THE DEVELOPMENT OF A RISK-OF-FAILURE EVALUATION TOOL FOR SMALL DAMS IN MZINGWANE CATCHMENT.

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ABSTRACT

World wide attention is given to the prevention of failure of medium to large sized dams, with little attention being paid to small dams. As a result the physical condition of small dams is generally poor, making them susceptible to failure. However, small reservoirs are an important source of both primary and productive water for rural communities. It is against this background that this study was carried out to assess the current physical condition of the small dams in the area of study and the factors responsible for this condition. The Information was used to develop a risk of failure evaluation tool for small dams. The tool helps to systematically and objectively classify risk of failure of small dams, there by assisting in the ranking of dams to prioritise for maintenance or rehabilitation purposes. This is important where resources are limited. The tool makes use of factors criteria such as seepage, erosion and others that are conventionally used to assess condition of dams. The description of the extent to which the criteria affect the physical condition of small dams was then standardised. This was mainly guided by similar methods used in other countries but mostly for large dams and by HR Wallingford's methodology for estimating risk of soil erosion. Cause effect diagrams were used to determine the stage at which each factor is involved in contributing to dam failure. Weights were then allocated to each factor depending on its stage in the process of causing dam failure. Small dams design and maintenance guidelines were also used to guide the ranking and weighting of the factors. The risk of failure was then classified as low, moderate, high or very high. The tool was used to classify 7 small dams in Mzingwane catchment. One was found to have a moderate risk of failure, 4 had a high risk of failure and 2 had a very high risk of failure. Also, results of the physical assessments carried out in the study area indicated that the majority of the reservoirs in the studied area were designed and constructed following the recommended design guidelines. However there was a general lack of maintenance on the dams, which resulted in deterioration of the reservoirs condition. At least 68% of the reservoirs were affected by erosion. At least 65% of the dams had trees growing and termite mounds on their embankment dam walls. A significant number of the dams (59%) were old, over 27 years old and probably past their economic lifespan. The physical condition was thus not inline with the recommended condition. The reasons can be broken down into lack of resources by responsible authorities such as DDF, limited stakeholder collaboration, unclear policies of handing over small dams to the communities. It was concluded in the study that the risk of failure of small dams in the area is high and security of water availability is threatened. The risk of failure evaluation tool could be used to help prioritise the use of the little available resources to target the most threatened dams for repair or rehabilitation. The tool needs to be tested in a wider geographical area to improve its usefulness.

Key words: Small Dams, risk of dam failure, risk of failure evaluation tool, security of water availability.

DECLARATION

I NGONIDZASHE L. MUFUTE hereby declare that this work has been done at my prior knowledge and in my own capacity in the Department of Civil Engineering at the University of Zimbabwe.

Date……………

Name….…….Signed……………………………

DEDICATION

This is a dedication to my parents Mr. and Mrs. Lucky Mufute who created conducive environment for me to pursue my dreams.

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LIST OF ACRONYMS

AEP	Annual Exceedance Probabilities
ANCOLD	Australian National Committee on Large Dams
AREX	Agricultural Research and Extension
ASWCC	Arkansas Soil and Water Conservation Commission,
BOR	Bureau of Reclamation
CADEC	Catholic Development Commission
DDF	District Development Fund
FEMA	Federal Emergency Management Agency
FRF	Flood Reduction Factor
GPS	Global/Ground Positioning System
ICOLD	International Commission on Large Dams
ICRAF	International Centre for research in Agroforestry
IWRM	Intergraded Water Resources Management
MPF	Maximum Probable Flood
NGO	Non Governmental Organization
NZSOLD	New Zealand Society On Large Dams
PMF	Probable Maximum Flood
PMP	Probable Maximum Precipitation
RDC	Rural District Council
RELMA	Regional Land Management Unit
SSAE	Soil Science and Agricultural Engineering
USA	United States of America
USC	Unified Soil Classification
USACE	United States of Army Corps of Engineers
VIDCO	Village Development Committee
WEDC	Water, Engineering and Development Centre
WV	World Vision
ZINWA	Zimbabwe National Water Authority

CHAPTER 1. INTRODUCTION

1.1 Background

World wide much attention is given to the prevention of failure of medium sized to large dams with little attention being paid to small dams (Pisaniello et. al., 2006). However, small reservoirs are a very important source of both primary and productive water for rural communities. Failure of small dams reduces the security of water availability and therefore threatens the livelihoods of the affected communities. Little attention is normally given to the risk of failure of these small dams because dam failure is normally viewed in the context of the risk that is posed to life and property downstream of the dam (Rettermeier,2001). Consequently medium to large sized dams are considered to pose high risk if they fail as compared to small dams, which are usually considered to be of low risk, as they do not normally result in huge losses of life and property damage if they fail. As a result, small dams are neglected and are generally in a poor physical condition and are susceptible to failure. In this study dam failure refers to the inability of a dam to hold water due to breaching or siltation. Risk of failure refers to the probability or possibility of failure. Physical condition refers to the state of the components of a dam such as spillways and dam wall in terms of the presence of deficiencies such as cracks, erosion and seepage.

The Zimbabwean Department of Water Development defines a small dam as a structure which has vertical height of less than 8 metres measured from the non-overflow crest of the wall to the lowest point on the downstream face of such wall or is capable of storing less than 1 000 000 m^3 of water at full supply level (Muyambo, 2000). This was taken as the definition of a small dam in this study.

As mentioned above, small dams are very important for ensuring water availability and sustenance of livelihoods for the rural communities. The importance of small dams in this regard is especially pronounced in semi-arid and water scarce areas such as Mzingwane catchment in Zimbabwe (Sithole and Senzanje,2006). As many as 1000 small dams are located in the Limpopo basin where the Mzingwane catchment is (Saunyama, 2005). In some places these small dams are the only source of water for domestic purposes as well as for productive uses such as livestock watering, brick making, fishing and irrigation (Sithole and Senzanje,2006).

In Zimbabwe, like in the rest of the world, inadequate care is being given to small dams (CARE Zimbabwe, 2002;). Without appropriate design, construction and maintenance, small dams eventually fail, depriving the communities and animals of the much-needed water that is vital for sustenance of life. It is against this background that this study was carried out to explore these issues and others that might lead to failure of small dams, and contribute towards solving this problem by developing a risk of failure evaluation tool.

1.2 Problem Statement

Small dams are not being properly maintained in Mzingwane catchment. Lack of resources was noted through a socio economic survey by Sithole and Senzanje (2006) as the major reason for this. This means that there is need to prioritise the use of the limited resources available. However there is no simple tool that would help achieve this through evaluating and quantifying risk of failure of small dams in the study area.

1.3 Justification

Small dams are an important source of water in semi-arid areas such as Mzingwane catchment (Sithole and Senzanje, 2006). Sustainable ways of preventing the failure of small dams should be found so as to ensure reliable water availability and sustenance of livelihoods in the area of study. Because of the limited availability of resources to maintain the small dams, there is need to stretch the effectiveness of the available resources by prioritising and targeting small dams for maintenance and rehabilitation programs. A risk of failure evaluation tool would assist in this regard. There is also lack of information on the actual factors determining the physical condition of small dams in the study area as there are no substantive records on the management of the dams. This came out in interviews held with District Development Fund personnel who are responsible for the design, construction and maintenance of communal small dams in Zimbabwe. Evaluation of risk of failure of dams requires such information (Rettermeier, 2001; Bowles, 1989; FEMA, 1987).

1.4 General Research Questions

- How does the physical condition of small dams in Mzingwane catchment compare with the recommended design and maintenance guidelines for small dams, and relate to dam failure and water availability?
- How can risk of failure evaluation help prevent dam failure and secure livelihoods in the area of study?

1.5 Specific Research Questions

- What is the physical condition of small dams in the study area?
- Is the state of the small dams in line with recommended design and maintenance guidelines for small dams?
- What are the issues resulting in the small dams being in the current physical state?
- Does the physical condition of small dams threaten dam failure and security of water availability in the area of study?
- How can the risk of failure of small dams be evaluated in the study area so as to help prevent their failure?

1.6 Main Objective

To develop a risk-of-failure evaluation tool for small dams in Mzingwane catchment.

1.7 Specific Objectives

- To qualitatively and quantitatively assess the physical condition of small dams in the study area.
- To compare the physical condition of the small dams to the recommended small dams design and maintenance guidelines.
- To identify the factors leading to the observed physical condition of the dams in the area of study.
- To develop a risk-of-failure evaluation tool for small dams.

CHAPTER 2 DESCRIPTION OF THE STUDY AREA

2.1 Introduction

The study was conducted in Mzingwane catchment. The Catchment is part of the Limpopo Basin. The Insiza sub-catchment covers an area of 3401 km^2 and is divided into two main hydrological zones, the Upper Insiza and the Lower Insiza (Onema, 2004). The study was confined to the upper Insiza. In terms of administrative boundaries, the study was carried out in the Godhlwayo area in Insiza District, Matebeleland South, Zimbabwe. Figure 1.1 shows the study area.

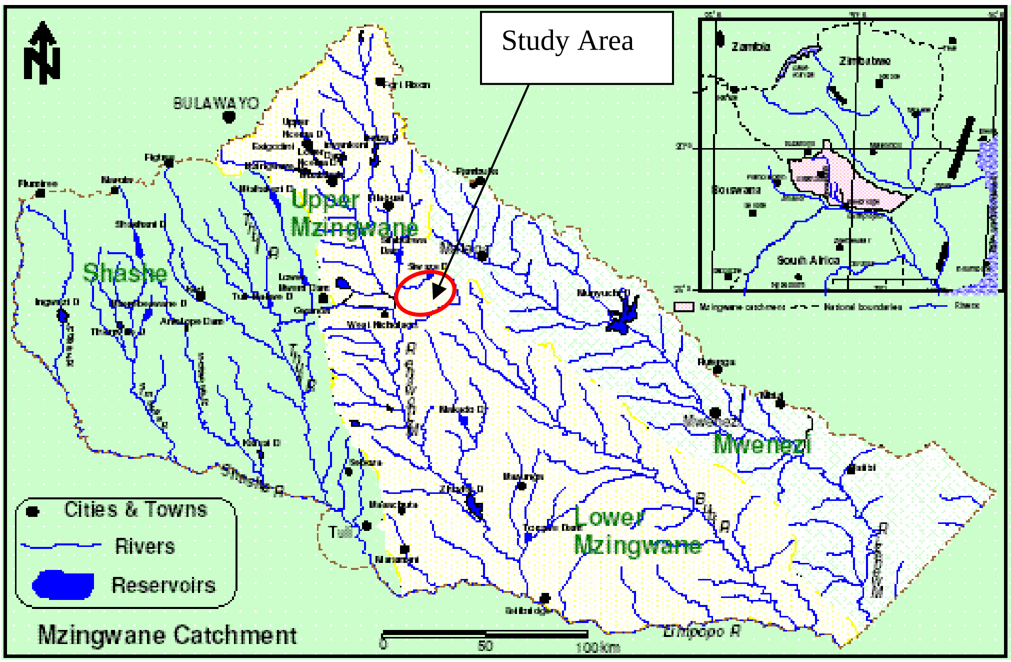

Figure 1.1: Project Study Area. (Source of map: Love et. al. ,2005.)

A total of 44 small dams were visited during the assessments (Table A.16 in Appendix 6) The assessed dams were in wards 4, to 9 and ward 12, which make up the Godlhwayo area. Five dams (11.4%) of the visited dams were in a Small Scale Commercial Farming area (ward 8), the rest were in communal areas. Of the visited dams, one is owned and managed by ZINWA (Siwaze dam). Four of them are farmer owned and the rest are community owned or managed communal dams.

2.2.0 Physioghraphy

2.2.1 Topography

The Insiza sub-catchment starts within the Highveld region, comprising a more or less gently undulating plateau with elevation greater than 1200m followed by the Middleveld region with a decline in the elevation (ranging from 600 to 900m). Undulating to rolling landscape with common rock outcrops characterize the Middleveld.

2.2.2 Soils

Soils in the Insiza Sub-catchment are considered to be coarse-grained sandy loams. Slightly heavier textures often occur in upper slope positions close to rock outcrops. Associated soils are gravelly and shallow (Onema, 2004).

2.2.3 Rivers in the area

The rivers and streams in the area are tributaries of the Limpopo River. Most rivers are able to provide water only for short periods of time each year in the catchment. On major reaches of the Limpopo and many of its tributaries, the flow of water in the river in dry years can occur for 40 days or less. When the rivers do flow, river water can contain up to 30% sand and silt (Saunyama, 2005).

2.2.4 Vegetation

According to Onema, (2004), the communal lands are characterized by relatively high population densities. The resultant disturbance of the vegetation by cultivation has greatly depleted the extent of climax woody cover. The northern part of the Insiza sub-catchment with moderate rainfall has low open woodland of thorny acacia trees associated with granitic or gneissic derived sandy soils. Where drainage is restricted or is on heavier textured soils, mopane trees become dominant. Towards the south of the sub-catchment, there is an area of transition with vegetation types and species changing with elevation from sparse low mopane woodland being gradually replaced by more open woodland. Some areas of the Insiza communal lands where rock outcrops are predominant are mainly bare apart from a small patch of multi- colored lichens and a few pockets of black humic sand supporting small bushes. The pediment slopes were under Miombo woodland although this has been largely replaced by cultivation.

2.3.0 Climate

2.3.1 Temperature, Rainfall and Evaporation

Values for air temperature are closely related to altitude with mean annual temperatures ranging from about 12^{0}C to 29^{0}C. Temperatures are lowest in June and July and highest in October.

The rainy season occurs between November and March and the spatial distribution of rainfall is quite variable over the entire catchment. The annual rainfall ranges from 250mm in the south to 550mm in the north of the catchment, with an average of about 350mm over the entire catchment (Love et. al, 2005). The study area is in the upper areas of the Mzingwane catchment where the average annual rainfall is 550mm as confirmed by rainfall records from ZINWA's Siwaze dam station as well as Dekezi Meteorological Department Sub Station. These stations are located in the area of study. A short and intense rainy season in the study area just like the other parts of the Limpopo river basin with highly unreliable rainfall, leads to frequent droughts. As a result of the frequent droughts and high evapotranspiration rates the catchment is generally water scarce and crop production is not secure. Actual figures for evaporation could not be obtained in the area of study but according to Onema (2004), evaporation from the surface area of reservoirs constitutes the major deduction from the total surface water potential.

2.3.2 Run Off

Mean Annual Runoff of the two hydrological zones (Upper and Lower Insiza) is 50mm and 38mm respectively (Onema, 2004). This means that the potential for run off generation is low, comparing to 120mm for Mazowe catchment for example, according to the Water Resources Management Strategy (WRMS) for Zimbabwe (2000). Also according to Onema (2004), the coefficient of variation of annual flows in this area ranges from 125% in the upper Insiza to 130 % in the lower Insiza. This implies that the potential surface yield of water in the study area varies significantly within a season. Table 2.1 shows the Insiza sub-catchment surface water summary.

Table 2.1 Insiza sub-catchment surface water summary. Source: Onema, 2004.

Sub Zone	Catchment	Area Km²	MAR mm	CV %	MAR 10^3m^3	Total potential			Present Utilization	
						Storage 10^3m^3	Yield 10^3m^3	Unit Yield mm	Storage 10^3m^3	Yield 10^3m^3
IN1	Lower Insiza	1829	38	125	70000	298000	33250	18.18	236476	54082
IN2	Upper Insiza	1572	50	130	79000	158000	36310	23.12	20194	8798

2.4.0 Water Availability and Water Uses

In the Godhlwayo area where the study was confined, there is only one medium sized dam with the rest being small dams. The community small dams are mostly under the management of the District Development Fund (DDF). The capacity of small dams could not be established due to lack of complete records in the area of study. The Medium sized dam is called Siwaze and is managed by the Zimbabwe National Water Authority (ZINWA).It has a capacity of 2.3 million cubic metres of water (ZINWA, 2006).

The greater part of the catchment is composed of ancient igneous rock formations, where ground water potential is comparatively low (Onema, 2004). The ground water potential of the study area has not been fully investigated (Moyo, 2005). However evidence on the ground seems to confirm that the potential is limited due to the poor yields of boreholes which were drilled in the area (Moyo, 2005). The few boreholes that are found in the area are also usually not working due to lack of repair and maintenance (Sithole and Senzanje, 2006). During the assessments of dam conditions in the course of this study, it was noted that dry river beds are also used as sources of water by the communities (Picture 12, Appendix 7). However these are used as a last resort, usually used when other sources such as dams and boreholes have failed or are too far to be accessed.

Major uses of water in the area are livestock watering, gardening and domestic purposes such as bathing, laundry and drinking (Sithole and Senzanje, 2006). Irrigation of small communal plots is also carried out using water from larger small dams and Siwaze dam. For example Siwaze dam supports a 20 ha irrigation scheme near Avoca, in the Godhlwayo communal area.

Given the above described scenario of water availability in the study area, it is evident that there are few alternative water sources to small dams. In fact, in some places of the study area, small dams are actually the only water source (Sithole and senzanje,2006). Small dams are therefore very important for ensuring water availability and sustenance of livelihoods for communities in the area of study.

CHAPTER 3. LITERATURE REVIEW

3.1 Introduction

3.1.1 Definition and Types of Dams

A dam is a barrier constructed across a watercourse for the purpose of storing water. The most common type is the earth fill or earthen dam. There are also concrete dams (gravity, arch, multi-arch, and buttress types) and dams constructed of masonry, timber, rock fill, steel, or combinations of these materials. Earth dams may be further classified as simple, core, and diaphragm. The simple embankment type consists of reasonably uniform material throughout, sometimes with a blanket of highly impervious material placed on its upstream face. This type of dam is also referred to as a homogeneous embankment dam. Core embankments have a central zone or core of carefully chosen material, which is less pervious than the rest of the dam. This dam is also referred to as a zoned embankment dam. Diaphragm type dams incorporate a relatively thin section of concrete, steel, or wood - sometimes referred to as a cut-off wall - in the central portion of the embankment. This forms a barrier to the flow of water percolating through the dam. (ASWCC, 2002: Muyambo, 2000; Shaw, 1977). In Zimbabwe the most common types of small dams are the earthen homogeneous and core embankment dams (Muyambo, 2000; Shaw, 1977). Figure 2.1 illustrates the principal parts of an earth fill dam. Understanding the purpose of these is essential to any evaluation of a dam's condition.

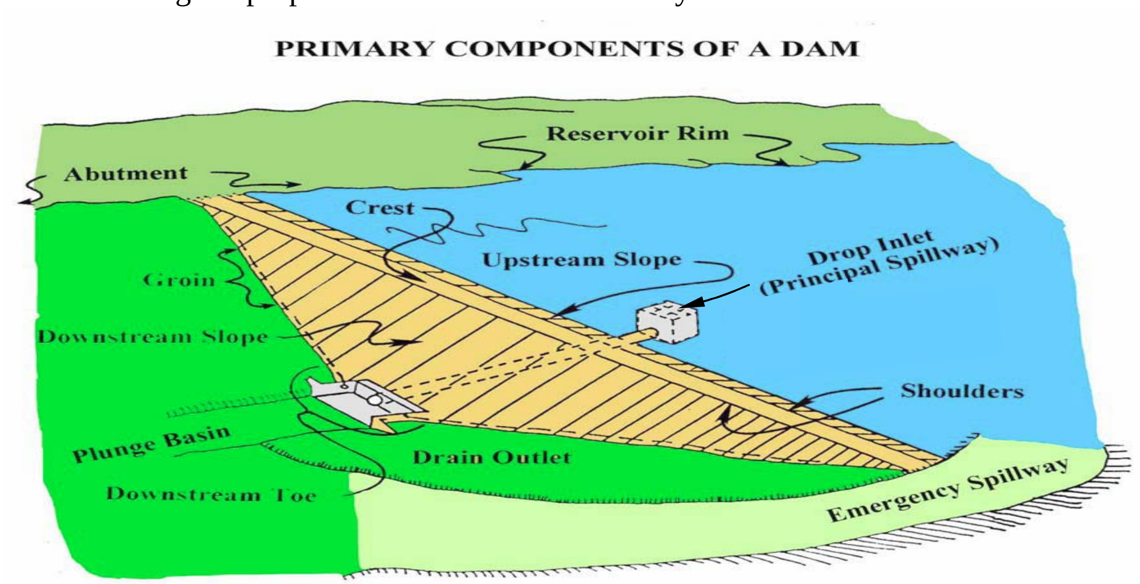

Figure 3.1: The principal parts of an earth fill dam. Source: (ASWCC, 2002)

3.1.2 Definition of a Small Dam.

The definition of a small dam varies worldwide. However it is based on the height and the storage capacity of the reservoir (Saunyama, 2005). The World Commission on Dams defines it as having a dam wall of less than 15 m in height and holding less than one million cubic metres of water. In the United States of America (USA), a small dam is defined as having a wall height of six metres or less, or having a capacity of less than $1.23 * 10^5$ m^3 of water (Senzanje and Chambari, 2002 quoted in Saunyama,2005).

The Zimbabwe Water Act of 1998 defines a small dam as a structure which: i.) has a vertical height of more than 8 metres but less than 15 metres measured from the non overflow crest of the wall to the lowest point on the downstream face of such wall or ; ii.) is capable of storing more than 500 000 m^3 but less than 1 000 000 m^3 of water at full supply level. Muyambo (2000) defines a small dam as a structure which: i.) has a vertical height of 10 metres or less measured from the non-overflow crest of the wall to the lowest point on the downstream face of such wall or; ii.) is capable of storing 1 000 000 m^3 of water or less at full supply level. The Department of Water defines a small dam as a structure which: i.) has vertical height of less than 8 metres measured from the non-overflow crest of the wall to the lowest point on the downstream face of such wall or; ii.) is capable of storing less than 1 000 000 m^3 of water at full supply level (Muyambo,2000).

In this study, the definition of a small dam is taken as that of the Zimbabwean Department of Water. This is because it is the local definition that best suits the type of reservoirs in the area this study was conducted. The Zimbabwe Water Act (1998)'s definition excludes dams with a capacity of less than 500 000 m^3 which are the majority of the small dams in the study area (CARE, 2002). Muyambo (2000)'s definition is not much different from that of the Department of Water.

3.1.3 The Role of Small Dams in Water Provision

Water scarcity is one of the most pressing issues facing humanity today. Provision of sufficient water is necessary for human health and poverty reduction. The most extreme shortages are experienced by those least able to cope with them – the most impoverished inhabitants of developing countries. This situation is especially pronounced in semi arid areas such as Mzingwane catchment where there are also very few alternative sources of water to small dams. In some places these small reservoirs are the only sources of water for communities (Sithole and Senzanje, 2006).Water from small dams is used for many purposes. They provide water for primary purposes such as drinking, cooking and bathing and for productive purposes such as irrigation, livestock watering and brick making (CARE, 2002). Thus they can play an important role in household income generation and livelihood strategies, for example by reducing over reliance on single production activities such as rain fed cultivation in areas where rainfall is not reliable.

3.2. Issues of Dam Failure

3.2.1 Problems Resulting From Failure of Small Dams.

Below are summarized effects of dam failure in general:

- Loss of life and damage to communities which live downstream of the dam as well as loss of investment. Dam construction is capital intensive and therefore if the dam fails a lot of investment money is lost and more resources have to be pooled together to reconstruct the dam if this is still feasible. Small dams especially those in rural settings are however usually assumed to have a low hazard risk. This means that in the event of failure, it is likely that very few lives and property will be lost as there are few permanent structures of high economic value or homes that are along water courses and can be affected by floods from a failed small dam (FEMA,1987),

- Dam failure can have a negative impact on the environment. It may result in loss of certain species that would have established their niche in the reservoir. Failure of a dam means loss of habitat to the species,
- Loss of water for both productive and primary uses which were depending on the dam for water supply.

From the point of view of small dams, especially for those in arid areas, loss of water is probably the most serious consequence of dam failure. As there are very few alternatives to small dams in some semi arid areas such as Mzingwane catchment, failure of a small dam in a locality can cause serious water problems. All the water uses including domestic and those that support livelihoods such as gardening and livestock watering would be seriously affected. Cases were reported of communities having to move livestock to the next water source which is usually another dam located kilometres away, after a dam had failed. (Sithole and Senzanje`, 2006).

3.2.2 Causes of Dam Failure

There are many complex reasons - both structural and non-structural - for dam failure. Many sources of failure can be traced to decisions made during the design and construction process and to inadequate maintenance or operational mismanagement (FEMA, 1987). Failures have also resulted from natural hazards such as large scale flooding, earthquake movement and poor environmental protection. The dam structure itself can be a source of risk due to possible construction flaws and weaknesses which develop because of aging. The site immediately surrounding the structure may also increase structural risk if the dam is not positioned or anchored properly or if excessive reservoir seepage erodes the foundation or abutments (ASWCC, 2002: FEMA, 1987).

Poor catchment practices can result in land degradation which in turn results in soil erosion. The eroded material eventually travels down the streams and river into reservoirs, causing siltation if they are in large amounts. As a result the dam will fail as it would no longer be able to hold water for the purposes it was constructed. In fact siltation is regarded as one of the greatest risks to the failure of small dams especially in communal areas where environmental protection practices are absent or ineffective (RELMA, 2005; CARE Zimbabwe, 2002 and Muyambo, 2000). However, from the perspective of the owner or manager, the structure of a dam is the starting point for thorough understanding of the potential for failure (FEMA, 1987).

3.2.3 Causes of Structural Failure of Dams

The International Commission of Large Dams (ICOLD) as discussed in FEMA, (2006), conducted a study on the causes of dam failure. According to the results of this study, for embankment or earth fill dams, the major structural cause for failure was piping or seepage. Other hydrologic failures were significant, including overtopping and erosion from water flows.

All earthen dams exhibit some seepage however, this seepage can and must be controlled in velocity and amount. Seepage occurs through the structure and, if uncontrolled, can erode material from the downstream slope or foundation backward toward the upstream slope. This "piping" phenomenon can lead to a complete failure of the structure. Piping action can be recognized by an increased seepage flow rate, the discharge of muddy or discoloured water below the dam, sinkholes on or near the embankment, and a whirlpool in the reservoir.

Earth dams are particularly susceptible to hydrologic failure since most sediments erode at relatively low water flow velocities. Hydrologic failures result from the uncontrolled flow of water over the dam (overtopping), around the dam, adjacent to the dam, and the erosive action of water on the dam's foundation. Once erosion has begun during overtopping, it is almost impossible to stop.

3.2.4 Types of Failures

According to FEMA (1987), types of dam failure can be classified as rainy day and sunny day failures. A rainy day failure could occur when heavy precipitation, in excess of that normally observed in the watershed above the dam, leads to high runoff. If the high water was to overtop the dam or add too much pressure, a rapid failure could result. A normal storm event could lead to overtopping the dam if the outlet works are plugged with debris, if the gates are jammed or broken.

Dams have also failed without any heavy precipitation. These failures are called sunny day failures. They are usually the result of neglected inspection programs and poor maintenance and operation of the dam. A sunny day failure could be caused by vandalism of the outlet works, such as damage to gate mechanisms, or if the outlet works are plugged with debris. Both rainy and sunny day failures can occur at new dams. New dams are very susceptible during initial filling and for a few years after filling. In fact, many dams have failed during their first filling (FEMA, 1987).

3.2.5 Examples of Failure of Earthen Small Dams.

The discussion in this section explores reasons why more care should be given to the physical condition of small dams.

The frequency of failures of small dams is much higher than that of large dams. This is mainly because of poor designing, poor quality construction and deterioration due to lack of proper maintenance mostly associated with small dams. In China for instance, according to Fu and Qing quoted in Pisaniello et al (2006), between the years 1950 and 1980, there was a total of 2796 dam collapses in the whole of China (roughly about 3.7% of all dams in China). Of this number 80% or 2263 were classified as small dams. It should however be noted that the above mentioned dams have been operating for 30 to 40 years and some for almost 50 years (Pisaniello et al, 2006). Thus, deterioration due to old age was also a factor contributing to the collapses.

Failure of small dams can sometimes result in loss of life and damage to property. For example in the USA, the Kelley Barnes Lake dam only 8m high, failed in 1977 killing a total of 39 people. Lake Lawn dam in Colorado which was also 8m high and stored only 830 000 m ^{3}, failed in 1982 killing 3 people and causing US $31million in damage (Pisaniello et. at., 2006).

In Southern Zimbabwe a lot of small dams which were an important source of water have failed, putting the livelihoods of local people at risk in the area of study (CARE Zimbabwe, 2002).

3.2.6 The Development of a Dam Safety Programme.

The significance of the dam failure problem points out the need for dam safety management and risk of failure evaluation programs. This is necessary so as to reduce the number of dams that fail. Such programs should be based on an evaluation to determine a dam's structural condition. The evaluation should identify problems and recommend remedial repairs, operational restrictions and modifications, or further analyses and studies to determine solutions to the problems.

A safety program comprises several components addressing the spectrum of possible actions to be taken over the short and long term (FEMA, 2002; ASWCC, 2002; NZSOLD, 1997). These actions include:

- Conducting preliminary and detailed inspections,
- Identifying repairs and continuing maintenance needs,
- Establishing periodic and continuous monitoring capabilities over the long-term,
- Establishing an emergency action plan to help minimize adverse impacts should the dam fail,
- Establishing operations procedures which recognize dam failure hazards and risks and,
- Documenting the safety program so that the information established is available at times of need and can be readily updated.

Development of a safety program involves a phased process beginning with collection and review of existing information, proceeding to detailed inspections and analyses, and culminating with formal documentation. Much of the preliminary work can be accomplished by the dam owner with the assistance of state and local public agencies. However, depending upon the number and seriousness of problems identified by the initial assessment, professional assistance by qualified engineers and contractors may be required.

The guidelines for assessing existing conditions are sequences of steps that will enable a dam owner to secure the information needed to determine the need for subsequent detailed investigations, repairs and maintenance (FEMA, 1987). The steps include:

- Reviewing existing data,
- Visiting the site,
- Inspecting the dam,

- Assessing significance of observed conditions and
- Deciding what to do next (FEMA, 2002; ASWCC, 2002; NZSOLD, 1997).

3.2.6.1 Reviewing Existing Data

The important first step is to collect and review available information on the dam - its design, construction, and operation. A first requirement is a good map of the site. Maps of the watershed and the downstream channel reaches are also valuable.

The design of the dam and its appurtenant structures should be reviewed to assess its actual performance compared to that intended. Engineering records originating during construction should be reviewed to determine if structures were constructed as designed. Records of subsequent construction modifications should be collected, as well as operation records which document the performance of the dam and reservoir.

Any previously prepared dam safety plans should be reviewed to determine if it is up to date and workable.

All these records should be incorporated into a notebook or file; they are most important in establishing a safety program and its supporting documentation.

3.2.6.2 Inspecting the Dam

It will be necessary to take a detailed and systematic look at all components of the dam and reservoir system. The description of the site's components should aid this inspection. The descriptions are generalized, and it must be recognized that dams and their components come in various shapes and sizes and differ greatly in detail. Features to inspect include:

- Access roads and ways,
- Upstream slope,
- Crest,
- Downstream slope,
- Left and right abutments,
- Spillways,
- Outlets and drains and
- Reservoir area (exposed and submerged).

Conditions to look for include deterioration, cracks and lumps, seepage, internal corrosion and weathering, settlement, and foundation rock deterioration. A dam may look stable but is susceptible to failure resulting from gradual deterioration of its internal structure. Regular and very detailed inspections and follow-up monitoring and maintenance are needed to assure the maximum level of safety.

3.2.6.3 Assessing Significance of Observed Conditions

Detailed information on conducting inspections and assessing the significance of observed conditions can be obtained from inspection guidelines (FEMA, 2002; ASWCC, 2002; NZSOLD, 1997).Typically, eroded areas, seepage, slides, and outflow draw the most attention.

3.2.6.4 Deciding What to Do Next

These initial activities will have provided a good start to establishing a dam safety program. Available information on design and construction of the dam and later structural modifications provides perspective on its existing condition relative to that intended. If no documentation exists then development of equivalent detail should be a first priority.

3.3.0 Recommended Small Dams Design and Maintenance Guidelines.

This section will highlight the recommendations on design, inspection and maintenance of small dams that were the basis of the assessments that were done in the study.

3.3.1 Design Guidelines

Embankment

- Slope gradient should be 1: 2.5 (vertical to horizontal distance) upstream and 1:2 downstream (Muyambo, 2000; Shaw, 1977). On dams less than 3m in height; it should be 1: 3 maximum upstream and 1:2.5 maximum on the downstream slope (RELMA, 2005).
- Dams should have riprap to protect upstream face from erosion and wave action. The constituent rock should not be single sized, but well graded mixture, have a maximum rock dimension of 600mm and have a limited proportion of fines (material less than 25mm) to less than 10% by weight.
- Fast growing, short rooted spreading grasses such as couch, star, kikuyu grasses should be used for downstream protection in wet environments
- Riprap as on the upstream slope, should be used for downstream protection in semi arid and arid climates, else grass cover should be established with the aid of irrigation.
- The crest width should not be less than 4 m for dams larger than 3m in wall height. And must not be smaller than 2m for dams smaller than 3m in height.
- Crest must have a slope of 1:50 towards the upstream slope (RELMA, 2005; CARE Zimbabwe,2002; Muyambo, 2000; Shaw, 1977)

Spillways.

- The sill should be located on solid rock that will not undercut or erode under the action of water. If this is not possible, the toe of the spillway must be protected and a lined return channel must be constructed to lead the water back to the main watercourse. This is done to prevent damage by floodwaters to the main dam wall or other works. Training walls should be used for this purpose.

- The end of any lined channel must terminate on solid rock or have a cut off down to solid ground to prevent undercutting and degradation (Muyambo, 2000; Shaw, 1977).
- Dry free board should not be less than 0.75 m (Muyambo, 2000; Shaw, 1977;) for dams higher than 3m and 0.5 for those less than 3 m (RELMA, 2005).
- An excavated spillway should have a slope of 3:100 towards reservoir (upstream) and 3:100 towards the downstream side. (WEDC, 2006; RELMA, 2005).

Soils

Coarse-grained material containing sufficient clay or silt to ensure reasonable imperviousness would be preferred over soils high in percentage of fines. Preferred soils are; gravel-sand-clays, sandy clays, gravel with excess silt or clay. Silty clays, organic clays and sands are not recommended. For dams less than 3m high, soils with 20 –30% clay content (especially clayey gravel, clayey sands) should be used. Alternatively inorganic clays can be used. Soils with a plasticity index of greater than 30 should be avoided. (RELMA, 2005; Muyambo, 2000; Shaw, 1977)

3.3.2 Inspection and Maintenance Guidelines.

It is recommended that a dam should be kept under regular visual inspection to note any deterioration taking place and taking appropriate action. All dams should be inspected regularly under normal operating conditions and immediately following any unusual event such as first filling, a flood, or an earthquake (ASWCC, 2002; NZSOLD, 1997; FEMA, 1987). Suggested times for normal inspections, at specific locations and for potential problems, are summarized in Table 3.1. To encourage the early detection and repair of any abnormalities and/ or deteriorating conditions, all dam owners should prepare inspection checklists and keep inspection records for their structures. Checklists or records should be tailored to reflect the particular characteristics of the dam and its associated structures.

Table 3.1. Suggested Inspection Times (Adapted from CARE Zimbabwe, 2002; ASWCC, 2002; NZSOLD, 1997; FEMA, 1987; US Government, 1977)

Location	Potential Problems	Suggested Inspection Time
Upstream Slope	Slope failure. (e.g. due to gulling, slumping, scarping and beaching)	After rapid draw down of reservoir.
	Slope protection deterioration. (riprap, grass cover)	After severe winds, heavy rains.
	Tree and shrub growth	Year round
Crest	Settlement	After heavy rains
	Tree and shrub growth	Year round
Down Stream Slope	Seepage	During and after high reservoir levels
	Slope failure	During and after high reservoir levels
	Tree and shrub growth	Year round
Down Stream Toe	Seepage	During and after high reservoir levels
	Bulging indicating slope a failure	During and after high reservoir levels
Spill Way	Debris Blocking Spill way or trash racks, erosion, deterioration of sills	After heavy rains and periodically through the rain season.
The whole dam wall	Erosion	After heavy rains and periodically through the rain season
	Burrows and termite mounds	Year round
	Cracks	Year round
	Damaged fencing	Year round
	Animal grazing	Year round
Low level outlet	Piping (On the areas around the pipe or channel in contact with the embankment material)	During and after high reservoir levels
Dam surroundings	Erosion, siltation	After heavy rains and periodically through the rain season (for erosion) During low reservoir levels (siltation)

3.4 Issues Related to the Physical Condition of Small Dams in Zimbabwe.

About 600 small to medium sized, low technology earthen embankment dams with average capacity of 100 000 m^3 were constructed in southern Zimbabwe where Mzingwane catchment lies, from late 1970s through to the year 2000 (CARE Zimbabwe, 2002). Unfortunately for various technical and social reasons, a large number of small dams constructed during these years either failed to meet community water needs or developed serious structural defects. Reasons range from poor siting and design of dams, to inadequate provision of information on maintenance to the communities (CARE Zimbabwe, 2002). Consequently the financial investments made to build a large number of small to medium sized dams in the communal areas have not realized full potential benefits for communities needing water resources.

In analyzing this situation CARE Zimbabwe (2002) found that the most debilitating impacts on dam sustainability were due to poor or non existent community management resulting in excessive siltation. This was especially the case with regard to the unchecked use of dam reservoirs as livestock watering holes, poor agricultural practices in the catchment areas, and no local management of common property resources. Care Zimbabwe also recognized that many small dams were either under used relative to the purposes for which they were intended, or were rapidly degrading because of competitive multi-purpose uses.

CARE's study was however concentrated in Masvingo province where they are mostly active in their work on small dams. These conditions are likely to be applicable to dams in Mzingwane subcatchment as it is also in Southern Zimbabwe and experiences similar climatic, physiographical rural conditions. This is evidenced by the general poor condition of both community owned and farmer owned small dams in Inzisa district according to a socio economic survey by Sithole and Senzanje (2006)

3.5.0 Dam Safety Evaluation.

There are two view points to dam safety evaluation; the conventional safety oriented or standards based approach, and the risk based approach (Rettermeier et.al., 2001; Bowles et.al., 1997).

3.5.1 Standards Based Approach

This is a safety evaluation system based on design, construction, inspection and maintenance guidelines or standards. These standards are usually set by the responsible authority mandated to over see dam issues in a country or part of country (Bowles et.al., 1997). The system is based on monitoring, surveillance, inspections and maintenance programmes. These are carried out on a particular dam according to the laid down standards or guidelines. This is done so as to keep the dam in a condition that is prescribed by, or to check whether the dam is performing according to the guidelines or standards. This ensures that the dam remains safe from failing. The standards or design-based approach assumes that there is no risk of failure associated with a dam (Rettermeier et.al., 2001).This is based on the assumption that dams are built to high design criteria. Thus the approach does not attempt to rank the dams involved according to the risk of failure.

As mentioned above, safety evaluation can also be carried out through monitoring, taking measurements or readings from instrumentation installed on the dam. An example of the use of instrumentation is the monitoring of seepage levels downstream of a dam wall in relation to design specifications (FEMA, 1987). The observations from inspections and instrumentation are then assessed or evaluated in comparison to standards or guidelines specifications.

Standards or design guidelines also specify the type of maintenance activities that need to be carried out on a dam. Examples of maintenance activities include making sure that no trees are growing and termite mounds or animal burrows are destroyed on the embankments. A conclusion is then made based on the assessments, on whether the dam is safe or not. Recommendations on what ever needs to be done are then given.

3.5.2 The Risk Based Approaches.

The term “Risk Based Approach” refers to the approach to design and evaluation of dams in which an acceptable safety condition is defined using information provided from a risk assessment and other decision inputs (Bowles et. al., 1997).Thus the risk based approach takes a risk of failure into account. Therefore the residual risk has to be determined, evaluated and managed even if failure seems unlikely (Rettermeier et.al., 2001). Risk assessment is a systematic process where experienced dam engineering professionals provide decision makers with estimates of the risks and associated uncertainties of system responses, outcomes, and consequences (Bowles, 1989). These words are explained in section 3.5.3. Risk based approaches focus on predicting dam performance and the confidence (or uncertainty) associated with these predictions.

If properly conducted, risk assessments can provide valuable information that may not otherwise be available from the conventional standards based approaches. It provides a means for quantifying the uncertainties that exist in dam safety evaluation. Quantitative examples of this information include: estimated probabilities of dam failure, the consequences of failure, and estimates of risk reduction for various structural and non-structural rehabilitation alternatives (Bowles et. al, 1997).

In addition, the process of conducting a risk assessment can provide qualitative benefits such as insights into the relative importance of various failure modes and loading types and ranges. A failure mode is a series of processes that lead to dam failure, where as loading types refers to the conditions under which a dam is operating. Therefore the systematic risk assessment process can be useful as a quality assurance tool for identifying risk reduction options in the design of rehabilitation measures, project operation, ranking and prioritisation of risks or emergency action planning (Bowles, 1989).

3.5.3 The General Procedure of the Risk Based Approach

Below is the description of the general approach that has been used in the development of most of the risk based models that are currently used in different countries. Risk model development commences with the identification of a sequence of events, beginning with events that can initiate dam failure and ending with the consequences of failure (Bowles, 1989).

The process of Risk Management can be divided into three stand alone processes; Risk Analysis, Risk Assessment and Risk Management. The flow chart in Figure 3.2 gives an overview of the fundamental terms and represents both the relationship of the individual steps (Risk Analysis, Risk Assessment, Risk Management) and their integration into the entire process of Risk Management.

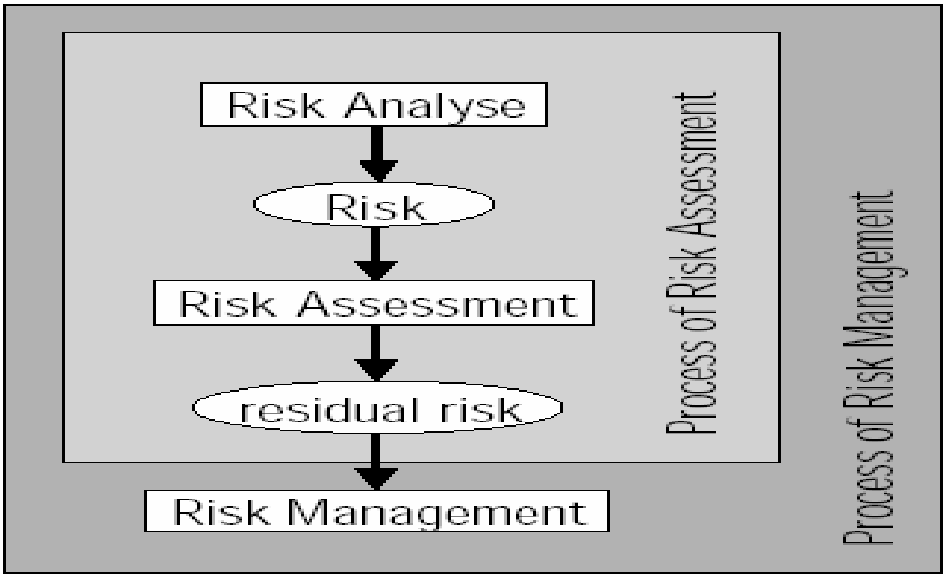

Figure 3.2: Risk Management Process. (Source: Rettermeir,et.al.,2001)

The risk of the dam is determined within the Risk Analysis process. The risk is defined as the measure of the probability of failure and the severity level of unfavorable effects (ICOLD, 1998). Thus the risk is determined as the product of failure probability and extent of the damage (Rettermeier et. al., 2001).

The evaluation or assessment of the risk comprises the consideration of alternative mitigation measures as well as the acceptance of risk. Risk Management covers the decision making for the development and conversion of a management plan as well as the monitoring of the implementation (Rettermeir et.al, 2001).

Before a Risk Assessment can be executed the risk must be determined qualitatively or quantitatively. There are many investigations for the quantitative determination of risk, particularly with respect to failure mode analysis and their effects. In addition, the qualitative estimation is quite usual, especially if the statistical basis is insufficient. Here experts and risk analysts estimate the risk by experience (Rettermeier et. al., 2001; Bowles et. al., 1989).

After the risk is determined, it must be evaluated whether it is acceptable. The risk acceptance depends on the hazard potential for humans, economics and environment. Here many different aspects take influence, for example, the most important point of discussion for German dams is acceptance with respect to human lives (Rettermeier et.al., 2001). Engineers alone should not come to the decision. Rather an interdisciplinary co-operation between engineers, sociologist, economist and others is necessary (Bowles, 1989).

If the risk is not acceptable, risk mitigation measures must be met. The risk can be reduced by modification of probabilities or consequences. Possible measures for example, include extended monitoring, structural or operational changes, emergency planning. The residual risk is evaluated/assessed with respect to the acceptance of risk and risk mitigation measures. Since cost as well as human demands need to be considered the risk evaluation should not only comprise cost-benefit analysis but also take non economic values into account (Rettermeier et.al.,2001).

The main focus of this study is risk analysis, therefore it is now considered in greater detail. The figure 3.3 shows the general stages involved in a risk analysis procedure.

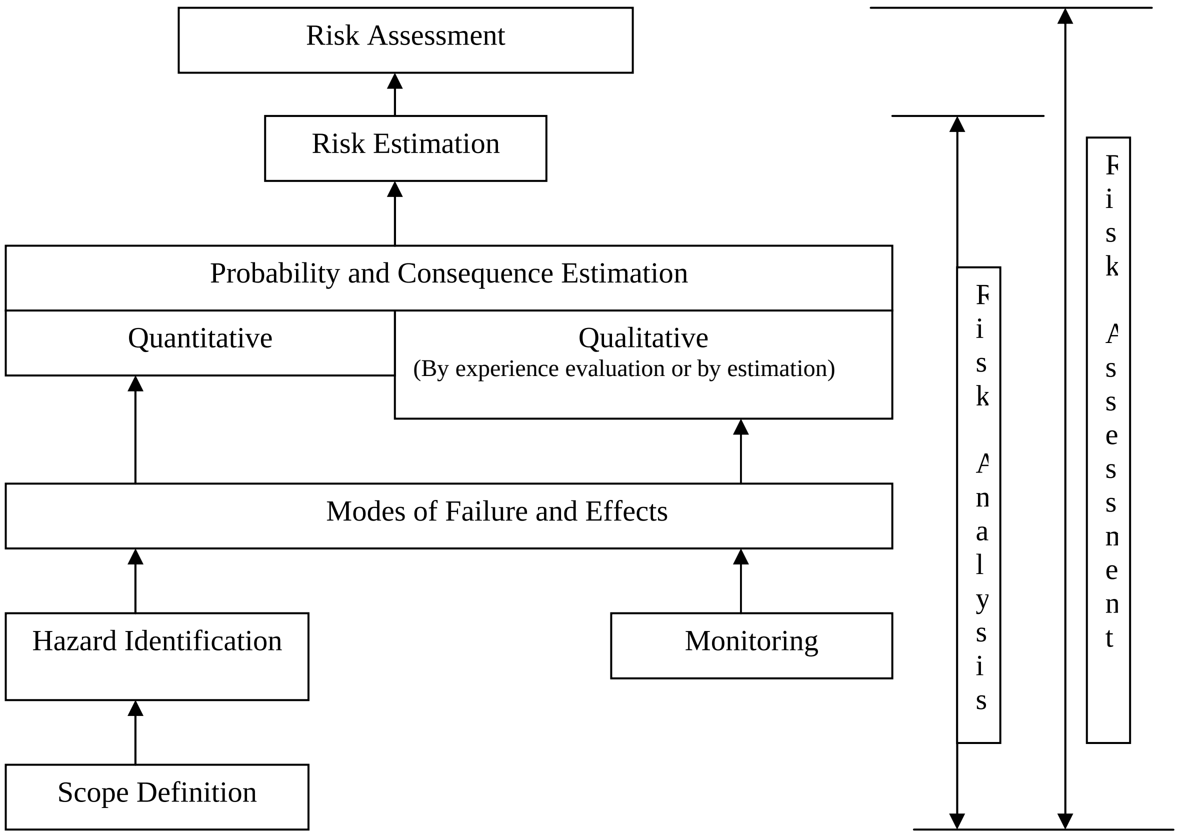

Figure 3.3 The Risk Analysis Process. (Adopted from Rettermeier,et.al.,2001)

i) Risk identification

During the identification step, professional judgment and experience, review of available information, and site visits are used to develop a list of the types of initiating events, system responses, outcomes, exposure factors, and consequences which apply to a particular dam-foundation-spillway-reservoir system (Bowles, 1989). The meanings of these terms are given in paragraph below. Using this information, an event tree (Figure 3.4) is developed.

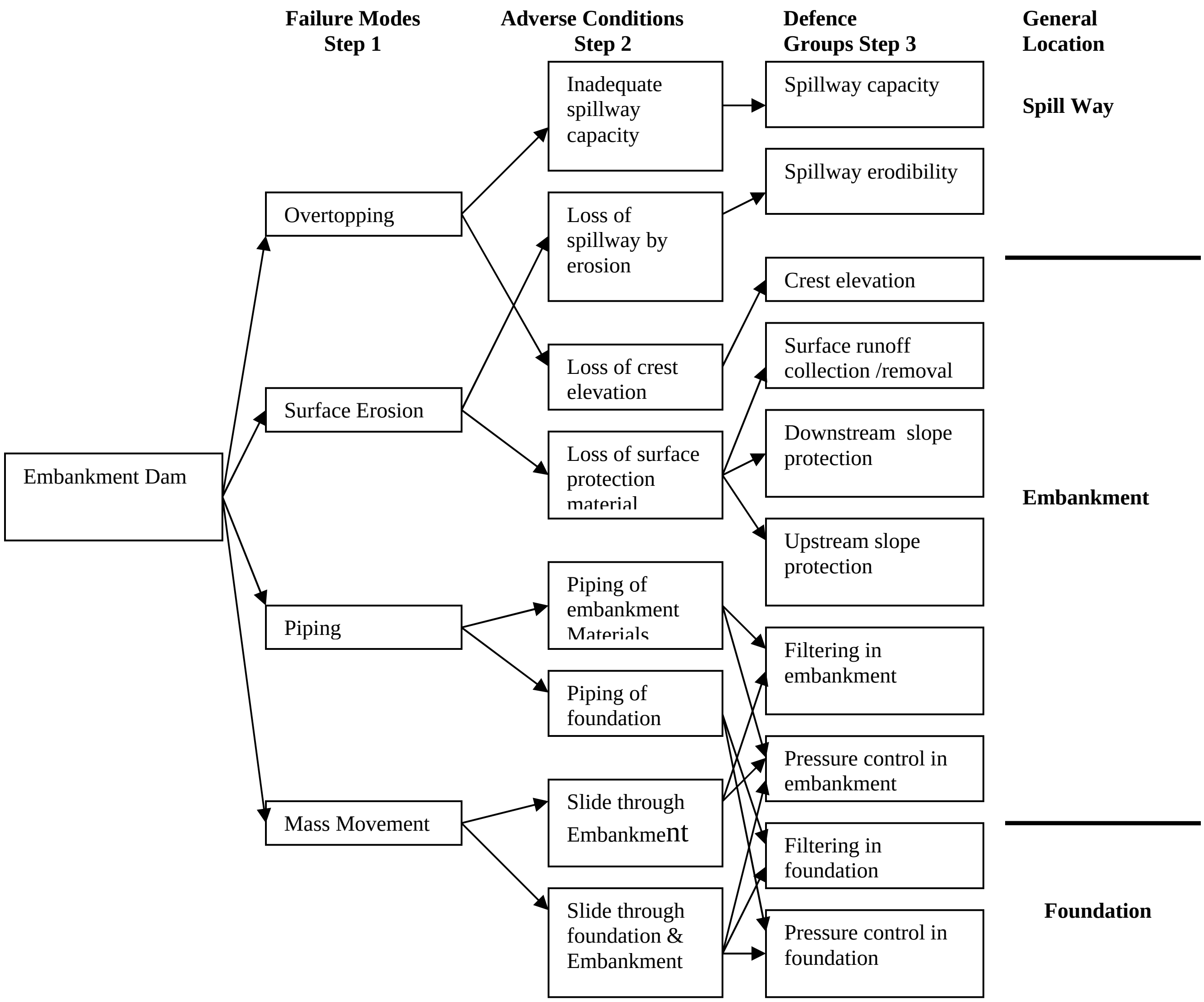

Figure 3.4 Flowchart for Defense Group (Dam Component) Importance. Source :(Defra ,2002)

Each branch in the event tree represents a failure mode. A failure mode is defined as the sequence of;

(1) A particular range of magnitudes of an initiating event such as a range of reservoir inflow magnitudes or seepage rate through an embankment,

(2) A system response (such as overtopping) and

(3) An outcome (such as dam breach).

An example of a failure mode for a particular dam could be the occurrence of an excessive flood, leading to embankment overtopping and ultimately a breached embankment.

The event tree is the risk model for dam safety risk assessment (Bowles et.al., 1989). Probabilities and consequences should be assigned to perform risk model calculations. Section 3.5.4 gives examples of risk based approaches currently in use in some countries such as USA.

Initiating events can be classified as external or internal. External events include earthquakes, floods, and upstream dam failure. Internal events include chemical/ physical changes in soil or concrete properties or latent construction defects (Rettermeier et. al.; Bowles, 1989). At low levels these events would not normally lead to dam failure. However, at high inflow rates a rapid rise in pool level could lead to overtopping for example.

Consequences of dam failure are classified as life loss and economic losses, which include property damage, cost of dislocations, and loss of project benefits. Environmental and social consequences of dam failure also can be considered (Rettermeier et. al., 2001; Bowles, 1989).

By performing a preliminary risk assessment, the relative importance of various factors can be assessed. For example the importance of hydrologic loading versus seismic loading, gate failure versus toe erosion can be assessed. This information can be used to make sure that relatively minor risk contributors are not given a disproportionate or unjustifiable part of the dam safety evaluation effort.

ii) Risk Estimation.

It involves assigning probabilities to each branch in the event-tree model (Figure 3.4) and assessing the consequences of dam failure for each failure mode.

The product of this stage is an estimate of the probability of failure and life loss or economic consequences that would be associated with each failure mode, or combination of failure modes, for the existing dam. If these risks are found to be high, the assessment proceeds to the next stage, which is risk assessment.

3.5.4 Risk Based Approaches from Different Countries.

Several risk based approaches are used in many countries in the world. They are oriented towards prevention of loss of life, economic loses and infrastructural damage in the area downstream of dams. So hazard classification of dams was an important factor of the approaches.

i) ANCOLD, Australia

The Australian National Committee on Large Dams (ANCOLD) first published its "Guidelines to Risk Assessment" in 1994. This publication and other relevant ANCOLD guidelines are summarized in Table A.9 in Appendix 5. Some of the main points relevant to these guidelines may be summarized as:

a) There are seven hazard classes, obtained from a matrix of five ranges of population at risk and four classes of damage and loss.

b) The return period of the design flood is obtained from a risk study.

c) Regarding the probability of adverse events, at this stage there is no comprehensive methodology for assessing the probability of failure for a dam on the basis of visual observations of a dam's condition (Defra, 2002).

ii) Portugal

This Portuguese Risk Index Evaluation was an early attempt to form an integrated system for assessing risks of dam failure (Defra, 2002). The assessment Table A.10 in Appendix 5 summarises the risk evaluation procedure which includes calculating the global risk index, although it is unclear how this index related to subsequent works. The main points are;
(a) Eleven aspects of the dam are considered, grouped under the external dam condition and the impact on failure,
(b) There are six possible levels of condition/ risk for each aspect, some being quantitative (For example the probability of exceedance of a flood) whilst others are qualitative.

iii) Federal Emergency Management Agency (FEMA)

The Agency came up with a system for preliminary safety evaluation of existing dams in the United States (Defra, 2002). As well as analytical techniques, it included tables for;
- Assigning a condition score to four elements of embankment dam condition and three elements of concrete dam condition (example in Table A.11) in Appendix 5
- The probability of failure is allocated, depending on the 'evaluation scores'.

The basis of these probabilities could not be established.

iv) Bureau of Reclamation (BOR)

The BOR manages 362 dams in the 17 western states of the US. The BOR safety programme was officially implemented in 1978. A technical priority system was developed in 1986 to rank dams. The main points are:
a) Risk is defined as (probability of load) x (probability of adverse response given load) x (consequence given adverse response)
b) Loads are considered under four categories namely, static, hydrologic, seismic, operation and maintenance, 30% of the marks being assigned to each of the first three and 10% to the last category
c) It appears to be a qualitative ranking system, rather than relating to absolute probabilities

v.) Army Corps of Engineers (USACE)

The USACE is responsible for federal dams in the eastern USA. A condition rating procedure was issued in 1999, which had the objective of "developing a rating procedure that describes the current condition of embankment dams in a uniform manner" (Derfra ,2002). It also produced a procedure for the prioritisation of maintenance and repair activities on embankment dams. Although it includes a system for ranking the relative importance of different threats, this is based on expert judgment rather than any probabilistic based system. Some of the key points relevant to this approach are:

(a) The development of the condition index (CI) which is a description of failure causing factor or condition. The methodology included a series of week long meetings with a panel of dam safety experts, who were asked a series of structured questions that related their technical experience to various aspects of embankment dam maintenance and repair. During each

meeting embankment dams were inspected in order to validate the procedures that had been developed.
(b) The hazard potential was put into one of three classes; namely loss limited to owner, no loss of life but some damage to third parties and loss of one or more lives
(c) A Condition Index (CI) is obtained, between zero and 100 based on a rating procedure that describes the current condition of a structure in a uniform manner. CI's are intended to be relatively objective measurements based on the series of questions used as part of the expert judgment.
(e) A flow chart for the defense (Dam component) group importance is given in Figure 3.4 and includes;

- Four failure modes (overtopping, surface erosion, piping, mass movement),
- Eight adverse conditions (cause or location of failure mode) and,
- Ten defense groups (an element that can be assessed and governs the cause of failure).

(f) Tables are given for each component, describing how the condition of that component is quantified.
(g) These ten components are then ranked in terms of relative condition. The priority ranking within the 10 defense groups is formed as a product of the following three numbers representing:

- Dam importance factor (consequence of failure),
- Importance of the defense group in relation to other defense groups on a given dam (from expert elicitation and does not change often)
- Defense group condition factor (100-CI)/100 (determined annually based on site inspection)

(h) An overall condition index is then calculated by summing the output of above.

vi) Washington State's Risk Based Approach.

It is a Risk Based Approach in a standard based framework. Under this approach probability methods, risk concepts, and elements of risk assessment are combined with decision making in setting performance standards that provide acceptable minimum levels of protection (Johnson, 2000). This approach is discussed at length in appendix 5.

3.5.5 Trend Towards Risk Based Approaches

Risk assessment is still a relatively new approach in the field of dam safety evaluation and decision-making. Interest in the potential for applying risk-based approaches to dam safety decision-making has accelerated in the last few decades (Bowles, 1989). An increasing number of organizations has begun to routinely use risk-based approaches in dam safety evaluation. These now include the U.S. Bureau of Reclamation, the Government of South Africa, the Government of the Netherlands, various Australian dam owners and regulators (Bowles, 1989). Section 3.5.4 above summarises examples of risk based approaches from various countries.

Some factors that have led to the increasing use of risk-based approaches include the following:

1. The absence of functional features, which are now considered to be the state-of-the-art in dam design, but which were not incorporated in many existing dams (such as downstream filters in embankments to dissipate pore pressure in the event of significant seepage).
2. The greater magnitude of extreme flood events such as the Probable Maximum Flood (PMF), which are prescribed using today's standards based approaches that currently have limitations in predicting such events.
3. The high cost of remedial works to address dam deficiencies such as inadequate spillways, and eroded dam walls.

3.5.6 Comparison Between Standards and Risk Based Approaches.

Standards based approaches focus on designing and safety evaluation of dams in which a satisfactory safety condition is defined by compliance with prescribed performance measures such as design, construction and maintenance standards. Risk based approaches on the other hand focus on design and safety evaluation of dams in which an acceptable safety condition is defined using information provided from a risk assessment and other decision inputs. Risk based approaches focus on predicting dam performance and the confidence (or uncertainty) associated with these predictions. In contrast, the sole use of traditional (standard based) approaches emphasizes factors of safety and compliance with standards, and do not provide defined clear indications of the level of confidence that is being attained in achieving satisfactory performance. However most of the risk-based approaches in use in various countries (section 3.5.4) incorporate testing, monitoring, and analysis, which are part of the standards based approaches (Bowles et.al., 1997).

3.5.7 Components of a Comprehensive Risk Management Program

A comprehensive dam safety risk management program should include many other components in addition to risk assessment for evaluating existing dam safety and alternative remedial actions. These other components are:

1. Provision of an appropriately designed, well maintained, and regularly exercised emergency warning system and emergency action plan,
2. A comprehensive monitoring and surveillance program with clear assignment of responsibilities for timely review and follow-up on collected data and reports,
3. A well trained operations and maintenance staff,
4. A well planned, adequately funded, and properly executed maintenance program,
5. Routine and periodic in-depth inspections and comprehensive dam safety reviews and updates of any previously conducted risk assessments that are being relied upon for dam safety decisions and,
6. An effective public consultation program (Bowles et.al.,1997).

All of these are important interrelated components in a comprehensive risk management program for any high hazard dam.

3.5.8 The Zimbabwean Scenario

Apart from the water act, which lays down various rules for small dam construction in the legal and administrative sphere, there are no standards governing dam design in Zimbabwe (Kabell, 1987). Only the Water Act (1998) and institution specific guidelines are used. At DDF, the institution responsible for small community dams, guidelines and design parameters are left entirely to the discretion and judgment of the engineer. However various principles and practices have evolved with experience over the years and are in use in the organisation.

Examples of guidelines that have been produced in the country on the design, construction and maintenance of small, medium sized and large dams are given below;

- A Guide to Design and Construction of Medium Sized Earth Dams in Zimbabwe (Shaw, 1977),
- Guidelines to the Design of Dams (Kabell, 1987),
- Design and Construction of Small Earth Dams (Muyambo, 2000)

However ZINWA, the organisation mandated with the designing, construction and maintenance of medium sized and large dams in Zimbabwe has also produced its own design, construction and maintenance guidelines. It uses these guidelines together with the Water Act of 1998 in guiding their work on dams. Risk based approaches are not being used in Zimbabwe according to outcomes of discussions held with ZINWA and DDF personnel during the course of this study.

3.5.9 The Need to develop a suitable risk of failure evaluation tool for small dams in Mzingwane catchment.

Although there are risk of failure evaluation tools from other countries as described in section 3.5.4. The tools are not suitable for use in the area of study, some of the reasons for this are;

- The main focus of risk of failure evaluation approaches described in section 3.5.4 is evaluating the risk of loss of life in the downstream area of the dam. According to the hazard rating of the dams (ASWCC, 2002; Dam safety branch, 2000; FEMA, 1987). The small dams in Zimbabwe have a low hazard classification as they are mostly located where there are few properties and homes that are located immediately downstream of the dams.
- They are based on quantitative data from regular monitoring and surveillance which is not possible on the small dams in the study area which do not have monitoring equipment. Also, regular inspection, monitoring and maintenance are not done due to lack of resources. In addition, according to assessments done on the ground during the course of this study, small dams in the area of study are not equipped with any monitoring devices such as piezometers for monitoring pore pressure.

There is also a need to identify failure causing deficiencies that are relevant to dams in Zimbabwe. Hence risk of failure approach based on these needs to be developed.

3.6 Chapter Conclusion

Dams are defined as barriers constructed across a water course to store water. There are several definitions of small dams world wide. In this study the Zimbabwean Department of Water's definition was adopted. The most common types of small dams in Zimbabwe are earthen dams of homogeneous and core embankment types. Small dams are an important source of water for both drinking and livelihood sustenance for rural communities especially in arid areas. Therefore the major problem resulting from failure of small dams in rural communities in Zimbabwe is the loss of water for livelihood sustenance. Major causes of failure of earthen dams include construction flows, seepage/ piping, overtopping and siltation. Lack of maintenance is also an important accelerator factor in causing dam failure. As a result of effects of dam failure, dam safety management programs are usually put in place to try and prevent dam failure. There are two basic approaches to dam safety evaluation; the conventional standards based approach and the risk based approach. The standards based approaches are based on design, construction, inspection and maintenance standards. The evaluations are carried out on a particular dam so as to keep the dam in a condition prescribed by, or to check whether the dam is performing according to standards. The approach does not attempt to quantify the risk of failure of a dam. The risk of failure approach refers to an approach to design and evaluation of dams in which an acceptable safety condition is defined using information provided from a risk assessment. Thus this approach quantifies the risk of failure of dams. Risk based approaches in use in several countries of the world are focused towards prevention of loss of life. They also rely on quantitative data from regular monitoring and surveillance which is not possible on the small dams in the study area which does not have installed monitoring equipment and regular inspection and maintenance programs in place due to lack of resources. It therefore follows that a risk of failure evaluation tool suitable for dams in the study area has to be developed.

CHAPTER 4. METHODS AND MATERIALS

This chapter is divided into 2 main parts; the first part (sections 4.1 to 4.5) is for the methodology for gathering data for the development of the risk evaluation tool. This was done through gathering information on the conditions under which small dams are being managed and assessing the physical condition of the small dams in the area of study. The second is for the development of the risk evaluation tool (section 4.6)

4.1 Reviewing of Records and Literature on Small Dams.

Reviewing of material on small dams in the area of study was done. Plans, specifications, construction history, records of operation, repairs, major floods and maintenance that could be obtained were reviewed. The reviews were done so as to gain an understanding of how small dams in the area of study were designed constructed and maintained and what conditions the dams have been subjected to. Design, construction and maintenance guidelines for small dams in Zimbabwe and other counties were also reviewed.

4.2 Interviews

Open ended questions (Appendix 1) and informal discussions were used in the following;

- Interviews with community members and individual farmers who own small dams were done to get some information on the history (construction, management and maintenance etc) of the small dams in the sub catchment.
- Key informants from institutions such as DDF, AREX, ZINWA and NGOs that are involved in small dam construction, management and maintenance were also interviewed. This was done so as to understand their involvement in the work and how they work with each other.

4.3 Field Measurements, Inspections, and Assessments

Inspections, measurements, monitoring and assessments were done on dam embankments, spillways, outlet and inlet works, visible areas of foundations, abutments and micro-catchment. In this study, micro catchment was defined as the environs of a small dam. This is taken as the dam environs; an area within a radius of 200m from the shores of the dam at full supply level. According to the findings of the socio economic surveys by Sithole and Senzanje (2006), 200m was considered by community members as the longest distance they are willing to travel to the reservoir to fetch water and carry it manually for gardens or other activities such as brick making that take place around small reservoirs. So this guided the definition of the micro-catchment used in this study.

Rapid and more detailed physical condition assessments were carried out. Rapid assessments (described in section 4.3.1) were more of qualitative (visual) and more to do with maintenance and inspection issues. Detailed assessments (described in section 4.3.2) were more of quantitative (measurements) and more to do with design issues. The assessments were done in accordance with design, construction and maintenances guidelines from Zimbabwe and other countries (WEDC, 2006; RELMA, 2005; ASWCC, 2002; CARE Zimbabwe, 2002; NZSOLD, 1997; FEMA, 1987; Kabell, 1987; Shaw, 1977; US Government, 1977). Rapid assessments were done on 44 small dams and detailed assessments were done on 9 of the 44 dams. The assessments were done so as;

- To find out how the small dams are being managed in relation to the design, construction and maintenance guidelines mentioned above,
- To assess the current physical condition and identify maintenance deficiencies on the dams and were possible the causes of this and,
- To get as much information as possible on the type of failure causing factors such as (seepage and erosion) that are relevant to the small dams in the area of study. This information was used in the development of the risk of failure evaluation tool.

4.3.1 Rapid Assessment of the Physical Condition of Small Dams

The activities as described below were done by physically walking and visually inspecting the dam wall starting from the crest on one end, walking to the other end inspecting the crest and the up stream slope. Then the spillway, after which the training-walls and the downstream slope were also inspected. The reservoir sides and throwback area were also assessed in the same way. In this process the following was done;

- Inspecting for seepage: Areas inspected included the down stream slope, downstream toe, abutments, areas near and on spillways and around and adjacent to outlets. Looked out for wet spots, or muddy areas and growth of greener grass than in surrounding areas, which can indicate the presence of concentrated seepage. Checking for the occurrence of ponding just at the toe of the embankment was also done.
- Checking for cracking.
  Where a crack was observed, the following was done;
  -Noting the type i.e. desiccation, transverse or longitudinal cracking,
  -Recording the location of the cracks, their depth, length, and width (using a tape measure).
- Checking for depressions: The following was done;
  - Photographing and/or recording the location, size, and depth of the depression.
- Checking for sinkholes:
  Where a sinkhole was observed the following was done;
  The location was noted and recorded.
- Checking for stability
  This was done by checking for and noting the presence of slides, scarping, toe bulging and arc–shaped cracks on upstream, crest and downstream slopes of the embankment.
- Checking for erosion
  - Rills, gullies, ruts, or other signs of surface runoff erosion on the upstream and downstream shoulders, spillways and abutments were looked for.
  - Unique problems, such as livestock or recreational vehicles that may be contributing to erosion were also checked for. Where surface runoff erosion was observed the following was done;
  - Recording findings and /or photographing the area.
  - Determining the extent or severity of the damage.
- Checking for inappropriate vegetative growth:

-Trees and shrubs were looked for on all areas of the dam. Findings were recorded, including the size and extent of the inappropriate vegetation.

- Checking for debris; Where debris (due to sliding on embankments or blocking spillway) was seen in and around the dam wall, photographing and or /recording of observations was done.
- Checking for presence of burrowing animals and termite mounds; Where they were evident, photographs of the area and/or records of size and number were taken.
- Checking for and recording any signs of deterioration, blockages and piping on inlets, outlets and drains was also done.
- Checking for the presence of a spillway/s on the dams was done.
- Checking whether the dams have toe drains to prevent seepage from weakening the dam embankment was done.
- Checking if the earth dams had a rip- rap layer especially on the upstream slope was also done.
- Noting soil type used for construction of the earthen embankments by visual assessments.
- Assessing the micro catchment condition (soils, erosion, vegetation condition and human activity) was also done. This was done by moving around the area within 200m of the dam measured from the estimated full supply level, visually assessing the condition of the soils, vegetation condition and human activity within this area. Soil types (general descriptions such as sandy, loam, gravely or clay) were noted. Vegetation cover and severity of erosion were also estimated according to descriptions given in Appendix 4.

4.3.2 Detailed Assessment of the Physical Condition of Small Dams

The following was done;

- Measurements to assess the side slopes and crest of the embankment (length, width, steepness of slopes and slope height) were carried out using tape measures and survey equipment).
- Measurements to assess for freeboard loss/ adequacy of freeboard;

- Measuring the vertical height difference between crest of the dam and the lowest point on the spillway using surveying equipment (Dumpy level).
- Estimating spillway width using a tape measure.
- Determining spillway slopes (both upstream and downstream where possible) using a dumpy level.
-determining catchment area sizes by marking of catchment areas of the dams on the 1: 50000 topographic maps of the study area and a planimeter was then used to determine the catchment area sizes[1].

- Collecting soil samples from downstream slope of the embankment. This was done through shallow auguring to a depth of 10cm. At least one sample per dam was collected and soil types were then visually and technically identified. Particle size analysis (Hydrometer method and sieve analysis) and soil consistency tests

[1] On small dams where the catchment area was too small to be determined from the 1:50000 topographical maps, it was estimated in the field by estimating the area visually.

(Determination of plastic and liquid limits) were done (USA Government, 1977; Smith, 1981; Soil Science and Agricultural Engineering (SSAE), University of Zimbabwe (UZ) student soil physics practical handout). The soil analysis was done in the Soil Science and Agricultural Engineering soil physics laboratory, at the University of Zimbabwe.

- Assessing adequacy of compaction of soil on the embankment. This was done indirectly through checking for subsidence and slumping and seepage on the down stream slope. Presence of these indicated inadequacy of compaction.
- Measuring diameter of riprap stones. Diameters of several stones were measured and an average diameter or range of diameters was then taken to indicate the riprap size.

4.4 Comparing the Physical Condition of the Dams to the Recommended Small Dams Design and Maintenance Guidelines.

Findings from rapid and detailed physical conditions were assessed and compared to respective and relevant recommended design guidelines for small dams. (Section 3.3.0) The following was compared to respective design guidelines;

- Downstream slopes
- Upstream slopes. Slopes and rip rap condition.
- Crest (width and slope)
- Spillway state, slopes, cross-section
- Adequacy of freeboard. The equation 1.0 below was used to determine the wet freeboard (Muyambo, 2000).

$$Q = 1.615\ BH^{3/2} \qquad \text{Equation (1)}$$

Where; Q is the discharge in cubic metres per second,
B is the width of the spill way
H is the wet free board or depth of water over the spillway.

This was done according to Shaw (1977)'s way of obtaining the Maximum Probable Flood (MPF) under Zimbabwean conditions. Q was obtained from MPF tables and the formula (Shaw,1977), after entering the value of the catchment area (which was estimated from 1; 50000 topographic maps using a Planimeter) A flood reduction factor (FRF) was also incorporated. The FRF was based on the return period of 100 years (Shaw, 1977; Muyambo, 2000)

The following assumptions were used;

Small dams have negligible flood absorption and therefore flood obtained from MPF tables was the outflow flood to be discharged by the spillway (Muyambo, 2000).

-The wet freeboard obtained was then added to the dry freeboard of 0.75 m for dams with dam walls higher than 3m and 0.5m dry freeboard for those with dam walls lower than 3m.

- The sum of the calculated wet and dry freeboards was then compared to the measured gross freeboard.

- Soil types as determined from visual assessments and laboratory assessment results were compared to the recommended soil types for use in earthen embankment construction (from design guidelines, section 3.3.1).

4.5 Identifying the Issues Resulting in the Present Physical Condition of the Dams in the Area of Study.

- Outcomes of reviews, interviews and the physical assessments described above were used.

4.6.0 Development of the Risk-of-Failure Evaluation/Estimation Tool for Small Dams.

The development process for the risk of failure evaluation tool is summarised in Figure 4.1

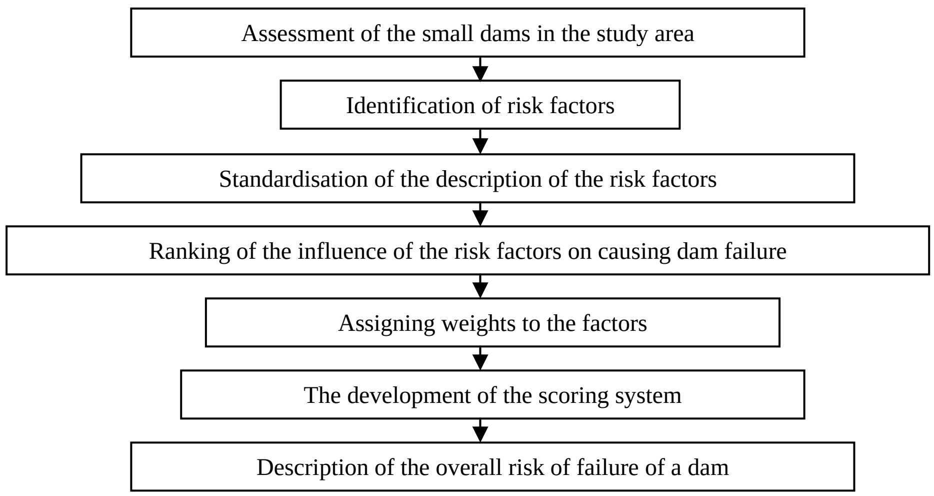

Figure 4.1. The Development Process for the Risk of Failure Evaluation Tool.

The detailed process for the development of the tool is given below.

4.6.1 Assessments of Small Dams in the Study Area

This was done during the rapid and detailed assessments. As the assessments were being done, management conditions, and the factors that were used in the development of the tool were identified and noted. Information looked for included;

- Responsibility for management of the assessed dams,
- design, construction and maintenance records for small dams,
- inspections ,surveillance and monitoring on small dams,
- Probabilistic precipitation data showing precipitation magnitude-frequency relationships used in checking adequacy of spillways,
- Identification of factors/criteria used to develop the risk of failure evaluation tool.

4.6.2 Identification of Factors/Criteria Used to Assess Risk.

Guidelines for the design and construction of small dams (RELMA, 2005; Muyambo, 2000; NZSOLD, 1997; Shaw, 1977; USA Government, 1977) and guidelines for the inspection and maintenance of small dams (WEDC, 2006; RELMA, 2005; ASWCC, 2002; NZSOLD, 1997; FEMA, 1987) were reviewed to get an understanding of what factors in general are responsible for causing failure in dams. The selection of the actual factors which were used in the development of the tool was also guided by the rapid and detailed assessments that were carried out in the area of study. These assessments helped to identify which factors of the ones given in guidelines are relevant to the situation on the ground in the area of study. The factors such as seepage, erosion and piping used in the development of the tool were identified and listed in the first column of table A.6 in Appendix 4.

4.6.3 The Development of a Method for Standardizing the Description of the Risk Factors.

This process aimed to standardize the description of the physical condition of dams and the seriousness of failure causing dam deficiencies such as seepage. An example is what is meant by ‘sparse’ and ‘extensive’, in describing tree growth and erosion respectively on an embankment. Estimated percentage contribution of each factor description to dam failure was also determined. An example of what is meant by ‘factor description’ is the description of erosion (a dam failure causing deficiency) as being moderate or extensive. This description depends on particular observations made on the ground. This process was guided by;

- Principles used in the risk based approaches used in other countries. Examples include approaches used in Portugal, Table A.10, the FEMA system Table A.11, and the Washington State system (Figure A.7 and Tables A.15),

- Principles used in the HR Wallingford’s methodology for estimating risk of soil erosion (CARE Zimbabwe, 2002).These are summarised in Table A.8 in the appendices,

- Observations from the assessments carried out in the area of study,

- Guidelines for the design ,construction and maintenance of small dams (RELMA, 2005; Muyambo, 2000; NZSOLD, 1997; Shaw, 1977; USA Government, 1977) and those for the inspection and maintenance of small dams (WEDC, 2006; RELMA, 2005; ASWCC, 2002; NZSOLD, 1997; FEMA, 1987).

Information from the comparison of the small dams’ physical condition and deficiencies with guidelines noted above was also used in describing the seriousness of contributions of the factors to dam failure. A comprehensive description of the seriousness of the factors’ contribution to risk of failure on a small dam was then done as presented in Table A.4 of Appendix 4. An extract is given in table 4.1.

Table 4.1 An extract of the Description of Risk Factors

Description of factor	Percentage contribution to risk of failure
Good,	0
Fair	5
Satisfactory	10
Less than satisfactory	30
Poor to bad	55

4.6.4. The Determination of the Criteria/Factor's Contribution to Dam Failure.

This stage involved the ranking of the influence of different factors/ criteria such as erosion, seepage, and piping in causing dam failure. Cause-effect diagrams were developed and used to determine the 'level' or stage at which each factor or criteria is involved in causing or contributing to dam failure. The four cause-effect diagrams that were developed (Figures A.1 to A.4. in Appendix 4) represent different possible failure modes (processes that would result in dam failure). The closer the factor is to causing dam failure, the lower its level is. 'Level' numbers in brackets in Figures A.1 to A.4 were determined by counting the number of other factors below that particular factor in terms of its closeness to causing dam failure. The factor's final level number was the average of the 'level' numbers counted. The number of 'levels' counted for each factor from all the four cause-effect diagrams was recorded in columns 2 to 5 in Table A.6, Appendix 4. Section A.4.2 in Appendix 4 has more information on how the ranking was done.

4.6.5 Allocation of Weights

Weights were also allocated to each factor depending on its 'level' in the process of causing dam failure. The process was guided by the cause effect diagrams and information from design, construction and maintenance guidelines. Weights were allocated based on the seriousness of the factors in causing dam failure. The lower the level of the factor on the cause effect diagrams, the higher the weight of the factor. Altogether 6 levels or stages were determined from the cause effect diagrams. For factors at level 6, which contribute the least to dam failure, a weighting index of 1 was allocated. Those factors at level 1, the most serious contributors to dam failure were allocated a weighting index of 6. The weighting indices of 1 to 6 were chosen to simplify the allocation of the indices to the 6 levels. The actual weight of each factor was then obtained according to equation 2 below.

Weight of factor = weighting index /6 **Equation (2)**

The weighting index was divided by 6 so as to express the weight as fraction of unity. This means that the highest weight was 1 and the lowest was 0.17. Tables A.6 and A.7 in Appendix 4 show the relationship between 'levels', weighting indices and weights of the factors considered.

4.6.6 Applying the Tool

For the purposes of applying the tool to evaluate the risk of failure of a dam, scores are allocated to each factor based on its description percentage and weight. The factor description percentage is allocated based on the observations from the field. The observations are described in the 'standard' format developed as described in section 4.6.3. Each factor's risk of failure score is obtained as shown by equation 3.

$$\text{Factor risk of failure} = \frac{\text{Factor description percentage} * \text{factor weight}}{100} \qquad \textbf{Equation (3)}$$

The factor description percentage is divided by 100 so as to convert the percentage into a fractional form.
The overall risk of failure score for the small dam is obtained from equation (4);

$$\text{Overall risk of failure score for small dam} = \frac{\sum \text{Factor risk of failure score}}{\text{Number of factors considered}} \qquad \textbf{Equation (4)}$$

The overall risk of failure score for a dam is then classified as being low, moderate, high or very high according to Table 4.2.

Table 4.2 Classification of the Overall a Dam's Risk of Failure Score

Overall Risk of Failure Score	0-0.05	0.05-0.1	0.1-0.15	Greater than 0.15
Description	Low	Moderate	High	Very High

4.6.7 Basis for the classification System

The obtained overall risk of failure scores were compared to general observations during assessments in the field. For example, Siwaze Dam is well managed by ZINWA and the inspection of the dam revealed that it was in good condition. This implies that its risk of failure was low. Its risk score was therefore used to guide the range for the 'low' classification. Shagwe had seepage problems and its risk of failure is therefore very high according to dam safety guidelines such as FEMA (2000). Its risk score together with that from the already breached dams Ngwabi and Chobukwa, were used to guide the definition of the 'very high' class of the risk score classification table.

4.7 Data Handling and Processing

Data processing and handling was done using the Micro Soft Excel package.

CHAPTER 5 RESULTS AND DISCUSSION

5.0 Reviews

The records of information that were obtained on the design, construction and management of small dams in the study area were not comprehensive. AREX managed to supply information containing only names of small dams in the area of study. NGOs working on small dams in the area could not supply the required information. No recorded information on the management of small dams was found from community institutions like dam committees.

A small dam's inventory for Insiza was obtained from DDF Filabusi District Offices. It contained information such as name, map number and grid reference location, catchment area size, mean annul runoff (MAR) and dam capacities. Most of the information however was either incomplete or had missing sections. The inventory did not contain the full list of all the communal small dams in the study area including some of the studied dams. Also, of the dams in the study area, only Avoca dam's capacity was in the inventory. It was given as 60 000m^3. A total of 50 small dams on the inventory were from the study area. This figure varied slightly from that obtained from an inventory from an AREX officer for the area. The AREX inventory indicated that the area of study had 57 small dams.

The catchment areas of small dams in Insiza District as given on the DDF inventory ranged from 0.01 km^2 to 134 km^2. For the 9 dams on which detailed studies were carried out, the catchment areas ranged from 0.16 km^2 to 16.7 km^2. These catchment areas where determined as explained in section 4.3.2 and from the DDF inventory

The inventory, which was last updated about 4 years ago, also contained information on the organizations which were chairing dam committees. According to the inventory, DDF chaired 19 dams in the area of study whilst CADEC chaired 4, Christian Care chaired 2, the community members chaired no dam committees and 18 dams were indicated as having no chairing institution. The institution indicated as chairing was the responsible institution for coordinating all management issues to do with the small dam concerned. However interviews with the communities on the ground revealed that most of the dam committees are presently defunct. They were only functional in the early years of dam operation. This was especially evident on small dams constructed by DDF.

No recorded information on dam maintenance was found from NGOs, DDF and community members. Design documents for dams in the study could not be located from DDF's files but some design drawings for small dams from other areas in Insiza district were found at DDF. These designs were found to be in line with design guideline recommendations for example, details of crest widths, and slopes sizes were found to be in line with design recommendations. This means that the dams constructed by DDF in the study area were most likely also to have been constructed following recommended design guidelines.

5.1 Implication of the Outcome of Reviews and Interviews on the Development of the Risk of Failure Evaluation Tool.

Risk of failure approaches used in other countries such as USA and Australia are based on the availability of updated records on maintenance, inspections and surveillance on small dams. (Section 3.5.4) However no maintenance records are kept for small dams in the area of study. Probabilistic precipitation data showing precipitation magnitude-frequency relationships for use in checking adequacy of spillways was also not available. This implies that the risk of failure evaluation approaches mentioned above were not suitable for risk of failure evaluation for small dams in the study area.

5.2 Roles of Organisations Involved in Small Dams in the Area of Study.

5.2.1 Role of DDF

According to interviews held with DDF staff at head office in Harare and at Filabusi district office in Matebeleland South, DDF are the custodians of small dams in Zimbabwe. They are responsible for construction and maintenance of small communal dams. This is in agreement with findings from earlier studies such as Sithole and Senzanje (2006). When NGOs or any other institution want to construct small dams in any area, they approach DDF who will then supervise or coordinate the exercise from feasibility studies right through to hand over to the communities. It also came out in the interviews that DDF and communities are supposed to be jointly responsible for maintenance but DDF is currently not doing any maintenance work because of limited resources. Lack of resources such as funds for maintenance and rehabilitation, transport and equipment were sited as the biggest problems that DDF personnel face in doing their work in small dams.

5.2.2. Role of NGOs

World Vision (WV) and CADEC were the main NGOs involved in construction and rehabilitation work on small dams in the area of study. Of the dams studied, Christian Care was involved in the construction of one dam, Chehondo in ward 9. Where as CADEC was involved in the construction or rehabilitation of at least 4 of the assessed dams, all of which were in ward 6. The NGOs indicated that they liaised with all relevant stakeholders involved in small dams sector such as Rural District Councils (RDCs), AREX, DDF, local communities and contractors. They were facilitators in the programs. They sourced and pay contractors who constructed the dams. They also involved villagers in the construction and maintenance of small dams under food for work programs. In some cases they would pay transport and subsistence allowances for officials from government institutions they worked with. They also supplied to the communities, basic tools for construction or maintenance such as shovels, wheel burrows and picks. The NGOs handed over management of the constructed dams to the community after basic training on maintenance.

Both NGOs also indicated that there is need to train the current DDF dam staff as they alleged that it is mostly new and little experienced in dam issues. This they claimed was compromising the availability of expert advice on issues of small dams to the communities they worked with.

They also claimed that because of limited equipment available to DDF for dam construction and rehabilitation, coupled with inexperienced staff, they have been forced in most cases to hire private contractors to design and construct the dams.

5.2.3 Role of AREX

It was also found out in a discussion with an AREX official for the area of study that AREX is not directly involved in the construction and management of small dams but other institutions such as NGOs work with them in activities to do with small dams. This is because AREX officials are generally well known and respected in the communities and are used as a gateway into the community. AREX also work with communities on issues such as good agricultural practices in the irrigation plots and nutrition gardens. They are also involved in the pegging and demarcation of the plots and gardens.

5.2.4 Stakeholder Collaboration

Even though it was mentioned in interviews with both NGOs and DDF that these organizations collaborate in their work on small dams, the communities on the ground claimed that the NGOs are the ones who come to assist them in small dams maintenance and rehabilitation. They also claimed that the NGOs are doing this mostly on their own without the involvement of DDF. This shows that the level of stakeholder collaboration is limited. Improved stakeholder collaboration would go a long way in improving the level of maintenance and repair of dams on the ground, thereby reducing the number of dams that fail. Reduced dam failures would result in increased security of water availability and hence more sustained livelihoods in the rural communities.

5.3 Rapid Physical Assessments

A total of 44 dams were assessed (Table A.16, Appendix 6). The physical condition of the dams was assessed using design, construction, inspection and maintenance guidelines as explained in the methods chapter. Interviews were also carried out with community members at the same time assessments were done. The assessed dams were in Wards 4 to 9 and in Ward 12.These Wards make up the Godlhwayo area. The number of dams assessed represents 77.2% of the total number of dams that are officially recognized in the area. Five dams or 11.4% of the visited dams were in a Small Scale Commercial Farming area (ward 8) and the rest are in communal areas.

Of the visited dams, one is owned and managed by ZINWA (Siwaze dam), 4 of the dams are farmer owned and the rest are community owned or managed communal dams. Three of the farmer-owned dams were also used by the surrounding communities for their domestic and livestock water needs. Below is a summary of the rapid assessments results and discussion. More detailed information on results of the rapid assessment is found in Appendix 2.

5.3.1 Seepage and leakages

Seepage does not seem to be a big problem in the area of study as it was noted that 97.7% of the assessed dams had no signs of unwanted seepage on their earthen embankments. Only 4.5% of the assessed dams had leakages on the masonry sections of their dam walls.

5.3.2 Cracks

No serious cracks or signs of budging were noted on all the assessed dams. The lack of serious cracks and bulging on the embankment walls was also an indication that the small dams' embankment walls were well compacted during construction and that the dam walls are stable.

5.3.3 Spillway Issues

Spillways existed on 100% of the assessed dams. At least one dam had its spillway raised without expert advice. This together with the existence leaking spillways, which are repeatedly repaired unsuccessfully by the communities (Picture 9, Appendix 7), as well as wide spread scarping and erosion (Pictures 5 and 6) indicated limited involvement in dam maintenance by the dam experts such as those from DDF.

5.3.4 Physical Condition

The poor physical state of the dams indicated for example by the presence of erosion (on 68.2% of assessed dams), wide spread scarping (on 77.3% of the studied dams), removal of fence (on 45.5%) of the assessed dams implied a general lack of repair and maintenance of the small dams in the study area. The lack of maintenance of dams in the area of study is also supported by the lack of functional maintenance committees on at least 72% of the assessed dams. This means that small dams repair and maintenance work in such areas is absent or irregular.

5.3.5 Siltation

Siltation was found to be evident on 79.5% of the assessed dams and this indicates that there are a lot of sediments being transported by the streams or rivers on which the dams are located (Picture 7, Appendix 7). This further indicates that there is need to improve the soil and water conservation practices in the dam catchment areas in the study area. It should however be noted that the siltation assessments were qualitative. Therefore more conclusive results should be obtained through detailed studies on siltation.

5.3.6 Cases of Dam Failure

Complete dam failure was also noted to have already occurred on four dams; on 2 as a result of overtopping of the embankment and breaching, on 1 as a result of spillway sill breaching and the other as a result of siltation. The breached dams were said to have failed due to cyclone Eline induced floods in the year 2000.

One of the dams, which failed due to a breached embankment, is Maninginingi dam located in Ward 9. An assessment of the dam showed that the spillway was completely blocked by soil. Trees about 4m tall were growing in the spillway channel. This indicated that the spillway blockage was a major contributor to the breaching. Chobukwa dam in Ward 6 was the other dam that had a breached embankment (Picture 11, Apendix 7). Detailed assessments revealed that its spillway was inadequate. The other failed dam had a breached spillway (Picture 10). Although assessments on the ground indicated that a 4 metre tall tree, which was found at the point where the breach occurred, could have weakened the spillway sill, inadequacy of the dam's spillway was also confirmed during detailed assessments as a contributory factor to the failure.

5.3.7 Use of Design Guidelines

The existence of spillways (on 100% of assessed dams), riprap (on 40.9% of the assessed dams), use of recommended soils for construction of embankments (on 100% of the sampled soils) and the existence of toe drains (on 84.1% of assessed dams), is an indication that design and construction guidelines were to a larger extent followed in the construction of the small dams in the area of study.

5.3.8 Identification of Factors used in the Development of the Risk of Failure Evaluation Tool.

Relevant factors to small dams in the area of study such as erosion, seepage and others that were used in the development of the risk evaluation tool were also identified during the rapid assessments. The full list of these factors is given in Table A.6 (first column) in Appendix 4.

5.4.0 Detailed Assessment of the Physical Condition of Small Dams

5.4.1 Results

Tables 5.1 and 5.2 show a summary of results of the detailed assessment of 9 small dams in the area of study. Appendix 3 contains more information on detailed assessments results. The Assessments were carried out mainly to investigate the physical condition of the small dams as compared to what is recommended by small dams design guidelines from Zimbabwe and other parts of the world (RELMA, 2005; Muyambo, 2000; NZSOLD, 1997; Shaw, 1977; USA Government, 1977). The assessments were also carried out to provide information for the development of the risk of failure evaluation tool. Such information included information on adequacy of spillways and suitability of soils for embankment wall construction.

Table 5.1 Detailed assessment of the physical condition of small dams- Results Summary

Factor		**As Recommended** (as a percentage of the assessed dams.)
Upstream Slope	Slope	44.4%
	Riprap size	100% (but 22.2% of small dams had no rip rap)
	Riprap Condition	33.3% (In fair condition or better)
Crest	Width	22.2%
	Slope	0%
	Direction of slope	11.1%
Down Stream Slope	Slope	44.4%
Freeboard Adequacy		22.2% (With adequate freeboard)
Spillway slopes	D/S slope	0%
	U/S slope	11.1%
Presence of unwanted Seepage		77.8%
Soils		100%
Micro Catchment Condition		44.4% (At least in satisfactory condition)
Siltation Risk		44.4% (with low risk)
Adequacy of compaction		100%

5.4 Discussion of Detailed Assessments Results

Poor embankment slopes condition (on 56.6% of the assessed dams) and poor riprap condition (on 66.7% of assessed dams) are some of the factors that further give more weight to the assertion that there is poor maintenance of small dams in the area of study.

Only 22% of the assessed dams had adequate freeboards, this means that the majority of the dams (78%) are susceptible to failure by floods overtopping the dam walls due to inadequate spillways. The inadequate freeboard could be mostly due to erosion, which is evident on one of the assessed dams, which failed due to overtopping of the embankment. Chobukwa, one of the failed dams discussed above, has a combination of a masonry and earthen embankment. Its spillway is very small, only about 4.6m wide and 80cm deep (Picture 7, Appendix 7). The spillway is engraved in the middle of the masonry section. This spillway as mentioned under the rapid assessment results section above was found inadequate. This indicated that some of the dams' spillways though to a smaller extend were not adequately designed. The dam was constructed by an NGO, with the assistance of the local community.

All the tested soils used for the construction of embankments were within the recommended type for dam wall construction. The soils were found to be all poorly graded coarse grained soils. Of the collected samples, 60% were found to be in the SC (Sandy clays) class and 40% were in the SM-SC class (clayey-sand -silt), according to the Unified Soil Classification (USC) system (Shaw, 1977; USA Government, 1977). Table 5.2 contains a summary of the soil analysis results.

Table 5.2 Laboratory Soil Analysis Results.

Sample Name	% Clay content	Plastic Limit	Liquid Limit	Plasticity Index PI	USC Classification
Dewa	11.51	15	21	6	SM-SC
Manzanlhophe	17.15	21	29	8	SC
Avoca	10.26	16	17	1	SM-SC
Mzambani	27.77	16	33	17	SC
Chobukwa (Light)	1.63	19	37	18	SC
Chobukwa (Red)	2.5	21	35	14	SC
Jubele Dube	24.42	13	28	15	SC
Ngwabi	12.24	15	21	6	SM-SC
Shagwe	15.24	15	29	14	SC
Majelimani	7.86	22	28	6	SM-SC

5.5.0. Other Outcomes from the Assessments, Interviews and Discussions with Community Members

5.5.1 Dam Management

DDF used to carry out repairs and maintenance on all dams they constructed or inherited from pre- independence institutions. Such dams constituted about 68% (30 dams) of the dams assessed. According to community members interviewed, there are no functional dam committees on such dams. This means that no body is currently being responsible for the management of these small dams.

DDF are currently incapacitated to carry out their mandate of looking after small state constructed communal dams. This coupled with unclear hand-over take-over policies, have resulted in small dams they constructed or inherited not being maintained fully. Hence their physical condition is deteriorating. The communities, to which the dams are handed over, are also short of resources to maintain the dams.

Where NGOs are assisting the communities by providing basic inspection and maintenance training, the dams are relatively in a better condition (on 18% of the studied dams). This shows that with little organization, training and material assistance, communities can improve the way they look after dams.

5.5.2 Issues to Do with Local Dam Committees.

On 18% of the assessed dams especially in Ward 6, there were no official dam committees in place but the councillor, Village Development Committee (VIDCO) and traditional leadership mobilized the community to do minimal maintenance such as cutting down trees and repair works. This was being done with assistance from NGOs such as World Vision and CADEC. The NGOs provided food rations to the villagers involved in doing the work. They also provided basic tools such as shovels, picks and wheel burrows needed to do the repair and maintenance work. The assistance by the NGOs was limited to the dams which were rehabilitated or constructed by the NGOs. The communities were also trained in basic maintenance such as dealing with termite mounds and cutting down trees on the embankment. However like everywhere else in the areas in which the assessments were done, the community members showed signs of limited technical knowledge on how to tackle issues such as erosion dam walls, riprap deterioration, scarping and leaking spillway sills. Such dams however were in much better physical condition than that of the dams, which were handed over to the communities by DDF and there was no external assistance in repair and maintenance.

On 15.9% of the dams visited which were constructed or inherited by DDF, the local communities led by village development committees, the councillor and traditional leaders mobilized communities for labour to do the repair work and to raise funds for the works. On such dams there were no official dam committees in place and no regular maintenance was carried out. The interviewed community members indicated that repair works were only done when it was necessary such as when a dam breach is imminent (When signs of imminent failure by overtopping are noted). This was because they did not have enough resources or any external assistance to carrying out regular repair and maintenance work.

5.5.3 Maintenance Issues

There were no regular maintenance programs in place and records of inspections and maintenance on all the assessed dams. The presence of erosion, scarping, poor riprap condition and leaking spillway sills (Picture 9, Appendix 7) revealed a lack of expert advice in the repair and maintenance of dams in the area of study. These dam defects required expert attention.

Of the assessed dams owned or initiated by farmers 50% were relatively better maintained than those formerly managed by DDF. However issues such as erosion, scarping and riprap deterioration were also being neglected (Pictures 5 and 6 in Appendix7). In 4.5% (50% of farmer initiated dams assessed) of the assessed dams, which were owned or initiated by farmers were virtually not being taken care of. Their physical condition was poor. The reason given was the lack of resources to carry out repair and maintenance. Lack of knowledge in dam maintenance issues was also evident in 25% of the cases as growth of trees on the dam walls (which only require the use of the widely available axe to cut down the trees) and blocking of spillways by soil which can easily be cleared by the use of hand hoes and shovels, were evident on the dams. This either indicates that the communal farmers lacked knowledge in basic inspection and maintenance procedures or they just did not take the issue of maintenance seriously. However all the interviewed farmers seemed to have some idea about basic dam maintenance requirements such as cutting trees from embankments and termite mounds, judging from what they said during interviews and discussions.

5.5.4 Ages of the Assessed Dams

Figure 5.1 shows the ages of the assessed dams as indicated on the dam walls or as given by the interviewed communities or DDF.

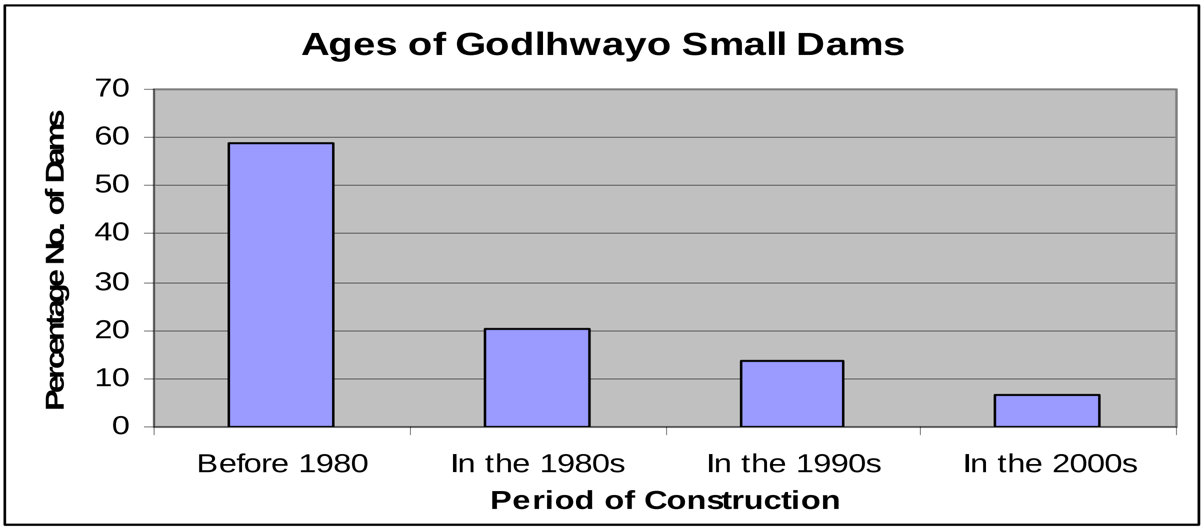

Figure 5.1 Ages of the Assessed Dams

Of the assessed small dams 59% were constructed 27 years or more ago. This indicates that the dams were approaching or had already outlived their economic lifespan. This paints a very gloomy picture about the future security of water availability in the area of study. Such old dams are likely to fail anytime. The results also show that instead of increasing the resources in the construction and rehabilitation of small dams, the opposite is actually happening. This is indicated by the fact that 20.45% of dams studied were constructed in the 1980s, 13.6% in the 1990s, before the figure further reduced to 6.81% in the new millennium. This decrease can be attributed to the reduced amount of resources available for the construction and rehabilitation of small dams. This is expected given the economic difficulties currently being experienced in Zimbabwe and the accompanying decrease in financial assistance from non-government sources such as international donors. The issue of reduced number of suitable undeveloped dam sites does not fully explain the decrease in dam construction as resources could still be channelled towards rehabilitation of existing dams that are in poor condition or have failed due to overtopping.

5.6 The Current Physical Condition of the Dams as Compared to the Recommended Small Dams Design and Maintenance Guidelines.

The results of both the rapid assessments and the detailed assessments (Table 5.1) and as discussed above, show that the current physical condition of the dams is not as recommended by the design and maintenance guidelines (sections 3.3.1 and 3.3.2). The findings also confirmed that maintenance of dams was minimal to absent and inspections are rarely carried out. No small dam maintenance records are kept in the area of study. Also according to the results, erosion, tree and shrub growth (Picture 3, Appendix 7), deteriorating riprap, inadequate slopes, seepage and loss of freeboard are some of the common deficiencies on the dams. However given that 91 % of the dams assessed were designed and constructed by DDF or NGOs through experienced contractors, the majority of the dams in the area of study are likely to have been constructed according to recommended guidelines. Assessments of the small dams also indicated that recommended design guidelines were generally followed in the construction of the dams. A comparison of some design documents found at DDF with design guidelines also showed that they were in line with the guidelines. Other evidence is the fact that 100% of the tested soil samples used in the construction of the dam walls were within recommended types. Most dams had recommended design dam wall components such as riprap (68% of dams assessed) and spillways (100% of dams assessed).

However there were clear cases of guidelines not being adequately followed as evidenced on one small dam which was constructed by an NGO being assisted with manual labour by the community. The cement lined spillway of the dam was constructed on the masonry part of the dam wall and it was found to be grossly inadequate. As a result the earthen part of the dam wall was breached.

However despite the fact that the majority of the small dams in the study area were constructed in line with recommended guidelines, due to neglect, old age and poor quality construction, their current physical condition is not as recommended.

5.7 Issues Resulting in the Present Physical Condition of the Small Dams.

These issues came out in the discussions, interviews and assessments of the physical condition of the small dams as mentioned above. The issues are now summarized below:

- Lack of repair and maintenance is the major reason why the dams are in the poor physical state.
- The lack of repair and maintenance is primarily due to the lack of resources being experienced by DDF, the institution mandated to design, construct and manage small dams in Zimbabwe. The institution is experiencing shortages of funds for carrying out its work on small dams. The available equipment is mostly obsolete .DDF also has a shortage of vehicles to go to the dam sites. There is high staff turnover and the new DDF staff also needs training and experience in order for them to effectively carry out their duties.
- The hand over/takeover policies for the responsibility of management of dams between DDF and communities are not clear. This has resulted in the communities being unsure of their role in small dams management
- There is limited stakeholder collaboration especially between DDF and the NGOs that are involved in the small dams sector.
- NGOs are however working on at least 18% of the studied dams. They construct, rehabilitate or help communities with basic tools for repair and maintenance of the small dams. The assistance by NGOS in providing tools for basic maintenance and giving food rations to the community members involved in the repair and maintenance work has resulted in a notable improvement in the carrying out of basic dam maintenance in the areas in which they operate. Such basic maintenance include cutting down of trees on embankments and destroying termite mounds. However more technically demanding problems such as erosion, scarping and leaking spillways remain largely unsolved.
- The prevalence of the more technically demanding dam deficiencies mentioned above indicates that the involvement of dam experts in the repair and maintenance of dams is largely limited.
- Some communities (in 15% of the assessed dams) were trying to repair and maintain dams on their own. These communities had basic knowledge of inspection and

maintenance issues but they lacked the financial resources and equipment to carry out more involving work such as repairing scarped slopes. There was also lack of properly organized structures such as functional dam committees to carryout the repair and maintenance work. This coupled with lack of policy guidelines on the role of communities in the management of small dams also resulted in situations whereby no one was held responsible for doing or supervising the work.

- Lack of incentives was also discouraging some otherwise committed members of the community from carrying out the work as they felt they would be doing work that would benefit all users of the dam at little or no return. Worse still they got little assistance from the majority of the people who benefited from using the dams.
- The majority of the dams (59%) were constructed before independence (1980) and are old, past their economic lifespan or approaching it. It is most likely that such dams can fail any time and are no longer holding their designed capacity of water. Wear and tear and old age have therefore taken their toll on such dams, hence their current poor condition.
- According to the community members interviewed, Cyclone Eline despite resulting in the breaching of at least 3 dams in the area also left the majority of the dams in a very poor condition. It is highly unlikely that most of these dams will survive floods of the magnitude of those caused by the cyclone. Cyclone Eline occurred in the year 2000. It caused heavy flooding in most parts of the Mzingwane catchment resulting in damage to infrastructure such as dams. At least 68.2% of the assessed dams showed effects of erosion as shown by the results (section 5.3).

5.8 The Implication of the Physical Condition of the Small Dams to Dam Failure and Security of Water Availability.

As noted in the sections above, the majority of the dams’ condition is poor. Some of the deficiencies as noted in sections above are that;

- Siltation is widespread,
- Spillways are inadequate,
- Slopes are scarped,
- There is seepage in some dams and
- The majority of the dams are beyond their economic life span.

These issues therefore, indicate that the risk of dam failure is high in the area of study. This in turn means that the security of water availability is very much threatened in this area where small dams are a major source water.

5.9 0 The Risk of Failure Evaluation Tool

5.9.1 Introduction

The authorities in charge of small dams generally experience resource constraints especially funds to maintain and rehabilitate dams. This is the case with DDF in Zimbabwe, according to interviews held with DDF personnel. In situations where resources are scarce there is need to prioritise the allocation of the few resources available. The risk of failure evaluation tool brings more objectivity in selecting the dams which are most affected by lack of care. It helps to systematically and more objectively classify the risk of failure of small dams, hence assisting in the selection or prioritisation of dams to attend to first. The tool, illustrated in a template form in Table 5.3 is therefore meant to assist the managers to make objective decisions in ranking the risk of failure of small dams they are responsible for maintaining.

The tool makes use of criteria such as seepage, erosion piping and many others that are traditionally used to assess the condition of dams. It estimates the extent to which these factors or criteria affect a particular dam in relation to dam failure. Scores and weights are allocated to each particular factor or criteria depending on its associated effect on dam condition and its presence on a particular dam.

It was revealed during assessments and interviews in the study area that

- There were no design, construction and maintenance records that are available for the dams in the study area.
- There is no regular maintenance, inspection and surveillance that is done on the small dams mainly due to lack of resources,
- There are no surveillance and monitoring instrumentation that was noted on the small dams during assessments,
- Probabilistic precipitation data showing precipitation magnitude-frequency relationships was not available for the area of study. Such data is needed for extreme events such as floods to implement risk based approaches such as one implemented by the Washington State (Appendix 5)This data is used in determining adequacy of spillway for existing dams when using the risk based approaches based on probabilistic data like the one used in the Washington State.

From the above findings it is noted that risk based approaches based on probabilistic data and strict inspection, monitoring of instrumentation, surveillance maintenance programmes cannot be applicable in the study area. Hence a risk evaluation tool based on available design, construction and maintenance guidelines without the application of probabilistic data was developed. A non probabilistic but numerical risk evaluation system was therefore developed so as to quantify the risk of failure associated with the small dams.

Table 5.3 below shows a template of the tool risk evaluation tool which was developed following the methodology described in section 4.6. It can be presented in the form of a spreadsheet**.** Table 5.4 is then used to classify the overall risk of failure of a dam as low, moderate, high or very high.

Table 5.3 The Risk Failure Evaluation Tool

Location on Dam	**Factor/Criteria**	**Description of factor** (The Numbers give the estimated percentage contribution to dam failure)	**Weight of Factor**	**Score**
Up Stream Slope	Presence of rip rap	Present(0)/not present(70)/ Not present but grassed(30)	0.42	
	Size of rip rap rocks	As recommended.(0) /not as recommended.(100)	0.42	
	Condition of rip rap	Bad(85)/ satisfactory(10)/ fair(5) / Good/NA(0)	0.42	
	Slope angles	As recommended.(0)/ not as recommended.(100)	0.24	
	Scarping	None(0)/Minor(5)/moderate(10)/extensive(30)/ severe(55)	0.67	
	Slumping	Present(100)/not present(0)	1	
Crest	Width	As recommended.(0)/ not as recommended.(100)	0.58	
	Slope	Angle & direction as rec.(0)/Only direction as rec.(25)/ Both not as rec.(75)	0.24	
	Settling	Present (100)/ not present(0)	1	
Down Stream Slope	Slope Angles	As recommended.(0)/ not as recommended.(100)	0.24	
	Slumping	Present(100)/not present(0)	1	
	Scarping	None(0)/ Minor(5)/moderate(10)/ extensive(30)/ severe(55)	0.67	
	Bulging	Present (100)/ not present(0)	1	
	Un wanted Seepage/Leakage	Present (100)/ not present(0)	0.83	
	Seepage toe	Present(0)/ not present(100)	0.67	
	Piping	Present (100)/ not present(0)	0.95	
	Ponding	Present (100)/ not present(0)	0.83	
Spillway	Slopes	Only D/S slopes as recommended(50)/ Only U/S slopes as recommended(50)/Both slopes not as recommended(100)/ Both slopes as rec./NA(0)	1	
	Presence	Present(0)/ not present(100)	0.92	
	Condition	Good/NA(0)/ Fair(5)/Satisfactory(10)/ Bad (85)	1	
	Blockages	Minor(5) / Moderate(10)/ Serious(85)	1	
	Breached	Breached (100)/not breached(0)	0.92	
Whole Embankment	Adequacy of compaction	Adequate(0)/ not adequate(100)	0.56	
	Soil type	Bad(85)/Satisfactory(10)/ Fair(5)/ Good(0)	0.6	
	Termite mounds/ animal burrows on embankment	Minor(5)/Moderate(10)/ Considerable(30)/ Severe(55)	0.5	
	Fencing	Absent(70)/ needs repair/partly in place(30)/ in place and in good condition(0)	0.17	
	Grass cover	Good(0)/Fair(5)/Satisfactory(10)/Sparse(30)/ Poor(55)	0.42	
	Animal grazing	Present (100)/ not present(0)	0.33	
	Foot paths	Present (100)/ not present(0)	0.67	
	Tree and shrub growth	Little(5)/Moderate(10)/ Dense(30)/ Very Dense(55)	0.5	
	Erosion	Minor(5)/Moderate(10)/ Extensive(30)/ Severe/massive(55)	0.71	
	Cracking	No cracking(0)/Mild(5)/Moderate(10)/ Serious(85)	0.58	
	Outlets condition	Good/NA(0)/Fair(5)/ Satisfactory(10)/ Bad(85)	0.75	
Freeboard Adequacy		Inadequate(95)/ Slightly inadequate(5)/ Adequate(0)	1	
Micro Catchment condition		Good(0)/Fair(5)/ Satisfactory(10)/ Less than satisfactory; (30)/ Poor to Bad (55)	0.58	
Siltation risk		Low(5)/Moderate(10)/ High(30)/ Very high(55)	0.92	
Total Score				
Risk Score		= total score/no of criteria considered		

Table 5.4 Classification of the Overall a Dam's Risk of Failure Score

Overall Risk of Failure Score	0-0.05	0.05-0.1	0.1-0.15	Greater than 0.15
Description	Low	Moderate	High	Very High

5.9.2 Using the Risk-of-Failure Estimation Tool

Listed below are the steps that should be followed in applying the risk-of-failure estimation tool to estimate the risk of failure of a particular dam.

1. A dam is inspected according to the dam inspection guidelines (Section 3.3.0). During the inspection process the identified factors such as tree and shrub growth, erosion, and others are 'described' as indicated in section 4.6.3. For example, vegetation would be described as sparse or dense depending on how it is observed on the ground and how this relates to the description given in section 4.6.3.
2. On the actual risk assessment estimation tool template or spreadsheet, percentage risk scores are allocated as described in section 4.6.6.
3. The score of each factor is then obtained by multiplying the percentage risk scores by weights of each factor. A factor risk score is given as indicated by equation 3.
4. The total risk score for the dam is then obtained by dividing the sum of the scores by the number of factors/ criteria considered (equation 4).
5. The overall dam risk of failure is then classified as low, moderate, high or very high according to its score, using Table 5.4.

Table 5.5 shows the completed spreadsheet of the evaluation of the risk of failure of Dewa dam. This is an example of how the tool was used to evaluate risk of failure of 10 dams in the study area.

Table 5.5. Spreadsheet of the completed risk evaluation of Dewa Dam

Location on Dam	Factor	Description of factor. (Number =percentage.)	Description of Factor (%)	Weight	Score
Up Stream Slope	Presence of rip rap	Present (0)/not present(70)/ Not present but grassed(30)	0	0.42	0
	Size of rip rap rocks	As recommended.(0) /not as recommended.(100)	0	0.42	0
	Condition of rip rap	Bad(85)/ satisfactory(10)/ fair(5) / Good/NA(0)	85	0.42	0.357
	Slope angles	As recommended.(0)/ not as recommended.(100)	100	0.24	0.24
	Scarping	None(0)/Minor(5)/ moderate(10)/ extensive(30)/ severe(55)	30	0.67	0.201
	Slumping/Beaching	Present(100)/not present(0)	100	1	1
Crest	Width	As recommended.(0)/ not as recommended.(100)	100	0.58	0.58
	Slope	Angle & direction as rec.(0)/Only direction as rec.(25)/ Both not as rec.(75)	75	0.24	0.18
	Settling	Present (100)/ not present(0)	0	1	0
Down Stream Slope	Slope Angles	As recommended.(0)/ not as recommended.(100)	0	0.24	0
	Slumping	Present(100)/not present(0)	0	1	0
	Scarping	None(0)/ Minor(5)/moderate(10)/ extensive(30)/ severe(55)	5	0.67	0.034
	Bulging	Present (100)/ not present(0)	0	1	0
	Un wanted Seepage/Leakage	Present (100)/ not present(0)	0	0.83	0
	Seepage toe	Present(0)/ not present(100)	0	0.67	0
	Piping	Present (100)/ not present(0)	0	0.95	0
	Ponding	Present (100)/ not present(0)	0	0.83	0
Spillway	Slopes	Only D/S slopes as recommended(50)/ Only U/S slopes as recommended(50)/Both slopes not as recommended(100)/ Both slopes as recommended/NA(0)	100	1	1
	Presence	Present(0)/ not present(100)	0	0.92	0
	Breached	Breached (100)/not breached(0)	0	1	0
	Condition	Good/NA(0)/ Fair(5)/Satisfactory(10)/ Bad (85)	10	1	0.1
	Blockages	Minor(5) / Moderate(10)/ Serious(85)	5	0.92	0.046
Whole Embankment	Adequacy of compaction	Adequate(0)/ not adequate(100)	0	0.56	0
	Soil type	Bad(85)/Satisfactory(10)/ Fair(5)/ Good(0)	5	0.6	0.03
	Termite mounds/ animal burrows on embankment	Minor(5)/Moderate(10)/ Considerable(30)/ Severe(55)	30	0.5	0.15
	Fencing	Absent(70)/ needs repair/partly in place(30)/ in place and in good condition(0)	70	0.17	0.119
	Grass cover	Good(0)/Fair(5) / Satisfactory(10)/ Sparse(30)/ Poor(55)	10	0.42	0.042
	Animal grazing	Present (100)/ not present(0)	100	0.33	0.33
	Foot paths	Present (100)/ not present(0)	100	0.67	0.67
	Tree and shrub growth	Little(5)/Moderate(10)/ Dense(30)/ Very Dense(55)	5	0.5	0.025
	Erosion	Minor(5)/Moderate(10)/ Extensive(30)/ Severe/massive(55)	30	0.71	0.213
	Cracking	No cracking(0)/Mild(5)/Moderate(10)/ Serious(85)	0	0.58	0
	Outlets condition	Good/NA(0)/Fair(5)/ Satisfactory(10)/ Bad(85)	0	0.75	0
Freeboard Adequacy		Inadequate(95)/ Slightly inadequate(5)/ Adequate(0)	5	1	0.05
Micro catchment condition		Good(0)/Fair(5)/ Satisfactory(10)/ Less than satisfactory; (30)/ Poor to Bad (55)	10	0.58	0.058
Siltation risk		Low(5)/Moderate(10)/ High(30)/ Very high(55)	30	0.92	0.276
Total Score					5.7005
Risk of failure score					**0.158**

Table 5.6 The Risk of Failure of Selected Dams in the Area of Study

Reservoir	Risk of Failure Score	Risk Priority Rank	Risk Classification
Siwaze	0.020	8	Low
Magelimani	0.134	3	High
Ngwabi	0.176	Breached	-
Dube Jubele	0.097	7	Moderate
Chobukwa	0.351	Breached	-
Mzambani	0.127	5	High
Avoca	0.128	4	High
Shagwe	0.167	1	Very High
Manzanlhophe	0.121	6	High
Dewa	0.158	2	Very High

Table 5.6 shows the risk of failure of selected Godlhwayo dams as evaluated using the risk-of-failure evaluation tool. Siwaze is a medium sized dam which is owned and managed by ZINWA, and was included for the purposes of analysis. Ngwabi and Chobukwa dams have already failed (Pictures 10 and 11, in Appendix 7). It can be seen from the chart that Siwaze has the lowest risk of failure. This reservoir is well maintained and its dam wall is in good condition and hence has a low risk of failure. Chobukwa has a breached dam wall and has a very small spillway and since it is already breached its risk score is very high. Similarly Ngwabi dam has a high-risk score and has a breached spillway. These two breached dams were included for the purposes of analysis. Of the dams that have not yet failed, Shagwe has the highest risk score, which means that it is the one which is likely to fail earlier than the rest of the dams. This is because of the leaking spillway and a sinkhole that is located on the upstream side of the joint of its training wall and the spillway sill (Pictures 1 and 2). From this analysis therefore it follows that the higher the risk score the greater the risk of the dam failing. Shagwe therefore should be prioritised when it comes to taking corrective action such as maintenance or repairs.

It is advised that the dams with the very high risk of failure should receive attention as soon as possible as they are likely to fail anytime. Dams in the moderate to low range are considered safe, and should be the least to be targeted in trying to improve the physical condition of the dams. The actual order of attending to the dam with deficiencies is determined by the ranking of the risk of failure of the concerned dams, starting with the highest rank. In the Assessed dams in Table 5.6, Shagwe dam will be given first priority as it is ranked number 1. Dewa dam will then be given second consideration.

It should however be noted that in some cases a dam may have a very high risk score but having deficiencies that are not economically feasible to address. An example of such a deficiency is siltation. In such instances it may be better to attend to the next dam on the priority list other than spend a lot of resources trying to tackle such a problem. Other external factors may need to be considered in Risk assessment (the process of making the final decision of rehabilitating a prioritised dam). Examples of such external factors include the number of uses and users of water from the dam, local politics and the overall cost of addressing the deficiencies. This means therefore that the tool should be taken as the initial stage (Risk analysis) in an integrated risk management programme that would help authorities to make decisions on dam maintenance.

5.9.3 Conclusion to the Chapter.

All of the assessed small dams were in a poor physical condition. This was indicated for example by the signs of erosion (on at least 68% of assessed small dams) and Tree and shrub growth (66%) on dam walls. With few exceptions, most small communal dams in the study area were built according to recommended design, construction and maintenance guidelines. But their current physical condition is not inline with these guidelines. However there were few clear cases of guidelines not being adequately followed as evidenced on one small dam which had an inadequate spillway. The dam was constructed by an NGO being assisted with manual labour by the community. The major reasons why the majority of the studied dams were in poor physical condition were; The limited repair and maintenance primarily due to the limited capacity of DDF, Unclear hand over of dams to communal people by DDF and NGOs, lack of resources, limited training in dam care, general lack of maintenance structures such as functional dam committees, lack of incentives and old age. A non probabilistic but numerical risk of failure evaluation tool was developed so as to quantify the risk of failure associated with the small dams. This tool can be used by water resources personel involved in the management of small dams to estimate the risk of failure associated with each particular dam. This would in turn help them to more systematically and objectively rank the dams that need to be repaired or maintained according to their closeness to failure. Dams, which are ranked as being at the greatest risk, would then be prioritised in the allocation of the resources for repair and maintenance. It should however be noted that in some cases a dam may have a very high risk score but having deficiencies that are not economically feasible to address. An example of such a deficiency is extensive siltation.

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

All of the assessed small dams were in a poor physical condition. This was indicated for example by the signs of erosion (on at least 68% of assessed small dams) and tree and shrub growth (66%) on dam walls.

With few exceptions, most small communal dams in the study area were built according to recommended design, construction and maintenance guidelines. But their current physical condition is not inline with these guidelines.

The major reasons why the majority of the studied dams were in poor physical condition are; limited repair and maintenance primarily due to the limited capacity of DDF, unclear hand over of dams to communal people by DDF and NGOs, lack of resources, limited training in dam care, general lack of maintenance structures such as functional dam committees, lack of incentives for locals willing to maintain small dams, limited appreciation of the need to maintain small dams by the communities and old age (at least 59% of assessed dams were more than 27 years old).

A numerical risk of failure evaluation tool was developed. It can be used by water resources personnel involved in the management of small dams to estimate the risk of failure associated with each particular dam. The tool could therefore go a long way in assisting in the allocation of scarce resources to meet an almost impossible task of maintaining in good condition thousands of small dams scattered across the arid regions of the Mzingwane catchment in Zimbabwe and the Limpopo basin at large.

Despite the majority of the dams in the study area being constructed according to recommended design guidelines, due to their poor physical condition resulting from lack of repair and maintenance and old age, the majority of small dams in the study area are at risk of failing. Security of water availability in the study area is therefore threatened. The application of the tool could thus help secure the sustainable availability of water to the rural communities who heavily rely on water from small dams in the arid regions of Zimbabwe and the Limpopo basin. This would go a long way in sustaining the livelihoods of communal people in the arid regions

6.2 Recommendations

Sustainable maintenance and rehabilitation systems for small dams should be put in place to ensure that the small dams in the study area remain in good physical condition and water availability is not threatened. The following is suggested;

- Capacitating DDF to take a leading role in coordinating and guiding the activities related to the design, construction and management of small dams. This could be done through training its staff members in technical and Integrated Water Resources Management (IWRM) skills, improving the staff’s conditions of service and providing funding for repairing and buying of equipment and vehicles for use in their work on small dams.

- Resolving ownership and management issues in small dams by making clear the policies on the role communities in the management of small communal dams. This will facilitate community participation in the management of the small dams. Further studies on the establishment of functional dam committees or other structures through which communities can repair and maintain dams in collaboration with DDF and other stakeholders such as NGOs would then be facilitated. This is necessary because the current set up is not working. This is indicated by the lack of functional dam committees on most of the dams that were handed over by DDF to the communities in the study area. This is despite the fact that committees were created during the handover of the management of the dams to the local communities. Improving the level of stake holder collaboration by the application of (IWRM) principles such as stakeholder participation and consultation would also be facilitated. This can create or facilitate linkages between institutions thereby reducing the impact of lack of resources on dam maintenance. Increased cooperation between NGOs and DDF through the supporting of DDF staff training programmes by NGOs for instance could reduce the impact of lack of experts to assist communities in dam maintenance.

- There is need however for targeting and prioritising dams that are most affected by lack of care as resources are limiting. This can be facilitated by the use of the risk of failure evaluation tool.

6.3 Areas for Further Research.

- An investigation to establish whether the substantial seepage down stream of certain studied dams is threatening the dams concerned.
- Detailed investigations of both quantity and quality of seepage and leakage that was observed on some of the studied dams, so as to determine if these are not seriously affecting the dam structures.
- Detailed studies of catchment conditions and siltation into reservoirs and their effect on dam capacities and failure in the area of study.
- Further testing of the developed risk of failure evaluation tool to ensure its applicability to small dams in different climatic and management set-ups.

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APPENDICES

Appendix 1 Interview Questions

A.1.1 Questions Asked to DDF Officials)

What is your policy role/mandate in small dams in Zimbabwe?
What is your actual role in small dams maintenance and rehabilitation?
What are the design, construction and maintenance guidelines that are used by your organisation on its work on small dams?
What is the role of communities in the management and maintenance of small dams?
Could you please explain the hand over process of management of small dams to the communities?
Do farmers/communities approach you when they want to construct small dams and is this mandatory?
Do NGOs approach you in siting, designing and construction and maintenance of small dams?
What is the procedure that should be followed by anyone who would like to construct small dams in Zimbabwe?
What are the problems that you encounter in your work on small dams?

A.1.2 Questions Posed to NGO Officials

What is your role in small dams?
Can you please explain the steps that you go through from feasibility studies to the point you hand over a small dam to the community?
Who are the stakeholders that you liaise with in your work in small dams and how do you liaise with them?
What are the problems that you encounter in your work and in liaising with other stakeholders in small dams?

A.1.3 Questions for Community Members

The questions were asked to traditional leaders, councillors, VIDCO chairs, and or elderly community members in a particular area where a dam is located

What is your role in the management of small dams?
What are the activities that you carry out in the management of small dams?
Is there a dam committee for this dam?
When was this dam constructed and by who? (Where information is not available on the dam wall)
What was your role in the construction of the dam?
Has the dam ever been repaired or breached, if so when?
Is DDF involved the management and maintenance of small dams in this area?
In your view how is this dam affected by siltation?
What are the problems that you encounter in trying to manage or maintain the small dams?

Appendix 2 Rapid Assessment Results Summary

Table A.1 Summary of Rapid Assessment Results

Factor/criteria	**Description**				
Un Wanted Seepage on embankment	Present	Not present			
	*3	41			
Cracking (Embankment)	Minor	Moderate	Severe		
	1				
Crest Depressions (Due To Erosion)	Minor	Moderate	Severe		
	26	12	1		
Sinkholes	Present on Spillway	Present on embankment	Present on embankment/train wall joint	Not present	
		2	1		
Stability	Stable	Not stable			
	44				
Erosion	Minor/limited	Moderate	Extensive	Severe/Massive	
	14	19	9	2	
Scarping	Minor	Moderate	Extensive	Severe/Massive	No Scarping
	10	15	9	8	2
Vegetative growth (Trees)	Little or no	Sparse	Dense	Very Dense	
	15	13	11	5	
Termite Mounds /Animal burrows	No mounds	Few	Several	Many	With huge mounds
	5	9	13	17	7
Presence of riprap	Present on upslope	Not present	Present on both slopes		
	26	15	3		
Condition of riprap	Good	Fair	Satisfactory	Bad	
	1	7	8	10	
Fencing	Fence Removed	No fence	Partly in place/ needs attention	Ok	Other type
	20	20	3	1	1
Piping	Observed	Not observed	Other		
	1	43			
Presence of Emergency spillways	Present	Not present	Masonry section as spillway		
	42		2		
	Good	Fair	Satisfactory	Poor	Bad

Overall condition of spillway	Good	Fair	Satisfactory	Poor	Bad
	2	4	20	11	7
Spillway Blockages	Minor	Moderate	Serious		
	37	5	2		
Presence of toe drains	Present	Not present			
	37	7			
Soil types	Good	Fair	Satisfactory	Bad	
			44		
Micro Catchment	Good	Fair	Satisfactory	Less than Satisfactory	Poor
	1	7	29	6	1
Siltation risk	Very High	High	Moderate	Low	
	4	7	24	9	
Embankment Outlet	On the Down slope	On the Up slope	Without outlet		
	12	1			
Blocked outlets	Blocked	Partially blocked	Not blocked but damaged/deteriorated	Minor damage / deterioration	
	2	1	5	5	
Foot path on embankment	Present	Not present			
	37	7			
Livestock Grazing on embankment	Limited	Pronounced	Extensive	No Grazing	
	8	22	11	3	
Grass Cover	Poor/ Limited	Satisfactory	Fair	Good	
	7	29	6	2	
Substantial D/stream seepage	Present	Not present			
	2	42			
Spillway Breaching	Breached, not repaired	Breached, repaired once	Breached, repaired more than once		
	3	1	2		
Dam wall Breaching	Breached, not repaired	Breached and reconstructed	Breached, repaired more than once, breached again		
		2	2		
Failed dams not holding water	Due to spillway breaching	Due to embankment breaching	Due to Siltation		
	1	2	1		

(*The number indicates the number of dams affected by the deficiency. For example unwanted seepage was noted or was present on 3 dams)

- One dam (Backley, ward 6) had a traditional tree branch ‘fence’ on the down stream slope. It seemed effective in preventing livestock grazing.
- Only one micro catchment (Chehondo dam, ward 9) had erosion prevention conservation structures in the dam wall/spillway abutment. These were in the form of stone check dams place in the spillway abutment to prevent run off from undercutting the abutment and spillway’s down stream.
- 5 dams (11,4%) of the visited dams had no masonry sill on their emergency spillways. Only one had a sill not constructed on a rocky surface.
- One dam, Bikibiki Dam in ward 8,had runoff draining from the rocky abutment onto the down stream dam slope end. The runoff was causing gulling, minor scarping and wetting of some sections of the dam slope.
- Two dams had a combination of masonry and earthen embankments and the masonry sections acts as the emergency spillway. (Gumbalo and Manzanlhope dams)
- At least 3 dams had spillways being raised, 2 by DDF and one by community. The one raised by the community was done without proper supervision of experts.

Appendix 3 Detailed Assessment Results Summary

A9.3.1 Sample results of the Detailed Assessment of the Physical Condition of Small Dams.

Table A.2 Sample Results of the Detailed Assessment of the Physical Condition of Small Dams: Mzambani Dam

Reservoir	**Mzambani**			
Location	**Measurements and Other Observations**		Design Guidelines Recommendations	Comments
Upstream slope	Slope length	4.25m		
	Slope Height	1.173		
	Slope width	4.101		
	Slope	1: 3.500	1:2.5 (Height>3m) 1:3 (Height <3m)	Less steeper than recommended, ok
	Rip Rap size	No rip rap	Max 600mm	Not as recommended
Crest	Height (Dam height)	1.838		
	Crest Width	0.8	2m	Slope not as recommended as it was sloping to both upstream and downstream from centre of crest
	Slope		1: 50	
Down Stream Slope	Slope length	4.8m		
	Slope Height	1.77m		
	Slope width	4.462		
	Slope	1:2.52	1:2 (Height>3m) 1:3 (Height <3m)	Slightly less than recommended
Freeboard Loss Assessments				
Spill Way	B	24.0m		
	CA	0.5km^2		
	Q	9.35m^3/s		
	H	0.388m		
	R D F	0.5		
	H + RDF	0.888 m		
	G freeboard(msd)*	0.785m	(< H+ RDF)	Spillway inadequate
	D/S slope	3:10.8	3:100	Eroded, steep
	U/S slope	3:261	3:100	Flatter than recommended
Embankment	Length	130m		

*msd = measured

B = width of the spillway; CA = Catchment Area

Q = Discharge; H = Wet Free board as obtained from equation 1.0

RDF = Recommended Dry Freeboard; GFB = Gross

Soils
Blackish Sandy clay
Soils are within the recommended class.
See table 5.2 for Consistency and Sieve Analysis test results

Adequacy of compaction analysis
No slides, scarping, toe bulging and arc–shaped cracks on upstream, crest and downstream slopes of the embankment. Therefore Compaction was deemed adequate.

Seepage
No seepage was observed. No seepage toe was observed

Micro Catchment analysis and siltation
There are few patches of bare ground around the dam covering about 20% of surface area on the sides and around throw back. Gulling was evident around the dam. The area around the reservoir has relatively dense tree cover. About 30% of dam area is covered by short grazed grass which covers the ground like a carpet. Reservoir not seriously threatened by siltation as less than 5% of reservoir area showed signs of siltation. Reeds and tall grass on the area where river enters dam could also be trapping some silt, preventing it from entering reservoir.

9.3.2 Laboratory Soil Analysis Results
The summarized results are in table 5.2.

Table A.3 Detailed Assessment of the Physical Condition of Small Dams- Results: Overall Summary

Location on Dam		**Reservoir**								
		Dewa	**Manzanlhope**	**Shagwe**	**Avoca**	**Mzambani**	**Chobukwa**	**Dube Jubele**	**Ngwabi**	**Magelimani**
Upstream Slope	*Slope*	1:2.1	1:2.4	-	-	1:3.5	-	1:1.9	1:1.29	1:3.5
	Riprap size (mm)	50-500	50-400	100-500	50-500	No riprap	50-450	100-400	No riprap	100-300
	Riprap Condition	Very bad	Fair	Bad	Satisfactor y	-	Bad	Fair	-	Fair
Crest	Height (m)	5.9	1.56 (earthen) 6 (masonry)	5.0	6.6	1.8	4.3 (masonry)	2.3	1.7	4.3
	Width	0.6	2.5 (earthen)	5.3	2.2	0.8	-	1	1.5	2.2
	Slope	1:38	1:37	-***	-***	-***	-	-***	-***	1:157***
	Direction of slope	Not as rec	As rec.	Not as rec.	Not as rec.	Not as rec.	-	Not as rec.	Not as rec.	Not as rec.
Down Stream Slope	*Slope*	1:2.1	1:3	1:2.3	1:1.8	1:2.5	-	1:1.8	1:2.3	1:3.3
Freeboard Loss / Adequacy (m)	*Calc.G.F.B*	1.907	1.38	1.793	1.2075	0.888	2.043	1.28	0.909	1.348
	Msd G.F.B	1.72	1.056	1.532	1.249	0.785	0.829	1.018	0.186	1.382
	Adequacy	Slightly. Inadequate	Inadequate	Slightly In adequate	Adequate	Slightly Inadequate	Inadequate	Slightly in adequate	In adequate	Adequate
Spillway slopes	*U/S slope*	3:20	N/A	Not msd	3:108	3:261	N/A	3:600	Eroded	3:208
	D/S slope	3:49	N/A	Eroded	1:625	3:11	N/A	3:283	Eroded	Eroded
unwanted Seepage		Not present	Not Present ****	Present	Not present	Not present	Not present	Not present	Not present	Not present
Soils		SM-SC	SC	SC	SM-SC	SC	SC	SC	SM-SC	SC
Micro Catchment Condition		L/ than satisfactor y	Satisfactory	Satisfactor y	L/ than satisfactor y	Fair	Poor	Fair	Fair	Less than satisfactory
Siltation Risk	*Area affected*	20%	14%	16.7%	20%	5%	70%	1%	11.1%	20%
	Risk	High	Moderate	Moderate	High	Low	Very high	Low	Moderate	High
Compaction		Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok

* Present on the masonry section ,:**Present on the ; *** Sloping towards both upstream slope and down stream slope; **** Filtering leakage was noted on several sections of the foundation and masonry wall on the Masonry section of the dam wall.

Calc.G.F.B = Calculated Gross Free Board ; Msd G.F.B = Measured Gross Free Board ; Rec. = Recommended

Appendix 4 The Risk Evaluation Tool Development Process Issues.

Table A.4 Standardizing the Description of the Risk Factors / Criteria.

Risk Factor	**Description of Factor (Percentages represents degree of risk.)** As an example ; If crest slopes were found with a slope as recommended, the crest slope for the particular small dam would be described as 'As recommended' and a risk contribution to dam failure for such a description would be '0%'. Similarly it would be 25% if only slope direction was found to be as recommended on a particular small dam. Similarly if unwanted seepage was found noted, the description would be 'present' and the allocated contribution to dam failure of this description would be '100%'				
Un wanted seepage on the D/S	Present	Not present			
	100%	0%			
Crest Slopes	Angle & direction As recommended	Only Direction as recommended	Both not as recommended		
	0%	25%	75%		
Seepage ponding on D/S toe	Not present	Present			
	0%	100%			
Cracking (embankment)	Mild	Moderate	Serious	No cracking	
	5%	10%	85%	0%	
	Longitudinal Crack <10mm	Transverse crack <10mm and not extending throughout the wall, Longitudinal >10mm,< 20mm)	Longitudinal crack > 20mm , transverse cracks crossing the whole width of dam wall , Transverse crack >10mm		
Depressions	Mild	Moderate	Serious		
	5%	10%	85%		
	< 10cm deep and resulting from erosion - Settlement greater less10% of original height.	> 10cm, <30cm due to erosion - settlement between 20 and 30% of original height.	- >30cm due to gulling, - Settlement greater than 30% of original height.		
Sinkholes	Mild	Threatening	Serious	No Sinkholes	
	5%	10%	85%	0%	
	Water infiltrating through spillway sill , no visible sinkhole	Sink hole/s through the spillway sill	Sink hole/s through the embankment wall or joint between embankment and training walls.		
Grass cover on slopes	Good	Fair	Satisfactory	Sparse	Poor
	0%	5%	10%	30%	55%
	See descriptions of what is meant by 'good', 'fair', etc for this particular factor under section A.4.1				
Tree and shrub growth	Little	Moderate	Dense	Very Dense	
	5%	10%	30%	55%	
	Little vegetation, no medium sized and large trees	Sparse vegetation comprising of small and medium sized trees, presence of few large trees.	Dense vegetation, all sizes of trees present	Very dense vegetation cover , all sizes of trees present.	
Termite mounds and/ animal burrowing	Minor	Moderate	Considerable	Severe	No mounds
	5%	10%	30%	55%	0%

<table>
<tr><td></td><td colspan="2">Few to several small mounds /burrows</td><td>Many small mounds/ burrows</td><td>Few big mounds/burrows</td><td>Few huge mounds/ burrows, many big ones.</td><td></td></tr>
<tr><td rowspan="2">Piping</td><td colspan="2">Present</td><td>Not Present</td><td></td><td></td><td></td></tr>
<tr><td colspan="2">100%</td><td>0%</td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">Slumping/bulging</td><td colspan="2">Present</td><td>Not Present</td><td></td><td></td><td></td></tr>
<tr><td colspan="2">100%</td><td>0%</td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">Ponding (just below toe)</td><td colspan="2">Present</td><td>Not Present</td><td></td><td></td><td></td></tr>
<tr><td colspan="2">100%</td><td>0%</td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">Presence of Spillways</td><td colspan="2">Present</td><td>Not Present</td><td></td><td></td><td></td></tr>
<tr><td colspan="2">0%</td><td>100%</td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">Spillway slopes</td><td colspan="2">Only U/S slopes as recommended</td><td>Only D/S slopes as recommended</td><td>Both slopes not as recommended</td><td>Both slopes as recommended</td><td></td></tr>
<tr><td colspan="2">50%</td><td>50%</td><td>100%</td><td>0%</td><td></td></tr>
<tr><td rowspan="3">Spillway Blockages</td><td colspan="2">Minor</td><td>Moderate</td><td>Serious</td><td></td><td></td></tr>
<tr><td colspan="2">5%</td><td>10%</td><td>85%</td><td></td><td></td></tr>
<tr><td colspan="2">Soil mounds/ debris covering less than 5% of spillway area upstream of dam wall</td><td>Soil mounds/ debris covering between 5 and 50% of spillway area upstream of dam wall</td><td>Soil mounds/ debris covering more than 50% of spillway area upstream of dam wall</td><td></td><td></td></tr>
<tr><td rowspan="3">Spillway Condition</td><td colspan="2">Good</td><td>Fair</td><td>Satisfactory</td><td>Bad</td><td></td></tr>
<tr><td colspan="2">0%</td><td>5%</td><td>10%</td><td>85%</td><td></td></tr>
<tr><td colspan="6">See descriptions of what is meant by ‘good’, ‘fair’, etc for this particular factor under section A.4.1</td></tr>
<tr><td rowspan="2">Presence of toe drains</td><td colspan="2">Present</td><td>Not present</td><td></td><td></td><td></td></tr>
<tr><td colspan="2">100%</td><td>0%</td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">Presence of riprap</td><td colspan="2">Present</td><td>Not present</td><td></td><td></td><td></td></tr>
<tr><td colspan="2">0%</td><td>100%</td><td></td><td></td><td></td></tr>
<tr><td rowspan="3">Condition of riprap</td><td colspan="2">Good</td><td>Fair</td><td>Satisfactory</td><td>Bad</td><td></td></tr>
<tr><td colspan="2">0%</td><td>5%</td><td>10%</td><td>85%</td><td></td></tr>
<tr><td colspan="6">See descriptions of what is meant by ‘good’, ‘fair’, etc for this particular factor under section A.4.1</td></tr>
<tr><td rowspan="3">Embankment soil type</td><td colspan="2">Bad</td><td>Satisfactory</td><td>Fair</td><td>Good</td><td></td></tr>
<tr><td colspan="2">85%</td><td>10%</td><td>5%</td><td>0%</td><td></td></tr>
<tr><td colspan="2">Organic clays, cracking clays or sands</td><td>Inorganic clays, coarse grained soils with less than 10% clay</td><td>Poorly graded Coarse grained soils with clay content between 10 and 20%</td><td>Poorly graded Coarse grained soils with clay content between 20 and 30%</td><td></td></tr>
<tr><td rowspan="3">Erosion on dam wall (excluding scarping)</td><td colspan="2">Minor</td><td>Moderate</td><td>Extensive</td><td>Severe/massive</td><td>None</td></tr>
<tr><td colspan="2">5%</td><td>10%</td><td>30%</td><td>55%</td><td>0%</td></tr>
<tr><td colspan="2">Rills on less than 50% of area.
Few small gullies</td><td>Rills on more than 50% of area.
Several small gullies</td><td>Several big gullies.
Few huge ones.
Small gullies all over the area</td><td>Several huge gullies.
Big and small gullies all over the area.</td><td></td></tr>
<tr><td rowspan="3">Scarping</td><td>None</td><td>Minor</td><td>Moderate</td><td>Extensive</td><td>Severe/massive</td><td></td></tr>
<tr><td>0%</td><td>5%</td><td>10%</td><td>30%</td><td>55%</td><td></td></tr>
<tr><td></td><td>Small scarping in isolated places</td><td>Small and large scarps in isolated places</td><td>Small and large scarps right across the slope. Few huge scarps</td><td>Large and huge scarps all over the slope.Presence of massive scarps</td><td></td></tr>
<tr><td>Embankment slope</td><td colspan="2">Only U/S slopes as recommended</td><td>Only D/S slopes as recommended</td><td>Both slopes not as recommended</td><td>Both slopes as recommended</td><td></td></tr>
</table>

angles(U/slope and D/slope)	50%	50%	100%	0%	
Crest width	As recommended	Not as rec.			
	0%	100%			
Crest slope	As recommended	Not as recommended			
	0%	100%			
Fencing	Present and in good condition	Needs repairs/partly in place	Not present		
	0%	25%	75%		
Animal grazing	Present	Not present			
	100%	0%			
Slope protection (rec. grass/ riprap)	Only U/S slopes as recommended	Only D/S slopes as recommended	Both slopes not as recommended	Both slopes as recommended	
	50%	50%	100%	0%	
Outlet Condition	Good	Fair	Satisfactory	Bad	
	0%	5%	10%	85%	
	No signs of deterioration/ damage/piping, Opening closing valves fully operational	Minor signs of damage/deterioration, no signs of piping, Opening closing valves fully operational	Moderate signs of damage/deterioration, no signs of piping, Opening closing valves needing attention but functional	Completely blocked, Opening valves completely removed / not closing/not opening, Signs of piping	
Adequacy of compaction	Adequate	Inadequate			
	0%	100%			
Adequacy of freeboard	Adequate	Slightly inadequate	Inadequate		
	0%	5%	95%		
	Msd G.F.B Within 5% of or more than *calculated G.F.B	Msd G.F.B 6-20% less than calculated G.F.B	Msd G.F.B More than 20% less than the calculated G.F.B		
Micro catchment condition	Good	Fair	Satisfactory	Less than satisfactory	Poor to Bad
	0%	5%	10%	30%	55%
	See descriptions of what is meant by 'good', 'fair', etc for this particular factor under section A.4.1				
Siltation risk	Low	Moderate	High	Very high	
	5%	10%	30%	55%	
	See descriptions of what is meant by 'Low', 'Moderate', etc for this particular factor under section A.4.1				

* Section 4.4 describes how the gross freeboard was obtained.

A.4.1 Definitions and Description of Terms and Risk factors

Trees

Descriptions based on observations from field assessments as no such descriptions were found in literature.

Large - > 10cm in diameter, more than 4m tall

Medium - 5 – 10 cm in diameter, 2 to 4 m in height.

Small - < 5cm in diameter, 2m in height.

Vegetative Growth on Embankment
Descriptions based on observations from field assessments as no such descriptions were found in literature.

Little - Trees covering less than 5% of surface area.
Sparse - Trees scattered on the area, between 5% and 40% of area.
Dense - Closely packed trees covering between 40 and 80% of area
Very dense - Closely packed trees covering more than 80% of the area.

Termite mounds and/ animal burrows
Descriptions based on observations from field assessments as no such descriptions were found in literature.

Few - Less than 5 in number
Several- Between 5 and 10
Many - More than 10
Small - Less than 10cm high, less than 5cm in diameter
Big - Between 10cm and 1m in height, between 5 and 10cm in diameter
Huge - Taller than 1 m, more than 1 m in diameter.

Spillway Condition
Descriptions based on observations from field assessments

Good - No leaks no damaged masonry, no notable signs of erosion.
Fair - Minor leaks, minor erosion signs, minor spalling on sill, small cracks on sill through which no leakage water is flowing.
Satisfactory - Moderate erosion signs on spillway and its abutments, few leaks/ seepage through sill wall or foundation, notable spalling on sill, sill cracks through which some leakage water is flowing but in small amounts
Poor -Severe erosion signs on spillway and its abutments, presence of sinkhole/s up stream of sill, sill masonry dislodged in some sections,
several sill cracks through which some leakage water is flowing in notable amounts.

Erosion on Embankment (Descriptions based on observations from field assessments)
Rill - Up to 5cm deep
Small Gully - Between 5cm and 20cm deep.
Big gully - Between 20 and 50 cm deep.
Huge gully - Deeper than 50cm

Table A.5 Erosion on Embankment (Descriptions based on observations from field assessments)

Minor	**Moderate**	**Extensive**	**Severe/massive**
Rills on less than 50% of area and or Few small gullies	Rills on more than 50% of area and or Several small gullies	Several big gullies. Few huge ones and or Small gullies all over the area	Several huge gullies and or Big and small gullies all over the area.

Scarping (Descriptions based on observations from field assessments)

Small - Less than 30cm deep.
Big/ large - Between 30 and 50cm deep
Huge - Between 50cm and 1m deep
Massive - more than 1m deep.

Embankment Slopes
Considered to be as recommended if the calculated value is within 5% of the recommended value.

Adequacy of Compaction (Based on inspection guidelines such as FEMA,(1987)and field observations.)
Compaction of soil on the embankment is taken as adequate if no signs of bulging are noted on the toes of slopes, no excessive settlement is noted especially on isolated points on the crest. Adequacy of Compaction also taken to infer slope stability.

Micro Catchment Issues

Definition of Micro Catchment
Micro catchment is taken as the small dam environs (area within 200m radius of the reservoir measured from the full supply level). This was arrived at after noting that 200m was noted to be the average maximum distance from which human activities around reservoirs such as gardening and brick making are usually located away from the reservoir. (Sithole and Senzanje, 2006: p36)

Relief of Micro Catchment (Guided by HR Walling ford 's Methodology for estimating risk of soil erosion CARE Zimbabwe, 2002)
Steep - average slope greater than 30%
Hilly - 10-30% slope, hills cover more than 50% of micro catchment
Rolling -5-10% slope, hills cover less than 50% of micro catchment
Relatively flat land - slope between 0 and 5%.

Vegetation Cover around Micro Catchment
(Guided by HR Walling ford's Methodology for estimating risk of soil erosion CARE Zimbabwe, 2002)

Bad -Little effective plant cover, ground bare or very sparse cover over 80% of micro catchment
Poor -Less than 30% of micro catchment is under good grass cover or forest cover

Less than satisfactory	- 30-40% of micro catchment is under good grass cover or forest cover
Satisfactory	-41-50% of micro catchment is under good grass cover or forest cover
Fair	-51-60% of micro catchment is under good grass cover or forest cover
Good	- More than 60% of micro catchment is under good grass cover or forest cover

Erosion Signs in Micro Catchment
(Guided by HR Walling ford's Methodology for estimating risk of soil erosion CARE Zimbabwe, 2002)

Minor	- Few actively eroding gullies draining directly into dam and /or watercourses; little undercutting of river banks along main water courses.
Moderate	- Some actively eroding gullies draining directly into dam and /or watercourses; moderate undercutting of riverbanks along main watercourses.
Extensive	-Many actively eroding gullies draining directly into dam and /or watercourses; active undercutting of riverbanks along main watercourses

Grazing in the Micro Catchment (Based on Field observations)

Minimal	- Little signs of grazing on the grass.
Moderate	- Clearly visible signs of grazing, but grass not grazed to the ground level.
Extensive	- Grass grazed all over the micro catchment, grass grazed to the ground level in some places
Severe	- Grass grazed all over the micro catchment, grass grazed to the ground level in most places.

Micro Catchment Condition (Based on field observations and Principles used in the HR Wallingford's Methodology for estimating soil erosion risk)

Satisfactory - Moderate grazing, satisfactory vegetation cover, no gardens and fields within 30m of watercourses, some fields within the micro catchment, moderate signs of erosion

Less than satisfactory - Extensive grazing, satisfactory vegetation cover, and or few gardens and no fields within 30m of watercourses, and or moderate signs of erosion

Poor - Extensive grazing, poor vegetation cover, few gardens and fields within 30m of watercourses, extensive signs of erosion

Bad - Severe grazing, bad vegetation cover, many gardens and some fields within 30m of watercourses, extensive to severe signs of erosion

Siltation risk (Based on Visual observations on assessed dams in the field and literature on effects of siltation on reservoirs such as CARE Zimbabwe,(2002), Page 74)

Low -Less than 10% of visible dam area covered by siltation, Micro Catchment at least satisfactory in condition. Stream carries very low sediment load.

Moderate -10-20% of visible dam area covered by siltation. Catchment condition satisfactory. Stream carries low sediment load.

High -Between 20 and 30% of visible dam area covered by siltation. Micro catchment condition less than satisfactory. Stream carries visibly large siltation load.

Very High -More than 30% of visible dam area covered by silt. Micro catchment condition poor to bad. Stream carries high sediment load.

Grass Cover on Embankment Slopes

(Guided by Field observations and maintenance guidelines such as FEMA, 1987)

Good - More than 80% of embankment area covered by complete grass cover no bare patches

Fair - Between 50 and 80% of area covered by complete grass cover no bare patches

Satisfactory - Between 30 and 50% of area covered by complete grass cover small patches of bare ground

Sparse -Between 20 and 30% of area covered by complete grass cover. Patches of bare areas covering up to 60% of area

Poor - Less than 20% of area covered by complete grass cover. Patches of bare areas covering more than 60% of area.

Condition of riprap (Guided by design and construction guidelines such as Shaw (1977) and field observations)

Good - No notable damage of riprap on slope ends and training wall. No signs of dislodged riprap along the slope length

Fair - Riprap removed /slumped in few places with no scarping and gulling evident on the slope and training wall. Riprap dislodged on slope ends due to human and animal traffic.

Satisfactory - Riprap removed /slumped in several places with no scarping and gulling evident on the slope and training wall. Minor dislodging of riprap on slope ends due to human and animal traffic.

Bad - Riprap slumped. Gulling and scarping taking place on slope and training wall, and or Riprap stones dislodged and scattered all over the slope

A.4.2 Ranking of Factors/Criteria

Cause effect diagrams were used to determine the relationships between the factors. The cause effect relations were used to determine the levels of each factor in relation to the main problem dam of failure/ breaching. Four failure modes or processes that results in dam failure were identified through brainstorming. As result, 4 cause-effect relation diagrams were determined and as shown in Figures A.1 to A.4.

An example of how the cause effect diagrams were formulated and levels determined is now given: Referring to figure A.1, Breaching can result from reduced spillway size (at level 1, indicated as ‘1’ in square brackets). Reduced spillway size in turn resulted from siltation (level 2, indicated as ‘2’ in square brackets). Siltation was as a result of erosion (level 3 indicated as ‘3’in the same bracket as the ‘2’ described above). Erosion in turn, was caused by poor catchment condition (level 4). At the same time, Dam failure can result from siltation (level 1). The Siltation resulted from erosion (level 2) which in turn resulted from poor micro catchment condition (level 3).

Figures A.1 to A.4: Cause Effect Diagrams Showing Relationships Between Identified Factors that Result in Dam Failure.

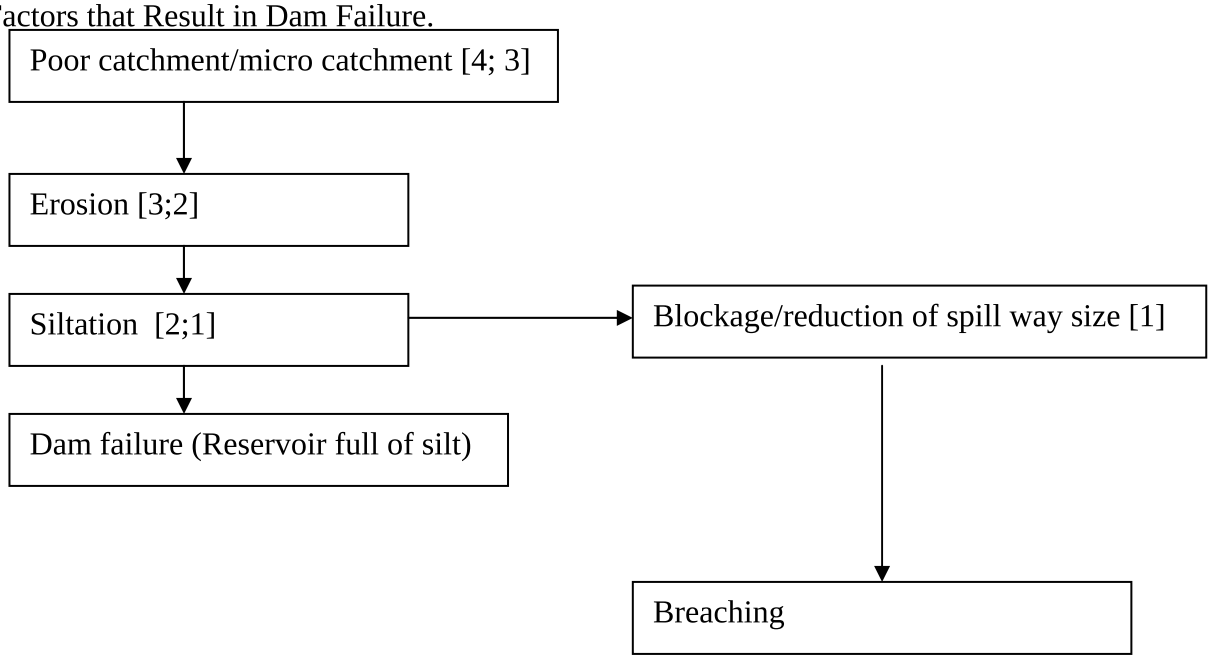

Figure A.1

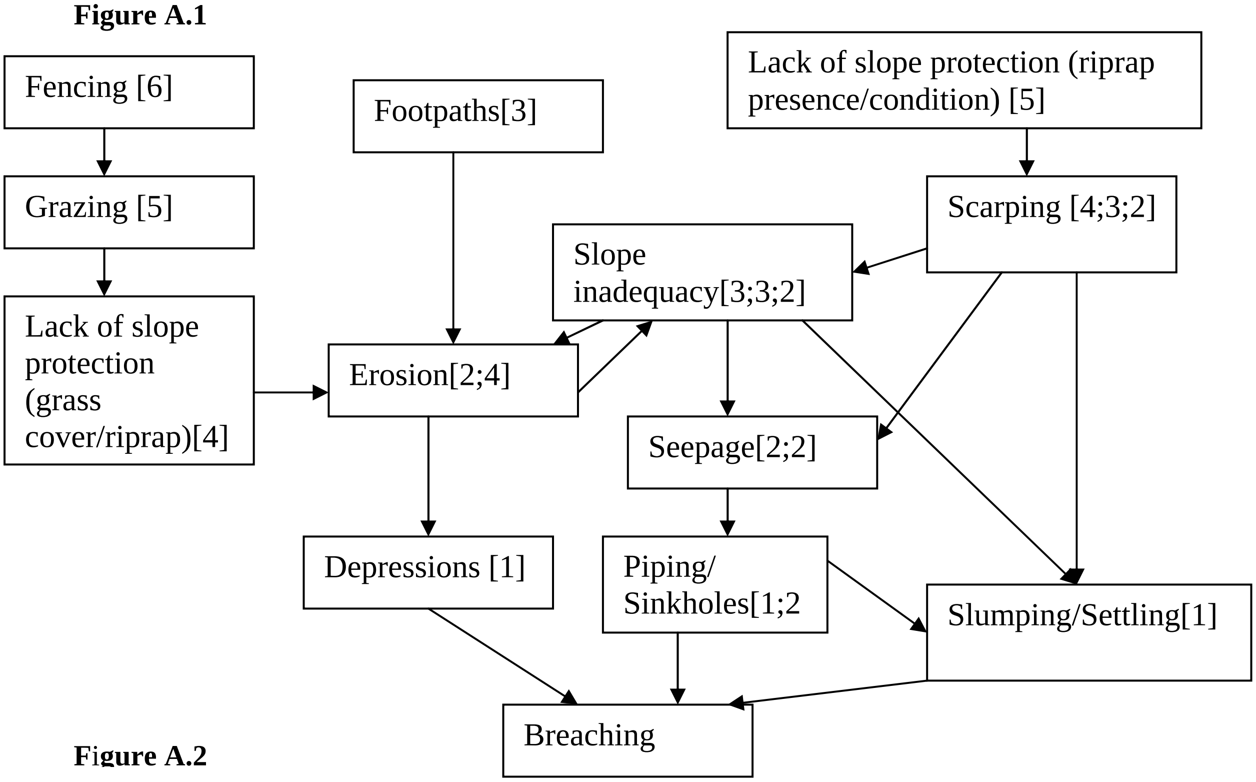

Figure A.2

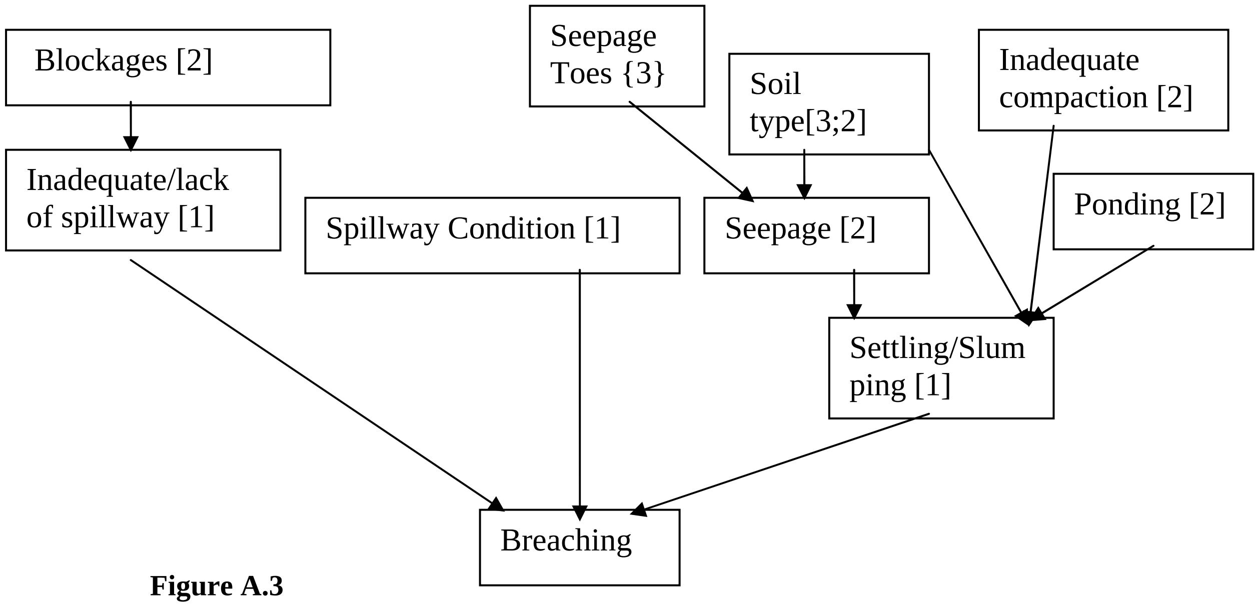

Figure A.3

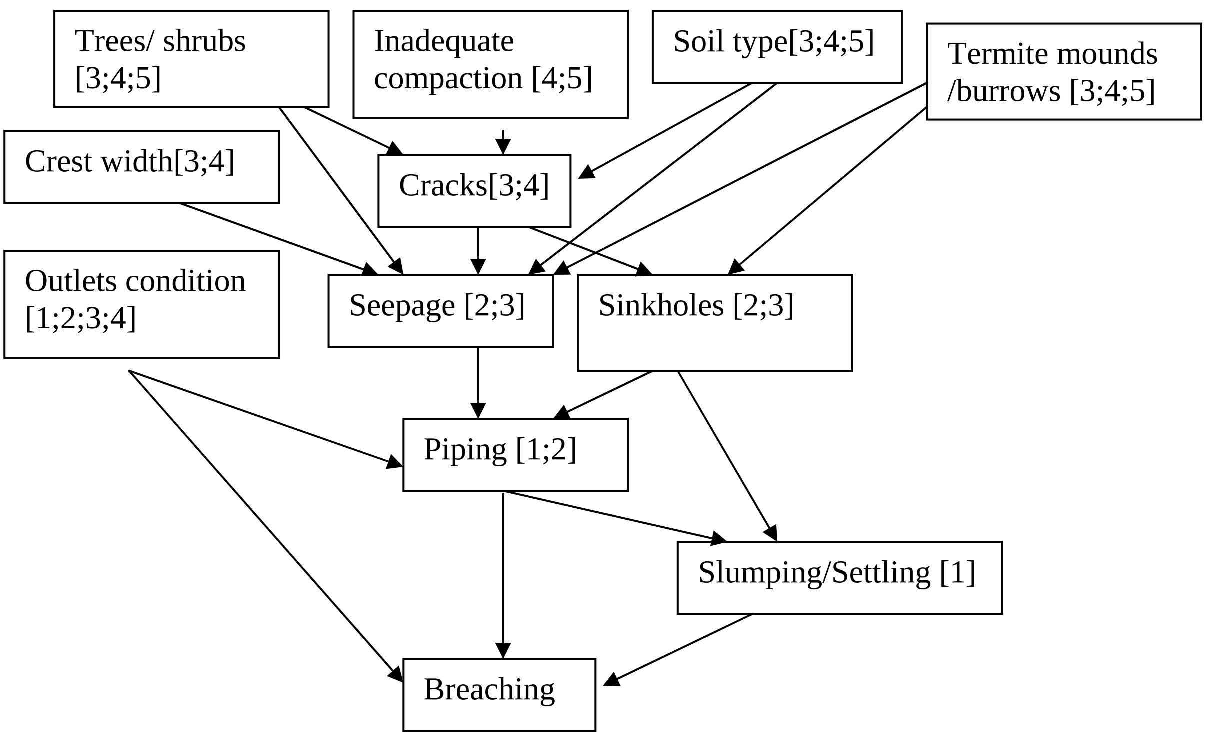

Figure A.4

Table A.6 Determination of Weights

Factor/Criteria	Levels					Average level	Weight Index	Weight
Trees and shrub growth	4	3	5			4	3	**0.50**
Soil type	4	3	3	2	5	3.4	3.6	**0.60**
Termite mounds/burrows	4	3	5			4	3	**0.50**
Inadequate compaction	4	2	5			3.67	3.33	**0.56**
Cracks	3	4				3.5	3.5	**0.58**
Crest width	3	4				3.5	3.5	**0.58**
Outlets condition	2	3	1	4		2.5	4.5	**0.75**
Unwanted seepage/Leakage(embankment)	2	2	2	2		2	5	**0.83**
Sinkholes	3	1	2	2		2	5	**0.83**
Piping	1	2	1			1,33	5.67	**0.95**
Fencing	6					6	1	**0.17**
Animal grazing	5					5	2	**0.33**
Grass cover	4	5				4.5	2.5	**0.42**
Rip rap presence/condition	4	5				4.5	2.5	**0.42**
Embankment Slopes	3	3		2		2.67	*4.33/3	**0.24**
Erosion	2	4	3	2		2.75	4.25	**0.71**
Foot paths	3					3	4	**0.67**
Depressions	1					1	6	**1**
Inadequate free board/spillway	1					1	6	**1**
Blockages	2	1				1.5	5.5	**0.92**
Lack of spillway	1					1	6	**1**
Spillway condition	1	1				1	6	**1**
Seepage toes	3					3	4	**0.67**
Slumping/bulging	1	1	1			1	6	**1**
Settling	1	1	1	1		1	6	**1**
Ponding	2					2	5	**0.83**
Scarping	4	3	2			3	4	**0.67**
Catchment condition	4	3				3.5	3.5	**0.58**
Siltation risk	3	1				2	5.5	**0.92**

* The slope weight was divided by 3 to cater for the contribution of 3 types of slopes (Upstream, crest and Down stream slope) their overall effect is added.

A.4.3 Determination of weights

For each factor, all the levels on the cause effect diagrams were noted and recorded in columns 2 to 6 in table A.6. An average level was then computed from these.
The higher the level means the further away the factor from causing breaching or dam failure, therefore the lower the weight. From the cause effect diagrams the highest level was six, that of fencing, therefore this was awarded the lowest weight of 1. The other weights of the levels were determined respectively as shown in the table A.7. Equation 2 was used to convert weight Indices into weights.

Table A.7 Relationships between levels and weights.

Level	1	2	3	4	5	6
Weight Index	6	5	4	3	2	1
Weight	1	0.83	0.67	0.50	0.33	0.17

Table A.8 Summary of Description of Catchment Characteristics in HR Wallingford's Methodology for Estimating Risk of Soil Erosion. Adopted from CARE Zimbabwe, (2002)

Catchment characteristic	**Description and erosion factor points allocated (in brackets)**			
Relief	Steep (40)	Hilly (30)	Rolling (20)	Flat (10)
Soil Type and drainage	Very Poor (40)	Poor (30)	Moderate (20)	Good (10)
Vegetation cover	Little (40)	Fair (30)	Good(20)	Excellent (5)
Signs of erosion	Extreme (80)	High (60)	Normal (20)	Low (0)

Appendix 5. Risk Based Approaches from Around the World

1. **ANCOLD, Australia** (Source: Defra,2002)

Table A.9 ANCOLD's guidelines used in the risk assessment approaches in Australia.

ANCOLD GUIDELINE	PURPOSE
Dam Safety Management (1994).	An approach to dam safety management which includes investigation, design, construction, surveillance, safety reviews, remedial action and emergency planning.
Risk Assessment (1994) **RA94** • Also refer to the Position Paper, ANCOLD 1998 • 2nd Edition under development at July 2001	A framework for the risk assessment of issues relating to dams.
Assessment of the Consequences of Dam Failure (2000) **CDF2000**	Identify priorities and/or make a first level consequence assessment, and thus assess Hazard Category. (see Stojmirovic, 2001, for application to Tasmania)
Selection of an Acceptable Flood Capacity for Dams, 2000 **AFC2000**	The basis for the provision of flood capacity at dams.
Design of Dams for Earthquake, 1998	The basis for the capability of dams to withstand earthquakes.
Environmental Assessment and Management, being prepared	Guidance of the natural environment social and economic assessment and evaluation process necessary to establish the feasibility of proposed dams and the management of existing dams and water conservation storages.
Business Planning and Performance Management, being prepared	An approach to dams asset management.
Guidelines on other physical aspects such as: • Concrete Faced Rockfill Dams (1991) • Design Criteria for Concrete Gravity Dams (1991) • Strengthening and Raising Concrete Gravity Dams (1992) • Guidelines Supplement to ICOLD Bulletin 75-Roller Compacted Concrete for Gravity Dams (1991)	Guidelines on design and construction requirements for specific dams.

Load Condition	Failure Mode	Recommended Methods	
		Preliminary and Portfolio Assessments	Detailed Assessment
Normal operating	Embankment instability and loss of freeboard	Historic performance plus judgement	Historic performance plus judgement, probabilistic analysis if sufficient data is available
	Internal erosion and piping in the embankment, foundation, and embankment to foundation	Historic performance with detailed failure paths; or event trees for all critical failure paths	Event trees for all failure paths
	Spillway wall instability	Analysis plus judgement	Analysis plus judgement
Flood	Embankment overtopping	Flood level AP usually estimated without modelling prior water level. Historic performance plus judgement to assess depth of overtopping giving failure	Flood level AP modelled with prior reservoir water level. Historic performance plus judgement to assess depth of overtopping vs probability of failure
	Embankment instability and loss of freeboard	Covered in normal operating load calculation	Historic performance plus judgement; probabilistic analysis if sufficient data available
	Internal erosion and piping in the embankment, foundation and embankment to foundation	Covered in normal operating load calculation if using historic performance; or event trees for all critical failure paths	Event trees for all failure paths
	Spillway and spillway energy dissipator scour and overtopping of spillway chute walls	Analysis, results of modelling if available, and judgement	Analysis, results of modelling if available, and judgement
Reservoir Rim Instability	Overtopping of dam by flood induced by landslide in the reservoir	Judgement based on topography, geomorphological mapping and historic landsliding	Landslide hazard assessed by air photo interpretation, inspection, and geomorphological mapping, and history and mechanics of sliding. Wave heights calculation from volume and velocity of slide.

Figure A.5. Extract of recommended methods for estimating the probability of failure for embankment dams**.** (Source: Defra ,2002.)

2. Portugal

Table A.10 . Portuguese Evaluation (Source : Defra,2002)

	External, or environmental conditions (Factor E)					**Dam condition/reliability (factor F)**				**Human/Economic hazard (factor R)**	
Partial Index	Seismicity	Reservoir Bank Slides	Floods Higher than Design Floods	Type of Reservoir Management	Aggressive Environment action (climate, water)	Structural Quality	Foundations	Flood Outlet Equipment	Maintenance Conditions	Reservoir Storage Volume (m3)	Downstream installations
i \ u	1	2	3	4	5	6	7	8	9	10	11
1	Minimal Or zero A<0.05g	Minimal Or zero	Very low probability (concrete dam)	Multi-annual, annual or seasonal storage	Very weak	Adequate	Very good	Reliable	Very good	$<10^5$	Non-inhabited zones without economic value
2	Low 0.05g<a< 0.1g	Low	-	-	Weak	-	Good	-	Good	10^5 to 10^6	Isolated areas agriculture
3	Middle 0.1g<a< 0.2g	-	Very low probability (fill dams)	Weekly storage	Medium	Acceptable	Acceptable	-	Satisfactory	10^6 to 10^7	Small towns agriculture craftsmanship
4	Strong 0.2g<a< 0.4g	-	-	Daily storage	Strong	-	-	-	-	10^7 to 10^9	Medium sized towns, small industries
5	Very strong a>0.4g	-	-	Pumped storage	Very Strong	-	Poor	-	-	$>10^9$	Large towns, industries, nuclear inst.
6(*)	-	Big slides	High probability	-	-	Inadequate	Poor or Bad	Insufficient not operational	Unsatisfactory	-	-

(*) Abnormal conditions; technically unavoidable intervention

a = peak ground acceleration at bedrock level

$$E = \frac{1}{5}\sum_{i=1}^{5} a_i \qquad F = \frac{1}{4}\sum_{i=6}^{9} a_i \qquad R = \frac{1}{2}\sum_{2i=10}^{11} a_i$$

$$\text{Global index}: \; a_g = E.F.R.$$

Federal Emergency Management Agency (FEMA)

Table A.11. Earth, Rockfill Dams – Evaluation Scale for Piping (Source : Defra,2002)

Evaluation Scale	Description	Correction relative to 'prior' probability
1	Good embankment, with no signs of defects or distress. Any seepage which exists is in agreement with design expectations (if available).	0.13
2	Generally good embankment, but evidence of minor defects, such as a few burrow holes, organic matter in embankment, etc	0.17
3	Embankment in good condition, minor seepage observed.	0.19
4	Localised vegetative growth which may indicate slight seepage free of soluble contents or suspended solids. Inadequate filter system.	0.39
5	Numerous burrow holes or tree growth along downstream slope only. Evidence of rotting debris in embankment, foundation, or abutments.	0.60
6	Numerous burrow holes along both sides of embankment. Brush and tree growth along both slopes.	1.00
7	Evidence of poor compaction and inadequate bond to foundation and abutments, which may lead to excessive seepage.	1.5
8	Evidence of only one of the following: Excessive seepage localised at joints, transverse cracking in embankment, foundations, or abutments, sand boils.	3.0
9	Excessive seepage at one or more of the locations listed in 8, and indication of embankment cracking and subsidence.	11.0
10	Distressed embankment, foundations and abutments evidenced by excessive seepage at joints, crack in embankment, fractures in foundation and abutment structure, sand boils etc.	18.0

Washington State's Risk Based Approach. (Source: Johnson (2000)

It is a Risk Based Approach in a standard based framework. Under this approach probability methods, risk concepts, and elements of risk assessment are combined with decision making in setting performance standards that provide acceptable minimum levels of protection. The approach was selected for two main reasons;

- The need to address the limitations of the PMF approach in predicting extreme floods events.
- The need to provide methods of analysis that are manageable with limited resources.

The state is responsible for over 800 dams, and has limited staffing and resources to apply towards detailed risk assessment. Performing quantitative risk assessments for every project had not been possible given these considerations. Employing risk concepts and procedures in standards based framework allowed the state to address these issues.

Probability and risk concepts were used in two main areas. The first was to develop risk based standards for dam design and evaluation of existing dams. The second was in the development of a risk based ranking system to prioritise compliance and enforcement efforts on existing dams with identified safety deficiencies.

The Development of Risk Based Standards.

The philosophy of the Washington dam safety program utilises several design principles that provide a framework for evaluating and establishing what design or performance levels are appropriate for the various elements of a dam. Examples of the various elements are spillway capacity, seepage and embankment stability. The primary principles that were used in the approach related to risk, are Balanced Protection and Consequence Dependant Design Levels.

Balanced Protection

A dam is comprised of numerous critical elements and like the old chain adage, "is only as strong as the weakest link". The term critical project element refers to an aspect of the structure, whose failure could precipitate the failure of the whole project (Johnson, 2000). Examples of critical elements are spillway and embankment slope stability. The goal of the balanced protection concept was to establish minimum design levels for the evaluation of each critical project element. For example, an appropriate Annual Exceedence Probability (AEP) of PMP events was established for evaluating adequacy of spillways.

Consequence Dependant Design Levels.

Standard practice in engineering is that the degree of conservation in design should correspond with the consequences of failure of a given element. If failure of a given element could pose a threat of loss of life, design levels are typically much more conservative. That conservatism increases with an increase in the potential magnitude of loss of life and property at risk. This concept is called Consequence Dependant Design Levels.

The above-described concepts of Balanced Protection and Consequent Dependent Design were implemented in what was termed the design step format. This format utilises eight steps. The design requirements become increasingly more stringent as the consequence of failure become more severe. Design step one has an annual Exceedence Probability of 1 in 500, and would apply where the consequences of dam failure are minimal and there would be no chance for lose of life. Design step 8 applies to large dams where failure would be catastrophic, with hundreds of lives lost. The AEP of step 8 was set at 1 in 1000 000. The design step 8's EAP is based on existing design standards and a review of recommendations for engineered structures within extreme consequences of failure, such as nuclear power plants.Figure A.6 shows a completed design step format.

Design Step	Exceedance Probability	Consequence Rating Points
1	1 in 500	< 275
2	1 in 1000	275 - 325
3	1 in 3000 (actually 3160)	326 - 375
4	1 in 10,000	376 - 425
5	1 in 30,000	426 - 475
6	1 in 100,000	476 - 525
7	1 in 300,000	526 - 575
8	1 in 1,000,000 (or theoretical maximum)	> 575

Figure A.6. Design Step Format (Source: Johnson,2000)

A critical question when using risk based design is 'what is acceptable (or tolerable) risk?' This implies that above some threshold design event/ performance level, loss of life would be tolerated. Design levels consistent with levels of safety provided by other engineering disciplines and government regulations were utilised to guide the development of the tolerable risk criteria in the dam safety field. Table A.12.

Table A.12. Benchmarks for Calibrating Point rating Algorithm For Use in Decision Framework (Source: Johnson,2000)

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

Note: AEP - Annual Exceedance Probability

Additional guidance in setting design levels was obtained by examining the levels of risk to which the public is exposed to in ordinary life. Examples of risks considered include risk from natural flooding, diseases and accidents.

Additive Point Rating Scheme

The next step in developing the risk-based standards was the development of an additive weighting scheme to determine numerical ratings of the consequences of dam failure. This scheme reflects the relative importance and range of severity of the impacts posed by each consequence. Cumulative rating points with values between 200 and 800 points were used to define the working range for the eight-step format. Factors were selected within the 3 general categories shown in Table A.13 which described the nature of the consequences of dam failure. Utility curves or consequence rating tables were developed for each of the indicator parameters in Table A.13 to implement the additive weighting scheme. A worksheet was then developed for compiling the rating points and selecting an appropriate design step, depending on the dam size and hazard rating. The point-rating scheme was calibrated using a wide cross-section of dam types and downstream settings to yield design steps consistent with the 5 benchmarks shown in Table A.12.

Table A.13 Numerical Rating Format for Assessing Consequences of Dam Failure (Source: Johnson,2000)

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

Probabilistic Design Data

Before the risk-based standards described above could be implemented, magnitude-frequency relationships were needed for extreme events such as floods and earthquakes. This type of information was available in Washington State but is not readily available to most states in the USA, and much work is still needed around the United States to develop probabilistic precipitation and seismic data for extreme events. Thus, Washington State had the necessary hydrologic data to employ them in a logical and consistent manner in their risk based design/performance practice. This data is used in determining a design storm event with an appropriate AEP to match the design/performance step for the dam in question. This storm is then used to compute the inflow design flood to size the spillway(s) for a new project, or to determine the adequacy of the spillway for an existing dam. In the seismic arena, the state has not yet developed suitable magnitude frequency relationships that can be used in the risk analysis.

Design Standards for Other Critical Elements

Besides the adequacy of spillway, other critical elements on existing dams such as outlets and seepage need to be considered as well. For these critical elements, a qualitative approach is used, rather than a quantitative assessment. This is achieved through review of the design and identification of deficiencies for the critical element, coupled with a qualitative assessment of the likelihood of failure based on past experience and engineering judgment.

Risk Prioritisation System

At the close of the 1980's, the Dam Safety Office had over 60 dams listed as having safety deficiencies. Many of these dams were projects inspected under the National Dam Safety Program from 1977-81, and had no action toward making repairs in 10 years. With such a large number of unsafe dams, and limited staffing, it became clear to the DSO that some way of prioritising these projects was needed. Thus, in conjunction with the development of the risk based standards, in 1990 the DSO developed a prioritisation ranking system for dams with safety deficiencies. The scoring and ranking algorithm developed by the DSO includes the following key ideas:

- For dams with similar deficiencies, those dams with the greatest consequences should be given higher priority.
- For dams with similar consequences, those dams with the more serious deficiencies should be given higher priority.
- For dams with similar deficiencies and similar consequences, those dams with a poorer chance for warning to the public should be given higher priority.
- Dams with only minor deficiencies should be ranked lower than dams with significant deficiencies, regardless of the consequences.
- The risk associated with three minor deficiencies is ranked just below that of one moderate deficiency.
- The risk associated with two moderate deficiencies is ranked just below that of one major deficiency.
- All things being equal, older dams should be given a higher priority.

These concepts were then incorporated into developing the equations for computing the number of priority points. Two different equations were developed for computing the priority points. The first equation is for dams where one or more of the safety deficiencies are rated moderate major or emergency. The second equation is for a project where all deficiencies are rated minor. These equations are shown in Table A.14

Table A. 14 Equations for Prioritisation Ranking (Source: Johnson,2000)

One or More Safety Deficiencies Rated Moderate, Major or Emergency	**Priority = [*Hazard Class*] + [*Warning*] + [Σ(*Seriousness of Deficiencies*)] + [*Age*/2]**
All Safety Deficiencies Rated Minor	**Priority = 0.5 ∗[[*Hazard Class*] + [*Warning*] + [Σ(*Seriousness of Deficiencies*)] + [*Age*/2]]**

Rating points were then developed for the consequences, adequacy of warning, and seriousness of deficiencies, as shown in Figure A.7.

RATING POINTS FOR CONSEQUENCES – BY HAZARD CLASS	
High Hazard	
Hazard Classification 1A - (100+ homes at risk)	500 points
Hazard Classification 1B – (11-99 homes at risk)	400 points
Hazard Classification 1C – (3-10 homes at risk)	300 points
Significant Hazard	
Hazard Classification 2 – (1 or 2 homes at risk)	200 points
Low Hazard	
Hazard Classification 3 – (0 homes at risk)	100 points
RATING POINTS FOR ADEQUACY OF WARNING	
Inadequate Warning – (< 10 minutes advanced warning)	100 points
Marginal Warning – (between 10 and 30 minutes)	50 points
Adequate Warning – (greater than 30 minutes)	0 points
RATING POINTS FOR SERIOUSNESS OF EACH DEFICIENCY (Primary focus on deficiencies that could lead to a dam failure or uncontrolled release of reservoir)	
Emergency Condition	250 points
Major Deficiency	145 points
Moderate Deficiency	65 points
Uncertain Seriousness	65 points
Minor Deficiency	20 points

Figure A.7 Rating Points for Prioritisation. (Source: Johnson,2000)

The seriousness of safety deficiencies are evaluated based on the matrix in Table A.15. This matrix is intended for guidance only, and ultimately, the final rating of seriousness of deficiencies is based on knowledge of the project and on engineering judgment.

Table A.15 Matrix for Evaluating Seriousness of Deficiencies (Source: Johnson,2000)

CONDITION	HYDRAULIC ADEQUACY	EMBANKMENT STABILITY	SEEPAGE ON EMBANKMENTS, FOUNDATION, ABUTMENTS	OUTLET CONDUIT(S)
SATISFACTORY	Can accommodate IDF	Meets criteria for static & seismic stability	Minimal seepage consistent with past behavior	KSU Conduit Rating > 8
MINOR DEFICIENCIES	Can only accommodate flood 1 step below Design Step	Meets criteria for static stability, marginal seismic stability under design earthquake	Minor seepage quantity, inconsistent with past behavior No evidence of internal erosion	KSU Conduit Rating 6-8
MODERATE DEFICIENCIES	Can only accommodate flood 2 steps below Design Step	Marginal static stability 1.3 < FS < 1.5 inadequate seismic stability or liquefaction under design earthquake	Moderate seepage quantity Or Anomalous increase in quantity Minor concerns of piping	KSU Conduit Rating 4-6
MAJOR DEFICIENCIES	Can only accommodate flood 3 steps below Design Step	Inadequate static stability 1.0 < FS < 1.3 inadequate seismic stability or liquefaction under design earthquake	Relative Large Seepage Quantity Multiple Points of Seepage And/or Significant concern of piping	KSU Conduit Rating 2-4
EMERGENCY	Cannot Accommodate 25-year Flood	Significant slope failures that intercept dam crest or involve major portion of the embankment	Large or rapidly changing seepage quantity Multiple points of seepage and ongoing piping	KSU Conduit Rating 0-2

The Achievements Realized by the Washington State by Using the Risk Based Approach

Since its implementation in 1990, the use of the risk-based standards approach has been quite successful in Washington State. It has provided a consistent level of protection against failure between projects located across the state, despite significant differences in seismic activity and rainfall. For dams that do not meet state standards, the state have been able to estimate the relative level of risk they pose, and prioritise their compliance efforts on those dam projects with the greatest risk. It has also allowed the state to inform dam owners not only that their dams are “unsafe”, but also educate them as to what level of risk their unsafe project poses to the downstream public. In addition, the state has utilized a prioritisation scheme for compliance efforts on unsafe dams, based on the relative risk of each project. These combined approaches have resulted in great progress in repairing the backlog of dams with identified safety deficiencies in the State of Washington. For example, of the 46 dams inspected under the National Dam Inspection Program still listed as unsafe in 1990, 40 had been repaired by 1999. In addition, 78 of the 101 additional dams identified by the state dam safety program since 1985, have been repaired.

Appendix 6. Assessed Dams in Insiza Sub Catchment (Godhlwayo Area)

Table A.16 Assessed Dams in Insiza Sub Catchment

Dam	**Ward**	**GPS Location**	**Owner**	**Comment**
Dewa	12	S 20°47.090′; E 029°30.975′	Community	
Mzambani	12	S 20°47.389′; E 029°32.047′	Community	
MaGelimani	12	S 20°49.318′; E 029°32.903′	Community	
Denje	12	S 20°47.574′; E 029°34.520′	Community	
Mashoko	8	S 20°44.304′; E 029°34.975′	Community	
Masuto	4	S 20°43.643′; E 029°27.494′	Community	
Manzanlhpe	4	S 20°42.734′ E 029°24.320′	Community	
Sifinini Dam	7	S 20°49.763′ E 029°33.884′	Community	
Avoca	12	S 20°48.591′ E 029°31.258′	Community	
Bova Dam	12	S 20°50.226′; E 029°30.359′	Community	
Siwaze	12	S 20°51.027′; E 029°29.406′	ZINWA	
Sababa	5	S 20°50.494′ ; E 029°25.594′	Community	
Embondweni	4	S 20°41.708′ ; E 029°28.242′	Community	
Sidzibe	5	S 20°48.663′; E 029°24.410′	Community	
Sapila	5	S 20°50.841′; E 029°23.973′	Community	
Moyo Musengi	5	S 20°51.026′ ; E 029°24.766′	Community	
Mabhada	4	S 20°45.536′; E 029°24.133′	Community	
Zilwane	4	S 20°45.881′ ;E 029°27.317′	Community	
Hlashtwayo	12	S 20°46.445′; E 029°28.406′	Community	
Jubele Dube	6	S 20°55.321′; E 029°27.924′	Farmer	
Chobukwa	6	S 20°52.9481′ ; E 29°27.357′	Community	Breached dam wall
Shagwe	6	S 20°54.968′ ; E 029°29.219′	Community	
Makoshe	6	S 20°56.676′ ; E 029°30.188′	Community	
Mabuze	4	S 20°55.989′ ;E 029°27.628′	Community	
Backley	4	S 20°55.929′ ; E 029°25.763′	Community	
Dolo	4	S 20°55.167′ ; E 029°26.492′	Community	
Lonto	6	S 20°55.290′ ; E 029°25.225′	Community	
Chengeta	12	S 20°51.037′ ;E 029°28.535′	Community	Completely silted
Ngwabi	12	S 20°49.428′ ; E 029°28.234′	Community	Breached spillway
Fulunye School Dam	12	S 20°48.740′ ; E 029°28.411′	Community	
Fulunye Main dam	12	S 20°47.873′ ; E 029°28.547′	Community	
Gwenyimo	9	S 20°40.292′ ;E 029°30.509′	Community	
Sanali	9	S 20°40. 805′; E 29°33.379′	Community	
Manyange	9	S 20°39. 854′ ; E 029°35.868′	Community	
Maninginingi	9	S 20°38. 471′ ;E 029°35.428′	Community	Breached Dam wall
Chehondo	9	S 20°40.614′ ; E 029°36.693′	Community	
Bikibiki	8	S 20°42.478′; E 029°032.281′	Community	
Edward	8	S 20°44.016′ ; E 029°31.644	Farmer	
Gondongwe	8	S 20°44.970′ ; E 029°32.441	Community	
Gumbalo	8	S 20°43.091′; E 29°36.499′	Community	
Konde Dam	9	S 20°42.212′ ; E 029°36.069	Farmer	
Singwambizi	7	S 20°55.911′; E 029°033.056	Community	
Maputi	7	S 20°52.853′ ;E 029°032.804′	Community	
Vocola	7	S 20°51.746′ ; E 029°33.170	Community	

Appendix 7. Pictures from the Study Area

Picture 1and 2. Leakage at Shagwe dam training wall

Picture 3. Thickets on Zilwane dam wall

Picture 4. Huge termite mound at Sidzibe dam wall

Picture 5. Scarping at Hlashtwayo dam

Picture 6. Scarping at Embondweni dam

Picture 7. Siltation at Chobhukwa dam. The spillway is encircled.

Picture 8. Leakage through masonry section of Gumbalo Dam

Picture 9. A sinkhole through Makoshe dam spillway sill

Picture 10. Breached Ngwabi dam spillway sill (Area circled)

Picture 11. Breached Chobukwa dam wall

Picture 12. People fetching water from a dry river bed in Ward 5