situations (status, wealth, education, family etc.) (Faber, 2009). From a societal point of view, an activity is acceptable in terms of the trade-off between risk and benefit for the total population (Vrijling *et al.*, 1998).

The preferences of an individual may be in contradiction with societal preferences, but if the acceptability of risk imposed by a engineering facility to human life is considered, the preferences of the society is more of interest than the preferences of an individual (Faber, 2009). However, although acceptability criteria should be viewed from a societal angle, the basic human rights of individuals as expressed by the "Universal Declaration of Human Rights" in section 2.4.2 should still be protected.

Individual and societal preferences should not be confused with individual or societal risk. These preferences purely influence the basis on which acceptability criteria for risk to individuals or society may be established.

Voluntary and involuntary risk

Another important aspect is the degree of voluntariness with which a decision is taken and the risk is accepted. From the point of view of an individual, the public is more tolerant to a greater risk from a voluntary action than to a lower risk from an involuntary action.

According to Diamantidis (2008), this pattern of preferences regarding voluntary and involuntary risks are revealed in accident statistics, where according to individuals of society, working in a factory is an involuntary activity, driving a car is a neutral (between voluntary and involuntary) activity and mountaineering is a completely voluntary activity. According to accident statistics, the probability of losing one's life in normal daily activities such as driving a car or working in a factory appears to be much lower than the overall probability of losing one's life when partaking in a purely voluntary activity such as mountaineering. However, individuals are less tolerant to involuntary activities (Diamantidis, 2008).

When societal decisions involving risk are made, the individuals may still have an opinion in accordance with their own standards, but their influence on the final outcome of the societal decision is democratically limited. Individuals might thus feel a sense of involuntariness and may therefore have a critical attitude towards societal decisions. Hence, risk acceptance criteria cannot be based on one absolute level of acceptability, but may be subject to the degree of voluntariness (Vrijling *et al.*, 1998).

Risk aversion

Risk aversion is the additional public opposition to an event which kills a large number of people over a series of smaller events which collectively result in the same number of fatalities. Risk aversion is influenced, not only by accidents itself, but also by the attention brought about by media and politics (Vrijling *et al.*, 1998). According to HSE (2001) the societal awareness of risk from an event which kills a large number of people may be amplified by the dramatisation of the issue and the use of value-laden terminology and images by the media.

2.5 Concluding summary

Dams play a number of roles in our society, including enhancing the quality of life of our society. However, dams are inherently associated with safety issues. Both internationally and in South Africa there are serious cases of dam failures which have caused human fatalities and economic losses. This stresses the need for the proper management and control of dam safety.

Internationally there are a number of organisations responsible for providing standards for the management of dam safety. In South Africa, the Department of Water Affairs (DWA) is the custodian of a large number of dams and is responsible for all aspects of law regarding dam safety.

The South African dam safety legislation requires regular dam safety evaluations of dams which are classified with a safety risk. In addition to the establishment of the dam safety legislation, a risk-based decision model for evaluating the safety of dams has been developed and is currently applied by DWA.

For a specific dam, the DWA risk analysis methodology combines the estimated probability of dam failure and the different consequences of dam failure to quantitatively define risks. These risks are evaluated against multiple acceptability criteria to assess the risk to human life and the economic, social, socio-economic and environmental impacts in case of dam failure. If the risks are evaluated as unacceptable in terms of the criteria, the rehabilitation of dams to improve their safety may be recommended.

DWA recently identified the need for reviewing decision criteria for the prioritisation of South African dams for rehabilitation. More specifically DWA required the criteria for acceptability of assessed risk to human life to be evaluated.

When establishing life safety criteria, the preferences of the relevant stakeholder should be considered. In South African dam safety acceptability criteria for risk to human life should be developed at a societal level since the rehabilitation of government owned dams are financed through public taxes and charges. In addition, the failure of a dam would provoke a political response and public discussion.

When decisions regarding societal risk is of concern, the fundamental and ethical principles of life safety should be considered. Further, the values, needs and concerns of society need to be incorporated.

In Chapter 1 it was identified that internationally a major existing approach for assessing risk to human life, is through the use of conventional acceptability criteria for human safety, where the risk to human life is most commonly expressed as the expected fatalities per year. Therefore the output from the risk analysis concerning risk to human life is a quantitative measure of consequence, the estimated number of fatalities in case of dam failure, and the associated probability of dam failure. This form of criteria are generally calibrated by analysing the safety levels of previous projects.

In the following, Chapter 3, the development and application of conventional acceptability criteria for risk to human life is provided. In Chapter 4, the current acceptability criteria for risk to human life used in South African dam safety are evaluated by comparing the criteria to international best practice methods identified in Chapter 3.

Chapter 3

Development and application of conventional acceptability criteria to assess risk to human life

3.1 Introduction

In this study the current acceptability criteria for risk to human life used in South African dam safety by the Department of Water Affairs (DWA) are evaluated by comparing to international best practice methods. DWA expresses risk to human life quantitatively as the combination of the probability of dam failure and the population at risk in case of dam failure (as shown in Fig. 2.6 in Chapter 2). Thus, in order to compare, international methods for quantitatively evaluating risk to human life are reviewed.

An existing approach for assessing the risk to human life of a project is through the use of conventional criteria for human safety, where risk to human life is most commonly expressed as the expected fatalities per year, i.e. the combination of the estimated probability and number of fatalities. This form of criteria do not take the costs of the safety measure into account and are generally calibrated by analysing safety levels of previous projects.

In this chapter existing literature on the use of conventional acceptability criteria to assess risk to human life internationally in different industries and more specifically in dam safety are reviewed to identify the international best practice method for comparison against South African dam safety criteria.

The chapter is structured as follows:

- A theoretical background of conventional criteria for risk to human life are presented.
    - The quantitative representation of conventional criteria for life safety as FN-criterion lines on FN-diagrams are discussed.
    - The evaluation of risk to human life as FN-curves against FN-criterion lines are discussed. In addition, the mathematics of constructing FN-curves are presented.
    - Additional factors which should be considered when defining FN-criterion lines are presented. These factors include whether risk to human life should be judged as "tolerable" or "acceptable" and "As Low As Reasonably Practicable (ALARP)".
- The historical development of conventional criteria for risk to human life are reviewed.
    - The development of quantitative risk to human life criteria from the 1960's to the 1990's are presented as obtained from a report on *"Societal Risks"* presented by Ball and Floyd (1998).
    - A brief overview on the development and application of societal risk criteria in the UK, Hong Kong and in the Netherlands are provided as presented in the findings of the report.
- The application of the criteria internationally in different industries and more specifically in dam safety are discussed.
    - The current application of conventional criteria internationally in different industries, and more specifically in Europe, is discussed with specific reference to a paper presented by Trbojevic (2005).
    - The current application of conventional acceptability criteria for risk to human life internationally in dam safety is presented as obtained from the International Commission on Large Dams (ICOLD) Bulletin 130 on *"Risk Assessment in Dam Safety Management"* (2005).
- Finally, a summary of the main findings is provided and the recommended life safety criteria for comparison against South African dam safety criteria are discussed.

3.2 Theoretical background of conventional criteria for life safety

As aforementioned, conventional criteria to assess risk to human life most commonly express risk to human life as the expected fatalities per year. Therefore, the output from a risk analysis concerning risk to human life is a quantitative measure of the probability of occurrence and the associated consequence, the estimated number of fatalities.

According to Faber (2009), the most commonly used format to quantitatively assess risk to human life is against risk acceptance criteria presented as FN-criterion lines on an FN-diagram. FN-diagrams have a double-logarithmic scale with the x-axis representing the number of fatalities (N) and the y-axis representing the annual frequency (F) of N or more fatalities occurring (Kroon and Maes, 2008). A double logarithmic scale is used since the range of the values obtained for F and N can span multiple orders of magnitude.

In this section the most important features of FN-criteria presented on FN-diagrams and the evaluation of the risk to human life as FN-curves against FN-criterion lines are discussed.

3.2.1 FN-criteria for risk to human life

A demonstrative example of an FN-diagram with two different FN-criterion lines are shown in Fig. 3.1. If the risk to human life is located below the FN-criterion line the risk is acceptable and conversely if the risk is located above it is unacceptable.

FN-criterion lines are mostly defined by two properties; the intersection with the y-axis (for N=1) and the slope of the line. The properties of the criterion lines shown in Fig. 3.1 are defined as follow:

- Intersection with y-axis (N=1):
  - For Criterion Line 1, if the frequency of 1 or more fatalities occurring is higher than 0.001 per year (i.e. 1 in 1 000 per year), it is unacceptable.
  - For Criterion Line 2 if the frequency of 1 or more fatalities occurring is more than 0.0001 per year (i.e. 1 in 10 000 per year), it is unacceptable.
- Both FN-criterion lines have the same slope of -1.

Criterion Line 1 is located one factor of 10 higher than Criterion Line 2, leading to a higher risk to human life being accepted by Criterion Line 1. Thus, the risk acceptability criteria set by Criterion Line 1 is less stringent than Criterion Line 2.

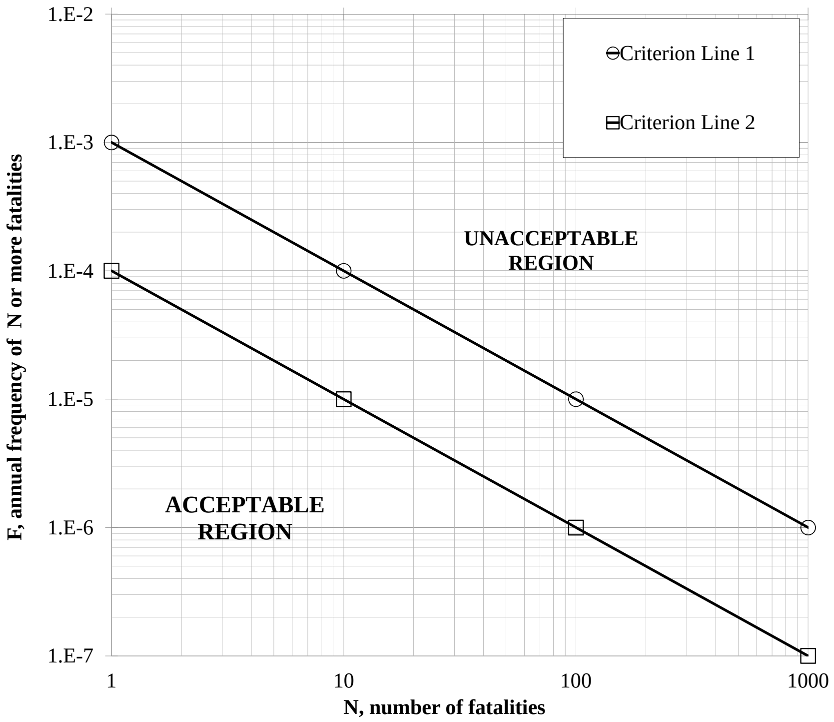

Figure 3.1: Illustrative FN-diagram demonstrating two different FN-criterion lines

The slope of the line represents the degree of risk aversion of the society (Kroon and Maes, 2008). As aforementioned in section 2.4.3 of Chapter 2, risk aversion is the additional public opposition to an event which kills a large number of people over a series of smaller events which collectively result in the same number of fatalities.

According to Ball and Floyd (1998), most FN-criterion line have slopes which are between -1 and -2. A slope of -1, is termed ’risk neutral’ and the weighting preference of preventing large accidents is proportional to the number of fatalities. If the slope is higher, for example -2, the society is ’risk averse’ and the acceptance criteria are more stringent on the number of fatalities.

3.2.2 FN-curves

To assess the risk to human life against FN-criteria, the results from a quantitative risk assessment is obtained, typically in the form of a predicted probability of occurrence (f) and the predicted number of fatalities (N) for the occurrence of an event. Note that the risk to human life could be plotted in two ways (CCPS, 2009):

- **Non-cumulative frequency basis**

  These diagrams are called fN-diagrams, and the risk is plotted as the discrete frequency, f, on the y-axis, of experiencing exactly N fatalities, on the x-axis.

- **Cumulative frequency basis**

  These diagrams are called FN-diagrams, and the risk to human life is plotted as the cumulative frequency, F, on the y-axis, of experiencing N or more fatalities, on the x-axis.

However, societal risk criteria are most commonly expressed as FN-criteria and therefore risk to human life is expressed as an FN-curve on an FN-diagram. According to Ball and Floyd (1998), if the results are depicted on an fN-diagram, the results are not readily interpretable.

To construct an FN-curve, a list of events, E, and their associated frequencies, f, and consequences, N, are compiled and sorted by decreasing value of N. For each event, the cumulative frequency is calculated as the sum of the preceding frequencies. For example for an event, N_3, the cumulative frequency is $F_3 = f_1 + f_2 + f_3$. Since the events are sorted by decreasing value of N, therefore $(N_1 > N_2 > N_3)$, F_3 is the cumulative frequency of all events causing at least N_3 fatalities. Hence, the frequency of N_3 or more fatalities occurring is F_3. The method for calculating cumulative frequencies, FN pairs are shown in Table 3.1.

Table 3.1: FN calculations from predicted frequency of occurrence, f, and the predicted number of fatalities, N for the occurrence of an event, E (CCPS, 2009)

Event	Event frequency (per year)	Event consequence	Cumulative frequency (per year)
E_1	f_1	N_1	$F_1 = f_1$
E_2	f_2	N_2	$F_2 = f_1 + f_2$
E_3	f_3	N_3	$F_3 = f_1 + f_2 + f_3$
...	...	...	...
E_n	f_n	N_n	$F_n = f_1 + f_2 + f_3 + ... + f_n$

An illustrative example of an FN-curve, representing the modelled risks obtained from a Eurotunnel Safety Case for a Channel Tunnel, is shown on an FN-diagram in Fig. 3.2 Evans and Verlander (1997). The FN-curve is located between two different FN-criterion lines, the negligible and intolerable line in the ALARP region. These concepts are described in the following section.

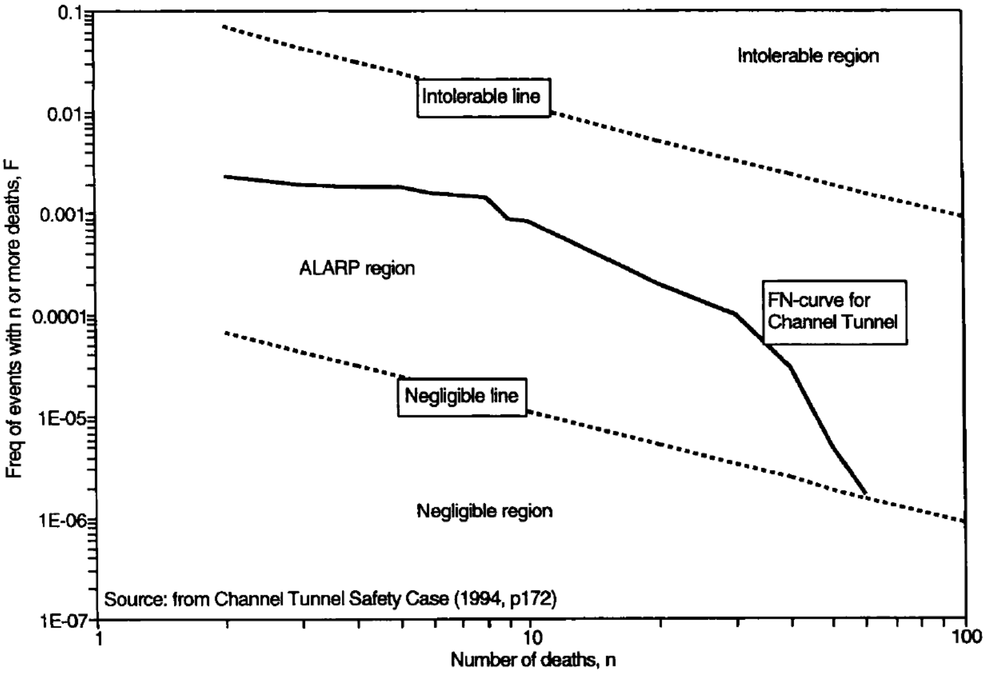

Figure 3.2: FN-curve for a Channel Tunnel assessed against FN-criteria (Channel Tunnel Safety Case, 1994, p.172 in Evans and Verlander, 1997)

3.2.3 Tolerability of risk

A risk can be judged as "acceptable" or "tolerable", however it must be noted that the two terms do not necessarily have the same meaning. The Health and Safety Executive (HSE) of the United Kingdom suggests in their document, *"Reducing risk, protecting people"*, that tolerable risk refers to a risk that society as a whole is willing to live with so as to secure certain benefits (HSE, 2001). Tolerable risk should be a risk worth taking and should be properly controlled. Tolerable risk would however not be acceptable to everyone since everyone would not necessarily agree to have the risk imposed on them. According to Melchers (2001), if a risk is tolerated, it does not mean that a risk is regarded as negligible, but instead it refers to a risk being kept under review and further reduced if possible.

HSE (2001) also suggests a generalised framework for the tolerability of risk which considers the principles on which risk criteria are based and also resembles the decision process people use in "everyday life". The framework is represented by means of a downward triangle as shown in Fig. 3.3.

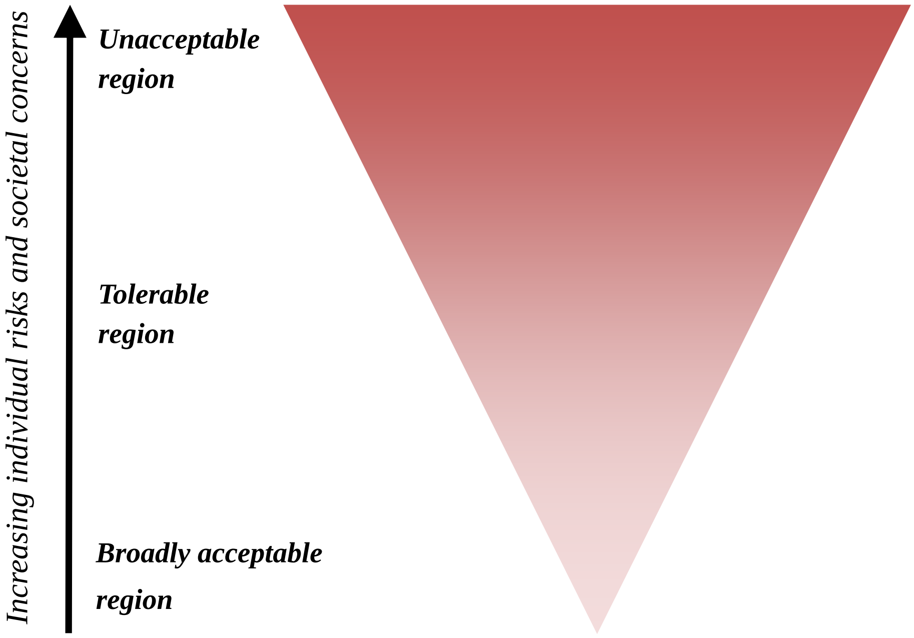

Figure 3.3: HSE tolerability of risk framework (HSE, 2001)

The increasing level of risk is represented by the width if the triangle. Further, three different regions of risk are presented in the tolerability of risk framework. These regions are described by HSE (2001) as follows:

1. *"**Unacceptable risks near the top of the triangle** - in this region risks would be regarded as unacceptable whatever the benefits unless they can be reduced to fall in a lower region or there are exceptional reasons for the activity or practice to be retained.*
2. ***Broadly acceptable risks near the bottom of the triangle** - risks falling into this region are generally regarded as insignificant and adequately controlled and would not usually require further action to reduce risks unless reasonably practicable measures are available.*
3. ***Tolerable risks between the other two regions** - risks in this region are typical of the risks from activities that people are prepared to tolerate in order to secure benefits, in the expectation that:*
    a) *the nature and level of the risks are properly assessed and the results used properly to determine control measures; AND*
    b) *the residual risks are not unduly high and kept as low as reasonably practicable (the ALARP principle); AND*
    c) *the risks are periodically reviewed to ensure that they still meet the ALARP criterion."*

The As Low As Reasonably Practicable (ALARP) principle is a more fundamental approach for setting tolerable risk levels. The term "reasonably" implies goodness, care and consideration, while "practicable" refers to what can be done or is feasible. Indeed many actions can be implemented to reduce risk, but only provided if the financial resources and benefits are sufficient. The joined term "reasonably practicable" is not defined explicitly in legislation, but according to Melchers (2001) it can be interpreted as the degree of risk balanced against time, cost and physical difficulty of implementing risk reduction measures.

According to HSE (2001) the implementation of the ALARP principle requires a "gross disproportion" test. The gross proportion is between the cost of an additional risk reduction measure, where the cost is considered in broad terms and may include time and effort in addition to the monetary aspects, and the estimated amount of risk reduction. If the cost of the safety measure is placed on one scale, and the amount of risk reduction is placed on the other scale, and it can be shown that the one is disproportionate to the other, it could be argued that the implementation of the safety measure to reduce risk was not reasonably practicable.

The framework for the tolerability of risk presented by HSE (2001) can be used similarly when evaluating the acceptability of risk to human life against FN-criterion lines. In Fig. 3.2, the FN-curve obtained from the Eurotunnel Safety Case is located between two different FN-criterion lines, the negligible and intolerable line. If the risk is located below the negligible line, the risks may be regarded as broadly acceptable. If the risk is located above the intolerable region, it should under no circumstances be accepted. In between the two criterion lines the ALARP region is defined. In this region risks are regarded as tolerable only if they are reduced to be As Low As Reasonably Practicable (ALARP).

In the following section, the historical development of FN-criteria internationally and in different industries are discussed.

3.3 Historical development of societal risk criteria

According to Ball and Floyd (1998), the need for societal risk criteria may be traced back to the 1960s and 1970s, where quantitative risk assessment techniques to evaluate major hazards were first applied. The outputs of the assessments, as the probability of an event occurring against the consequences in case the event occurs, demanded some criteria against which they could be assessed.

The report on *"Societal Risks"* presented by Ball and Floyd (1998) was commissioned by the Health and Safety Executive (HSE) of the United Kingdom (UK) and presents an overview of the development and application of societal risk criteria over 30 years. The report specifically focusses on the development of criteria in the UK, Hong Kong and in the Netherlands. A brief overview of the findings in the report are presented in the following.

3.3.1 Developments in the United Kingdom

According to Ball and Floyd (1998), in the 1960's the nuclear industry in the United Kingdom (UK), UK Atomic Energy Authority (UKAEA), was the first industry to develop acceptance criteria. The criteria was based on the relationship between the size and the acceptable frequency of releases of radioactive iodine from nuclear accidents which originated in the so-called Farmer Curve, as shown in Fig. 3.4.

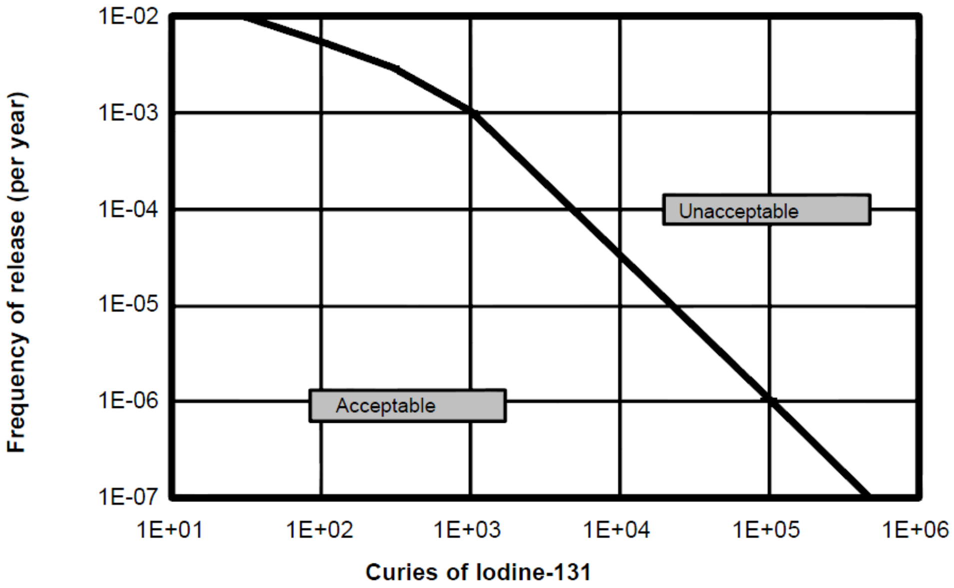

Figure 3.4: Farmer Curve developed by th UK Atomic Energy Authority (UKAEA) in the 1960s (Ball and Floyd, 1998)

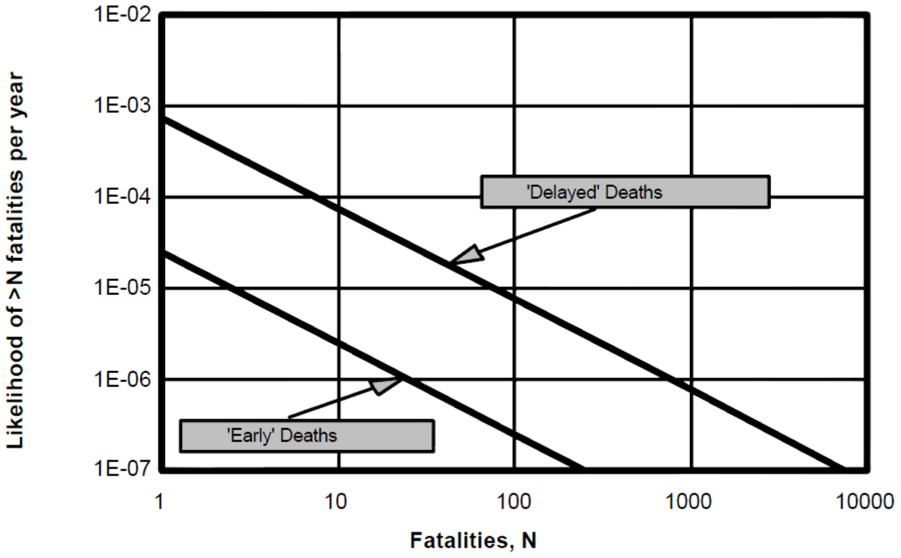

Figure 3.5: Revised Kinchin curve proposed by the UK Atomic Energy Authority for nuclear power plants in 1982 (Ball and Floyd, 1998)

Another major first influence in the development of societal risk criteria, was by the Advisory Committee on Major Hazards (ACMH, 1976 cited in Ball and Floyd (1998)):

"in a particular plant a serious accident was unlikely to occur more often than once in 10,000 years i.e. 10^{-4} *per year ... this might perhaps be regarded as just on the borderline of acceptability.*

A serious accident was never defined, but has often been taken (by practitioners) as 10 or more fatalities (Ball and Floyd, 1998). This defined singular FN-point for acceptability (10, 10^{-4}). The UK Atomic Energy Authority (UKAEA) further developed societal risk criteria from a single point criterion to FN-based societal criteria for nuclear power plants as shown in Fig. 3.5.

In the 1980's, research into the "tolerability of risk" from nuclear power stations was commissioned by the HSE. The report presented by the HSE in 1988 presented useful information on the tolerability of risk framework and could also be applied to other industries than the nuclear power plant industry. This framework focussed mostly on individual risk and no attempt was made to further develop FN-criteria. However, in the report a discussion on the "tolerability" of major accidents, with particular reference to the risks associated with the Canvey Island and the Thames Barrier, was presented.

The works presented by the HSE provided a basis for setting risk criteria in the transport risk study published by the Advisory Committee on Dangerous Substances (ACDS). The proposed societal criteria is shown on the FN-diagram in Fig. 3.6. These societal risk guidelines incorporated an ALARP region with the negligible level of risk located three factors of 10 lower than the intolerable level.

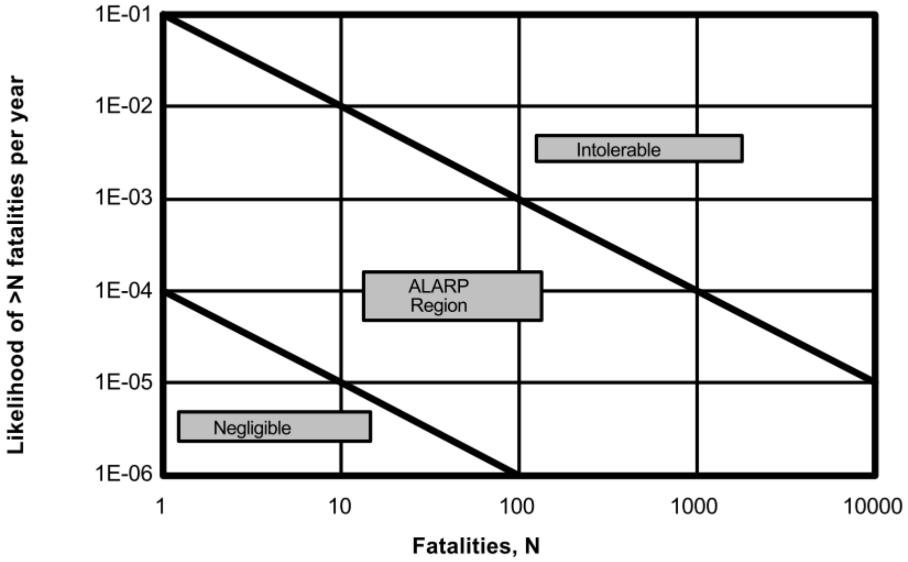

Figure 3.6: FN-criteria developed by the UK Advisory Committee on Dangerous Substances (ACDS, 1991 cited in Ball and Floyd (1998))

The Offshore Safety Division within the HSE also proposed societal risk criteria to be used in offshore situations as shown in Fig. 3.7. The criteria were developed using the individual risk criteria presented by the HSE report in 1988 and incorporates an ALARP region similar to the societal risk criteria developed by ACDS.

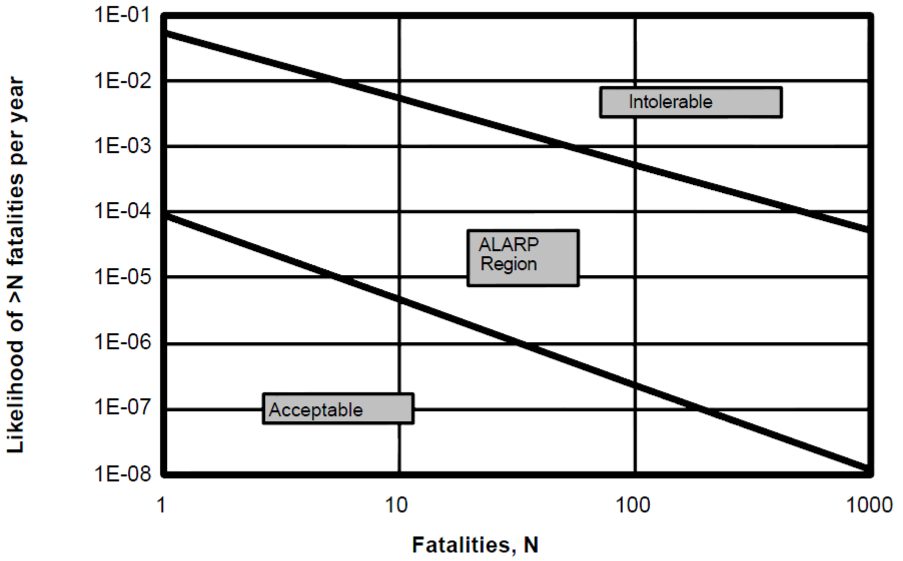

Figure 3.7: FN-criteria developed by the Offshore Safety Division within the HSE (1991 cited in Ball and Floyd (1998))

The "tolerability of risk" framework was revised by the HSE, accounting for developments since 1988, and a report was reissued in 1992 and thereafter in 2001 in the report *"Reducing Risk, Protecting People"*.

The properties of the FN-criteria shown in Fig. 3.5, 3.6 and 3.7 are summarised in Table 3.2 with respect to the industry to which the criteria may be applied to, the different zones defined on the FN-diagram, the anchor point to define the FN-criteria, the slope of the line, and the consequence (N or more fatalities) and frequency (F) cut-off points.

Table 3.2: Characterisation of FN-criteria shown in Fig. 3.5, 3.6 and 3.7 as developed in the UK (Ball and Floyd, 1998)

	Revised Kinchin curve (1982)	**ACDS - UK (1991)**	**UK Offshore (1991)**
Application	one nuclear reactor in the UK	"identifiable community" close to a dangerous goods transport route in the UK	offshore installations
Zones	2 - above and below suggested "permissible" criteria lines	3 - Intolerable, ALARP, Negligible	3 - Intolerable, ALARP, Acceptable
Anchor point	None specified	2×10^{-4} per year for 500 or more fatalities (lower limit of "intolerable"), upper limit of "negligible" 1000 times lower	"Tolerable" individual risk of 1×10^{-3} per year, "Broadly acceptable" individual risk of 1×10^{-6}
Line slope	-1	-1	-1 and -1.3 for tolerable and broadly acceptable lines respectivey.
Consequence cut-off	None specified	None	1000
Frequency cut-off	1×10^{-7} per year	1×10^{-8} per year	1×10^{-8} per year

Trbojevic (2005) additionally describes the evolution of societal risk criteria in the UK, from the 1980s and extending into the 2000s. The evolution of the upper tolerable risk level is shown in Fig. 3.8.

- In 1981 a Canvey Report presented by the HSE, suggested that an event with 1500 fatalities and a frequency of 2×10^{-4} per year can be judged as intolerable. The proposed slope for FN-criteria was -1, implying no risk aversion, based on historical records for the chemical industry.
- In 1991, the Advisory Committee on Major Hazards (ACMH) proposed an upper tolerable risk level through the point, 500 fatalities and a frequency of 2×10^{-4} per year, and a slope of -1.

- In 2001, the HSE in their document *Reducing risk, protecting people,* suggested that 50 fatalities and a frequency of 2×10^{-4} per year may be judged as intolerable risk (HSE, 2001). The slope of the FN-criteria is also -1.

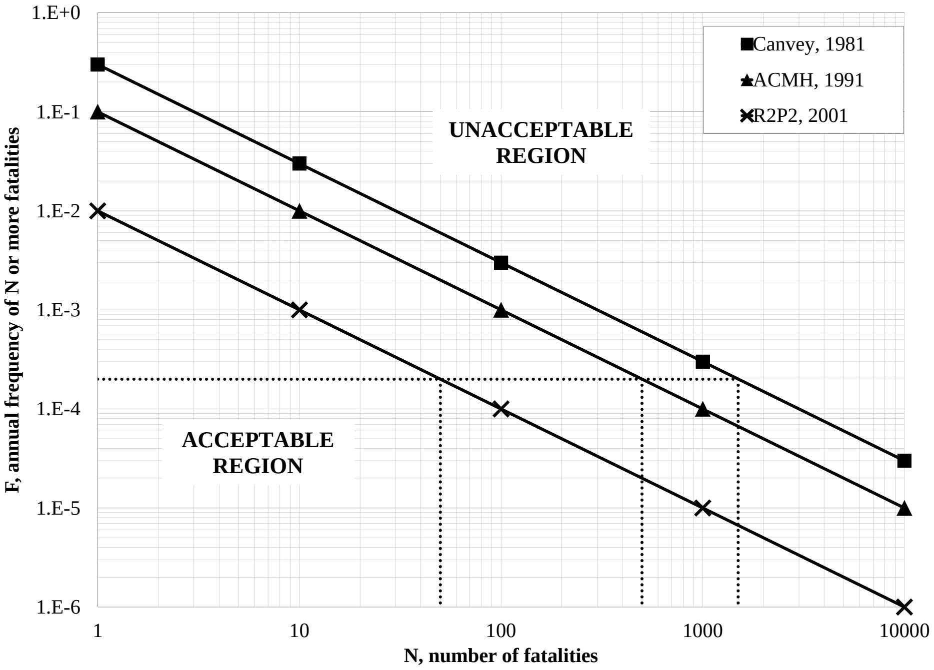

Figure 3.8: Evolution of the upper tolerable risk level in the UK (Trbojevic, 2005)

In Fig. 3.8 the corresponding fatalities for a frequency of 2×10^{-4} per year, as described for each situation above, is shown. It is interesting to note that upper tolerable risk level became more stringent as the years progressed. This could be attributed to experts gaining more experience and knowledge in the trends and acceptability of hazards occurring and thereby concluding that the criteria may become more stringent.

For the societal risk criteria proposed by the HSE (2001), the broadly acceptable level of risk is suggested to be three factors of 10 lower than the upper tolerable risk level.

3.3.2 Developments in Hong Kong

In 1981 the Hong Kong government commissioned a study associated with hazardous installations on the Tsing Yi Island which were within close proximity of residential apartment blocks (Ball and Floyd, 1998). The study stressed the need to oversee risk management of such facilities with particular regard to land-use planning. Additional studies in the 1980's of other hazardous facilities further stressed the need. In 1987 societal risk criteria based on the ACMH criterion point and the Kinchin criteria developed in the UK, were formalised as part of *"Interim Risk Guidelines"* published by a Government Committee. The societal risk criteria are shown in Fig. 3.9. The singular point of (10,10^{-4}) as proposed by the ACMH in 1976 is incorporated and in addition, for N = 1 000 fatalities or more, a risk with a potential for greater loss of life is not acceptable.

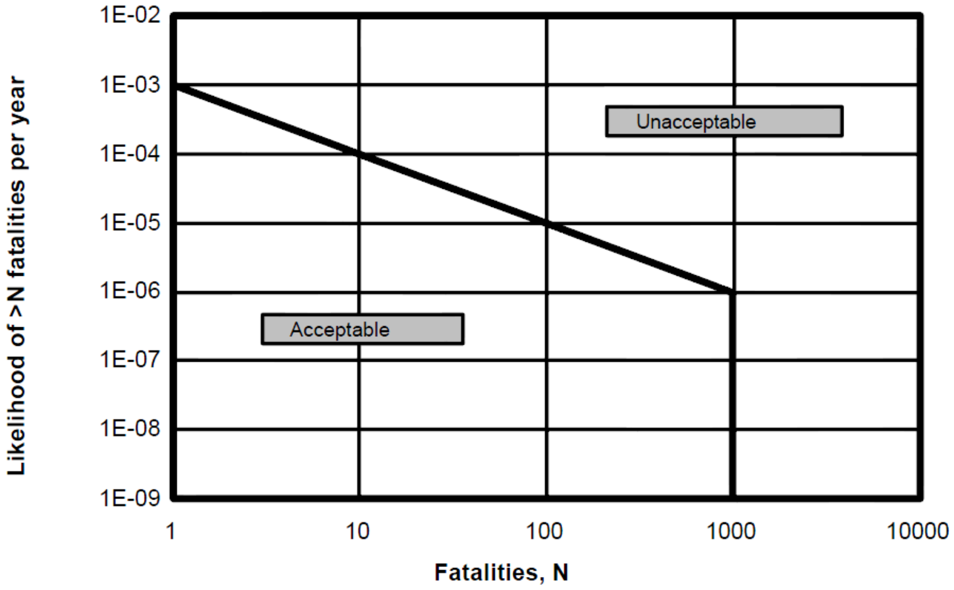

Figure 3.9: Societal risk criteria proposed by Hong Kong for hazardous installations in 1988 (Ball and Floyd, 1998)

These societal risk guidelines proposed by Hong Kong as shown in Fig. 3.9 were revised in 1993, incorporating an ALARP region. The acceptable risk level was defined two factors of 10 lower than the unacceptable risk level with the ALARP region located within, as shown in Fig. 3.10.

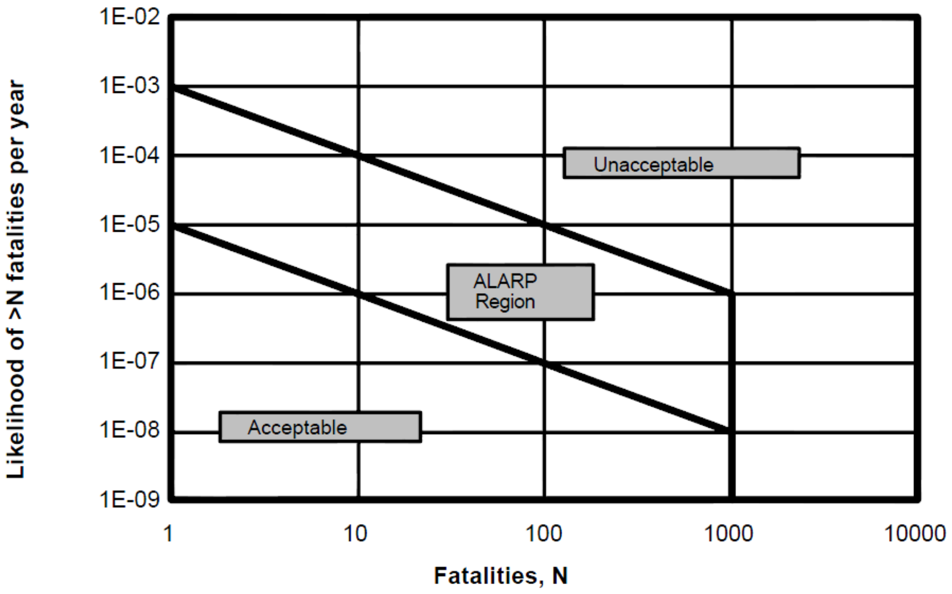

Figure 3.10: Revised societal risk criteria proposed by Hong Kong for hazardous installations in 1993 (Ball and Floyd, 1998)

Following the UK's lead, the Hong Kong Government commissioned two transport of dangerous goods studies. These studies led to proposed societal risk criteria in 1997 for the transport of dangerous goods, including LPG and Chlorine, as shown in Fig. 3.11 and 3.12.

The properties of the Hong Kong FN-criteria shown in Fig. 3.9, 3.10, 3.11 and 3.12 summarised in Table 3.3. The same properties that were tabulated for UK criteria are shown for Hong Kong criteria.

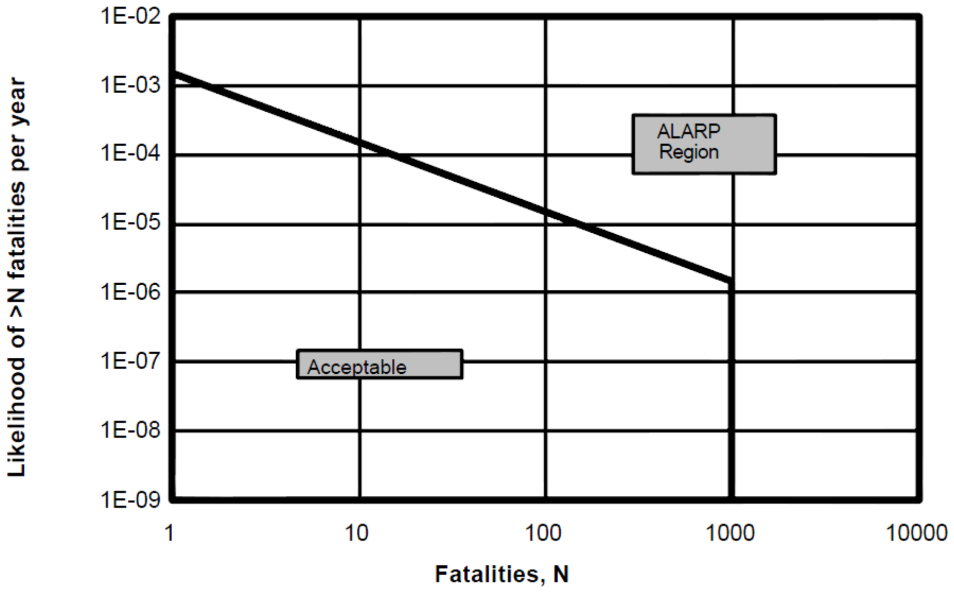

Figure 3.11: Societal risk criteria proposed by Hong Kong for transport of dangerous goods in 1997, LPG (Ball and Floyd, 1998)

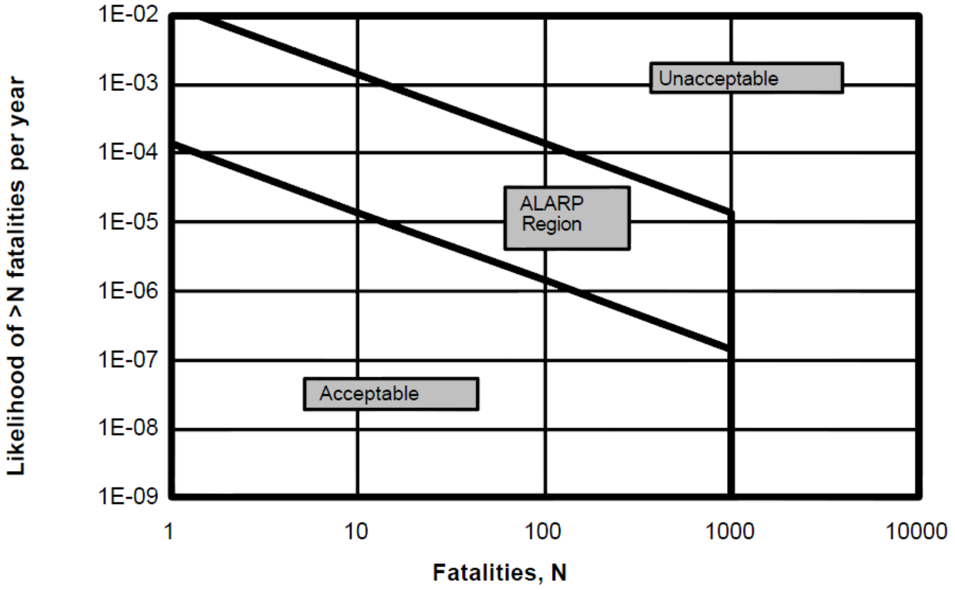

Figure 3.12: Societal risk criteria proposed by Hong Kong for transport of dangerous goods in 1997, Chlorine (Ball and Floyd, 1998)

Table 3.3: Characterisation of FN-criteria shown in Fig. 3.9, 3.10, 3.11 and 3.12 as developed in the Hong Kong (Ball and Floyd, 1998)

	Hong Kong (1988)	**Hong Kong (1993)**	**Hong Kong DG Transport - LPG (1997)**	**Hong Kong DG Transport - Chlorine (1997)**
Application	development of, or near to, a Potentially Hazardous Installation	Those close to a Potentially Hazardous Installation (in Hong Kong)	Those close to a LPG transport routes (in Hong Kong)	Those close to Chlorine transport routes (in Hong Kong)
Zones	2- Unacceptable and Acceptable	2- Unacceptable, ALARP, Acceptable	2- ALARP, Acceptable	2- Unacceptable, ALARP, Acceptable
Anchor point	1×10^{-4} per year for 10 or more fatalities	1×10^{-4} per year for 10 or more fatalities (lower limit of 'unacceptable' - as before). Acceptable limit 100 times lower	Based on existing Potentially Hazardous Installations (PHI) and number of LPG PHIs	Acceptable limit 100 times lower than unacceptable limit
Line slope	-1	-1	-1	-1
Consequence cut-off	1000 fatalities	1000 fatalities	1000 fatalities	1000 fatalities
Frequency cut-off	1×10^{-9} per year	1×10^{-9} per year	1×10^{-9} per year	1×10^{-9} per year

3.3.3 Developments in the Netherlands

Following accidents involving hazardous materials which occured in Europe, the Province of Groningen in the Netherlands issued societal risk criteria in 1978 as shown in Fig. 3.13. The FN-diagram consists of an unacceptable zone, a zone for further assessment and evaluation, and an acceptable region. For N < 1 the slope of the criteria is -1, therefore risk neutral. For N > 1, the slope of the FN-criteria is -2, thereby incorporating risk aversion. In addition, for the lower limit of unacceptability, at N = 1 000 fatalities or more a risk with a potential for greater loss of life is not acceptable. For the upper limit of acceptability, the consequence cut-off is at N = 10 fatalities.

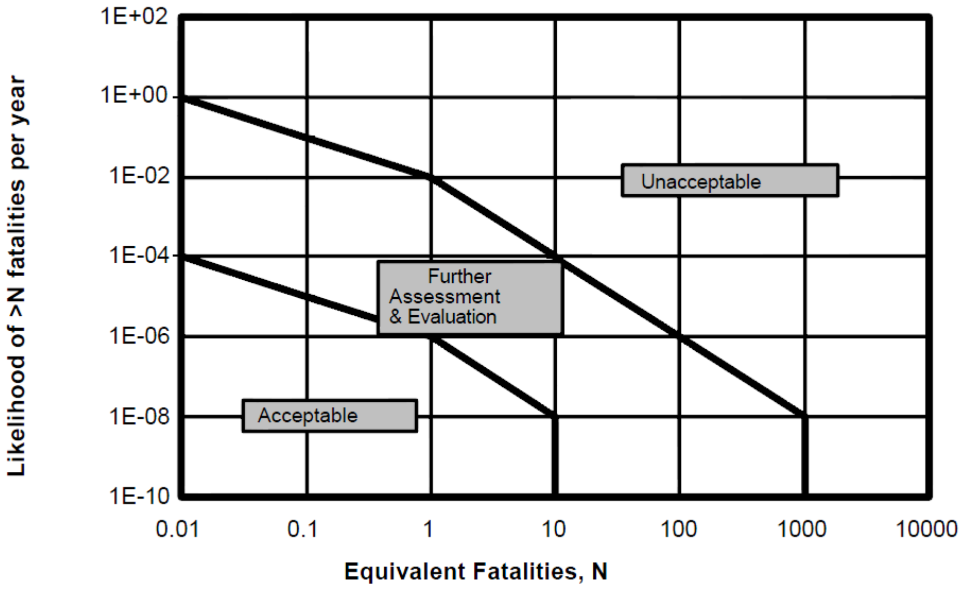

Figure 3.13: Societal risk criteria proposed by the Province of Groningen in the Netherlands in 1978 (Ball and Floyd, 1998)

During the 1980s, numerous risk studies conducted by the Dutch Government, led to the formulation of formal societal risk criteria as shown in Fig. 3.14. The FN-diagram consists of three regions, an unacceptable region, a region where reduction is desired and an acceptable region. The slope of the FN-criteria is -2, thereby incorporating risk aversion.

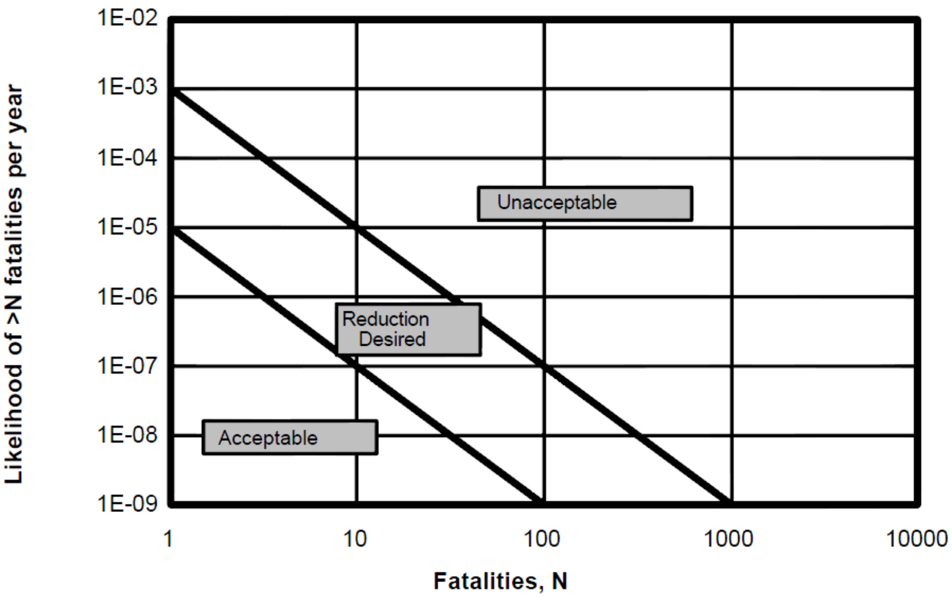

Figure 3.14: Societal risk criteria proposed by Dutch Government in the 1980s (Ball and Floyd, 1998)

In 1996, the criteria were revised and the acceptable region was removed since it was understood that the "acceptable" line was of limited value to land use planners. Instead an As Low As Reasonably Achievable (ALARA) region is defined. The revised criteria are shown in Fig. 3.15.

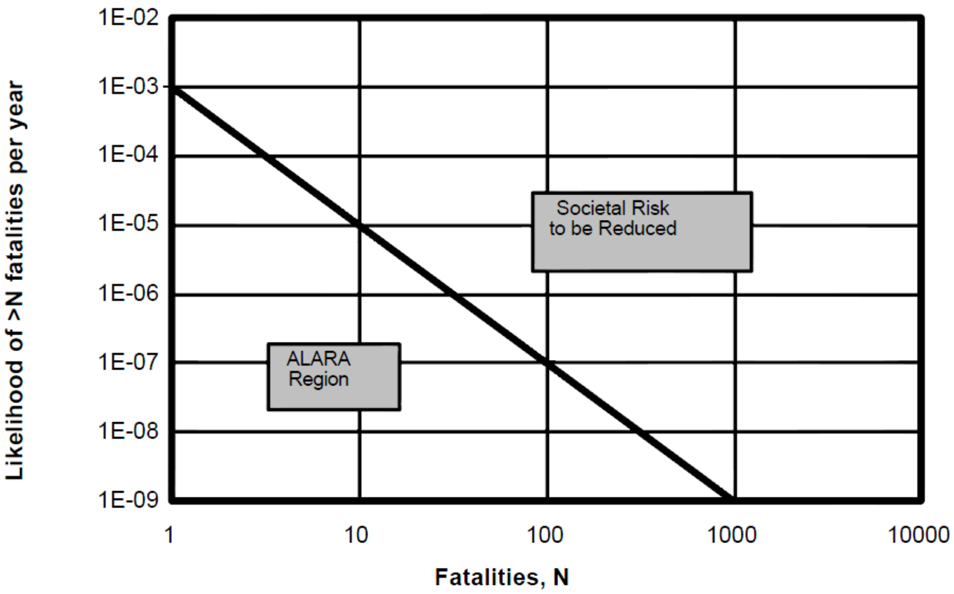

Figure 3.15: Revised societal risk criteria proposed by Dutch Government in 1996 (Ball and Floyd, 1998)

Based on the studies in Hong Kong on the transport of dangerous goods, societal risk criteria were proposed in 1995/1996 in the Netherlands as shown in Fig. 3.16.

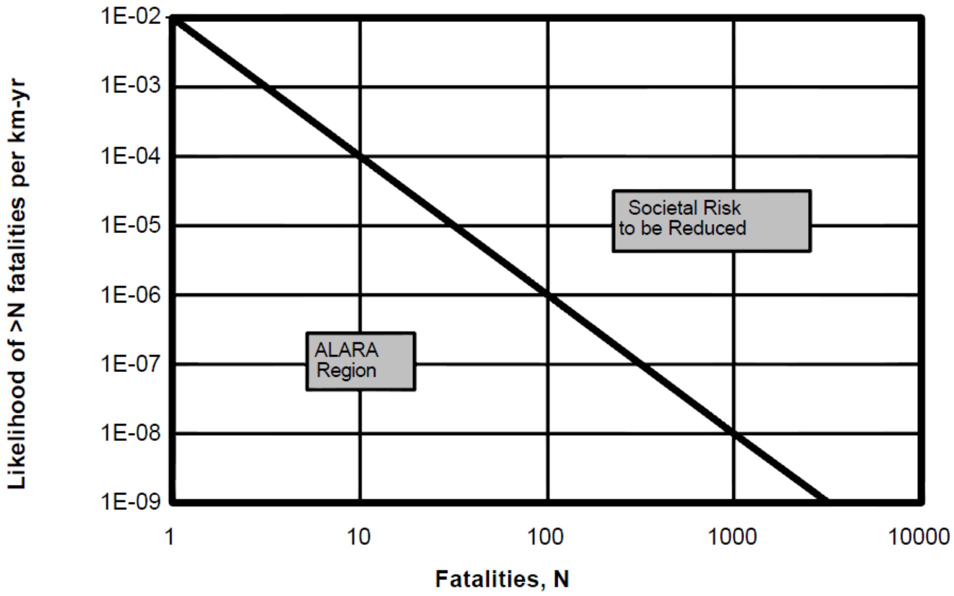

Figure 3.16: Proposed societal risk criteria for transport of dangerous goods by Dutch Government in 1996 (Ball and Floyd, 1998)

The properties of the Netherlands FN-criteria shown in Fig. 3.13, 3.14, 3.15 and 3.16 are summarised in Table 3.4.

Table 3.4: Characterisation of FN-criteria shown in Fig. 3.13, 3.14, 3.15 and 3.16 as developed in the Netherlands (Ball and Floyd, 1998)

	Groningen Curve (1978)	**Netherlands (1980s)**	**Netherlands (1996)**
Application	a facility handling dangerous goods (in the Netherlands)	Those close to existing hazardous facilities (in the Netherlands)	Those close to existing hazardous facilities (in the Netherlands)
Zones	3 - Unacceptable, Further assessment and evaluation, Acceptable	3- Unacceptable, Reduction Desired, Acceptable	2- Societal risk to be reduced, ALARA
Anchor point	1×10^{-4} for 10 or more fatalities (for unacceptability level of risk)	1×10^{-5} per year for 10 or more fatalities (lower limit of 'unacceptable'), 1×10^{-7} per year for 10 or more fatalities (upper limit of 'acceptable')	1×10^{-5} per year for 10 or more fatalities
Line slope	-1 for 0.01 to 1 fatality and -2 for >1 fatality	-2	-2
Consequence cut-off	1000 (lower limit of unacceptability) 10 (upper limit of acceptability)	1000 fatalities	1000 fatalities
Frequency cut-off	1×10^{-10} per year	1×10^{-9} per year	1×10^{-9} per year

3.3.4 Concluding summary regarding the historical development of FN-criteria

There appears to be many points of similarity between the FN-criteria as it developed from the 1960s to 1990s in the UK, Hong Kong and Netherlands. The societal risk criteria have been developed for risks associated with large scale facilities, including hazardous installations such as nuclear and offshore facilities, and transport of dangerous goods. Although developed for different industries, the criteria are interlinked, in particular due to the slope of the criterion lines and the defined anchor points.

With regards to the slopes of criterion lines, the UK and Hong Kong use a slope of -1, which resembles risk neutrality. On the other hand, the Netherlands have adopted a slope of -2, incorporating risk aversion. However, Ball and Floyd (1998) found that there is no compelling rational for the view of increasing societal aversion, and therefore a slope of -1, representing risk neutrality, is recommended.

In addition it can be seen that most of the criteria define three regions for risk:

- risks that are so high that they are to be judged as unacceptable/intolerable;
- risks that are so low that they are to be judged as acceptable/negligible;
- risks in between where the trade-off between risks and benefits need to be considered (e.g. using ALARP).

According to Ball and Floyd (1998), to facilitate the comparison between the criteria, the limit for "intolerability" may be comparable to "unacceptabile and "acceptable" may be compared to "negligible".

The upper limit of tolerability is often set at 10^{-4} for 10 or more fatalities (or 10^{-5} in the Netherlands). The acceptable/negligible line tends to be located two or three factors of 10 (100 or 1000) lower on the frequency (F) scale.

In addition, it must be noted that for some criteria, such as the criteria developed in Hong Kong, the criteria are truncated vertically and thus an upper limit for the potential loss of life is defined.

3.4 Application of societal risk criteria

The historical development of FN-criteria was reviewed in the previous section. In the following, the current application of conventional criteria internationally in different industries and also more specifically in international dam safety are discussed.

3.4.1 International societal risk criteria

Trbojevic (2005) compares societal risk criteria for different countries in Europe, including the Netherlands, Czech Republic, the UK and France, as described:

Netherlands

The Dutch criteria were developed in 1996, as described in section 3.3 and illustrated in Fig. 3.15. A slope of -2 is assumed for the FN-criteria, thereby incorporating risk aversion.

Czech Republic

The upper tolerable risk level of risk in the Czech Republic for existing installations corresponds to the criterion used in the Netherlands. For new installations the FN-criteria are more stringent and is one factor of 10 lower on an FN-diagram.

UK

As presented in section 3.3, in 2001 the HSE suggests in their document *"Reducing risk, protecting people"* (also referred to as R2P2), that 50 fatalities and a frequency of 2×10^{-4} per year may be judged as intolerable risk (HSE, 2001). The slope of the FN-criteria is -1.

In 2004, the HSE in their document *"Guidance on 'as low as reasonably practicable' (ALARP) Decisions in Control Of Major Accident Hazards (COMAH)"*, shows acceptability criteria for societal risk in a risk matrix. Trbojevic (2005) uses the risk matrix to define two FN-criterion points; $(1, 10^{-3})$ and $(100, 10^{-6})$. The slope for the FN-criterion is -1.5, thereby incorporating some risk aversion.

France

The French criterion depends on the minimum distance of the specified level of harm from the hazard source. Trbojevic (2005) assumes a constant frequency of 1×10^{-7} per year over the full range of fatalities for the FN-criterion.

The FN-criteria described for the different countries in Europe are compared against each other in Fig. 3.17.

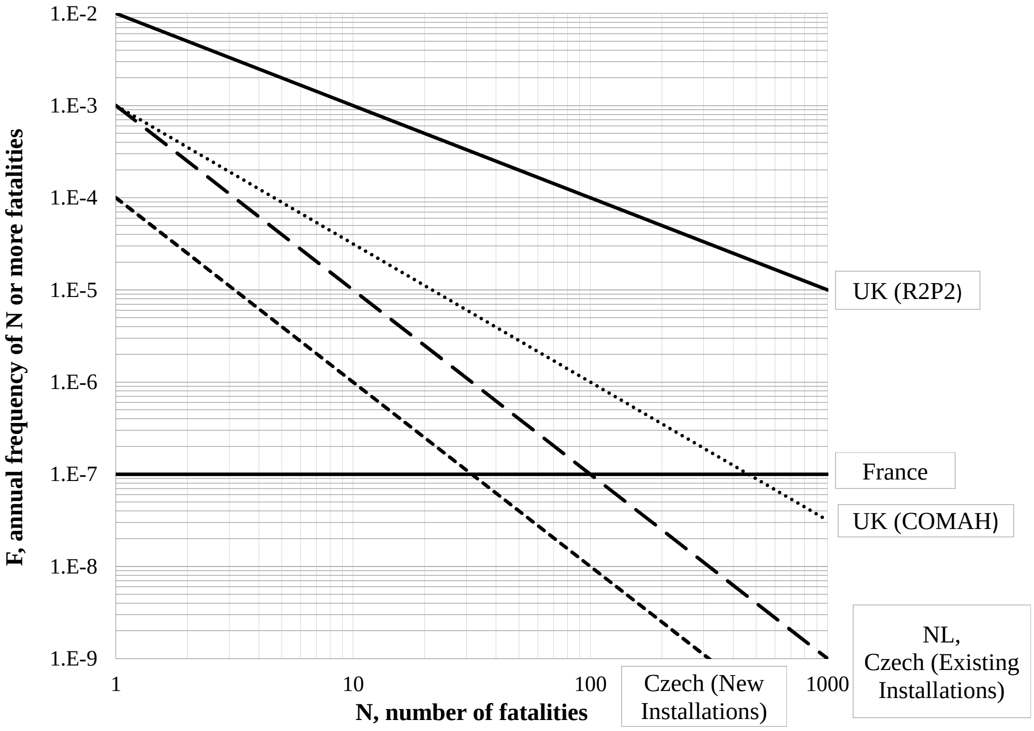

Figure 3.17: Comparison of societal risk criteria in Europe (Trbojevic, 2005)

The criteria defined in the Netherlands and Czech Republic for existing installations coincide, while the Czech criteria for new installations are one factor of 10 more stringent. For the COMAH criteria defined in the UK and the criteria defined in the Netherlands and Czech Republic for existing installations, the FN-point for one fatality (N = 1) coincides. The main difference in the criteria may be attributed to the different degrees of risk aversion implemented in terms of the slopes assumed for the FN-criteria. For the French criterion line, if the frequency is higher than 1×10^{-7} per year, the risk is judged as unacceptable. For a low number of fatalities, this criteria may require uneconomical safety measures.

3.4.2 Application of societal risk criteria in international dam safety

In the previous two sections, the historical development and application of FN-criteria internationally in different industries were discussed. The criteria were defined for large scale facilities, including hazardous installations, such as nuclear and offshore facilities, and the transport of dangerous goods. However, the criteria from one industry may not always be directly applied to another industry since it could be impracticable to accept the same safety levels. Thus, the application of FN-criteria in international dam safety are reviewed to define international best practice criteria to compare to South

African dam safety criteria.

The International Commission on Large Dams (ICOLD) published Bulletin 130 on *"Risk Assessment in Dam Safety Management"* (2005) which outlines the current application of risk-based methods in international dam safety. It includes responses to a survey completed by respective ICOLD member countries. The outline of the collected information for 24 countries are presented in section 2.3.3 of Chapter 2. Within the collected information, the application of risk evaluation techniques to establish acceptability criteria for risk to human life are described.

From the 24 responding countries, 11 show a view on risk evaluation, where 9 of the countries explicitly discuss risk criteria. These countries include: Australia, Canada, Czech Republic, Germany, the Netherlands, New Zealand, South Africa, United Kingdom and the USA (ICOLD, 2005). Norway and Sweden raise concerns over risk evaluation. A basic outline of the views of the responding countries are outlined as obtained from the ICOLD Bulletin 130 (2005).

Australia

According to ICOLD (2005), tolerable risk levels have not yet been established for dams by the government or by regulatory agencies. For other industries there are examples of tolerable risk level policies that have been implemented by legislation, such as the criteria established in the state of Victoria in the Occupational Health and Safety Regulations and in the state of New South Wales by the regulator for land use planning (LUP).

The Australian Committee On Large Dams (ANCOLD), a organisation responsible for providing dam safety standards, proposes tolerability criteria for risk to human life in their *"Guidelines on Risk Assessment"* (2003). FN-criteria are defined for new and existing dams as shown in Fig. 3.18. The FN-criterion line for new dams is one factor of 10 more stringent than for existing dams. According to ANCOLD (2003), the marginal cost of reducing risk for an existing dam is generally more than for new dams. Thus, by weighing the costs and benefits against each other it is not reasonably practicable to reduce the risk of existing dams to the same levels as new dams.

The criterion lines are truncated horizontally, i.e. for 100 or more fatalities a limit is set for the annual frequency of occurrence. According to ANCOLD (2003), technology does not allow for the construction of dams with smaller probabilities of failure and thus it is impracticable to reduce dam safety levels to more stringent criteria.

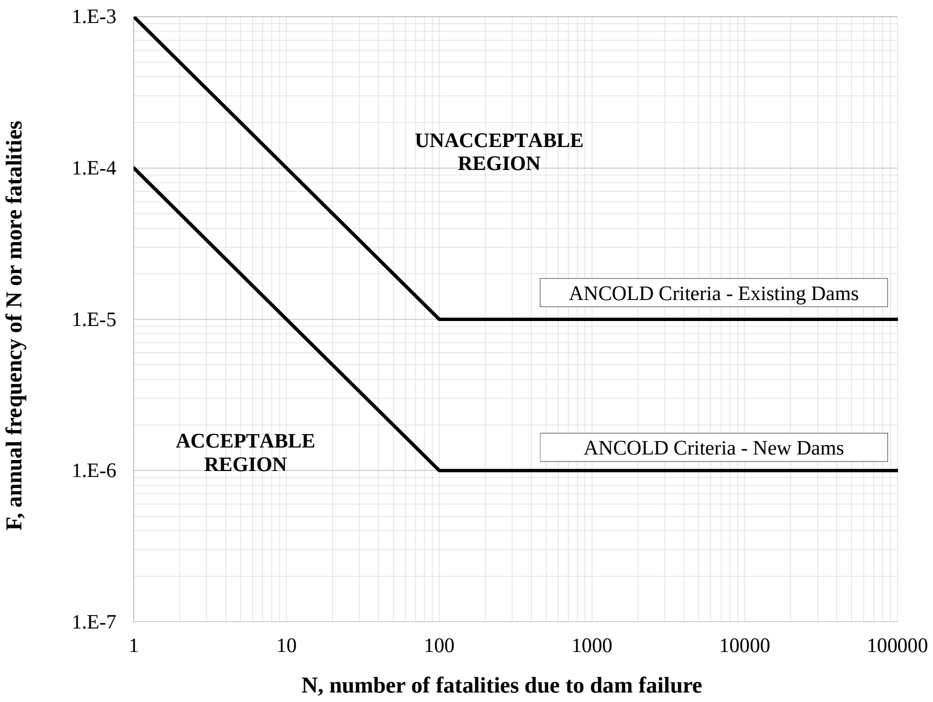

Figure 3.18: ANCOLD proposed FN-criteria for new and existing dams (Adapted from ANCOLD (2003))

According to ICOLD (2005), one regulator, the New South Wales Dam Safety Committee (NSW-DSC), were prepared to consider the results of risk assessments in dam safety, but this has not been endorsed by any policies. However, in 2006 the Committee suggested tolerable risk criteria in their *"Risk Management Policy Framework"* which are based primarily on a critical review of the ANCOLD guidelines for new and existing dams. The NSW-DSC FN-criteria for new and existing dams are illustrated in Fig. 3.19 and Fig. 3.20 respectively. A negligible risk level is located two factors of 10 lower than the tolerable risk level.

A limit is set for the potential of losing more than 1000 lives, since the Committee believes it would be seen as catastrophic by society at an international scale and the economic costs of such large tragedies would be great. A limit is also set for the probability of occurrence, since it becomes increasingly difficult to reliably estimate the frequency of fatalities occurring at low levels. The FN-diagram for existing dams, shown in Fig. 3.20, also requires a full SBA when the probability of failure becomes very low and the number of fatalities become very high. The SBA refers to the Standards Based Approach, where risks are controlled using established engineering practice and standards, as discussed in section 2.3.3 of Chapter 2.

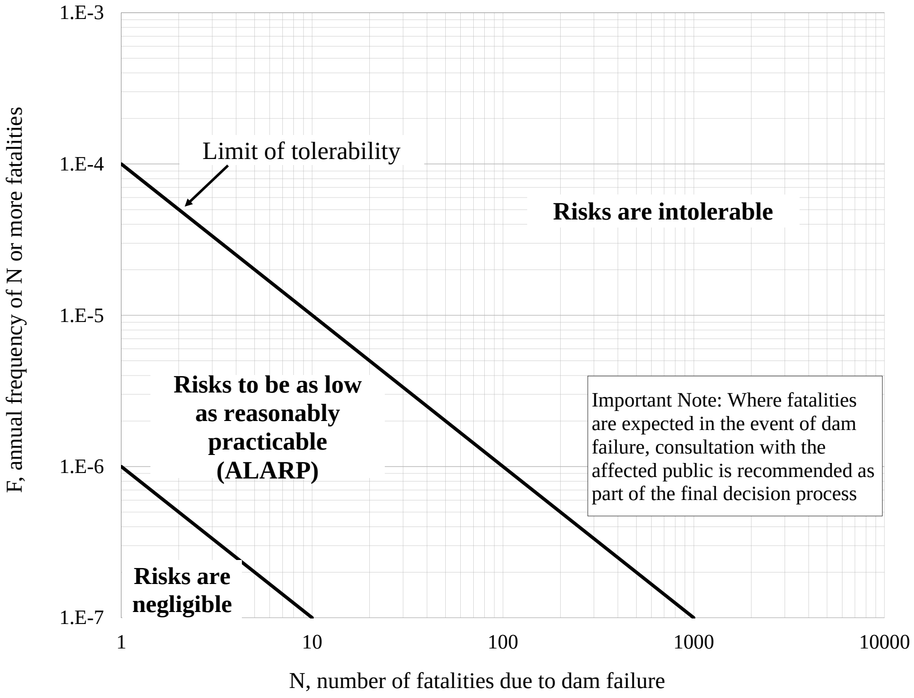

Figure 3.19: New South Wales Dam Safety Committee FN-criteria for new dams (Adapted from NSW-DSC (2006))

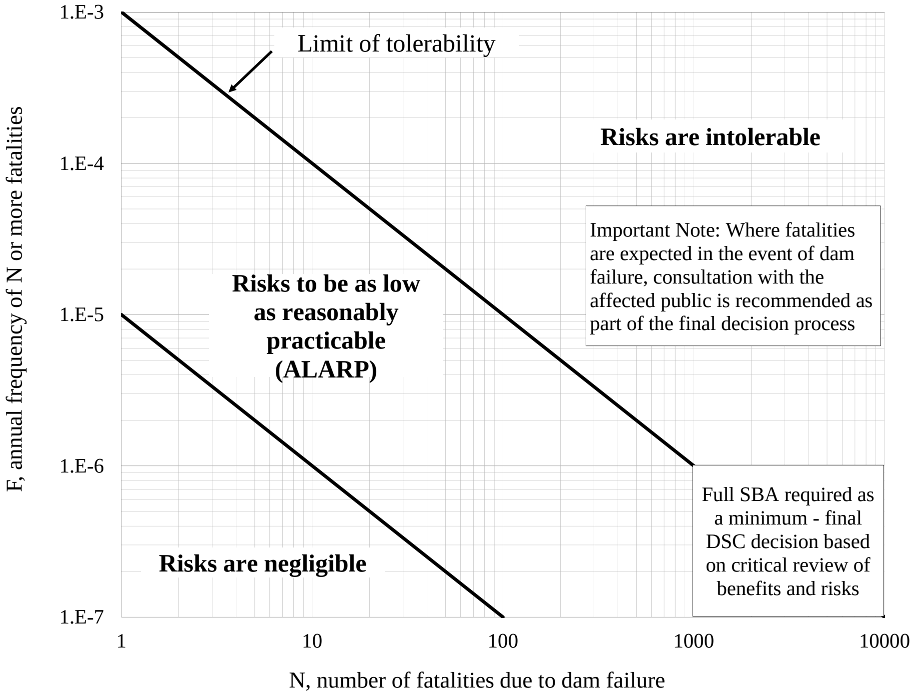

Figure 3.20: New South Wales Dam Safety Committee FN-criteria for existing dams (Adapted from NSW-DSC (2006))

Canada

In Canada the scientific validity of quantifying the probability of dam failure for decisions regarding life safety and consequently the values and use of risk analysis methods are questioned by dam owners and regulators. Thus, no formal life safety criteria for dams exists in Canada, but instead they rely on traditional dam engineering practices for improving dam safety.

It must be noted that some risk assessment activities have been developed, but have been abandoned. They include (ICOLD, 2005)):

- *"the abandonment of tolerable life safety criteria by BC Hydro in 1997, although they are still erroneously widely quoted internationally;*
- *the use of necessarily limited embankment dam piping statistics from a population of dams to derive the probability of failure of an individual dam; and*
- *the use of subjective probabilities within event trees."*

Czech Republic

In the Czech Republic dams are categorised based on the potential consequences associated with the existence of the dam, this is also referred to as a "Primary" risk assessment. The "Secondary" risk assessment requires evaluating the actual technical state or local conditions at the dam, but these results are not considered for categorising the dam.

A "Risk Analysis and Risk Evaluation System" determines a "Risk Assessment Factor", which is based on the consequences of dam failure, including the number of lives lost, property losses, the interruption of infrastructure downstream, the damages directly to the dam body, losses of profits, and a range of environmental damages. The factor is quantified using dam break wave downstream. However, no accepted tolerable life safety criteria exist for dams within Czech Republic.

Germany

According to ICOLD (2005) risk assessment does not have a long tradition in Germany, but an increasing sensitivity towards environmental hazards and risks stressed the treatment of dam-related risks. The draft of the revised German technical standards for dams, E DIN 19700-10/11, pursue a concept where maximal safety is stressed and the assessment and mitigation of the remaining risks are required. This standard applies semi-quantitative considerations and no formal quantitative life safety criteria are defined.

Netherlands

The Ministry of Housing, Physical Planning and Environment in the Netherlands have set risk criteria for hazardous installations, transport routes and airports (ICOLD, 2005). The approach was developed outside the framework of dams.

New Zealand

ICOLD (2005) states that there are no absolute life safety criteria available in New Zealand. The Australian and New Zealand Standard, AS/NZS 4360 (2004) on *"Risk Management"* notes that decisions regarding risk acceptability and treatment are based on financial, social, technical, humanitarian and other criteria which depend on the objectives and interests of the stakeholders (including the owner and society). In addition, the standard notes that when assessing risk treatment options that risks should be made As Low As Reasonably Practicable (ALARP). Therefore, it is the responsibility of local authorities or asset owners to ensure that risks, costs and benefits of risk reduction measures are balanced to satisfy the needs of the societies they serve.

South Africa

The application of risk analysis and risk management to dam safety in South Africa have been described in section 2.3.4 of Chapter 2. In order to provide guidelines to decision-makers on the acceptability of risks obtained from the risk analysis methodology, five impact graphs and a graph representing the risk level was developed by the Department of Water Affairs (DWA). The estimated risks are assessed against a dividing line on the graphs, defining the border between acceptable and unacceptable risk. The six different graphs developed by DWA include; population at risk, social impact, financial impact, socio-economic impact, environmental impact and the risk level graph, as illustrated in in Fig. 2.6 of Chapter 2.

United Kingdom

According to ICOLD (2005), the "tolerability of risk framework" for hazardous industries developed by the Health and Safety Executive (HSE) in the United Kingdom (UK) may be considered in dam safety. Although it does not currently have a role in dam safety, some practitioners consider that the framework may be used as a standard against which dam owners may be judged in the event of dam failure or serious incident. The "tolerability risk of framework" has been described in section 3.2.3.

USA

The use of risk assessment varies from no formal use to the adoption of risk assessment as a normal dam safety process in the United States of America (USA). Some instances where risk analysis techniques are applied to dam safety in the USA are outlined by ICOLD (2005):

US Bureau of Reclamation

In 1997 the US Bureau of Reclamation suggested in their guidelines criteria for evaluating life safety risks. In 2003 these guidelines have been replaced by revised *"Guidelines for achieving public protection in dam safety decision making"*. The guidelines provide two measures, previously referred to as the two-tier system. The first measure addresses individual risk, and the second addresses societal risk. The societal risk criteria are depicted on an fN-diagram. However, it must be noted that fN-criteria should not be misinterpreted as FN-criteria (refer to section 3.2.2).

US Army Corps of Engineers

The US Army Corps of Engineers (USACE) is responsible for 600 dams throughout USA. They are applying risk assessments to the dams as part of a research and development program. Interim guidelines presented by the USACE in 2009, *"Interim Tolerable Risk Guidelines for US Army Corps of Engineers Dams"* include tolerable risk to human life guidelines (Munger *et al.*, 2009).

The guidelines present FN-criteria for assessing societal risk. According to Munger *et al.* (2009), the criteria were adapted from the criteria presented by ANCOLD and NSW-DSC, illustrated in Fig. 3.18, 3.20 and 3.19 earlier in this section. For new and existing dams the tolerable risk level is shown in Fig. 3.21 and Fig. 3.22. Similar to the ANCOLD and NSW-DSC guidelines, the tolerable risk level is one factor of 10 more stringent for new dams.

According to ICOLD (2005), Norway and Sweden raise concerns over risk evaluation but do not explicitly use FN-criteria. In Norway the dam safety profession concentrates on refining the estimation of the probability of dam failure before developing more detailed consequence analyses and risk criteria. In Sweden instead of calculated probabilities and the application of FN-diagrams, criticality indices are determined and the owner decides from the nature and magnitude of the determined criticalities to what level of higher safety the dam needs to be upgraded.

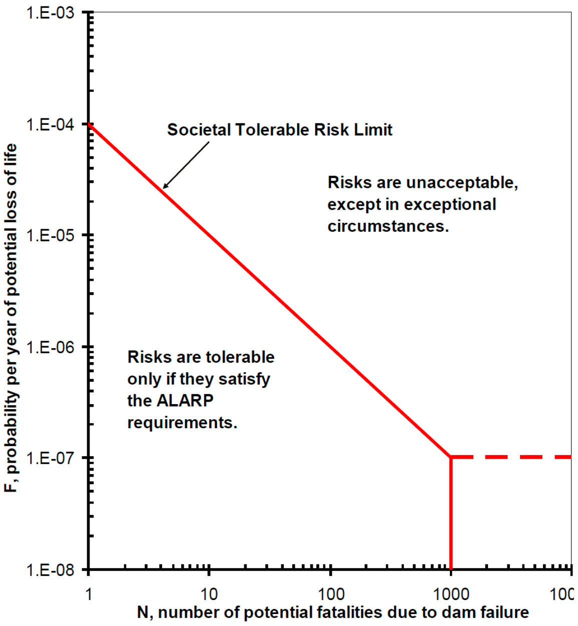

Figure 3.21: USACE FN-diagram for new dams (Munger *et al.*, 2009)

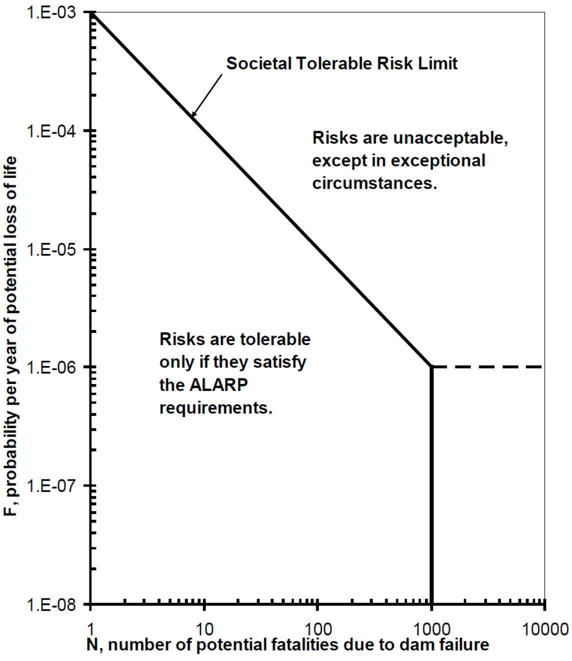

Figure 3.22: USACE FN-diagram for existing dams (Munger *et al.*, 2009)

3.5 Summary of main findings

Internationally, the conventional method to quantitatively evaluate the acceptability of risk to human life is against FN-critera on an FN-diagram, with the x-axis representing the number of fatalities (N) and the y-axis the probability (F) of N or more fatalities occurring. The life safety risks are evaluated against the FN-criteria, where the risks are expressed as the expected fatalities per year.

FN-criterion lines are mostly defined by two properties; its intersection with the y-axis and the slope of the line. The intercept with the y-axis define the stringency levels of the criteria, i.e. if the criteria intercepts the axis at a lower probability of occurrence, the criteria are more stringent. The slope of the line represents the degree of risk aversion of society, i.e. the opposition of society to large scale accidents over smaller scale accidents which collectively result in the same number of fatalities. If the slope is -1 it represented "risk neutrality", whereas an increased slope, for example -2, describes risk aversion.

In addition, different regions may be defined through FN-criteria; the broadly acceptable region, where risks may be regarded as negligible, the intolerable region, where risks should not be accepted, and the ALARP region within the other two regions, where risks may be regarded as tolerable only if they are reduced to be As Low As Reasonably Practicable.

The implementation of ALARP requires that the costs of a safety measure and the amount of risk reduction are balanced against each other. If the costs are disproportionate to the reduction, it is not reasonably practicable to implement the safety measure. Consequently it is not reasonably practicable to reduce risks to more stringent safety levels and a higher risk is accepted. Thus, although FN-criteria do not explicitly evaluate the costs associated with safety measures, the stringency of risk levels may implicitly incorporate the cost of reducing risks.

Historically there seems to be many points of similarity between FN-criteria as it developed internationally for different industries. With regards to the slope of FN-criteria, some industries incorporate the view of risk aversion. However, it is argued by Ball and Floyd (1998) that there is no compelling rational for this view and a slope of -1 is preferred.

Although there are many similarities between international FN-criteria, the criteria from one industry may not always be readily applied to another industry, since it could be impracticable to accept the same safety levels. In dam safety, the application of life safety criteria in different countries are presented by ICOLD (2005). According to ICOLD (2005), risk analysis methods are still gaining acceptance in international dam safety. Although many countries present a view and acknowledge that risk-based tools are useful within dam safety, there are many contradicting opinions and views. This causes certain countries to be hesitant to clearly define quantitative FN-criteria for life safety.

In Australia, ANCOLD proposes FN-criteria for new and existing dams. The NSW-DSC in Australia also defines FN-criteria for new and existing dams which are based on the ANCOLD criteria. In the USA, the USACE defines FN-criteria for life safety which were adapted from the criteria developed by ANCOLD and NSW-DSC.

For this study it was therefore decided to compare the South African dam safety criteria for risk to human life to the life safety criteria developed by ANCOLD. This comparison will be done in the next chapter.

The following properties of ANCOLD criteria, illustrated in Fig. 3.18, are summarised:

- The gradient of the ANCOLD criteria is -1, which implies risk neutral decision making, as recommended internationally.
- The criteria has a lower probability of occurrence cut-off and also defines different criteria for new and existing dams, thus incorporating measures of reasonable practicality.
- ANCOLD criteria are based on engineering judgement, and implicitly incorporate additional considerations, such as cost considerations for reasonable practice.

Chapter 4

Evaluation of South African dam safety acceptability criteria for risk to human life

4.1 Introduction

In Chapter 1 it was identified that a large number of dams owned by the Department of Water Affairs (DWA) in South Africa are in need of rehabilitation works. A methodology using risk analysis to evaluate if dams should be rehabilitated have been developed and is currently applied by DWA. In this methodology the probability and the consequences of dam failure are combined to define the risks. These risks are evaluated using multiple acceptability criteria to assess the risk to human life and the economic, social, socio-economic and environmental impacts in case of dam failure.

In this chapter, the criteria used in the DWA decision process to establish acceptability of assessed risk to human life will be evaluated by comparing to international best practice methods identified in Chapter 3.

Risk to human life is quantitatively defined by DWA as the combination of the probability of dam failure and the population at risk in case of dam failure. The population at risk is the number of people exposed to the dambreak flood in case of dam failure. Internationally, acceptability of risk to human life is assessed using the estimated number of human fatalities in case of dam failure as a consequence measure as opposed to the population at risk used by DWA. The expected number of fatalities can be statistically predicted based on the population at risk and assumptions related to the warning time available to the population at risk in case of dam failure. DWA uses their own in-house developed prediction model for this purpose. The statistical basis for this model is not documented and is therefore unknown. Other prediction models are available internationally which are based on the statistical analysis of data of dam failures and the associated fatalities (Hartford and Baecher (2004)). In order to compare DWA risk criteria to its international counterparts it is necessary to incorporate a suitable prediction model to convert "population at risk" to "expected number of fatalities".

The chapter is structured as follows:

- Evaluation of South African dam safety criteria for risk to human life;
  - by comparing to the international best practice method for assessing the acceptability of risk to human life identified in Chapter 3,
  - in terms of the international best practice method for predicting loss of life.
- South African case studies of dams are assessed in terms of the proposed evaluation criteria to assess risk to human life.
- A summary of the main findings is provided.

4.2 Evaluation of South African dam safety criteria in terms of international criteria

In Chapter 3 it was found that in international dam safety acceptability criteria for risk to human life are not widely applied and are still in the process of gaining acceptance. However, a number of countries have based their criteria on the FN-criteria proposed by the Australian National Committee On Large Dams (ANCOLD) as illustrated in section 3.4.2 of Chapter 3. South African dam safety criteria are therefore compared to the ANCOLD criteria.

4.2.1 South African dam safety criteria compared to ANCOLD criteria

In this section the current dam safety criteria for risk to human life used by ANCOLD and in South African dam safety are defined. Thereafter the ANCOLD criteria are compared to South African dam safety criteria by finding the implied South African Warning Times (WTs) needed for South African criteria to correspond to ANCOLD criteria.

4.2.1.1 ANCOLD acceptability criteria for risk to human life

The Australian National Committee on Large Dams (ANCOLD) depicts risk to human life on an FN-diagram, with the estimated number of fatalities due to dam failure represented on the x-axis and the annual frequency of N or more fatalities occurring on the y-axis. The risk is evaluated in terms of its acceptability according to FN-criteria defined by ANCOLD as shown in Fig. 4.1.

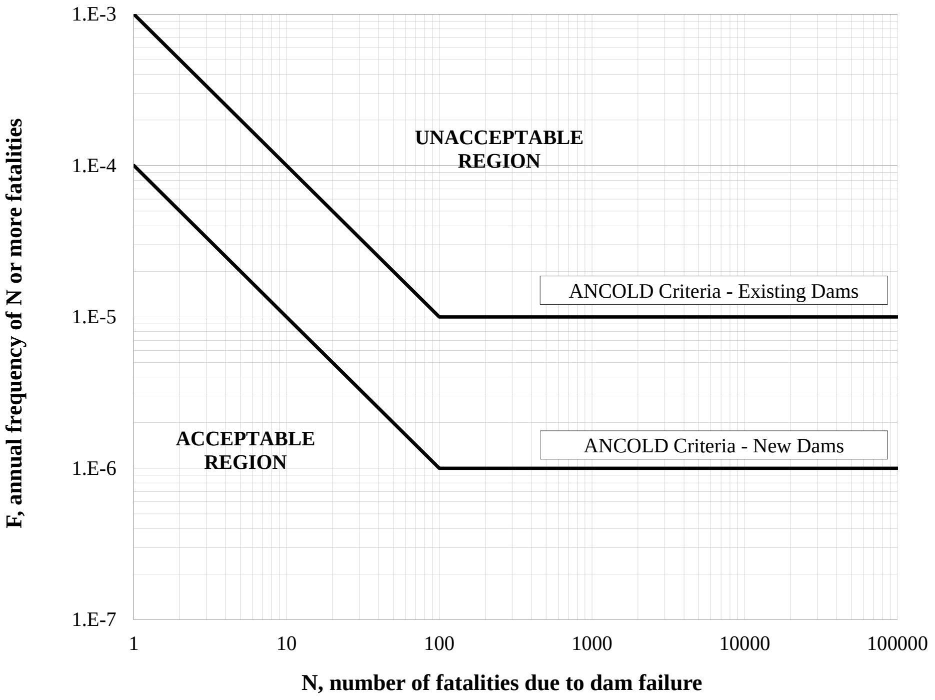

Figure 4.1: ANCOLD acceptability criteria for risk to human life for new and existing dams (ANCOLD, 2003)

The following properties can be observed from the ANCOLD FN-criterion lines shown in Fig. 4.1:

- Intersection with the y-axis (N=1):
  - For Existing dams, if the frequency of 1 or more fatalities occurring is higher than 1E-3 per year (i.e. 1 in 1 000 per year), it is unacceptable.
  - For New Dams, if the frequency of 1 or more fatalities occurring is more than 0.0001 per year (i.e. 1 in 10 000 per year), it is unacceptable.
  - The criterion line for existing dams is one factor of 10 higher than the criterion line for new dams and is therefore less stringent. According to ANCOLD (2003), the marginal cost of reducing risk for an existing dam is generally more than for new dams, therefore it is not reasonably practicable to reduce the risk of existing dams to the same levels as new dams, as described in Chapter 3.
- Both FN-criterion lines have the same slope of -1 which resembles zero risk aversion. This slope corresponds to what is generally accepted as good practice internationally, as described in Chapter 3.

- Both criterion lines are truncated horizontally, since technology does not allow for the construction of dams with smaller probabilities of failure and it is impracticable to reduce dam safety levels to more stringent criteria.

4.2.1.2 South African dam safety criteria for risk to human life

In South Africa, the Department of Water Affairs (DWA) presents the risk to human life of a dam on a population at risk (PAR) diagram, where the population at risk refers to the number of people exposed to the dambreak flood in case of dam failure. The PAR-diagram, with the PAR represented on the x-axis and the annual probability of the occurrence of dam failure on the y-axis, is shown in Fig. 4.2. A criterion line is depicted on the PAR-diagram to distinguish between acceptable and unacceptable risk to human life.

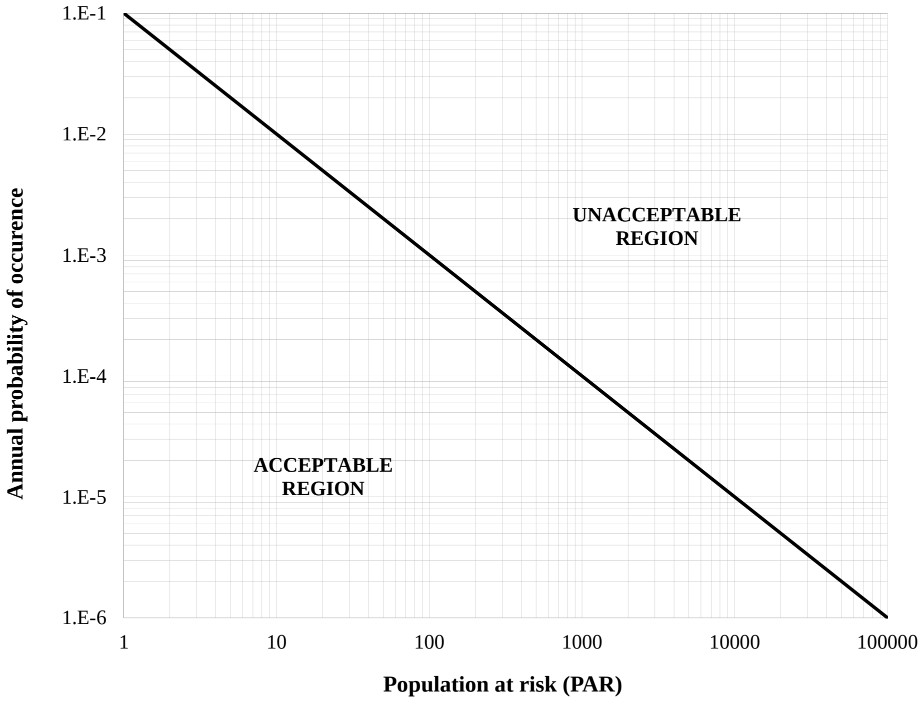

Figure 4.2: DWA acceptability criteria for risk to human life (Hattingh and Oosthuizen, 2009)

According to Hattingh and Oosthuizen (2009), the criterion line coincides with impact accepted voluntarily in South Africa and was developed using statistics of construction accidents as well as statistics of accidents from all modes of transport in South Africa. However, the statistical basis for the development of the criteria are not documented and thus unknown.

The following properties of the acceptability criteria for risk to human life can be observed:

- Intersection with the y-axis (PAR=1):

  For PAR=1, if the frequency of 1 "human at risk" is more than 1E-1 (1 in 10) per year it is unacceptable.

- The slope of the criterion line is -1.

It should be noted that this safety criterion differs significantly from the FN-diagrams used by ANCOLD in that it uses population at risk (PAR) as a consequence measure instead of number of fatalities (N). To estimate the number of fatalities in the case of dam failure, DWA predicts what portion of the population at risk will become fatalities, depending on warning time assumptions. However, the estimated number of fatalities is not used in their risk evaluation.

This DWA prediction model collectively uses the PAR and the warning time (WT) available for the PAR to escape the dambreak flood. The number of fatalities, expressed as the loss of life (LOL) by DWA, can be estimated from the diagram shown in Fig. 4.3.

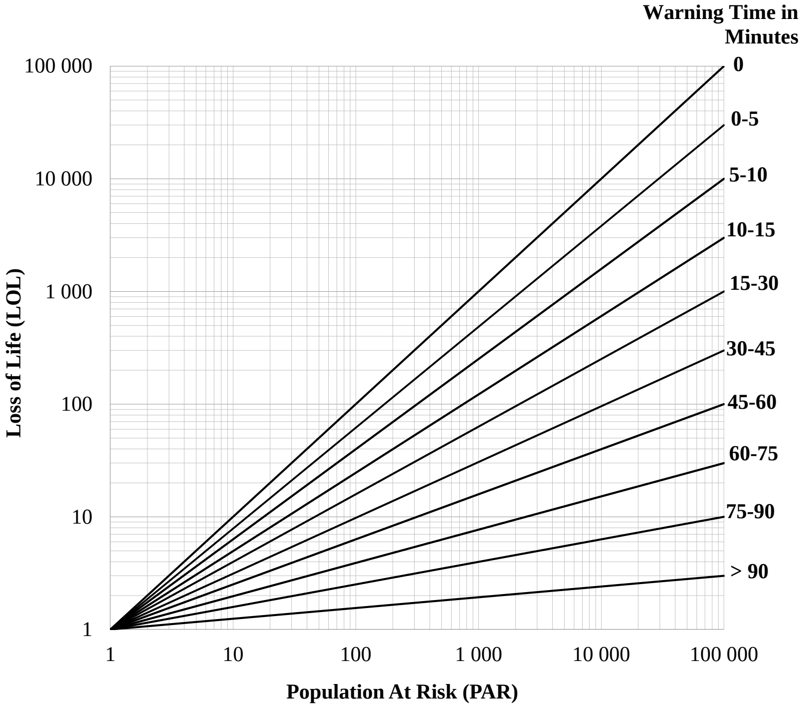

Figure 4.3: DWA prediction model to estimate of loss of life based on population at risk and warning time (Hattingh and Oosthuizen, 2009)

The gradiënts of the lines in Fig. 4.3 represent different WTs, with smaller gradiënts associated to larger warning times. The gradiënt of the line determines the relationship between PAR and LOL as shown in Eq. 4.2.1:

$$LOL = \frac{\Delta y}{\Delta x} \cdot PAR \tag{4.2.1}$$

If the WT is increased, the gradiënt of the line decreases and the LOL estimated for a particular PAR decreases. According to Hattingh and Oosthuizen (2009) actual historical data for dam failures were used to develop the diagram shown in Fig. 4.3. However, the statistical basis used to develop the prediction model is not documented and is therefore unknown.

4.2.1.3 Implied South African warning times for acceptability criteria to correspond to ANCOLD criteria

Since two different consequence measures are used by ANCOLD and DWA in evaluating the acceptability of assessed risk to human life, i.e. the number of fatalities and population at risk respectively, it is difficult to compare the criteria to each other. In order to compare, for a certain probability of occurrence the implied warning time that would result in the same number of expected fatalities (LOL or N) from DWA criteria and from ANCOLD criteria is computed.

The following steps are followed to determine the implied South African warning times for DWA criteria to correspond to ANCOLD criteria:

- **ANCOLD criteria for new and existing dams**: For the ANCOLD FN-criterion lines shown in Fig. 4.1, the annual probability of occurrence and the corresponding number of fatalities (N), which may also be expressed as loss of life (LOL), are obtained as shown in Table 4.1 for existing dams and in Table 4.2 for new dams.

- **South African dam safety criteria used by DWA**: For the DWA-criterion line shown in Fig. 4.2, the annual probability of occurrence and the corresponding population at risk (PAR) are obtained and shown in both Table 4.1 and Table 4.2.

- For the different probabilities of occurrence, the LOL obtained from ANCOLD criteria may be plotted against the PAR obtained from DWA criteria on a similar diagram used by DWA to predict the LOL for a particular PAR and a dambreak flood warning time (WT) as shown in Fig. 4.4. The position of the plotted points may be used to find the implied South African warning times needed for DWA criteria to correspond to ANCOLD criteria for existing and new dams.

The results for the implied warning times are summarised in in Table 4.1 and 4.2 for existing and new dams.

Table 4.1: Existing dams - Implied South African warning times for DWA criteria to correspond to ANCOLD criteria

Probability of occurrence (P_f)	Loss of Life (LOL)*	Population At Risk (PAR)**	Implied South African Warning Time (WT)
1E-1	-	1	-
1E-2	-	10	-
1E-3	1	100	**>90 minutes**
1E-4	10	1 000	**± 60 minutes**
1E-5	100	10 000	**30-45 minutes**
1E-5	1 000	10 000	**± 10 minutes**
1E-6	-	100 000	-

* From ANCOLD criteria for existing Dams (refer to Fig. 4.1)

** From South African dam safety criteria (refer to Fig. 4.2)

Table 4.2: New Dams - Implied South African warning times for DWA criteria to correspond to ANCOLD criteria

Probability of occurrence (P_f)	Loss of Life (LOL)*	Population At Risk (PAR)**	Implied South African Warning Time (WT)
1E-1	-	1	-
1E-2	-	10	-
1E-3	-	100	-
1E-4	1	1 000	**>90 minutes**
1E-5	10	10 000	**± 75 minutes**
1E-6	100	100 000	**45-60 minutes**

* From ANCOLD criteria for New Dams (refer to Fig. 4.1)

** From South African dam safety criteria (refer to Fig. 4.2)

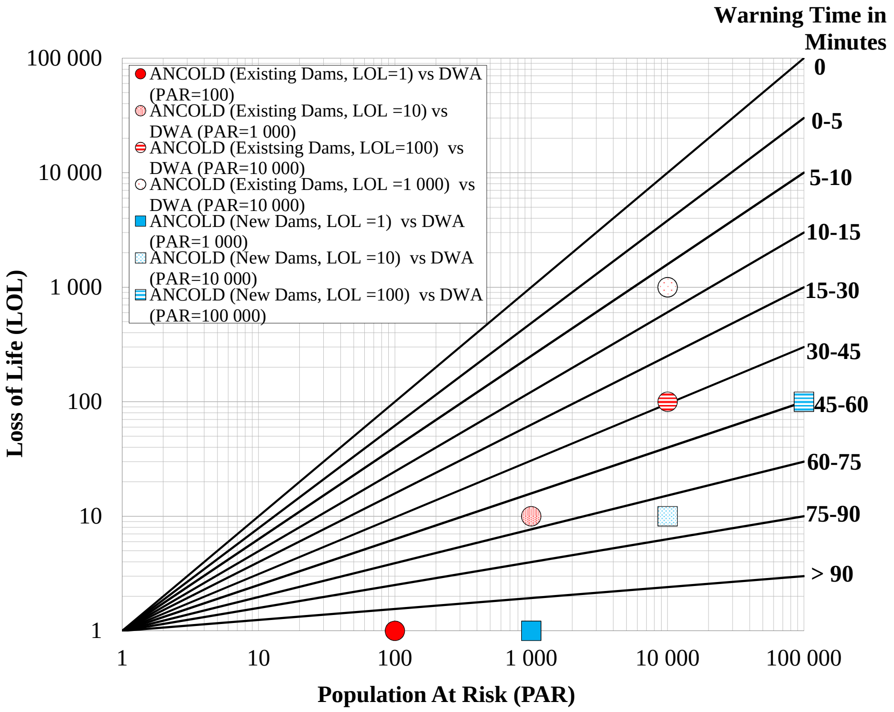

Figure 4.4: Implied South African warning times for DWA criteria to correspond to ANCOLD criteria for existing and new dams

The implied warning times differ depending on the probability of occurrence of the dam failure event. This is not logical as the warning time will depend on the type of dam, geology, warning time systems and so forth, and not on the probability of dam failure.

The results obtained for the implied WTs are shown on the DWA PAR-diagram in Fig. 4.5 for existing dams. For higher probabilities of occurrence large warning times are needed to adhere to international best practice risk criteria. Therefore at higher probabilities of dam failure, DWA dams are accepted at less stringent safety levels than ANCOLD criteria. For low probabilities of occurrence, the warning times needed to adhere to ANCOLD criteria decreases. DWA therefore over designs for low probability events and even for very small WTs DWA dams comply with ANCOLD criteria.

The implied WTs obtained for new dams are shown on the DWA PAR-diagram in Fig. 4.6. A similar pattern may be observed where the WTs decrease as the probability of occurrence decreases. However, the overall implied South African warning times which should be available to the population at risk such that DWA predicted loss of life corresponds to ANCOLD criteria are higher for new dams than for existing dams. This is due to the fact that ANCOLD implements more stringent safety criteria for new dams, while DWA makes no distinction between new and existing dams.

The DWA risk criteria thus has an inherent flaw, that by using PAR instead of N, the influence of WT is excluded and inconsistent WT assumptions seem to be embedded in the current criterium.

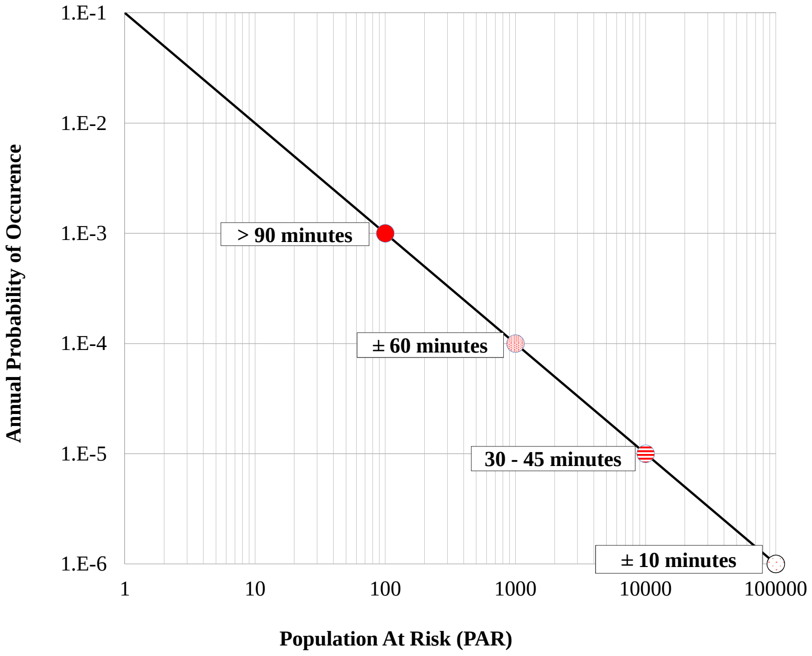

Figure 4.5: Implied South African warning times for DWA criteria to correspond to ANCOLD criteria for existing dams illustrated on PAR-diagram used by DWA

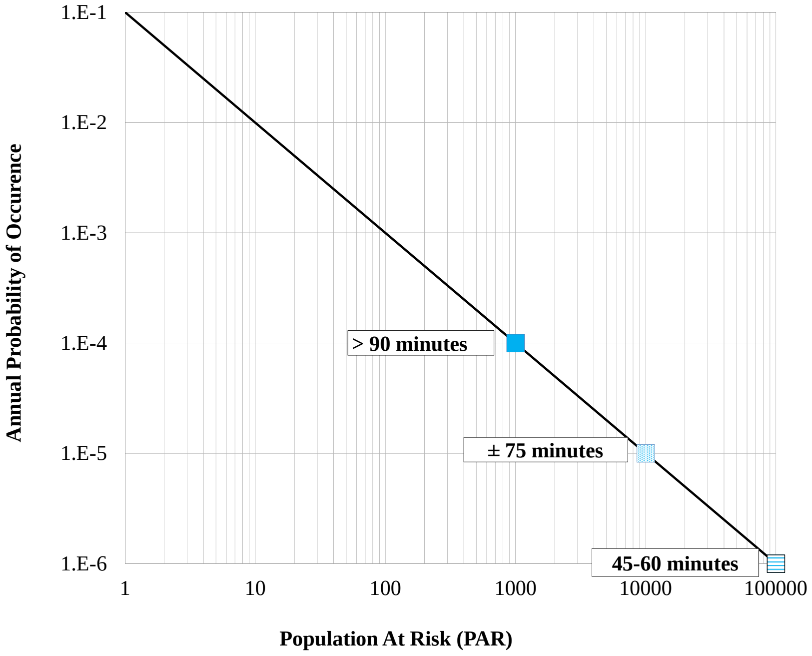

Figure 4.6: Implied South African warning times for DWA criteria to correspond to ANCOLD criteria for new dams illustrated on PAR-diagram used by DWA

4.2.1.4 Discussion of results obtained for the implied South African warning times:

Since ANCOLD and DWA use two different consequence measures to assess risk to human life, a rational basis to compare the acceptability criteria was by determining the implied South African warning times needed for the DWA criteria to correspond to ANCOLD criteria. The warning times which should be available to the PAR for the DWA predicted LOL to correspond to the LOL established by ANCOLD criteria for new and existing dams are summarised in Table 4.3.

Table 4.3: Summary of implied South African warning times needed for DWA criteria to correspond to ANCOLD criteria for new and existing dams

South African Dam Safety Criteria		**Warning Time (WT)**	
P_f	Population at risk (PAR)	Existing Dams	New Dams
1E-3	100	**>90 minutes**	**-**
1E-4	1 000	**±60 minutes**	**>90 minutes**
1E-5	10 000	**30-45 minutes**	**±75 minutes**
1E-6	100 000	**± 10 minutes**	**45-60 minutes**

In Table 4.3 it can be seen that the values obtained for the implied WTs for both new and existing dams are inconsistent. For higher probabilities of occurrence, longer WTs are needed for the DWA predicted LOL to correspond to the LOL established by ANCOLD criteria. However, in practice it must be noticed that each dam break case is situation specific and often a high WT cannot be achieved. For example, if a dam has an inadequate system in place to alert the population downstream of a dam break, then a high WT can't always be assured.

Since for higher probabilities of occurrence, higher WTs are needed for the DWA predicted LOL to correspond to the LOL established by ANCOLD criteria and these high WTs cannot always be assured, it can be concluded that a higher risk to human life is accepted by the South African dam safety criteria. Therefore the criteria used by ANCOLD to assess the risk to human life are considered more stringent, especially for new dams.

However, the implied WTs above were obtained using Fig. 4.4 and this DWA life loss prediction model has no well documented rational scientific background which describes how it was developed. Therefore, it may not be justified to use this graph. In the following section, the model used by DWA to predict LOL for different warning times in case of dam failure is evaluated in terms of international best practice methods for predicting loss of life.

4.2.2 Evaluation of South African life loss prediction model for dam failure

To predict the loss of life (LOL) in case of dam failure, DWA uses the population at risk (PAR) and the warning time (WT) available to the PAR to escape the dambreak flood. In this section, international best practice methods for estimating LOL in the case of dam failure are investigated and a valid method which similarly predicts the LOL for a PAR and WT available to the PAR in case of dam failure is compared to the DWA prediction model.

4.2.2.1 Factors influencing loss of life in case of dam failure

There are different factors that influence the expected loss of life in case of a dambreak flood. According to Hartford and Baecher (2004) and Jia-Qian *et al.* (2009) the main factors are:

- Population at risk
- Warning times
- Flood severity
- Human response

According to Hartford and Baecher (2004), human behaviour may be highly variable and uncertain and contains both physical and psychological dimensions. Hartford and Baecher (2004) further notes that in the case of a dambreak flood, the survival of an individual downstream in the affected area will depend on a range of choices that is available to the individual upon receiving warning of the flooding. Since there are so much randomness in the psychology, physiology and physics of human responses, models for predicting loss of life may have very large uncertainty bounds.

4.2.2.2 International methods for predicting loss of life from dam failure

According to Jia-Qian *et al.* (2009), Hartford and Baecher (2004) and Aboelata *et al.* (2003), the main methods which may be used to estimate the lives lost in case of a dam failure include:

- Regression approaches developed by Lee *et al.* (1986), Brown and Graham (1988) and DeKay and McClelland (1993).
- The object loss frequency approach by Graham (1999).
- Reiter (2001) proposes a GIS method for estimating life loss, the RESCDAM method.
- Simulation approach by Assaf and Hartford (2002).
- Aboelata *et al.* (2003) evaluates life loss in case of dam failure by using a GIS model.

Regression approaches:

The Lee *et al.* (1986), Brown and Graham (1988) and DeKay and McClelland (1993) methods are empirical methods for predicting life loss in case of dam failure. They are based on statistical analyses of historical information. More specifically, a regression analysis is used where the relationship between a dependent variable and one or more independent variables are determined. As the independent variables are varied, the regression analysis shows how the dependent variable will change. For the methods, the population at risk and the warning time available to the population are obtained from historical flood records and these are used to derive relations to predict the loss of life.

The Brown and Graham (1988) method consists of three separate formulas which are used to predict the LOL from PAR and WT as a categorical variable (Hartford and Baecher, 2004). However, DeKay and McClelland (1993) states that there should be more significant interaction between the WT and PAR to predict LOL and they suggest that WT should be used as continuous measure.

According to DeKay and McClelland (1993), the Lee *et al.* (1986) method uses a continuous measure of WT. This method reports results that are very similar to the Brown and Graham (1988) method, but it is not limited to dam failures and estimates the LOL for a wider range of effects, including riverine flooding.

The DeKay and McClelland (1993) method uses the same historical data as the Brown and Graham (1988) method, but the historical record is revised and additional case studies are included. A continuous measure of WT is used and the LOL predicted decreases exponentially with an increased WT and increases nonlinearly with an increased PAR. The method also incorporates an additional measure, the force conditions, which accounts for the depth and velocity of flood waters in case of dam failure. For example, when the flood waters are swift, the predicted LOL is greater and this effect is incorporated by a force variable.

According to DeKay and McClelland (1993), the Brown and Graham (1988) and Lee *et al.* (1986) methods are the only other methods that estimate the loss of life using empirical data. DeKay and McClelland (1993) further states that these methods are important contributors to literature but the statistical procedures used are inadequate. The primary purpose of the work by DeKay and McClelland (1993) was to reanalyse the historical records of dam failures to develop a model for loss of life using more justifiable procedures.

Object loss frequency (OLF) approach:

The Graham (1999) method is also referred to as the "object loss frequency" (OLF) approach (Hartford and Baecher, 2004). The OLF is equivalent to a fatality rate or the fraction of lives lost from the people at risk. The OLF and loss of life in case of dam failure are based on historical cases of dam failures. This method forms the basis of the US Bureau of Reclamation's (USBR) "flood severity based method" which qualitatively incorporates the hydrodynamics of the flood, i.e. the average depth and velocity of the flood, the human reactions in terms of the warning time available and the "flood severity understanding", to determine what the OLF in case of dam breach flooding will be. This method incorporates in addition to historical records, the physical processes and behaviour during the flood, which are evaluated on the basis of engineering judgement.

GIS Approach:

The RESCDAM method presented by Reiter (2001) follows the same principles of the Graham (1999) method, but uses a computer-aided GIS/public population register analysis to define the population at risk and the impact on the population at risk, including the different flood severity zones, living conditions and vulnerability of the population at risk. Aboelata *et al.* (2003) uses a similar approach, a modular geographical information system (GIS) modelling system for estimating potential loss of life from natural and dam-failure floods.

Simulation approach:

The simulation approach by Assaf and Hartford (2002) models a general emergency scenario environment that is intended to provide information for emergency planning for floods (Hartford and Baecher, 2004). It consists of logical statements set up by means of dam breach modelling and the simulation of emergencies. How people respond to flood warnings incorporates the hydrodynamic conditions which a person have to deal with in case of flooding. One output of the simulation process is a probability distribution of loss of life for various different scenarios.

4.2.2.3 Comparison of DWA life loss prediction method to international best practice method

The DWA life loss prediction model was discussed in section 4.2.1 where the LOL could be predicted from the PAR and WT available to the PAR in case of dam failure using the diagram shown in Fig. 4.3. According to Hattingh and Oosthuizen (2009) the diagram was developed using actual historical data, however, there is no well-documented basis for the DWA life loss prediction model. International methods which similarly estimate the LOL from the PAR and WT based on historical data were discussed and include the Lee *et al.* (1986), Brown and Graham (1988) and DeKay and McClelland (1993) method. For this study the method proposed by DeKay and McClelland (1993) was chosen as the most valid method to compare against the DWA methodology for predicting LOL, since:

- This method was developed using a collection of historical data of 25 case studies from the 1950's onwards.
- The PAR considered for the case studies include a wide range, the PAR ranges from 5 000 to 58 000 people.
- The actual LOL is given against the predicted LOL for the different case studies in the study by DeKay and McClelland (1993). In comparing the values, the predicted LOL approaches the actual obtained values for the LOL.
- According to DeKay and McClelland (1993), the Brown and Graham (1988) and Lee *et al.* (1986) methods are important contributors to literature but the statistical procedures used are inadequate and the work by DeKay and McClelland (1993) reanalysed the historical records of dam failures to develop a more justifiable procedure for predicting life loss in case of dam failure.

In the following, a more detailed description of the method proposed by DeKay and McClelland (1993) is provided and thereafter the DeKay and McClelland (1993) method is compared to the DWA life loss prediction model.

DeKay and McClelland (1993) method :

The DeKay and McClelland (1993) method method uses a regression approach to estimate the LOL from the population at risk (PAR) and the warning time (WT) in case of dam failure. In addition, High Force (HF) and Low Force (LF) conditions are considered when determining the LOL. The HF condition is used when the PAR is located in a canyon and the flood waters in case of dam failure are very deep and swift. The LF condition is used when the PAR is located on a plain and the flood waters are shallow and slow.

The two equations for determining the LOL for both HF and LF conditions are shown in Eq. 4.2.2 and Eq. 4.2.3 (DeKay and McClelland, 1993).

$$LOL_{HF} = \frac{PAR_{HF}}{1 + 13.277(PAR_{HF}^{0.440})e^{[2.982(WT_{HF})-3.790]}} \tag{4.2.2}$$

$$LOL_{LF} = \frac{PAR_{LF}}{1 + 13.277(PAR_{HF}^{0.440})e^{[0.759(WT_{HF})]}} \tag{4.2.3}$$

Where,

LOL_{HF} and LOL_{LF} = Loss of Life for High Force and Low Force conditions respectively

PAR_{HF} and PAR_{LF} = Population at Risk for High Force and Low Force conditions respectively

WT_{HF} and WT_{LF} = Warning Time for High Force and Low Force conditions respectively

Eq. 4.2.2 and 4.2.3 may be simplified as shown in Eq. 4.2.4 and 4.2.5.

$$LOL_{HF} \approx 0.075(PAR_{HF}^{0.560})e^{[-2.982(WT_{HF})+3.790]} \tag{4.2.4}$$

$$LOL_{LF} \approx 0.075(PAR_{HF}^{0.560})e^{[-0.759(WT_{HF})]} \tag{4.2.5}$$

Comparison of DeKay and McClelland (1993) method to DWA prediction model:

Both the DWA method and the DeKay and McClelland (1993) method use PAR and WT as input parameters to predict the LOL. For both methods the LOL is estimated for a range of PAR and the following WTs:

- Small WT: 0 minutes
- Medium WT: 30-45 minutes
- Large WT: 90 minutes

For the three sample WTs and over a logarithmic range of PAR the LOL is estimated through the DeKay and McClelland (1993) method for both HF and LF conditions using Eq. 4.2.4 and 4.2.5. The results are shown in Table 4.4.

Table 4.4: Predicted loss of life over a range of population at risk and for 3 different warning times using the DeKay and McClelland (1993) method for High Force (HF) and Low Fore (LF) conditions

Population At Risk (PAR)	**Estimated Loss of Life (LOL)**							
	Small WT: 0 minutes		**Medium WT:** 30-45 minutes				**Large WT:** 90 minutes	
			30 minutes		45 minutes			
	HF	LF	HF	LF	HF	LF	HF	LF
1	4	1	1	1	1	1	1	1
10	13	1	3	1	2	1	1	1
100	44	1	10	1	5	1	1	1
1 000	159	4	36	3	17	3	2	2
10 000	577	14	130	9	62	8	7	5
100 000	2095	48	472	33	224	27	24	16

For a small WT and HF conditions, the DeKay and McClelland (1993) method overestimates the LOL, i.e. the predicted LOL is more than the PAR, which is not credible. According to DeKay and McClelland (1993), the predicted values will more often be too high than it is too low, since the formulation is based on historical data obtained from the most severe flash floods.

Note that DWA predicts the LOL for a WT interval, for example the LOL can be obtained over a range of PAR and for a WT interval between 30-45 minutes. The DeKay and McClelland (1993) method predicts the LOL for a specific WT. In order to compare, for the DWA model the LOL is obtained over a WT interval (e.g. 30-45 minutes) and for the DeKay and McClelland Method (1993) the LOL is obtained for the start and end value of the WT interval (e.g. for both 30 and 45 minutes).

The LOL predicted for a small WT (0 minutes) through the DeKay and McClelland (1993) method is plotted against the range of PAR to compare to the DWA predicted LOL as shown in Fig. 4.7.

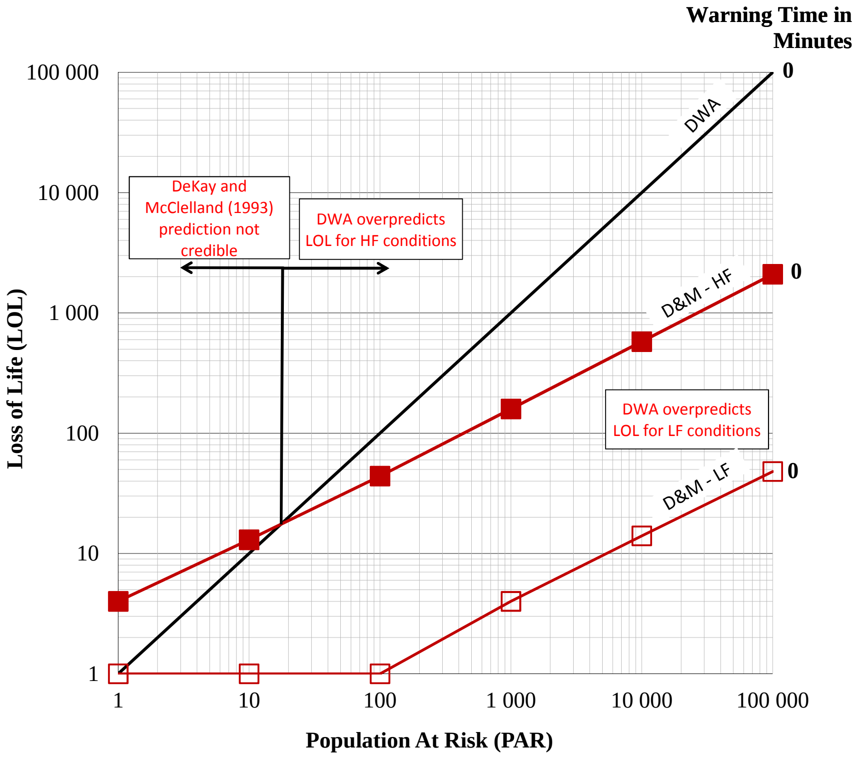

Figure 4.7: DWA predicted LOL compared to DeKay and McClelland (1993) predictions for a small warning time (0 minutes)

Below a PAR of ± 20, the DeKay and McClelland (1993) method for HF conditions gives unrealistic LOL predictions, since the predicted LOL is more than the PAR. Above a PAR of ± 20, DWA overpredicts the LOL in comparison to the DeKay and McClelland (1993) predictions for HF conditions. In addition, the DWA method completely overpredicts the LOL compared to the DeKay and McClelland (1993) method for LF conditions.

For a medium warning time (30-45 minutes), the predicted LOL obtained from the DeKay and McClelland (1993) method are plotted against the PAR to compare to the DWA predicted LOL as shown in Fig. 4.8.

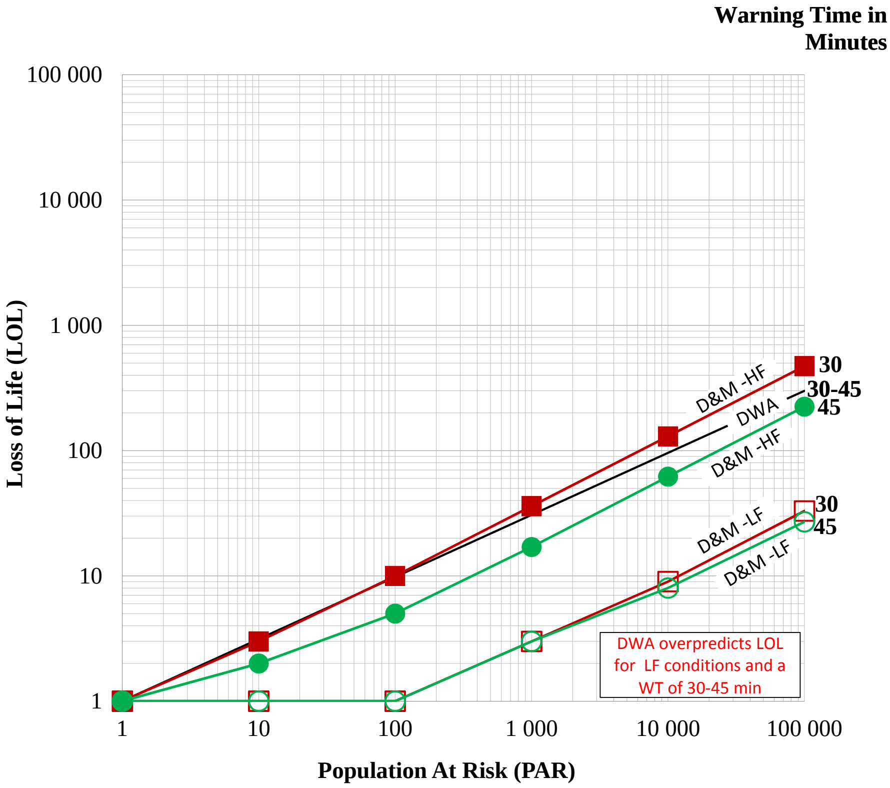

Figure 4.8: DWA predicted LOL compared to DeKay and McClelland (1993) predictions for a medium warning time (30-45 minutes)

The two methods give similar LOL predictions for HF conditions and a WT of 30-45 minutes, the predictions are certainly within uncertainty bounds of each other. When the DeKay and McClelland (1993) prediction for LF conditions is compared to the DWA predicted LOL for a WT of 30-45 minutes, the DWA method severely overpredicts the LOL.

In Fig. 4.9, the LOL predicted through the DeKay and McClelland (1993) method and DWA method are plotted against the PAR for a large WT (90 minutes). Below a PAR of ± 1 000 people, the DWA method overpredicts the LOL compared to the DeKay and McClelland (1993) prediction for HF and LF conditions. When the PAR is above ± 1 000 people, the DWA method underpredicts the LOL

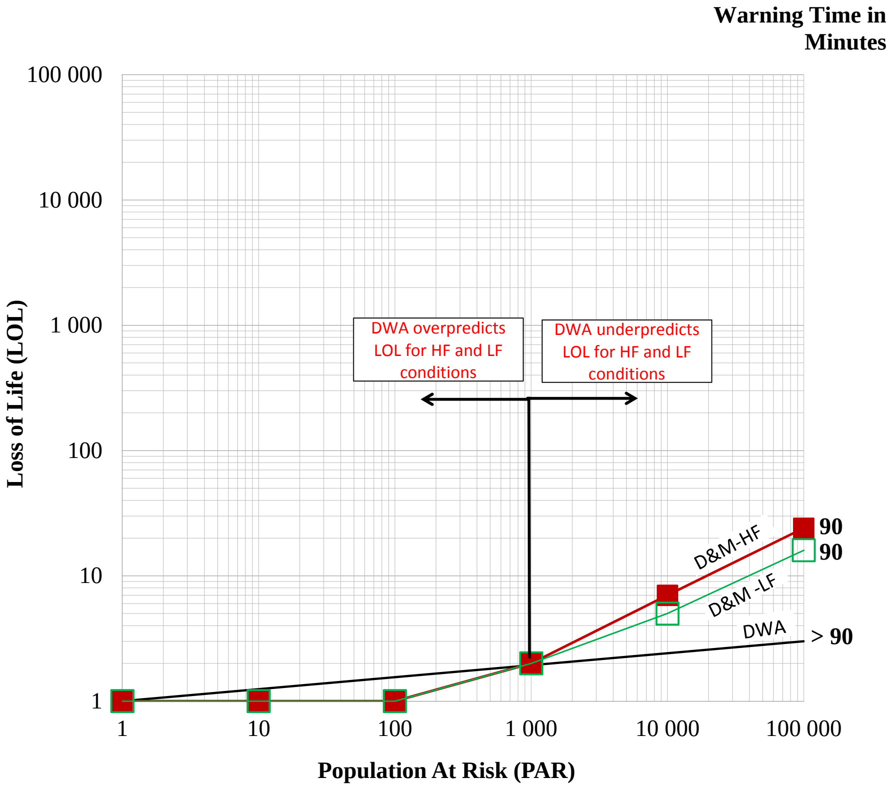

Figure 4.9: DWA predicted LOL compared to DeKay and McClelland (1993) predictions for a large warning time (90 minutes)

In Fig. 4.10, the results obtained for a small, medium and large WT when the DWA predicted LOL is compared to the DeKay and McClelland (1993) predicted values for HF conditions are summarised. This is also done for LF conditions in Fig. 4.11. In both Fig. 4.10 and Fig. 4.11 it can be seen that DeKay and McClelland (1993) predicts LOL values within a much more narrow range than the DWA model. Further, DWA generally overpredicts the LOL for small and medium WTs and underpredicts the LOL for large WTs. In addition, DWA severely overpredicts the LOL for a small and medium WT for LF flood conditions.

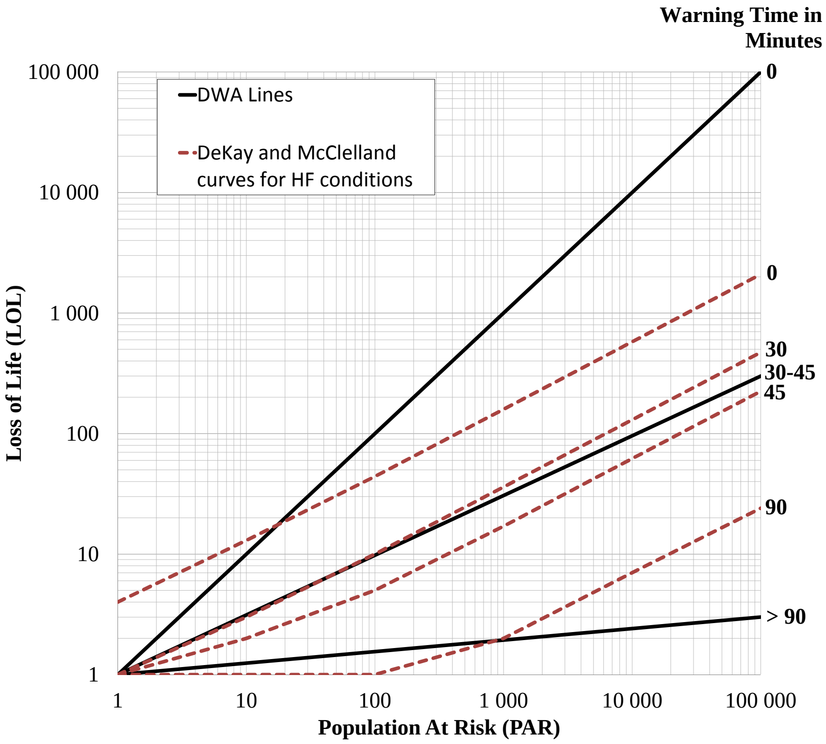

Figure 4.10: DWA predicted LOL compared to DeKay and McClelland (1993) predictions for HF conditions

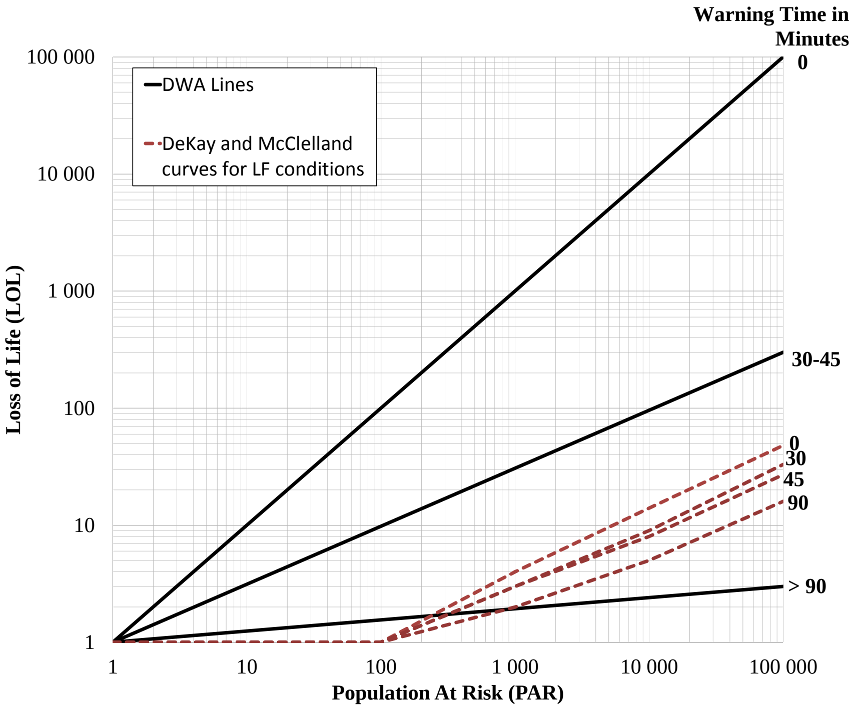

Figure 4.11: DWA predicted LOL compared to DeKay and McClelland (1993) predictions for LF conditions

4.2.2.4 Discussion of results obtained when evaluating South African life loss prediction model for dam failure

Comparing the DWA method and the DeKay and McClelland (1993) method for predicting LOL, inconsistent results were obtained since the DWA method either over or under predicts the LOL, depending on the WT under consideration. However, some useful conclusions may be made.

Considering the results obtained for HF conditions, the following conclusions were made:

- For a small WT and as the PAR increases, it was found that the DWA method overpredicts the LOL compared to the DeKay and McClelland (1993) prediction. This may lead to conservative decisions regarding life safety in cases where severe consequences are expected, i.e. the DWA prediction model unwittingly implies risk averse decision making.
- For a medium WT, predictions from DWA and DeKay and McClelland (1993) are similar.
- For a large WT and a small PAR, the DWA method overpredicts the LOL compared to DeKay and McClelland (1993) predictions. This may lead to unnecessarily conservative decisions in cases where low consequences are in fact expected.

When the DWA predicted LOL is compared to the DeKay and McClelland (1993) predicted values for LF conditions it was observed that DWA in most cases severely overpredicts the LOL. DWA does not distinguish between HF and LF conditions in their prediction model, but the DWA predictions are more comparable to the DeKay and McClelland (1993) predictions for HF conditions and are too conservative for LF conditions where low consequences are expected.

In summary, in cases where severe consequences are expected the current DWA criteria implies conservative decision making regarding life safety. DWA is also conservative in life safety decisions in cases where low consequences are expected. This may to some extent off-set the unconservative life safety decisions of DWA that is implied when the DWA and ANCOLD criteria for assessing risk to human life were compared in section 4.2.1, where the DWA criteria were observed to be less stringent than the ANCOLD criteria at higher probabilities of failure.

In order to compare the DWA life safety criteria to the ANCOLD criteria it is suggested to incorporate the DeKay and McClelland (1993) method life loss prediction model to convert "population at risk" to "estimated number of fatalities", since this prediction model has a well-documented and rational scientific basis.

4.2.3 Comparison of DWA acceptability criteria to ANCOLD criteria using the DeKay and McClelland method for predicting loss of life

In section 4.2.1 the DWA acceptability criteria for risk to life were compared to ANCOLD criteria. However, since two different consequence measures are used by DWA and ANCOLD, the DWA life loss prediction model was used to determine the implied warning time needed for the predicted LOL from DWA criteria to correspond to ANCOLD criteria. In this section the DWA and ANCOLD criteria are compared to each other, but instead of using the DWA prediction model to find implied WTs, the DeKay and McClelland (1993) method is incorporated to convert "population at risk" to "loss of life". This is useful since the DWA criteria can be directly compared to ANCOLD criteria.

To compare the criteria:

- For different probabilities of failure, P_f, the population at risk (PAR) is obtained from the PAR-diagram used by DWA as shown in Fig. 4.2.
- The PAR and an assumed WT are used to obtain the Loss Of Life (LOL) through the DeKay and McClelland (1993) prediction model.
- The LOL is plotted against the P_f to obtain the equivalent DWA FN-criterion line, which can be compared to the ANCOLD FN-criteria.

For three sample probabilities of failure (P_f) and WTs, the LOL obtained for HF conditions are shown in Table 4.5.

Table 4.5: LOL estimated from DeKay and McClelland (1993) method for HF conditions

P_f	**PAR***	**LOL****		
		Small WT 0 min	Medium WT 45 min	Large WT 90 min
5E-5	2 000	235	26	3
5E-6	20 000	851	91	10
5E-7	200 000	3088	330	36

* PAR obtained from South African dam safety criteria for the P_f (refer to Fig. 4.2)

** LOL obtained from DeKay and McClelland (1993) method for High Force conditions (refer to Eq. 4.2.4)

The LOL are plotted against the corresponding P_f as co-ordinate points on an FN-diagram. If a line is drawn through all the points with a small, medium and large WT, DWA equivalent FN-criterion lines could be obtained as shown for HF conditions in Fig. 4.12.

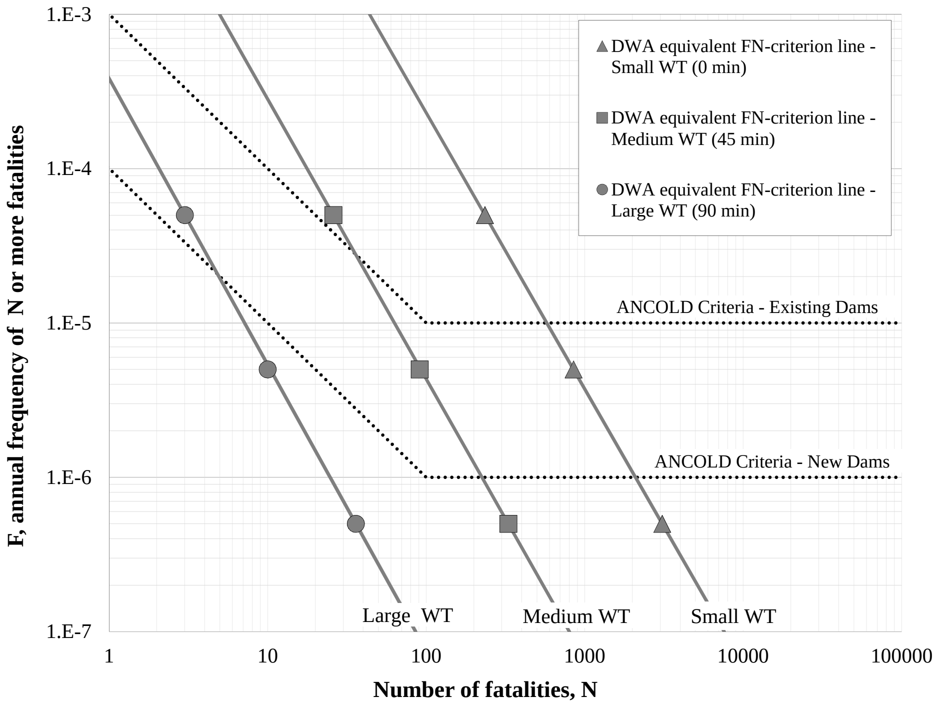

Figure 4.12: ANCOLD FN-criteria compared to DWA equivalent FN-criterion lines for HF conditions

The LOL is obtained for LF conditions, using the same three sample probabilities of failure (P_f) and WTs as shown in Table 4.6.

Table 4.6: LOL estimated from DeKay and McClelland (1993) method for Low Force (LF) conditions

		LOL**		
P_f	**PAR***	Small WT 0 min	Medium WT 45 min	Large WT 90 min
5E-5	2 000	6	3	2
5E-6	20 000	20	11	7
5E-7	200 000	70	40	23

* PAR obtained from South African dam safety criteria for the P_f (refer to Fig. 4.2)

** LOL obtained from DeKay and McClelland (1993) method for Low Force conditions (refer to Eq. 4.2.5)

Similarly the LOL obtained for LF conditions is plotted against the corresponding probabilities of failure (P_f's) for different WTs to obtain DWA equivalent FN-criterion lines as shown in Fig. 4.13.

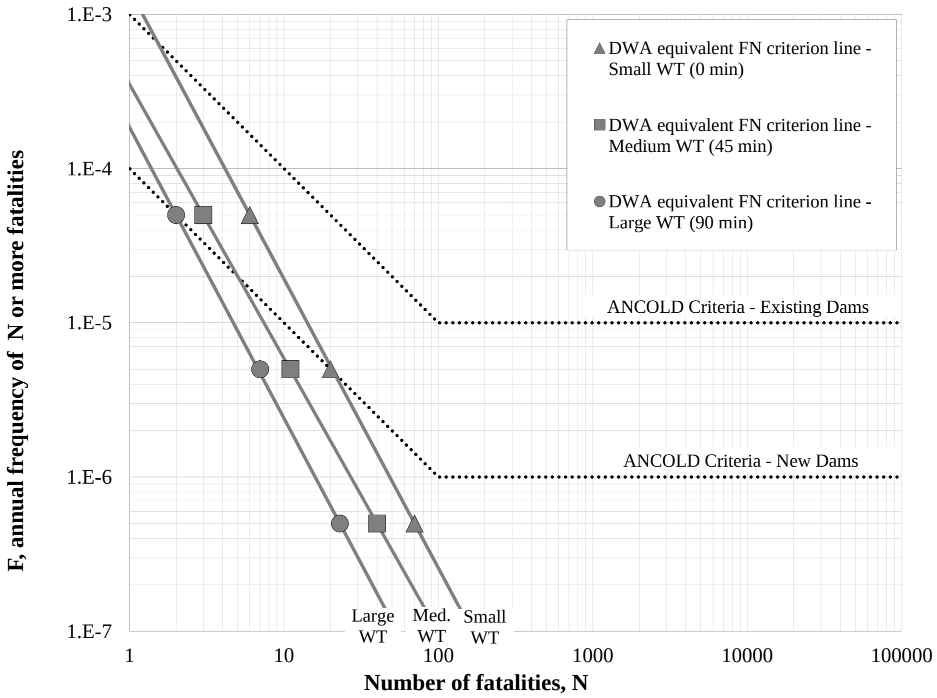

Figure 4.13: ANCOLD FN-criteria compared to DWA equivalent FN-criterion lines for LF conditions

The following interpretations regarding the DWA equivalent FN-criterion lines are made:

- The DWA equivalent FN-criteria are different depending on the assumed warning time of the dam under consideration and whether LF or HF conditions are expected.
- For HF conditions, illustrated in Fig. 4.12:
  - If the WT is small, the equivalent DWA acceptability criteria are significantly less stringent than the ANCOLD life safety criteria for new and existing dams. This implies less conservative life safety decisions by DWA where severe consequences are expected.
  - As the warning time increase, the DWA equivalent criteria become comparable to ANCOLD criteria.
- For LF conditions, illustrated in Fig. 4.13:
  - The DWA equivalent FN-criteria are more stringent than the ANCOLD criteria for existing dams and are more or less comparable to ANCOLD criteria for new dams.
- The gradiënt of the DWA equivalent FN-criterion lines are steeper than the ANCOLD FN-criterion lines, which have a slope of -1 equivalent to zero risk aversion, and thus portray higher risk aversion.

Discussion of results:

The DWA equivalent FN-criteria are different for different WTs. However, this should not be the case. Acceptable risk to human life should not be a function of warning time (or for that matter, of whether a HF or LF condition is expected). These things will influence the risk level but should not influence the acceptability criteria.

ANCOLD acceptance criteria distinguish between criteria for new and existing dams: since the marginal cost of reducing the risk for an existing dam is generally more than for new dams, less stringent risk levels are accepted for existing dams. Only if it could be argued that in all or most small WT systems it is significantly more costly to implement risk reduction measures, would there be a basis for shifting the criterion line as a function of WT (similar to new vs. existing dam criterion lines). However, when a dam is rehabilitated it is expected that the probability of dam failure will decrease, but it is not expected to influence the WT available. Therefore, the costs of rehabilitation works are independent of WT and consequently there is no basis for different acceptance criteria based on WT.

The gradiënt of the DWA criterion lines are steeper than -1, therefore implying that risk aversion is incorporated. However, as discussed in Chapter 3, Ball and Floyd (1998) suggests that there is no compelling evidence for the view of increasing societal aversion, and therefore a slope of -1, representing risk neutrality, is generally accepted as good practice internationally.

The DWA equivalent FN-criteria has no lower bound truncation of P_f, as does the ANCOLD FN-criteria, i.e. even though it may be impracticable to reduce the P_f below 10^{-6} according to ANCOLD criteria, the DWA criteria requires this in many cases.

4.2.4 Final recommendation for DWA acceptability criteria for risk to human life

DWA uses population at risk as a consequence measure instead of lives lost, however, loss of life is a generally accepted consequence measure used internationally as described in Chapter 3. Further, since several factors influence how many of the PAR will be converted into LOL, including the WT and the flood condition under consideration, this consequence measure introduces several inconsistencies in the implied DWA equivalent acceptability criteria. Also, the DWA life safety criteria has no well-documented scientific basis which describes how it were developed.

These inconsistencies could be eliminated by switching to ANCOLD criteria for life safety. The following properties may then be observed:

- In assessing risk to human life, ANCOLD uses the estimated number of fatalities as a consequence measure, which is most commonly used on an international level.

- The line position is not a function of WT or HF/LF conditions.
- A line slope of -1, representing risk neutrality and recommended internationally, is used.
- According to ANCOLD (2003) it is impracticable to reduce the safety levels of a dam of smaller probabilities of failure. Thus a lower cut-off for probability of occurrence is used, i.e. the criterion lines are truncated horizontally.
- The ANCOLD criteria are based on what is considered to be good engineering practice, based on historically acceptable levels of safety and implicitly taking other considerations, for example cost considerations into account, albeit on the basis of engineering judgement.

Switching to ANCOLD would not imply an enormous change in our current safety levels. However, it would imply a more consistent treatment of risk across the board of different WTs and flood severity levels. Also, switching would not require more risk analysis effort than what is currently expended, since LOL is already included or estimated as part of standard risk estimation procedures performed by DWA. However, it is proposed that the current DWA life loss prediction model is replaced by the DeKay and McClelland (1993) model, since this life loss prediction model has a well-documented and rational scientific basis.

In the following section, case studies of South African dams that were identified to be in need of rehabilitation works by DWA, are evaluated in terms of the ANCOLD criteria to identify if the need for rehabilitation works are justified when assessing the risk to human life.

4.3 Evaluation of South African case studies of dams in terms of proposed acceptability criteria for risk to human life

According to a dam safety rehabilitation progress report presented by the Department of Water Affairs (DWA) (Segers, 2012), in the years 2004/2005, 166 of the 314 government owned dams were identified to be in need of rehabilitation works. The need for rehabilitation works were stressed through dam safety evaluations, which also included a risk analysis performed for the dams.

Of the South African government owned dams that were identified to be in need of rehabilitation works, eleven case studies of dams are used in this study. For each of the case studies the risk to human life estimated through the DWA risk analysis methodology are evaluated according to the ANCOLD life safety criteria to identify if the decision to rehabilitate was justified.

The risk to human life, as the combination of the estimated initial probability of failure (P_f) before the dam is rehabilitated and the estimated loss of life (LOL) in case of dam failure, were obtained from DWA dam safety inspection reports. It must be noted that DWA estimates an interval for the P_f and the LOL, representing the level of confidence of the data. The maximum and minimum values of the interval for the P_f and the LOL for the eleven case studies are shown in Table 4.7.

Note that for Bospoort Dam two different scenarios were considered in the DWA risk analysis: Case 1a, where the sluice gates were assumed to be functioning normally during failure, and Case 1b, where the gates were assumed to not function normally during failure.

Table 4.7: Estimated initial probability of failure and LOL for 11 case studies obtained from DWA inspection reports

	Dam	**Estimated P_f**		**Estimated LOL**		**Reference**
		Min	Max	Min	Max	
1a	Bospoort Dam (Gates Functioning)	1E-3	1E-2	9	13	Hattingh (2005)
1b	Bospoort Dam (Gates Not Functioning)	1E-2	1E-1	9	13	Hattingh (2005)
2	Klein Maricopoort Dam	1E-4	1E-3	3	5	Kelefetswe (2005)
3	Toleni Dam	5E-4	5E-3	2	3	Muller (2000)
4	Lakeside Dam	2E-4	2E-3	200	400	van Vuuren (2005), Oosthuizen (1999)
5	Vaalkop Dam	2E-5	2E-4	35	350	Nightingale (2005), Slabbert (2000)
6	Rust De Winter Dam	5E-5	5E-4	13	13	Coetzer (2003), Nightingale (1994)
7	Makotswane Dam	3E-4	3E-3	5	8	Naidoo (2005)
8	Kromellenboog Dam	2E-4	2E-3	18	19	Segers (2005)
9	Albert Falls Dam	1E-4	1E-3	100	170	Nightingale (2004), Hattingh (1996)
10	Glen Brock Dam	1E-3	1E-2	21	29	Brink (2006)
11	Wentzel Dam	1.11E-3	1.11E-2	156	312	de Lange (2002), Hattingh (1994)

The risk to human life for the eleven case studies are presented on an FN-diagram by plotting the probability of failure against the LOL as shown in Fig. 4.14. Due to the interval, the risk is presented in the form of a block. The risk for the case studies are assessed against the ANCOLD acceptability criteria, as illustrated in Fig. 4.14. Since existing dams in need of rehabilitation works are considered in this study, the risk is evaluated against the acceptability criteria for existing dams proposed by ANCOLD.

The risk to human life for case studies 2, 3, 5 and 6 are located close to or on the border of the ANCOLD acceptability criterion line for existing dams. However, the majority of the risk to human

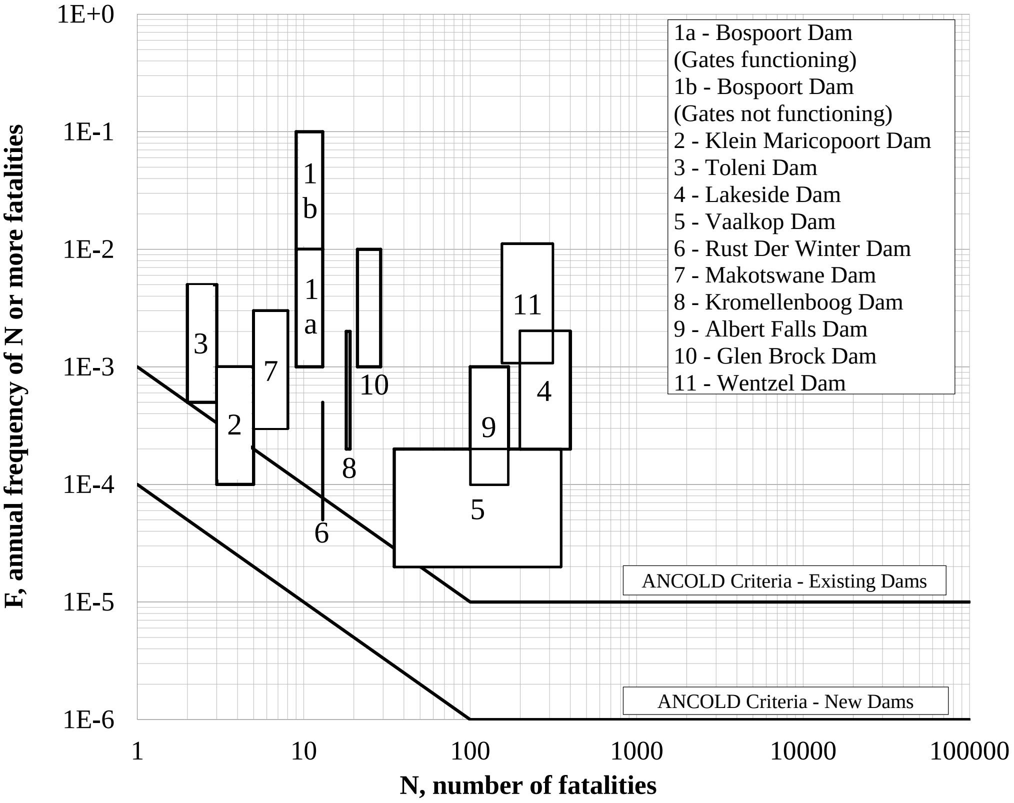

Figure 4.14: Evaluation of risk to human life for DWA case studies in terms ANCOLD acceptability criteria for new and existing dams

life for the case studies are located within the unacceptable region of the ANCOLD criteria and the decision to rehabilitate the dams are justified.

4.4 Summary of main findings

In this chapter the South African dam safety criteria for risk to human life were evaluated by comparing to international best practice methods.

In Chapter 3 it was identified that the life safety criteria proposed by ANCOLD are widely applied in international dam safety. The ANCOLD criteria were thus chosen as valid criteria to compare to the South African DWA dam safety criteria. However, the criteria could not be directly compared since two different consequence measures are used by ANCOLD and DWA to assess risk to human life, namely the loss of life and population at risk respectively.

DWA uses their own in-house developed model to predict what portion of the population at risk will become fatalities, based on assumptions related to the warning time available to the population at risk in case of dam failure. To compare the DWA and ANCOLD criteria, the implied warning times that would result in the same number of expected fatalities from DWA criteria and from ANCOLD criteria were computed.

At high probabilities of failure the implied warning times needed for DWA criteria to adhere to ANCOLD criteria were high. These large warning times cannot always be realistically assured. It was thus concluded that at high probabilities of failure a higher risk to human life is accepted for DWA dams, i.e. ANCOLD criteria have more stringent safety levels. For low probabilities of occurrence, DWA overdesigns and even for very small warning times DWA dams comply with ANCOLD criteria.

The DWA in-house method for predicting loss of life was developed many years ago using historical data and the statistical basis for the model is unknown. In order to justify the DWA life loss prediction model, it was compared to another internationally developed and widely used method for predicting loss of life.

The DWA model was compared to the DeKay and McClelland (1993) method for predicting loss of life. The DWA method either over or under predicts the loss of life in comparison to the DeKay and McClelland (1993) method, depending on the warning time and flood severity under consideration. For cases where severe consequences are expected, DWA overpredicts the loss of life and thus implies conservative decision making regarding life safety. DWA also overpredicts the loss of life in cases where low consequences are expected, leading to very conservative life safety decisions. This to some extent may off-set the unconservative decision making regarding life safety that was implied by the warning times needed for DWA criteria to adhere to ANCOLD criteria.

It was proposed that the current DWA life loss prediction model should replaced by the DeKay and McClelland (1993) model, since this life loss prediction model has a well-documented and rational scientific basis.

The DeKay and McClelland (1993) method was used to convert "population at risk" to "loss of life". In this way DWA equivalent FN-criteria were developed and could be directly compared to ANCOLD FN-criteria.

In comparing the DWA equivalent FN-criteria to the ANCOLD criteria, it was seen that the DWA criteria have several underlying inconsistencies, namely;

- different criteria were defined depending on the warning time and flood severity condition under consideration,
- DWA criteria implies less conservative life safety decision making in cases where severe consequences are expected and too conservative decisions in cases where low consequences are

expected, and

- unrealistically low P_f are expected in some situations, which may not be practically achievable.

These inconsistencies can be eliminated by switching to ANCOLD criteria, which already evaluates risk to human life in terms of the international norm by considering loss of life. Switching to ANCOLD does not imply significant changes in the current dam safety levels used by DWA. However, it would imply a more consistent treatment of risk across the board of different WTs and flood severity levels.Also, using ANCOLD criteria for risk to human life does not require more risk analysis effort since loss of life is already estimated as part of the standard DWA risk analysis procedure.

South African case studies of government owned dams that were identified in terms of DWA acceptability criteria to be in need of rehabilitation works were evaluated according to ANCOLD criteria. The majority of the risk to human life estimated by DWA for the case studies were evaluated as unacceptable according to ANCOLD criteria. Thus, the rehabilitation of these dams are justified.

It must be noted however that the ANCOLD criteria are based on what is considered to be good engineering practice, based on historically acceptable levels of safety and implicitly taking other considerations, for example economic considerations into account, albeit on the basis of engineering judgement.

In the following chapter, Societal Willingness To Pay (SWTP) is proposed as an additional decision tool to assess if the rehabilitation of dams are justified. In this instance, only the societal preferences for investments into life safety through the rehabilitation of a dam are considered.

Chapter 5

SWTP as a lower bound constraint on dam safety levels

5.1 Introduction

In Chapter 4 the acceptability criteria used by the Department of Water Affairs (DWA) in South Africa to assess the risk to human life imposed by dams were evaluated by comparing to international best practice methods. It was found that internationally the conventional method used to judge the acceptability of risk to human life is through the use of FN-diagrams, where the estimated probability of dam failure is assessed in combination with the estimated number of fatalities in case of dam failure. DWA does not evaluate risk to human life using FN-criteria and through investigation it was found that their current procedures have implicit inconsistencies in the way risk is allocated. In order to eliminate these inconsistencies it was proposed to switch to the FN-criteria defined by Australian National Committee On Large Dams (ANCOLD) for new and existing dams.

When a dam is rehabilitated, it is expected that the probability of dam failure will be reduced and consequently the expected risk to human life, as the combination of the probability of failure and the estimated loss of life, should be reduced. However, these rehabilitation works come at a cost.

The rehabilitation of South African government owned dams is financed via public taxes or public charges. In addition, the level of these investments are large. This could be demonstrated by considering the expenditure for the rehabilitation of dams conducted by DWA.

Since 2005/2006, a dam safety rehabilitation programme was initiated by DWA and 19 dams identified by DWA to be in need of rehabilitation works have been rehabilitated in full (Segers, 2012). For an additional 9 dams, the civil works of rehabilitation works were completed, but the mechanical refurbishment works are still outstanding. A further 94 remaining dams identified to be in need of rehabilitation works are in different stages of design, construction, planning or requires further assessments before action could be taken. In Table 1.1 in Chapter 1 a summary of the expenditure for the rehabilitation works conducted by DWA since the years 2005-2006 is provided. The total expenditure up until the 2011-2012 financial year is estimated to be more than R 1.5 billion.

Since society essentially finances the rehabilitation of dams, it should be ensured that these large investments into life safety are actually worthwhile for society. In this sense it must also be noted that the societal resources that can be allocated to improving life safety through dam rehabilitation works are limited. If the cost of reducing the risk to human life is disproportionate to the actual reduction in risk to life through dam rehabilitation works, these resources may be redirected into other sectors, for example into health care, transportation services and education, which may better the quality of life of society, i.e. the same money may save more lives elsewhere.

Instead of independently evaluating the risk to life imposed by a dam and the investment cost into reducing the risk to life, a joint indicator may be used which unites both aspects. This may be achieved through socio-economic utility theory where utility is a measure of its own, but can equally be transformed into other units, such as life expectancy or income. Societal Willingness To Pay (SWTP) is a utility function which may be used as an effective tool to determine the acceptable level of expenditure that is required by society in exchange for a reduction in risk to human life (Pandey *et al.*, 2006). It is a measure of society's preference to exchange money for life-years, through investments into risk reduction measures.

Investments are not always driven by safety concerns. Often investments are made for economic reasons. In these cases, larger investments can be justified and its magnitude should be dictated by economic optimisation. SWTP dictates that investments should be made into all effective life saving measures, where "effective" implies a life saving measure where more lives per monetary unit is saved than the SWTP threshold. Thus, the available technology or life-saving or risk reduction measures available within a certain industry will significantly affect what is considered to be effective. SWTP can thus be used to define a minimum level of investment into life safety for a given industry or system. Higher levels of investments are allowed and should be made if it is economically desirable.

In this chapter SWTP is suggested as an additional tool to assess if the investment into reducing risk to human life through the rehabilitation of a dam is required by society. The chapter is structured as follows:

- A theoretical background on SWTP as a utility function is provided.
    - The principles on which the SWTP concept is based, are considered.
    - The derivation of SWTP from the Life Quality Index (LQI) is described.
    - The SWTP threshold for different technologies, projects or activities with different available life saving measures and associated costs is described.
- The SWTP concept is applied to South African dam safety to evaluate if an investment into life safety through dam rehabilitation works is required by society.
    - The SWTP-value which will be used for this study is described.
    - Acceptability criteria based on the SWTP concept is developed for a case study of a South African dam.
    - The factors which may influence the stringency of the SWTP criteria are discussed, including the SWTP-value used, the estimated investment cost for rehabilitation works and the estimated improvement in life safety due to rehabilitation works.
- SWTP criteria are developed for additional case studies of South African dams. For each case study the SWTP criteria have different levels of stringency due to different best practice technologies and associated costs available to reduce risk to life. The South African case studies of dams are evaluated in terms of their respective SWTP criteria to determine if investments into life safety are considered efficient by society.
- The SWTP criteria developed for the South African dam case studies are compared to ANCOLD conventional criteria for assessing risk to human life. The fundamental differences between the criteria are discussed.
- A summary of the main findings is provided.

5.2 Background to SWTP

Since society essentially finances dam rehabilitation works, society should in some way benefit from the rehabilitation works through an improvement of life safety. In addition, societal resources are limited and the investments into dam rehabilitation works should be justified. The main question which needs to be answered is: "How much can society afford to invest into improving life safety through the rehabilitation of a dam?".

In order to provide some answer to this question, the Societal Willingness To Pay (SWTP) model is suggested which determines the acceptable level of expenditure that is required by society in exchange for a reduction in risk to human life and without compromising the quality of life of a society (Pandey *et al.*, 2006).

In this section the principles on which SWTP is based are firstly considered and thereafter the basic derivation of SWTP and the use of technology curves are discussed.

5.2.1 Principles on which SWTP is based

In broad terms, risk should be managed to serve public interest. The fundamental principles for managing risk are summarised as four principles by Pandey and Nathwani (2004). The principles form the basic foundation from which the SWTP concept is derived.

1. **The Accountability Principle**: *"Decisions for the public in regard to health and safety must be open, quantified, defensible, consistent and apply across the complete range of hazards to life."*

   When managing risks to life on society's behalf, it should be ensured that the basis on which decisions are made are the same. This principle provides a clear statement of what the public has a right to expect and also provides support for decision makers.

2. **The Principle of Maximum Net Benefit**: *"Risks shall be managed to maximize the total expected net benefit to society."*

   This principle is based on the utilitarian concept of welfare which requires "the greatest good for the greatest number". The efficiency of an investment into an activity to reduce risk to life may be assessed by finding how much reduction in risk to life does the investment ensure, and this may be compared to the reduction in risk to life obtained if the investment is redirected elsewhere.

   In addition the principle requires that all persons in a group should be treated equally. Therefore this principle cannot be applied in the situation where some individuals can be identified to carry a higher burden of risk. In this case the impacts on an individual must be dealt with separately. It must be noted that identifiable individuals may not be knowingly "sacrificed" to the "greater good of the group".

3. **The Kaldor-Hicks Compensation Principle**: *"A policy is to be judged socially beneficial if the gainers receive enough benefits that they can compensate the losers fully and still have some net gain left over."*

   This principle states that if a policy ensures that the losers are fully compensated, they are by definition transformed into non-losers. In this case the policy should be "Pareto optimal", thereby ensuring that an optimum or at least the neutral is achieved for all. These compensating measures may include compensation in the form of money or relocation. The affected individual is given the primary weight in choosing the form of the compensation measure.

4. **The Life Measure Principle**: *"The measure of health and safety benefit is the expectancy of life in good health."*

   When assessing the reduction in risk to human life, the net benefit should be assessed and maximised in terms of length of life in good health. Length of life in good health may be assessed using life expectancy. Therefore if an investment into an activity to reduce risk to human life is assessed, the increase in life expectancy is considered. Life expectancy is a reliable statistical measure used universally.

   It must be noted that the term "lives saved" is a misleading measure and "life expectancy" is preferred. If a specific activity is expected to reduce risk to life, the relevant issue is not life or death, but the reduction in the specific cause of mortality. Death is certain, it is only the timing of mortality which is uncertain. Thereby a more meaningful and scientifically correct measure is "life expectancy" instead of "lives saved" when the reduction of risk to life is assessed due to an investment into an activity.

5.2.2 Derivation of SWTP

An investment to reduce the risk to life imposed by a technical facility may be compared to the Societal Willingness To Pay (SWTP) for a marginal increase in life safety to evaluate whether the investment into life safety is worthwhile to society (Fischer *et al.*, 2011). In effect, the marginal life saving cost (how much is spent to increase life safety by a margin) is compared to the SWTP for a marginal increase in life safety (how much should be spent to increase life safety by a margin).

The Societal Willingness To Pay (SWTP) approach is based on the Life Quality Index (LQI). The LQI is a function of two social indicators; the life expectancy at birth which represents longevity and safety, and the Gross Domestic Product (GDP) per person which represents the quality of life of a society. According to Pandey and Nathwani (2004), both factors may be reliably obtained from statistical data to quantitatively express the health and wealth of a nation.

In this section the basic derivation of the Life Quality Index (LQI) and Societal Willingness To Pay (SWTP) is discussed as obtained from Pandey and Nathwani (2004).

The LQI may be formulated as shown in Eq. 5.2.1.

$$L = G^q E \tag{5.2.1}$$

Where,

G = the Gross Domestic Product (GDP) per person (\$/person/year)

E = the life expectancy at birth (years/person)

q = parameter which reflects the trade-off placed on the consumption and the value attached to the length of life

The parameter q depends on the fraction of time spent producing G, and the remaining time, the leisure time, available for the enjoyment of E. Therefore the parameter q is the ratio of average work time to leisure time. If the parameter w corresponds to the amount of time spent producing income that supports consumption and the remaining time (1-w) corresponds to the the leisure time available to a person, the relationship used to estimate q may be represented as shown in Eq. 5.2.2:

$$q = \frac{w}{(1-w)} \tag{5.2.2}$$

Where,

w = the fraction of time spent producing income that supports consumption

$(1$-$w)$ = the remaining fraction of time corresponding to leisure time

A person can increase his/her leisure time by either reducing the time spent in producing G and thereby sacrificing consumption, or by reducing risk to life in order to increase life expectancy (Pandey and Nathwani, 2004).

In order to have a better understanding on what the LQI concept is based, a brief derivation is firstly provided and thereafter the development of SWTP from the LQI principle is provided.

Derivation of LQI:

According to Pandey and Nathwani (2004), the LQI concept is based on the general idea that a person's enjoyment of life, or utility, in an economic sense is dependant on a continuous stream of resources available for consumption and the time to enjoy. Hence there are two determinants of life quality; income to support consumption and the time to enjoy.

The lifetime utility for a person at a certain age is the total consumption over the remaining life time. According to Pandey and Nathwani (2004) the expected value of a lifetime utility of a person at age a is shown as the product of the utility function for consumption and the utility function for longevity as shown in Eq. 5.2.3:

$$L(a) = u(c)e(a) = c^q e(a) \tag{5.2.3}$$

Where,

$L(a)$ = lifetime utility of a person at age a

$u(c)$ = utility function for consumption

$e(a)$ = utility function for longevity

The utility function for consumption and longevity take certain factors into account as discussed:

Utility function for consumption:

For the utility function for consumption, $u(c)$, a power utility function and constant consumption rate, c, is assumed. This leads to the utility function for consumption becoming c^q. The parameter q is also referred to as the elasticity of utility regarding consumption. The parameter q is taken as a constant regardless the level of consumption, leading to the consumption rate being the same for rich and poor (Pandey and Nathwani, 2004).

The parameter q has been described above as the ratio of average work time to leisure time. In this context, q is taken as the measure of tradeoff between the utility for consumption and utility for longevity. According to Pandey and Nathwani (2004), in a well-developed country with a well-developed economy and standard of living, an increase in life expectancy outweighs consumption consideration, and hence the q parameter is typically very low. In opposition, for a poor country, a large consumption consideration outweighs an increase in longevity and hence the value for q is typically high.

Utility function for longevity:

When the utility function for longevity, *e(a)*, is determined a discount rate, or also commonly referred to as the rate of time preference for consumption, is taken into account. This rate of time preference for consumption compensates for the fact that individuals tend to undervalue the prospect of future consumption in comparison to the current consumption (Pandey and Nathwani, 2004). This rate of time preference for consumption should not be confused with the interest rate for inflation.

To determine the lifetime utility for a person at a certain age the basic formulation shown in Eq. 5.2.3 may be used. Pandey and Nathwani (2004) further describes that the quality of life of a population at a societal level may be determined using the aggregate value of the lifetime utilities for all persons in a society. The life quality of a society is determined by integrating the lifetime utility over the distribution of population age and consumption rate. This takes into account for "the greatest good for the greatest number" principle as described in the principle of maximum net benefit in section 5.2.1.

Integrating Eq. 5.2.3 over the lifetime of a person, the LQI may be derived as shown in Eq. 5.2.4. For simplification, the consumption rate c is assumed to be equivalent to the GDP per person per year, *G*. In addition, the age-distribution of a population, *f(a)*, is taken into account.

$$LQI = \int_0^T L(a) f(a) da = c^q \int_0^T e(a) f(a) da = G^q E \tag{5.2.4}$$

E denotes the discounted life expectancy, averaged over the age-distribution of a population. This ensures that the same value is placed on the preference for gaining life expectancy for a population. Therefore equal weight is assigned to life years regardless of being young or old.

The diagram in Fig. 5.1 shows how the three components of the LQI concept relate to human concerns: creation of wealth, duration of life, and time available to enjoy life in good health.

It must be noted that only a brief introduction to the development of the LQI concept has been provided. The full derivation of the Life Quality Index (LQI) concept is formally described in Pandey and Nathwani (2004). Further derivation and verification of the LQI concept are discussed in peer-reviewed literature, such as in literature by Pandey *et al.* (2006), Ditlevsen and Friis-Hansen (2005), Rackwitz *et al.* (2005) and in the Joint Committee of Structural Safety (JCSS) technical report by Rackwitz (2008). The development of SWTP concept from the LQI principle is discussed next.

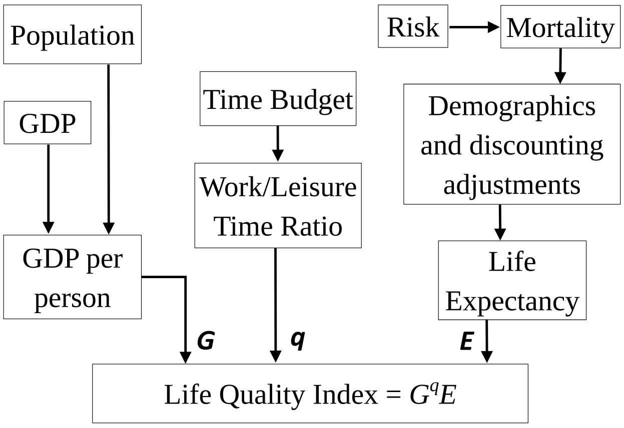

Figure 5.1: Conceptual model of the Life Quality Index (LQI) (Pandey and Nathwani, 2004)

Societal Willingness To Pay (SWTP):

An investment into an activity which leads to a reduction in risk to life will affect the LQI by leading to an improved quality of life. Using Eq. 5.2.1 a small change in the LQI due to the implementation of a project or regulation can be assessed as shown in Eq. 5.2.5 (Nathwani *et al.*, 2008).

$$\frac{dL}{L} = \frac{dG}{G} + K\frac{dE}{E} \tag{5.2.5}$$

Where,

dG = the monetary cost of implementing the project (negative), or the monetary benefits which arise from the existence of the project (positive)

dE = the change in life expectancy due to a change in the risk associated with the project

$K = 1/q$

From the net benefit criterion described in section 5.2.1 it is required for an investment into an activity to reduce risk to life to be maximised. For an investment into life safety influencing both G and E, the change in the LQI should be positive. Hence Eq. 5.2.5 can be rewritten to formally obtain acceptability criteria as shown in Eq. 5.2.6.

$$\frac{dG}{G} + K\frac{dE}{E} \geq 0 \tag{5.2.6}$$

The LQI concept relates to the Societal Willingness To Pay (SWTP) concept where SWTP determines the acceptable level for an investment into reducing risk to life that is required by society (Nathwani *et al.*, 2008). SWTP therefore defines the lower boundary for acceptable decisions and may be obtained as the exact value ($\frac{dL}{L} = 0$) of Eq. 5.2.6. If the terms are re-arranged, the SWTP for a marginal increase in life expectancy may be obtained as shown in Eq. 5.2.7:

$$SWTP = -dG = GK\frac{dE}{E} \quad (\$/person/year) \tag{5.2.7}$$

It must be noted -dG corresponds to an investment and therefore a loss of income, hence the value is negative.

The marginal life saving costs for a project can be compared to SWTP for a marginal increase in life safety and threshold criterion may be derived as shown in Eq. 5.2.8 (Fischer *et al.*, 2011). Society requires that an investment, *-dG*, into a life saving activity should at least be equal to the SWTP for a marginal increase in life expectancy (Fischer *et al.*, 2011), i.e. if the investment does not comply with this criterion, it is not acceptable according to society.

$$-dG \geq SWTP = GK\frac{dE}{E} \simeq GKC_x d\mu \tag{5.2.8}$$

It must be noted that the *dE/E* parameter in Eq. 5.2.8 may not always be easily quantified. Instead it may be calculated as the product of the mortality change (dμ) and a demographic constant (C_x) which may be obtained from life tables presented by Rackwitz (2006). The demographic constant takes age-averaging and discounting into account which have been discussed in the derivation of the LQI concept above.

For age-averaging, two mortality reduction schemes may be considered; the Π-regime and the Δ-regime (Faber and Virguez-Rodriguez, 2011). The Π-regime is the case where the change in mortality is proportional over the age distribution. It implies that persons who are more susceptible to mortality (typically due to weakened physical state), are more subject to the phenomenon (Lentz, 2007). The Δ-regime is the case where the change in mortality is uniformly distributed over all ages. It implies that a phenomenon will affect every member of a society, regardless of each individual's age (Lentz, 2007).

The investment into an activity to reduce risk to human life may be assessed against SWTP using technology curves as discussed next.

Technology curves:

If an investment is made into an activity to reduce risk to life, a technology curve may be obtained as shown in Fig. 5.2. The shape of the curve depends on the effectiveness of life saving measures and the cost therof. As the investment into life safety increases the risk to life is reduced.

For different activities, projects, technologies the curves are defined differently since the cost of reducing the risk to human life are different for each activity/project/technology. For example, if two different industries such as the dam safety and transportation industry are considered, the best practice technologies available in one industry could result in higher risk reductions at lower costs than for the other industry. The same could be observed within one industry, where different solutions are available for reducing risk to life, however, the costs of the risk reducing solutions could differ vastly.

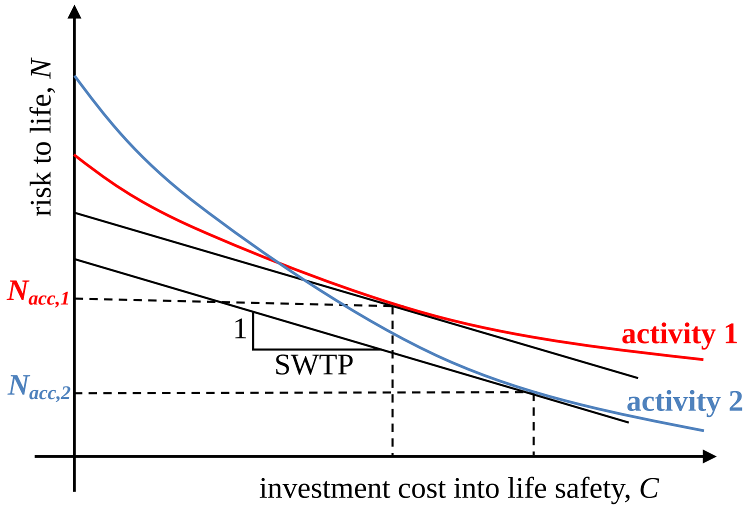

Figure 5.2: Reduction of risk to life with increased investment in life safety - Adapted from Fischer *et al.* (2011)

In Fig. 5.2 sloping lines meet each technology curve at a point of tangency. The gradiënt resembles SWTP for a marginal increase in life safety and the point of tangency defines the lower bound for acceptable investments into reducing risk to life as defined by society.

SWTP dictates that investments should be made into all life saving measures which are considered efficient by society, i.e. where more lives per monetary unit is saved than the SWTP threshold. The region for efficient investments is shown in Fig. 5.3. SWTP thus defines the minimum level of investment into life safety for a given industry or system. However, it must be noted that investments are not always driven by safety concerns and additional investments for economic, environmental or other reasons are allowed.

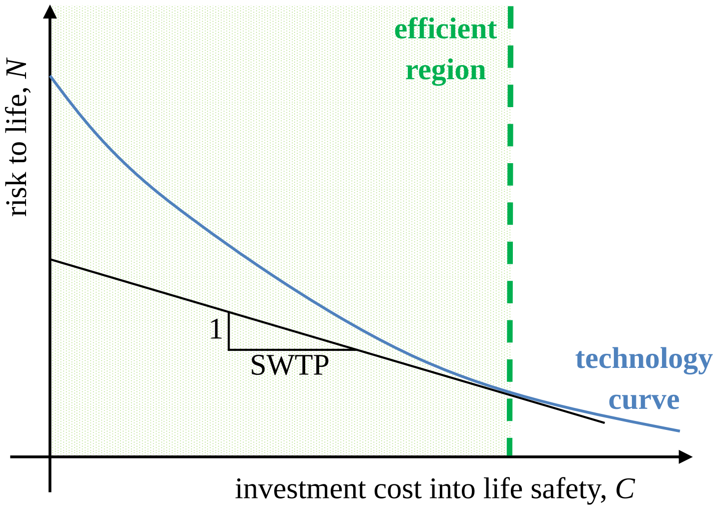

Figure 5.3: Effective region for investments into life safety defined by SWTP - Adapted from Fischer *et al.* (2011)

Since each technology curve in Fig. 5.2 is different due to different available life saving measures and associated costs, the point of tangency defined by SWTP is different for different systems and industries. This leads to a different lower bound for investments into life safety to be considered efficient by society, for each different dam rehabilitation project.

In the following section the SWTP concept is applied to this study and criteria are developed to evaluate if an investment into reducing risk to life through the rehabilitation of a dam is required by society.

5.3 SWTP acceptability criteria for the evaluation of South African dams for rehabilitation works

The aim of this section is to develop an FN-criterion line that would define an absolute lower boundary of acceptable safety, based on SWTP principles, i.e. all life saving strategies that are considered efficient in terms of society's preference to exchange money for life years must be implemented. Additional safety measures may also be implemented, but this would be done based on other considerations, such as economic optimisation.

5.3.1 Application of SWTP concept to South African dam safety

It is expected that an investment into dam rehabilitation works should decrease the probability of dam failure and consequently the expected risk to human life, as the combination of the probability of failure and the estimated loss of life, should be reduced. Technology curves may be developed for a dam in need of rehabilitation works using incremental values for the investment costs and the corresponding reduction in risk to life to plot a locus of points on a similar graph as shown in Fig. 5.2. If incremental values are not available and only the final value for the investment cost and the reduction in risk to life can be obtained for dam rehabilitation works, a "technology line" instead of a "technology curve" can be defined as shown in Fig. 5.4. The slope of the technology line is defined by the marginal cost (ΔC) for a marginal decrease in risk to life (ΔN).

To find whether the investment which has been made into life safety complies with SWTP requirements, the "technology line" developed for dam rehabilitation works may be evaluated against the gradiënt defined by SWTP for a marginal increase in life safety. If the gradiënt of the technology line is steeper than the SWTP gradiënt, the investment is required by society. If not, the investment is not required by society but may still be made based on economic, environmental, or other considerations in addition to safety.

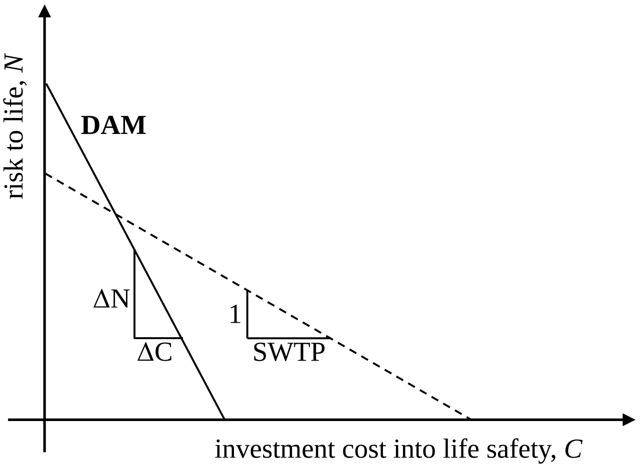

Figure 5.4: Scenario where the slope of the technology line for dam rehabilitation works is steeper than gradiënt defined by SWTP

In Fig. 5.4, the slope of the technology line defined for the dam rehabilitation works is steeper than the gradiënt defined by SWTP. The relationship between the slopes of the two lines are shown in Eq. 5.3.1.

$$\frac{1}{SWTP} \leq \frac{\Delta N}{\Delta C} \tag{5.3.1}$$

The relationship in Eq. 5.3.1 may be re-arranged as shown in Eq. 5.3.2.

$$SWTP \geq \frac{\Delta C}{\Delta N} \tag{5.3.2}$$

In Eq. 5.3.2 the investment cost per marginal life saved (ΔC/ΔN) is less than the SWTP. As defined in section 5.2.2, an investment into life safety should at least be equal to SWTP for a marginal increase in life expectancy (Fischer *et al.*, 2011). Therefore the investment into life safety is efficient and should be made. The lower boundary set by SWTP defines what investments are considered to be efficient and all efficient life saving measures should be implemented.

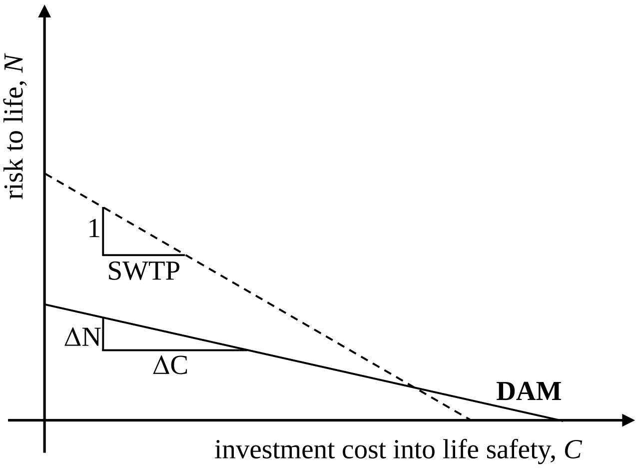

Figure 5.5: Scenario where the slope of the technology line for dam rehabilitation works is less steep than gradiënt defined by SWTP

In Fig. 5.5 the scenario is considered where the slope of the technology line for a dam rehabilitation works is less steep than the gradiënt defined by SWTP. The relationship between the slopes of the lines are shown in Eq. 5.3.3.

$$\frac{1}{SWTP} \geq \frac{\Delta N}{\Delta C} \tag{5.3.3}$$

The relationship in Eq. 5.3.3 is also re-arranged and the equation shown in Eq. 5.3.4 is obtained.

$$SWTP \leq \frac{\Delta C}{\Delta N} \tag{5.3.4}$$

In Eq. 5.3.4 the investment cost per marginal life saved (ΔC/ΔN) is more than SWTP. The investment into life safety is considered to be inefficient and is therefore not required in terms of the lower boundary set by SWTP.

Using the relationship shown in Eq. 5.3.4, the absolute value or the lower boundary for an investment into life safety through the rehabilitation of a dam as defined by SWTP may be found as shown in Eq. 5.3.5.

$$\frac{1}{SWTP} = \frac{\Delta N}{\Delta C} \tag{5.3.5}$$

Re-arranging Eq. 5.3.5, the minimum required reduction in risk to life for an investment into life safety to be considered efficient for a specified SWTP may be obtained as shown in Eq. 5.3.6.

$$\Delta N = \frac{\Delta C}{SWTP} \tag{5.3.6}$$

Where,

ΔN = the reduction in risk to human life due to the rehabilitation works [lives/yr]

ΔC = the cost of the rehabilitation works [R/yr]

$SWTP$ = the Societal Willingness To Pay [R/life]

The units for the parameters in Eq. 5.3.6 are shown. Note that the estimated cost of rehabilitation works (ΔC) is annualised (R/yr). Applying basic economics theory, the Present Worth (PW) of the investment cost, determined at the year of the design for the rehabilitation works, may be converted to an Annual Worth (AW) as shown in Eq. 5.3.7 (Blank and Tarquin, 2008).

$$AW = PW.[\frac{(1+i)^n}{(1+i)^n - 1}] \tag{5.3.7}$$

Where,

AW = the Annual Worth of cost of rehabilitation works [R/yr]

PW = the Present Worth of cost of rehabilitation works [R]

i = the inflation rate [%]

n = the life time of the structure [yrs]

For the rehabilitation investment to be considered efficient, a minimum reduction in risk to human lives (ΔN) are required. Considering the basic principle that expected risk is the product of probability and consequence, the minimum reduction in risk to human life (ΔN) could be expressed as a function of the reduction in the probability of dam failure ΔP_f (which depends on the effectiveness of the rehabilitation strategy) and the estimated number of lives lost (LOL) in case of dam failureas shown in Eq. 5.3.8.

$$\Delta N = \Delta P_f \times LOL \tag{5.3.8}$$

Where,

LOL = Loss of Life [lives]

$\Delta\ N$ = the minimum reduction in risk to human life required for an investment into rehabilitation works [lives/yr]

$\Delta\ P_f$ = the reduction in probability in failure due to the rehabilitation works [1/yr]

This relationship implies that a rehabilitation investment may be considered inefficient because;

a) the rehabilitation strategy available is not effective, leading to a small reduction in the probability of dam failure ΔP_f,

b) the dam was already fairly safe, thus rehabilitation also leads to only a small improvement in ΔP_f, or

c) the number of expected lost lives (LOL) in case of failure is already so low that the risk is considered acceptable.

The lowest number of expected lost lives (LOL) for which an investment into life safety is still considered efficient by society is given by rearranging the relationship in Eq. 5.3.8 to obtain the relationship shown in Eq. 5.3.9.

$$LOL = \frac{\Delta N}{\Delta P_f} \tag{5.3.9}$$

The reduction in the probability of failure due to rehabilitation works (ΔP_f) may be calculated as the difference between the initial probability of failure ($P_{f(initial)}$) before rehabilitation works are conducted and the final probability of failure ($P_{f(final)}$) after the dam has been rehabilitated. This relationship is shown in Eq. 5.3.10.

$$\Delta P_f = P_{f(initial)} - P_{f(final)} \tag{5.3.10}$$

The initial probability of failure ($P_{f(initial)}$) is estimated through the risk analysis methodology developed by DWA to evaluate dams in term of their safety and aid decision making regarding rehabilitation works at South African government owned dams. The final probability of dam failure after it has been rehabilitated ($P_{f(final)}$) is assumed to be equivalent to a well-engineered dam with no known deficiencies. According to Oosthuizen (2002), the interval used by DWA for a well-engineered dam with no known deficiencies is between 1E-5 and 1E-6 per year.

In summary, if the investment into life safety (ΔC) is known, the minimum required reduction in risk to human life (ΔN) which will make the investment efficient in terms of society's preferences may be determined for a SWTP-value using Eq. 5.3.6. If the initial probability of dam failure ($P_{f(initial)}$) is known, the reduction in the probability of failure (ΔP_f) may be determined from Eq. 5.3.10 as the difference between the initial and final probability of failure. With both the minimum reduction in risk to human life (ΔN) and the reduction in the probability of dam failure (ΔP_f) known, the lowest number of lost lives (LOL) for which the investment would still be considered efficient by society may be obtained from Eq. 5.3.9. In effect, to obtain the lower boundary for LOL for which society would still require rehabilitation works, a SWTP-value, the investment cost into dam rehabilitation works and the initial probability of dam failure before rehabilitation are required as input parameters.

In the following, the SWTP-value which will be used in this study is discussed. Thereafter, the minimum LOL for which an investment into rehabilitation works are considered efficient by society are determined for specific case studies of South African government dams.

The risk to human life estimated for the specific dam case study by the DWA risk analysis methodology may be assessed against the lower boundary of LOL for which an investment is required by society. DWA estimates the risk to human life as the combination of the initial probability of failure (P_f) and the predicted LOL in case of dam failure. For the initial probability of failure, if the LOL estimated by DWA is more than the minimum LOL for which an investment into life safety is considered efficient by SWTP criteria, the investment into rehabilitation works is required by society. If the LOL estimated by DWA is less than the minimum LOL required for an investment to be considered efficient, the dam rehabilitation works is not required by society, but may still be considered based on economic, environmental, or other considerations in addition to safety.

From this criterion point, SWTP criteria may be developed for a wider range of initial probabilities of failure. The initial probability of failure is used to define the criterion point, since the proposed investment is evaluated according to the risk that the dam poses before it is rehabilitated.

5.3.2 SWTP-value to be used for the study

In section 5.2.2 the derivation of the SWTP concept based on the Life Quality Index (LQI) is discussed. The basis of the LQI and consequently the SWTP is that societal preferences with respect to investments into life safety can be described by jointly considering nation-specific social indicators for life expectancy at birth, GDP per person and the ratio between work and leisure time. In South Africa, there are some factors which may cause the SWTP-value not to reflect the true preference of our society.

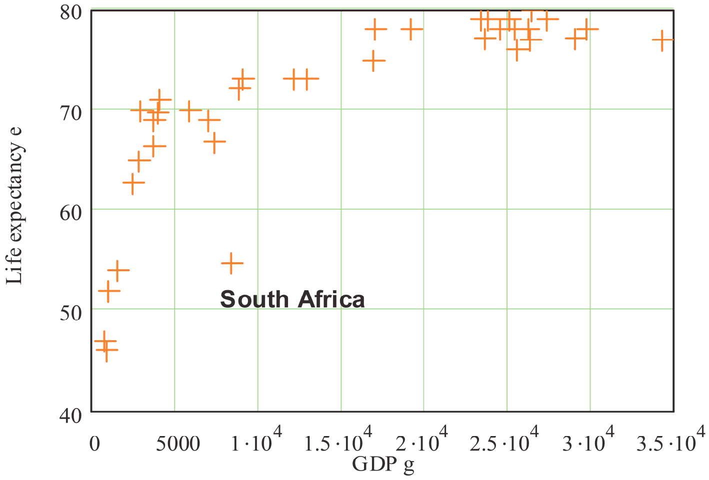

Figure 5.6: Life expectancy vs GDP for different countries (Rackwitz, 2008)

Rackwitz (2008) demonstrates the relationship between the life expectancy at birth and GDP per person for different countries by plotting the nation-specific life expectancy at birth against the GDP per person. Fig. 5.6 demonstrates that the two factors are highly correlated across countries. This trend may also be observed in similar plots presented by Lentz (2007) and Faber and Virguez-Rodriguez (2011). The general trend observed for the data pairs, i.e. the life expectancy at birth and GDP per person, may be used as criteria to assess if the development of an individual nation complies with the underlying principles of LQI (Faber and Virguez-Rodriguez, 2011).

In South Africa the life expectancy at birth for citizens is low. This could be attributed to the HIV epidemic observed in South Africa (StatsSA, 2011). In addition, the GDP per person for South Africa is not purely dependant on the income produced through the work time of South African citizens but is highly dependent on other factors, such as income produced from mining gold (StatsSA, 2012*a*). Rackwitz (2008) plots the relationship between life expectancy at birth and GDP for South Africa. Since the life expectancy is artificially low and the GDP is artificially high in South Africa the data point is an outlier compared to the values obtained for other countries as shown in Fig. 5.6. The development in South Africa therefore does not correspond to the underlying principles of LQI where a joint development in the health and life safety (through life expectancy at birth) and wealth (through GDP per person) is observed.

In addition to the life expectancy at birth and GDP per person, the LQI is also a function of the time necessary for work. The parameter q has been described in section 5.2.2 as the ratio of average work time to leisure time. According to Fischer *et al.* (2011), the parameter can be derived based on two main assumptions, namely that humans optimise their leisure to work ratio, and that the fraction of time spent for work observed in society is already in an optimal state. South Africa has a high percentage of joblessness and correspondingly a low employment rate (StatsSA, 2012*b*). This low employment rate is not the preference of our society, but rather due to our unfortunate political history. The low South African employment rate may lead to the wrong interpretation of the parameter q. It may indicate a low value for work time *(w)*, which in turn leads to a higher value for leisure time *(1-w)*. In effect the value for q will typically be low and this may be wrongly interpreted as South African citizens preferring enjoyment of life *(1-w)* over spending time earning a higher income. This will in turn lead to a SWTP value which indicates an artificially high preference to exchange money for life years.

Since there are so many South African factors that violate the underlying assumptions of the LQI derivation, the SWTP-value for South Africa may be a significant outlier in comparison to SWTP-values obtained for other countries at similar levels of development. The SWTP-value for South Africa may not be a true reflection of society's preference regarding investments into life safety. Therefore, it is proposed to instead use an Earth value for SWTP (ESWTP) as developed by Faber and Virguez-Rodriguez (2011). According to Faber and Virguez-Rodriguez (2011), the ESWTP is based on observations from 71 countries, representing more than 70% of the Earth population. Faber and Virguez-Rodriguez (2011) further states that the ESWTP conforms well with the preferences underlying the LQI principle, i.e. the joint development of health and life safety (life expectancy at birth), economy (GDP per person) and the necessary time to work (described by q as the ratio of work time to leisure time).

Faber and Virguez-Rodriguez (2011) developed different values for ESWTP, based on a discount rate (also referred to as the rate of time preference for consumption) and a mortality reduction scheme. The application of the rate of time preference for consumption and mortality reduction scheme has been discussed in the derivation of SWTP in section 5.2.2. According to Arrow (1995) a rate of time preference for consumption of 3% can be commonly assumed. In addition a uniform mortality reduction scheme (Δ-regime) is assumed which indicates that mortality is distributed uniformly over all ages (Faber and Virguez-Rodriguez, 2011). Taking the discount rate and mortality reduction scheme into account, the ESWTP obtained from Faber and Virguez-Rodriguez (2011), is $US 517,000/life.

In order to apply the ESWTP to South Africa, U.S. Dollars are converted to the South African currency, Rand. The yearly average exchange rates for converting U.S. Dollars to Rand were obtained from the International Revenue Service (2012) from the years 2006 to 2011, since the investment costs for rehabilitation works for case studies of South African dams considered later in this study were estimated within this time frame. The average of the exchange rate values for the 6 years were $US 1 = R 7.83, which leads to an ESWTP of R 4.048 million/life.

5.3.3 Developed SWTP-criteria for South African dam safety

With a defined SWTP-value, the lowest number of lost lives for which an investment into dam rehabilitation works would be considered efficient by society may be determined, as described in section 5.3.1.

For different case studies of dams, the SWTP-criterion will lead to a different lower bound for each dam. The technology curve for a dam defines how effective the rehabilitation work is to reduce risk to lives. These curves are different for different dams leading to different a lower bound defined by SWTP for each dam.

The computations described in section 5.3.1 is applied to a case study of a South African government owned dam that has been identified to be in need of rehabilitation works. The calculation procedure is shown for Klein Maricopoort Dam. This dam was also evaluated using conventional acceptability criteria for risk to human life in Chapter 4.

Firstly the minimum required reduction in risk to human life (ΔN) for an investment into life safety to be considered efficient is calculated using Eq. 5.3.6. In order to determine ΔN, the SWTP-value and the estimated investment cost into rehabilitation works are required. The SWTP-value was defined in section 5.3.2 as R 4.048 million/life. The investment cost of the proposed dam rehabilitation works obtained from the DWA design report for rehabilitation works is estimated as R 39.33 million (van Wyk *et al.*, 2008*b*). In determining ΔN an annualised value for the investment cost is needed. Therefore, the estimated cost for rehabilitation works, determined in the year 2008, should be annualised over the life time of the dam.

The annualised cost (Annual Worth) of implementing the rehabilitation works are calculated from the estimated investment cost (Present Worth value in 2008) using Eq. 5.3.7 illustrated in section 5.3.1. The annualised cost, assuming an average life time of a dam of 50 years (n = 50 years) and an inflation rate of 7% (i = 7%), is shown:

$$AW = PW.[\frac{(1+i)^n}{(1+i)^n-1}] = (R39.33\,mill.).[\frac{(1+7\%)^{50}}{(1+7\%)^{50}-1}] = R2.85\,mill./yr \tag{5.3.11}$$

With the known SWTP-value and annualised investment cost into dam rehabilitation works, the minimum ΔN for an investment into dam rehabilitation works to be required by society is determined from Eq. 5.3.6 as shown:

$$\Delta N = \frac{\Delta C}{SWTP} = \frac{R2.85\,mill./yr}{R4.048\,mill./life} = 0.704\ lives/yr \tag{5.3.12}$$

Next, the lowest number of expected lost lives (LOL) for which an investment is required by society is calculated using Eq. 5.3.9. For this calculation the minimum reduction in risk to human life (ΔN) and the reduction in the probability of failure ($\Delta\ P_f$) due to the dam rehabilitation works are required as input parameters. The minimum ΔN has already been determined for Klein Maricopoort Dam as 0.704 lives/yr. However, the $\Delta\ P_f$ still needs to be determined as the difference between the initial probability of failure ($P_{f(initial)}$), before the dam is rehabilitated, and the final probability of failure ($P_{f(final)}$), after the dam has been rehabilitated.

The initial probability of failure for Klein Maricopoort Dam was determined through the DWA risk analysis methodology and the results of the risk analysis are included in the DWA dam safety inspection report. DWA estimates an interval for the probability of failure (P_f) and the maximum and minimum value of the interval for Klein Maricopoort Dam is estimated as 1E-3 and 1E-4 per year (Kelefetswe, 2005).

The change in probability of dam failure is determined as shown in Table 5.1. $P_{f(final)}$ is assumed to be between 1E-5 and 1E-6 per year as defined in section 5.3.1. The final probability of failure ($P_{f(final)}$) is very small in comparison to the initial probability of failure ($P_{f(initial)}$), leading to the change in probability of failure (ΔP_f) being approximately equal to the $P_{f(initial)}$.

Table 5.1: Calculation of the lower bound of expected lost lives (LOL_{lbound}) for which an investment into rehabilitation works at Klein Maricopoort Dam is required by society

	Max	**Min**
$P_{f(initial)}$	1.00E-03	1.00E-04
$P_{f(final)}$	1.00E-05	1.00E-06
ΔP_f (Eq. 5.3.10)	9.99E-04 ≈ 1.00E-3	9.99E-05 ≈ 1.00E-4
LOL_{lbound}* (Eq. 5.3.9)	712 lives	7112 lives

**Note that the LOL is always rounded up in order to be conservative.*

The lower bound of expected lives lost (LOL_{lbound}) for which an investment into rehabilitation works at Klein Maricopoort Dam would still be considered efficient by society is determined using Eq. 5.3.9 with the calculated ΔP_f and ΔN as input parameters. The results are shown in Table 5.1. Note that since DWA estimates an interval for the probability of failure, a maximum and minimum value for the LOL_{lbound} is determined.

The LOL_{lbound} determined for an initial probability of dam failure, is assessed against the LOL estimated by DWA for the same initial probability of failure through the DWA risk analysis. If the LOL estimated by DWA is more than the LOL_{lbound} developed using SWTP criteria, an investment into rehabilitation works is considered efficient and is required by society. If the LOL estimated by DWA is less than the LOL_{lbound}, an investment into dam rehabilitation works is not efficient and not required by society.

The maximum and minimum value estimated by DWA for the LOL is 3 and 5 as obtained from the DWA dam safety inspection report for Klein Maricopoort Dam (Kelefetswe, 2005). Comparing the LOL estimated by DWA to the LOL_{lbound} shown in Table 5.1, it is seen that both the minimum and maximum value of the LOL estimated by DWA is less than the interval obtained for LOL_{lbound}. Therefore, an investment into dam rehabilitation works at Klein Maricopoort Dam is not required by society.

From this criterion point, i.e. for an initial probability of dam failure and the LOL_{lbound} for which an investment into rehabilitation works is required by society, acceptability criteria may be developed for a wider range of initial probabilities of failure.

Either or both the maximum and minimum initial probability of failures and the corresponding LOL_{lbound} as obtained in Table 5.1 may be plotted as co-ordinate points on an FN-diagram. For both the maximum and minimum initial probability of failures and the corresponding LOL_{lbound}, a criterion line may be obtained through the points on the FN-diagram. This results in a criterion line with a slope of -1, i.e. zero risk aversion, which is generally accepted as good practice as described in Chapter 3. For Klein Maricopoort Dam a line with a slope of -1 is plotted through the two co-ordinate points as shown in Fig 5.7.

The risk to human life estimated by DWA through a risk analysis may be plotted on the FN-diagram. If the risk to human life is located above the SWTP criterion line, the investment into rehabilitation works to improve life safety is required by society. If the risk to human life estimated by DWA is located below the line, the investment into rehabilitation works is not required by society.

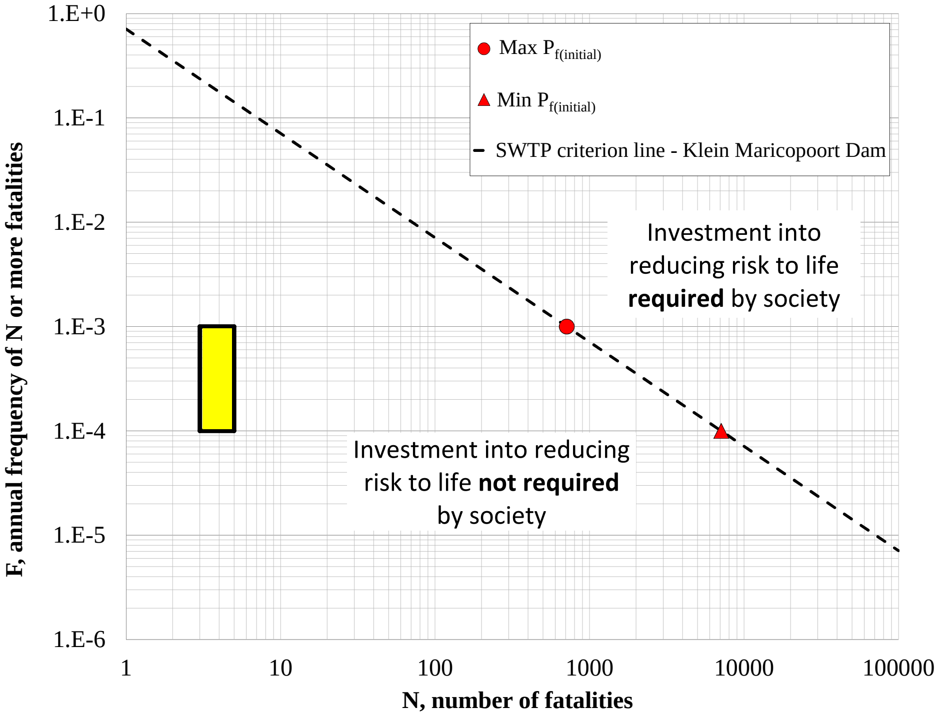

Figure 5.7: SWTP criterion line for Case Study 2 (Klein Maricopoort Dam)

For Klein Maricopoort dam, the maximum and minimum value for both the initial probability of failure and the LOL are plotted on the FN-diagram as shown in Fig. 5.7. Due to the interval, the risk to life is presented in the form of block, representing the level of confidence of the data. The expected risk for Klein Maricopoort Dam is located below the SWTP criterion line, implying that an investment into rehabilitation works to improve life safety is not required by society.

In the following, factors which may influence the position of the SWTP criterion line are investigated.

5.3.4 Factors influencing the position of the SWTP criterion line

In section 5.3.3 a SWTP criterion line presented on an FN-diagram is developed for Klein Maricopoort Dam. This criterion line is based on the lowest number of lives lost LOL_{lbound} for which an investment into life safety is required by society. To determine the LOL_{lbound}, a SWTP-value, the investment cost into dam rehabilitation works (ΔC) and the initial probability of dam failure ($P_{f(initial)}$) are required as input parameters. Therefore, if these three factors are varied, the position of the SWTP criterion line on the FN-diagram may be influenced. The influence of varying each of the three factors is investigated.

The cost of rehabilitation works (ΔC)

If the cost of the rehabilitation works are increased and decreased by a factor of 2 and 4, the position of the SWTP criterion line will change as shown in Fig. 5.8. Decreasing the investment cost leads to a smaller minimum reduction in risk to life (ΔN) for an investment to be considered efficient by society. This also leads to a decreased value for the lowest number of lives lost LOL_{lbound} for which an investment into life safety is required by society. Consequently the SWTP criterion line becomes more stringent. If the implementation cost for rehabilitation works is increased, the balance between the investment cost and reduction in risk to human life becomes disproportionate to each other. Consequently the SWTP criterion line becomes less stringent.

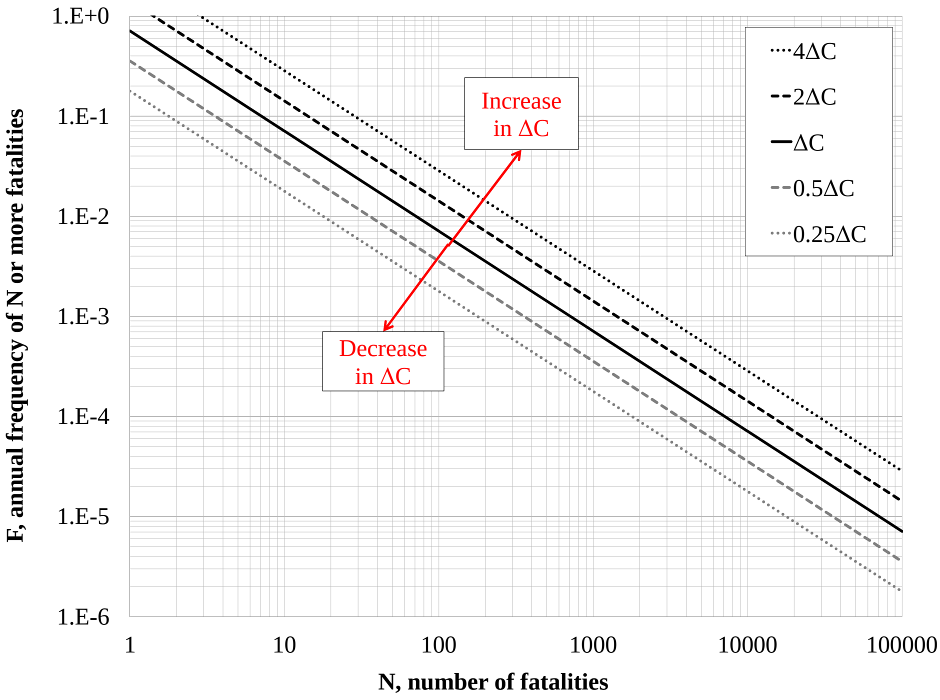

Figure 5.8: Effect of increasing and decreasing the cost of rehabilitation works on the position of the SWTP criterion line

SWTP-value

If the SWTP-value is increased and decreased by a factor of 2 and 4, the position of the SWTP criterion line will change as shown in Fig 5.9. For an increased SWTP-value the criterion line becomes more stringent and for a decreased SWTP-value the criterion line becomes less stringent. It is expected that the acceptability criteria become more stringent if the SWTP-value is increased, since society is more willing to pay for a reduction in risk to life.

It must be noted when the SWTP-value is increased by a factor of 2 and 4, the SWTP criterion line are within one span (factor of 10) of each other. Thus, the criterion is not unduly sensitive to the assumed SWTP-value. The criterion line is equally sensitive to changes in the SWTP-value or changes in the estimated investment cost. As long as these values are accurate in terms of their order of magnitude, the SWTP criterion seems to be sufficiently well defined to be of practical use.

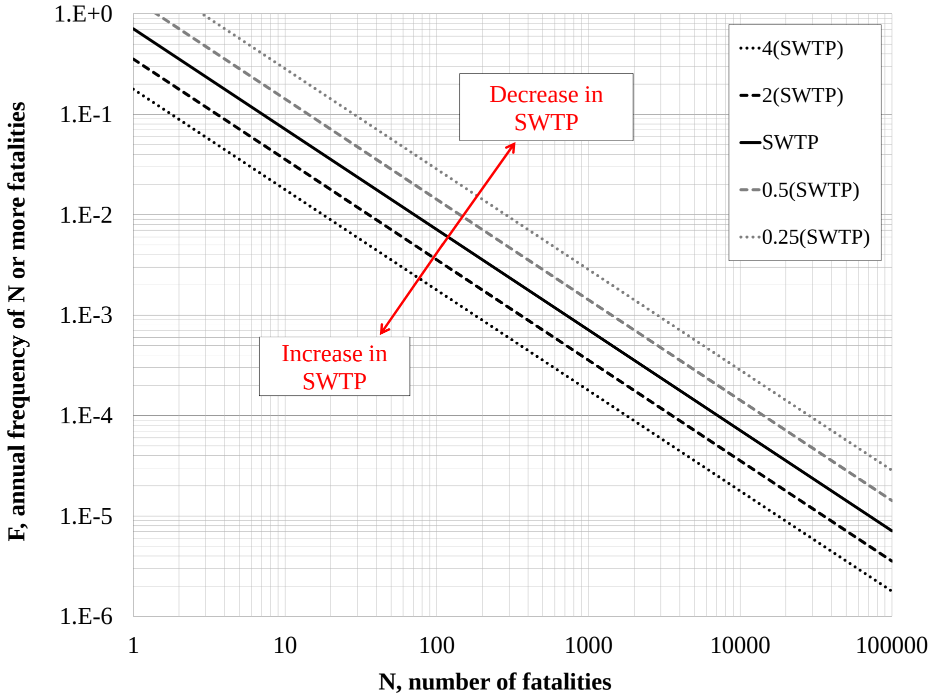

Figure 5.9: Effect of increasing and decreasing the SWTP-value on the position of the SWTP criterion line

Initial probability of failure ($P_{f(initial)}$)

The influence of the initial probability of failure ($P_{f(initial)}$) on the SWTP criterion line is investigated by increasing and decreasing the $P_{f(initial)}$ by a factor of 10^1 and 10^2.

The lowest number of expected lost lives (LOL_{lbound}) for which an investment is required by society is determined using the different values of the initial probability of failure ($P_{f(initial)}$). The results for the LOL_{lbound} for Klein Maricopoort Dam are shown in Table 5.2. If a criterion line is obtained for each of the corresponding points on a FN-diagram, it is seen that an increase or decrease in the $P_{f(initial)}$ does not influence the position of the criterion line but defines different points on the same SWTP criterion line as shown in Fig. 5.10.

Table 5.2: Lower bound LOL for which an investment is required by society obtained for an increased and decreased $P_{f(initial)}$

$P_{f(initial)}$	LOL_{lbound}
1.E-01	8
1.E-02	71
1.E-03	**712**
1.E-04	7823
1.E-05	78222

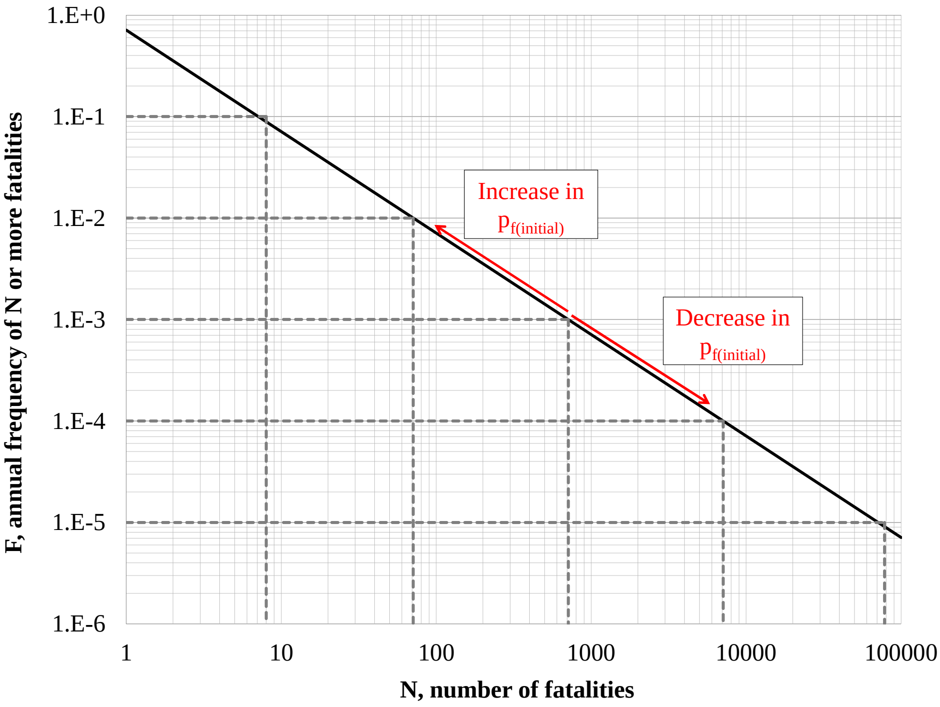

Figure 5.10: Effect of increasing and decreasing the initial probability of failure on the position of the SWTP criterion line

In summary, the value of the investment cost into rehabilitation works and the value of SWTP affects the position of the criterion line. If the investment cost is increased, the SWTP criterion line becomes less stringent. If the SWTP-values is increased, the SWTP criterion line becomes more stringent. The initial probability of failure does not have an effect on the position of the criterion lines, but only defines different points on the SWTP criterion line.

For different case studies of dams the rehabilitation strategy of reducing risk to life is different, thus the investment cost of reducing risk to life is dam specific. This leads to SWTP defining a different lower bound for an investment to be considered efficient by society at each dam. The SWTP-criterion lines will therefore have different levels of stringency, depending on the rehabilitation strategy for the specific dam.

In the following section, SWTP criterion lines are developed for more case studies of South African government owned dams and the risk to human life for each dam is assessed against the dam specific criterion line.

5.4 Evaluation of South African case studies of dams in terms of proposed SWTP-criteria

5.4.1 Development of SWTP-criteria for different case studies of South African dams

In this section SWTP criterion lines, similarly to the SWTP criterion line that was developed for Klein Maricopoort Dam in section 5.3.3, are developed for different case studies of South African government owned dams. The risk to human life estimated through the DWA risk analysis methodology for the case studies is assessed against this criteria to determine if an investment into life safety through rehabilitation works is required by society.

For this study, the same eleven case studies of South African dams that were identified to be in need of rehabilitation works by DWA and were evaluated according to conventional acceptability criteria for risk to human life in Chapter 4 are used. To develop the criterion lines based on SWTP, the initial probability of failure and the investment cost of implementing rehabilitation works are needed.

For each of the case studies the initial probability of failure before rehabilitation works are implemented are obtained from the risk analysis performed by DWA as part of their inspection reports. The initial probability of failure for the eleven case studies of dams are shown in Table 5.3 and corresponds to the values used in Chapter 4.

In addition, the estimated cost of the rehabilitation works for each of the case studies is obtained from the design report for the rehabilitation works. The estimated investment cost for rehabilitation works for the eleven case studies are shown in Table 5.4.

The estimated cost (PW) of implementing rehabilitation works for the eleven case studies as obtained from DWA design reports are annualised as shown in Table 5.5. The annualised cost (AW) of implementing the rehabilitation works are calculated using Eq. 5.3.11, assuming an average life time of a dam of 50 years (n = 50 years) and an inflation rate of 7% (i = 7%).

Table 5.3: Estimated initial probability of failure for 11 case studies obtained from DWA inspection reports

Case study nr.	**Dam**	**Estimated $P_{f(initial)}$**	
		Min	Max
1a	Bospoort Dam (Gates Functioning)	1.00E-03	1.00E-02
1b	Bospoort Dam (Gates Not Functioning)	1.00E-02	1.00E-01
2	Klein Maricopoort Dam	1.00E-04	1.00E-03
3	Toleni Dam	5.00E-04	5.00E-03
4	Lakeside Dam	2.00E-04	2.00E-03
5	Vaalkop Dam	2.00E-05	2.00E-04
6	Rust De Winter Dam	5.00E-05	5.00E-04
7	Makotswane Dam	3.00E-04	3.00E-03
8	Kromellenboog Dam	2.00E-04	2.00E-03
9	Albert Falls Dam	1.00E-04	1.00E-03
10	Glen Brock Dam	1.00E-03	1.00E-02
11	Wentzel Dam	1.11E-03	1.11E-02

Table 5.4: Estimated investment cost for rehabilitation works are DWA dam case studies, obtained from dam safety rehabilitation design reports

Case study nr.	**Dam**	**Estimated investment cost (R)**	**Reference**
1a	Bospoort Dam (Gates Functioning)	R 84 342 339.28	Cameron-Ellis (2007)
1b	Bospoort Dam (Gates Not Functioning)	R 84 342 339.28	Cameron-Ellis (2007)
2	Klein Maricopoort Dam	R 39 330 000.00	(van Wyk *et al.*, 2008*b*)
3	Toleni Dam	R 23 662 252.68	Pienaar and Badenhorst (2007)
4	Lakeside Dam	R 25 194 000.00	Badenhorst and Rix (2008)
5	Vaalkop Dam	R 24 225 000.00	Rix *et al.* (2006)
6	Rust De Winter Dam	R 21 318 000.00	van Wyk *et al.* (2008*a*)
7	Makotswane (Buffelsdoorn) Dam	R 16 956 360.00	van Wyk *et al.* (2006)
8	Kromellenboog Dam	R 19 157 426.40	Badenhorst and Trümpelmann (2008)
9	Albert Falls Dam	R 16 530 000.00	Badenhorst and van Wyk (2008)
10	Glen Brock Dam	R 17 600 000.00	Chaloner (2009)
11	Wentzel Dam	R 14 250 000.00	van Wyk and Badenhorst (2007)

Table 5.5: Estimated cost of rehabilitation works for 11 case studies obtained from DWA design reports

Case study nr.	Dam	Year of cost estimate	Estimated cost - PW (incl. VAT)	Annualised cost - AW (i = 7%, n = 50)
1a	Bospoort Dam (Gates Functioning)	2007	R 84 342 339.28	R 6 111 433.21/yr
1b	Bospoort Dam (Gates Not Functioning)	2007	R 84 342 339.28	R 6 111 433.21/yr
2	Klein Maricopoort Dam	2008	R 39 330 000.00	R 2 849 845.88/yr
3	Toleni Dam	2007	R 23 662 252.68	R 1 714 563.27/yr
4	Lakeside Dam	2008	R 25 194 000.00	R 1 825 553.45/yr
5	Vaalkop Dam	2006	R 24 225 000.00	R 1 755 339.86/yr
6	Rust De Winter Dam	2008	R 21 318 000.00	R 1 544 699.07/yr
7	Makotswane Dam	2006	R 16 956 360.00	R 1 228 655.29/yr
8	Kromellenboog Dam	2008	R 19 157 426.40	R 1 388 144.23/yr
9	Albert Falls Dam	2008	R 16 530 000.00	R 1 197 761.31/yr
10	Glen Brock Dam	2009	R 17 600 000.00	R 1 275 293.35/yr
11	Wentzel Dam	2007	R 14 250 000.00	R 1 032 552.86/yr

Using the SWTP-value, the initial probability of failure before rehabilitation works are conducted and the estimated investment cost into rehabilitation works, the lowest number of expected lives lost (LOL_{lbound}) for which an investment into dam rehabilitation works are required by society may be obtained for each of the eleven case studies. From the LOL_{lbound}, SWTP criterion lines are obtained for each of the case studies as illustrated on an FN-diagram in Fig. 5.11.

From Fig. 5.11 it is seen that a bandwidth of SWTP criterion lines were developed for the eleven case studies. Differences in the criteria are attributed to differences in the estimated investment cost for rehabilitation works. As discussed in section 5.3.4, a decreased investment cost leads to more stringent SWTP criteria. For Case Study 1a and 1b of Bospoort Dam, the criterion line is the least stringent, and comparing the estimated investment cost for rehabilitation works at Bospoort Dam to the other case studies it is seen that the investment cost for Bospoort Dam is the highest. The SWTP criterion line obtained for Case Study 11 is the most stringent, with the estimated cost of implementing rehabilitation measures the lowest.

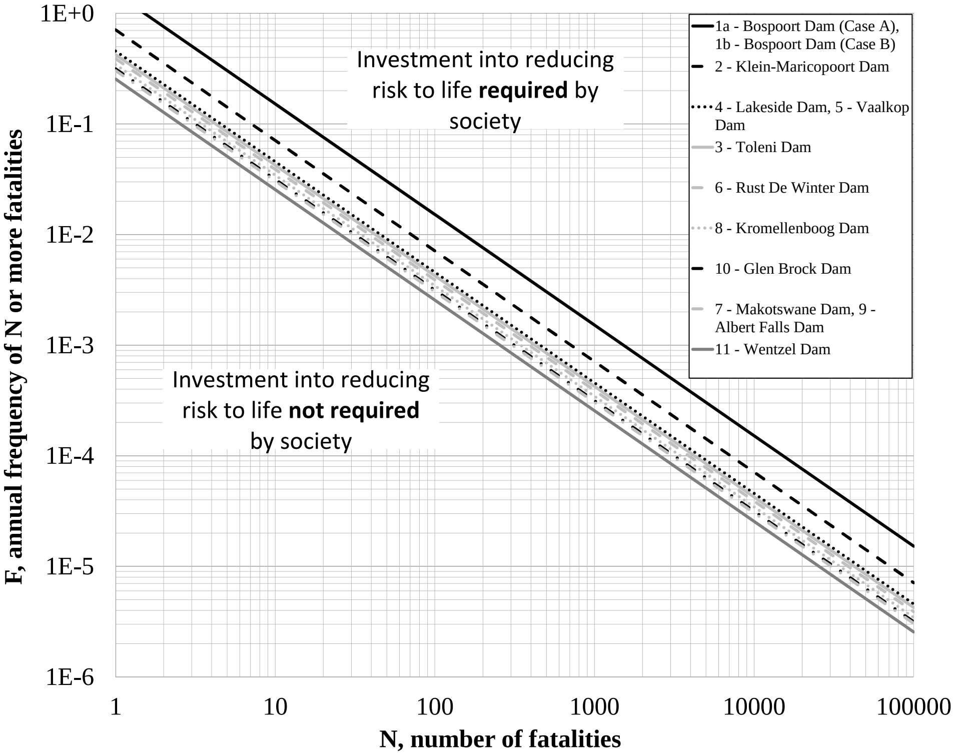

Figure 5.11: SWTP criterion lines developed for the DWA Case Studies

5.4.2 Evaluation of risk to life in terms of proposed SWTP-criteria for South African case studies

For each of the eleven case studies the actual risk to human life, as the combination of the initial probability of failure ($P_{f(initial)}$) and the estimated loss of life (LOL) in case of dam failure, were obtained from DWA dam safety inspection reports and are shown in Table 4.7 of Chapter 4. The risk to life for the case studies is plotted on the FN-diagram and are evaluated in terms of the SWTP criterion lines as shown in Fig. 5.12.

In Fig. 5.12 the risk to human life for the eleven DWA case studies are mostly located below the criterion lines developed using SWTP. Therefore, investments into life safety through dam rehabilitation works were in most cases not required by society. Case Study 4 is located partially above its SWTP criterion line and case study 11 is locate almost entirely above its SWTP criterion line, which implies that in these cases, society does require the rehabilitation works from a life safety perspective.

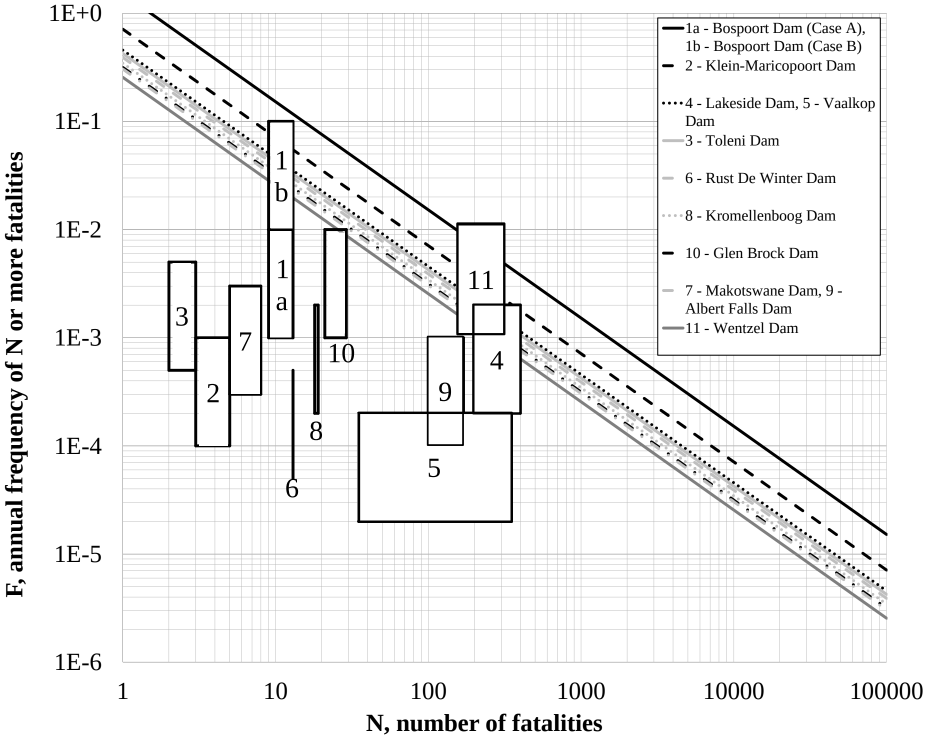

Figure 5.12: Evaluation of risk to human life for DWA case studies in terms of developed SWTP criterion lines

5.5 Comparing the SWTP criterion lines to ANCOLD conventional acceptability criteria for risk to human life

In Chapter 4 the risk to human life for the eleven case studies of DWA owned dams were evaluated in terms of proposed ANCOLD conventional acceptability criteria for existing dams. The risk to life were in most cases within the unacceptable region of the criteria and it was therefore concluded that the rehabilitation of these dams are justified. The same risk to life for the case studies were in most cases within the acceptable region of the SWTP criterion lines developed in this study, where investments into life safety is not considered efficient by society. In Fig. 5.13 both the bandwidth of SWTP criterion lines and ANCOLD conventional criteria for risk to life are shown. The ANCOLD criteria are much more stringent than the SWTP criterion lines. However, it must be noted that the SWTP and ANCOLD criteria are two completely different sets of criteria and are therefore not directly comparable.

The SWTP criteria only accounts for society's preference to exchange money for life years. It does not account for:

- economic motivations, such as the fact that the dam might be vital for farming or industrial activities,

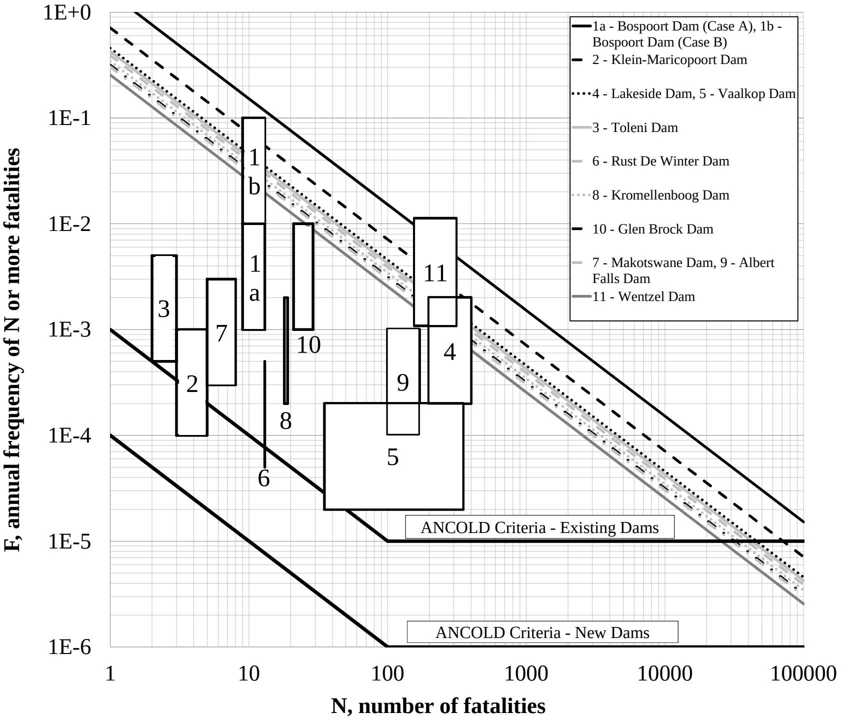

Figure 5.13: Comparison between ANCOLD conventional acceptability criteria for risk to human life and SWTP criterion lines developed for DWA case studies

- damages in case of failure,
- environmental implications of failure, and so forth.

These factors may all be good reasons to further increase dam safety above and beyond the lower boundary defined by SWTP. DWA takes these additional factors into account by evaluating the acceptability of economic, environmental, social and socio-economic impacts and the risk level of dams in case of failure on five additional graphs (see Fig. 2.6 of Chapter 2).

ANCOLD criteria are based on what is considered to be good engineering practice, based on historically acceptable levels of safety, taking all of the above mentioned factors into account, albeit on the basis of engineering judgement.

The ANCOLD criteria implicitly accounts for factors external to life safety. The SWTP criteria only accounts for societal preferences for life safety, but further investments are allowed if it is desirable due to economical, environmental or other reasons.

5.6 Summary of main findings

Since society essentially finances dam rehabilitation works through public taxes and charges they should in some way benefit from the rehabilitation works through an improvement of life safety. In this sense it must be noted that societal resources are limited and large investments into dam rehabilitation works should be worthwhile for society, i.e. if the costs of reducing risk to life is disproportionate to the actual reduction in risk to life, the same resources may need to be redirected into other sectors where the same money may save more lives elsewhere.

Instead of independently evaluating risk to life and the investment cost into reducing risk to life, Societal Willingness To Pay (SWTP) may be used as an effective tool to determine society's preference to exchange money for life-years, through investments into risk reduction measures. The SWTP concept is based on the Life Quality Index (LQI) which is a measure of the life quality of a society. An investment into life safety should lead to an improved life quality. The SWTP may be derived from the LQI to define the absolute lower boundary for acceptable investments into life safety required by society. An investment should be made to at least comply with the minimum requirement set by SWTP, however, investments are not always driven by safety concerns and higher levels of investments are allowed if it is economically desirable.

To apply the SWTP concept to South African dam safety an applicable SWTP-value had to be defined. The SWTP-value is derived from the LQI using nation-specific social indicators, such as the life expectancy at birth, GDP per person and the ratio of work to leisure time. In South Africa it was found that the social indicators are influenced by several factors that violates the underlying assumptions of the LQI derivation. This may cause the South African SWTP-value to not reflect the true preference of our society, also leading to a SWTP-value which is a significant outlier compared to SWTP-values obtained for other countries at similar levels of development. Consequently an Earth value for SWTP (ESWTP) that was developed by Faber and Virguez-Rodriguez (2011) was used in this study.

Based on the principles of SWTP and the proposed ESWTP, FN-criterion lines were developed for specific case studies of South African dams to define an absolute lower boundary of acceptable safety, i.e. all life saving strategies which are considered efficient in terms of society's preference to exchange money for life years must be implemented. Since the available best practice technologies for rehabilitation works are different for each dam, a different lower bound for acceptable investments into life safety required by society were defined for each dam. This lead to different FN-criterion lines obtained at various levels of stringency for the case studies of South African dams.

The risk to human life estimated by DWA through risk analysis methods were evaluated in terms of the SWTP criterion lines. For most of the DWA case studies further investments into reducing risk to life through rehabilitation works were not required by society. Rehabilitation were only required in two of the eleven cases. However, the SWTP criteria only accounts for society's preferences for life safety and does not account for additional considerations such as economic motivations, damages in case of dam failure, environmental implications and other factors. These may all be good reasons for further investments into dam safety beyond the lower boundary defined by SWTP.

Since SWTP does not account for other factors which may be require further investments into dam safety, it should not be used as the only criteria to evaluate dams for rehabilitation works. These additional factors may be addressed by considering the impact graphs developed by DWA for evaluating dams in terms of economic, environmental, socio-economic and other implications in case of dam failure (Fig. 2.6 of Chapter 2).

In Chapter 4, the conventional acceptability criteria defined by ANCOLD implicitly takes economic, environmental and other impacts in addition to life safety into account when evaluating the dams for rehabilitation works. It is therefore concluded that either the ANCOLD criteria or the SWTP criteria, with the additional consideration of economic, environmental and other factors, may be used to evaluate dams for rehabilitation works.

The additional investments which are not driven by societal preferences for life safety may be dictated by the decision maker or owner's (public or private) preferences requiring economic optimisation. The economic optimum implies higher safety levels than the lower bound for investments into life safety defined by SWTP requirements. However, should the economic optimum be at a lower safety level than that dictated by SWTP, the SWTP minimum safety level must be enforced.

In the following chapter additional criteria based on economic optimisation is developed to evaluate dams for rehabilitation works.

Chapter 6

Economic optimisation as a decision tool for the evaluation of South African dam rehabilitation works

6.1 Introduction

In Chapter 5, Societal Willingness To Pay (SWTP) for a marginal increase in life safety is used to evaluate if an investment into dam rehabilitation works is required by society. However, the criteria established by SWTP only take societal preferences for life safety into account and further investments could be required by the decision maker or the owner (public or private) to ensure that an economic optimal solution for the rehabilitation works is obtained.

In this chapter, additional criteria are proposed to evaluate to what level investments should be made into rehabilitation works to obtain an economic optimal solution.

The economic optimum is obtained by evaluating the profitability of a project and ensuring the monetary net benefit is maximised. It must be noted that this criterion is primarily of interest to the decision maker or owner (public or private) and is of little interest to society. In addition, in determining the economic optimum the acceptability of risk to human life is not explicitly evaluated, but the compensation costs for loss of human life due to dam failure are taken into account.

The chapter is structured as follows:

- The basic principles of economic optimisation is described.
  - The concept of satisfying the preferences of the decision maker or owner (public or private) by ensuring that a maximum monetary net benefit is obtained through an investment into a project is discussed.
  - The objective function for determining the economic optimum for a project is described.
  - The need to ensure that a monetary optimal investment into a project also satisfy the lower boundary for an investment established by SWTP is discussed.
- The principles of economic optimisation are applied to South African dam safety.
  - Criteria based on economic optimisation are developed to evaluate investments into dam rehabilitation works.
  - Case studies of South African government owned dams that have been identified by DWA to be in need of rehabilitation works are evaluated in terms of the proposed criteria to evaluate if the investment is economically beneficial.
  - The results are compared to the results obtained when evaluating the case studies in terms of conventional acceptability criteria for risk to human life (Chapter 4) and according to criteria established by SWTP for a marginal increase in life safety (Chapter 5).
- The ratio of the cost of rehabilitation works to the reduction in the probability of dam failure is used to propose alternative life safety criteria with some measure of economic efficiency taken into account.
- A summary of the main findings is provided.

6.2 Background to economic optimisation

In this section the decision maker or owner's requirements for an economically optimal investment into a project is described. Thereafter, the objective function for determining if an investment into a project is economically beneficial is presented. Lastly, the boundary condition for investments are established through the minimum safety level defined by SWTP.

Satisfying the preferences of the decision maker or owner through economic optimisation:
In Chapter 5, SWTP for a marginal increase in life safety is used to determine the acceptable level of expenditure that is required by society in exchange for a reduction in risk to human life and without compromising the quality of life of a society. Therefore, the criteria established by SWTP only takes societal preferences for life safety into account.

However, the acceptable level of expenditure into a project may also be defined by the decision maker or owner (public or private) of the technical facility. The decision maker or owner may require further investments to account for other factors, in addition to what is required by society for life safety. These additional considerations could include:

- economic activities for which the dam is vital,
- repair and replacement costs in case of dam failure,
- compensation costs for lost lives on case of failure,
- environmental implications or rehabilitation needed in case of failure, and so forth.

To ensure that an economically optimal solution is obtained, the profitability of a project is evaluated and the monetary net benefit is maximised (Rackwitz, 2002).

Objective function for economic optimisation:
For typical engineering facilities, the monetary net benefit could be calculated using the objective function shown in Eq. 6.2.1. All the quantities in Eq. 6.2.1 are measured in monetary units. In addition, expected values, as the product of probability of occurrence and consequence, should be taken for the parameters of the objective function (Rackwitz, 2002).

$$Z(p) = B(p) - C(p) - D(p) \tag{6.2.1}$$

Where,

$B(p)$ = the benefit derived from the existence of the facility

$C(p)$ = the cost of design and construction

$D(p)$ = the expected cost of failure

p = the vector of all safety relevant factors

In the objective function, the investment costs (C) and the expected cost of failure (D) are subtracted from benefit (B) to determine the profit (Z) (Lentz, 2007). The parameter p is the safety parameter and if it is increased, the investment costs $C(p)$ will be increased, but the expected damage costs $D(p)$ will be reduced since a safer facility will reduce the probability of failure. An increase in the safety parameter, p, will also have an effect on the benefit, $B(p)$, since a safer facility reduces the likelihood of down-times where no benefit or revenues may be generated.

According to Lentz (2007) the expected costs of failure D may consist of two factors; loss of investment goods or external damage. The loss of investment goods may include the complete loss of the facility, requiring a total reconstruction. External damages may include the loss of off-site property and compensation costs for the loss of human life. Therefore, unlike the previous two decision tools developed in this study, i.e. conventional life safety criteria and SWTP criteria, the objective function does not evaluate the risk to human life, but the economic losses are considered. However, the economic losses include compensation costs for the loss of human life in case of failure.

SWTP as a lower boundary for economic optimal investments:

Economic optimisation usually implies higher safety levels than what is required by SWTP for life safety. However, if the economic optimum is at a lower safety level than what is required by SWTP, the SWTP minimum safety level should be enforced.

In Fig. 6.1 the risk to life as a function of investment cost is shown as a technology curve. As the investment into life safety increases, the risk to life decreases. Fig. 6.1 was obtained and adapted from Fischer *et al.* (2011) and corresponds to the technology curve defined in Fig. 5.2 in Chapter 5.

The SWTP for a marginal increase in life safety is depicted as a gradiënt in Fig. 6.1. The point of tangency where the SWTP equals the gradiënt of the technology curve, defines the lower boundary for investments into life safety as required by society. Thus, society requires that investments should be made to decrease the risk to human life at least to this point, i.e. where more lives per monetary unit is saved than the SWTP threshold.

Furthermore, according to Lentz (2007), if the monetary net benefit generated from the existence of the technical facility is considered, feasible decisions for investments are decisions which lead to a positive monetary net benefit as shown in Fig. 6.1. If no or a negative monetary benefit is generated from the decision, it is not justified. The maximum point in the feasible domain is the point where the monetary net benefit generated from the existence of the structure will be an economic optimum.

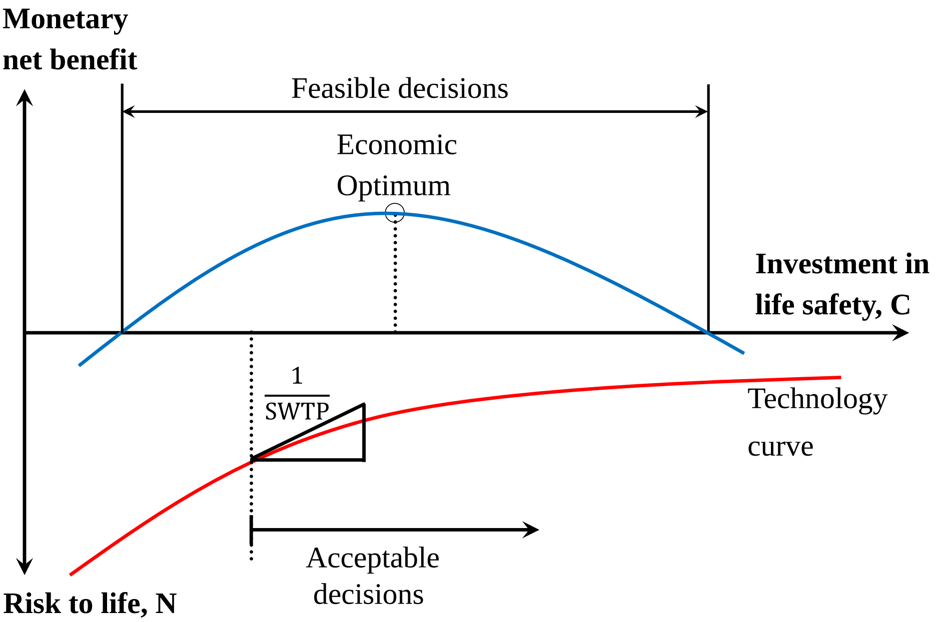

Figure 6.1: Technology and monetary net benefit curve - Adapted from Fischer *et al.* (2011)

If the economic optimum is not within the acceptable region defined by SWTP, it is not acceptable to make investments only to achieve an economically optimal structure. The investment should be increased to satisfy SWTP requirements. Fig. 6.2 illustrates the case where the economic optimum is not within the acceptable region established by society. According to Rackwitz and Streicher (2002) it is unlikely for structures to be economically optimal but not acceptable in terms of SWTP and hence the condition in Fig. 6.2 is rarely encountered.

In summary, the acceptability of an investment into reducing risk to life is based on requirements set by society through SWTP. SWTP criteria enters the decision problem as a lower boundary condition and determines the minimum level for investments which should be made into a technical facility. Further investments are typically required by public or private decision makers to ensure a maximised monetary net benefit.

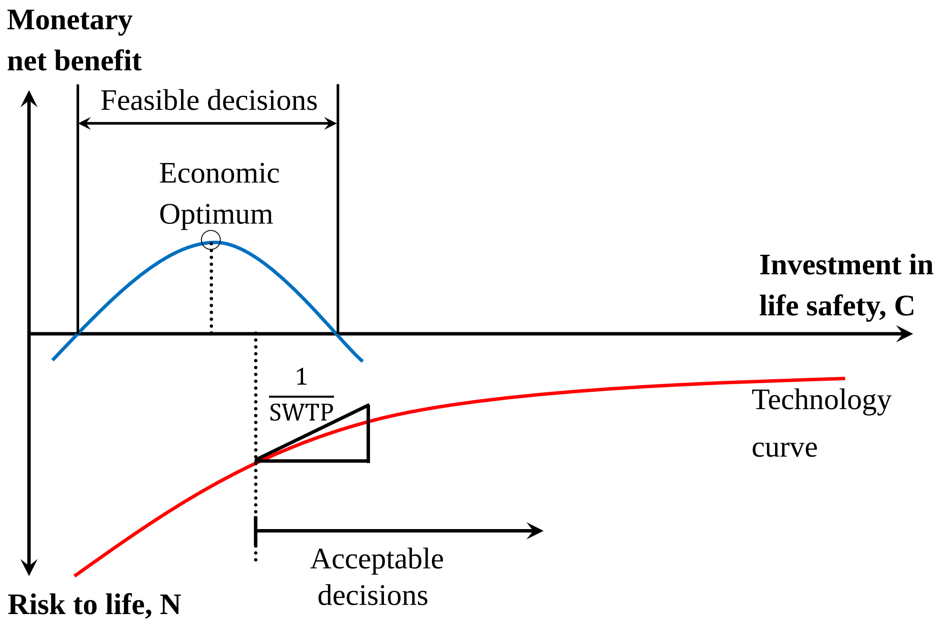

Figure 6.2: Case where the economic optimum does not comply with SWTP lower boundary for acceptable decisions - Adapted from Fischer *et al.* (2011)

In the following section the theoretical background of economic optimisation is applied to South African dam safety to evaluate dams for rehabilitation works.

6.3 Application of economic optimisation to South African dam safety

In this section criteria are developed to evaluate if investments into dam rehabilitation works are economically beneficial. Case studies of South African government owned dams are evaluated in terms of the proposed criteria. The results are compared to the results obtained when the same case studies are evaluated according to conventional acceptability criteria for risk to human life (Chapter 4) and to criteria established by SWTP (Chapter 5).

6.3.1 Development of criteria based on economic optimisation for the evaluation of South African dam rehabilitation works

To evaluate if an investment into dam rehabilitation works yields an economic optimal solution, the objective function shown in Eq. 6.2.1 of section 6.2 are maximised for different decision alternatives. The alternative with the highest monetary net benefit should be preferred.

For this study the decision problem considered consists of two decision alternatives, namely whether a dam should be rehabilitated or not. The decision problem therefore does not vary with the safety parameter p shown in Eq. 6.2.1, but consists of two discrete possibilities; rehabilitate or do-nothing. For each decision alternative the net benefit (Z) is calculated:

$$Z = B - C \tag{6.3.1}$$

Where,

B = the benefit of rehabilitation works

= reduction in D, the expected cost of failure

C = the cost of rehabilitation works

The benefit (B) does not take the monetary benefit generated from the existence of the facility into account but considers only the additional benefit derived from rehabilitating the dam, i.e. if a dam is rehabilitated a decreased probability of failure is expected and the product of the reduced probability and the cost of dam failure will result in a reduced expected cost of failure D.

For the do-nothing alternative, both B and C will be zero. For the rehabilitate alternative, the cost of rehabilitation works (C) need to be less than the benefit (B) obtained through a reduced probability of failure, for the alternative to be preferred.

The two alternatives are compared to each other in terms of expected cost of failure and the implementation costs associated with each alternative as shown in Table 6.1.

Table 6.1: Interrelation of the expected cost of failure and implementation costs associated with two different decision alternatives when considering a dam for rehabilitation works

Decision Alternative	Probability of failure	Consequences of failure	Expected cost of failure	Cost of implementation
Do-Nothing	High	High	High	No costs
Rehabilitate	Lowered	High	Lowered	Cost of rehabilitation

In the following, a more detailed description of each component of the objective function in Eq. 6.3.1 is presented. However, in order to ensure the utility is calculated in a consistent manner, the expected costs of failure and the estimated investment cost for rehabilitation works should be converted to the same year in the timeline of the dam rehabilitation project.

The timeline for a dam rehabilitation project is shown in Fig. 6.3. At point *I* the dam safety evaluation is performed. At this point in time the risk analysis is performed, where the initial probability of dam failure and the costs of dam failure are estimated. From the results of the dam safety evaluation, the decision for rehabilitation works could be recommended. At point *II* the design for rehabilitation works commence and the investment cost for the rehabilitation works are estimated. At point *III* the rehabilitation works are completed and the dam has a lower probability of failure (final probability of failure). The design life time for the rehabilitated dam is assumed to be 50 years, from points *III* to *IV*.

For this study, the point in time where the rehabilitation works are completed, point *III* in Fig. 6.3, is used as a reference point and therefore all costs will be converted to this year.

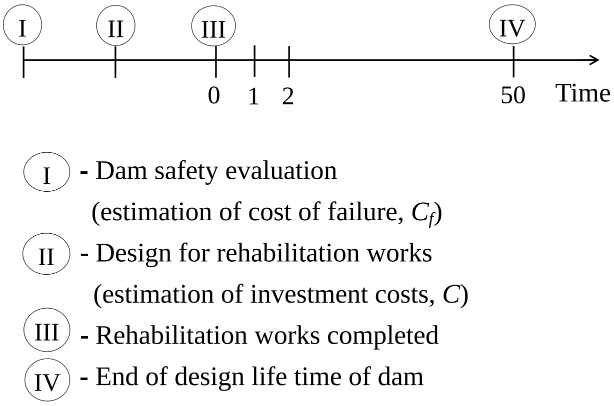

Figure 6.3: Timeline for dam rehabilitation project

Benefit (B)

The benefit of rehabilitation works *B* is the reduction in the expected cost of failure *D*, expressed as the product of the reduced probability of dam failure and consequences of dam failure.

The change in the probability of failure (ΔP_f) due to the dam rehabilitation works is calculated as the difference between the initial probability of failure ($P_{f(initial)}$) before rehabilitation works are conducted and the final probability of failure ($P_{f(final)}$) after the dam has been rehabilitated. This relationship is represented by Eq. 5.3.10 in Chapter 5. If the decision is to do-nothing, there will be no change in the probability of failure which will lead to a zero benefit *B*.

The cost of failure (C_f) is determined considering the financial impacts if a dam fails. According to Oosthuizen (2002), in South African dam safety the cost of failure is estimated as the direct and indirect economic losses due to dam failure, as described in section 2.3.4 of Chapter 2. The direct economic losses could include the damage to the structure, loss of agriculture and the costs of emergency relief, while the indirect economic losses could include the loss of future benefits. The Department of Water Affairs (DWA) estimates the direct and indirect financial impacts as part of the risk analysis performed for dams in dam safety inspections, thus at point I in Fig. 6.3.

According to Lentz (2007), the financial impacts should also take the compensation cost for loss of human life into account. The compensation costs are calculated as the product of the Societal Value of a Statistical Life (SVSL) and the estimated loss of life (LOL) in the case of dam failure. The estimated loss of life in case of dam failure may be obtained from the risk analysis performed by DWA for dams as part of their dam safety evaluations, while the SVSL is the amount which should be compensated for each fatality (Faber and Virguez-Rodriguez, 2011).

The LQI principles are used as a consistent basis for deriving the SVSL, similarly to how SWTP was derived in Chapter 5. Where SWTP is expressed using Eq. 5.2.7, the SVSL may be derived similarly from LQI as described by Holický (2009*a*) and Faber and Virguez-Rodriguez (2011).

$$SVSL = GKE \quad (\$) \tag{6.3.2}$$

Where,

G = the Gross Domestic Product (GDP) per person ($/person/year)

E = the age-averaged discounted life expectancy (years/person)

$K = 1/q$, where q is the parameter which reflects the trade-off placed on the consumption and the value attached to the length of life.

The SWTP and SVSL should not be confused with each other. SWTP defines the acceptable level for an investment into improving life safety as required by society, while SVSL is the amount of money which should be compensated for each fatality when failure occurs. The SWTP enters cost optimisation as a boundary condition and the SVSL enters as a cost of failure (Faber and Virguez-Rodriguez, 2011).

In Chapter 5 an Earth value was used for the SWTP and for consistency an Earth value for SVSL (ESVSL) is also used. The ESVSL obtained from Faber and Virguez-Rodriguez (2011), assuming rate of time preference for consumption of 3% per annum, is $US 629,000. The same rate of time preference for consumption as used to define the ESWTP in section 5.3.2 of Chapter 5 is used. Using the same average exchange rate for converting U.S. Dollars to Rand ($US 1 = R 7.83) as used in section 5.3.2 of Chapter 5, the ESVSL becomes R 4.925 million.

Taking the direct, indirect economic losses and the compensation costs for lives lost into account, the total cost of failure may be calculated as shown:

$$C_f = Direct\ Economic\ Losses + Indirect\ Economic\ Losses + SVSL \cdot LOL \tag{6.3.3}$$

The cost of failure C_f is estimated as part of the dam safety evaluation, therefore at point *I* in Fig. 6.3. C_f is converted to the reference point in time used for this study, thus to the year where the rehabilitation works are completed (point *III* in Fig. 6.3), by using basic economics principles (Blank and Tarquin, 2008).

$$C_{f(III)} = C_{f(I)}.(1+i)^n \tag{6.3.4}$$

Where,

$C_{f(III)}$ = Cost of failure at year of completed rehabilitation works (point *III* in Fig. 6.3) [R]

$C_{f(I)}$ = Cost of failure at year of dam safety evaluation (point *I* in Fig. 6.3) [R]

i = the inflation rate [%] (assumed $i = 7\%$ in this study)

n = the number of years between $C_{f(III)}$ and $C_{f(I)}$ [yrs]

To determine the benefit, the reduction in the expected cost of failure $C_{f(expected)}$ need to be determined. This expected cost represents a present worth (*III*) expected cost of failure and is determined from Eq. 6.3.8.

Failure can take place in any year of the design life of the dam, thus at any point between *III* and *IV* in Fig. 6.3. The probability of failure in each year is determined according to Eq. 6.3.5 (Holický, 2011). The failure probability in year *r* is the product of the annual P_f and the probability of the dam not failing before year *r*:

$$P_f(r) = P_f.(1-P_f)^{(r-1)} \tag{6.3.5}$$

The cost of failure in year *r*, discounted to the present worth at *III*, is determined from:

$$C_{f(III)}(r) = C_f.Q(i,r) \tag{6.3.6}$$

Q(i,r) is a discount factor which converts the cost at year *r* to the start of the life time of the dam, thus at point *III* in Fig. 6.3. *Q(i,r)* is expressed using basic economics theory (Blank and Tarquin, 2008):

$$Q(i,r) = 1/(1+i)^r \tag{6.3.7}$$

The parameter i represents the inflation rate.

The expected cost of failure can be determined by finding the sum of the present worth expected cost of failures over the life time of the dam:

$$C_{f(expected)} = C_f \sum_{r=1}^{n} P_f(r) Q(i,r) \tag{6.3.8}$$

Holický (2011) simplifies the formulation shown in Eq. 6.3.8 to:

$$C_{f(expected)} = C_{f(III)}.P_f.PQ(i,n) \tag{6.3.9}$$

The factor PQ is a time factor accounting for the fact that failure can take place in any year of the design life and adjusts the present worth annual expected cost of failure to a present worth expected cost of failure at the start of the life time of the dam at point *III* in Fig. 6.3. The factor PQ is formulated by Holický (2011) as follows:

$$PQ = \frac{1 - \frac{(1-P_f)}{(1+i)}^{n}}{1 - \frac{(1-P_f)}{(1+i)}} \tag{6.3.10}$$

Where,

P_f = the annual probability of failure

i = the inflation rate [%] (assumed $i = 7\%$ in this study)

n = the life time of the facility

Finally, the benefit, as the reduction in the expected cost of failure, may be calculated taking the time factor PQ into account:

$$B = C_{f(III)}.\Delta P_f.PQ \tag{6.3.11}$$

Where,

PQ = time factor accounting for the fact that failure can take place in any year of the design life

ΔP_f = the change in annual probability of failure

$C_{f(III)}$ = the cost of failure

To summarize, the benefit is calculated by considering the following:

1. The change in the probability of failure is determined.
2. The cost of failure is obtained at the year of the dam safety evaluation.
3. The cost of failure is converted to the reference point in time considered for this study, at the year when the rehabilitation works are completed.
4. The present worth annual expected cost of failure is determined as the product of the annual probability of failure and the cost of failure.
5. By incorporating a time factor, the present worth annual expected cost of failure is adjusted to a present worth expected cost of failure.
6. The benefit is the reduction in this present worth expected cost of failure due to a reduction in the probability of failure.

Cost of rehabilitation works (C)

When considering the objective function for the decision problem to rehabilitate a dam or not, the parameter C takes the estimated investment cost of the rehabilitation works into account.

The cost of the rehabilitation works is estimated when the design for the rehabilitation works are conducted (at point *II* of Fig. 6.3). In order to be consistent, the estimated cost of rehabilitation works are converted to the year where the rehabilitation works are completed, to point *III* in Fig. 6.3, using basic economics principles (Blank and Tarquin, 2008).

$$C_{(III)} = C_{(II)}.(1+i)^n \tag{6.3.12}$$

Where,

$C_{(III)}$ = Cost of rehabilitation works at year of completed rehabilitation works (point *III* in Fig. 6.3) [R]

$C_{(II)}$ = Cost of rehabilitation works at year of rehabilitation design (point *II* in Fig. 6.3) [R]

i = the inflation rate [%] (assumed $i = 7\%$ in this study)

n = the number of years between $C_{(III)}$ and $C_{(II)}$ [yrs]

In the following section the net benefit (Z) for two alternatives (rehabilitate and do-nothing) are compared for case studies of South African dams to evaluate if the rehabilitation works are economically beneficial.

6.3.2 Evaluation of South African case studies of dams in terms of proposed economic optimisation criteria

In this section the same eleven case studies of South African government owned dams that were evaluated for rehabilitation works in terms of proposed methods in Chapter 4 and 5 are considered. For each case study, the monetary net benefit of both decision alternatives, do-nothing or rehabilitate, are compared to each other. The decision alternative with the maximum expected net benefit is preferred.

For the case studies the parameters B and C needed for the objective function, shown in Eq. 6.3.1, are obtained as follow:

Benefit (B) for case studies of South African dams

To determine the benefit of rehabilitation works as shown in Eq. 6.3.11, the following input parameters are needed:

- Time factor, PQ, determined using Eq. 6.3.10. For the calculation an inflation rate of $i = 7\%$ and a life time of a dam of $n = 50$ years is assumed.
- The change in probability of failure, ΔP_f, determined using Eq. 5.3.10 in Chapter 5.
- The cost of failure, C_f, determined using Eq. 6.3.3.

For the rehabilitate alternative, the initial probability of failure $P_{f(initial)}$ and the final probability of failure $P_{f(final)}$ are needed to determine the change in the probability of failure ΔP_f. In Chapter 4 the initial probability for each of the eleven case studies of South African government owned dams are shown in Table 4.7 as determined by DWA through the risk analysis conducted for dam safety evaluations. As mentioned in Chapter 4, DWA estimates an interval for the initial probability of failure and the maximum and minimum value of the interval are shown. The final probability of failure after a dam has been rehabilitated ($P_{f(final)}$) is assumed to be between 1E-5 and 1E-6 per year. This interval is used by DWA for a well-engineered dam with no known deficiencies and it is assumed that a dam which has been rehabilitated in full will be equivalent this (Oosthuizen, 2002). For the do-nothing decision alternative there is no change in the probability of failure and ΔP_f is zero.

To determine the cost of failure C_f, the financial impacts due to dam failure for each case study need to be determined. As described in section 6.3.1 the financial impact takes the direct and indirect economic losses as well as the compensation costs for loss of human life into account, where for the compensation costs the loss of life (LOL) in case of dam failure is required.

The LOL was obtained from DWA dam safety evaluation reports and the maximum and minimum value for the intervals for the case studies are shown in Chapter 4 in Table 4.7. The direct and indirect economic losses were also obtained from DWA dam safety inspection reports and the values for the intervals for the different case studies are shown in Table 6.2.

Table 6.2: Estimated direct and indirect economic losses obtained for DWA case studies

			Estimated economic losses		
			At year of dam safety evaluation*		
Case Study Nr.	Dam		Year	Min	Max
1a	Bospoort Dam	Direct	2005	R 3 mil.	R 6 mil.
1b		Indirect		R 30 mil.	R 60 mil.
2	Klein Maricopoort Dam	Direct	1999	R 3.9 mil.	R 39 mil.
		Indirect		R 39 mil.	R 390 mil.
3	Toleni Dam	Direct	2000	R 0.058 mil.	R 0.58 mil.
		Indirect		R 0.58 mil.	R 5.84 mil.
4	Lakeside Dam	Direct	1999	R 6.71 mil.	R 67.1 mil.
		Indirect		R 67.1 mil.	R 671 mil.
5	Vaalkop Dam	Direct	2000	R 15 mil.	R 150 mil.
		Indirect		R 150 mil.	R 1 500 mil.
6	Rust De Winter Dam	Direct	1994	R 2.09 mil.	R 20.85 mil.
		Indirect		R 20.85 mil.	R 208.5mil.
7	Makotswane Dam	Direct	2005	R 1.6 mil.	R 18 mil.
		Indirect		R 16 mil.	R 180 mil.
8	Kromellenboog Dam	Direct	2005	R 70 mil.	R 700 mil.
		Indirect		R 700 mil.	R 7 000 mil.
9	Albert Falls Dam	Direct	2004	R 20 mil.	R 40 mil.
		Indirect		R 60 mil.	R 2 000 mil.
10	Glen Brock Dam	Direct	2006	R 5 mil.	R 10 mil.
		Indirect		R 20 mil.	R 40 mil.
11	Wentzel Dam	Direct	1994	R 0.55 mil.	R 5.5 mil.
		Indirect		R 5.5 mil.	R 55 mil.

* Refer to point *I* in Fig. 6.3

Note that for Case Study 1 of Bospoort Dam, two different scenarios were considered by DWA for the risk analysis: Case 1a where the gates will be functioning normally during failure, and Case 1b where the gates will not be functioning normally during failure.

Cost of rehabilitation works (C) for case studies of South African dams

The estimated costs of the rehabilitation works for each of the case studies are obtained from their respective design reports for the rehabilitation works. The estimated investment costs are shown in Table 5.4 in Chapter 5.

Both the estimated total costs of failure and the estimated investment costs for rehabilitation works have to be converted to the year where the rehabilitation works were completed, at point *III* in Fig. 6.3, in order to be consistent in determining the parameters for the objective function. For the case studies, the years when the rehabilitation works were completed are shown in Table 6.3.

Table 6.3: Year of completed rehabilitation works at DWA dam case studies (Dube, 2012)

Case Study Nr.	Dam	Year
1a 1b	Bospoort Dam	2009
2	Klein Maricopoort Dam	2011
3	Toleni Dam	2010
4	Lakeside Dam	2009
5	Vaalkop Dam	2007
6	Rust De Winter Dam	2010
7	Makotswane Dam	2008
8	Kromellenboog Dam	2009
9	Albert Falls Dam	2010
10	Glen Brock Dam	2010
11	Wentzel Dam	2008

The economic optimum for each decision alternative were calculated using the procedure described in section 6.3.1. Since the economic losses, LOL and initial probability of failure are presented as an interval, the economic optimum for each decision alternative are calculated for two extremes; a minimum and maximum boundary. The minimum boundary will give the smallest estimate of the monetary net benefit, while the maximum boundary will give the largest estimate of the net benefit. The values which are used for the maximum and minimum boundary are shown in Table 6.4.

To obtain the maximum value for the ΔP_f, the largest value for the $P_{f(initial)}$ and the smallest value for the $P_{f(final)}$ are used. To obtain the minimum value for the ΔP_f, the smallest value for the $P_{f(initial)}$ and the largest value for the $P_{f(final)}$ are used.

For illustrative purposes, the monetary net benefit for the rehabilitate and do-nothing decision alternatives for Case Study 2 of Klein Maricopoort Dam are calculated using the objective function,

Table 6.4: Maximum and minimum boundary for each decision alternative

	Minimum Boundary	Maximum Boundary
Direct Economic Losses	Min.	Max.
Indirect Economic Losses	Min.	Max.
loss of life (LOL)	Min.	Max.
Change in probability of failure (ΔP_f)	Min.	Max.
Initial probability of failure ($P_{f(initial)}$)	*Min.*	*Max.*
Final probability of failure ($P_{f(final)}$)	*Max.*	*Min.*

Z = B - C, and the results are compared against each other. The calculation procedure for the two decision alternatives, considering both the maximum and minimum boundary is shown in Table 6.5.

For both the maximum and minimum boundary, the Klein Maricopoort do-nothing decision alternative yields in a higher monetary net benefit than the rehabilitate option. Therefore, the do-nothing decision alternative should be preferred.

Table 6.5: Economic optimisation calculation procedure for Case Study 2 (Klein Maricpoort Dam)

		REHABILITATE		**DO-NOTHING**	
		MIN	**MAX**	**MIN**	**MAX**
Probability of failure					
Annual probability of failure	$P_{f(initial)}$	1.00E-04	1.00E-03	1.00E-04	1.00E-03
	$P_{f(final)}$	1.00E-05	1.00E-06	1.00E-04	1.00E-03
	ΔP_f	9.00E-05	9.99E-04	0.00E+00	0.00E+00
Time factor (i = 7%, n = 50 years)	PQ for ΔP_f	14.75	14.58	14.77	14.77
Costs of failure					
Economic losses	Direct	R 3.9 mil.	R 39 mil.	R 3.9 mil.	R 39 mil.
	Indirect	R 39 mil.	R 390 mil.	R 39 mil.	R 390 mil.
	Total economic losses	R 42.90 mil.	R 429.00 mil.	R 42.90 mil.	R 429.00 mil.
Compensation costs for loss of human life	SVSL	R 4.93 mil.	R 4.93 mil.	R 4.93 mil.	R 4.93 mil.
	LOL	9	13	9	13
	Total compensation costs	R 14.78 mil.	R 24.63 mil.	R 14.78 mil.	R 24.63 mil.
Total cost in case of failure at point *I* in Fig. 6.3	$C_f(I)$ - In year 1999	R 57.68 mil.	R 453.63 mil.	R 57.68 mil.	R 453.63 mil.
Total cost in case of failure at point *III* in Fig. 6.3	$C_f(III)$ - In year 2011	R 129.90 mil.	R 1 021.65 mil.	R 129.90 mil.	R 1 021.65 mil.
Cost of rehabilitation works					
Cost of rehabilitation works at point *II* in Fig. 6.3	$C_{(II)}$ - In year 2008	R 39.33 mil.		R 0.00 mil.	
Cost of rehabilitation works at point *III* in Fig. 6.3	$C_{(III)}$ - In year 2011	R 48.18 mil.		R 0.00 mil.	
Parameters of objective function					
Benefit measure	B = $C_{f(III)}.\Delta P_f$.PQ	R 0.17 mil.	R 14.88 mil.	R 0.00 mil.	R 0.00 mil.
Cost of rehabilitation works	C = $C_{(III)}$	R 48.18 mil.	R 48.18 mil.	R 0.00 mil.	R 0.00 mil.
Monetary net benefit					
	Z = B - C	R -48.01 mil.	R -33.30 mil.	R 0.00 mil.	R 0.00 mil.
	Preferred option	**Do-Nothing**	**Do-Nothing**		

Table 6.6 illustrates the preferred option (rehabilitate or do-nothing) obtained when the monetary net benefit for the two decision alternatives for the eleven DWA case studies are compared against each other.

Table 6.6: Preferred option (Rehabilitate or Do-Nothing) revealed from an economic optimisation procedure for 11 DWA case studies of dams which have been rehabilitated

	Dam	**MIN BOUNDARY**	**MAX BOUNDARY**
1a	Bospoort Dam Case A - Gates Functioning	Do-Nothing	Do-Nothing
1b	Bospoort Dam Case B - Gates Not Functioning	Do-Nothing	Do-Nothing
2	Klein-Maricopoort Dam	Do-Nothing	Do-Nothing
3	Toleni Dam	Do-Nothing	Do-Nothing
4	Lakeside Dam	Do-Nothing	**Rehabilitate**
5	Vaalkop Dam	Do-Nothing	Do-Nothing
6	Rust De Winter Dam	Do-Nothing	Do-Nothing
7	Makotswane Dam	Do-Nothing	Do-Nothing
8	Kromellenboog Dam	Do-Nothing	**Rehabilitate**
9	Albert Falls Dam	Do-Nothing	**Rehabilitate**
10	Glen Brock Dam	Do-Nothing	**Rehabilitate**
11	Wentzel Dam	**Rehabilitate**	**Rehabilitate**

It must be noted that the maximum boundary considers the scenario where it is most likely for the preferred option to be to rehabilitate. Case studies 4, 8, 9, 10, 11 in Table 6.6 represents situations where the rehabilitate alternative is preferred for the maximum boundary.

For the minimum boundary it is least likely for the rehabilitate option to be preferred. Case Study 11 in Table 6.6 represents the situation where the monetary net benefit for the rehabilitate option is higher than for the do-nothing decision alternative for both the maximum and minimum boundary.

For the eleven case studies, the Department of Water Affairs (DWA) originally recommended rehabilitation works. However, when considering the monetary benefit obtained from the rehabilitate and do-nothing decision alternative, the rehabilitation works for case studies 1a, 1b, 2, 3, 5, 6 and 7 are not justified.

In the following section the results that were obtained when considering economic optimisation are compared to the results obtained when the case studies were evaluated in terms conventional acceptability criteria for risk to human life and according to SWTP criteria presented in Chapter 4 and 5 respectively.

6.3.3 Comparison of the recommendations for rehabilitation works through economic optimisation criteria, ANCOLD life safety criteria and SWTP criterion lines

In this study, the eleven case studies of South African dams are evaluated for rehabilitation works in terms of conventional acceptability criteria for risk to human life (Chapter 4), SWTP criteria (Chapter 5) and economic optimisation criteria (this chapter). The following results were obtained:

- **Conventional criteria for risk to human life**

  In Chapter 4, the case studies of South African government owned dams were evaluated in terms of the proposed ANCOLD conventional criteria for risk to human life. The risk to human life for the eleven case studies of South African dams are mostly within the unacceptable region of the ANCOLD criteria for existing dams as illustrated in Fig. 6.4. Case studies 2, 3, 5 and 6 are located on the border of acceptable and unacceptable, but are still mostly within the unacceptable region. Therefore, the rehabilitation of the eleven case studies of dams to decrease the risk to human life to comply with conventional criteria are justified.

- **SWTP criteria**

  In Chapter 5, SWTP is introduced to evaluate if investments into life safety through rehabilitation works are required by society. SWTP criterion lines were developed for the eleven case studies of dams which are also illustrated in Fig. 6.4. The risk to human life for the case studies are mostly located within the acceptable region of the SWTP criteria. However, the risk to human life for case studies 4 and 11 are located within the unacceptable region and thus investments into life safety were required.

- **Economic optimisation criteria**

  In this chapter the preferences of the decision maker or owner, who require an investment into rehabilitation works to yield in an optimal economic solution, are considered. In Fig. 6.4 the preferred decision alternative, rehabilitate or do-nothing, determined when comparing the monetary net benefit for the two decision alternatives of the eleven case studies are shown. The key for the preferred options is also shown in Fig. 6.4.

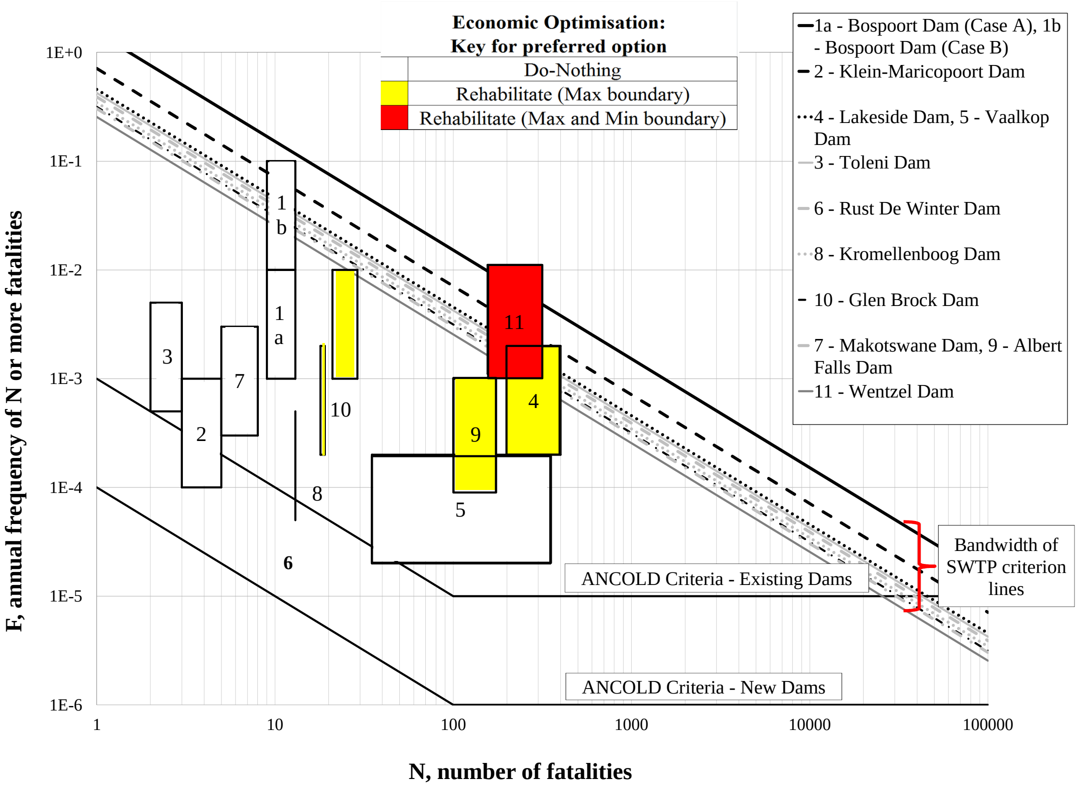

Figure 6.4: Risk to human life for case studies compared to SWTP criterion lines and ANCOLD acceptability criteria for risk to human life

Discussion of results:

Generally, case studies close to the SWTP criterion lines also require rehabilitation from the economic optimisation perspective, while case studies far from the SWTP lines are less likely to require rehabilitation from an economic perspective, especially if these cases expect low LOL in case of failure. This is due to the fact that lost lives are economically taken into account through compensation costs. All of the case studies are mostly within the unacceptable region of the ANCOLD conventional criteria for risk to human life. ANCOLD does not only consider human safety, but is based on engineering judgement, i.e. it also takes economic considerations into account in a non-explicit way. However, based on the current study, the ANCOLD requirements seem to be fairly conservative.

The following similarities in the results are observed:

Economic optimisation: Rehabilitate (maximum and minimum boundary)

Case Study 11 provides the only example for which economic optimisation required rehabilitation for both the minimum and maximum boundary assumptions. In addition, the risk to human life for Case Study 11 is unacceptable in terms of SWTP criteria and an investment into reducing risk to human life through dam rehabilitation works to satisfy the preferences of society is required.

Further, the risk to human life is located far within the unacceptable region of the ANCOLD criteria for existing dams and rehabilitation works are justified when considering conventional criteria for life safety. Therefore, when considering Case Study 11, rehabilitation works are justified in terms of all three proposed decision tools.

Economic optimisation: Rehabilitate (maximum boundary)

For case studies 4, 8, 9 and 10, rehabilitation is required based on economic optimisation for the maximum boundary assumptions defined in Table 6.4. The maximum boundary considers the situation where rehabilitation will be most likely recommended, i.e. the benefit, as the combination of the maximum change in probability of failure and the maximum expected costs of failure will be large in comparison to the costs of rehabilitation works.

The risk to human life for case studies 4, 9 and 10 are located close to the bandwidth of SWTP criterion lines and rehabilitation also becomes a concern when societal preferences are considered. The risk to life is also located in the unacceptable region of ANCOLD conventional acceptability criteria on the FN-diagram. The rehabilitation works are thus justified in terms of the ANCOLD criteria which explicitly evaluates risk to life, but also implicitly accounts for economic considerations.

For Case Study 8, although rehabilitation is recommended through economic optimisation, the risk to human life is not located close to the bandwidth of SWTP criterion lines. Therefore an investment to reduce risk to human life to satisfy the lower boundary set by SWTP is not required. The LOL estimated by DWA is low compared to the LOL estimated for other case studies. This leads to low compensation costs for loss of human life. The estimated direct and indirect economic losses for this dam are very high in comparison to the other case studies, as can be seen in Table 6.2. In addition, the estimated investment cost for rehabilitation works is low in comparison to the estimated investment costs at other dam case studies. If the objective function Z = B - C is considered, a high benefit (B) may be obtained for the investment cost into dam rehabilitation works (C), justifying the recommendation for rehabilitation works.

Although the risk to life for Case Study 8 is located within the acceptable region of SWTP criteria, it is still located within the unacceptable region of the ANCOLD acceptability criteria. Thus rehabilitation is justified to reduce risk to human life to satisfy this criteria, which does not only account for societal considerations, but also accounts for additional considerations such as economy.

Economic optimisation: Do-nothing

In terms of the monetary net benefit obtained for the do-nothing and rehabilitate decision alternatives for case studies 1a, 1b, 2, 3, 5, 6 and 7, the do-nothing decision alternative results in a higher net benefit and should be preferred. In addition, the risk to human life presented on the FN-diagram for the case studies are not located close to the SWTP criterion lines developed for the DWA case studies. Therefore, investments to reduce life safety risks are also not required by the SWTP criteria. In terms of ANCOLD acceptability criteria, the risk to human life for case study 1a, 1b, 3 and 7 is located within the unacceptable region of the ANCOLD criteria and rehabilitation works are justified according to this criteria. The risk to human life for case studies 2, 5 and 6 are located on the border between acceptable and unacceptable in terms of criteria established by ANCOLD.

When considering the economic optimisation procedure, the factors which may have influenced the preferred option to be to do-nothing are discussed for the following case studies:

- **Case Study 1a (Bospoort Dam - Case A with gates functioning during flood conditions)**:

  For Case Study 1a of Bospoort Dam, the situation where the sluice gates of the dam are functioning normally during flooding is considered. For the objective function, Z = B - C, it is noted that the investment cost to rehabilitate the dam (C) is very high in comparison to the benefit (B) of rehabilitation works. Subsequently rehabilitation is not recommended.

- **Case Study 1b (Bospoort Dam - Case B with gates not functioning during flood conditions)**: For Case Study 1b of the same dam, the situation where the sluice gates are closed during flooding is considered. The initial probability of dam failure is higher than the failure probability of Case Study 1a. Thus, a higher reduction in the probability of failure is expected, leading to a higher benefit obtained through rehabilitation. However, the investment cost to rehabilitate the dam (C) is still high in comparison to the benefit (B) and thus rehabilitation is not recommended.

- **Case Study 2 (Klein Maricopoort Dam)**:

  For Case Study 2, the initial probability of dam failure is low. Consequently the reduction in the probability of failure through rehabilitation works is not very large. This leads to a low benefit (B), as the combination of the changed probability of failure and the costs in case of failure. Thus, the investment cost to rehabilitate the dam (C) is high in comparison to the benefit (B).

- **Case Study 3 (Toleni Dam)** :

  For this case study, the LOL and direct and indirect economic losses are estimated to be fairly low in comparison to other case studies. This leads to a fairly low reduction in the expected cost of failure which causes the expected benefit (B) to be low.

- **Case Study 5 (Vaalkop Dam)** :

  For Case Study 5, the initial probability of failure is low in comparison to other case studies. Even though the economic losses and LOL are failry high in comparison to other case studies, rehabilitation works would lead to only a small reduction in the probability of dam failure. Thus the benefit (B), in terms of improved safety, is low in comparison to the investment cost (C).

- **Case Study 6 (Rust De Winter Dam)** :

  For Case Study 6, the initial probability of failure is also low leading to the small change in the probability of failure when the dam is rehabilitated. When considering the objective function, the investment cost to rehabilitate the dam (C) is thus high in comparison to the low expected benefit (B).

- **Case Study 7 (Makotswane Dam)** :

  For Case Study 7, the estimated LOL and economic losses in case of dam failure are low compared to other case studies. Thus the expected benefit from rehabilitating the dam is low.

For the case studies 1a, 1b, 2, 3, 5, 6 and 7, although all three decision tools do not recommend rehabilitation works, it must be noted that other factors identified by DWA may have lead to the decision to rehabilitate these dams. As mentioned in Chapter 2, DWA evaluates different types of consequences of dam failure in combination with the probability of failure through the risk analysis methodology. The risks which are evaluated using multiple acceptability criteria include, in addition to risk to human life and economic impacts, the social impacts, socio-economic impacts and environmental impacts of dam failure. DWA also evaluates an additional factor in combination with the other impacts, the risk level, which considers the expected fatalities per exposed hour against the annual risk of both direct and indirect financial losses. The expected loss of life per exposed hour only applies to humans directly exposed to the hazard and may include fishermen, motorists and workers in the downstream area of the dambreak. The risk level were described in Chapter 2.

The risk analysis which forms part of the dam safety evaluations performed by DWA for these dams (case studies 1a, 1b, 2, 3, 5, 6 and 7) are revisited to identify what other factors may have influenced the decision to rehabilitate:

- **Case Study 1a and 1b (Bospoort Dam)**: In the dam safety evaluation report performed for Bospoort Dam (Hattingh, 2005), the risk analysis for the scenario where the radial gates are functioning normally during overtopping (Case Study 1a) showed the following results;

  - the *risk to human life*, expressed as population at risk (PAR) by DWA, the *social* and the *direct financial impacts* are evaluated as acceptable according criteria established by DWA.
  - The *indirect financial impacts* and the *socio-economic* and *environmental impacts* are unacceptable according to DWA criteria.
  - In addition the *risk level* were found to be completely unacceptable in terms of DWA criteria.

  For the scenario where the radial gates does not function normally during flood conditions (Case Study 1b):

  - All the impacts and the *risk level* are unacceptable in terms of DWA criteria.
  - It could therefore be concluded that the decision to rehabilitate the dam was not only influenced by the scenario where the gates are functioning during flooding where the indirect financial, socio-economic and environmental impacts are unacceptable, but could also be influenced by the perceived likelihood of the scenario where the gates does not function normally during overtopping.
  - Also, the DWA criteria do no take the cost of rehabilitation measures into account.

- **Case Study 2 (Klein Maricopoort Dam)**: In the dam safety evaluation report performed for Klein Maricopoort Dam (Kelefetswe, 2005), the risk analysis showed the following results;

  - The *risk to human life* and the *financial impacts* are on the border between acceptable and unacceptable according to DWA criteria.
  - The *social* and *ecological impacts* are moderate but still acceptable in terms of DWA criteria.
  - In addition, the *risk level* were found to be moderate to high but still acceptable in terms of DWA criteria.

- **Case Study 3 (Toleni Dam)**: In the dam safety evaluation report performed for Toleni Dam (Muller, 2000), the risk analysis showed the following results;

  - The *risk to human life*, *socio-economic* and *social impacts* are acceptable in terms of DWA criteria.
  - The *financial impacts* as well as the *environmental impacts* in case of dam failure are borderline between acceptable and unacceptable in terms of DWA criteria.

  - In addition, the *risk level* is evaluated to be high but still acceptable according to DWA criteria.

- **Case Study 5 (Vaalkop Dam)**: In the dam safety evaluation report performed for Vaalkop Dam (Nightingale, 2005), the risk analysis showed the following results;
  - The *risk level* are acceptable in terms of DWA criteria.
  - The *risk to human life* and *socio-economic*, *social* and *environmental impacts* are borderline between acceptable and unacceptable in terms of DWA criteria.
  - In addition, the *direct and indirect economic losses* are unacceptable according to DWA criteria.

- **Case Study 6 (Rust De Winter Dam)** : In the dam safety evaluation report performed for Rust De Winter Dam (Coetzer, 2003), the risk analysis showed the following results;
  - The *risk to human life*, the *economic impacts* and *risk level* were moderate to high but still acceptable in accordance to DWA criteria.
  - The *socio-economic impacts* in case of dam failure are moderate but also still acceptable in terms of DWA criteria.

- **Case Study 7 (Makotswane Dam)**: In the dam safety evaluation report performed for Makotswane Dam (Naidoo, 2005), the risk analysis showed the following results;
  - All the evaluated risks, including risk to human life, *economic, socio-economic, social, environmental and risk level*, were borderline between acceptable and unacceptable in terms of DWA criteria.

When comparing the recommendations for rehabilitation works for the eleven case studies using the three different decision tools proposed in this study (conventional acceptability criteria for risk to human life, lower boundary for investments into life safety defined SWTP and economic optimisation) the decision to rehabilitate the dams are not always justified in terms of all three methods. All three methods may be used to assess the dam for rehabilitation works, but it must be noted that the additional factors such as the socio-economic, social and environmental impacts and the risk level may influence the decision to rehabilitate the dam. Therefore, the three decision tools proposed in this study can not be used as the only decision support tools for rehabilitation. On the other hand, the current DWA criteria do not take the cost of rehabilitation works into account in any way and this should be remedied.

In most cases the risk to life were evaluated as acceptable according to the lower boundary criteria defined by SWTP. However, higher safety levels were required for some cases, based on economic optimisation evaluations. This confirms the observation described in section 6.2, that it unlikely for the SWTP boundary to govern the investment into rehabilitation works and that economic optimisation would typically dictate the decision. Thus, criteria which effectively incorporate this consideration into the decision process is needed.

In the following section alternative criteria are developed to instead of independently evaluate societal preferences for life safety through SWTP criteria and the economic efficiency of dam rehabilitation works, incorporate both considerations into a single-evaluation criteria for evaluating dams for rehabilitation works.

6.4 Development of single-evaluation life safety criteria which incorporates some measure of economic efficiency

The SWTP criteria only consider societal preferences for investments into life safety, while the economic optimisation criteria consider the decision maker or owner's preferences for a maximised monetary net benefit through an investment into rehabilitation works. For the case studies of dams, the risk to life were in most cases acceptable in terms of SWTP criteria, thereby complying with the lower bound constraint for dam safety levels. However, for some cases rehabilitation were recommended through economic optimisation and thus economic optimisation dictated the decision to rehabilitate the dam.

It could be argued that a three phase approach would be the best, where the acceptability of risk to life is first evaluated using SWTP, followed by economic optimisation as possible motivation to rehabilitate and finally incorporating environmental, socio-economic, social and risk level considerations into the decision. On the other hand, the first two steps could be replaced by a single-evaluation criteria, which accounts for both considerations and would be more convenient and easy to use. In this section, a single-evaluation criteria is proposed as an alternative, where the risk to human life are primarily assessed (through FN-criteria), but with some measure of economic efficiency of rehabilitation taken into account by setting less stringent criteria for dams where rehabilitation works are excessively expensive or achieves little improvement in safety. This is similar to what ANCOLD does by defining two criterion lines for new and existing dams.

To differentiate between the efficiency of rehabilitation works for different dams, the ratio of the investment cost for the dam rehabilitation to the reduction in the probability of dam failure ($C/\Delta P_f$)

is proposed as an efficiency measure. If a large ΔP_f can be achieved at a small cost, this is very efficient and it is therefore reasonably practicable to implement more stringent safety criteria for these dams. On the other hand, if only a small ΔP_f is achieved at a large cost, it might not be reasonably practicable to rehabilitate and less stringent criteria should apply to such cases.

Note that ΔP_f does not fully describe the benefit of rehabilitation works, since in some cases (even with a large ΔP_f) the benefit may be low due to small losses in case of dam failure. However, to calculate the benefit requires the involved considerations of section 6.3.1.

In the following, FN-criteria, with different stringency levels are developed based on a "low", "medium" and "large" efficiency ratio ($C/\Delta P_f$).

To develop this FN-criteria, $C/\Delta P_f$ ratios are determined for the eleven DWA case studies considered for this study. This is done by dividing the annual cost of the rehabilitation works by the average reduction in the probability of failure to obtain a cost per percentage reduction in probability of failure.

The annual cost of rehabilitation works (Annual Worth (AW)) has been determined for the eleven case studies of dams and are shown in Table 5.5 in Chapter 5 of this study. The average change in the probability of failure (ΔP_f) due to the dam rehabilitation works are calculated as the difference between the average initial probability of failure ($P_{f(initial)}$) before rehabilitation works are conducted and the average final probability of failure ($P_{f(final)}$) after the dam has been rehabilitated. The average initial probability of failure is determined by finding the average of the maximum and minimum interval of the $P_{f(initial)}$ shown in Chapter 4 in Table 4.7. The average final probability of failure after a dam has been rehabilitated ($P_{f(final)}$) is assumed to be the average of 1E-5 and 1E-6 per year.

The $C/\Delta P_f$ ratio, as a cost per percentage reduction in the probability of failure, is obtained for the eleven DWA case studies as shown in Table 6.7. In order to differentiate between the efficiency of the rehabilitation works, the ratios obtained in Table 6.7 are divided into a "small", "medium" and "large" intervals as shown in Table 6.8. In this way, the case studies are used to obtain practical intervals for what can be considered as "small", "medium" and "large" ratios.

Table 6.7: Investment cost for a reduction in probability of failure for the case studies of South African government owned dams, expressed as a cost to ΔP_f ratio

Case Study Nr.	**Dam**	**Average ΔP_f** $[\frac{\%}{year}]$	**Cost estimate (AW)** $[\frac{R}{year}]$	**C/ΔP_f** **[R/%]**
1a	Bospoort Dam (Case A)	5.49E-01	R 6.11 mil./yr	R 11.12 mil./%
1b	Bospoort Dam (Case B)	5.50E+00	R 6.11 mil./yr	R 1.11 mil./%
2	Klein-Maricopoort Dam	5.45E-02	R 2.85 mil./yr	R 52.34 mil./%
3	Toleni Dam	2.74E-01	R 1.71 mil./yr	R 6.25 mil./%
4	Lakeside Dam	1.09E-01	R 1.83 mil./yr	R 16.68 mil./%
5	Vaalkop Dam	1.05E-02	R 1.76 mil./yr	R 167.98 mil./%
6	Rust De Winter Dam	2.7E-02	R 1.54 mil./yr	R 57.32 mil./%
7	Makotswane Dam	1.64E-01	R 1.23 mil./yr	R 747.13 mil./%
8	Kromellenboog Dam	1.09E-01	R 1.39 mil./yr	R 12.68 mil./%
9	Albert Falls Dam	5.45E-02	R 1.20 mil./yr	R 22.00 mil./%
10	Glen Brock Dam	5.45E-01	R 1.28 mil./yr	R 2.32 mil./%
11	Wentzel Dam	6.10E-01	R 1.03 mil./yr	R 1.69 mil./%

Table 6.8: Intervals defined for C/ΔP_f

Case Study Nr.	**Dam**	**C/ΔP_f [R/ %]**	**SMALL** R1 mil./% < (C/ΔP_f) < R10 mil./%	**MEDIUM** R10 mil./% < (C/ΔP_f) < R100 mil. /%	**LARGE** (C/ΔP_f)> R100 mil./%
1a	Bospoort Dam (Case A)	R 11.12 mil./%		Y	
1b	Bospoort Dam (Case B)	R 1.11 mil./%	Y		
2	Klein-Maricopoort Dam	R 52.34 mil./%		Y	
3	Toleni Dam	R 6.25 mil./%	Y		
4	Lakeside Dam	R 16.68 mil./%		Y	
5	Vaalkop Dam	R 167.98 mil./%			Y
6	Rust De Winter Dam	R 57.32 mil./%		Y	
7	Makotswane Dam	R 7.47 mil./%	Y		
8	Kromellenboog Dam	R 12.69 mil./%		Y	
9	Albert Falls Dam	R 22.00 mil./%		Y	
10	Glen Brock Dam	R 2.32 mil./%	Y		
11	Wentzel Dam	R 1.69 mil./%	Y		

In Chapter 4 of this study, the ANCOLD FN-criteria, which based on what is considered to be good engineering practice, were proposed as conventional criteria for evaluating the risk to human life imposed by dams. The ANCOLD criterion line for new dams is one factor of 10 more stringent than the criterion line for existing dams. This criterion line is suggested as the criterion line for the case studies where the investment is "small" for a reduction in the probability of failure, since it is very efficient and reasonably practicable to implement more stringent safety criteria for these dams.

The ANCOLD criterion line for existing dams is suggested as the criterion line for the case studies with a "medium" investment for a reduced probability of failure. The case studies are more likely to fall within the acceptable region of the less stringent criterion line and hence the decision to rehabilitate may not always be justified.

A new criterion line one factor of 10 higher than the ANCOLD acceptability criterion line for existing dams is suggested as the criterion line for a "large" C/ΔP_f ratio. Since only a small ΔP_f is achieved at a large cost, the decision to rehabilitate may not always be reasonably practicable and the least stringent criteria should apply to such cases. The "small", "medium" and "large" criterion lines are illustrated on an FN-diagram in Fig. 6.5.

The risk to human life for the 11 case studies are presented on the FN-diagram. DWA estimates the risk to life in the form of a block representing the level of confidence of the data, thus an interval for the loss of life (LOL) and the probability of failure is defined. For this investigation, the average of the two intervals are obtained and these corresponding values are plotted as co-ordinate points on an FN-diagram instead of using an interval for the loss of life (LOL) and the probability of failure.

The co-ordinate points for the 11 DWA case studies are shown on an FN-diagram in Fig. 6.5. The efficiency of an investment to reduce the probability of dam failure in terms of the "small", "medium" or "large" intervals defined in Table 6.8 are shown for each case study (with "S" for "small", "M" for "medium" and "L" for "large").

If the case studies are evaluated in terms of the newly defined "small", "medium" and "large" FN-criterion lines;

- All of the DWA case studies which were analysed to be in the "small" interval, will fall in the unacceptable region of the "small" $C/\Delta P_f$ criterion line and should be rehabilitated.
- All of the DWA case studies which were analysed to be in the "medium" interval are within the unacceptable region of the "medium" criterion line. However, these case studies are located closer to the border of the criterion line.

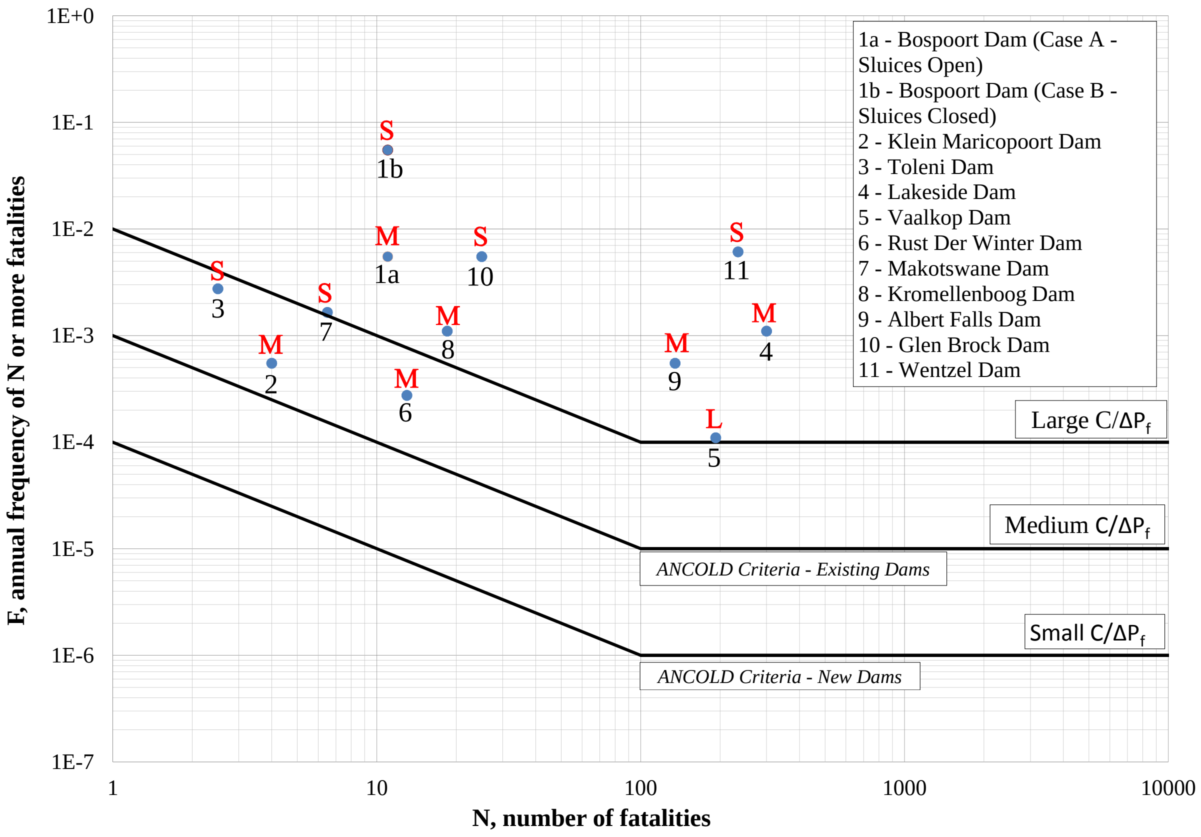

Figure 6.5: Proposed FN-criteria based on C/ΔP_f ratio

- The DWA case study which were analysed to be in the "large" interval, falls on the border between acceptable and unacceptable for the criterion line.

For the C/ΔP_f criteria, all the case studies require rehabilitation. This corresponds to the DWA decisions that were taken. Based on the SWTP evaluation together with the outcomes of the economic optimisation evaluation for the eleven case studies, some dams should not have been rehabilitated and thus there may be some reason to argue that these suggested criterion lines can be moved one factor of 10 higher. However, more case studies will be necessary refine this criteria.

The C/ΔP_f criteria are suggested as a first step to evaluate dams for rehabilitation works. It requires a single evaluation which incorporates life safety and economic considerations, which is easy and convenient to use, and does not require a refined estimation for the cost of rehabilitation works. Thereafter, if it is necessary, the rehabilitation decision could be confirmed by evaluating the dam in terms of SWTP and economic optimisation criteria, which requires a more involved estimation of the failure costs and the investment cost for rehabilitation works.

However, it should be noted that the $C/\Delta P_f$ criteria are by no means perfect. For example, when developing the criteria, only the investment cost for a reduced probability of failure is considered, while through economic optimisation the benefit of an investment into rehabilitation works additionally considers the costs of dam failure.

It should also be noted that this criteria does not account for other factors, such as the socio-economic, social and environmental impacts and the risk level, which may influence the decision to rehabilitate the dam. These factors should be considered separately and requires expertise in different areas. DWA addresses these factors in the risk analysis performed for dam safety evaluations, and the multiple criteria which may be used to evaluate these factors are illustrated in Fig. 2.6 in Chapter 2.

6.5 Summary of main findings

The principles of economic optimisation are applied to this study as an additional tool to evaluate if rehabilitation works at a dam is economically beneficial. The monetary net benefit for two decision alternatives, do-nothing or rehabilitate, is obtained for case studies of South African government owned dams and the decision alternative with the maximum monetary net benefit should be preferred.

For the eleven South African dam case studies, the recommendation for rehabilitation works through economic optimisation was compared to the recommendations through the other decision tools proposed in this study, including the ANCOLD conventional acceptability criteria for risk to human life suggested in Chapter 4, and the lower boundary for investments defined by SWTP for a marginal increase in life safety suggested in Chapter 5. The DWA decision to rehabilitate the dams were not always justified in terms of all three methods. Additional factors such as the socio-economic, social and environmental impacts often influenced the decision to rehabilitate the dam. Consequently the three methods proposed in this study can not be used exclusively as decision support tools for rehabilitation.

When considering the eleven DWA case studies, the economic optimisation always resulted in safety levels higher than what was required by SWTP. This confirms the observation in literature, which states that SWTP is generally a lower bound constraint which rarely governs the design (Rackwitz and Streicher, 2002). Thus, economic optimisation would typically dictate whether or not a dam should be rehabilitated and we need criteria that would effectively incorporate this consideration in the decision process. The current DWA criteria do not take the costs of rehabilitation measures into account.

A single evaluation criteria is developed where life safety is primarily assessed through FN-criteria, but with some measure of economic efficiency of rehabilitation taken into account. The ratio of the costs of rehabilitation works to the reduction in the probability of failure $C/\Delta P_f$ is proposed as an efficiency measure. When a large ΔP_f can be achieved at a small cost, it is very efficient and therefore reasonably practicable to implement more stringent safety criteria for these dams. On the other hand, if only a small ΔP_f is achieved at a large cost, it might not be reasonably practicable to rehabilitate and less stringent criteria should apply to such cases.

The $C/\Delta P_f$ criteria developed in this chapter are suggested as a first step to evaluate South African dams for rehabilitation works. This set of life safety criteria are easy and convenient to use. The rehabilitation decision could then be further validated by applying the SWTP and economic optimisation criteria, but these methods require more involved estimations of rehabilitation and failure costs.

It should be noted that the $C/\Delta P_f$ criteria are by no means perfect since it does not incorporate the economic impacts of dam failure. It also does not incorporate other factors, such as the socio-economic, social and environmental impacts and the risk level, which could require dam rehabilitation works. These factors should be considered separately and requires expertise in different areas. DWA evaluates these additional factors through multiple acceptability criteria which is illustrated in Fig. 2.6 in Chapter 2.

Chapter 7

Conclusions and Recommendations

In addition to the number of roles dams play in society, the development of large dams enhances the quality of life of society. However, dams are inherently associated with safety issues and although dam safety related incidents may be rare, there are serious cases of human fatalities and economic losses that have been caused by dam failures, both internationally and in South Africa. This necessitates the proper management and control of dam safety.

Internationally there are a number of dam safety organisations, regulators, governments or dam owners responsible for providing standards for the management of dam safety. In South Africa, the Department of Water Affairs (DWA) is the custodian of a large number of dams and is responsible for all aspects of law regarding dam safety.

The purpose of the South African dam safety legislation is to improve the safety of dams by determining the level of control over dams and requiring regular dam safety evaluations. In addition to the establishment of the dam safety legislation, a risk-based model aiding decisions regarding the adequacy of dam safety levels has been developed and is currently applied by DWA. Although not specifically required by the dam safety legislation, it has become standard to perform a risk analysis as part of dam safety evaluations.

For a specific dam, the risk analysis methodology combines the estimated probability of dam failure and the different consequences of dam failure to quantitatively define risks. These risks are evaluated against multiple acceptability criteria to assess the risk to human life and the economic, social, socio-economic and environmental impacts in case of dam failure. If the risks are evaluated as unacceptable in terms of the criteria, the rehabilitation of dams to improve their safety may be recommended.

According to DWA, dam building reached its peak in South Africa in the 1980's. Since then there has been a shift in dam engineering from the design of dams to the maintenance and rehabilitation of dams. In the years 2004/2005, DWA identified 166 of the 314 South African government owned dams to be in need of rehabilitation works. This encouraged the initiation of the dam safety rehabilitation program by DWA in the years 2005/2006. It is estimated for the total expenditure for rehabilitation works since the start of the program up until the 2011/2012 financial year to be more than R 1.5 billion.

DWA recently identified the need for reviewing decision criteria for the prioritisation of South African dams for rehabilitation. More specifically DWA required the criteria for acceptability of assessed risk to human life to be evaluated.

In this study, current criteria used by DWA were evaluated by comparing to international best practice methods for evaluating the acceptability of risk to human life. Further, the lower bound for investments into life safety required by society was identified using SWTP as a utility function. In addition, the motivation for further investments, above the lower bound for life safety defined by SWTP, was investigated. These motivations for further investments could include the economic motivations for which the dam is vital, the damage costs in case of dam failure and environmental, socio-economic and social implications of dam dailure. Finally, single-evaluation criteria were proposed to primarily evaluate life safety, but with some measure of economic efficiency incorporated.

International best practice methods for evaluating risk to human lives:

Internationally, risk to life is most commonly quantitatively assessed through conventional acceptability criteria. The acceptability criteria are commonly presented as FN-criteria on an FN-diagram, with the x-axis representing the number of fatalities (N) and the y-axis the probability (F) of N or more fatalities occurring. The life safety risks are evaluated against the FN-criteria, where the risks are expressed as the expected fatalities per year.

FN-criteria are mostly defined by two properties; namely the intersection with the y-axis and the slope of the criterion line. The slope of the criterion line describes risk aversion. Risk aversion is the additional public opposition to an event which kills a large number of people over a series of smaller events which collectively result in the same number of fatalities. Risk aversion is not only influenced by the accidents itself, but also by the attention brought about by the media and politics. An FN-criterion line with a slope of -1 represents a "risk neutral" society, while an increased slope, for example -2, is more stringent and describes "risk aversion".

In addition, the stringency levels of FN-criteria could be influenced by the As Low As Reasonably Practicable (ALARP) principle, where if the cost of a safety measure is disproportionate to the actual risk reduction, it is not reasonably practicable to accept more stringent criteria.

Internationally criteria have been developed for life safety risks associated with large scale facilities, including nuclear and offshore facilities and the transport of dangerous goods. Through investigation it was found that there are similarities between the criteria used in the different industries in terms of the anchor point and the slope of the criterion line. Generally a slope of -1, corresponding to risk neutrality, is regarded as good practice. According to Ball and Floyd (1998) there is no compelling rational for incorporating risk aversion into the criteria.

The criteria for these industries may not be directly applied to dam safety since it may be impracticable to accept the same safety levels. In international dam safety, the application of life safety criteria in different countries are presented by ICOLD (2005). Many countries acknowledge that risk-based tools are useful within dam safety, but there are many contradicting views and opinions and some countries are hesitant to explicitly define FN-criteria for life safety.

In Australia, the Australian National Committee On Large Dams (ANCOLD) proposed FN-criteria for new and existing dams. Several other dam safety organisations, such as the New South Wales Dam Safety Committee (NSW-DSC) also in Australia and the U.S. Army Corps of Engineers (USACE) in the USA, have based their criteria on the ANCOLD criteria. In this study it was therefore decided to compare South African dam safety criteria for risk to human life to the ANCOLD criteria. The following properties were observed from ANCOLD criteria:

- An internationally recommended slope of -1 is used.
- Different criteria are defined for new and existing dams, since the marginal cost of reducing the risk for an existing dam is generally more than for new dams. Thus, it is not reasonably practicable to reduce risks to life for existing dams to the same safety levels of new dams.
- The criteria have a lower probability of failure cut-off due to technology not allowing for the construction of dams with lower probabilities of failure, and thus it is not reasonably practicable to reduce dam safety levels to more stringent criteria.
- ANCOLD criteria are based on engineering judgement, and implicitly incorporate additional considerations, such as cost considerations for reasonable practice.

Evaluation of South African dam safety criteria for risk to human lives:

The Department of Water Affairs (DWA) quantitatively estimates life safety risks as the combination of the probability of dam failure and the population at risk (PAR) in case of dam failure. The PAR is the number of people exposed to the dambreak flood. These risks are evaluated against criteria presented on a PAR-diagram. However, international methods assess risk to life most commonly as the expected *fatalities* due to dam failure. This provided a challenge for evaluating South African dam safety criteria by comparing to ANCOLD criteria, since two different consequence measures are used.

DWA uses their own in-house developed models for predicting what portion of the population at risk would become lives lost, based on assumptions related to warning times available to the population at risk in the event of a dam break. The DWA criteria were therefore compared to ANCOLD criteria by finding the implied warning times needed for DWA criteria to correspond to ANCOLD criteria, i.e. for a certain probability of failure, the implied warning time needed such that the DWA predicted loss of life would correspond to that of ANCOLD.

The DWA criteria were compared to ANCOLD criteria for both new and existing dams. For existing dams, at high probabilities of failure, large warning times are needed for DWA criteria to adhere to ANCOLD criteria. These high warning times are not always realistically achievable and thus such DWA dams are accepted at less stringent safety levels than ANCOLD dams. At low probabilities of failure, the warning times needed for DWA criteria to correspond to ANCOLD criteria decreases and becomes very small. Consequently DWA overdesigns for low probability events.

A similar pattern was observed when the implied warning times needed for new dams were computed. As the probability of failure decreases, the implied warning times decrease. As expected, the warning times which are needed for the criteria to correspond are higher than for existing dams, implying that new DWA dams are accepted at less stringent safety levels than ANCOLD criteria for new dams. This is expected because DWA does not differentiate between new and existing dams in their acceptance criteria. Again, the large warning times required may not be achievable, implying that a higher risk to human life is accepted by South African dam safety criteria.

The DWA model for predicting loss of life was developed based on historical data for dam failures. However, the statistical basis is not documented and unknown. Other life loss prediction models are available internationally and it was suggested to validate the DWA prediction model by comparing to an international best practice prediction model.

The DeKay and McClelland (1993) model uses a regression approach to predict the loss of life in case of dam failure from the population at risk and assumptions related to the warning time, similar to the DWA model. An additional factor is incorporated by the DeKay and McClelland (1993) model, namely a force factor, accounting for the severity of the dambreak flood on the predicted life loss. Unlike the DWA model, it has a well-documented scientific basis which can be validated; it is based on the statistical analysis of actual historical data compiled from the 1950's onwards which applies to a wide range of population at risk, and the DeKay and McClelland (1993) predicted life loss compares well with the actual historical data.

The DeKay and McClelland (1993) predicted loss of life was compared to DWA predicted values for a range of population at risk and for different warning times. For both high force and low force flood conditions, the DeKay and McClelland (1993) model predicts the loss of life within a more narrow range than the DWA method. For high force conditions, DWA generally overpredicts the loss of life for small and medium warning times. This may lead to conservative decision making regarding life safety where severe consequences are expected. In this way DWA unwittingly incorporates risk aversion in decision making. For low force conditions DWA severely overpredicts the loss of life for small and medium warning times. Thus, the DWA predictions are too conservative for low force conditions where low consequences are expected. For large warning times, DWA generally underpredicts the LOL in comparison to DeKay and McClelland (1993).

The conservative life safety decisions implied by the DWA life loss prediction model may to some extent off-set the unconservative life safety decisions of DWA that is implied when the warning times needed for DWA criteria to correspond to ANCOLD criteria were computed. However, it is proposed that the current DWA life loss prediction model is replaced by the DeKay and McClelland (1993) model, since this life loss prediction model has a well-documented and rational scientific basis.

Further comparisons of the DWA criteria to ANCOLD were made by using the DeKay and McClelland (1993) prediction model to convert "population at risk" to "loss of life". In this way, DWA equivalent FN-criteria were developed which can be directly compared to ANCOLD criteria. Different DWA criterion lines were obtained, depending on assumptions regarding the available warning time and flood severity condition.

This result is unwanted as it implies a fundamental flaw in the currently used DWA criteria: while warning time and flood severity will influence the level of risk that is imposed by a given dam, the criteria that dictates what level of risk is deemed to be acceptable should be independent of the underlying characteristics of individual dams. The ALARP principle may be used as an argument to define different acceptability criteria for broad categories where reasonable practice may dictate less stringent safety requirements. This is for example the argument behind ANCOLD's different criterion lines for new and existing dams. However, warning time and flood severity certainly do not qualify as rational parameters that would influence reasonable practice in broad.

For a small warning time and high force conditions the DWA equivalent FN-criteria were less stringent than the ANCOLD criteria. Thus less stringent safety levels are implied by DWA criteria in cases where severe consequences are expected. For a large warning time and low force conditions, the DWA equivalent criteria were more stringent, which implies too conservative decision making in cases where low consequences are expected.

Further, the gradient of the DWA FN-criterion lines were steeper than -1, which is in opposition to the risk neutral slope of -1 which is generally accepted as good practice internationally.

Thus, several problems with the current formulation of DWA life safety criteria came to light by comparing to ANCOLD criteria. It is therefore suggested to eliminate these by switching to ANCOLD life safety criteria, which;

- Evaluates risk to life using fatalities as a consequence measure, which is most commonly used internationally. Using PAR as a consequence measure is fundamentally flawed because the number of fatalities which may come from the PAR is greatly dependent on factors such as warning time and flood severity, which is dam specific.
- The gradient of the ANCOLD criteria is -1, which implies risk neutral decision making, as recommended internationally.
- The criteria has a lower probability of occurrence cut-off and also defines different criteria for new and existing dams, thus incorporating measures of reasonable practicality.

Switching to ANCOLD would not imply an enormous change in the current DWA safety levels. However it would imply a more consistent treatment of risk across the board of different warning times and flood severity levels. Further, using ANCOLD criteria would not imply more risk analysis effort than what is currently required, since DWA already estimates the loss of life as part of their standard risk analysis procedures.

Societal Willingness To Pay (SWTP) as a lower bound constraint on dam safety levels:
The levels of investments into dam rehabilitation works are large. Further, since the rehabilitation works are essentially financed by society through public taxes or charges and these societal resources are limited, the investments should be worthwhile for society. If the cost of reducing the risk to human life is disproportionate to the actual reduction in risk to life through dam rehabilitation works, these resources may be redirected into other sectors, for example into health care, transportation services and education, which may better the quality of life of society, i.e. the same money may save more lives elsewhere.

Societal Willingness To Pay (SWTP) is a utility function which effectively determines the lower bound for investments into life safety required by society. It is based on the Life Quality Index (LQI) which jointly considers the social indicators of a nation, including the life expectancy at birth, GDP per person and the work to leisure time ratio, to give a measure of the quality of life of a society. An investment into life safety should lead to an improved life quality.

To apply SWTP to South African dam safety a reasonable SWTP values had to be used. In South Africa, the relationship between our life expectancy and GDP per person is an outlier compared to values obtained for other countries at similar levels of development. Our life expectancy is artificially low due to HIV and our GDP is artificially high due to our richness in mineral resources. In addition, the low employment rate in South Africa leads to the wrong interpretation of the work to leisure time ratio. In effect, these South African social indicators violate the underlying assumptions of the LQI derivation, and the SWTP-value for South Africa may not be a true reflection of our society's preference regarding investments into life safety. Instead, an Earth value for SWTP (ESWTP) developed by Faber and Virguez-Rodriguez (2011) was used in this study. The ESWTP is based on observations for more than 70% of the Earth population and conforms well to LQI principles.

Based on the ESWTP, criteria were developed for different case studies of dams for which DWA required rehabilitation works to define the lower bound for investments into life safety. The SWTP criteria developed for the different case studies were presented as criterion lines on an FN-diagram, and the risk to life for the case studies could be evaluated in terms of these criterion lines to determine if investments into life safety are required. Since the available best practice technologies for rehabilitation works are case specific, the investment cost for reducing risk to life depends on the dam under consideration and consequently different SWTP criterion lines are obtained for each dam. Fortunately, the positions of these lines were within one span (factor of 10) of each other, which implies a fairly low level of sensitivity of the SWTP criteria to factors such as the rehabilitation cost and the SWTP value, i.e. as long as these values are estimated within the correct order of magnitude, useful criteria may be derived.

Only two of the eleven case studies required rehabilitation works on the basis of the SWTP criteria.

The SWTP criteria only account for societal preferences for life safety. Further investments into safety should be made if it is required by other considerations, such as economic motivations for the existence of the facility, damage costs in case of dam failure or environmental implications. Thus, SWTP criteria cannot be used exclusively to evaluate dams for rehabilitation works, and these other factors should be taken into account. This could be done by using SWTP criteria in conjunction with the DWA criteria evaluating the acceptability of economic, environmental, social and socio-economic impacts of dam failure and the risk level of dams.

The level of additional investments may be dictated by the decision maker or owner of the facility on the basis of economic optimisation.

Economic optimisation as a decision tool for evaluating South African dams for rehabilitation: Economic optimisation requires evaluating the profitability of a project and ensuring that a maximum benefit is obtained at the lowest cost. It accounts for other considerations, in addition to the societal requirements for life safety, including economic motivations for which the dam is vital, damage costs of dam failure and compensation costs for lives lost due to dam failure. It typically dictates higher safety levels than what is required by SWTP. However, should the economic optimum be at a lower level than what is dictated by SWTP, the SWTP minimum safety level must be enforced.

The principles of economic optimisation were used to evaluate if investments into dam rehabilitation works were economically beneficial. The objective function for determining the monetary net benefit included the benefit of rehabilitating the dam and the investment cost of rehabilitation works. The benefit does not consider the incomes generated from the existence of the facility, but considers only the additional benefit derived from rehabilitation works, i.e. a reduced probability of dam failure which in combination with the cost of failure results in reduced expected cost of failure. The cost of failure include the estimated economic losses and the compensation costs for lives lost in case of dam failure. The compensation cost is determined as the product of the estimated lives lost and the Societal Value of a Statistical Life (SVSL) . SVSL is derived from the LQI concept, similar to SWTP. However, SWTP and SVSL should not be confused with each other. SVSL is the amount which should be compensated for each fatality, while SWTP defines the acceptable level for investments into life safety.

In each case study two decision alternatives were considered for economic optimisation, the do-nothing or rehabilitate alternative. The alternative with the highest monetary net benefit should be preferred. For the rehabilitate alternative the costs of rehabilitation works should be less than the benefit obtained through rehabilitation works for the alternative to be preferred.

Five of the eleven case studies required rehabilitation on the basis of economic optimisation. The DWA assessment reports for the other cases reveals that two cases did not really require rehabilitation based on DWA criteria (although a number of risks were judged to be fairly high in these cases). The four remaining cases were rehabilitated based on environmental, social, socio-economic and risk level considerations.

Case studies of South African dams evaluated in terms of proposed decision tools:

Eleven case studies of South African government owned dams that were originally recommended for rehabilitation works by DWA, were evaluated in terms of the three decision tools proposed for this study namely; ANCOLD criteria for existing dams, SWTP criteria and economic optimisation.

The risk to life for the case studies were mostly within the unacceptable region of the ANCOLD criteria, justifying the recommendation for rehabilitation works. ANCOLD primarily evaluates life safety but incorporates economic considerations in a non-explicit way.

When the case studies were evaluated according to SWTP criteria, which only takes societal preferences for life safety into account, the risk to life were mostly within the acceptable region of the criteria. Thus investments into rehabilitation works were not required, i.e. the lower boundary for life safety were satisfied.

For five cases the economic optimisation criteria required further investments into dam rehabilitation works, above the lower boundary defined by SWTP.

In effect, rehabilitation was not always recommended in terms of all three decision tools. Additional factors considered by DWA, such as the socio-economic, social and environment impacts of dam failure and the risk level, could and should also influence the decision to rehabilitate. Therefore, the three decision tools should not be used as the only decision support tools for rehabilitation works.

Since economic optimisation in most cases recommended higher safety levels than what is required by society through SWTP, criteria which effectively incorporate these observations into the decision process are needed. Also, the current DWA evaluation does not take the cost of rehabilitation works into account in any way and this could be improved.

Recommended FN-criteria for evaluating DWA dams for rehabilitation works:

It could be argued that a three phase approach would be the best, where the acceptability of risk to life is first evaluated using SWTP, followed by economic optimisation as possible motivation to rehabilitate and finally incorporating environmental, socio-economic and social considerations into the decision. However, both of the first two tools require fairly involved calculations, since the investment cost for rehabilitation works and the expected failure cost have to be estimated as input parameters.

Instead it is proposed to replace the first two steps by a single-evaluation criteria, which accounts for both considerations and would be more convenient and easy to use. To this purpose FN-criteria were developed to primarily evaluate risk to life, but which implicitly incorporates the economic efficiency of rehabilitation works. The FN-criteria are fairly similar to ANCOLD criteria, but instead of using descriptive differentiation as in the case of ANCOLD ("new vs. "existing" dams), the ratio of the investment costs for rehabilitation works to the reduction in the probability of failure $C/\Delta P_f$ is used as an efficiency measure, based on which stringency levels for safety are required. If a large reduction in the probability of failure could be obtained at a small investment cost, the safety measure is economically efficient and it is reasonably practicable to reduce the risk to more stringent safety levels. In contrast, if only a small reduction in the probability of failure could be obtained at a large cost, the safety measure is not as efficient and thus it is not reasonably practicable to accept stringent safety levels. FN-criteria were developed with different levels of stringency for "small", "medium" and "large" efficiency ratios ($C/\Delta P_f$).

The case studies considered in this study were used to define practical ranges for the efficiency ratios. The "small" efficiency ratio was defined to coincide with the ANCOLD criterion line for new dams, the "medium" efficiency ratio with the ANCOLD criterion line for existing dams, and an additional "large" efficiency ratio criterion line, one factor of 10 less stringent than previous two were defined.

If the case studies are evaluated in terms of this newly developed criteria, rehabilitation works are required for all the cases, corresponding to the original DWA decision.

Based on the outcomes when the dams were evaluated in terms of SWTP and economic optimisation criteria, some dams should not have been rehabilitated. This could suggest an argument for moving the criterion lines to an even less stringent safety level, but for this to be properly motivated more case studies should be considered.

The above FN-criteria are proposed as a first step to evaluate dams for rehabilitation works. It is well-aligned with ANCOLD criteria which is based on good engineering practice and engineering judgement. The additional DWA considerations for rehabilitation decisions, including the economic, socio-economic, social and environmental impacts in case of dam failure as well as the risk level should be accounted for as a second step. Thereafter, if further validation is required, the SWTP and economic criteria could be considered additionally.

In summary, when evaluating South African dams for rehabilitation works, the diagram shown in Fig. 7.1 could be considered. The DWA estimated risks, as the combined probability and consequences of dam failure, could be evaluated against the FN-criteria proposed in this study, which primarily evaluates risk to life, but implicitly incorporates a measure of economic efficiency. In addition, the risks should be evaluated against DWA multiple acceptability criteria for economic, environmental, social and socio-economic impacts of dam failure and the risk level of dams. From these evaluations the rehabilitation decision could be recommended. If a more refined analysis is required, the risks together with a detailed estimated investment cost for rehabilitation works could be used to additionally evaluate the rehabilitation decision in terms of SWTP and economic optimisation criteria.

When developing criteria for life safety, it should be noted that life safety risks are highly complex. Life safety risks are estimated as the combination of the probability of failure and the consequence (in this study the loss of life in case of dam failure). Both of these factors are based on a joint consideration of analytical and historical aspects, requiring expert judgement. Consequently these factors are subject to high degrees of uncertainties. However, determining the life safety risks were beyond the scope if this study and instead the decision problem of what could be regarded as acceptable life safety risks was investigated.

To develop life safety criteria proves to be a difficult task since the values, needs and preferences of society need to be well comprehended. Fundamental principles, such as the principles developed by the Universal Declaration of Human Rights, as well as ethical principles for life safety should also be accounted for. Additionally, acceptable safety levels are not only dictated by societal preferences, but the preferences of the decision maker or owner could also influence the decisions in terms of the economic efficiency of the safety measures.

The tools developed in this study are therefore inherently associated with uncertainties, where there is always a possibility for refining the criteria. One way of doing this could be by incorporating more case studies of South African government owned dams in the development of the criteria.

The decision tools could also be applied to other fields in the industry. However, this could not be done directly, and the criteria should be calibrated to industry specific acceptable safety levels. It should also incorporate the available best practice technologies for reducing risks and the associated

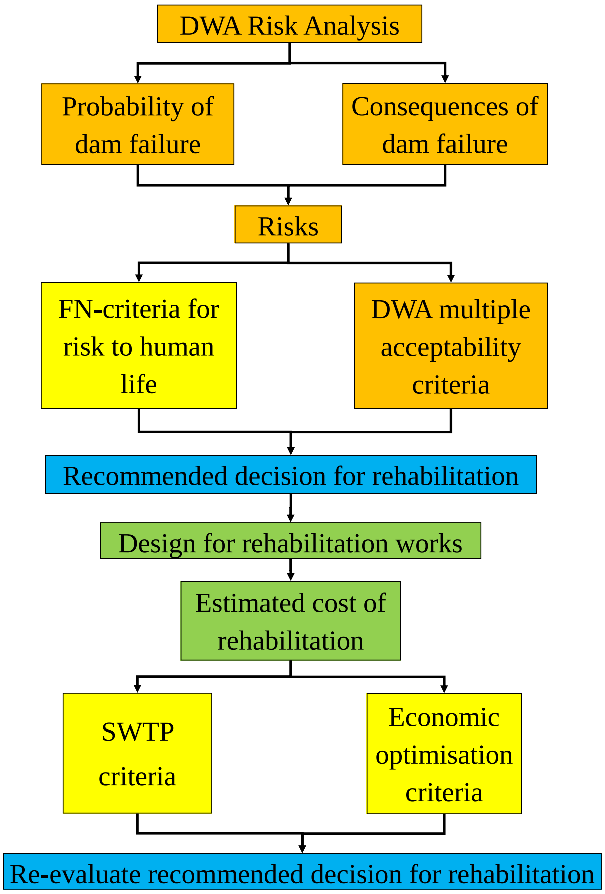

Figure 7.1: Proposed decision model to evaluate South African dams for rehabilitation works

costs within the specific industry.

The tools developed in this study do not serve as absolute criteria, but are guidelines, which should be considered in conjunction with engineering expert judgement. The criteria serve as useful tools for validating the decision to rehabilitate dams. In addition, these tools are useful for prioritising dam rehabilitation works. Through this, DWA could make informed decisions and efficiently allocate financial resources to the improvement of dam safety in South Africa.

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