REVIEW OF THE SELECTION OF ACCEPTABLE FLOOD CAPACITY FOR DAMS IN SOUTH AFRICA IN THE CONTEXT OF DAM SAFETY

J Cullis • A Görgens • S Lyons

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Water Research Commission

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by

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This report forms part of a series of reports. The other reports in the series are:

Görgens A.H.M., Lyons S., Hayes L., Makhabane M. and Maluleke D. 2006. *Modernised South African Design Flood Practice in the Context of Dam Safety* (WRC Report no 1420/2/07)

Görgens A.H.M. 2006. *Joint Peak-Volume Design Flood Hydrographs for South Africa* (WRC Report no 1420/3/07

WRC/Ninham Shand. 2006. *Dam Safety Hydrology Toolbox*[1]

DISCLAIMER

[1] The web-based Toolbox is available on the Ninham Shand web-site, or can be obtained on CD from Ninham Shand, PO Box 1347, Cape Town, 8000 (Tel. No. 021-4812400).

EXECUTIVE SUMMARY

This Report is intended to be used as a tool to assist the dam safety practitioner in the selection of acceptable flood capacity for dams in South Africa. Acceptable flood capacity (AFC) for dams can be defined as follows:

> *The overall flood capacity, including freeboard where required, which provides an appropriate level of safety during normal operating conditions and against flood initiated dam failure to protect the community and environment to acceptable risk levels, within the total context of overall dam safety from all load cases.*

The primary focus of this Report is a review of the *SANCOLD Guidelines on Dam Safety in Relation to Floods*, which outlines the currently recommended approach for the selection of AFC for dams in South Africa. This Review, which is one of the primary outputs from a WRC research project (K5/1420) entitled "Updated Guidelines and Design Flood Hydrology Techniques for Dam Safety", was compiled on the basis of a literature review, key stakeholder interviews, responses to a questionnaire of dam safety professionals and two workshops of dam safety professionals. Specific areas of the *Guidelines* that are considered include the general approach to dam safety assessment, the classification of dams, and the recommended minimum standards for generalised and site-specific dam safety assessments.

In addition to the general review, this Report also contains a summary of the findings from a number of technical investigations into specific aspects of the *Guidelines* and associated design flood techniques used in South Africa. These include a review of extreme rainfall methodologies, extreme flood methodologies, design flood methodologies, storm losses and the role of risk-based dam safety assessments. These investigations were also conducted as part of the WRC Project and the details are contained in a separate report entitled *Modernised South African Design Flood Practice in the Context of Dam Safety* (Görgens et al., 2006).

It is important to note that this Report is not intended to replace the existing *SANCOLD Guidelines*, but to assist in the application of these *Guidelines*. However, the findings of the Review and the associated technical research indicate that the *Guidelines* do need to be updated in a number of areas, or even possibly be replaced by a different approach to dam safety assessment in relation to floods in South Africa. This was not achievable as part of this Research report, but it is recommended that a technical committee be established by DWAF or SANCOLD, with support from the WRC, to take the preliminary findings of this Review of the *SANCOLD Guidelines* and produce a suite of updated Guidelines for the Selection of Acceptable Flood Capacity in South Africa.

It is important to note that this Review of the *Guidelines* should always be used in conjunction with expert and experience-based judgement, with reference to continuing professional development and in full knowledge of the limitations of, and concerns raised about, the processes and supporting methods proposed in the *Guidelines*. Methodologies, standards or processes described in this Report should in no way be regarded as a substitute for prudent engineering judgement in the selection of acceptable flood capacity for dams in South Africa.

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This Report has been developed through a process of consultation with members of the dam safety community of South Africa. These include dam owners in terms of municipalities and DWAF, the Dam Safety Office, other DWAF officials, selected practising engineers and hydrologists and approved professional persons. These professionals were canvassed through individual interviews, a questionnaire and a workshop to develop a Framework for Best Practice and a second workshop on Design Flood Methodologies. The Project Team would like to thank all those dam safety professionals who voluntarily gave up their time to assist in the development of this Report.

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LIST OF ACRONYMS

AEP	Annual Exceedence Probability
ANCOLD	Australian National Committee on Large Dams
DCFP	Design Capacity Flood Peak
DSO	Dam Safety Office
DWAF	Department of Water Affairs and Forestry
ICOLD	International Committee on Large Dams
MDCD	Maximum Design Capacity Discharge
MEFL	Maximum Extreme Flood Level
MMFP	Maximum Man-made Flood Peak
MNOL	Maximum Normal Operating Level
MSED	Maximum Safety Evaluation Discharge
PMF	Probable Maximum Flood
PMP	Probable Maximum Precipitation
QRA	Quantified Risk Assessment
RA	Risk Assessment
RDD	Recommended Design Discharge
RDF	Recommended Design Flood
RI	Recurrence Interval
RMF	Regional Maximum Flood
SED	Safety Evaluation Discharge
SEF	Safety Evaluation Flood
SANCOLD	South African National Committee on Large Dams
WRC	Water Research Commission
ZIIF	Zero Incremental Impact Flood

Part 1: Dam Safety in South Africa

1. INTRODUCTION

1.1 Background

South Africa has 3 991 registered dams as of the 31st March 2006 (DWAF, 2006). Approximately 56% of these dams were classified as small dams (maximum wall height of between 5 m and 12 m) with low hazard rating in terms of potential loss of life or damage to property, i.e. Category I dams. At the other end of the scale there are nearly 275 large dams (maximum wall height of more than 30m) with high hazard rating, i.e. Category III dams. South Africa has the highest number of large dams of all countries in Africa and is registered by ICOLD as one of the major dam building nations of the world. Due to the limited natural availability of water and the high degree of variability of rainfall, the country is highly dependent on these dams to ensure reliable supply of water for domestic consumption as well as to support the demands of all areas of economic development.

The structural failure of any of these dams would pose a significant threat not only to people and property downstream of the dam, but also to the communities and industries that depend on them for a reliable source of water, as well as the ecosystems of the rivers, wetlands and estuaries below these dams. South Africa has a relatively good record regarding dam failures. Since 1987, 164 cases of failure or severe damage have been recorded. All but two of these failures were for small, low hazard dams (i.e. Category I). In the few cases where fatalities have occurred, it has been only indirectly attributed to the failure of the dam. Of these incidents of failure, 39% have been attributed to inadequate spillway capacity. In addition 36% of the 887 dams evaluated between 1987 and 2001 were recorded as having spillway capacity less than required. Ensuring the safety of both new and existing dams in South Africa is of vital importance to all the people of this country; therefore, ensuring that dams have acceptable flood capacity is a priority.

1.2 Aims and Objectives

In 1991 the South African National Committee on Large Dams (SANCOLD) published the *Guidelines on Safety in Relation to Floods*. There have been a number of developments in the dam safety field, both locally and internationally, since these *Guidelines* were developed in the late 1980s. In recognition of this situation the Water Research Commission (WRC), with the support of the Dam Safety Office (DSO) of the Department of Water Affairs and Forestry (DWAF) and SANCOLD, appointed Ninham Shand to conduct a study (Project Number: K5/1420) with the following objectives:

I To establish updated guidelines for the safety evaluation of dams in relation to floods;

II To derive a methodology for design flood hydrograph estimation based on joint occurrence of flood peaks and flood volumes, through analysis of historically measured flood hydrographs in all regions of South Africa; and

III To develop a modernised set of design tools for the generation of complete flood hydrographs for dam safety evaluation or spillway design.

This Report addresses the first of these three aims and has been developed through a process of participation by a cross section of practitioners from the dam safety community and related professional stakeholders in South Africa. The second and third aims are addressed in a separate report, titled *Modernised South African Design Flood Practice in the Context of Dam Safety* (Görgens et al., 2006). This report is referred to as the *Research Report*.

1.3 Linkage to Existing and Future Guidelines

The point of departure of this Report is the SANCOLD *Guidelines on Safety in Relation to Floods* (SANCOLD, 1991), hereafter referred to as the *SANCOLD Guidelines*. It was recognised in the Preface to the *SANCOLD Guidelines* that, as more information and knowledge were developed, they would have to be revised. This Report represents the next step in this process of improving the tools available to dam safety practitioners for ensuring the safety of dams in South Africa.

In a survey of dam safety professionals, conducted as part of this Project in March 2004 (see **Appendix A**), it was found that, in general, the *SANCOLD Guidelines* have been useful in ensuring South Africa's relatively good dam safety record. There were, however, some minor concerns raised with the content of the *SANCOLD Guidelines*, as well as some very strong opinions on a few specific aspects.

Of the 21 respondents to the survey, the majority (61%) felt that the *SANCOLD Guidelines* needed to be updated, but that they only required a minor revision. This sentiment was re-enforced in a workshop attended by over 30 dam safety professionals, also conducted as part of this Project in October 2004 (see **Appendix B**).

It is recognised that the *SANCOLD Guidelines* will need to be updated, or possibly even replaced with some other suitable aid. This, however, was not possible under this project given the extent of the technical research still required to support the updating of the *Guidelines*. This led to a change in the objective of the Study from producing updated guidelines to producing a review of the existing *SANCOLD Guidelines*. This change in the objective of this Study was fully supported by the WRC Reference Group at it Meeting on 17th February 2006. It is recommended that a representative technical committee be established that can commission additional technical work and research based on the findings of this review. This committee will then be in a position to update the *Guidelines* or to produce a new set of aids for dam safety in relation to floods. This process would best be driven and possibly funded by the DWAF through the Dam Safety Office, and supervised by SANCOLD and the WRC.

Until new Guidelines are operational, this Review is meant to act as a tool to be used in conjunction with the existing *SANCOLD Guidelines* to assist dam safety professionals in determining the acceptable flood capacity for a proposed dam or an existing dam. This Review, as with all guidelines, should always be used in conjunction with expert and experience-based judgement, continuing professional development and in full knowledge of the limitations of, and concerns about, the processes and supporting methods presented in this Review and used by the practitioner. **Methodologies, minimum standards or processes described in this Review or any other Guideline can in no way be regarded as a substitute for informed, prudent engineering judgement.**

1.4 Methodology

The basic methodology used to develop this Review was as follows:

- A brief survey of the current state of dam safety in South Africa
- An extensive literature review looking at best practice with regards to dam safety in relation to floods in South Africa and from around the world.
- Interviews with key personnel at DWAF
- A survey by questionnaire of a wide range of dam safety professionals
- A workshop of dam safety professionals to discuss a framework for dam safety in South Africa
- Research into extreme flood and extreme rainfall determination methodologies used in South Africa with a particular focus on the PMP, PMF and RMF.
- Research into the development of an updated design flood methodology using joint probabilities of flood peak and flood volumes.
- A technical workshop to discuss the Review and the updated methodologies

In addition, regular input was given by the members of the WRC Reference Group who met on an annual basis to review the progress of the Project.

1.5 Report Structure

This Report is structured in four parts:

Part 1: Dam Safety in South Africa
Part 2: Review of the *SANCOLD Guidelines for Safety in Relation to Floods*
Part 3: Review of Design Flood Methodologies
Part 4: Recommendations for updating the *SANCOLD Guidelines*

The first part addresses the general situation with regards to dam safety in South Africa. This section includes information on the current regulatory structure and the existing records of dam failures in the country. It also contains a summary of the findings of a survey of dam safety professionals on the current attitudes towards dam safety in South Africa. Part 1 ends with a discussion on a proposed framework for dam safety in South Africa.

The second part looks at the *SANCOLD Guidelines for Safety in Relation to Floods* (SANCOLD, 1991). This part discusses the different components of the *Guidelines* and raises some of the issues and concerns relating to the application of the *Guidelines*.

In response to the review of the *Guidelines*, some applied research has been conducted into particular methodological aspects of the *Guidelines*. A summary of the findings of this research is presented in Part 3 with more detailed reports given in the report titled *Modernised South African Design Flood Practice in the Context of Dam Safety* (Görgens et al., 2006).

The final part of the Report outlines a number of recommendations for the updating of the *SANCOLD Guidelines in Relation to Floods*.

2. THE STATE OF DAM SAFETY IN SOUTH AFRICA

2.1 Current Dam Safety Legislation

Dam safety in South Africa is enforced by the following legislation:

- Chapter 12 of the National Water Act, 1998 (Act No. 36 of 1998)
- Regulations on Dam Safety published in Government Notice R.1560 of 25th July 1986

The National Water Act (NWA) is widely recognised as one of the most advanced pieces of water law in the world (World Bank, 2002). In order to bring the Regulations on Dam Safety up to date with the requirements of the new Water Act, the 1986 Regulations have been reviewed and updated by the Dam Safety Office (DSO) of the Department of Water Affairs and Forestry (DWAF). They should be available in the public domain in the near future (Chemaly, 2006, pers comm.).

The Regulations apply to all dams defined as dams with a safety risk. A dam with a safety risk is defined in the NWA (Section 117*(c)*(i)) as:

> "*any dam which can contain and store or dam more than 50 000 cubic meters of water,…and which has a wall of a vertical height of more than five metres,…*"

The Minister can also declare any other dam to be a dam with a safety risk according to Section 118(2) and 118(3)*(a)* of the NWA.

The Regulations outline the responsibility of the dam owners regarding the requirements for assessing the safety of a dam with a safety risk along with the requirements for other tasks such as designing, constructing, altering, repairing, impounding water in, maintaining, monitoring or decommissioning of a dam with a safety risk. The Regulations give wide powers to the Director-General and the Minister who acts through the DSO, as well as stipulating the requirements of Approved Professional Persons (APP), who are authorised to carry out dam safety inspections and design. The Regulations also list the requirements for both the design report for a new dam as well as the requirements for a safety evaluation of an existing dam. These requirements differ for the three categories of dams and it is important that these requirements are met before approval can be given for the construction of a new dam or the safety evaluation of an existing dam.

Unlike some other areas of engineering, design standards for dams have not been prescribed in the legislation. This is in recognition of the fact that each dam represents a unique combination of factors that influence the safety of the dam. It is therefore of paramount importance that the dam safety practitioner apply his or her mind to the specific conditions associated with the dam.

Aware of the necessity to provide guidance to those charged with evaluating the safety of existing dams as well as the designers of new dams, the South African National Committee on Large Dams (SANCOLD) issued a set of guidelines on Safety Evaluation of Dams:

- Report 1: *Interim Guidelines on Safety in Relation to Floods* (SANCOLD, 1986)
- Report 2: *Interim Guidelines on Dam Break Floods* (SANCOLD, 1990)

- Report 3: *Interim Guidelines on Freeboard for Dams* (SANCOLD, 1990)
- Report 4: *Guidelines on Safety in Relation to Floods* (SANCOLD, 1991)

In addition a draft for a fifth guideline entitled *Risk Analysis for Dams, A Review,* was prepared, but has yet to be finalised and published. At the same time a compendium of South African design flood determination techniques was produced (Alexander, 1990). Alexander's handbook brought together empirical, deterministic and probabilistic techniques for calculation of design flood, but his brief did not include the introduction of updates or significant improvements to the techniques used (Görgens, 2002). This handbook has been subsequently updated (Alexander, 2000), but again the techniques were simply reported and not updated. The result of this is that some of the techniques used to evaluate dam safety floods, such as the HRU 'unit hydrograph' method, are still only based on flood records pre-dating 1969 (HRU, 1972). In addition a number of newer techniques such as the SCS Method and the Run-hydrograph method are not included in the Handbook.

2.2 Registered Dams and Dam Failures in South Africa

The Regulations on Dam Safety became fully effective in South Africa on 25 January 1987. In the first year approximately 2250 dams were registered (Nortjé, 2002). Prior to this date and the formation of the DSO few records were kept of dam failures or major incidents in South Africa and as a result any attempt to analyse failures prior to this date is very difficult. Table 1 shows a list of recorded dam incidents prior to 1987 as compiled by Van den Berg and Birkenbach (1990). This classifies some 66 failures starting with the Springfontein Dam failure in 1869.

Table 1 Causes of Dam Failures or Severe Damage as Recorded prior to 1987

Causes of Dam Failure or Severe Damage	Number of Failures Registered	Percent of Failures	Percent of Dams with safety risk (Total = 2250)
Failure due to flooding	14	21	0.6
Erosion of bywash spillways of embankment dams	6	9	0.3
Erosion/undermining of foundation or abutment (concrete spillways and weirs)	3	5	0.1
Piping / internal erosion	13	20	0.6
Slope stability (embankment dams)	7	11	0.3
Failure of outlet pipe	1	2	0.0
Seepage problems	2	3	0.1
Failure during construction	7	11	0.3
Excessive settlement	7	11	0.3
Erosion due to wave action	1	2	0.0
Earthquake	2	3	0.1
Alkali-aggregate reaction	3	5	0.1
TOTAL	66	100	2.9

Since the introduction of dam safety regulation in 1987, the Dam Safety Office has been responsible for collecting information on reported dam failures and incidents and while this information is far more reliable than that prior to 1987, there are still a large number of minor dam failures and some quite large near-misses that do not get reported. There have been 164 recorded dam failures or major incidents in South Africa between 1987 and 2002 (Nortjé, 2002). The most common causes of dam failure are listed in Table 2.

Table 2 Causes of Dam Failures or Severe Damage as Recorded: 1987 to 2002

Causes of Dam Failure or Severe Damage	Number of Failures Registered	Percent of Failures	Percent of Dams with safety risk (Total = 3645)
Spillway capacity less than required	64	39	1.8
Erosion of bywash spillways of embankment dams	32	20	0.9
Erosion/undermining of foundation or abutment (concrete spillways and weirs)	13	8	0.4
Piping (often near outlet	20	12	0.5
Slope stability (embankment dams)	13	8	0.4
Failure of outlet pipe	7	4	0.2
Seepage problems	5	3	0.1
Failure during construction	3	2	0.1
Sabotage	2	1	0.1
Mud or sand boils downstream of dam toe	2	1	0.1
Excessive settlement	2	1	0.1
Erosion due to wave action	1	1	0.0
TOTAL	164	100	4.5

It is very difficult to say from these figures if the introduction of the Regulations on Dam Safety or the *SANCOLD Guidelines* has reduced the number of dam failures. What is striking is the high percentage of failures due to flooding and insufficient spillway capacity (21% prior to 1987 and 39% between 1987 and 2002). In addition a number of the failures during construction can be attributed to the flooding of the temporary cofferdams and diversion works. A further point that needs to be made is that of these 164 recorded dam failures only two of the dams were classified as Category II or III dams. One of these failed during construction and the other was not built to specification after the APP was not allowed to remain involved with the project (Nortjé, 2002).

In South Africa there has been relatively little loss of life as a result of dam failures. In cases when a dam failure has resulted in a death, it is often as a result of indirect consequences such as people trying to drive over a flooded bridge or accidents caused as a result of temporary diversions around a bridge or road damaged by flooding (Chemaly, 2003).

2.3 Recorded Dam Failures Internationally

The prevalence of overtopping as the main cause of failure in South Africa is reflected internationally. A summary by ICOLD of dam incidents up till 1986 (ICOLD, 1995) found that for earth and rockfill dams the most common cause of failure was overtopping (31% as primary cause and 18% as secondary cause) followed by internal erosion in the body of the dam (15% as primary and 13% as secondary) and in the foundation (12% as primary and 5% as secondary). Overtopping was also the most common cause of failure in masonry dams (43%) followed by internal erosion in the foundation (29%). For concrete dams, however, internal erosion and insufficient shear strength of the foundation each accounted for 21% of failures.

2.4 Recorded Deficiencies in Dam Safety Reports in South Africa

In terms of near misses, 2238 deficiencies have been reported in South Africa as a result of dam safety evaluations done at 1039 dams as of 31st March 2006 (DWAF, 2006). The most prominent of these are shown in **Table 3**. Approximately 31% of the dams assessed were found to have inadequate spillway capacity.

Table 3 Most prominent deficiencies identified through Dam Safety Assessment Report of 1039 dams as of 31st March 2006

Deficiencies Identified	Number Registered	Number Rectified
No O&M manual and/or EPP	847	377
Spillway capacity lower than present day criteria	318	77
Trees and vegetation to be removed	196	82
Excessive loss of water	109	27
Damage to spillway lining (cavitation or erosion)	74	20
Excessive settlement on embankments	72	21
Inadequate monitoring (instrumentation)	70	23
Burrowing animals	65	22
Erosion due to wave action (upstream)	62	15
Slope stability (earth and rockfill dams)	53	14
Stability inadequate (gravity and buttress dams)	52	18
Erosion at toe of dam wall or downstream	41	9
Outlet works equipment not functioning	30	8
Wet patches observed	27	16
Slope protection maintenance inadequate	24	10
Inadequate surface drainage or erosion by rainfall	24	10
High pore pressure/uplift forces/blocked drainage	20	5
Unserviceable outlet works	18	6
Damage to outlet works (cavitation)	16	3
Concrete strength loss (AAR swelling/ shrinkage/ aggregate)	15	4
Excessive cracks/differential movement (mass concrete)	15	5

2.5 Attitudes Towards Dam Safety in South Africa

In discussions with key personnel at DWAF and in a survey of twenty-one dam safety professionals conducted in March 2004 (See **Appendix A**) it was found that in general the respondents were happy with the current state of dam safety in South Africa. Most aspects of Dam Safety, including the current state in general, dam safety legislation, the capacity and consistency of the DSO and the performance of APPs, were given an average rank of about four out of five meaning "above average".

Respondents were less happy with the performance of the construction sector in dam safety and gave it an average rank of 3.2. The area of greatest concern was with the commitment to safety by the dam owners, which had an average rank of 2.6 (2 is "below average" and 3 is "average"). This concern was also highlighted in a number of the general comments by the respondents, particularly with regards to Category I dams, which do not require the services of an APP. Suggestions were made on the need to educate dam owners, and in particular farmers who construct small dams (Category I or smaller), on their responsibility for ensuring the safety of their dam, as well as the possibility of financial support to enable them to employ the services of a professional engineer.

Just over 50% of respondents to the questionnaire felt that there was insufficient agreement on what constituted best practice with regards to both dam safety in general and with regards to floods in particular. About 89% felt that this could be improved through updating the *Guidelines*, while 71% felt that more regular conferences or courses would help and 64% felt that a regular journal was a good idea. Other suggestions for improving the agreement on "best practice" included the distribution of interesting case studies by the DSO, the training and mentoring of junior engineers, and a more active involvement of SANCOLD along the lines of the Australian National Committee on Large Dams (ANCOLD).

Some of the recommendations for improving dam safety in South Africa and on developing a Framework for Best Practice that were drawn from the feedback received in the survey, the interviews and a literature review of the application of guidelines for dam safety in relation to floods, are given in **Box 1** and **Box 2**, respectively.

Box 1: Recommendations for Improving Dam Safety in South Africa

1. Encourage greater knowledge transfer amongst dam safety professionals and other stakeholders. This can by done by the organising of more regular conferences, workshops and continuing education courses, as well as the publishing of an annual newsletter by SANCOLD or the DSO detailing dam safety events during the year. The DSO already produces an annual report that could form the basis for this newsletter.

2. Aid in the development of junior dam safety engineers through supporting continuing education courses, the publishing of case studies/newsletters and the hosting of more regular conferences.

3. Engage the dam owners on their responsibility for the continuing safety of their dams, particularly small farm dams. This could be done by drawing them into the planned new structure of SANCOLD and through the distribution of the DWAF pamphlets on *Your Dam.*

4. Engage the insurers of dams and farmers in the debate on dam safety to make them aware of the regulations regarding dam safety, the requirements for good maintenance and the potential risks that unsafe dams pose to lives and the financial viability of farms. This would help to put financial pressure on dam owners to ensure the safety of their dams

5. Appoint a panel of experts who will review the guidelines on a regular basis (say every 5 years) based on a workshop/conference organised by SANCOLD and the DSO.

Box 2: Recommendations for Developing a Framework for Best Practice

1. Consider maintaining the core of the design and safety evaluation process outlined in the existing *Guidelines*.

2. Increase the role of Risk Assessment in line with the proposed requirements for risk assessment included in the latest update of the South Africa Regulations on Dam Safety.

3. Review the current requirements for RDF and SEF by comparing them to annual exceedence probabilities based on statistical analysis of observed floods and/or probable loss of life for a number of dam sites throughout South Africa.

4. Present the requirements for RDF and SEF in a consistent way that takes into consideration the characteristics of the individual catchments and dam type.

5. Develop guidelines on risk assessment for South Africa based on the Australian Guidelines as well as the current methods used by DSO and DWAF.

6. Re-enforce the link to guidelines on other aspects of dam safety, such as risk assessment, free board, dam break floods, operation and maintenance, geological and structural safety.

7. Investigate the relationship between RMF, PMF, 1 in 10 000 year flood, as well as suggested factoring of the RMF/PMF in the SANCOLD *Guidelines*, and annual exceedence probabilities using probabilistic analysis of observed flows for different regions in SA.

8. Develop a Framework of Best Practice and present it at a national workshop on dam safety. Use this workshop to derive the outline of an updated set of guidelines and further supporting information, as deemed necessary by the members of the Dam Safety community.

3. STRATEGIC FRAMEWORK FOR BEST PRACTICE

AFC	***Acceptable Flood Capacity*** **(ANCOLD, 2004)** *The overall flood capacity, including freeboard where required, which provides an appropriate level of safety during normal operating conditions and against flood initiated dam failure to protect the community and environment to acceptable risk levels, within the total context of overall dam safety from all load cases.*

The main objective for dam safety assessment in relation to floods is to ensure that dams are built and maintained with acceptable flood capacity. The above definition of acceptable flood capacity (AFC) is taken from the Australian National Committee on Large Dams (ANCOLD, 2004). This definition of AFC captures the key requirements for dam safety assessment in relation to floods and this Report subscribes to this concept and its definition.

In order to determine the requirements of AFC for a dam it is important to understand the strategic context in which this is to be done. This broader picture is presented as the *Strategic Framework for Best Practice for Dam Safety* shown in **Appendix C** that was developed during a workshop of dam safety professionals**.** The Framework comprises a number of Levels, or Frames, that start with the very general considerations defining the operating environment in which dam safety professionals have to function (Level 1) and work down to the finer details of the individual methods to be used in dam safety assessment and dam design (Level 6).

3.1 Level 1 and 2: Operating Environment and Key Principles

Level 1, the *Operating Environment*, comprises the realities of South Africa that constitute the world in which the dam safety practitioner must operate. Relating to this *Operating Environment* are a number *of Key Principles*, Level 2, that must be borne in mind during the dam safety assessment or dam design process. These *Key Principles* are essentially of a socio-political nature rather than a purely scientific nature as, ultimately, the level of safety required is decided on socio-political and economic grounds. Scientific information is required to inform this decision, but it is not based on the scientific information alone. One of the most important of these principles is that public safety is paramount.

3.2 Level 3: Regulatory System

The *Regulatory System*, Level 3, is the next frame surrounding the approach to dam safety assessment. While this forms part of the *Operating Environment*, it too is subject to the *Guiding Principles* of Level 2. The regulatory system for dam safety in South Africa has already been discussed earlier in this Report.

3.3 Level 4: General Approach

Level 4 describes the *General Approach* to dam safety assessment in South Africa. The points in the framework represent some of the key issues that were generated through the October 2004 Workshop of dam safety professionals (see **Appendix B**).

- Dam safety assessment in South Africa is currently based on recommended standards, but incorporates risk assessment as a pre-screen tool and as an additional check when required for site-specific calculations.
- Minimum Standards are not prescribed in legislation, but are recommended in guidelines and other guiding professional documents.
- Guidelines set recommended standards, but do not prescribe specific methods and allow for professional judgement to account for site-specific conditions.
- Conservative pre-screening is based on a generalised AFC check and is used to streamline the safety assessment process for small, low hazard dams.
- The hazard potential of a dam is measured in terms of loss of life, economic losses and potential threat to resource quality (i.e. the aquatic environment).
- Guidelines must be supported by continuing education and technical literature to enhance professional judgement and capacity building.
- Separate processes are recommended for the design process for new dams and for the safety assessment of existing dams.
- Specific procedures relative to each scientific/technical domain should be developed.
- With regards to the safety in relation to floods, two flood scenarios are considered: a design flood for normal operating conditions and a safety evaluation flood for extreme flood conditions.

3.4 Level 5: Processes

The *General Approach* to dam safety assessment described in Level 4, is operationalised through a set of supporting *Processes*, Level 5. Each individual scientific/technical domain relevant to dam safety assessment and design has a separate set of processes that must be followed. These are represented as sub-frames in **Appendix C**. These domains interface in the integrated assessment of the overall safety of a dam, which in itself requires a separate set of procedures to be carried out. As mention above, however, there is merit in looking to integrate these domains throughout the safety assessment process, but this would require a move to a more risk based approach to dam safety assessment.

This Report focuses on the currently recommended processes and procedures for the *floods* domain of dam safety assessment. These are presented in the SANCOLD *Guidelines for Dam Safety in Relation to Floods* (SANCOLD, 1991). The aim of this Report is to review the recommended procedures and standards contained in the SANCOLD *Guidelines* and do some limited applied research into particular aspects of the *Guidelines* with a view towards supporting the future updating of the SANCOLD *Guidelines*. Currently there are not guidelines to assist dam safety professionals in the procedures required in the other technical domains and it is recommended that development of such guidelines be considered particularly in light of the capacity constraints facing the future of dam safety professionals in South Africa.

Each *Process* has a number of procedures for which different methods (Level 6) of analysis, design and assessment will be required. The relationship between Processes and Methods is not the same as between the other levels in the framework. While the dam safety professional will generally follow a route through from the outer frames to the inner, more detailed, frames, the route between the processes and methods is not one-directional, as each process will have a number of procedures with specific supporting methods. As a result, the dam safety professionals will be continuously moving between the *Processes* frame and the *Methods* frame as each procedure is performed using the most appropriate method, before they move on to the next procedure in the process.

3.5 Level 6: Supporting Methodologies

Level 6 is essentially a toolbox of methods that the dam safety professional can call on for a specific procedure. South Africa already has a well-developed set of existing methods for design flood determination for dam safety assessment comprising deterministic, empirical and statistical methods, as well as methods that look to integrate the assessment of dam safety under each of the scientific/technical domains in terms of risk at a screening level. Part of this Report looks into the suite of methodologies currently available to dam safety professionals with regards to extreme rainfall, extreme floods and design floods. In most cases there will be a number of methods to choose and it is left up to the professional judgement of the practitioner to ensure that he makes use of the most appropriate method for the specific requirements of the dam and its location.

Part 2: Review of the SANCOLD Guidelines in Relation to Floods

4. BACKGROUND TO THE REVIEW OF THE SANCOLD GUIDELINES

The primary objective of this section of the Report is to review the current *SANCOLD Guidelines on Safety in Relation to Floods* (SANCOLD, 1991). This is done by briefly discussing the following key components:

- The General Approach to Dam Safety Assessment
- The Classification of Dams
- Generalised Safety Criteria
- Site Specific Safety Criteria

The chapters that follow contain more detailed discussions on the use of the RMF and PMF, issues relating to extreme rainfall estimation techniques, and the role of risk assessment as these were found to be some of the key areas of concern with the existing SANCOLD *Guidelines*.

Mr Alan Chemaly (2001) provided the project team with notes on some of the other "uses" and "abuses" of the SANCOLD *Guidelines* based on his experience in the Dam Safety Office. These are listed below:

- Catchment area incorrect because not double checked
- Use of suites of computer programmes as a "black box"
- "Plug-and-chug". Use of empirical formulae (e g. RMF) by inserting parameters, calculation of floods, and acceptance of a result without further consideration of order of magnitude etc.
- "Mixing of codes". For example the Q50 or Q100 is calculated from HRU 1/72 and an "adjusted" RMF for small catchments is calculated using QT/RMF ratios in Appendix 6 and 7 of TR 137
- "Blind use" of floods from dam safety inspection reports for other applications without checking the floods.
- Lack of appreciation of the value of "sensitivity analysis", i.e. more interest in the size of flood only rather than "differences" in water levels with changes in flood.
- Not sufficient guidance on determination of the SEF in small catchments
- Use of only RDD (or RDF) and SED (or SEF) floods for spillway evaluation. No consideration given to the maximum capacity of a spillway “back calculated” to an incoming flood of QT.
- Depth and duration of overtopping of dams not adequately addressed.
- Acceptance of dimensions of spillways without a check when dam safety inspections are carried out.
- Use of discharge coefficients for ogee spillways when evaluating a flat open channel spillway.
- A "rampant" tendency to use the smallest flood possible to satisfy a client who wants to spend as little as possible, and expects the best service/product.

5. GENERAL APPROACH FOLLOWED BY THE SANCOLD GUIDELINES

5.1 Standards-based Approach

The approach to the selection of AFC presented in the *SANCOLD Guidelines on Safety in Relation to Floods* (SANCOLD, 1991) is predominantly "standards-based", as opposed to "risk-based". His is the accepted practice in a number of countries, but the growing support for risk-based safety assessments, particularly for the safety evaluation of an existing dam, has resulted in risk being incorporated in a more significant manner in guidelines for dam safety assessment in various countries.

Risk analysis is part of the existing SANCOLD *Guidelines* (Section 3.4.4 of SANCOLD, 1991), but its use is representative of the attitude towards risk assessment at the time that they were developed. Much has changed in the attitude towards risk assessment as part of dam safety and its role in the dam safety guidelines needs to be reviewed (see **Appendix F** for a more detailed discussion on risk based dam safety assessments).

5.2 Different Flood Scenarios

In a standards-based approach the AFC is determined by checking the spillway capacity against a set of recommended minimum standards. In most countries, including South Africa, these standards are set for two flood scenarios as follows:

- **Design flood** conditions during which, provided normal maintenance work is executed on a regular basis, the spillway operates without damage to any of its components or to the associated dam structure.

- **Extreme flood** conditions during which the spillway operation may result in substantial damage to its components and/or to part of the dam structure but would not result in catastrophic failure of the dam.

5.2.1 Freeboard Requirements for Design Floods

One of the main differences between the design flood and the extreme flood (or safety evaluation flood) scenarios is the allowance for freeboard. In the design flood scenario freeboard must be considered while in the extreme flood case it is not required. The extent of the freeboard required under the design flood scenario can be determined by making use of the *Interim Guidelines on Freeboard in Dams* (SANCOLD, 1990b).

Total Freeboard
The vertical distance between the normal full supply level (FSL) and the nominal non-overspill crest of the dam, excluding chamber, but including adequately designed parapets and wave barriers proud of the crest. Freeboard is usually divided into two components, namely the flood surcharge rise above FSL, the primary component, and a secondary component allowing for wind, wave and surge effects.

The most important factors to be considered when determining the required freeboard are:

- Wind generated waves
- Wind set-up
- Seiches (resonance)
- Flood surges
- Landslide-induced waves
- Earthquake-induced waves

There was some debate during the workshop of Dam Safety professionals as to whether the design flood should even be considered as part of the safety evaluation procedure. It was, however, decided that the checking of the design flood and associated freeboard allowance was an important part of checking the overall flood capacity of the dam and should therefore remain part of the process. In some cases the design flood scenario could be more critical than the extreme flood scenario if the appropriate freeboard is recognised. This highlighted the importance of considering the design flood requirements as part of the dam safety assessment process and the concern that some practitioners were not taking the requirements for freeboard seriously enough. It was recommended that the current *Interim Guidelines on Freeboard* (SANCOLD, 1990) should also be reviewed and updated if necessary.

5.2.2 Consideration of Man-made Floods

Another important point that was raised at the workshop of dam safety professional was the need to consider man-made floods. This is particularly important for the lower dam in a pump-storage scheme, but would also apply to any dam downstream of another dam. Failure of the upper dam could create a significant man-made flood that could cause a domino effect if the lower dam has insufficient spillway capacity to handle the flood. Other areas of concern would be off-channel storage dams, which could overtop if the pumps filling the dam fail to stop when the full supply level is reached.

5.3 New and Existing Dams

In the *SANCOLD Guidelines on Safety in Relation to Floods* the selection of AFC for both the design of a new dam, and the safety evaluation of an existing dam, were considered in the same process. This has the advantage of resulting in a relatively simple flow diagram. It may, however, be worth considering separate flow diagrams for new and existing dams in future updates of the *Guidelines* to enable more details and intermediary steps to be incorporated.

Flow diagrams that could be considered for the two separate processes are shown in **Appendix E** and **Appendix F**. These are based on the same general approach as the current *Guidelines*, but have taken into account some of the suggestions made during this review process. In addition it is recommended that a separate process be developed for the safety evaluation of dams that are to be decommissioned. This is in line with the proposed new Regulations for Dam Safety, which require a safety assessment as part of the application for decommissioning of a dam.

5.4 General and Site Specific Calculations

Most dam safety guidelines, including the *SANCOLD Guidelines*, make use of a generalised pre-screening step to reduce the burden of determining the AFC for small, low hazard dams. All dams should be subject to the pre-screening generalised AFC check, but dams that have insufficient flood capacity, or are high hazard dams, or are medium and large dams with a significant hazard rating, require more detailed site-specific calculations that must consider a family of design and safety evaluation hydrographs rather than just consideration for the flood peak.

The dam safety professionals consulted in this project were in agreement that pre-screening based on generalized safety criteria was important in that it recognised the need to be efficient in terms of time and resources, but that it was important to subject larger and more hazardous dams to more detailed investigations. There was, however, a range of opinions on the recommended standards given for both these levels of safety evaluation. It was felt that the recommended minimum standards given for the various flood scenarios were the crux of the SANCOLD *Guidelines* and need to be addressed in future updates.

5.5 Risk Analysis

The current *SANCOLD Guidelines* do give the opportunity for practitioners to make use of risk analysis in the site-specific calculations. As mentioned above, however, there has been much development in the field of dam safety risk assessment and analysis that is not captured in the current description of risk analysis.

Risk analysis is included in the SANCOLD *Guidelines* as an *alternative* method for the site-specific check of the AFC, and this has been used by some practitioners in South Africa for a more risk-based dam safety assessment rather than as an alternative to a site specific calculation based on the recommended standards for the SEF.

Anticipated changes in the new Regulations, will address this concern by putting more emphasis on risk assessment and giving the DSO the option of requesting a risk assessment for any Category II or III dam.

5.6 Zero Incremental Impact Flood

A further alternative method for the site-specific check of the AFC is the calculation of the Zero Incremental Impact Flood (ZIIF).

ZIIF	***Zero Incremental Impact Flood*** **(SANCOLD, 1990)** *The flood that would just cause the dam to fail, but would not be such as to cause a significant increase in the downstream damage or potential loss of life.*

The method for determining the ZIIF is outlined in the *SANCOLD Guidelines*. There are, however, some concerns that the methodology described is not consistent with the methodology used to determine the ZIIF in other countries. This needs to be considered when using this approach and in the future updating of the SANCOLD *Guidelines*.

Few practitioners currently make use of the opportunities afforded to them in the SANCOLD *Guidelines* of using risk assessment or the ZIIF to check the AFC of a dam. It is recommended that in future updates of the *Guidelines*, the role of risk assessment and the ZIIF be strengthened in this regard.

6. CLASSIFICATION OF DAMS IN SOUTH AFRICA

In the standards-based approach to selecting the AFC, the first step is the classification of the dam. In South Africa, the first level of classification is in terms of the requirements of the National Water Act of 1998. The dam safety requirements of the National Water Act and the Dam Safety Regulations only apply to dams that are defined as a dam with a safety risk. A dam with a safety risk is determined initially in terms of dam wall height (greater than 5 m) and volume (greater than 50 000 m^3), but the Minister, through the DSO, has the power to declare any dam as a dam with a safety risk.

National Water Act (RSA, 1998), Chapter 12, Section 117:

(c) "dam with a safety risk" means any dam -

- *i: which can contain, store or dam more than 50 000 cubic metres of water, whether that water contains any substance or not, and which has a wall of a vertical height of more than five metres, measured as the vertical difference between the lowest downstream ground elevation on the outside of the dam wall and the non-overspill crest level or the general top level of the dam wall;*
- *ii: belonging to a category of dams declared under section 118(2) [i.e. by the Minister in the Gazette] to be dams with a safety risk; or*
- *iii: declared under section 118(3)(a) to be a dam with a safety risk [i.e. by the Minister in writing to the dam owner*

All dams that are defined as a dam with a safety risk are further classified according to the Regulations in terms of size and hazard potential rating. In this review the system of classification in the current Regulations and hence in the current *SANCOLD Guidelines* was found to be consistent with similar approaches used in other countries.

The current size classification (**Table 4**) appeared to be satisfactory (although it was pointed out that there are likely to be a large number of dams measuring just less than 5 m in height!).

Table 4 Size classification in the *SANCOLD Guidelines*

Size Class	Maximum wall height in metres (m)
Small	More than 5 m but less than 12 m
Medium	Equal to or more than 12 m, but less than 30 m
Large	Equal to or more than 30 m

The number of dams in each size class registered in South Africa, as of 31st March 2006, is shown in **Table 5** (DWAF, 2006).

Table 5 Distribution of dams registered according to size class

Size class	Number	%
Small (5 m – 12 m)	3132	72.6%
Medium (12 m – 30 m)	998	23.1%
Large (30 m and higher)	183	4.2%
Total	**4313**	100

The number of dams registered in South Africa, as of 31st March 2006, according to reservoir storage capacity is shown in **Table 6** (DWAF, 2006).

Table 6 Distribution of registered dams according to reservoir storage capacity

Capacity (x 10^6 m^3)	Number	%
0,05 - 0,10	1079	25.0%
0,10 - 0,25	1573	36.5%
0,25 - 1,00	1042	24.2%
1,00 - 10,00	429	9.9%
10,00 - 100,00	128	3.0%
100,00 +	62	1.4%
Total	**4313**	**100**

During this Review a number of concerns were raised with the current hazard classification system in the *SANCOLD Guidelines* shown in **Table 7**.

Table 7 Current hazard classification in the *SANCOLD Guidelines*

Hazard Potential	Potential Loss of Life	Potential Economic Loss*
Low	None	Minimal
Significant	Not more than 10 lives	Significant
High	More than 10 lives	Severe

* For classification purposes potential economic losses less than R2 million and more than R20 million (1991) would be considered “minimal” and “great” respectively.

Some of the concerns with this hazard classification system are as follows:

- There is no consideration of the potential damage to “resource quality”, which is in contrast to the objectives of the National Water Act.
- The type and method of construction or present structural conditions of a dam and its history of surviving large floods are not considered.
- There needs to be more of an explanation with regards to the different levels of hazard potential. This was particularly relevant to the potential threat to life.

The first of these concerns is addressed in the proposed new Regulations, which includes the potential impact on the resource quality in the hazard classification table. The potential impact on resource quality is classified as low, significant and severe.

To address the second concern, some countries such as France (DEFRA, 2002) and China (Liu, 2002) adopt different safety flood requirements for concrete and embankment dams. In some cases, in South Africa, exceptions are made for dams that have been standing for many years, even if they do not have acceptable flood capacity in terms of the recommended standards in the SANCOLD *Guidelines* (Section 3.8 of the *SANCOLD Guidelines*).

In a risk-based system these dam-specific factors are incorporated into the estimation of the probability of failure based on the specific response of the dam to the identified threat. They can also be taken into account in a standards-based approach by specifying a recommended range of possible minimum requirements and factors that should be used to decide within the range. It is recommended that these considerations be taken into account when determining future AFC standards.

To address the third concern, it is recommended that future guidelines contain more detailed descriptions of various hazard classes. The DSO currently has its own guidelines for classifying dams, particularly with regards to roads that may be in the path of the dam break flood. These guidelines should be formalised either by way of separate guidelines on hazard classification or at least in terms of more generic descriptions of the different hazard classes in future guidelines for dam safety assessment.

An example of such a more detailed description of a specific hazard potential classification is given in **Table 8**, which is the description used to describe a dam with a high hazard potential. This example comes from the dam safety guidelines of British Columbia in Canada. The three categories for classification in this case mirror the South Africa categories of potential loss of life, potential economic loss and the threat to resource quality, which is to be introduced with the proposed new Regulations.

Table 8 Example of Downstream Hazard Classification - British Columbia, Canada.

HAZARD POTENTIAL	Loss of Life	Economic and Social Loss	Environmental and Cultural Loss
HIGH	Some potential for multiple loss of life involving residents, and working, traveling, and/or recreating public. Development within inundation area typically includes highways, railways, commercial and working areas, locations of concentrated recreational activity and scattered residence. Estimated fatalities less than 100	Substantial economic losses affecting infrastructure, public and commercial facilities in and beyond inundation area. Typically includes destruction or extensive damage to concentrated commercial land uses, highways, railways, power lines, pipelines, and other utilities. Scattered residences may be destroyed or severely damaged. Estimated direct and indirect (interruption of service) costs could exceed $1 million.	Loss or significant deterioration of nationally or provincially important fisheries habitat (including water quality), wildlife habitat, rare and/or endangered species, unique landscapes or sites of cultural significance. Feasibility and/or practicality of restoration/or compensation is high.

Future guidelines on hazard potential classification should not only include more detailed descriptions of the various hazard classes based on the consequences of failure, but should also consider vulnerability and adaptive capacity, which will have a significant impact on the potential risk a dam poses to society. In this regard it is important to consider bringing risk concepts into the hazard classification system. The guidelines should also encourage the use of advances in Geographic Information Systems (GIS) to produce hazard potential maps from dam-break flood analysis.

7. CATEGORISATION OF DAMS

Having determined the size and hazard class of the dam, the Category of dam is determined according to **Table 9**, which appears in both the Regulations and the *SANCOLD Guidelines*. This Review encountered no concerns about this specific table and it appears to conform well to international best practice. Again, the Minister, through the DSO, has the power to change the category of dam, based on site-specific considerations, should it be deemed necessary to ensure public safety.

Table 9 Categorisation of dams having a safety risk in *SANCOLD Guidelines*

Size Class	Hazard Potential Rating		
	Low	Significant	High
Small	Category I	Category II	Category II
Medium	Category II	Category II	Category III
Large	Category III	Category III	Category III

The Category of dam is then used to determine the requirements in terms of the design and safety evaluation report for the dam, as defined in the Regulations, and forms the basic framework for the selection of the AFC in a standards-based approach to dam safety as currently practised in South Africa. The setting of different standards for different categories of dams was considered to be an efficient way of addressing dam safety by placing more effort and responsibility on the processes relating to Category II and III dams.

A breakdown of the total numbers of dams in each class and each category currently registered in South Africa (as of March 2006) is given in **Table 10** and **Table 11**, respectively and is shown graphically in **Figure 1** (DWAF, 2006).

Table 10 Classification of existing dams according to size class and hazard potential rating (31st March 2006)

Size class	Hazard potential rating			Total
	Low	Significant	High	
Small	2199 (55.1%)	724 (18.1%)	40 (1%)	**2963 (74.2%)**
Medium	279 (7%)	469 (11.8%)	133 (3.3%)	**881 (22.1%)**
Large	2 (0.1%)	17 (0.4%)	128 (3.2%)	**147 (3.7%)**
Total	**2480 (62.1%)**	**1210 (30.3%)**	**301 (7.5%)**	**3991 (100%)**

Table 11 Category classification of existing dams (31st March 2006)

Category classification	Number of dams	%
Category I[2]	2232	55.9
Category II	1484	37.2
Category III	275	6.9
Total	**3991**	**100**

[2] Thirty-three of these dams are actually medium size dams that have been classified as Category 1 by the DSO due to the low hazard rating.

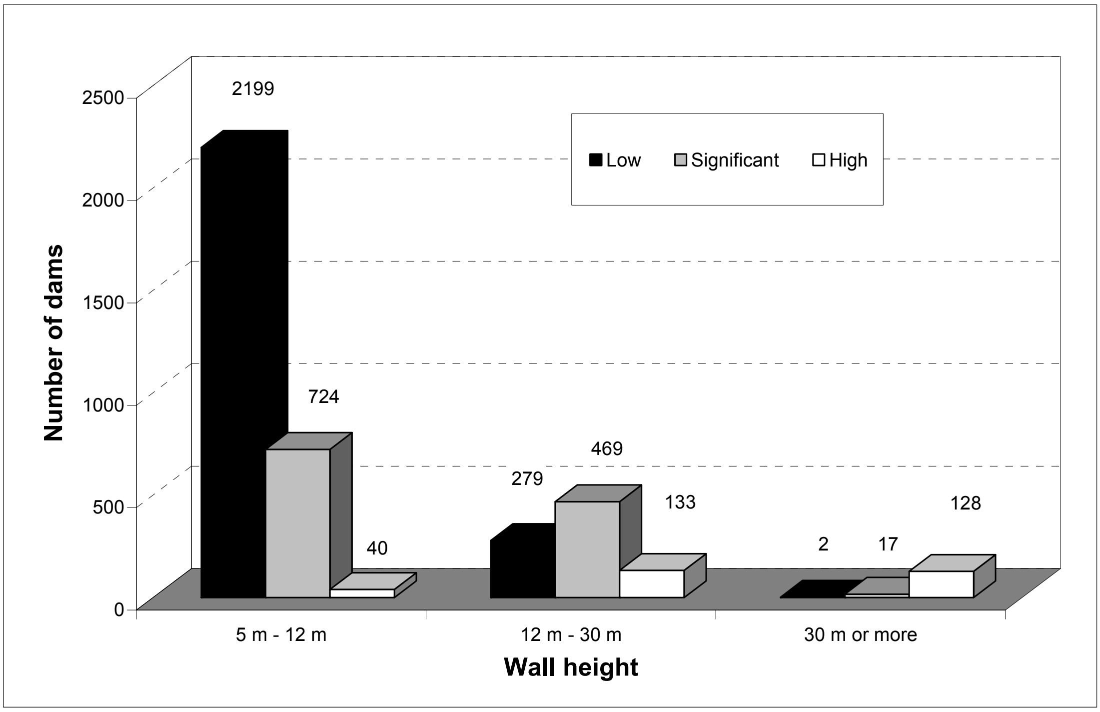

Figure 1 Classification of existing dams according to size class and hazard potential rating (31st March 2006)

A concern that was raised in this regard was the large number of Category I dams and that these were the dams that tended to be most prone to failure. The potential consequences of these failures are admittedly much less severe than for Category II and III dams, but is was still felt that more emphasis needed to be placed on ensuring the safety of these smaller dams. It was, however, felt that this could not necessarily be achieved through updating of the SANCOLD *Guidelines*. The concerns related more to the attitude of the owners of these small dams and the problems with effectively regulating them rather than to improper design or safety evaluation standards.

8. GENERALISED ACCEPTABLE FLOOD CAPACITY CRITERIA

The aim of the generalised AFC check is to act as a pre-screening step to reduce the burden of determining the AFC for small, low hazard dams. This pre-screening step is based on a simple generalised process, where only the maximum flood peak and maximum discharge through the spillway under both design and extreme flood scenarios are considered. For the generalised safety criteria the *SANCOLD Guideline* specifies minimum flood capacity requirements in terms of the Recommended Design Discharge (RDD) and the Safety Evaluation Discharge (SED).

8.1 Recommended Design Discharge

The SANCOLD *Guidelines* give a minimum standard for the RDD as a flood peak of a certain recurrence interval (RI) that can be passed by the spillway during normal operating conditions.

RDD	***Recommended Design Discharge*** **(SANCOLD, 1990)** *The Recommended Design Discharge is the level pool peak discharge, which has the relevant value shown in [**Table 12**] and provides the preliminary basis for checking the design of the spillway system for a new or an existing dam. The spillway system must accommodate the RDD without damage. The requirement is conditional, however, in the case of an existing dam.*

Table 12 Suggested Return Periods for the RDD

Size Class	Hazard Potential		
	Low	Significant	High
Small	20 - 50	100	100
Medium	100	100	200
Large	200	200	200

The method recommended in the *SANCOLD Guidelines* and currently used by the majority of practitioners to determine the RDD is derived from the relevant Regional Maximum Flood (RMF) given in DWA Technical Report 137 (Kovacs, 1988) (although there are a number of other methods available for determining the RDD). The RMF, which replaces the earlier "Creager-value" method still used in some parts of the world (Liu, 2002), has been calculated by applying the Francou-Rodier (1967) empirical regional envelope method to southern African conditions (Kovacs, 1988). This method uses observed extreme floods in a region to determine a regional K value that relates catchment area to maximum flood discharge. The individual return period floods are then calculated by applying a regionalised relevant factor to the appropriate RMF (Kovacs, 1988).

There have been concerns that in certain areas this method over-estimates the flood discharge when compared to both deterministic and probabilistic approaches. Görgens (2002), for example, re-evaluated Kovacs's data set using a more appropriate plotting formula in accordance with the UK Flood Studies Report (1975) and concluded that, on average, for K-value regions 5.0-5.6, it appeared that the 1:50, 1:100 and 1:200 year estimates may need to be factored down by 0.7, 0.8 and 0.9, respectively.

As part of this Study, the results of the RMF factoring method were compared to probabilistic derived design flood peaks for a number of dam sites and flow gauges across the country. It was found that in a number of cases the RMF factors require revision.

DWAF has also found that on a number of occasions the design floods calculated using the RMF factoring method differ significantly from those calculated using a variety of other methods. These observations tend to show that the RMF factoring method is more conservative, i.e. gives a higher peak value for a given return period than other methods (Van der Spuy, 2004).

Despite these concerns, the RMF method provides a useful tool for pre-screening purposes, as it is familiar to practitioners, gives quick results that are repeatable, and is known to be very conservative, as it is derived from an envelope of extreme flood values. The exceptions tend to be for small catchments in the transition zone (i.e. less than 100 km^2 in K-value regions 4.6, 5, 5.2, 5.4 and 5.6, less than 300 km^2 in K-value regions 3.4 and 4, and less than 500 km^2 in K-value region 2.8), as well as in predominantly urban catchments. In these cases the practitioner is advised to consider using an alternative method such as the Rational Method, the SCS Method, or the probabilistic extrapolation of observed flood peak data to determine the design flood peak with the required RI.

8.2 Safety Evaluation Discharge

In accordance with the *SANCOLD Guidelines*, the SED is given in terms of the RMF, which is calculated according DWA Technical Report 137 (Kovacs, 1988). The SED for different categories of dams is determined by scaling the RMF up or down as shown in **Table 13**, where subscript (-Δ) means choose the K-value region numerically one step lower, and subscript (+Δ) means choose the K-value region numerically one step higher, than that in which the dam site is located.

SED	***Safety Evaluation Discharge* (SANCOLD, 1990)** *The Safety Evaluation Discharge (SED) is the level pool peak discharge, which has the relevant value recommended in [**Table 13**] and provides the initial screen for checking the adequacy of the spillway system of a new or an existing dam under extreme flood conditions. Although substantial damage may result from occurrence of the SED, the design must be such that the dam will not fail*

Table 13 RMF-based value for the SED given in the SANCOLD Guidelines

Size Class	Hazard Potential Rating		
	Low	**Significant**	**High**
Small	$RMF_{-\Delta}$	$RMF_{-\Delta}$	RMF
Medium	$RMF_{-\Delta}$	RMF	$RMF_{+\Delta}$
Large	RMF	$RMF_{+\Delta}$	$RMF_{+\Delta}$

A number of concerns have been raised during this review regarding the linkage between the SED and the RMF. These include:

- the data set of flood peaks used to calculate the RMF in TR 137 ended in 1987 - subsequent floods in certain areas have meant that the K value has already had to be adjusted upwards in five regions;
- the statistical inconsistency represented by the -Δ and +Δ factoring method (i.e. in the region for K = 4, +Δ implies an increase in the K value of 15% to K=4,6, while in the region for K= 5, +Δ implies an increase in the K value of only 4% to K=5,2);
- the unknown safety factor implicit in the fitting of an envelope curve to the RMF data;
- the inconsistency in the RMF in terms of recurrence interval for different parts of the country;
- the limited applicability of the RMF in small or urbanised catchments.

To address the first concern some preliminary investigations have been done to check Kovacs' envelope curves with more recent flood events, as part of this Study. The results indicate that there are a number of cases where the envelope curves have been exceeded by subsequent events. This is particularly the case in K-value regions 3.4, 5, 5.4 and 5.6 as shown in **Table 14**.

Table 14 Number of Gauges in Record with Maximum Flood Peaks Exceeding the Regional Envelope Curves from TR137

K-region	No of stations	No of stations exceeding Kovacs' curve
3.4	3	2
4	2	0
4.6	18	0
5	54	1
5.2	12	0
5.4	1	1
5.6	1	1

To accommodate these possible changes the proposed new dam safety regulations define the RMF in terms of the original Francou-Rodier equation stating that the practitioner must use the currently accepted values for the co-efficients for the particular area of concern. These coefficients would either be from TR137 (Kovacs, 1988), results such as Görgens (1990), a review of existing or new flood records, such as that conducted for this Study, or other appropriate research.

There was some debate on the potential to replace the $RMF_{-\Delta}$ and $RMF_{+\Delta}$ factoring method with a simple proportion of the RMF. This proposal, however, was rejected by the Technical Workshop on 8th May 2006 as it was considered to be statistically incorrect. If anything the factor should be applied to the K-value in the equation and not to the flood RMF flood peak. It was therefore decided to keep the current system of factoring the SED for different categories of dams, but it is an area that warrants further investigation.

In terms of addressing the concern over the level of safety incorporated in using the RMF, some initial research has been done as part of this Study on determining an average RI or AEP for the RMF. The results of this study are given in **Table 15** and discussed in more detail in **Section 11** of this Report.

Table 15 Estimated Recurrence Intervals for the RMF related floods

Probability Distribution	Design Flood	Median RI (years)	Lower 95 Percentile RI (years)
Log-Pearson Type III	RMF	6 000	100
	$RMF_{+\Delta}$	18 800	200
	$RMF_{-\Delta}$	1 200	50
GEVpwm	RMF	3 000	200
	$RMF_{+\Delta}$	6 000	400
	$RMF_{-\Delta}$	900	50

9. SITE-SPECIFIC ACCEPTABLE FLOOD CAPACITY CRITERIA

The *SANCOLD Guidelines* require, that if a dam fails the generalised AFC check, or is a new high hazard dam, or a medium or large dam with a significant hazard rating, then it is obligatory that site-specific analysis is the basis for the evaluation of the safety status under extreme flood conditions. The level of detail required for site-specific calculations varies between Category II and III dams and is outlined in the Regulations, but the same procedures apply. The main differences between the generalised AFC check and the site-specific AFC check are:

- Instead of using a generalised empirical flood determination technique, such as the RMF, techniques are used that utilise physical data from the specific catchment under consideration.
- Instead of looking only at the flood peak, site-specific evaluation is concerned with the entire hydrograph, or family of hydrographs, for the design and safety evaluation flood and the ability of the dam to pass these through the spillway system.

9.1 Recommended Design Flood

For the design flood scenario, the SANCOLD *Guidelines* require that the dam must pass the recommended design flood (RDF) with a recurrence interval similar to that of the RDD.

RDF	***Recommended Design Flood* (SANCOLD, 1991)** *When site-specific hydrological calculations are required, the term flood (implying a hydrograph) is used rather than discharge (implying unrouted level pool outflow possibly requiring to be routed). The RDF is a single flood hydrograph or a family of hydrographs having return periods suggested in* [**Table 16**] *and must, after routing, be accommodated by the spillway system without damage. (Again in the case of an existing dam the requirement is conditional)*

Table 16 Recommended Return Periods for the RDF given in the *SANCOLD Guidelines*

Size Class	Hazard Potential		
	Low	Significant	High
Small	20 – 50	100	100
Medium	100	100	200
Large	200	200	200

The shape and the duration of the flood hydrograph will have a significant impact on the maximum flood level in the reservoir and for this reason it is important that a family of hydrographs be considered, before selecting the one that results in the highest reservoir level to be used as the design flood for determining the AFC of the dam.

The degree of flood attenuation in the reservoir, and therefore the potential benefit to be derived from flood routing, can be assessed by estimating the flood volume likely to be associated with a single flood event. If the flood volume is large relative to the volume of available surcharge storage, i.e. the volume between the spillway crest and non-spillway crest levels, flood routing would probably not have any significant effect on the spillway dimensions.

Görgens (1990), seeking a quick guide to the necessity or otherwise of routing, examined a couple of dozen or more cases for which level pool routing had been performed. The regression of the peak discharge attenuation ratio (Q_{out}/Q_{in}) on the area ratio in the following equation was found to have a correlation coefficient of 0.82:

$$\frac{Q_{out}}{Q_{in}} = 0.99 - 5.56\frac{A_r}{A_c}$$

where: A_r is area of reservoir at full supply level (FSL)

A_c is area of catchment commanded by the dam.

Thus if the area of the reservoir at FSL is as great as 10% of the area of the catchment, attenuation, i.e. (1 - Q_{out}/Q_{in}), could be as high as 57%. **It is important to note that the above equation gives a measure of the potential impact of routing, and is not a suitable equation to be used to determine the final impact of routing.** For this an appropriate routing equation should be used.

A number of methods can be used for calculating the RDF. Unlike the RDD, there are no purely empirical methods for determining the RDF except possibly to take the RI factored RMF and apply a simple triangular hydrograph based on multiples of the time of concentration. This method, however, is not recommended except maybe for very small, low hazard dams. Some of the approaches currently used in South Africa for determining the RDF are listed below:

- Deterministic Methods
  - Rational Method (peak only) (Alexander, 1990)
  - Modified Rational Method (peak only) (Alexander, 2003)
  - SCS Method (full hydrograph) (Schmidt and Schulze, 1987)
  - Unitgraph (full hydrograph) (HRU, 1972)

- Hybrid Methods
  - Run-hydrograph method (full hydrograph) (Hiemstra, 1972)
  - Joint peak-volume method (full hydrograph)[3] (Görgens et al., 2007)

Of concern is the fact that such a range of methods tends to give a range of design flood values and can be influenced by the subjective decision-making of the practitioners. There appears to be no current agreement on what constitutes best practice, although some of the methods have been found to give better results in specific situations. For this reason, it is important that careful thought be put into the selection of appropriate design flood determination methods.

It is further recommended that **at least two design flood methods should always be used** and that reasons for selecting the final design flood hydrograph or set of hydrographs be clearly

[3] This proposed new flood hydrograph generation methodology has been developed as part of this study and is reported on in more detail in the Görgens et al (2006).

stated. When selecting a family of design hydrographs, it is important to also consider double-peaked hydrographs, as these have on occasion been found to be more of a threat to the safety of a dam than single-peaked floods with a higher peak.

9.2 Safety Evaluation Flood

For the site-specific AFC check of the extreme flood scenario, the SANCOLD *Guidelines* require that the dam must be able to pass the SEF without causing the dam to fail.

SEF	***Safety Evaluation Flood* (SANCOLD, 1991)** *Again, where site-specific hydrological calculations are required, the SEF is the flood hydrograph which after routing through the reservoir system may bring the dam to the point of failure but the resulting damage, although substantial, must not be such as to cause failure of the dam. The RMF-based values given in* [**Table 13**] *provide guidance to choice of peak of the hydrograph for the relevant size and hazard rating but independent methods must be employed to verify whether or not the RMF basis leads to acceptable realistic flood values.*

The recommended standard for the SEF is given in the *SANCOLD Guidelines* as follows:

"For MEDIUM and LARGE HIGH hazard dams and LARGE dams of SIGNIFICANT hazard, the incoming hydrograph shall be the PMF. For dams of smaller size and lesser hazard the PMF may be downrated proportionately to the interrelationship of corresponding SED values…" (SANCOLD, 1991, p34)

This Review has found that this statement provides one of the major areas of concern regarding the *SANCOLD Guidelines*. It is noted that the above statement is considered to be an "instruction" and not a guideline. It implies that the only method for determining the SEF is to use the PMF. There are, however, a number of concerns with the use of the PMF and the factoring of the PMF as implied by the above statement. This requirement of the SANCOLD *Guidelines* does not allow the practitioner to apply their professional judgement and to utilise some alternative method that they feel might be more appropriate in a given situation. As guidelines are often interpreted as codes in a court of law, there is a concern that there is no scope for the application of engineering judgement in cases when the PMF is not appropriate for the calculation of the SEF.

The PMF is defined as a flood event with close to zero annual exceedence probability. In South Africa the standard method for determining the PMF is to determine the probable maximum precipitation (PMP) using HRU 1/72 and then to apply some deterministic technique for converting the PMP to a PMF based on maximising the conditions for the catchment. The primary methods used for determining the PMF from the PMP are as follows:

- Rational Method (peak only) (Alexander, 1990)
- SCS Method (full hydrograph) (Schmidt and Schulze, 1987)
- Unitgraph (full hydrograph) (HRU, 1972)

A variety of methods for determining the PMF are used in other countries, but most of these are similar to that adopted by HRU 1/72.

There are, however, a number of concerns with the use of the PMF both locally and internationally. Some of these concerns are listed below:

- The deterministic calculation of the PMF implies some physical upper limit to flood-producing rainfall.
- The HRU PMF is not true to the definition of the PMF as a "minimum probability flood", but is in fact a "maximum probable flood", as it is derived from an envelope of maximum observed values of storm rainfall.
- The deterministic PMF is based on some upper envelope of observed values (storm rainfall in the case of HRU 1/72), which needs to be continually checked and updated (see **Section 10**).
- There is very little information available on storm losses during extreme events and the runoff percentage envelopes proposed in HRU 1/72 are highly subjective and have been questioned during this Study (see **Section 12**).
- The deterministic derivation of the PMF from the PMP is highly subjective and can differ substantially, depending on the assumptions made by the practitioner and the specific method used.

Despite these concerns the PMF is still the most commonly used flood for the safety evaluation flood internationally, although there have been some concerns raised in the USA about the rationale of designing dams to pass the PMF, which is seen as being unreasonably conservative (Graham, 2002).

To address some of the above concerns with the PMF, initial research has been conducted in this study into particular aspects of the PMF. These are discussed in later sections of this report and focus on:

1. Reviewing the PMP envelope curves used in HRU 1/72 to ascertain if these have been exceeded by recent heavily rainfall events.
2. An investigation into the storm losses from heavy rainfall events across the country.
3. An initial investigation into the RI or AEP of the PMF (and RMF) using a variety of probabilistic techniques to extrapolate observed flood data.

Given the concerns with the factoring of the SED for lesser dams in terms of RMF and $RMF_{+\Delta}$ or $RMF_{-\Delta}$, as discussed in Section 4.5.2, some practitioners do not adhere to the requirements of the *SANCOLD Guidelines on Safety in Relation to Floods* for determining the SEF for Category I and II dams, but revert back to the minimum standards given in the *Interim SANCOLD Guidelines on Safety in Relation to Floods* (SANCOLD, 1986). These recommended minimum standards are given in terms of multiples of the PMF (or the RMF), as shown in **Table 17**. This is also the case for small and urban catchments where it is not appropriate to use the RMF.

Table 17 Recommended Return Periods for the SED and SEF from the *SANCOLD Interim Guidelines on Safety in Relation to Floods* (Table 5.1)

Size Class	Hazard Potential		
	Low	Significant	High
Small	0.4 x RMF 0.2 x PMF	0.7 x RMF 0.5 x PMF	1.0 x RMF 0.7 x PMF
Medium	0.7 x RMF 0.5 x PMF	1.0 x RMF 0.7 x PMF	1.5 x RMF 1.0 x PMF
Large	1.0 x RMF 0.7 x PMF	1.5 x RMF 1.0 x PMF	1.7 x RMF 1.1 x PMF

Given the variability in the PMF values derived through different methodologies, it is important that the practitioner should consider carefully the different methodologies used. If necessary, a range of methodologies should be considered to determine the critical set of extreme flood hydrographs that satisfy the minimum criteria for the SEF. As with the RDF, it is important to also consider double-peaked hydrographs.

To address some of the concerns with regards to the use of the PMF, ANCOLD has developed a methodology for determining a safety evaluation flood used as a "fall-back flood" if the preferred risk-based approach is not possible. The recommended standards for the SEF are given for different levels of hazard classification in terms of the PMF, the "PMP design flood" or a flood with a specified AEP ranging from 10^{-2} to 10^{-6} (ANCOLD, 2000).

The difference between the PMF and the PMP design flood is that the PMP design flood is the flood derived from the PMP using AEP-neutral assumptions, while the PMF is described as the flood resulting from the PMP coupled with the worst flood-producing catchment conditions that can reasonably be expected. To determine the specified AEP floods they use a method that assigns an AEP to the PMF-based value and then links this to the maximum flood that can be determined at the limit of probabilistic extrapolation of the available data (e.g. the 1:100 year flood). The floods with the required assigned AEP are then read off this extrapolation. A similar method has been developed by Rowbottom et al. (1986) for use in the UK that considers the slope between the 1:100 year flood and the 1:50 year flood when assigning an AEP to the PMF.

It is proposed that a similar approach be considered for use in South Africa. Based on the observation of design and safety evaluation flood criteria from other countries, as well as the results of some of the preliminary research into the estimated recurrence interval of the RMF and PMF in South Africa done as part of this review, it is proposed that the minimum standards given in **Table 18** be considered for the assigned AEP for the various categories of dams.

Table 18 Possible Standards for the SEF in Terms of Assigned Annual Exceedence Probabilities Proposed by the Project Team

Size Class	Hazard Potential		
	Low	Significant	High
Small	**10^{-2} to 10^{-3}**	**10^{-2} to 10^{-3}**	**10^{-3} to 10^{-4}**
Medium	**10^{-2} to 10^{-3}**	**10^{-3} to 10^{-4}**	**10^{-4} to 10^{-5}**
Large	**10^{-3} to 10^{-4}**	**10^{-4} to 10^{-5}**	**PMF or $>10^{-5}$**

It is proposed that the deterministically derived PMF continues to be used for the large high hazard dams and that this be assigned an AEP of between 10^{-4} and 10^{-5}. Note that the median RI for the PMF using the GEVpwm probability distribution was found to be equal to approximately 1:30 000 years (i.e. an AEP of between 10^{-4} and 10^{-5}). The assigned AEP for the other categories of dams refers to the flood determined using the abovementioned approach of linking the assigned AEP of the PMF to the maximum flood at the limit of probabilistic extrapolation of the available data, or to the slope of the line between the 1:50 and 1:100 year floods.

It is proposed that the assigned AEP for medium sized dams with significant hazard rating be between 10^{-3} and 10^{-4}. This is based on the estimated median RI for the RMF being found to be equal to approximately 1:3 000 years.

It is important to note that these standards and the proposed methodologies are mere proposals by the Project Team and still need to be sufficiently considered by the dam safety community before they, or similar values and methodologies could be considered as a replacement (or alternative) to the current standards in which the SEF is derived in terms of the PMF and the current system of factoring the PMF in relation to the ratio of RMF to $RMF_{-\Delta}$ or $RMF_{+\Delta}$.

Part 3: Applied Research on Design Flood Methodologies

10. REVIEW OF EXTREME RAINFALL METHODOLOGIES

10.1 Introduction

For South Africa, the only established guidelines for the estimation of PMP are those set out in the HRU 1/72 Report (HRU, 1972). Although the HRU presents a conservative and pragmatic approach for the estimation of PMP, it is also based on only about 30 years of rainfall data from 1932 to the 1960s. Since the 1960s, however, South Africa has experienced several large flood events, some of which caused extreme damage and loss of life. The aim of this research (under WRC project K5/1420), was to check the HRU PMP envelope curves for both large – and small-area storms against estimates based on the latest available rainfall data and, where necessary, propose improvements or sound warnings to practitioners using the HRU PMP envelope curves in design.

10.2 Methodology

For the checking of the HRU PMP curves for large-area storms (Figures D2-D28 of HRU 1/72), six large storms were selected based on literature information and institutional knowledge. These storms as well as their date of occurrence are shown in **Table 19**.

Table 19 Selected Large-Area Storms

Storm Event	Date
South Eastern Cape	1981
Laingsburg, Karoo	1981
Cyclone Domoina Floods	1984
KwaZulu-Natal Floods	1987
Orange River Basin	1988
Limpopo Floods	2000

For each storm a detailed site-specific analysis was performed where the storm isohyets were ultimately produced for the critical duration/s. To be able to draw the isohyets, rainfall data for all the rainfall stations identified within the region of the storm was obtained using a database developed by Lynch (2004) and by using the Daily Rainfall Extraction Utility developed by Kuntz (2004). The rainfall record was then inspected and the critical storm duration/s identified. The spline method in ARCVIEW, which is similar to inverse distance weighting, was then used to draw the isohyets. The storm boundary was identified. This was accomplished by considering one of the following three methods:

- Defining the storm boundary by HRU Meteorologically similar regions (only possible if the storm completely covered a HRU region)

- Defining the storm boundary by taking a proportion of the peak (rainfall in excess of one-third and two-thirds of the peak rainfall)
- Defining the storm boundary by identifying the storm cells

Each storm was assessed and a decision was made as to which boundary method would be considered. Once the boundary of the storm was identified, the average-areal rainfall could be calculated from the isohyets. The average-areal rainfall at a particular storm duration was then plotted against the appropriate HRU PMP envelope curve (identified by HRU region) of maximum probable precipitation (mm) versus area (km^2). **Figure 2** is an example of such a plot that was produced for the KwaZulu-Natal floods of September 1987, where critical storm duration of 1-day, 2-days and 3-days were considered and where the storm boundary was defined by HRU region (Region 13).

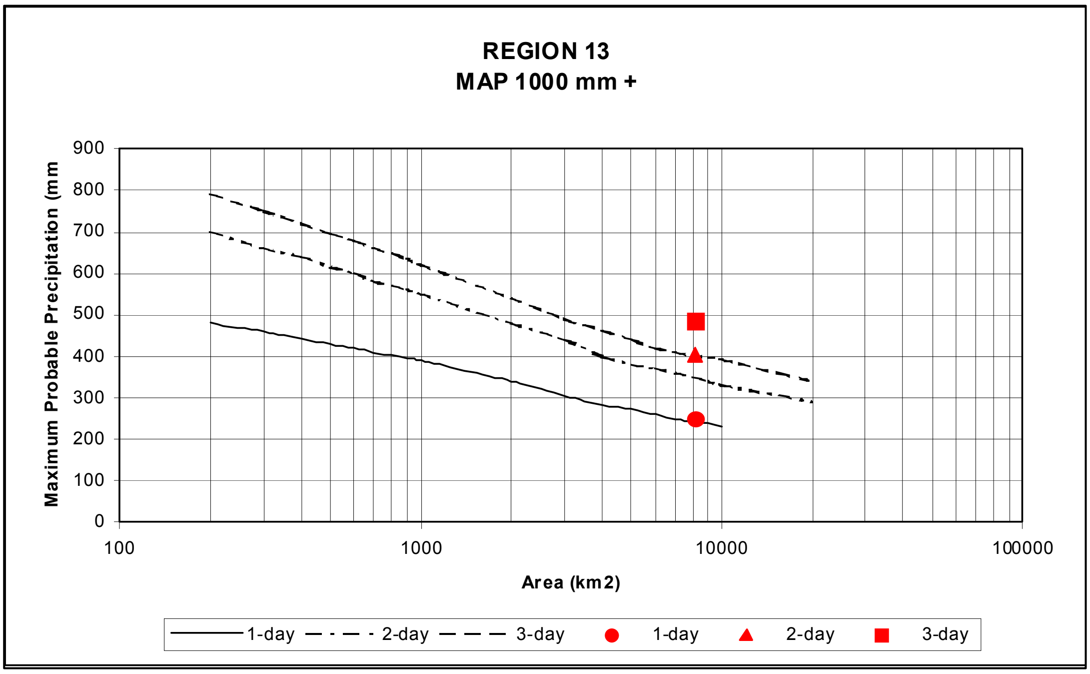

Figure 2 HRU PMP envelope curves for Region 13 (1000 mm+) with 1-day, 2-day and 3-day duration rainfall for the September 1987 storm

For the estimation of the PMP for short durations, the HRU 1/72 provides an experience diagram comprising of envelopes of the highest point precipitation for various storm durations observed in different regions of the country (HRU Figure C.4). An envelope curve for the entire country is also provided. As a preliminary check of these envelope curves, the maximum point rainfall observed in the storms identified above for various durations were plotted against the respective curves. An example of such a plot is shown in **Figure 3** for Cyclone Domoina and the KwaZulu-Natal floods.

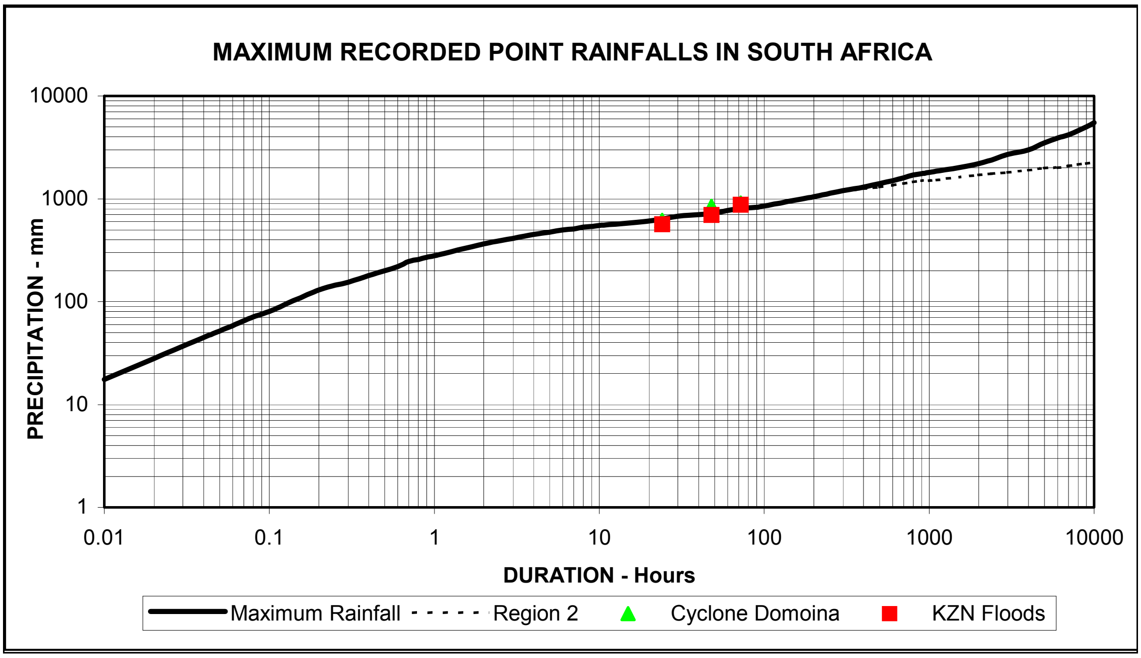

Figure 3 Maximum point rainfalls for Cyclone Domoina and KwaZulu-Natal Floods plotted against small-area storm curves for Region 2 and the Maximum Point Rainfall envelope curve

10.3 Conclusions

For the large-area storm analysis, the HRU PMP envelope curves were exceeded on a number of occurrences. In particular, the KwaZulu-Natal floods of 1987 stand out. These floods were the result of a cut-off low, which is a fairly commonly occurring South African weather system.

The results obtained in the analysis for large-area storms are summarized in **Table 20**, where a tick indicates that the HRU PMP envelope curves were exceeded and a cross indicates that they were not exceeded. The number of crosses is slightly deceiving, in that although the HRU PMP curves were not exceeded, the storm rainfalls were approaching the curve.

These results suggest that the HRU PMP envelope curves for Large-Area storms may be underestimating the maximum precipitation which could occur in a number of regions in South Africa. The impact may be greater than the results shown due to the fact that the HRU PMP envelope curves were developed from maximised and transposed storms, while the storms used in this research have not been maximised or transposed. For the small-area storms, the maximum envelope curve for the entire country (HRU 1/72 Figure C4) was exceeded by the current data on three occasions and the regional curves approached or exceeded on four instances. This once again highlights that the HRU envelope curves may be underestimating the short duration extreme rainfall.

In light of the above findings, there is obvious concern that the PMF may be underestimated using the HRU 1/72 PMP curves. Therefore, until the HRU PMP envelope curves can be modernised to include a longer and more current portion of rainfall data, the hydrological practitioner should practice due care when applying the current curves for the estimation of the PMF.

Table 20 Summary of results obtained for Large-Area storms

Flood	Year	HRU Region affected	METHOD USED TO DETERMINE STORM BOUNDARY									
			HRU Region				Proportion of peak			Storm cells		
			1-day	2-day	3-day	4-day	1-day	2-day	3-day	1-day	2-day	3-day
Cyclone Domoina[4]	1984	Region 17 (500 – 1000 mm)				✓						
Limpopo	2000	Region 18 (250 – 500 mm)		✓		✗						
				✗								
		Region 18 (500 – 1000 mm)		✗		✗						
				✗								
Orange River Basin	1988	Region 10 (250 – 500 mm)								✓	✗	
										✗	✗	
KwaZulu-Natal	1987	Region 13 (1 000 mm+)	✓	✓	✓		✓	✓	✓	✓	✗	✗
Laingsburg	1981	Region 5 (0 – 500 mm)								✗	✗	
		Region 6 (250 – 500 mm)								✗	✗	
South Eastern Cape	1981	Region 6 (250 – 500 mm)	✓	✗	✗							

✓ = HRU PMP curve exceeded
✗ = HRU PMP curve not exceeded

[4] Cyclone Domoina was not analysed by covering a complete HRU region, however, the method of analysis is closest to this method.

11. REVIEW OF EXTREME FLOOD METHODOLOGIES

11.1 Introduction

The requirement in the *SANCOLD Guidelines on Safety in Relation to Floods* that the SED and the SEF be determined in relation to the RMF and the PMF, respectively has for some time been a major area of debate in the dam safety community. A selection of the concerns with the use of the RMF and PMF encountered are listed below:

- The data set of flood peaks used to calculate the RMF in TR 137 ended in 1988. Subsequent floods in certain areas have meant that the K-value has already had to be adjusted upwards in five regions.
- The K-values developed from an envelope of observed extreme floods incorporates an unknown and subjective factor of safety that may not be consistent between regions.
- The calculation of the PMF implies some physical upper limit to flood producing rainfall (PMP).
- The data used to develop the PMP estimates in HRU 1/69 and 1/72 considered only about 30 years of rainfall records from 1932 to 1962. Since the 1960s, however, South Africa has experienced numerous large flood events, the rainfall for which may have exceeded these PMP curves.
- There is a high degree of subjectivity in terms of selecting key catchment characteristics and flood hydrograph generation techniques, which, at a specific site, can lead to a wide range in estimates of the magnitude of the PMF.
- The proportioning of the PMF or RMF for different categories of dams as recommended in the *SANCOLD Guidelines* is mathematically inconsistent with probability theory generally used in design flood determination.
- The RMF is considered to give unreliable results for small catchments or ones that are predominantly urban in nature.

To address some of the concerns raised about the use of the RMF (including its variants $RMF_{+\Delta}$ and $RMF_{-\Delta}$) and the PMF, research was undertaken under this Project to attempt to link a recurrence interval (RI), or annual exceedence probability (AEP) to these design floods using South African flood data. By expressing the PMF in terms of an AEP, for example, it is hoped that some degree of consistency will be introduced into the estimation of the SEF. It is also hoped that by the use of AEPs, consistency between the SED and SEF can be achieved, which is currently lacking in the *SANCOLD Guidelines*. The potential to move away from RMF and PMF based criteria to AEP based criteria is also in line with the increasing use internationally of probabilistic concepts for design flood determination and risk analysis in dam safety assessments.

In addition, the internal consistency in the methodology used to derive the RMF and PMF was investigated by producing a spatial distribution of PMF versus RMF ratios for South Africa. Not only would this give an indication of the relationship between the two extreme design flood concepts, but would also highlight any inconsistencies within the methodology used to derive them.

11.2 Annual Exceedence Probability of the RMF and PMF

For the estimation of the AEP of the RMF (including its variants $RMF_{+\Delta}$ and $RMF_{-\Delta}$) and the PMF, probabilistic flood analysis was performed where selected distributions were fitted to the flow records (annual maxima) of 48 dam sites and 32 flow gauge stations across South Africa. Only flow records of 30 years or higher were selected and a sample fairly representative of the whole country was pursued. The Log-Pearson Type III (LPIII), GEV using methods of moments (GEVmm) and GEV with probability weighted moments (GEVpwm) distributions were used in the analysis, together with the Cunane plotting position.

With the RMF calculated using the equations in Table 6 of Kovacs's 1988 TR 137 report, and the PMF determined using the HRU 1/72 Unit Hydrograph methodology, the RI of these two design floods for each measuring station was determined from their respective plots of flood peak (m^3/s) versus RI. These values of RI were then plotted on graphs of RI (years) versus catchment area, which were produced separately for each of the three selected distributions.

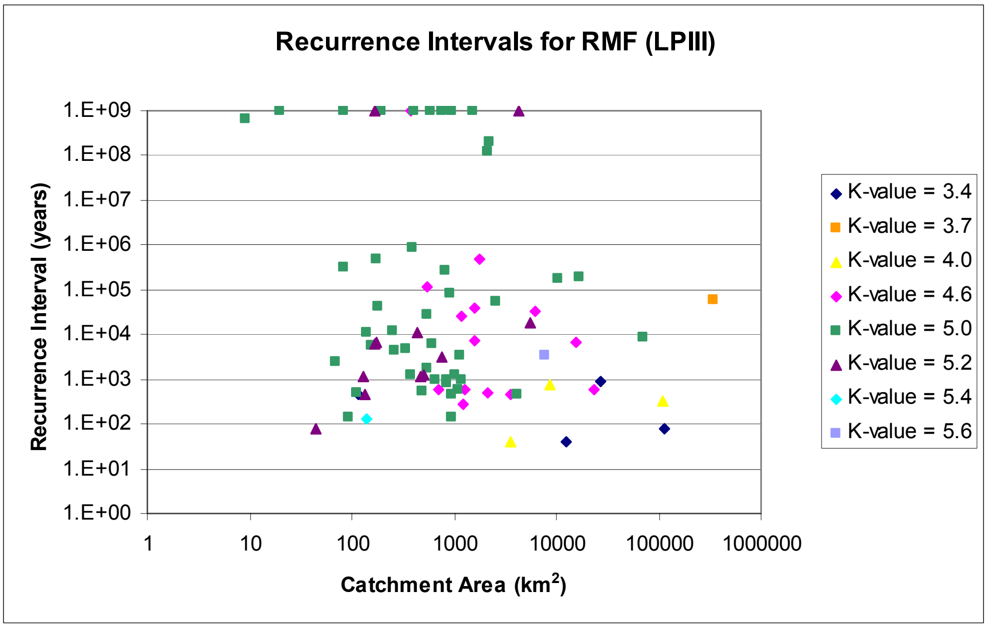

Figure 4 Estimated Recurrence Interval of the RMF using the LPIII distribution

The clustering trend seen in the above diagram was found to be similar in the RMF, $RMF_{+\Delta}$ and $RMF_{-\Delta}$ data as well as the PMF data, but it was less evident for the PMF data. The more random pattern associated with the PMF RI data might indicate possible inconsistencies in the PMF methodology, in comparison to the RMF method that can be considered as more structured.

For a meaningful proportion of stations, the RI for the RMF and PMF was estimated to be as high as 1:10^9 years or greater. The probability distributions for these gauging station flood records have a flatter slope in comparison to the rest of the stations. Given the spread of the RIs, the average practitioner might find it more useful to consider RI percentiles. **Table 21** and **Table 22** present the outcomes for the median and lower 95 percentiles. Of the three probabilistic distributions used, the GEVmm distribution gave noticeably higher percentile RI values in comparison to those derived from the LPIII and GEVpwm distributions for both the

RMF related floods and the PMF. The GEVmm fit to the flood data was often problematic and therefore has been excluded from **Table 21** and **Table 22**.

Table 21 Estimated Recurrence Intervals for the RMF related floods

Probability Distribution	Design Flood	Median RI (years)	Lower 95 Percentile RI (years)
Log-Pearson Type III	RMF	6 000	100
	$RMF_{+\Delta}$	18 800	200
	$RMF_{-\Delta}$	1 200	50
GEVpwm	RMF	3 000	200
	$RMF_{+\Delta}$	6 000	400
	$RMF_{-\Delta}$	900	50

Table 22 Estimated Recurrence Intervals for the PMF

Probability Distribution	Median RI (years)	Lower 95 Percentile RI (years)
Log-Pearson Type III	100 000	300
GEVpwm	30 000	600

11.3 Spatial distribution of PMF/RMF ratios

In general, given their different conceptual origins, the magnitude of the PMF is expected to be much larger than that of the RMF. *The SANCOLD Guidelines*, however, specify that:

"Where it is necessary to establish a reasonable upper limit to the peak discharge at a site, that is, a value having a probability of exceedence close to zero (what is usually referred to as the probable maximum flood, PMF) such value, where determined by the methods explained in the SANCOLD handbook (Alexander, 1990), should nowhere exceed twice the RMF nor the value derived by assigning to the catchment a K-value of 6.0 in the Francou-Rodier equation. Higher values than these would exceed all reasonable expectations for South African conditions" (SANCOLD, 1991, p23).

To gain a better understanding of the relationship between the magnitude of the RMF and PMF on a national scale, a spatial distribution of PMF/RMF ratios for each of the flow measuring stations was produced for South Africa as part of this research. By considering the spatial distribution of the ratio PMF/RMF, it might also provide some insight into the internal consistency in the respective methodologies used to derive the two types of design floods, as well as the relative anomalies resulting from any inconsistencies. **Figure 5** shows a map of these ratios that have for simplicity of comparison been arranged according to the following groups: PMF/RMF < 1, PMF/RMF between 1 and 2, PMF/RMF between 2 and 3, PMF/RMF between 3 and 4 and PMF/RMF > 4.

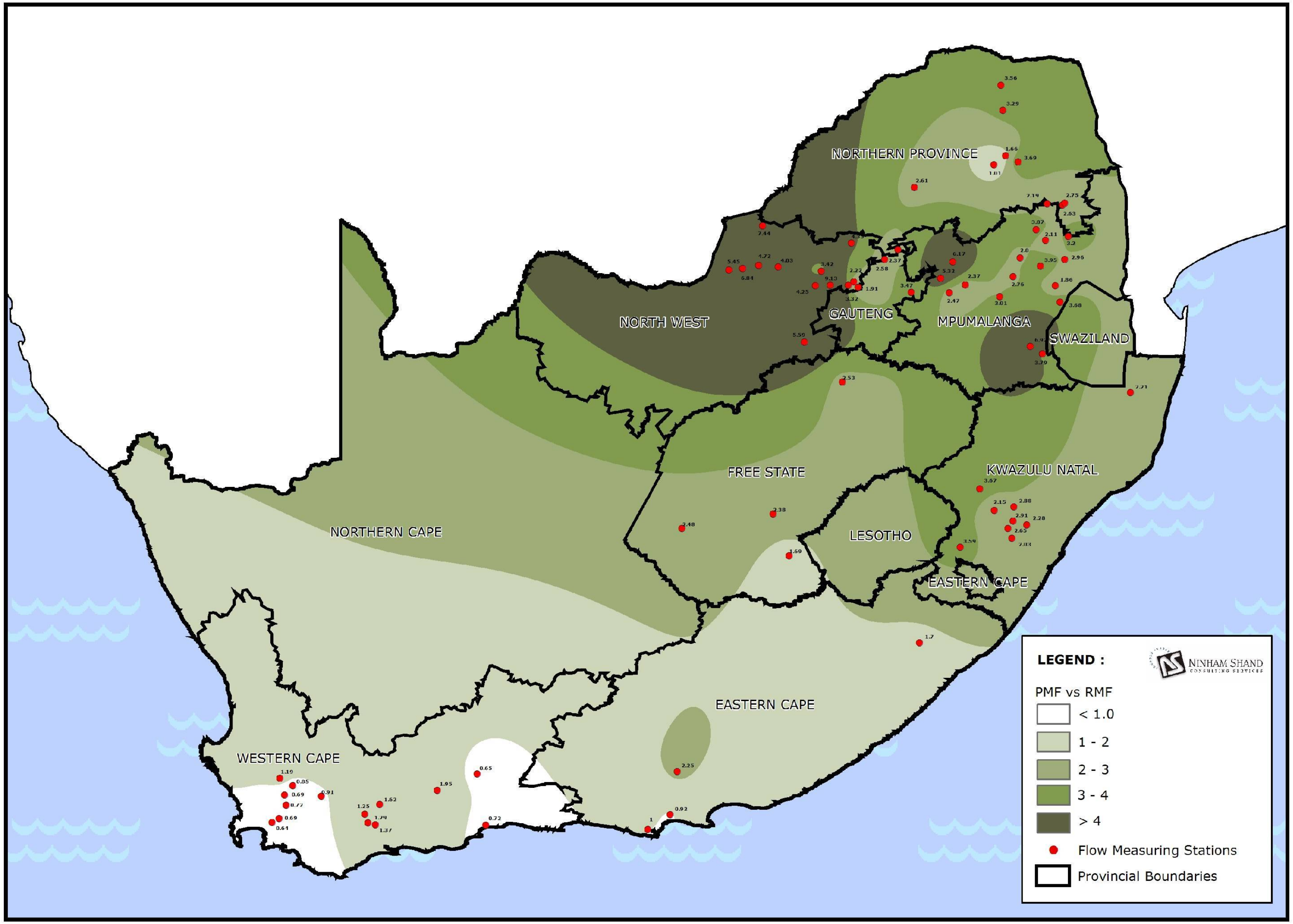

Figure 5 **Map indicating the spatial distribution of PMF/RMF in South Africa**

11.4 Applicability of K-Region Maximum Flood Envelope Curves

Over two decades have passed since the maximum flood envelope curves were developed by Kovaćs and concern was raised that there is a possibility of larger flood events having been recorded sine 1988 that may have exceeded the derived maximum flood envelope curves for the RMF. In order to investigate this, the maximum observed flood peak from the database of primary flow records for 91 flow measuring and dam sites up till 2002 was identified. These floods peaks were then plotted against Kovaćs's envelope curves for the relevant K-region. The envelope of world recorded flood peaks was also included in the plots. It was found that at a number of sites the maximum flood peak had exceeded the RMF as determined using the relevant K-value. These sites, all of them dam sites, were located in K-regions 3.4, 5, 5.4 and 5.6. The plot of observed maximum flood peaks for K-region 5 is given in **Figure 6** and a summary of all the sites where the observed flood peak exceeded the RMF is given in **Table 23**.

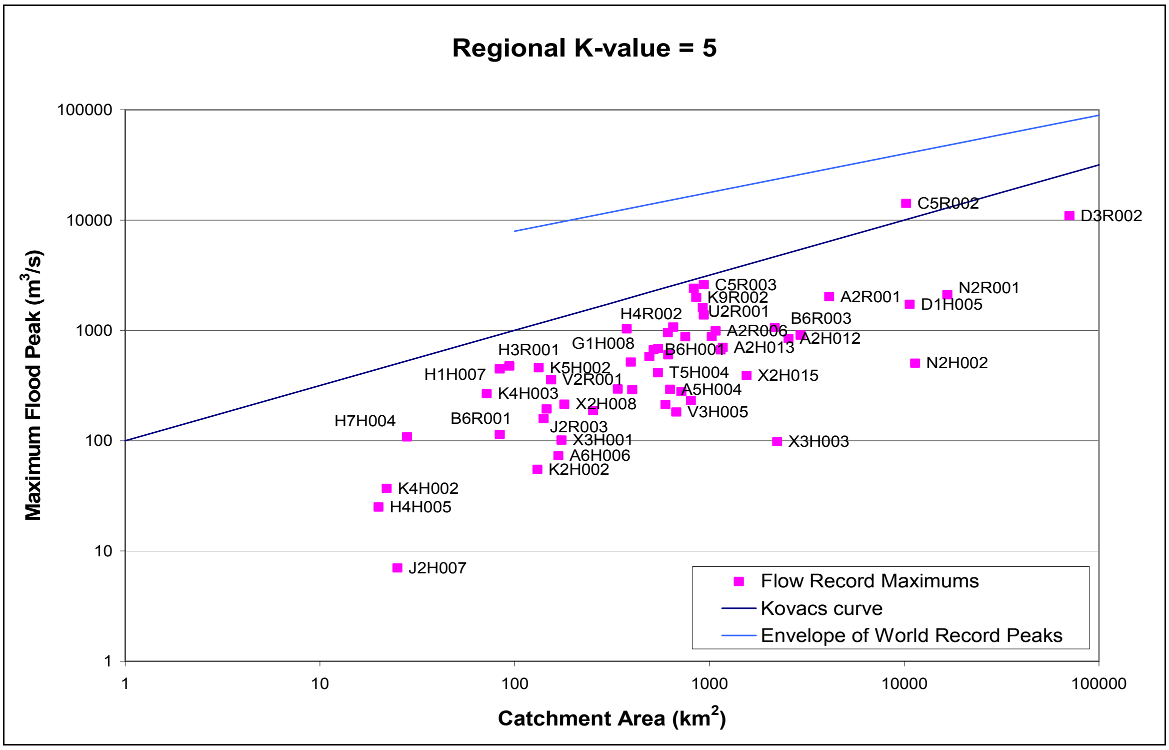

Figure 6 Maximum observed flood peaks for K-value 5

Table 23 Sites where the Maximum Observed Flood Peak has exceeded the RMF

Gauge	Maximum Observed Flood Peak (m^3/s)	K-Value Region	Catchment Area (km^2)	Regional Maximum Flood (m^3/s)	Percentage above RMF (%)
A2R005	403	3.4	114	175	130
B3R002	3179	3.4	12262	2622	21
C5R002	14135	5	10264	10131	40
L9R001	2514	5.4	138	2016	25
W4R001	16761	5.6	7814	15591	8

11.5 Conclusion

With regards to an investigation into the possible assignment of a return period to the PMF, it appears that prior to this project no such work has been carried out in South Africa. More attention has instead been given to the possible assignment of a return period to the RMF, although research in this field has been very limited. In Kovaćs's 1988 publication, he provides a Table in Appendix 6 listing factors (Q_T/RMF) that can be applied to the RMF in order to determine the magnitude of a design flood (Q_T) of known recurrence interval. For the 1:200 year flood, the average Q_T/RMF for South Africa is 0.69. This implies that the RMF can be seen to be nearly 1.5 times the magnitude of the 1:200 year flood. This in turn could indicate the return period of the RMF to be significantly larger than the 1:200 year flood, should flood frequency analysis be performed.

The only other known investigation into the possible assignment of a recurrence interval to the RMF in South Africa is a pilot study undertaken by Pegram et al. (2004). Pegram et al. based their research on Kovacs's original database of annual flood peaks, and using flood frequency analysis concluded that it is reasonable to assume the RMF to have a return period of the order of 200 years. This differs quite substantially from the result of this current research that shows in fact the lower 95 percentile RI of the RMF to be 1:200 years. This difference in result could be attributed to the difference in approaches undertaken by the authors. It is important to note, however, that the approach undertaken was to use conventional methods most commonly used in South Africa, such as the use of the HRU 1/72 Unit Hydrograph method for the derivation of the PMF and conventional probability distribution fitting procedures using the full available record of annual maxima.

The median RMF RI value was found to be around 1:3 000 to 1:6 000 years. This represents a fairly large flood and can therefore be viewed as quite conservative for the pre-screening process proposed in the Guidelines. It has also been brought to our attention that the perception among practitioners, who have experience with determining extreme design floods, is that the RMF might have a RI of between 1:1 000 and 1:10 000 years, which is in line with the findings of this research.

The median RI of the PMF was found to be around 1:30 000 to 1:100 000 years, which is greater than the median RMF RI by about a factor of 10. It is expected that the PMF be larger than the RMF as it is, by definition, the most extreme flood that could be expected within a catchment. This is also in line with the roles these two extreme floods play in the Guidelines, which indicate the PMF to be a larger value than the RMF.

At this stage in the research, an attempt to "update" the guidelines in terms of expressing the SED and SEF as RI values was not made. Instead, this research was rather intended to orientate hydrological practitioners in South Africa regarding the possible RI of the RMF and PMF, so that he/she can be guided in design and safety evaluation decisions.

From **Figure 5**, it is evident that a clear spatial pattern of PMF/RMF ratios exists across the country. There appears to be a trend that the PMF/RMF ratios increase from the coast towards the interior. Although the derived spatial distribution can only be viewed as an initial indication (based on the results of only 80 measuring stations across South Africa), it is evident that for more than half of the country the magnitude of the PMF is larger than twice the magnitude of the RMF. The variation in the values of PMF/RMF might indicate possible inconsistencies in the methodology used to derive the PMF, as opposed to the RMF methodology, which is considered as more structured. These possible inconsistencies could be due to the subjectivity involved in selection of the catchment characteristics and the flood hydrograph technique used to derive the PMF. Inconsistencies could also arise from the use of the HRU PMP values, which might need to be revised in light of the extreme storm events that have occurred across South Africa since 1960, which was the HRU's final year of data.

12. REVIEW OF DESIGN FLOOD LOSSES

Catchment characteristics have an important effect on the rainfall-runoff process in terms of the 'storm rainfall losses'. Storm rainfall losses occur as the catchment experiences a change in storage, while it absorbs (dependent on the infiltration rate of the soil), retains or delays (surface, near-surface and river bank detention) and loses (evaporation and groundwater seepage) some of the rainfall. Therefore, not only will storm losses dictate the design flood magnitude and the shape of the resulting flood hydrograph, but they can also have an impact on the recurrence interval (RI) associated with the resulting design flood. In arid areas, for example, where evaporation losses are high and the antecedent catchment moisture low, one could expect the RI of the resulting flood to be lower than that of the causative rainfall, in comparison with humid areas where the RI of the flood and its causative rainfall can be expected to be similar.

A generalised South African approach for the estimation of storm rainfall losses based on regionalised functions is given in HRU Report 1/72 (HRU, 1972). Here storm rainfall losses are presented as a percentage of the total storm rainfall and expressed as a function of Veld-Zone and catchment size. The HRU methodology was based on 30 years of rainfall data from 1932 to the 1960s. The SCS method developed for South African application (Schmidt and Schulze, 1987), also considers storm rainfall losses, but is only applicable to small catchments (originally developed for catchments < 8 km^2), although many practitioners report its satisfactory use for larger catchment of up to 80 km^2. These methods, as well as at-site investigations performed by the Department of Water Affairs and Forestry, are reviewed as part of the WRC Study on Updated Guidelines and Design Flood Methodologies and are presented in the main Research Report for the WRC project (Görgens et al., 2006). To put the South African methodologies into context, various international approaches are also reviewed.

In addition to the review of methodologies this Study also undertook a preliminary review of the representativeness of the HRU regionalised storm loss functions in the light of relevant storm rainfall and flood volume data assembled in the Study, as well as in recent national studies by Smithers and Schulze (2002) and Lynch (2004).

For the investigation into regional storm losses in South Africa, five methods were considered, which were bench-marked against the method described in HRU 1/72. The four methods used were as follows:

- Method 1: An exact repeat of the HRU Veld-Zone-based methodology (Average losses approach), but with the use of the 1'x1'-gridded design rainfalls for a range of RIs published by Smithers and Schulze (2002).
- Method 2: A further modification of the HRU methodology, additional to Method 1, in which the RI flood peaks produced and described elsewhere in this Project are used.
- Method 3: An alternative modification of the HRU methodology, additional to Method 1, in which average standardised flood volumes, conditional on standardised flood peak and RMF-K-Region, and produced and described elsewhere in this Project, are used.
- Method 4: Conventional storm runoff percentage calculations, based on a comparison of observed rainfall surfaces for selected observed historical floods in representative catchments.

Methods 1 to 4 considered the "average" design storm losses approach as reported in HRU 1/72, but with each Method progressively deviating from the latter approach with the increased utilisation of raw data for the estimation of the flood volumes. Method 1, for example, remained true to the HRU methodology for the derivation of the design flood volumes, whereas Method 4 deviated wholly from the HRU methodology by making use of observed historical floods in representative catchments. All methods deviated from the HRU methodology with respect to the design rainfall in that the design rainfall produced by Smithers and Schulze (2002) was used throughout. Method 5 investigated the regional approach to minimum design storm losses by the consideration of historical extreme floods and their causative rainfall.

From the results of the analysis for Methods 1, 3 and 4, one of the overriding observations is that the existing HRU regional storm losses curves (Figure G2 of HRU 1/72) can be seen to be broadly representative of mid-range values for Veld-Zone Group A (Veld-Zone 2) and Veld-Zone C (Veld-Zones 1, 3, 8 and 9). This indicates that the HRU regional storm loss curves, which are described as "average curves" in the 1972 report, might still be considered as reasonably representative for the estimation of "average" design storm losses for these Veld-Zones within South Africa.

Another prominent observation for Veld-Zone Group A was that there were a number of values that exceeded 100% runoff / 0% loss. This phenomenon, which was evident in all of the Methods, is indicative that the design rainfalls in these regions are too low. This can be expected in mountainous regions, such as Veld-Zone 2, where there is a lack of representative high-elevation, high-rainfall records.

A concern brought to light by this research is that the "average" HRU storm loss curve for Veld-Zone Group B (Veld-Zones 4, 5, 6 and 7) might be plotting too low, i.e. that it might be underestimating the storm runoff percentage. This was evident in the results for Veld-Zone 5 using Method 4, which is shown in **Figure 7**. Although it is noted that more data would be required to make a solid deduction of this point, this concern was also a finding in the hydrology study for the Lesotho Highlands Water Project (Lahmeyer et al., 1986), which considered Veld-Zone 4.

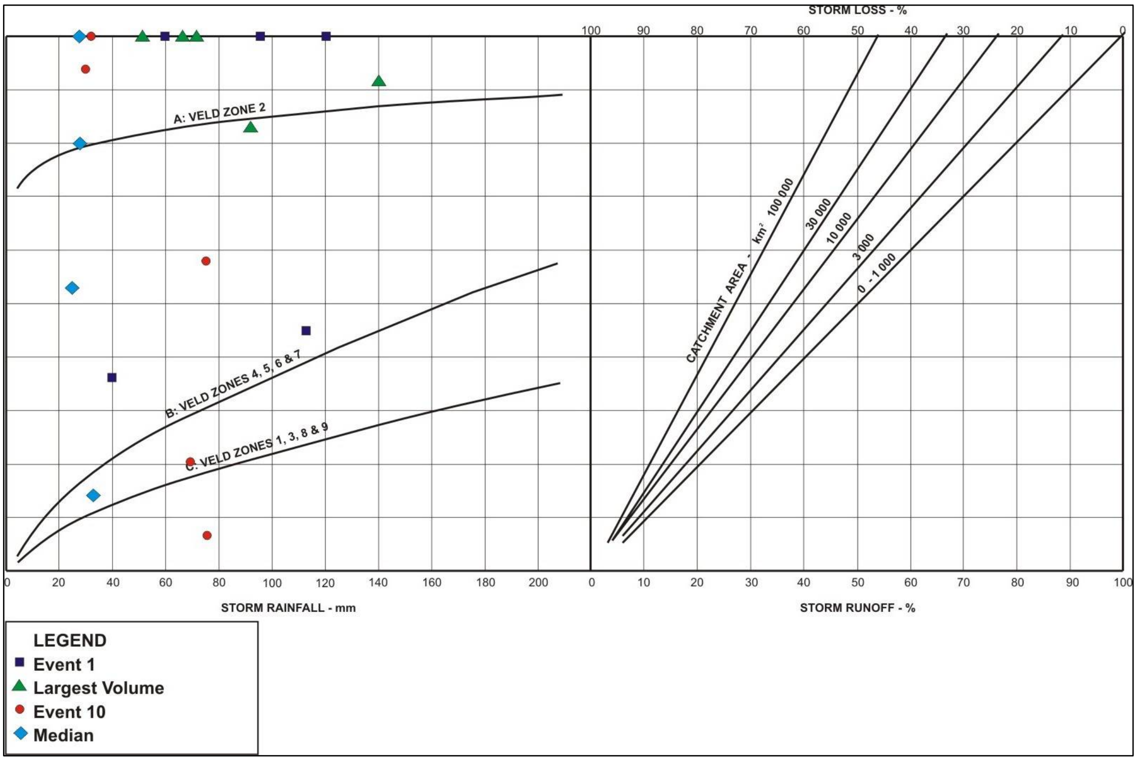

Figure 7 Method 4: Regional storm loss curves for recorded events in Veld-Zone 5

For this assessment of the HRU regional minimum storm loss curves, it can be broadly deduced that the representative HRU envelope curves (Figure G1 of HRU 1/72) can still be considered as valid for use within South Africa. A review of historical extreme flood events found that on only one occasion, the inner envelope curve, labelled as "envelope of recorded floods", was exceeded, and that the outer envelope curve, labelled as "estimate of maximum runoff efficiency", was never exceeded. There were, however, some concerns about the plotting positions of some events in that their representative runoff percentages were quite low for what would be expected from an extreme event, which typically would be biased towards a wet catchment. This appears to be an artefact of the algorithm used in the extraction software used in this Study that need a manual override for long-duration storms (4 days or greater). It is, however, recommended that these and other concerns raised as part of this review be addressed in future research on storm losses.

13. REVIEW OF THE UNITGRAPH DESIGN FLOOD METHOD

The Unitgraph method described in HRU 1/72 (HRU, 1972) is still the most commonly used design hydrograph generation approach used in South Africa. As part of this Study a comparison of the Unitgraph-based design flood estimates with probabilistic estimates was made using the Log Pearson Type III (LP III) and General Extreme Value (GEV_{pwm}) probability distributions. The flood records for 40-gauged catchments were used to determine design flood estimates for recurrence intervals of 1:2, 1:5, 1:10, 1:20, 1:50 and 1:100 years. These were grouped according to the Veld Zone Types of HRU 1/72. Group A consisted of Veld-Zone 2, Group B included Veld-Zones 4, 5, 6 and 7 and Group C included Veld Zones 1, 3, 8 and 9.

In general it was found that the Unitgraph-based approach produced higher design flood peak estimates for Veld-Zone Groups B and C than the two single-site probability analysis approaches. In contrast the results for Group A compared well. The results for Group C are shown in **Figure 8**. The median over-estimation for Groups B and C is about 60% (for RI of 1 in 100 years).

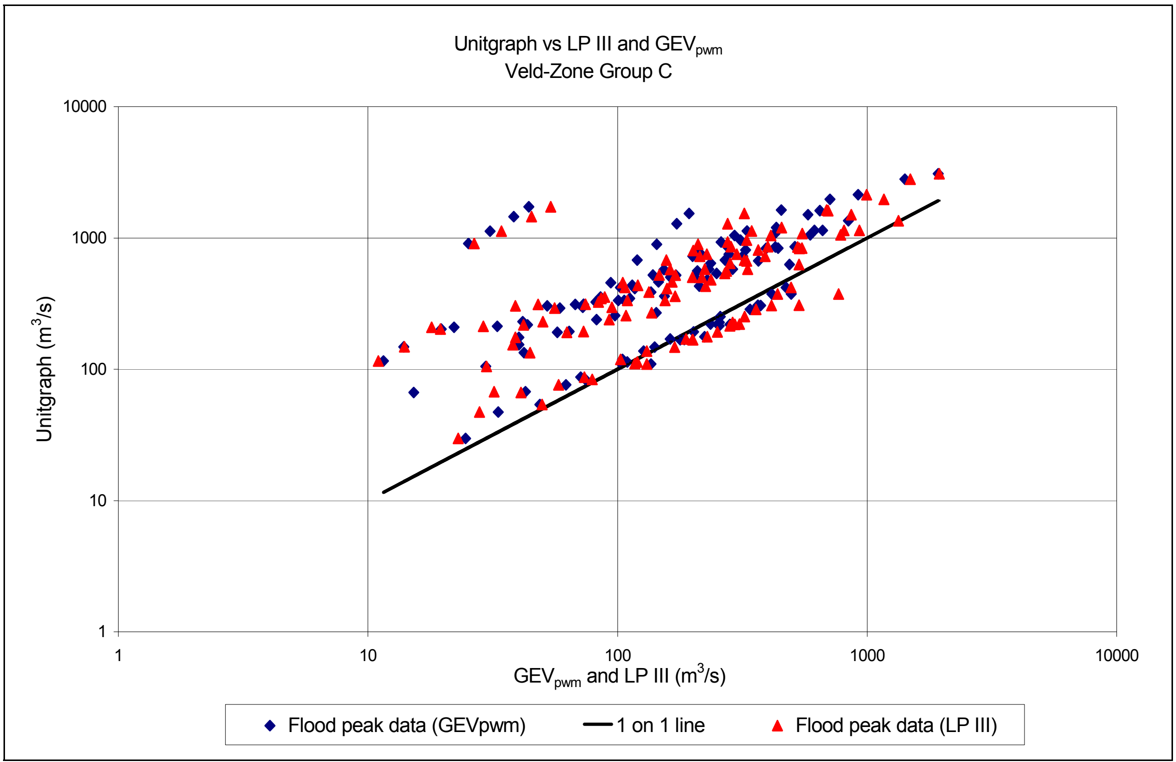

Figure 8 Comparison of design flood estimates for Veld-Zone Group C

Further investigations into the quartile range (25% to 75%) of estimated flood peaks for a range of recurrence intervals from 1 in 2 years to 1 in 100 years, showed a much greater range of variation for the estimates using the probability distributions than from the Unitgraph approach. While a relatively narrow range of results is desirable for producing consistency in design flood estimates across the country, it is not necessarily reflective of the natural variability of flood peaks, particularly at the higher end of the range of RIs. This effect is shown in **Figure 9**, which is a plot of the quartile range of the estimated flood peaks using the Unitgraph and the Log-Pearson III probability distribution normalised by the estimated 1:2 year flood for each gauge in Group C (Veld-Zones 1, 3, 8 and 9).

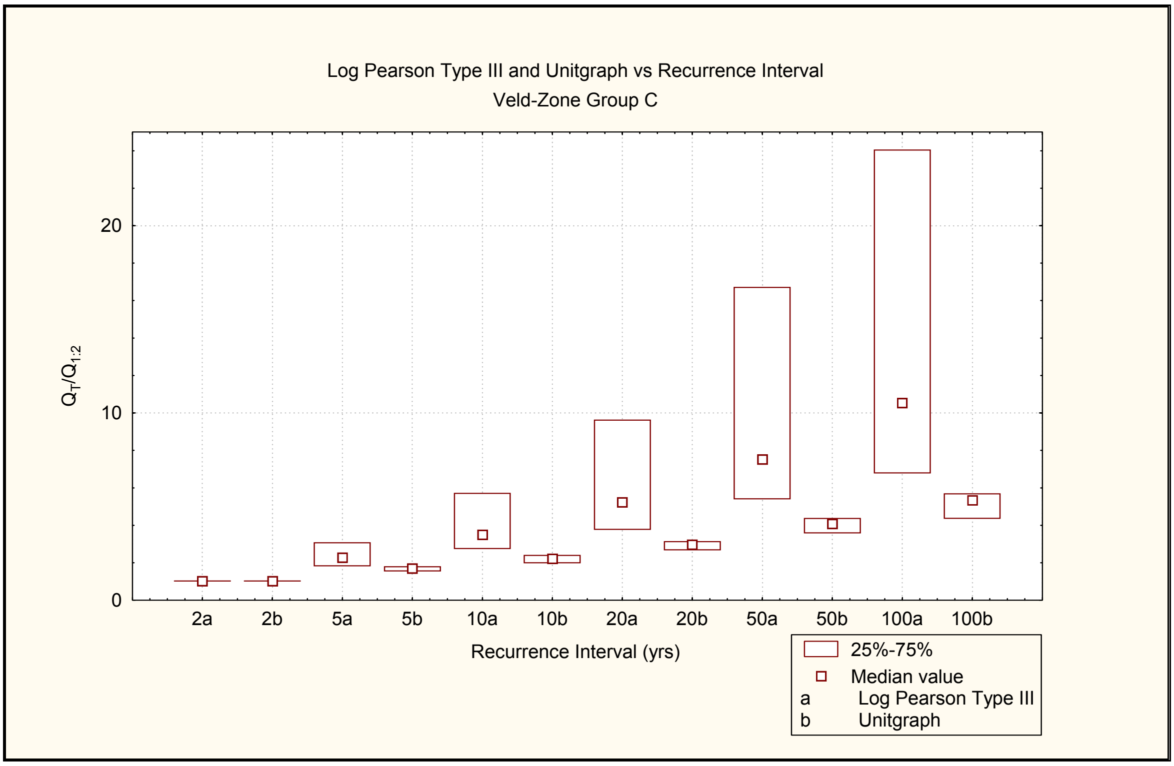

Figure 9 Standardised quartile range differences by RI for Veld-Zone Group C

A similar range in the higher RI floods is also noted in Group B, although the range is not as wide. There is a much narrower range in the estimated design flood peaks in Group A, which represents only a single Veld-Zone, and the ranges is similar for both the Unitgraph method and the probabilistic estimates of design flood peak.

14. REVIEW OF THE USE OF JOINT PROBABILITY DESIGN FLOOD METHODOLOGIES

While there has been continuing interested in the use of probabilistic analysis for determining design flood peaks, there have been few recent attempts to link this to the probability of flood volumes. For dam safety assessment in relation to floods it is important that flood volume be considered particularly with regards to the design and safety evaluation for medium to large dams that require site-specific investigations.

Earlier research on the statistical relationship between flood peak and flood volume for South African rivers was done by Hiemstra and Francis (1979), in support of the so-called "Runhydrograph" approach. This research showed that peak-volume pairs sampled from 43 flow gauging station records were approximately log-Normally distributed in bi-variate space. The Runhydrograph approach, however, is not in general use in the dam safety field in South Africa. This may be due to the fact that the methodology was not developed specifically for dam safety professionals and therefore tends to fall outside of their comfort zone.

To address this concern as well as to develop further insight into the link between flood peak and flood volume a new approach has been developed as part of this Study. The new methodology is called the Joint Peak Volume (JPV) method. The general approach is described below, but a more detailed discussion on the development of the methodology is presented in a separate report emanating from this study (Görgens, 2006).

The objective of the JPV approach is to provide the flood hydrology designer with modernised procedures and tools that link the empirical frequency of flood volume exceedence to flood peak magnitude in a regional context. This enables the designer to determine, for any given design flood peak, the exceedence frequency of any design flood hydrograph volume, regardless of the methodology used to estimate the flood peak.

With the aid of customised software, called *EX-HYD*, significant flood hydrographs were extracted, on a "peak-over-threshold" (POT) basis, from primary stage records provided by the DWAF for more than 200 flow-gauging stations as well as the inflowing flood peaks and volumes for more than 80 dams across South Africa. These partial duration flood peak sequences were screened for statistical stationarity and other evidence of unacceptable upstream human impacts. The 12 000+ joint peak-volume (JPV) pairs and 9 000+ flood hydrographs that were extracted from the 139 gauging station and dam inflow records that survived the screening were appropriately standardised to facilitate examination in various alternative regionally pooled groupings. This examination broadly confirmed the log-Normal character of the POT partial duration data sets.

Exceedence percentiles of "standardised volumes conditional on standardised POT peaks" were derived for each of the regional pooling options. The locus of each of these exceedence percentiles in joint peak-volume space displayed a fundamentally linear character. Therefore, the JPV design tools developed include, inter alia, a set of linear functions that describe the exceedence relationships of standardised flood volumes conditional on standardised POT flood peaks for two alternative sets of regionally pooled catchments. The relationship for the high K-value regions is shown in **Figure 10**.

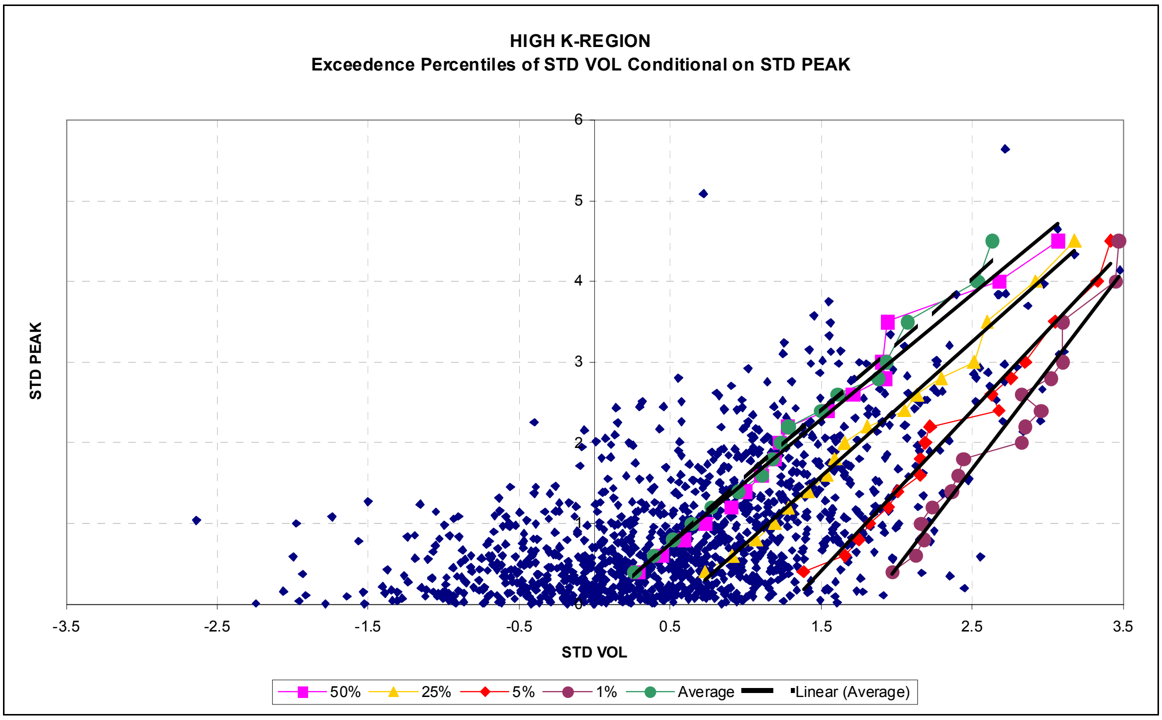

Figure 10 Relationship between standardised flood volumes and flood peaks for the high K-Value Regions

A design flood peak provides the entry point to the JPV methodology. Once a design flood peak has been determined by any method, be it empirical, deterministic, probabilistic, or their hybrids, one or more relevant typical standardised observed hydrographs as shown in **Figure** 11 are selected and then dimensionalised via that design flood peak. The linear JPV exceedence percentile functions are then used to determine the "severity" of the design flood hydrograph in conditional volume terms.

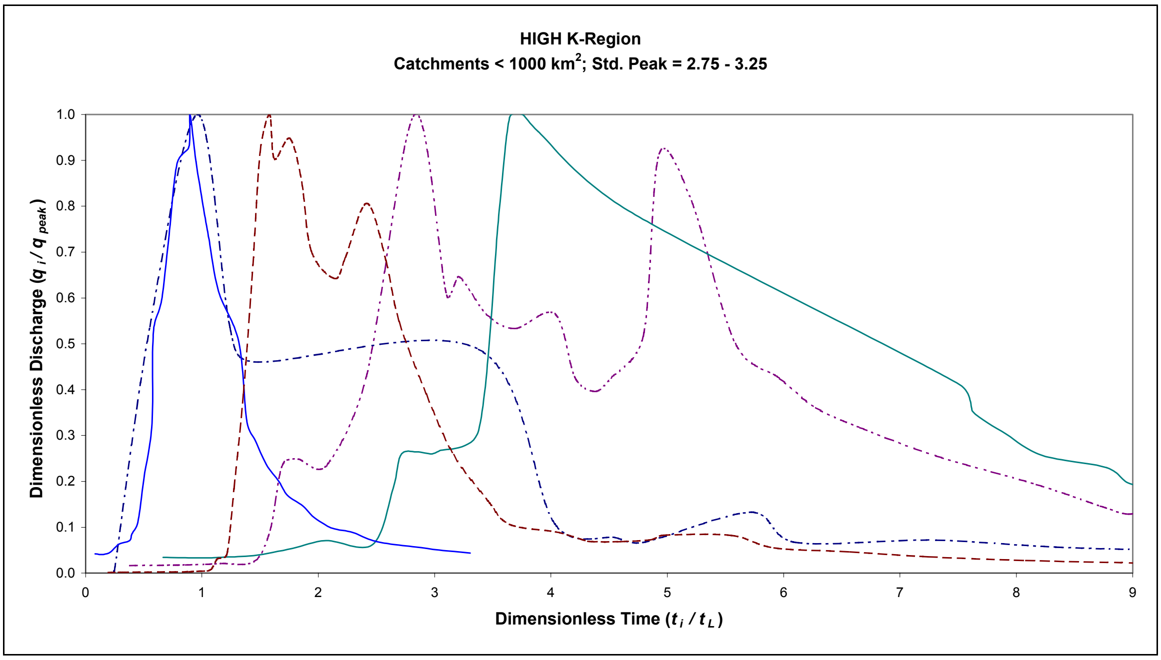

Figure 11 Typical standardised hydrograph shapes for the High K-Value Regions

In terms of design flood peaks, specifically, this research has made us aware that a modernised alternative to the aging design flood peak estimation methods used in South African practice would be useful to design flood practitioners. Therefore, the JPV approach also includes a regional pooling method that allows the estimation of design flood peaks and volumes at ungauged sites for any given annual exceedence probability (AEP) or recurrence interval (RI), based either on large-scale regions of "similar flood response" catchments, or on customised localised groupings of "hydrologically similar" catchments. This is a hybrid method that comprises both multi-variate regressions (in which catchment descriptor values are used), and empirically derived pooling of the statistical parameters of observed flood records for hydrologically similar sets of catchments. The results of the design flood estimates using the pooled data is compared in **Figure 12** with the results of the unitgraph method. **Figure 12** shows better clustering of the pooled estimates around the equivalent single site probabilistic estimates than obtained using the unitgraph-based estimates shown in **Figure 8**.

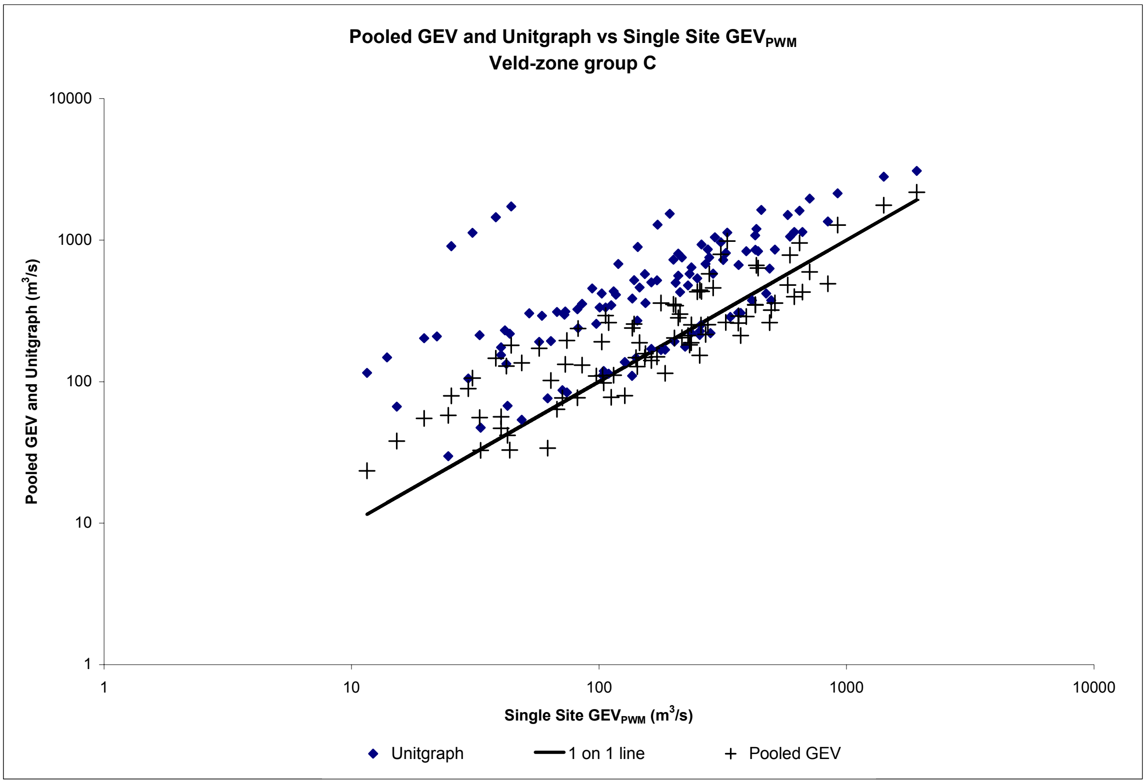

Figure 12 Comparison of design flood estimates using single site and pooled data for Veld-Zone Group C against unitgraph-based estimates

15. REVIEW OF THE ROLE OF RISK ANALYSIS AND ASSESSMENT

There is a growing trend in the dam safety community to make more use of risk assessments in dam safety evaluations. Some of the reasons for this include (after Bowles et al., 1998):

1. **engineering considerations:** e.g. the review of existing dams that do not meet current state-of-the art-practice and are ageing and deteriorating. Current classification of dams is largely based on subjective criteria (Cluckie,1990). Concerns raised that designing according to the PMF will make safety improvements to dams un-affordable and incomparable to the cost of safety measures in other fields (Graham, 2000);
2. **societal considerations:** e.g. increased downstream development, increased knowledge of risk and risk averse nature of the public, the difficulty of relating to the low probabilities of risk associated with dams and the increased involvement in affected communities on dam safety and design issues; and
3. **business and public policy considerations:** e.g. privatisation of dams, a shift away from prescriptive regulations and government emphasis on risk-benefit justification in other sectors.

Two levels of risk assessment are proposed in the process for selecting the AFC for dams in South Africa. The first of these is a simple scoping level risk assessment that is used to evaluate the risks attached to the various failure modes at the start of a safety evaluation as well as to give an initial indication of the potential risk to society of a newly designed dam failing as a result of overtopping. It is also recommended that such a simplified risk analysis be conducted for all temporary works such as coffer dams to determine the risk posed to society during the relatively short lifetime of such structures.

The second level of risk assessment is a more detailed quantified risk assessment that may be required by the DSO for larger dams as a final check of the potential risk to society posed by certain Category II or III dams. This would be of a much higher level of assessment than the scooping level risk assessment and would be concerned with site-specific characteristics as opposed to the generalised criteria that would be used for the simple scoping level risk assessment.

15.1 Background to Risk Analysis and Risk Assessment

A short discussion on risk based dam safety assessment is included as **Appendix D**. It outlines the definition of risk, risk analysis and risk assessment. It also outlines the stages of a risk assessment and gives some indication on the difference between a risk based dam safety assessment and a standards based dam safety assessment (the general form used in South Africa), and some of the advantages and disadvantages of risk based assessment. This is an area currently experiencing growth in the dam safety field and one that the practitioner should be aware of. The two types of risk assessment proposed in this Report are fairly simplistic, but in future revisions of the proposed processes it is likely that risk assessment will come to play a more important role in ensuring the safety of dams in South Africa.

15.2 Scoping Level Risk Assessment

It is recommended that a simplified risk assessment be conducted during the initial stages of a dam safety evaluation so as to be able to highlight the areas of greatest threat to the safety of the dam as well as to prioritise efforts on ensuring the safety of the dams that pose the greatest threat to society. A risk assessment as part of the dam safety evaluation will also help to prioritise the remedial measures that will have the greatest impact on the safety of the dam to ensure that these are done first rather than the remedial measures that are the easiest or cheapest to do. During the selection of AFC for the design of a new dam, it is recommended that a simple risk assessment be carried out based on the estimated probability of failure determined during the generalised AFC check. This will be useful in getting a first order estimate of the potential risk to society posed by the dam.

The basic steps are the same as for any risk assessment, but the actual values are determined in a simplistic way, often based on expert opinion, for the proposed scoping level risk assessment. The basic steps are:

1. Identify all the possible failure modes.
2. Estimate the probability of failure of the dam under each of these failure modes.
3. Calculate the consequences of failure in terms of loss of life or economic and environmental losses.
4. Assess the risk posed to society by multiplying the probability of failure with the consequences of failure and compare with other dams and with acceptable risk criteria for society.

A simple approach would be to determine the probability of failure of the dam due to overtopping as described for determining the annual exceedence probability of the maximum safety evaluation discharge (MSED) (i.e. the flood discharge that will just cause the dam to fail) using the generalised AFC check. The probability of failure due to other failure modes would most likely have to be based on some subjective expert opinion. The consequences of dam failure in terms of the probable loss of life and possible economic losses are calculated as part of the hazard classification process. The risk to society is then calculated simply by multiplying the consequences of failure by the probability of failure. This level of risk is then compared to general levels of acceptable risk in society, or the risk associated with other similar dams, or could be used to compare different remedial measures to determine which one is a priority. A simplified scoping level risk assessment of such a nature is currently used by the DSO to make a quick check of the risk associated with a specific dam (Chemaly, 2003).

15.3 Quantified Risk Analysis

A more detailed quantified risk assessment and analysis may be required by the DSO for Category II and III dams that pose a potentially high level of risk to society. The process for conducting such a risk assessment is outlined in the notes on risk based dam safety assessment in **Appendix D**. It is similar to that used for the scoping level simplified risk assessment, but greater detail is required in terms of determining the probability of failure and the consequences of failure. Where as the simplified risk assessment was based on the probability of failure due to overtopping as calculated based on the estimated annual exceedence probability of the MSED, the more detailed quantified risk assessment should consider the probability of failure based on the maximum safety evaluation flood (MSEF) (i.e. the flood hydrograph or set of hydrographs that will just cause the dam to fail) and take into account other factors determining the probability of failure such as the probable reservoir level. In addition the risk associated with the dam should be checked against much more detailed standards of acceptable risk such as those presented by Oosthuizen (2002).

The methods and tools necessary for a quantified risk assessment are still being developed. Two examples of these have been developed in Australia (ANCOLD, 2004) and the UK (Brown et al*.,* 2004). In South Africa, DWAF currently uses a simplified scoping level quantified risk assessment to prioritise on remedial measures for its dams (Oosthuizen, 2002) and practitioners should consider this as an option if and when the DSO requests a quantified risk assessment for a particular dam. It is important that, should the DSO require a quantified risk assessment to be carried out on a certain dam, that the practitioner is aware of the latest international best practice in this regards and that all assumption, calculations, methods and criteria for assessment be recorded.

Part 4: Recommendations for Updating the SANCOLD Guidelines

16. RECOMMENDED WAY FORWARD FOR THE SANCOLD GUIDELINES

Based on the research conducted for this Project the following recommendations are made for the way forward with regards to updated *Guidelines for Safety in Relation to Floods*.

16.1 Update the SANCOLD Guidelines

This Research found that while the *SANCOLD Guidelines in Relation to Floods* (SANCOLD, 1991) have been useful to the majority of dam safety professionals, there are a number of areas in which there are concerns. It is recognised that some form of guidance is required to support the assessment of the safety of dams in South Africa, and it is recommended that the findings presented in this Report be used to inform such guidance and eventually to inform the development of a new set of aids and tools to support dam design and safety evaluation. It is recommended that a representative technical committee be established to facilitate the updating of the *SANCOLD Guidelines*, as was the case with their original development. This technical committee should also consider updating the other *SANCOLD Guidelines*, such as the guidelines on dam-break floods, and freeboard, as well as developing new guidelines on risk assessment and dam safety inspections. It would be appropriate for this committee to be established by DWAF, through the Dam Safety Office, but that this be done in collaboration with SANCOLD and the WRC.

16.2 Revised Terminology

There is a need to clearly define the various flood concepts used in dam design and safety evaluation in relation to floods. The first step is to consider the use of the term Acceptable Flood Capacity (AFC). It is also necessary to clearly distinguish between the various floods under consideration, i.e. a clear distinction needs to be made between recommended standards and the flood capacity of the dam. A list of possible floods to be defined and considered in the safety evaluation process include:

MDCD: Maximum Design Capacity Discharge
MMMF: Maximum Man Made Flood
MSED: Maximum Safety Evaluation Discharge
RDCD: Recommended Design Capacity Discharge
RDCF: Recommended Design Capacity Flood (Inflow and Outflow Hydrographs)
RSED: Recommended Safety Evaluation Discharge
RSEF: Recommended Safety Evaluation Flood (Inflow and Outflow Hydrographs)
ZIIF: Zero Incremental Impact Flood

One of the main concerns with the use of the RMF is that it is currently defined in the *SANCOLD Guidelines* in terms of the original TR137 Report. This means that it is not flexible to changes in conditions as a result of more recent flood events. This has been addressed in the proposed new regulations by referring the definition of the RMF to the original Francou-Roudier equation but with a factor determined from the most recent available information rather than TR137 directly.

16.3 Use of the RMF and PMF

As has been discussed in this Report there is some concern with the use of the RMF and PMF in the *SANCOLD Guidelines*. In general it was found that the RMF is a useful tool for a generalised check of AFC. It is, however, important that the envelope curves be checked and updated on a regular basis, as this Study has found that there have been a number of occasions when the RMF envelop curves have been exceeded by more recent flood events.

It was also concluded that the PMF is a useful concept and is still the international standard for extreme floods for large high hazard dams. There are, however, a number of concerns relating to the use of the PMF. Some research has been done as part of this project to try to address some of these concerns as part of this project. This research, however, has not been conclusive and it is important that the concerns relating to the RMF and PMF be investigated further so as to inform any future updating of the *SANCOLD Guidelines*.

16.4 Assigned Annual Exceedence Probability for the SEF

Although it was found that the use of the PMF as the SEF for Category III dams is in line with international standards, it is proposed that a new method for factoring the SEF for different categories of dams be considered. It is proposed that the following method be considered and investigated for possible adoption in South Africa: Assigning an AEP to the PMF and then interpolating the flood associated with an assigned AEP between that of the PMF and the maximum flood at the limit of extrapolation of observed data for different categories of dams. This is similar to methods currently being considered in Australia and the UK.

16.5 Visual Check of AFC against Generalised Safety Evaluation Criteria

One suggestion for improving the generalised AFC check would be to consider the flood capacity of the dam in relation to the minimum standards rather than simply checking to see if the recommended design or safety evaluation flood can be accommodated. The current process requires the calculation of an RDD or an SED, which is then routed through the reservoir to check the flood capacity. What should also be calculated, is the maximum discharge capacity that the reservoir can accommodate under design and flood conditions. A hydrograph with this peak is then backrouted through the reservoir to determine the approximate recurrence interval, which is compared with the recommended standards. The advantage of this is that it considers the flood capacity of the dam directly and can be used to determine a level of safety as well as lay the foundation for a simple risk assessment of the dam. It also provides the opportunity for a visual check on the acceptable flood capacity by plotting the various discharges and flood peak values in terms of annual exceedence probability on lognormal probability paper.

16.6 Probabilistic Flood Determination Methodologies

As streamflow records get longer, and methodologies are developed there is growing expertise and interest in using probabilistic flood determination methodologies for design floods. Some new concepts in terms of conditional probabilities of flood peaks and volumes have been explored as part of this research, but there is room for further development of these methodologies.

16.7 Risk Assessment and Analysis

The attitude to risk assessment in the dam safety community has changed greatly in recent years. Most countries are now putting a greater emphasis on risk based dam safety assessment. Some countries, such as Australia, are trying to change the whole basis of their dam safety assessment from standards based to risk based. These changes need to be considered in a South African context and a full investigation into suitable methods for risk based dam safety assessment in South Africa needs to be initiated.

16.8 The Role of SANCOLD, DWAF and the WRC

SANCOLD is currently being restructured. As part of this restructuring it is important for SANCOLD to consider what role it will play in the South African dam safety community. In Australia, ANCOLD plays a very active role in terms of driving the development of guidelines and producing regular bulletins that highlight recent developments in the dam safety field. There is a need for a similar organisation to take ownership of dam safety in South Africa.

SANCOLD does, however, have limited resources. It is therefore important that they work in conjunction with the DWAF through the DSO to fund the development of updated Guidelines and if possible regular bulletins and conferences to ensure that dam safety professionals are kept up to date with best practice. The requirements for Continuing Professional Development (CPD) for registered engineers should assist in this. Where specific areas of research are required to support the development of particular aspects of ensuring dam safety, then SANCOLD and/or DWAF should support the WRC in funding researchers and consultants to undertake this research.

17. CONCLUDING REMARKS

This Report is intended as a tool to assist dam safety practitioners in performing their duty to society by selecting the AFC for a dam, either with regards to the spillway design for a new dam, or for the safety evaluation of an existing dam in relation to floods. It is not intended as an update to the existing *Guidelines on Safety in Relation to Floods* (SANCOLD, 1990). In the future it is hoped that the findings and recommendations from this Report will be incorporated into an updated guideline document or the replacement of the guidelines with some other tool deemed to be most appropriate to facilitate the design and safety evaluation of dams in South Africa.

This Report goes hand in hand with the existing *SANCOLD Guidelines on Safety in Relation to Floods*, and does not represent a code for dam safety assessment. Instead it is meant to act as a tool to facilitate the selection of acceptable flood capacity and should always be used in conjunction with expert judgement, experience, continuing professional development and in full knowledge of the limitations and concerns of the recommended minimum standards, the processes and supporting methods used by the practitioner. **Any methodology, standard or process described in this Report or in the Guidelines can in no way be regarded as a substitute for prudent engineering judgement.** In this regard it is imperative that the dam safety practitioner adheres to one of the key principles of dam safety assessment in South Africa: public safety is paramount, and if there is any doubt, then a precautionary principle should be adopted.

18. REFERENCES

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APPENDIX A :

Report on Survey of Dam Safety Professionals

APPENDIX A: Report on Survey of Dam Safety Professionals

Introduction

This report serves to comment on the preliminary results of a survey of a number of Dam Safety professionals in South Africa as part of the WRC Project K5/1420 entitled *Updated Guidelines and Design Flood Hydrology Techniques for Dam Safety*. The survey of Dam Safety professionals complements a literature review and interviews with key stakeholders in DWAF for the purpose of assessing local and international practices regarding Dam Safety in relation to floods, and will be used in the development of a Framework of Best Practice. This Framework will then be presented to stakeholders at a national consultative workshop and the workshop will be used to convert the Framework into updated guidelines, or something similar, regarding dam safety in relation to floods. Any comments or observations arising out of these findings are welcome and should be sent to the project team to be considered when developing the Framework. The purpose and objectives of this survey of Dam Safety professionals are as follows.

Purpose:

- To Assist in the Development of a Draft Framework for Best Practice Regarding Dam Safety in Relation to Floods.

Objective:

- Make Dam Safety professionals aware of the current project to review and update the SANCOLD guidelines.
- To survey a number of Dam Safety professionals in South Africa on their perceptions of the current state of Dam Safety in South Africa and the application hitherto of the SANCOLD guidelines.
- To incorporate the replies into the development of the Draft Framework for Best Practices
- To develop an initial list of stakeholders for the purpose of soliciting public comment on the Draft Framework as part of its development.

Method

The first step was to draw up a list of current dam safety professionals. The core of this list was the list of currently registered Approved Professional Persons (APP), as supplied by the Dam Safety Office of DWAF. Additional names were added to this list based on the advice of the Dam Safety Office. This additional list included people working for DWAF, who where not on the list of registered APPs and individuals who had either retired or were heavily involved in performing dam safety evaluations or designs, but had yet to register or were in the process of registering to become an APP. In total 80 individuals were identified and their email addresses obtained.

A brief four-page questionnaire was prepared in consultation with the Dam Safety Office and a currently registered APP, Mr Alan Shelly. This questionnaire (Reproduced in Appendix 1) contained 21 questions based on the following themes:

- Personal details including number of years and location of experience
- A personal comment on the currently level of dam safety in South Africa and the factors

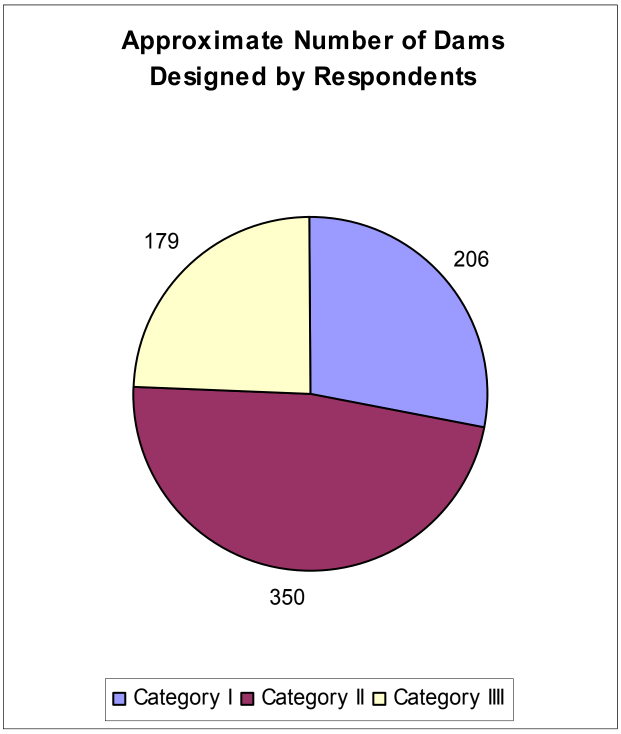
affecting this.

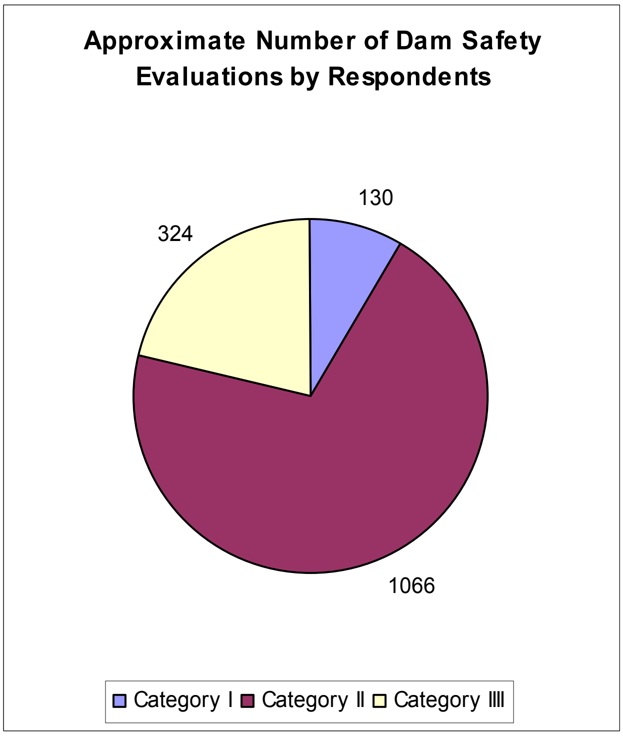
- Comments on the current practice of dam safety evaluation in SA, the use of the SANCOLD guidelines and the need to update these.
- The role that the Probable Maximum Flood (PMF), quantified risk assessment (QRA) and probabilistic flood determination techniques should play in dam safety.
- General comments on the challenges facing Dam Safety in South Africa and what this project should aim to achieve in order to meet these challenges and be of most value to the Dam Safety community.

This questionnaire, along with a covering letter briefly outlining the objectives of the project, were emailed to the identified stakeholders. Reference was made to the Working Report prepared as Progress Report 1 for this project on the literature review and interviews with key stakeholders at DWAF on the current state of Dam Safety in South Africa and internationally, providing additional information on the objectives of the project and the current state of Dam Safety in SA. However none of the stakeholders requested a copy of this report.

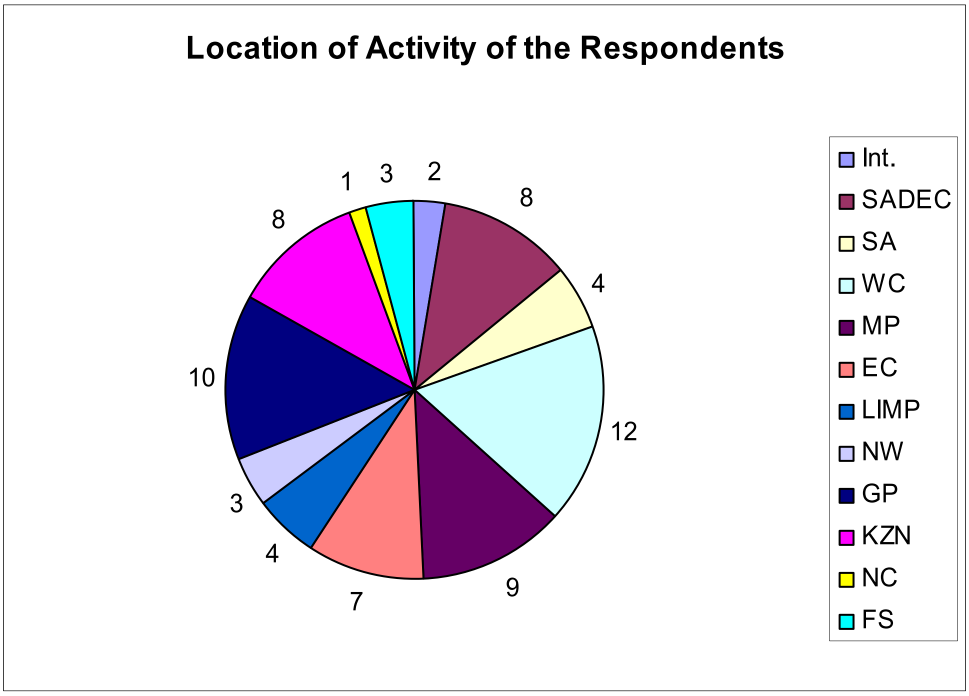
Results

In total 28 replies were received, out of the initial sample set of 80 Dam Safety professionals. This represents a 35% response rate, which is relatively high for a questionnaire of this nature. The list of people who responded to the questionnaire, along with the name of their organization, is given in Appendix 2. The 28 Dam Safety Professionals who responded to the survey had, on average about 20 years of experience each and represented in total of over 550 years of experience in Dam Safety. The approximate number of dams designed and safety evaluations performed by the respondents for each category of dam are shown in the charts below.





The respondents were active in a wide range of areas within South and southern Africa as shown in the Chart below. Many of the respondents are active in more than one area.



In general, the questions were answered satisfactorily, but there where a few cases where the replies showed some confusion about the nature of the question being asked. A summary of the results is given in Appendix 3, which shows the percentage of responses to each answer for each question. Many of the respondents added additional comments to their answers. These written comments are shown in Appendix 4. Some of the key findings from the results are discussed in the following section.

Discussion

Comments on Current State of Dam Safety in South Africa

The respondents were generally happy with the current state of Dam Safety in South Africa. Most aspects of Dam Safety, including the current state in general, dam safety legislation, the capacity and consistency of the Dam Safety Office and the performance of APPs, were given an average rank of about 4, meaning "Above Average". Respondents were less happy with the performance of the construction sector in dam safety and gave it an average rank of 3.2. The area of greatest concern was with the commitment to safety by the dam owners, which had an average rank of 2.6 (2 is "below average" and 3 is "average"). This concern was also highlighted in a number of the general comments by the respondents, particularly with regards to Category I dams, which do not require the services of an APP. Suggestions were made on the need to educate dam owners, and in particular farmers who construct small dams (Category I or smaller), on their responsibility for ensuring the safety of their dam, as well as the possibility of financial support to enable them to employ the services of a professional engineer.

In terms of the possible causes of dam failure, 75% felt that the design flood was too low and 61% felt that failure was due to poor dam design, while 68% felt that more attention should be paid to Category I dams where the vast majority of failures occurred. The issue of changing catchment characteristics after the initial design or safety evaluation was also raised.

The majority of respondents (86%) considered the current approach to Dam Safety evaluation as standards based, but a high proportion of these felt that it was a combination of standards based, deterministic and risk based.

Just over 50% felt that there was insufficient agreement on what constituted best practice with regard to both dam safety in general and with regards to floods in particular. About 89% felt that this could be improved through updating the Guidelines, while 71% felt that more regular conferences or courses would help and 64% felt that a regular journal was a good idea. Other suggestions for improving the agreement on "best practice" included the distribution of interesting case studies by the DSO and the training and mentoring of junior engineers. One respondent was very firm in their suggestion for improving "best practice" by placing responsibility at the door of SANCOLD.

> "*Bring SANCOLD Technical Committees "out of the dark" and aim to bridge an apparent ten-year "backlog" where no one really knows what they are doing i.e. transparency required. Also change the current situation where the "average dam engineer" is UNABLE to "make contributions to" and/or "benefit from" the set-up. If you look at the ""Australian brotherhood"-South Africa is "decades behind".*

Current Practice of Dam Safety Evaluation in Relation to Floods

All respondents made use of the SANCOLD Guidelines on Safety in Relation to Floods, but only half used the Handbook on Flood Estimation Techniques (Alexander, 1990). About 86% made use of the Guidelines on Free Board, but only 36% used the Guidelines on Dam Break Floods.

Respondents used a variety of methods for determining the Recommended Design Flood (RDF) and the Safety Evaluation Flood (SEF). These methods can be broadly categorised as Empirical (RMF, TR 137), Statistical (Probabilistic) or Deterministic (SCS, Unit Hydrograph). The percentages of respondents using each type of method are shown in the table below. Only five of the respondents appeared to have used the Zero Incremental Impact Flood approach, as specified in the Guidelines.

Design Flood	***Empirical***	***Statistical***	***Deterministic***
Recommended Design Flood	45%	23%	77%
Safety Evaluation Flood	47%	16%	47%

Only four of the respondents used only one method, while the vast majority (86%) used some form of subjective weighting to account for the different flood peak values calculated using the different techniques. About 43% of respondents found that certain methods worked better in particular areas, such as in the Western Cape where the RMF did not appear to apply to mountainous regions and general concerns with the RMF such as its use in small and unusual catchments and cases where the PMF is less than the RMF or vice versa. In terms of the minimum requirements for the RDF and the SEF set in the SANCOLD Guidelines, 57% felt that they were suitable and did not need to be changed, but 36% where unsure.

The Role of the PMF, Quantified Risk Assessment (QRA) and Probabilistic Techniques

Only 18% of respondents felt that probabilistic techniques had no role to play in Dam Safety in South Africa. The responses to the potential role that probabilistic techniques should play are shown in Table 2.

Potential role of probabilistic flood determination techniques	*Yes*	*No*
Included in a basket of other techniques	56%	8%
Used to develop regional flood probability relationship curves	44%	0%
Used to upgrade relevant flow gauging stations	36%	8%
Used to check how extreme the RMF is	48%	0%

Half of the respondents felt that Quantified Risk Assessment (QRA) should play a greater role in the choice of dam design (with 29% unsure), while 61% felt that it should play a greater role in Dam Safety Evaluation (with 24% unsure). About 57% felt that, if QRA is to be included in Dam Safety design and evaluation in South Africa, an expert body should monitor it, given its specialist nature.

In terms of the PMF, 64% felt that it still had a role to play, but that this should only be applied to large and high hazard dams. Part of the reason for this was that international funding requires it, but it was noted that the RMF should still receive adequate weight and that meteorological work and research needs to be completed to establish realistic South African PMPs, as the system only works if the base data is meaningful.

How to Improve Dam Safety in South Africa

In terms of what should be done to ensure that South African Dam Safety practices are in line with international standards, only 7% felt that we needed to change our Dam Safety Philosophy, 57% felt there was a need to review the minimum design flood requirements used for different types and classifications of dams, 46% saw the need to review and update our design flood methodology, but only 21% felt the need to reassess the use of the SEF and the RDF.

None of the respondent felt that the SANCOLD Guidelines should either be kept as they are or completely rewritten and redeveloped from scratch. Most respondents felt that they needed to be updated, but 61% felt that they only required a minor revision while 18% felt that a major revision was required. Some respondents felt that there was a need to augment the reviewed guidelines either with regular debate (25%), continuing education (18%) and dam safety manuals (18%).

Many of the respondents felt that these other actions should complement, rather than replace the guidelines as they still have a valuable role to play in providing a bench mark for legal risk, ensuring a consistent approach to dam safety and for building capacity among junior engineers.

General Comments on the Challenges Facing Dam Safety in South Africa

Financial and capacity constraints were two of the major challenges facing Dam Safety in South Africa. A number of respondents commented on the difficulty in training up young engineers to replace the more senior ones, particularly as fewer dams are being built and therefore providing less opportunity to gain experience. For this reason it was felt that the Draft Framework on Best Practice should look to transfer current experience-based knowledge to junior engineers.

It was also felt that a major challenge lay with small dams, as large dams would generally be well funded, would involve an experienced design team and would have sufficient motivation for on going monitoring and maintenance. It was felt that Category II dams are particularly prone to inadequate monitoring and maintenance, with cost/budget concerns often being raised as a reason not to provide sufficient resources for Operation and Maintenance programmes. Some respondents commented that Category I and smaller dams require innovative design to keep costs down and require an improved commitment to dam safety by the owners of these smaller dams. Related to this was the challenge of educating dam owners about their responsibilities and ensuring the follow up on the requirements of regulations or guidelines. One of the suggestions was to distribute the DWAF pamphlets *Your Dam, Your Responsibility* and *Your Dam: Answers to questions most frequently asked about the inspection and maintenance of small dams*. It was suggested that information about dam failures and case studies of dams that have failed after the implementation of the Guidelines should be distributed to the dam safety community on a regular basis.

Respondent's suggestions for the Way Forward

Some suggestions from the respondents for the way forward for this project are as follows:

1. Concentrate on improving current design flood guidelines
2. Develop a 2005/2006 version of the HRU 1/72 approach and manual
3. Improve the rational method for small catchment areas.
4. Look to adapt/correct the RMF to work for small catchment areas
5. Resolve the RMF/PMF debate.
6. Look to include risk based decision making in the guidelines
7. Develop effective, acceptable risk guidelines for Category I dams.
8. Provide the dam safety community with information on how many of the dams that failed were built after the implementation of the Guidelines.
9. Do not develop a magic suite of computer programs where only the academics know what is in the black box.
10. Also consider compiling essential guidelines on geological/geotechnical aspects of dam safety, followed by guidelines on hydraulic gates and corrosion aspects.
11. Reduce the required minimum size for the classification of a dam.

It should be noted that the authors of this Report do not necessarily agree with each of the above suggestions by the respondents.

Recommendations

The following recommendations for improving dam safety in South Africa and on developing a Framework of Best Practice can be been drawn from consideration of the feedback received in this survey as well as the interviews and literature review conducted by the project team.

For Improving Dam Safety in South Africa

1. Encourage greater knowledge transfer amongst dam safety professionals and other

stakeholders. This can by done by the organising of more regular conferences, workshops and continuing education courses, as well as the publishing of an annual newsletter by SANCOLD or the DSO detailing dam safety events during the year. The DSO already produces an annual report that could form the basis for this newsletter.

2. Aid in the development of junior dam safety engineers through supporting continuing education courses, the publishing of case studies/newsletters and the hosting of more regular conferences.
3. Engage the dam owners on their responsibility for the continuing safety of their dams, particularly small farm dams. This could be done by drawing them into the planned new structure of SANCOLD and through the distribution of the DWAF pamphlets on Your Dam.
4. Engage the insurers of dams and farmers in the debate on dam safety to make them aware of the regulations regarding dam safety, the requirements for good maintenance and the potential risks that unsafe dams pose to lives and the financial viability of farms. This would help to put financial pressure on dam owners to ensure the safety of their dams
5. Appoint a panel of experts who will review the guidelines on a regular basis (say every 5 years) based on a workshop/conference organised by SANCOLD and the DSO.

For Developing a Framework for Best Practice in Relation to Floods:

6. Consider maintaining the core of the design and safety evaluation process outlined in the existing guidelines, but
   a. Increase the role of Risk Assessment in line with the requirements for risk assessment included in the latest update of the South Africa Regulations on Dam Safety.
   b. Review the current requirements for RDF and SEF by comparing them to annual exceedence probabilities based on statistical analysis of observed floods and/or probable loss of life for a number of dam sites throughout South Africa.
   c. Present the requirements for RDF and SEF in a consistent way, that takes into consideration the characteristics of the individual catchments and dam type.
7. Develop Guidelines on Risk Assessment for South Africa based on the Australian Guidelines as well as the current methods used by DSO and DWAF.
8. Re-enforce the link to guidelines on other aspects of Dam Safety, such as Risk Assessment, Free Board, Dam Break Floods, Operation and Maintenance, Geological and Structural safety.
9. Investigate the relationship between RMF, PMF, 1 in 10,000 year flood, as well as suggested factoring of the RMF/PMF in the Guidelines, and annual exceedence probabilities using statistical analysis of observed flows for different regions in SA.
10. Develop a Framework of Best Practice and present it at a national workshop on Dam Safety. Use this workshop to derive the outline of an updated set of guidelines and further supporting information, as deemed necessary by the members of the Dam Safety community.

APPENDIX A1 :

Questionnaire on Best Practice regarding Dam Safety In South Africa

APPENDIX A1

Questionnaire on Best Practice Regarding Dam Safety in South Africa

1 Name: ________________________ 2 Organisation: ________________________

3 Years of experience with regards to Dam Safety _______________

4 Approximate number of dams that you have designed and/or inspected/evaluated by category

	Category I	Category II	Category III
Design			
Safety Inspection/Evaluation			

5 In which region/s of the country are the majority of these dams located?

____

In 2003 there where 3706 registered dams (56% being Category I). Since 1987 there have been 166 failures, 40% due to overtopping and the vast majority being Category I dams.

6. How would you rate the state of the following aspects of dam safety in South Africa?

1 = Poor 2 = Below Average 3 = Average 4 = Above Average 5 = Excellent

. Performance of dam safety in general in terms of minimal failures or incidents ☐
. Dam Safety Legislation (NWA and Regulations) ☐
. Capacity of the Dam Safety Office ☐
. Consistency of the Dam Safety Office ☐
. SANCOLD Guidelines. ☐
. Performance of Approved Professional Persons (APPs). ☐
. Performance of the Construction sector. ☐
. Commitment to Dam Safety by Dam Owners ☐
. Other ____ ☐

5 Given the prominence of overtopping as the failure type, which of the following causes would you attribute this to?

. Design Flood too low? **YES / NO / Don't Know**
. Poor dam design? **YES / NO / Don't Know**
. Dam not built to design specification? **YES / NO / Don't Know**
. Poor dam construction? **YES / NO / Don't Know**
. Human error or mechanical failure? **YES / NO / Don't Know**
. Other ____

2 The majority of these failures are of Category I dams. Should more attention be paid to the safety of this Category of dams? **YES / NO / Don't Know**

3 Do you regard South Africa's Dam Safety evaluation approach as any of the following?

i. Standards Based **YES / NO / Don't Know**
ii. Deterministic **YES / NO / Don't Know**
iii. Risk Assessment Based **YES / NO / Don't Know**
iv. Other ______________________________ **YES / NO / Don't Know**

4 It has been suggested that there is no need for Guidelines as people tasked with performing a safety inspection/evaluation or dam design should know what constitutes "best practice" in this regard. Is there sufficient agreement in South Africa on what constitutes "best practice" in Dam Safety?

i. With regard to dam safety in relation to floods **YES / NO / Don't Know**
ii. With regards to dam safety design or inspection/evaluation in general. **YES / NO / Don't Know**
iii. How could this be improved?
   a. Updated Guidelines. **YES / NO / Don't Know**
   b. More regular conferences/courses. **YES / NO / Don't Know**
   c. Regular Journal/Newsletter **YES / NO / Don't Know**
   d. Other ______________________________

5 Which of the following documents do you make use of on a regular basis?
(Tick relevant boxes)

i. Gazetted Regulations on Dam Safety ☐
ii. SANCOLD Guidelines on Safety in Relation to Floods ☐
iii. SANCOLD Guidelines on Free Board for Dams ☐
iv. SANCOLD Guidelines on Dam Break Floods ☐
v. SANCOLD Handbook of flood estimation techniques (Alexander, 1990) ☐

6 What flood estimation techniques do you generally use to determine the required flood?

i. Recommended Design Flood ______________________________
ii. Safety Evaluation Flood ______________________________
iii. Zero Impact Failure Flood ______________________________

7 Do you find that different methods are better suited for particular situations or in certain parts of the country? **YES / NO / Don't Know**

Please elaborate briefly______________________________

____

8 If you use a variety of methods that give different results, how do you choose between them?

i. Normally only use one method ☐

ii. Take the Average of all methods ☐

iii. Use the method that results in the worst flood. ☐

iv. Use some form of subjective weighting to choose a “reasonable” answer. ☐

v. Other ______

9 What is your view of the minimum requirements for the recommended design flood or the safety evaluation flood as given in the SANCOLD Guidelines? (you may select more than one option)

i. They are suitable and do not need to be changed. **YES / NO / Don't Know**

ii. They are too high **YES / NO / Don't Know**

iii. They are too low **YES / NO / Don't Know**

iv. There is too much of a gap between the RDF and the SEF **YES / NO / Don't Know**

v. They give no indication of the factor of safety of the dam **YES / NO / Don't Know**

vi. Other ______

10 What role, if any, should probabilistic flood determination methods play in dam safety in South Africa?

(you may select more than one option)

i. They have no role to play in dam safety evaluations **YES / NO / Don't Know**

ii. They should be included in a basket of flood determination techniques **YES / NO / Don't Know**

iii. They should be used to develop regional flood probability relationship curves similar to the UK Flood Index Growth Curves. **YES / NO / Don't Know**

iv. They should be used to upgrade the relevant flow gauging station rating to incorporate the highest flows on record **YES / NO / Don't Know**

v. They should be used to check how extreme the RMF is **YES / NO / Don't Know**

vi. Other ______

11 What should be done to ensure that South African dam safety practices are in line with international standards?

(you may select more than one option)

i. Change our Dam Safety philosophy **YES / NO / Don't Know**

ii. Apply the same philosophy to all stages of the dam life **cycle** **YES / NO / Don't Know**

iii. Set different standards for different types of embankment **YES / NO / Don't Know**

iv. Reassess the use of the SEF and RDF **YES / NO / Don't Know**

v. Review and update our design flood methodology **YES / NO / Don't Know**

vi. Review the minimum design flood requirements used for different types and classification of dams. **YES / NO / Don't Know**

vii. Other ______

12 The role that Quantified Risk Assessment (QRA) should play in Dam Safety is one of the issues currently being debated internationally. Quantified Risk Assessment in this context involves deciding if a dam is safe by calculating the risk associated with the dam in terms of the product of the probability of failure of the dam and the consequences of that failure, i.e. the probability that somebody will be killed rather than the probability that the dam will fail.

RISK = HAZARD (i.e. probability of failure) x CONSEQUENCE of failure

This calculated risk can then be compared to other dams, alternative designs and safety measures or against other acceptable levels of risks to society.

i. Should QRA play a greater role in the choice of dam design? **YES / NO / Don't Know**
ii. Should QRA play a greater role in dam safety evaluations? **YES / NO / Don't Know**
iii. Should QRA be monitored by an expert body, given its specialist nature? **YES / NO / Don't Know**

13 Both internationally and domestically the conceptual issues surrounding the use of the Probable Maximum Flood (PMF) has been much debated. Should the PMF still play a role in South African dam safety evaluations in the future? YES / NO / Don't Know

14 Which of the following statements, referring to the SANCOLD Guidelines do you agree with?

i. They do not need to be updated and should be kept as they are ☐
ii. They need to be updated, but only require a minor revision ☐
iii. They need to be updated, but require a major revision ☐
iv. They need to be completely rewritten and redeveloped from scratch ☐
v. They should be discarded and replaced by one of the following
   a. Codes of Practice ☐
   b. Dam Safety Manuals ☐
   c. Supporting Textbooks ☐
   d. Structured Continuing Education ☐
   e. Regular Debate on "Best Practice" ☐
   f. Other ____ ☐

15 Please comment on what you see as the major challenges facing Dan Safety in South Africa and what this project should aim to achieve in order to meet these challenges and be of most value to the Dam Safety Community.

____
____
____
____
____

APPENDIX A2 :

List of People Who Responded to the APP Questionnaires

APPENDIX A2

List of People Responded to the APP Questionnaires

Name	Organisation
J. Kroon	DWAF
W. Hendry	Knight Haw Hendry (Pty) Ltd
F. J. De Lange	Daling de Lange & Van Tonder
K. D. Elliot	Zimbabwe Government, DWAF
H. Campbell	Camdekon Engineers
H. Keller	SKC Engineers (Pty) Ltd
P. J Gouws	MME
N. A. Burke	Zimbabwe GOVT Water
A. J Shelly	Ninham Shand
M. Kolesky	MBB Consulting Engineers
A. Chaloner	UWP Consulting Engineers
D. van Bladeren	SRK Consulting
C. R. Clanahan	C.R. H. Clanahan & Associates
D. Moore	GHD (Pty) Ltd
A.L. Melvill	Sandy Melvill
P. J. Le Roux	GMKS
D. L. Webb	DL Webb & Associates
D. I. van Wyk	Ninham Shand
P. C. Blersch	Ninham Shand
P. A. Ballantine	Ninham Shand
D. Badenhorst	BKS (Pty) Ltd
A. G. Chemaly	DWAF
A. White	SRK Consulting
C. J. Abrahamson	Knight Piesold
A. Botha	Ingerop Africa
C.F. Watermeyer	Merman Eng Enterprises cc.
Q Shaw	ARQ (Pty) Ltd.
D.J. Hagen	Arcus Gibb

Total = 28

APPENDIX A3 :

Summary of Reponses to APP Questionnaire on Dam Safety In South Africa

Appendix A3: Summary of Responses to APP Questionairre on Dam Safety

Total Response Number		**28**											
Ques No.	**Question**	**Avg**	**Total**										
1	Name												
2	Organisation												
3	Years of experience	18.9	454										
4ai	Design category I	10.3	206	Category I			Total	735					
ii	Design cateegory II	13.0	350	Category II									
iii	Designe category III	7.5	179	Category IIII									
4bi	Safety inspection I	8.1	130	Category I			Total	1520					
ii	Safety inspection II	39.5	1066	Category II									
iii	Safety inspection III	14.7	324	Category IIII									
5	Location of experiances	**Int.**	**SADEC**	**SA**	**WC**	**MP**	**EC**	**LIMP**	**NW**	**GP**	**KZN**	**NC**	**FS**
	No of people	2	8	4	12	9	7	4	3	10	8	1	3
6	How would you rank the following aspects of Dam Safety in South Africa?												
		Average Rank											
i	Dam Safety in General	3.7			1 Poor								
ii	Dam Safety Legislation	4.1			2 Below Average								
iii	Capacity of the DSO	3.9			3 Average								
iv	Consistency of the DSO	4.1			4 Above Average								
v	SANCOLD Guidelines	3.7			5 Excellent								
vi	Performance of APPs	3.8											
vii	Construction sector	3.2											
viii	Dam Owners	2.6											
		Count				**Percentages**							
7	To what would you attribute the prominence of overtopping as a failur type?	**Yes**	**No**	**DK**		**Yes**	**No**	**DK**					
i	Design Flood too low	21	2	5		75	7	18					
ii	Poor dam design	17	5	6		61	18	21					
iii	Dam not to design specification	9	9	10		32	32	36					
iv	Poor dam construction	9	10	9		32	36	32					
v	Human error/mechanical failure	3	10	15		11	36	54					
8	Should more attension be paid to the safety of Category I dams?	19	6	3		68	21	11					
9	Do you regard SA's Dam Safety evaluation approach as …												
i	Standard Based	24	2	2		86	7	7					
ii	Deterministic	12	7	9		43	25	32					
iii	Risk Assessment	12	8	8		43	29	29					
10	Is there sufficient aggreement on what constitutes "best practice"?												
i	In relation to floods	11	14	3		39	50	11					
ii	In relation to Dam Sfaety in general	9	15	4		32	54	14					
iii	How should this be improved?												
a	Updated Guidelines	25	1	2		89	4	7					
b	conferences	20	3	5		71	11	18					
c	Journal	18	2	8		64	7	29					
11	Which of the following do you use on a regular basis?												
i	Gazetted Regulations	25	0	3		89	0	11					
ii	SANCOLD Guidelineson Safety Relation to Floods	28	0	0		100	0	0					
iii	SANNCOLD Guidelines on Free Board for Dams	24	1	3		86	4	11					
iv	SANCOLD Guidelines on Dam Break Floods	10	2	16		36	7	57					
v	SANCOLD Handbook of flood estimation teechniques	14	1	13		50	4	46					
		Count				**Percent excl 4.**							
12	What flood estimation techniques do you use?	**1**	**2**	**3**	**4**	1	2	3					
	(1=Empirical, 2=Statistical,3=Deterministic,4=Other)												
i	Recommended Design Flood	10	5	17	6	45	23	77					
ii	Safety Evaluation Flood	9	3	9	9	47	16	47					
iii	Zero impact Failure Flood	1	1	3	5	4	4	13					

		Count				Percentages		
		Yes	No	DK		Yes	No	DK
13	Do you find different methods better suited for particular situations?	12	4	12		43	14	43
14	How do you chose between the results of various methods?							
i	Normally only use method	4	0	24		14	0	86
ii	Take the average of all methods	1	1	26		4	4	93
iii	Use one that results in the worst flood	2	1	25		7	4	89
iv	Use some form of subjevtive weighting	24	0	4		86	0	14
15	What is your view of the minimum requirements in the SANCOLD Guidelines?							
i	Suitable and do not need to be changed	16	2	10		57	7	36
ii	They are too high	3	9	16		11	32	57
iii	They are too low	2	9	17		7	32	61
iv	There is too much of a gap between the RDF and SEF	5	8	15		18	29	54
v	They give no indication of the factor of safety of the dam	5	4	19		18	14	68
16	What role should probabilistic flood determination techniques play?							
i	no role to play in dam safety evaluations	5	9	14		18	32	50
ii	should be included in a basket of flood determination techniques	16	2	10		57	7	36
iii	should be used to develop regional flood probability	11	1	16		39	4	57
iv	should be used to upgrade the relevent flow guaging station	10	2	16		36	7	57
v	should be used to check how extreme the RMF is	14	0	14		50	0	50
17	What should be done to ensure that SA is in line with international standards?							
i	Change our Dam Safety philosophy	2	14	12		7	50	43
ii	Apply the same philosophy to all stages of the dam life cycle	12	2	14		43	7	50
iii	Set different standards for different types of embankment	10	5	13		36	18	46
iv	Reassess the use of the SEF and RDF	6	10	12		21	36	43
v	Review and update if necessary our design flood methodology	13	3	12		46	11	43
vi	Review the minimum design flood requirements used for different types	16	2	10		57	7	36
18i	Should QRA play a greater role in the choice of dam design	14	6	8		50	21	29
ii	Should QRA play a greater role in dam safety evaluations	17	4	7		61	14	25
iii	Should QRA be monitored by an expert body , given its specialist nature	16	4	8		57	14	29
19	Should the PMF still play a role in SA dam safety evaluations in the future	18	7	3		64	25	11
20	What are you feelings on the SANCOLD Guidelines?							
i	They do not need to be updated and should be kept as they are.	0	3	25		0	11	89
ii	They need to be updated, but only require a minor revision	17	2	9		61	7	32
iii	They need to be updated, but require major revision	5	2	21		18	7	75
iv	They need to be completely rewritten and redeveloped from scratch	0	3	25		0	11	89
v	They should be discarded and replaced by one of the following							
a	codes of practice	3	0	25		11	0	89
b	Dam Safety Manuals	5	0	23		18	0	82
c	Supporting Textbooks	3	0	25		11	0	89
d	Structured Continuing Education	5	0	23		18	0	82
e	Regular Debate on "Best Practice"	7	0	21		25	0	75
f	Other	2	0	26		7	0	93

APPENDIX A4 :

Written Comments in Response to the Questionnaire to Dam Safety Professionals

APPENDIX A4

Written comments in Response to the Questionnaire to Dam Safety Professionals

7. Given the prominence of overtopping as a failure type, which of the following causes would you attribute this to? Other

Financial constraints lowering standards
Poor spillway design
Poor spillway maintenance
Category I not subject to APP (Yes)
APPs can be "Intimidated" by dam owners because a proposed dam could be "too costly" – too much freeboard and/or “spillway perceived to be large".
Frequency of floods in excess of the design flood for Cat I dams generally higher than the other Categories. In many cases this is considered an acceptable risk and failure by overtopping may not necessarily be unsafe.
Changing catchment conditions leading to increased flooding.
Category I dams were historically constructed by farmers or other untrained persons, with little or no design and with farming equipment. It is not surprising that failures are normally Category I and the risk of failure is usually accepted by the dam owner when weighed against the additional cost of obtaining professional advice.
Many Category I dams not designed at all. I have come across builders who say, "Dambou is maklik! ‘n dam is maar net ’n hoop grond"
Inadequate supervision by APE and poor engineering
Zero to minimum maintenance

10. Is there sufficient agreement in South Africa on what constitutes "best practice" in Dam Safety? How can this be improved? Other.

DSO distribute interesting cases
Bring SANCOLD Technical Committees "out of the dark" and aim to bridge an apparent ten-year "backlog" where no one really knows what they are doing i.e. transparency required. Also change the current situation where the "average dam engineer" is UNABLE to "make contributions to" and/or "benefit from" the set-up. If you look at the "Australian brotherhood"-South Africa is "decades behind".
Updates should be simple to use.
Guidelines are essential to provide a bench mark for legal risk and providing clients with a required reasonable standard-the pressure will always be on to cut back costs and spillway can be expensive.
I do not believe that the answers to the above should mean that Guidelines are not required – they are required since people performing safety inspections/evaluations are not necessarily expert in all aspects of the dam safety and assessment thereof (e.g. Assessment of design floods).
Need Guidelines for consistent approach, with particular reference to RMF/PMF controversy.
On the job training and mentoring of young practitioners.
Publish short accounts of failures/case studies-but there is a possible legal problem, if any. Conclusions are drawn and the cases are sub judice.
I believe that an evaluation of the average age of APPs in 1987 and 2004 would reveal a substantial increase. This suggests that the system in its present format is not sustainable.
Comment: Continuing education is taken into account in appraising candidates for approval as APP.
Transfer of pod of knowledge to younger engineers.

13. Do you find that different methods are better suited for particular situations or in certain parts of the country? Elaborate.

Advised by specialist.
PMF must be considered for big dams. For big catchments certain methods give unrealistic values.
RMF does not apply in mountainous part of Western Cape.
Small catchments require special consideration.
PMF less than RMF in some places and vice versa. So, naturally, a 1;80 to 1:100 year flood in one part of the country could be larger than a 1:200 year flood elsewhere.
The methods above OK for majority of cases but there are exceptions.
RMF based floods are often not suitable for every small or unusual types of catchments.
Small catchment e.g. ESC-method Large catchments, e.g. Rational and other
RMF concept not applicable in mountainous catchments in the Western Cape.
RMF need to be applied with care in Western Cape coastal area. Refer to research done by Professor Alexander at UP regarding regional calibration factors for deterministic methods. KZN coastal area is influenced by cyclones.
So I am told by experts. And I rely on their advice.
PMF does not work well in the Cape.
The relationships of results of different methods can be regional based. Please put this question to Dr W V Pitman, e-mail pitmanwv@iafrica.com.
I am generally working in the same areas i.r.o K values, etc.

15. What is your view of the minimum requirements for the recommended design flood or the safety evaluation flood as given in the SANCOLD Guidelines?

Must be approached realistically for every dam and application.
RMF often high.
These questions relate to Hydrology and Statistics neither of which are in my field but I doubt that they are too low.
Is for the APP to determine when he/she uses flood guidelines to evaluate the safety of a dam.
The current flood guidelines are "very deficient" when it comes to small catchments between 1.0 km^2 and 5.0 km^2 and provide little practical guidance, i.e. you cannot use RMF but you can determine a PMF!
Generally suitable, but as with all guidelines should be treated with care and evaluated in each situation. A guideline can be departed from but this should be accompanied by a well-reasoned assessment and explanation.
I use recommended methods and am not qualified to comment on whether they are good/bad or indifferent.
For catchments approaching 1 $km^{2,}$, the down rating of the PMF factor does not provide a realistic SEF as the factor approaches 1 – need distinction for small catchments.
Simplistic and not appropriate to floods or earthquake design of dams.
They must be constantly reviewed based on recorded floods
Tried produced in 1988-necomal incorporate more recent record in an update.

16. What role, if any, should probabilistic flood determination methods play in dam safety in South Africa? Other

For high dams
Once again I am not qualified to comment. This is a field for the experts to assess.
The risk of dam failure in respect to floods and to earthquake should be co-ordinated.

17. What should be done to ensure that South African dam safety practices are in line with international standards? Other.

Find out how far behind we are with "international standards" and rectify identified shortcomings, where appropriate, to suit South Africa circumstances. We do not necessarily have to "keep up with the Jones's", i.e. international is not necessarily "always credible or suitable" because of the word INTERNATIONAL.
Generally, the philosophy and guidelines are suitable but regular research and review should be done to ensure that the guidelines could be updated for the benefit of the whole dam safety community and public safety.
By "International Standards", I understand "Developed World Standards". I have worked in several countries around the world, all of which would be considered developing countries, and none have dam safety standards that approach the SA standards.
Just because our procedures differ from those of other countries does not make them worse. However, we should be open to improving our practices if better methods develop in other countries. However what works for another country may not necessarily work for SA (e.g. hydrology, economics, materials, etc. may be very different, which would mean that other methods/practices would not apply to our SA conditions).

18. What role should Quantified Risk Assessment play in Dam Safety in SA?

Risk and hazard are highly subjective issues. A concrete gravity dam with an uncontrolled spillway and an embankment dam with a fully gated spillway in a remote African environment present completely different risk profiles. Some engineers may think that the latter type is completely inappropriate in such an environment and yet Swiss engineers built such a dam just 15 years ago, with a maximum spillway capacity equivalent to a 1 in 10 000 year flood. Often the economics of the situation will anyway be the determining factor.
QRA in RSA should not equate with QRA in Europe and America

19. Should the PMF still play a role in South African dam safety evaluations in the future?

But also give adequate weight to the RMF.
But international funding still requires the use of PMF.
Particularly for Cat III and high-risk Cat II dams.
Yes, but meteorological work and research needs to be completed to establish realistic South African PMPs. The system works if the base data is meaningful.
On my understanding that this is an event that should occur once, never! It should be applied to major, high hazard dams. That is the experts believe the derivation of the value of the magnitude of the event!

20. Which of the following statements, referring to the SANCOLD Guidelines do you agree with?

Updating if any to be done on merit.
(Why "re-invent the wheel"? South Africa already has very scarce resources in the field of "dam engineering" and will be unable to "develop from scratch". More innovative approaches to the problem are "a must".
They should be reviewed and updated by a panel of expects on regular basis (say 5-10 years).

21. Please comment on what you see as the major challenges facing Dan Safety in South Africa and what this project should aim to achieve in order to meet these challenges and be of most value to the Dam Safety Community.

The dam owners should be made aware of the significance of inspection that dam safety inspections are a waste of money. The problem lies in the fact that "small farmers" generally have the most "unsafe" dams and are latest able on most reluctant meet the costs of safety inspections.
Financial constraints.
As an Engineer who does not regularly work on dam design and safety, it is always convenient and reassuring to have used documented "best practice" or codes.
The implementation of proposals contained in dam safety inspection reports should be enforced more vigorously.
There are still a vast amount of dams that were built without a license, permit, etc. Owners (especially farmers) either ignore or do not know that dams need to be registered. Private companies must be engaged to assist with this.
Presently, a dam of 11 m high is considered as a Cat 1 dam. In my view, this is a big dam that must be handled by an Engineer.
It is a challenge to train juniors as fewer dams get built. Guidelines: should be clear and consistent must be practical and simple to apply must not be hair splitting and pedantic, and must be comprehensive and try to cover all situations which, if not, must point the readers to further literature.
i) Number of experienced Engineers reducing rapidly with no one to replace them. ii) No follow up on implementation iii) Cost of safety inspections must not be made too high iv) Inspections should indicate areas of weakness- not go into too much detail v) Experience is essential for APP vi) Is it necessary to apply each time to be APP ?
i) A person should be classified as an APP for various types and Categories of dam as a once off process. It costs unnecessary time and money to be approved for each dam to be inspected. This is the method used in the United Kingdom, Australia, Zimbabwe, and probably most of the member countries of ICOLD. In fact this is basically the case at present, except one has to go through all the paper work for each inspection. ii) Much time and money is spent on producing O&M Manuals and Emergency Evacuation Plans, which are for most part ignored. It is in the owner's best interests to follow the advice given in the O&M Manual and his, together with the community, to be fully conversant with the Emergency Plans, nevertheless is there anyway in which this situation may be improved? DWAF have two excellent pamphlets, "*Your Dam Your Responsibility"* and "*Your Dam Answers to the questions most frequently asked about the inspection and maintenance of small dams"*. Perhaps these could be distributed more widely and often. I am sure that the law already covers the Emergency aspect but the force of the law is probably not the best way to go, apart from the difficulties of policing it. For the large dams, there should be periodic trial runs of the procedure to be followed, just as one has "fire drill" in large buildings, especially if the community at large is at risk, i.e. a dam upstream of a river running through a town. iii) Is there any way in which the cost of inspections could be made cheaper for the smaller dams? Subsidies come to mind but why this should be funded by you and I, the taxpayer? After all the

inspections are to the owner's benefit, in that weaknesses that are a danger not only to others but also to his investment, are brought to his attention because in general he has not done much inspection himself.
Dam Safety office should play a far greater role in APP evaluations. They know the people better than the committee members do. The committee's impartiality is also questioned.
Get back on track with much more research in the field of practical flood hydrology. We have had more than a DECADE of "inactiveness" or "being in limbo" and still have not improved on "flood determination methodology". (i) Why not develop a 2005/2006 version of HRU 1/72? (ii) Why not perfect the good old rational Method for tiny catchment areas? (iii) Why not "adapt"/correct the RMF to work for every small catchment areas. It gives ridiculously large floods for small catchment areas. (iv) Did you know that I used the obsolete Creager formula to obtain the PMF for Berg River Dam to resolve a DWAF flood dispute in less than ten minutes. Surprisingly, don't you think!
Concentrate on improving the current flood guidelines, i.e. initially compile one document really top class followed by updated freeboard guidelines. The WRC project must not be bold and bite off more than it can chew.
We do not want a magic suite of computer programmes where only the academics know what is in the black box. This does very little for dam safety because most researchers have little exposure to "every day dam safety engineering" and are rarely involved with the overall dam safety package.
New dams are designed with the required available best technology and are well checked by many people involved. Old existing dams need attention to ensure that they comply with acceptable standards. All dams require proper operation and maintenance in line with acceptable standards. Existing owners are not always paying sufficient attention to this aspect and need to be encouraged to do so.
Dam Safety must be paramount in any dam design, but legislation and guidelines should not be so onerous as to have a large impact on the design or inspection costs of a dam. Cogniscance must be taken of the dam category and whether the consequences of a failure of smaller dams could be tolerated. Existing guidelines and legislation have been easy to use and any changes needed should be minor.
We need to be relevant to society and dam owners must be included as willing partners and role players. Dam safety has been legislated and the cost of inspections, which could be substantial for farmers with limited resources. The need to inspect dams every 5 years, particularly lower category dams should be reviewed.
Challenge: Dam safety criteria and practices implemented Project aim: Documents and evaluate/develop criteria, methods, standards, practices Risk based decision making must be included
Educating dam owners to bring them on board on the importance of dam safety Ensuring that local norms and guidelines are in line with international standards, but are appropriate for local conditions.
Development of effective, acceptable risk guidelines for design floods for category I dams - these dams cannot be designed as Category III dams as the cost of the spillway will be excessive to the cost of the dam, but it should still provide reasonable protection against failure. The RMF/PMF issue needs to be solved-suggest different guidelines for Western Cape.
More continuing education, and communication with APPs, communication with public/owners of dams. The growing tendency for APPs to quote for Dam Safety inspections with little or no information about the dam is unsatisfactory and some other way of establishing consultants' fees requires consideration as some danger could result in the present system.
Having enough expertise to perform the required inspections on smaller dams category I and II dams.
The major challenge is the scarcity of trained practitioners. Too few people interested in and prepared to work at the technical issues. Most bright young engineers find more satisfaction and rewards in management and technical engineering seems to be regarded as a lesser and un-inviting career. The solution is to pay real engineers more.
Consider international practice and aim for a consistent approach.
I see no problems with the "formally" approved/designed/-constructed dams safety inspections

Category III and II dams. However, Category II dams in particular seem to be prone to inadequate maintenance and monitoring, with budget/cost always being raised as a reason not to provide sufficient resources for OMM programmes. Category I dams need innovative design- especially for flood passage – to make the affordable and here ongoing education/ case studies are required. Seepage issues (what is acceptable) need to be addressed and I think there is a need for an obligatory investigation on each failure or damage occurrence.
Convince Dam Owners of the risk of floods and rectify inadequate spillway capacity. Reviewing the guidelines to ensure that we use a realistic, but conservative approach.
Presenting this questionnaire with the statement in relation to the number of failures of Category I dams is likely to skew the answers received. If this information is to be presented, it should be qualified by the age of the dams that failed and the associated damage and loss of life. How many of the Category I dams that have failed since 1987 were designed and built after the implementation of the 1990s flood guidelines? The dam safety community should be provided with this sort of information on a regular basis, in order to be adequately informed to make the decisions required in this questionnaire.
Implement any good suggestions Consider compiling essential guidelines on geological/geotechnical aspects of dam safety, followed by guidelines on hydraulic gates and corrosion aspects.
Transfer of current real knowledge to junior engineers.

APPENDIX B :

Report on Workshop of Dam Safety Professionals held at the University of Stellenbosch on "Updated Guidelines and Design Flood Techniques for Dam Safety"

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Background to the Workshop

A workshop of Dam Safety professionals was held at the Department of Civil Engineering, University of Stellenbosch, on Thursday the 21st October 2004. The workshop was held in connection with WRC Project K5/1420 on "Updated Guidelines and Design Flood Techniques for Dam Safety". In total, 37 professionals from all areas of dam safety in South Africa attended the workshop and participated in a lively debate on the past record of dam safety in South Africa, the merits of the current SANCOLD Guidelines for Dam Safety in Relation to Floods (SANCOLD, 1999), the challenges for the future of dam safety in South Africa and a Framework for Best Practice. The feedback from the workshop will ultimately be used by the project team to develop a set of updated guidelines for dam safety assessment in relation to floods, as required for the WRC Project.

Proceedings of the Workshop

The workshop comprised four sessions. In the first morning session, Professor André Görgens, the project team leader, presented the objectives of the overall WRC project as well as the objectives of the workshop. The focus of the workshop was not aimed at achieving consensus on updated guidelines, but to initiate a debate on the broader Framework for Best Practice and some of the key issues to be considered regarding the future of dam safety in South Africa. The intention of the workshop was also not to discuss the merits of the individual hydrological methods used in the safety evaluation of dams in relation to floods, as these would be the focus of a separate technical workshop to be held at a later stage in the project. Mr James Cullis then presented a summary report of the progress of the project team in regards to the development of the updated guidelines. He presented the findings of a literature review on dam safety in South Africa as well as an investigation into the application of the current SANCOLD Guidelines in South Africa, based on interviews with key stakeholders in DWAF and a survey of a number of dam safety professionals. He also presented some figures on how the classification of dams and the selection of design flood and extreme floods in South Africa compared with those used in other countries.

The second session focussed on the current SANCOLD Guidelines for dam safety assessment in relation to floods (SANCOLD, 1991). There was much debate on the merits of using guidelines as well as the link between the guidelines and the supporting methodologies. In general, it was felt that the concept of guidelines was useful, but that the current Guidelines needed to be updated in light of advances in methodologies and shifts in attitudes towards dam safety assessment.

Mr Cullis presented a Strawdog Draft Framework of Best Practice for Dam Safety Assessment that had been developed by the project team. The framework consisted of six levels or frames:

- Level 1: Operating environment
- Level 2: Guiding principles

- Level 3: Regulatory system
- Level 4: Approaches
- Level 5: Procedures
- Level 6: Methods

Debate focussed on the contents of the first three levels of the framework and an attempt was made to classify the contents of these levels in terms of "Rules of the Game" or "Key Uncertainties" so that they could be used to develop a Foxy Matrix[1] for aiding the decision on how to update the existing guidelines.

In the final session, the participants entered the fourth level of the framework and debated the approaches that were most appropriate given the rules of the game and key uncertainties identified in the previous session. The key considerations were: the type of aids that were required, the debate over a silo-based approach that kept each facet of dam safety separate or an integrated approach, and the role that risk assessment should play in dam safety assessment in South Africa.

The workshop closed at this point and did not go into the fifth or sixth level of the framework. The project team indicated that the ideas and comments from the workshop would be incorporated into their proposal for updating the current SANCOLD guidelines in which they would explore the possible processes and methods needed to support the approaches favoured by the workshop participants. The main findings from the workshop that will help guide this process are described in the following sections of this Report.

Session 1: Dam Safety in South Africa

The following key issues came out of the debate on the current state of dam safety in South Africa:

- South Africa has a relatively good safety record with relatively few fatalities resulting directly from the failure of a dam. There has, however, been insufficient research to clarify whether the current SANCOLD guidelines have improved the safety of dams in the country, but it was felt that, where unexpected failures have occurred, it was not as a result of the guidelines, but due to other factors such as poor construction, mechanical failures or people putting themselves at risk.
- There is a major concern over the number of illegal, unregistered dams in the country. Illegal dams often occur as a result of delays in the licensing and approval of small dams. The appointed approved professional person (APP) has to distance himself from these illegal dams, which results in these dams being built without suitable supervision or the proper safety standards being applied. Any new regulations, or guidelines, relating to dam safety assessment must therefore not result in unnecessary delays in the processing of a license or the registration of a dam. There needs to be a trade-off between the statutory requirements to ensure safety and the capacity to regulate them.
- The safety of dams in South Africa is governed by a critical triangle between the dam owner, the APP and the Dam Safety office. The weak link in this chain is often the dam owner. As a result, any effort to improve the safety of dams in South Africa should include

[1] The Foxy Matrix is a scenario planning tool developed by Chantell Ilbury and Clem Sumter (2001) that helps in making strategic decisions.

educating the owners about the importance of the prescribed safety standards and procedures.

- As with other countries in the world, over-topping is the primary cause of dam failure. Insufficient spillway capacity is the second most common deficiency recorded during safety evaluations, after inadequate operations and maintenance manuals (OMM), and emergency preparedness plans (EPP).
- When considering the safety of dams it is important to consider the requirements of the constitution, in particular the right to a safe environment, the right to water and the right to safety. These issues should all be considered when classifying a dam and not simply the impact that the dam failure will have in terms of the economic cost of direct damage or the potential loss of life.

Session 2: The SANCOLD Guidelines in Relation to Floods

- Generally there was agreement that guidelines of some sort are required for dam safety assessment in South Africa. Although certain individuals have reservations about the use of guidelines, this is not the case of the majority of dam safety professionals. It was, however, noted that there are some areas in which the current guidelines are deficient and that these should be addressed. It was also noted that the more concerning issues lay with the state of the supporting methodologies and the way the guidelines were put into practice rather than the actual content of the guidelines.
- The potential for failure due to man-made floods, such as uncontrolled releases from pump-storage schemes, is not addressed in the current guidelines and should be incorporated into the updated guidelines.
- It was agreed that the screening approach used in the current guidelines is helpful in streamlining the process, but it is important to ensure that this is quite a conservative screen and that if there is any uncertainty, more detailed calculations should be performed. It should be impossible for any dam to pass the screening phase that ends up failing in the more detailed site-specific calculations phase.
- It was recommended that best practice should include determining the recurrence interval of the equivalent incoming flood at which the spillway capacity is reached and comparing this to the required design flood and extreme floods rather than simply checking to see if these two floods would pass through the dam. This would give an indication of how safe the dam is and introduces the beginnings of some form of risk assessment to the safety evaluation process. This is already practised by some APPs and should be encouraged.
- The importance of being able to assign a recurrence interval (RI) to the Regional Maximum Flood (RMF) was highlighted. Various informal assessments have put the RI of the RMF at between 1:200 and 1:1000 years. The concern was raised that if the RMF is only the 1 in 200 year flood, then were our design standards not too low? This is further complicated by the use of RMF+Δ and RMF-Δ in the current safety evaluation discharge (SED) table. The ratio of these is not consistent across the country, which complicates the estimation of the RI, and hence annual exceedence probability (AEP), of our existing safety evaluation floods and is statistically indefensible.

- There was some debate on whether the guidelines, as they relate to safety assessment and not necessarily design requirements, should even be concerned with the design flood and should rather focus on the safety evaluation flood only. It was, however felt that the design flood should be included in the safety evaluation process addressed in the guidelines.
- There was some concern over the arbitrary numbers used in the classification of dams in terms of loss of life. It was recommended that details of how the potential loss of life was calculated, and not simply that it was above or below 10, should be included as part of the safety assessment or design report and that this would go some way to addressing this concern. There was some support for the concept of having only two different categories: either some possible loss of life or no possible loss of life.

Session 3: The Draft Framework for Best Practice

The first three levels of the Framework were brainstormed and the updated draft framework is given in Appendix A. Some of the main issues that came out of the discussion of the draft framework were as follows:

- The draft framework is a useful way of putting into context the requirements for the updating of the current SANCOLD guidelines.
- In regards to Level 1, the **Operating Environment**, it was important to include:
- The obligation contained in the Constitution to ensure a safe environment and in DWAF's commitment to protecting resource quality. It was noted that this has been incorporated into the new dam safety regulations that include the potential hazard to resource quality as a third column in the classification of dams.
- Adequate future capacity in terms of dam safety professionals and dam operators was seen as a key uncertainty that could in the future, have a major impact on the safety of dams.
- The presence of the large number of illegal dams and the impact that any delays in the processing of licenses would have on this number was also a fact of the operating environment, but the ability of DWAF to address this regulatory concern was a key uncertainty.
- In regards to Level 2, the **Guiding Principals** it was important to note:
- The avoidance of unnecessary cost should not be seen as an excuse for reducing the level of safety. It was proposed that DWAF could provide support in cases where the owner of a strategically important dam is really not able to maintain the safety of their dam. If this is the case, however, the option of forcing the owner to remove the dam should also be considered as a last resort.
- It is important to recognise that design flood determination is an "art" and that often qualitative factors relating to dam safety are just as important as quantitative factors. Deviations from the guidelines should therefore be permitted, provided they can be suitably motivated.
- In regards to Level 3, the **Regulatory Environment**, it was noted by the Dam Safety Office that revised Dam Safety Regulations are currently being developed and have been sent to ECSA for approval. These new regulations take into consideration some of the issues arising out of the debate on the guidelines, such as including the potential hazard to the

resource and the inclusion of risk assessment as a more fundamental component of the dam safety assessment process.

Session 4: Considering the Approaches to Dam Safety Assessment

During the final session there was some debate on the approach that should be adopted in terms of updating the guidelines. The issues raised have helped in determining the proposed approach outlined in the Framework of Best Practice. Some of these issues discussed were as follows:

- DWAF currently uses a standards based approach for the safety evaluation of new dams, but risk assessment is used for existing dams given the availability of additional information.
- Risk assessment is also useful in terms of prioritising a set of dams or a list of options for improving the safety of a single dam as well as for making a business case for improving safety of a dam that could not otherwise be motivated for on purely economic grounds.
- There needs to be more of a balance between the different "silos/disciplines/area" of dam safety. Flooding is often the "silo/discipline" that receives the greatest attention, but there are serious concerns in the other “silos/disciplines” particularly with regard to construction or the capacity to maintain mechanical items such as radial gates. The operation and maintenance silo provides the opportunity to cover any deficiencies in the other silos.

The general feeling in this final session was that the dam safety professionals appreciated the opportunity to participate in the development of the updated guidelines. There was, however, some concern that the document that should come out of this project should not include the word *"updated"* in the title. There was also some support for the idea that the document should not be called *"guidelines"* at all. This was done in recognition of the legal interpretation of the term "guidelines" and the concern that it could lead to APPs not suitably applying their mind to the problem. One suggestion was that the final document simply be termed *The Safety Evaluation of Dams in Relation to Floods* and that this be used as a tool to assist the dam safety professional with his understanding of what constituted best practice, but that this be used in conjunction with other aids such as the revised Regulations, the Framework for Best Practice, continuing education and technical manuals and reports relating to the specific methods available.

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SANCOLD. 1991. *Guidelines on Safety in Relation to Floods.* The South African National Committee on Large Dams, Pretoria.

APPENDIX B1 :

Updated Framework Of Best Practice

APPENDIX B1: UPDATED FRAMEWORK OF BEST PRACTICE

The updated *Framework for Best Practice for Dam Safety,* which incorporates the comments from the workshop, is shown as Figure 1. The *Framework* comprises a number of layers or frames that start with the very general issues defining the environment in which dam safety professionals have to operate (Level 1) and work down to the finer details of the individual methods to be used in dam safety assessment (Level 6).

Level 1 contains facts about the world in which we have to operate. Relating to this Operating Environment are a number of Key Principles (Level 2) that must be borne in mind when developing any aid to assist in a dam safety assessment and indeed should be maintained during the actual dam safety assessment or design process. These Key Principles are essentially of a political nature rather than a purely scientific nature as at the end of the day the level of safety required is decided on political and economic principals for which scientific information is required to inform this decision.

The next frame surrounding the approach to dam safety assessment is the Regulatory Environment (Level 3). While this forms part of the Operating Environment, it too is subject to the Guiding Principles of Level 2. These three outer frames represent to a large extent the Rules of the Game and the Key Uncertainties relating to dam safety assessment in South Africa. We have little or no control over them and as mentioned before they are largely political and not scientific. They must, however, guide the selection of suitable approach to dam safety assessment.

Level 4 describes the general Approach to be adopted. Based on the discussions at the workshop relating to both the Rules of the Game and the Key Uncertainties as well as the possible approach options, the following conclusions were drawn on the type of approach that should be adopted for dam safety assessment in South Africa:

- The approach used should not differ to greatly from the current guidelines but these should be updated and placed in a framework of best practice.
- The guidelines should be supported by continuing education and the development of technical literature on new and existing methodologies.
- While the guidelines should still set certain safety standards, they should not prescribe specific methods, but rather provided information on the most appropriate methods to be used in a particular situation.
- The guidelines should set standards in terms of acceptable flood and risk criteria for different categories of dam, but should not prescribe individual methods and must allow for deviations in exceptional cases based on professional judgement and motivation.
- Risk assessment should be incorporated in the updated guidelines particular with regards to the periodic safety assessment of multiple dams or safety options, in the pre-screening of key failure modes during a safety assessment and in determining the relative safety of a dam or recommendations arising from a safety assessment.
- Pre-screen based on generalised design criteria should be utilised to streamline the process, but it must be conservative.

- Separate guidelines should be produced for each silo of dam safety assessment, including construction and operations and maintenance, but the overall safety assessment should be based on an integration of these silos.
- Separate processes should be followed for safety evaluation during design, construction, routine safety inspections and removal of dams. These processes, would, however make use of similar supporting methods.
- The guidelines should be updated in light of the requirements of the new Regulations. The main changes to the Regulations involve the inclusion of the potential hazard to the resource, changes to the definition of the Safety Evaluation Flood and the requirement for a risk assessment to be conducted during the design and safety evaluation of Category III dams.

The general approach to dam safety assessment described in Level 4, requires a set of supporting Processes (Level 5) and these Processes must be developed for each individual silo as sub-frames and in terms of the overall integration of silos. Three separate processes are currently being developed by the project team for this level, but only in relation to the floods silo. These relate to the safety assessment of dams during the design phase, for routine safety inspections during the operating life of the dam, and the safety evaluation for the removal of a dam. Each Process will have a number of procedures for which different methods (Level 6) of analysis and assessment will be required. The relationship between Processes and Methods is not the same as between the other levels in the framework. While the dam safety professional will generally follow a route through from the outer frames to the inner, more detailed frames, the route between the processes and methods is not one directional as each process will have a number of procedures with specific supporting methods. As a result the dam safety professional will be continuously moving between the Processes frame and the Methods frame as each procedure is performed using the most appropriate method and he moves on to the next procedure in the process. Level 6 is essentially a Toolbox of methods that the dam safety professional can call on for a specific procedure. In most cases their will be a number of methods to choose from and while the guidelines should give some assistance on which method is most appropriate for a given situation, it will ultimately be left up to the professional judgement of the practitioner to ensure that he makes use of the most appropriate method.

South Africa already has a well-developed set of existing methods for dam safety assessment in relation to floods, including deterministic, empirical and statistical methods, as well as ones that look to integrate the assessment of dam safety under each of the silos in terms of risk at a screening level. It is proposed that the updated guidelines simply make recommendations as to which methods are appropriate for each of the required procedures, but that the final decision should be left up to the individual practitioner.

Level 1: Operating Environment

- National Strategic Objectives => economic growth, job creation, poverty alleviation
- National Water Act
- Growing public concern about the risks associated with dams
- Growing public understanding of risk concepts in relation to other industries
- Capacity constraints of future dam safety professionals
- International best practice
- Attitudes and financial constraints of dam owners
- Declining number of new dams being built
- Obligations to a safe environment contained in the Constitution
- Large number of illegal dams in the country

Level 2: Guiding Principles of Dam Safety Assessment in South Africa

- Public safety is paramount
- Integrated assessment of risk to society and reduction to acceptable levels
- Avoidance of unnecessary cost with in the limits of safety.
- Recognise the role of professional judgement
- Any Tools developed must facilitate professionals development and capacity building of future Dam Safety professionals
- Transparency and consistency of methodologies used in recognition of public opinion and legal concerns

Level 3: Regulatory System relating to Dam Safety in South Africa

- Dam Safety Regulations
- Dam Safety Office
- Licensing requirements
- ECSA requirements to register as an APP.

Level 4: Approaches to Dam Safety Assessment

- Similar approach to the current guidelines but placed in a framework of best practice supported by continuing education.
- Standards based approach should be maintained as the core of the guidelines, but risk assessment should be incorporated particular with regards to the safety assessment of multiple dams or safety options.
- Guidelines should give acceptable standards, but not prescribe a particular method and instead point to the possible options.
- Pre-screen should be utilised to streamline the process, but it must be conservative.
- Separate guidelines should be produced for each silo, but the overall safety assessment should be based on an integration of the silos.
- Separate guidelines should be followed for design, construction, safety evaluation and removal of dams.

Level 5: Processes required for Dam Safety Assessment

Structural	Floods	Geotechnical	Construction	Operation and Maintenance
Level 6: Methods	Level 6: Methods	Level 6: Methods	Level 6: Methods	Level 6: Methods

Integrated Safety Assessment

Level 6: Methods

Figure 1 Framework of Best Practice for Dam Safety Assessment in South Africa

APPENDIX C :

Strategic Framework for Best Practice for Dam Safety

APPENDIX C: Strategic Framework for Best Practice for Dam Safety

Level 1: Operating Environment

- The obligation on the State to ensure a safe environment for all is contained in the Constitution and must be honoured in all public administrative processes including dam safety regulation.
- National Strategic Objectives such as economic growth, job creation, and poverty alleviation must be considered.
- There is growing public understanding of risk concepts in relation to economic activities including the risks associated with dams
- Dam safety in South Africa must conform to international best practice.
- South Africa faces significant capacity constraints in terms of the availability future dam safety professionals and operators.
- The attitudes and financial constraints of dam owners must be considered in the dam safety assessment process, but cannot be used as a motivation for reducing safety standards.
- The number of new dams being built in South Africa and around the world has been declining, which provides a reduced opportunity for ne dam safety practitioners to develop their skills through practical experience.
- There are already a sizeable number of illegal dams in the country and ways must be found to ensure their safety.

Level 2: Guiding Principles

- Public safety is paramount.
- The overall risk to society, the economy and the environment must be reduced to acceptable levels.
- Unnecessary costs must be avoided within the limits of safety.
- The importance of professional judgement and sit- specific variations must be recognised.
- Dam safety decision support tools must facilitate professionals development and capacity building.
- Transparency and consistency of procedures and methodologies used must be maintained in recognition of public opinion and legal obligations and concerns.

Level 3: Regulatory System

- National Water Act (RSA, 1998) and Dam Safety Regulations.
- Requirements for approval by the Dam Safety Office.
- Requirements for obtaining a Water Use Licence.
- Requirements to register as an approved professional person.

Level 4: General Approach

- Dam safety assessment in South Africa is based on recommended Standards, but incorporates Risk Assessment as a pre-screen tool and an additional check when required.
- Minimum Standards are not prescribed in legislation, but are recommended in "Guidelines" and other guiding professional documents.
- "Guidelines" set recommended Standards, but do not prescribe specific methods and allow for professional judgement to account for site-specific conditions.
- Conservative pre-screening is based on a generalised acceptable flood capacity check and is used to streamline the safety assessment process for small, low hazard dams.
- The hazard potential of a dam is measured in terms of loss of life, economic losses and potential threat to resource quality (i.e the aquatic environment).
- "Guidelines" must be supported by continuing education and technical literature to enhance professional judgement and capacity building.
- Separate processes are recommended for the design process for new dams and for the safety assessment of existing dams.
- Specific procedures relative to each scientific/technical domain should be developed.
- With regards to the safety in relation to floods, two flood scenarios are considered: a design flood for normal operating conditions and a safety evaluation flood for extreme flood conditions.

Level 5: Specific Procedures

Structural	Floods	Geotechnical	Construction	Operation and Maintenance
Level 6: Methods	Level 6: Methods	Level 6: Methods	Level 6: Methods	Level 6: Methods

Integrated Safety Assessment

Level 6: Methods

APPENDIX D :

Notes on Risk-based Dam Safety Assessment

APPENDIX D: Notes on Risk Based Dam Safety Assessment

James Cullis

What is Risk Analysis?

A simplistic engineering definition of risk is given by (Wium, 1988) as -

"An expression of the probability (or likelihood) that something unpleasant will happen owing to hazardous circumstances that could have harmful consequences, usually expressed as the probability of occurrence of the particular event and the effect of the event (financial loss, loss of life, etc.)"

This standard definition of risk can be expressed by the equation:

RISK = HAZARD X CONSEQUENCES

The detailed definitions of other risk analysis terms referred to in this Report are given at the end of the Report, but their relationship to each other can be described in the following way. Failure of a dam poses a *threat* to the downstream *population at risk*. The possibility of this threat being realized is the *hazard* and this can be a function of the probability of a flood occurring that exceeds the design capacity of the dam (*load)* and the *resistance* of the dam to this load. For a well engineered dam with no known deficiencies the practical limit of probability of failure (*hazard*) is about 10^{-5} (Oosthuizen, 2002). The *consequences* of the failure of the dam are the number of lives that will be lost or the financial or environmental implications.

The level of the consequences is a function of the nature of the dam failure and the *vulnerability* of the affected population (e.g. how many people are in the flood zone) and their *capacity* to cope with the flood (ISDR, 2002). The concept of vulnerability and coping capacity, which in itself is very complicated, is not really well explored in the dam safety field, with the most common considerations being warning time, which is based on the distance from the dam and the time of day. There is, however, much debate on this topic in other fields of study, particularly in the field of natural disaster studies and emergency management plans (ISDR, 2002) that can and should, be incorporated into the field of dam safety analysis. The risk equation is now defined as:

RISK = HAZARD X (VULNERABILITY/CAPACITY)

Vulnerability and capacity are themselves a function of Physical, Economic, Social and Ecological factors (ISDR, 2002).

In this example if the dam failure with a probability of 10^{-5} threatens the lives of 1000 people, but half of them are able to survive the flood as a result of a coping capacity of 2, then the consequence of the dam failure will be the loss of 1000/2 = 500 lives. The risk associated with this dam, in terms of potential loss of life, is then equal to 10^{-5} x 500 = 0.005 or 1 in 200. The *realisation* of the risk, i.e. the death of the 500 people due to the failure of the dam would be a *disaster*.

The above process, which calculates the risk to society of particular dam, is defined as *Risk Analysis* and forms only part of the process of *Risk Assessment* shown in **Figure 1**. Risk assessment takes the results of the risk analysis and compares them either to the risk associated with other dams or other scenarios (know as a *Portfolio Risk Assessment*), or with specified acceptable levels of risk determined in advance (know as a *Quantitative Risk Assessment*).

<table>
<tr><td rowspan="3">RISK ANALYSIS</td><td colspan="2">IDENTIFICATION OF RISK FACTORS</td><td rowspan="6">RISK ASSESSMENT</td></tr>
<tr><td>HAZARD</td><td>VULNERABILITY/ CAPACITIES</td></tr>
<tr><td>Determines geographical location
intensity and probability</td><td>Determines susceptibilities and
capacities</td></tr>
<tr><td rowspan="3"></td><td colspan="2">Estimation of level of risk</td></tr>
<tr><td colspan="2">Evaluation of risk</td></tr>
<tr><td colspan="2">Socio-economic cost/benefit analysis
Establishment of priorities
Establishment of acceptable levels of risk
Elaboration of scenarios and measures</td></tr>
</table>

Figure 1: Stages of Risk Assessment
(source: ISDR, 2002)

The estimation of the level of risk associated with dam failure is currently practiced in a number of countries, including South Africa, where it is used to prioritise existing dams for rehabilitation purposes (Chemaly, 2003, pers. comm.) and to evaluate the safety of individual dams owned by DWAF (Oosthuizen, 2003, pers. comm.). Different methods are used in these two cases, but they are both classed as *portfolio risk assessments (PRA)*. A PRA can be defined as a method for cost-effectively prioritising dam safety measures and further investigation for a group of dams or safety measures (USSD, 2003). It is a relative measure and not an absolute value.

Incorporating risk analysis into design criteria for dams requires further steps to be taken as part of a full *Quantitative Risk Assessment (QRA)* process. This process involves the evaluation of the risk associated with a particular dam (calculated in the risk analysis phase) in regard to acceptable levels of risk in society. In the past the difficulty in deciding on an acceptable level of risk, particularly with regards to potential loss of life, was one of the main reasons for not including risk analysis in design guidelines (USACE, 2000). Improvements in our understanding and techniques for risk analysis and assessment, as well as the changing perception of the public to matters of risk, particularly in the field of insurance and risk from other natural and man-made hazards, are behind the move to re-consider the introduction of risk based design criteria and safety guidelines for dams.

How does Risk-Based Differ from Standards-Based Design?

The risk assessment framework for use in dam safety guidelines is shown in **Figure 2**. The difference between the risk based approach and traditional practice is rooted in probabilistic versus deterministic methods and decision criteria (Hatford, 1997).

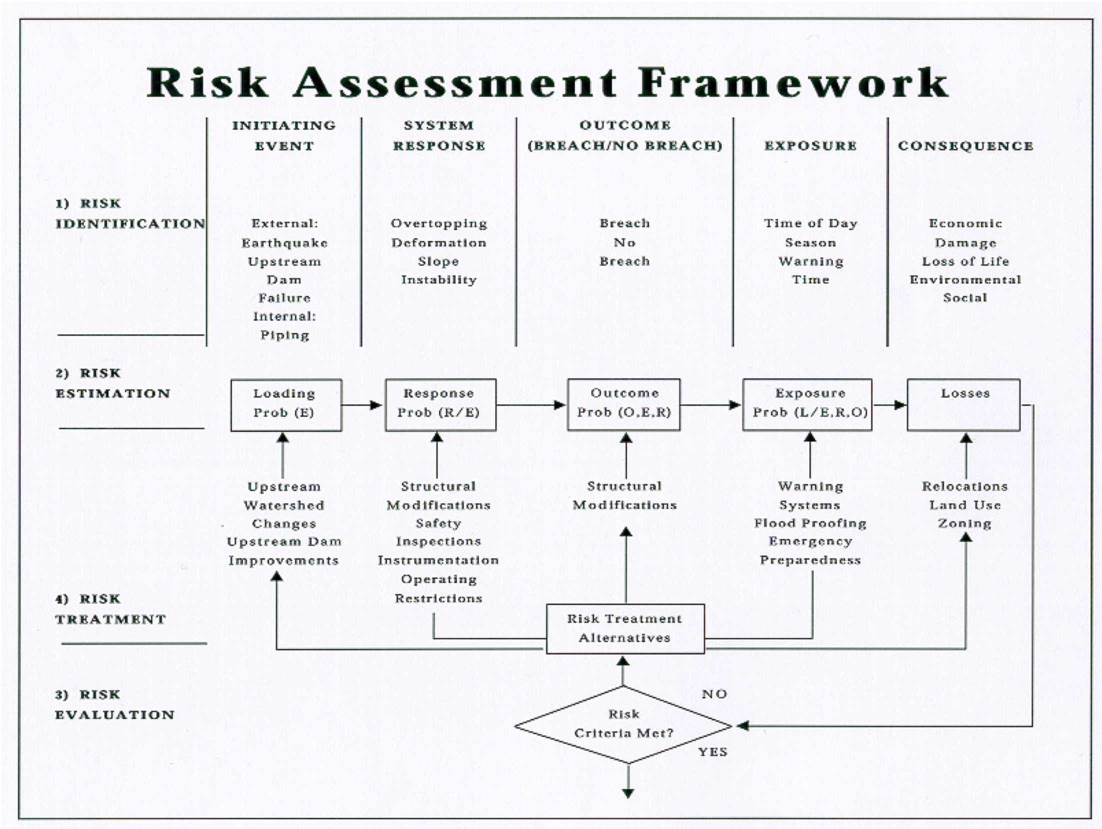

Figure 2: Risk Assessment Framework
(source Bowles *et al.* 1998)

In the risk based method the use of probability distribution functions (PDFs) means that the uncertainties in estimating the loads (or actions) and modelling the reactions and consequences can be retained throughout the analysis and result in the calculation of risk as a measure of the probability and extent of any effect to health property or the environment. The traditional, standards based, deterministic approach, selects design values as actions and even though they may be based on a certain probability of occurrence (return period) they are entered as unique values and load combinations and one set of reactions is calculated for each load function, irrespective of the relative probability of the load combination or the uncertainty in the models used to calculate the reaction. Unlike the risk analysis approach the consequences of the reaction are calculated separately, based on a certain failure mode. Again, neither the probability of the various failure modes, nor the uncertainty in the models used to calculate the consequences associated with each are calculated (Darbre, 2000).

The Risk Analysis Process

The amount of detail and information required to perform a risk assessment depends on the objective of the risk analysis, the importance of the results, which would depend on the hazard class of the dam and the budget and available resources. McCann (1998) identifies five levels of risk analysis with increasing complexity.

1. Scoping
2. Ranking
3. Detailed
4. Comprehensive
5. Full Scope

The fundamental process of a risk analysis is the same. The four basic steps (after Fell *et al,* 2000) are:

1. Failure mode identification
2. Analysis to estimate the probability of failure of the dam
3. Calculation of the economic and environmental losses of life in the event of the dam failing
4. Assess the risk and compare with other dams or options and/or acceptable risk criteria.

Failure Mode Identification

The identification of possible failure modes is the most critical part of any risk analysis (Fell *et al,* 2000) and should be conducted by suitably experienced professionals with full access to all relevant information about the dam. The outcome is a list of possible failure modes, their effect on the project functionality and an event tree leading to the failure. the main failure modes that need to be considered in a South African context (Oosthuizen, 2002) are:

- Concrete Gravity dams
  - Sliding (also important for Arch dams)
  - Overturning
- Embankment Dams
  - External erosion
  - Internal erosion
  - Slope stability

Probability of Failure

The first step in calculating the probability of failure is to determine the probability density function for each of the action, or loads on the dam. The estimation of the probability of floods liable to pose a threat to a dam is an area that is currently under going a large degree of debate (Alexander, 2001; Görgens, 2001; Graham 2000, DEFRA, 2002, Cluckie *et al,* 1990).

Once the probability distribution of the incoming floods has been established, as well as the probability distribution of the reservoir levels, the calculation of joint probability can be based on the stochastic-deterministic methods of Laurenson (1974) (Green and Hill, 1999). There are a number of existing methods for estimating the probability of failure under different water levels that are well documented (Ang and Tang, 1984; Harr, 1987; Oosthuizen and Elges, 1998; Elges and Knoesen, 1998: Fell *et al,* 2000). Probability distribution functions can be calculated for all failure modes, but some such as internal erosion, piping or terrorist attack are less conducive to probabilistic analysis than failure due to flooding or earth quakes and may require the conversion of expert opinion to mathematical probability. The fact that all failure modes can be compared in the common currency of probability of failure leading to risk, is one of the strengths of using risk-based analysis to provide an integrated set of safety evaluation and design guidelines (DEFRA, 2002).

The common thread of all risk-based procedures is that they represent a sequential cause-effect chain (Kreuzer, 2000). The probability of failure and the associated risk developed along the chain of events and can be calculated in two main ways (after Fell *et al,* 2000):

- Event Tree – most common method based on conditional probabilities. Does incorporate some subjective decisions.
- Stochastic analysis – e.g. Monte Carlo Simulation, not currently used much, but has potential, particularly with regards to estimating the uncertainties associated with estimating probabilities.

Consequences of Failure

There are many methods for determining the consequence of a dam failure, almost all of them involve mapping the inundated area as a result of specific types of failure and determining the number of people living in this area (population at risk), as well as the infrastructure and land-use in the inundated area. There are many models and software programmes to assist in determining the consequences of failure. These include models that simulate the actual dam break and the flood wave generated as well as GIS based programs to map the inundated area.

Most countries avoid the difficulty of assigning a value to human life by separating the potential loss of life from the potential economic and environmental losses. In South Africa the impact of a dam failure (Oosthuizen, 2002) is determined according to five factors:

- Population at risk (in numbers)
- Financial impact (including direct and indirect cost) (in Rands)
- Socio-economic impact (a subjective assessment from insignificant to extreme)
- Social impact (as above)
- Ecological impact (as above)

Risk Assessment

As discussed above the "risk" is the product of the "probability of failure" and the "impact/consequence" of that failure. In South Africa (Oosthuizen, 2002), the risk is presented in the form of five impact graphs that relate the impact of a dam failure to the probability of failure and a single risk analysis graph that has annual risk of fatalities per exposed hour on one axis and risk of financial loss on the other (**Figure 3**). The graphs are divided into different levels of risk with the main distinction being between acceptable and unacceptable levels of risk.

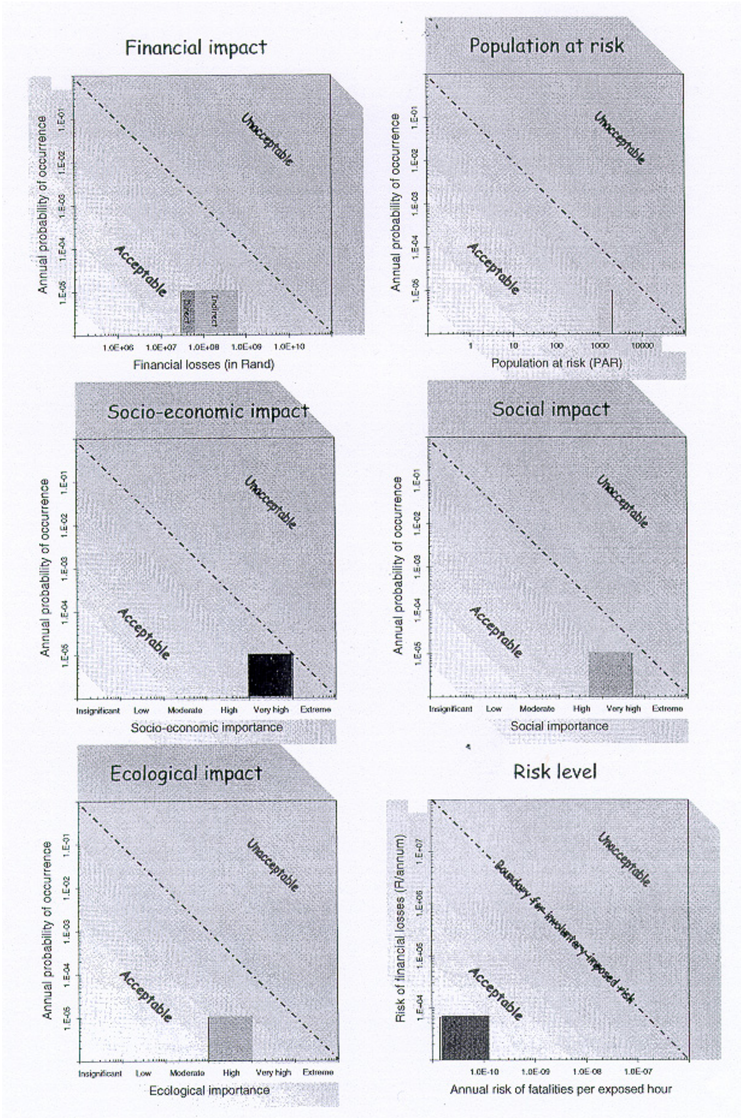

Figure 3: Typical impact and risk level graphs used in South Africa (source: Oosthuizen, 2002)

Why the move towards a Risk-Based Analysis of Dam Safety?

The current international debate on the incorporation of risk based dam safety analysis introduces a paradigm shift away from the currently, almost universally accepted standards based approach (such as currently embodied in the SA Guidelines) (Bowles *et al,* 1997). The main justification for this is the recognition that no dam can be designed with zero risk of failure and that decision making inherently takes place under conditions of uncertainty (Kreuzer, 2000). There is also a general international trend away from removing risk at all cost to managing risk with in acceptable levels as practices in the nuclear and aeronautical sectors.

There are a number of drivers behind this paradigm shift, which Bowles *et al* (1998) classify as

1. **engineering considerations** (e.g. the review of existing dams that do not meet current state-of-the art-practice and are ageing and deteriorating. Current classification of dams is largely based on subjective criteria (Cluckie,1990) Concerns raised that designing according to the PMF will make safety improvements to dams un-affordable and incomparable to the cost of safety measures in other fields (Graham, 2000)),

2. **societal considerations** (e.g. increased downstream development, increased knowledge of risk and risk averse nature of the public, the difficulty of relating to the low probabilities of risk associated with dams and the increased involvement in affected communities on dam safety and design issues), and
3. **business and public policy considerations** (e.g. privatisation of dams, a shift away from prescriptive regulations and government emphasis on risk-benefit justification in other sectors.)

The drive for a risk-based approach is also supported by developments in the field of estimation of extreme flood events. The standards based approach adopts the principle that a dam should be designed to pass a certain percentage of the probably maximum flood (PMF) with out failure, called the Safety Evaluation Flood (SEF) in South Africa. The ratio of the SEF to the PMF is dependent on the hazard classification of the dam and is generally based on engineering judgement of a suitable factor of safety rather than any sound analytical procedure. Hence in the standards based approach there is no probability assigned to the SEF (Green and Hill, 1999). In addition the standards based approach does not account for joint probability. It assumes the worst-case scenario, which involves the combination of a number of low probability events such as:

- Maximum Precipitation
- Minimum areal reduction
- Saturated catchment.
- Minimal impact of routing
- Full reservoir

For example Andres (2000) shows how a return period for the design flood for a reservoir increases by a factor of between 2.8 and 7.4 when the joint probability of incoming flood and reservoir level is considered rather than the return period of the incoming flood alone.

What are the Benefits of Risk Based Analysis?

Risk assessment and analysis has a number of distinct advantages over traditional standards based approaches to dam safety assessment. Some of these include the fact that risk based analysis and assessment:

- Recognises and quantifies the risk inherent in all civil engineering design.
- Aids in the preparation of emergency action plans by becoming part of the extended practice of risk management (which incorporates risk assessment and risk analysis)
- Enables all possible causes of failure to be compared on an equal footing and thus prevent the tendency to focus safety measures on areas that are easier to calculate or define rather than areas that pose the greatest risk.
- Starts with the cause of failure, such as the level of over-topping, rather than with the size of a prescribed flood.
- Is more inclusive of the effected population in the decision making process.
- Supports the inclusion of non-engineering concepts, such as vulnerability and capacity of the threatened community into the assessment and reduction of risk associated with the building and operating of a dam.

- Results in a consistent level of risk being applied to all aspects of dam safety during the full life cycle of the dam.

What are the Concerns with a Risk Based Approach?

While risk analysis is gaining acceptance in terms of dam safety evaluation, there are still a number of concerns limiting its role in dam safety design (DEFRA, 2002). Some of these concerns are as follows:

- Difficulty in assigning a probability distribution function to extreme events particularly in regards to the joint probability of flood peak and flood volume.
- Safety evaluation with regards to floods and earthquakes lends itself to a probabilistic risk-based approach, but other methods of failure need further consideration.
- Deciding on the level of tolerable risk, particularly with regard to loss of life (Vick, 2000).
- Dam failures may be more strongly dependent on the dominantly deterministic nature of engineers' yes-no decisions based on insufficient knowledge, data, capacities, etc. than on the probabilistic nature of natural events such as floods and earthquakes (De Mellow, 2000). The inclusion of human errors into risk assessment needs to be investigated, but again lessons can be learnt from studies in other fields such as shipping and health (Kreuzer, 2000)
- While we are becoming more accustomed to statistics and the probability of risk (De Mellow, 2000), the "public confession" of a residual risk is still problematic (Sieber, 2000) and gives rise to the view held by many critics of risk analysis as "designing dams to kill people" (Hartford, 1998).
- The search and scrutiny of input data is more demanding than for traditional deterministic safety evaluation (Kreuzer, 2000).
- Unlike the aviation industry, there is a relatively small data set (only 45,000 large dams, many of them with little available data and all of them unique) (Kreuzer, 2000), which limits the reliability of statistically based safety methods.
- The perception of risk is often more important than the actual risk. For example numerous, studies have shown that the general public are more averse to events with low probabilities, but high consequences (e.g. dam failure), than events with high probability, but low consequences (e.g. automobile accidents) despite the fact that these two events may have the same mathematical level of risk.
- The application of risk analysis to dam safety is a relatively unstable concept and is still being developed and reviewed. This leads to the conclusion of introducing it in a phased way to support existing deterministic methods rather than to replace them outright as is being considered in the UK as part of an integrated approach to reservoir safety (DEFRA, 2002).

What are some of the International Trends in Risk Based Safety Guidelines?

Many countries are currently exploring the possibilities of incorporating risk assessment as part of their dam safety guidelines. Some of these international trends are summarised below.

- Australia, Canada and Portugal are the leaders in the move to adopt a risk based analysis into dam safety design and have already included it in dam safety guidelines (Hartford, 1998; Salmon, 1997; ANCOLD, 2004), but even these countries feel that risk analysis is not sufficiently advanced or practical to completely replace deterministic approaches to design safety guidelines.

- Other countries such as the US, UK, France, Spain and Germany are currently in a research phase and considering including risk-based analysis into their dam safety analysis guidelines (Kreuzer , 2000; Brown and Root, 2004).
- In China (Xiao *et al,* 2000) and Brazil (Krauch *et al,* 2000), risk analysis is not formally incorporated into dam safety guidelines, but has been used to analyse the risk of failure at various stages in the design and construction of dams.

Some dam safety practitioners already make use of risk analysis in the safety evaluation of dams. The Dam Safety Office for example makes use of a simple risk analysis to check the results of dam safety assessment reports (Chemaly, 2003, *pers. comm.*), while DWAF makes use of a well developed risk analysis procedure to do a comparative analysis of the safety of its own dams (Oosthuizen, 2002, *pers. comm.*), which has been successfully been applied to over 400 dams. Risk analysis was included in the SANCOLD *Guidelines on Safety in Relation to Floods* (SANCOLD, 1991), but received a low priority. The type of risk analysis presented in the Guidelines was more of a cost optimisation exercise than a risk analysis as it is interpreted now, and resulted in a reluctance of dam safety practitioners to include it in their safety assessment, due to the reluctance to assign monetary values to human lives and the difficulty and resources required in determining the consequences of failure. The view of risk analysis as a tool for dam safety practitioners has changed much since these guidelines were developed and the role of risk analysis in South Africa is likely to become more significant as the Regulations on Dam Safety and the Guidelines come under review.

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APPENDIX E :

Proposed Flow Diagram for the Selection of Acceptable Flood Capacity for the Design of a New Dam

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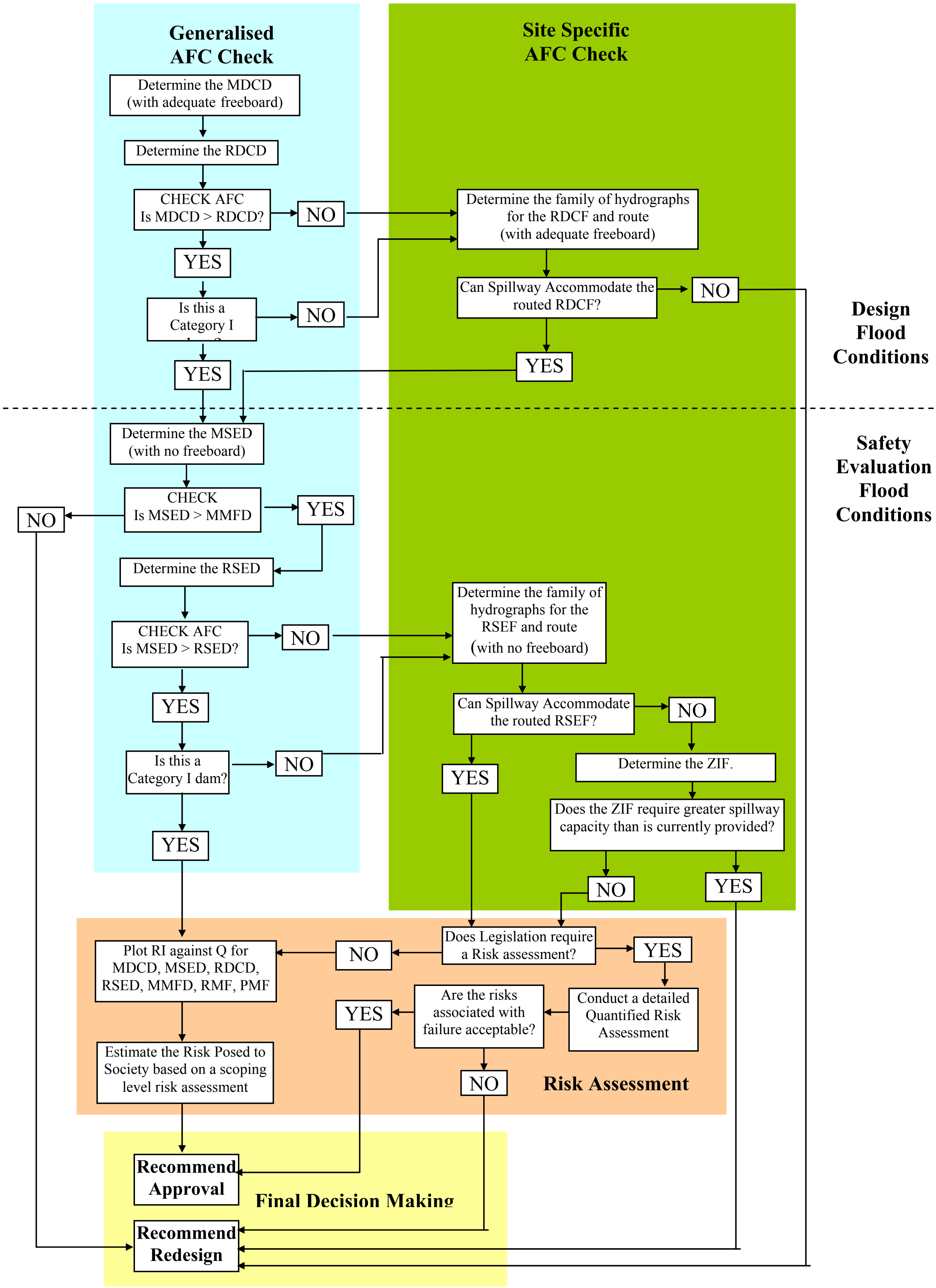

APPENDIX F :

Proposed Flow Diagram for the Selection of Acceptable Flood Capacity for the Safety Evaluation of an Existing Dam

APPENDIX F: Proposed Flow Diagram for the Selection of Acceptable Flood Capacity for the Safety Evaluation of an Existing Dam