

**FARM DAM SILTATION, SEDIMENT MANAGEMENT AND
SEDIMENT SOURCE TRACING IN THE ZEERUST-
SWARTRUGGENS AREA, NORTH WEST PROVINCE**

NDE SAMUEL CHE

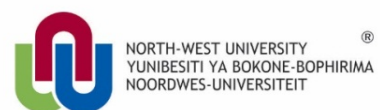
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degree of a Masters in Environmental Sciences at the Mafikeng
Campus of the North-West University**

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It all starts here [™]



DECLARATION

This study presents original work by the author and has not been plagiarized. The author of this work has fully read and understood the NWU plagiarism policy. Where uses of other author work has been made, it was fully acknowledged.

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ABSTRACT

The North-West province in South Africa is a semi-arid landscape vulnerable to soil erosion and sediment related problems. There is high dependence on small farm dams for the provision of water for cattle and irrigation. However, loss of small farm storage capacity due to sediment accumulation is a growing threat to water provision which cannot be ignored. There is widespread experience from pioneering work of Foster and co-workers in the Karoo region of South Africa on the use of environmental magnetism and environmental radionuclides to reconstruct important events in the history of catchments and to understand the drivers and trends in soil erosion and sediment dynamics. Such work needs to be extended to other parts of the country where similar problems exist to better assess the techniques and help better understand and address the dual problems of soil erosion and sedimentation.

The first part of the study entailed an inventory and mapping of small farm dams in the farming areas of Zeerust and Swartruggens in the North West province. It included the survey of sediment-related problems and sediment management at farm level. In the second part two specific sub-catchments were selected to test the application of environmental magnetism and environmental radionuclides for sediment tracing.

Forty four small farm dams were mapped and investigated. The newest was less than 5 years old and the oldest over 100 years old. Most of the dams were built with mud and stone along main stream courses to capture runoff and provide water for livestock and irrigation. Thirty four percent of the dams are heavily silted. However, sixty four percent of them are still functional in terms of holding water for a full season. The loss of dam's storage impacted negatively on the farming operations and most of the farmers (81 %) were aware of this. However, most of them were not addressing the source of the problem of dam siltation as many chose to manage the sediment through cleaning the sediment from the dams every 4 to 6 years. Thus dam siltation in the study area is a big challenge with huge potential financial and livelihood implications for the farmers.

On the use of environmental magnetism for sediment source tracing, the statistical analysis showed that only magnetic susceptibility (MS) was able to distinguish between topsoil and

subsoil and between burnt topsoil and unburnt topsoil in one of the two sub-catchments investigated. None of the remanant magnetic parameters managed to distinguish the potential sediment sources. The analysis of the environmental radionuclide concentrations in sediment and potential sediment source materials confirmed the potential of unsupported ^{210}Pb as an alternative to ^{137}Cs in soil erosion and sedimentation studies in the catchments. The successful magnetic and radionuclide parameters were used in a multivariate sediment mixing model to estimate the proportion of sediment coming from the identified sources in Dam 1. The result showed that 100% of the sampled sediment was mobilized from top soil. Although unexpected, this result may be a reflection of the complexity of sediment mobilization processes influenced by various factors including the nature and spatial distribution of the rainfall. The result may also reflect the sediment sampling which considered only recently deposited sediment, which may have come from a specific source.

Keywords: dam siltation, sediment source tracing, environmental magnetism, environmental radionuclides.

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CHAPTER ONE: INTRODUCTION AND PROBLEM STATEMENT

1.1 Background

Soil erosion and sediment related problems represent major challenges around the world and particularly pose serious threats both to land and water resources (Mullan, 2013). In sub-Saharan Africa, land degradation induced by soil erosion is considered to be one of the causes of stagnating agricultural productivity growth (Schmitter *et al.*, 2010; Bindraban *et al.*, 2012). Soil erosion also causes off-site problems such as mobilization and transportation of sediment and associated contaminants into reservoirs (Fukuyama *et al.*, 2010; Dercon *et al.*, 2012; Mukundan *et al.*, 2012). The transfer of sediments into dams (reservoirs) can also lead to the loss of storage capacity thereby reducing their effective life span (Moussa, 2013).

In South Africa, soil erosion is a major problem as 70% of the country's surface is affected by varying intensities and types of erosion (le Roux, 2007). Evidence from different studies in South Africa shows widespread soil erosion and high soil erosion rate ($>150 \text{ t ha}^{-1}\text{y}^{-1}$) (Le Roux *et al.*, 2007; Hughes and Mantel, 2010) leading to increased sediment accumulation in rivers systems and farm dams (Foster *et al.*, 2008; Baade *et al.*, 2012).

Many farming areas in South Africa are heavily dependent on storage reservoirs to maintain reliable water supplies at times of water stress (Foster *et al.*, 2008). However, according to Boardman *et al.* (2009) many of South Africa's small farm dams have become mere sediment traps. Inventories on the siltation of dams induced by soil erosion provide a stark reading indicating a dramatic increase in the extent of dam siltation leading to speculation about future water security. For example, Boardman and Foster (2011) in a study in the Sneeuberg region revealed that out of the 95 dams that were inspected 45 (47%), were full of sediment with little or no storage capacity. Many water storage reservoirs are accumulating sediments at a rapid pace. This makes it difficult to meet the demand for water thereby threatening farm livelihoods. Thus, the loss of reservoir storage capacity due to sediment is considered a major water provision threat (Boardman and Foster, 2011).

In the last few decades, considerable attention has been focused towards understanding the problem of reservoir sedimentation and to develop strategies to combat it. Sediment source fingerprinting (or tracing) is one of such strategies. The strategy is increasingly being used to document the relative significance of catchment sediment sources in different regions of the world (Motha *et al.*, 2004; Foster *et al.*, 2007; Hughes *et al.*, 2009; Collins *et al.*, 2010a;

Collins *et al.*, 2011; Rowntree *et al.*, 2012; Slimane *et al.*, 2013). Sediment source fingerprinting aims to identify and estimate the amount of sediment originating from various catchment sources over a range of spatial and temporal scales on the basis of a comparison of selected sediment and source material properties or fingerprints. Sediment source fingerprinting helps land-use planners to better understand catchment sediment dynamics in terms of both spatial provenance and source types. Improved understanding of the origin of sediment is therefore considered to be a key requirement to design and target effective soil erosion control and sediment management strategies (Collins *et al.*, 1998).

1.2 Statement problem

There is a high dependence on small farm dams in the farming areas of the North-West province of South Africa for the provision of water for livestock and irrigation. Like in many parts of the country, this has been necessitated by an increase in the frequency of droughts and erratic rainfall. Although the North-West province is regarded as a low risk region for soil erosion and dam siltation as compared to other provinces in the country (Eastern Cape, Limpopo and Kwa Zulu-Natal) (Le Roux *et al.*, 2008), the farming area between the towns of Zeerust and Swartruggens is seriously affected by dam siltation. Most of these farm dams are constructed on small rivers draining relatively small catchments and thus tend to silt much more rapidly than major dams located in larger rivers. There is little information available on the dam siltation and sediment management challenges in the study area and most parts of the North-West province. Thus a study of this will be necessary.

Also, reliable information on the sediment sources in terms of top soil or subsoil and burnt or unburnt areas is essential to identify the soil erosion processes producing the sediment and the extent to which burning of the veld is causing soil erosion and sediment related problems. This information will help to design effective management strategies for soil conservation and sediment management. The growing understanding of small farm dam sedimentation dynamics and sediment sources obtained from the use environmental radionuclides and magnetism (Boardman and Foster, 2008, 2011; Boardman *et al.*, 2009; 2010; Foster *et al.*, 2012) needs to be extended to other parts of the country where similar problems exist to help not only evaluate the utility of the techniques but also to address the problem.

1.3 Aim of the study

The study seeks to investigate sedimentation and sediment source dynamics of small farm dams in the farming areas between Zeerust and Swartruggens in the North-West province, South Africa.

1.4 Specific objectives

In line with the above-mentioned aim, the study seeks to achieve the following objectives:

1. To analyse small farm dam siltation and sediment management practices in the study area from the farmer's perspective
2. To test the feasibility of using environmental radionuclides and magnetism to trace sediment in the chosen sub-catchments
3. To suggest strategies that can be implemented to control dam siltation.

1.5 Theoretical framework

The study is based on the conceptual framework of sediment source fingerprinting/tracing put forward by Walling and Collins (2000) (Figure.1.1).

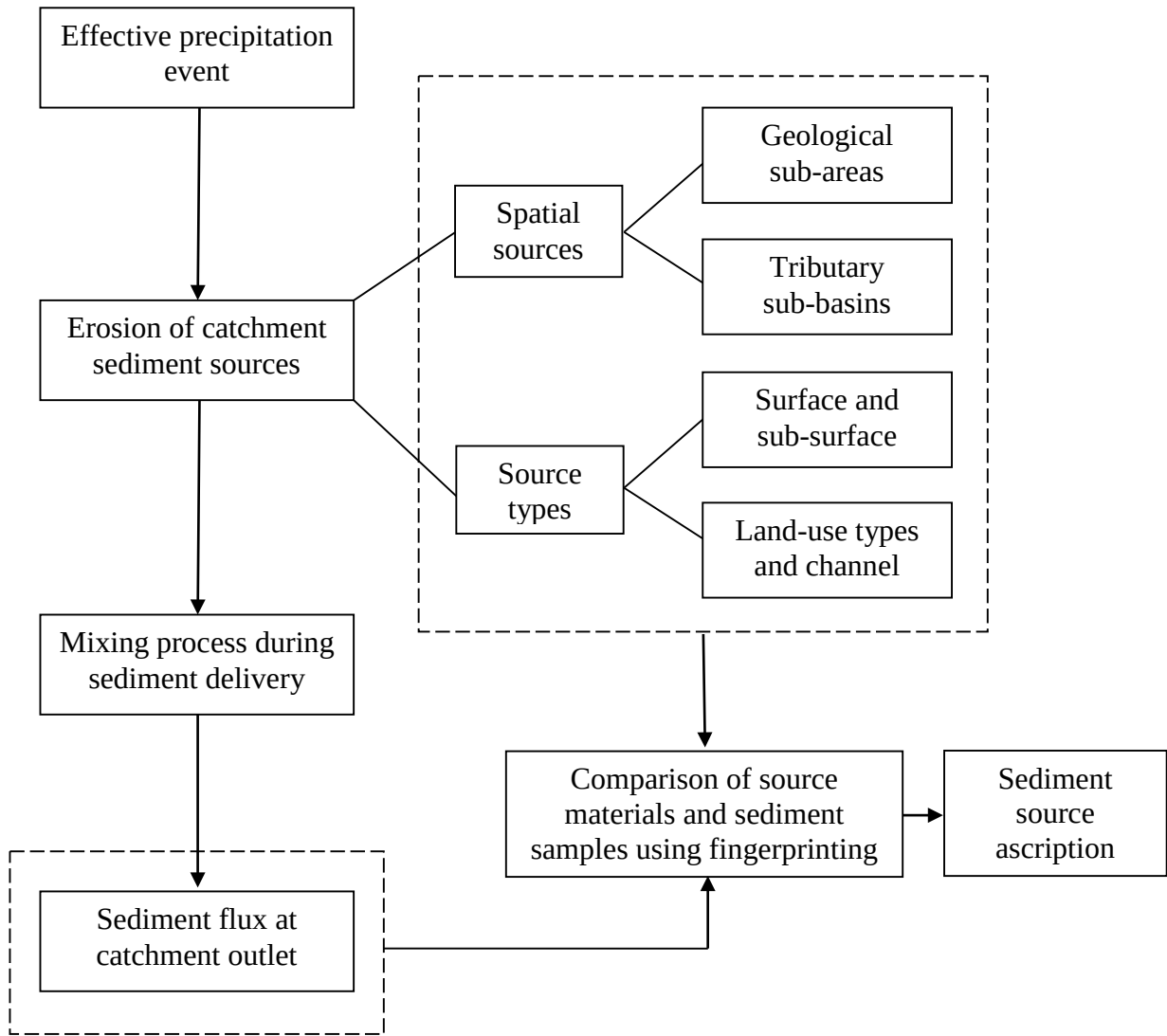


Figure 1.1: The conceptual framework of sediment source fingerprinting (adapted from Walling and Collins, 2000).

According to this framework, soil eroded and transported within a river system from diverse locations with distinct soil or land-use types or from a specific depth-range in the soil profile maintains (during erosion, transport and ultimately deposition) its unique and quantifiable fingerprints reflected in its chemical or physical properties (Walling, 2005; Hancock and Pietsch, 2008). The potential sources of sediment can be specific (for example, various land uses, surface or subsurface sources) or general (e.g. tributary sub-basins, or geological subarea). The former constitutes sediment source type while the later sediment provenance (Collins *et al.*, 1998). A comparison of the properties (e.g. environmental radionuclides,

magnetism, geochemistry, etc.) of sediment and those of its source areas can help distinguish the potential sediment sources and estimate the proportion coming from various sources.

1.6 Rationale of the study

The construction of farm dams is prevalent in many agricultural areas of the country. Small farm dams are cheaper to build as compared to large dams and offer farmers a means to retain stream flows for irrigation or watering livestock and game animals. However, few studies done in the country have focused their attention on small farm dams and sediment problems (Foster *et al.*, 2007; 2008; 2012). Dam siltation can be a very serious threat to the livelihoods of the farmers concerned, thus any attempts to understand and address this problem will go a long way to achieve sustainable livelihoods.

The current research is envisaged to enhance the understanding of farm dam siltation in the study area. Also, from the methodological perspective, the refining and testing of the existing sediment fingerprinting techniques will help the scientific community to assess the potential and challenges of the techniques. The practical significance is related to the fact that the study seeks to address the important national problem of reservoir sedimentation by understanding sediment sources. This study will enable land users to plan management based on improved understanding of the existing problems.

1.7 Definitions of key terms

- Small farm dam: in this study small farm dam refers to any structure or barrier either build by stones, earth or both to collect and store water or is not more than 4 m in height and not more than 3 m in depth.
- Dam siltation: is the excessive accumulation of sediment in dams resulting in a reduction of their ability to fulfil their water storage function.
- Environmental radionuclide: a radionuclide is an atom with an unstable nucleus, characterized by excess energy available to be imparted either to a newly created radiation particle within the nucleus or via internal conversion. In this study, it refers specifically to, caesium-137 and unsupported lead-210, which are anthropogenic and natural radionuclides respectively that reach the earth's surface through rain or dry fallout.

- Sediment source fingerprinting (tracing): a set of techniques aimed at identifying and estimating the proportion of sediments originating from different sources based on the comparison of the properties of the sediment with those of the individual potential sources.
- Environmental magnetism: magnetic properties of environmental samples (soils, sediments, rocks) acquired from the type, amount and size of grains of magnetism bearing minerals.

1.8 Outline and structure of the research

Chapter one provides an overall introduction, states the research problem, outlines the aim and objectives of the study. The theoretical framework guiding the study and definition of key terms are also provided. Chapter two reviews literature related to the topic. Chapter three will give a detailed description of the study area and the field observation, laboratory methods, and statistical techniques used. Chapter four and Chapter five present and discuss the research results. Chapter six outlines the research conclusions and recommendations.

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

This chapter reviews published research related to the research topic. The first section looks at issues around small farm dam siltation and sediment management practices. The second section presents a review of sediment source fingerprinting techniques and the basis of using environmental magnetism and environmental radionuclides in sediment studies.

2.2 Small farm dams: the concept

Small dams have been constructed in many countries for numerous reasons that range from hydroelectricity, flood control and water supply. By the year 2000, the number of small dams worldwide was estimated to be in millions (Verstraeten and Poesen, 2000; Sahagian, 2000). Long considered as a soil and water conservation and drought proofing measure, these structures have been increasingly used for small-scale irrigation and livestock watering in Sub-Saharan Africa (Venot and Krishnan, 2011). In many parts of the world, the construction of small farm dams represents an important farm-scale intervention to increase water availability for agriculture especially where water availability is highly variable due to climate variability.

Defining a small farm dam is contentious. There are as many definitions as are criteria (size, type of infrastructure, mode of management) and threshold values (volume, height, number of farmers, irrigation area) to define a small farm dam. Thus, the concept can vary widely depending on the point of consideration of the stakeholders involved (Venot and Krishnan, 2011). However, it is generally agreed that small farm dams are structures with a retaining barrier across a stream not more than 4 m in height and the reservoir not more than 3 m in depth. It should be noted that the term “small farm dam” is used synonymously with “small reservoir”. Some of the terms used in this study such as reservoir, small farm dam and pond have been used by different authors in different environmental settings to investigate dam sedimentation and sediment source (Verstraeten and Poesen, 2000). However, the focus of this study is on small farm dams constructed mainly for agricultural purposes such as irrigation and watering of livestock.

2.3 Loss of small farm dam capacity and economic implications

On a global scale, small farm dams have proven to be important in sustaining developmental activities as they serve various uses such as, livestock and wildlife farming, fisheries, irrigation, recreation, and domestic uses (Senzanje *et al.*, 2008), by enhancing local population's income and contributing to food security in the local communities (Chihombori *et al.*, 2013; de Fraiture *et al.*, 2013). Similarly, Boardman *et al.* (2009) emphasize the role small farm dams play in economic development and sustenance of rural areas. The multipurpose nature of small farm dams has largely gone unrecognised in terms of their importance for various uses (Lloyd *et al.*, 1998). However, the loss of dam storage capacity due to sediment accumulation in many existing reservoirs threatens the sustainability of water supply and economic activity. As cited by Gyasi and Schiffer *et al.* (2005) in a community-needs study in Ghana, reveals that the majority of the small scale farmers in the communities complain of siltation of their dams. Chitata *et al.* (2014) report on the high rate of siltation as a result of anthropogenic activities where farms that are mostly suitable for crop production where converted to animal rearing. Hughes and Mantel (2010) observed that the construction of small farm dams represents an important farm-scale intervention that can increase the reliability of water supplies for agricultural production.

In the semi-arid landscapes across Africa, thousands of small farm dams have been constructed to maintain a continuous supply of water as aforementioned. However, the high rate of dam siltation caused by poor land management and accelerated soil loss impedes the efficient use of farm dams (Boardman and Foster, 2011; Benmansour *et al.*, 2013). Verstraeten and Poesen (2000) reported that high sedimentation rates result in loss of dam water retention capacity after only 3-4 years. Slimane *et al.* (2013) examined the rapid siltation of reservoirs in North Africa and noted that they filled up with sediment in less than 10 years after construction. Siltation of small farm dams is regarded as one of the greatest risks to the success of small farm dams in Zimbabwe (Chihombori *et al.*, 2013).

Reservoir sedimentation is a world-wide problem with annual loss in storage capacity estimated at 1% of original water storage capacity. The World Bank estimated that dam siltation costs USD 13 billion per year as at 2003 (de Villiers and Basson, 2007 cited from Palmier, 2003) which involves restoration and dam maintenance to keep a reasonable storage capacity. A similar estimate of the damage due to sedimentation in reservoirs in South Africa was estimated at R53 million per year in 1988 (Verstraeten and Poesen, 2000). Some of the

costs of dam siltation are related to the cost of soil erosion prevention and dam cleaning. These economic costs associated with small farm dam siltation at the farm scale directly impinge on rural livelihoods and development.

South Africa is among those nations which are heavily dependent on reservoirs to maintain a continuous supply of water during drought due to its semi-arid climate (Foster *et al.*, 2009). Besides farming related use, small farm dams are also used to reduce the transfer of sediment downstream by retaining the sediment. Boardman and Foster (2011) report on the potential threat of dam breaching and both the release of stored sediment into downstream channels by reconnecting up stream sediment production areas to downstream water course.

Soil erosion and sediment delivery processes vary across landscape due to differences in the attributes of sites and kind of processes operating at different locations. The in-flowing of soil that takes up the active storage capacity is a common problem encountered by farmers in the study area. In addition to siltation in small farm dams, other challenges such as limited and high variability of rainfall limit the flow in the catchments. These by itself pose a challenge to sustainability and management of small farm dams thereby affecting the economic livelihoods of farmers. Okoba and De Graaff (2005), in a study on farmer's perception on soil erosion and sediment delivery in Kenya discovered that the farmers were ignorant of the seriousness of the on-going soil erosion and reluctant to implement changes. Chitata *et al.* (2014) report on the lack of systematic survey by the community to reduce reservoir siltation. This then gave the researcher the impetus to analyse small farm dam's siltation and sediment management practices from the farmers perspectives. What measures were taken by farmers to achieve a reduction in soil loss and sediment delivery into dams and what were the roles that the farmers play to curb this on-going problems. It is however noted that, farmer's perception on reservoir siltation varies from one region to another depending on the prevailing climatic conditions.

2.4 Managing farm dam siltation

The continued loss of small farm dams is a clear indication that there is no adequate sediment management or the existing strategies are not effective. Different approaches have been used to reduce sediment inflow into reservoirs through land use change notably re-afforestation, contour ploughing, and other erosion control strategies. However, their benefit in reducing dam sedimentation has not been clearly demonstrated (Annandale, 2011).

To improve small farm sediment management there is a need to identify sediment source areas to inform the design of management plans. Figure 2.1 presents a sediment management approach geared toward preserving reservoir capacity by minimizing the amount of sediment arriving into the reservoir from upstream. This approach is based on reducing small farm sedimentation by reducing sediment loss from upstream so that only a smaller portion of the incoming sediment can enter the dams. By appraising sediment sources in the area of the catchments experiencing soil erosion and confirming the linkages between sediment sources in the stream network, it is possible to implement preventive measures by reducing channel erosion and to prevent siltation of downstream reservoirs. As pointed out by Foster *et al.* (2009), small farm dams have been neglected in the literature and their wider role in the landscape has been ignored. This study therefore adopting an exploratory research approach to document small farm dam siltation by exploring farmer's perception on small farm dam's siltation and the management strategies used will help to better understand the current problem at hand.

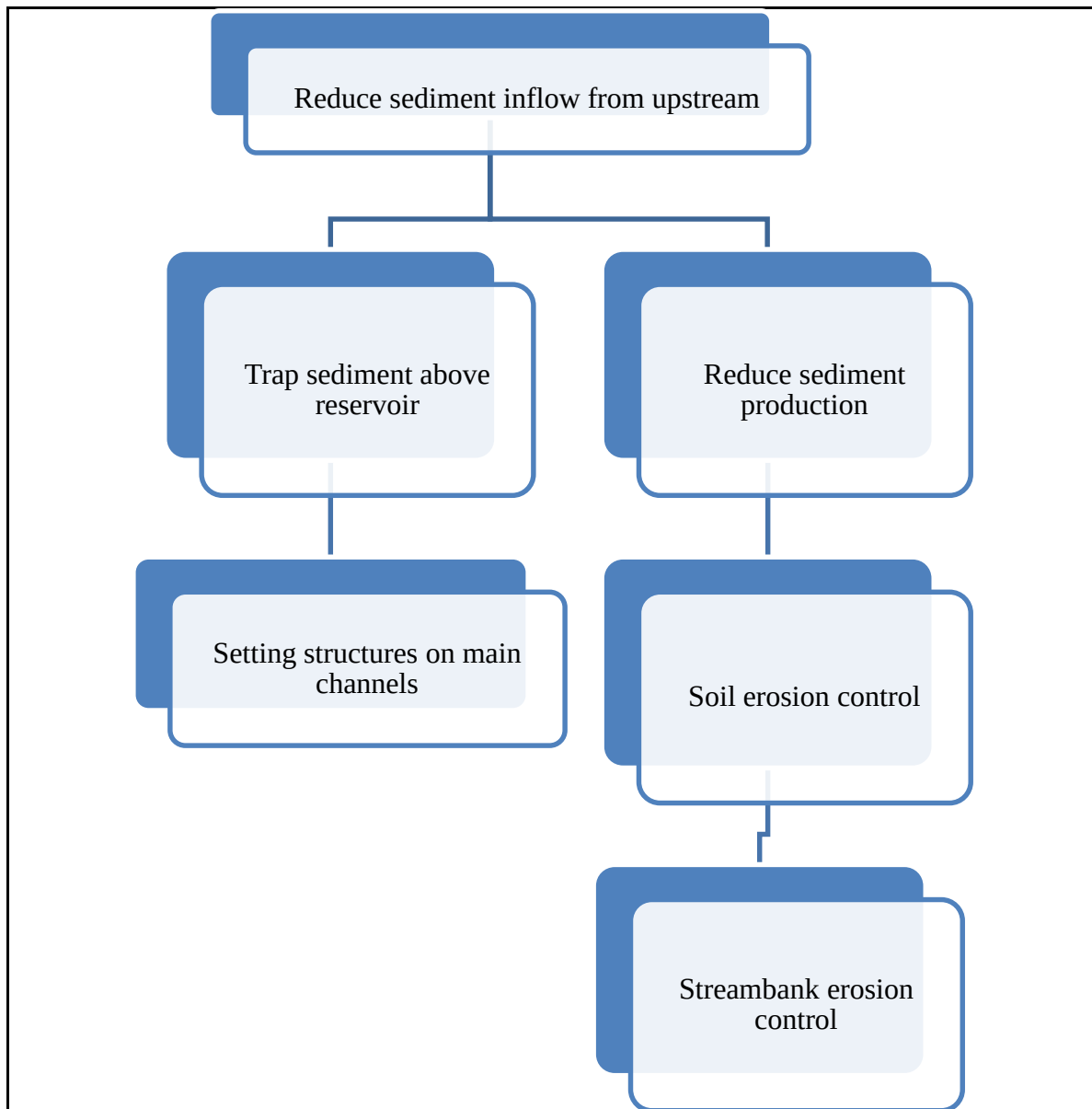


Figure 2.1: Framework for sediment management (adapted from Kantouch and Sumi, 2010).

2.5 Identifying the sources of sediment in fluvial systems

Sediment related problems have long been recognised as an environmental threat and various studies have tried to address the problem of identifying and estimating the amount of sediment coming from diverse sources in a range of settings (Collins et al., 1997a, 1998; Collins and Walling, 2002). Improved understanding of catchment suspended sediment sources represents an essential prerequisite for assisting the design and implementation of targeted management strategies for controlling off-site sediment problems (Collins and Walling, 2004). Resources could be wasted if, for example, control strategies focus on

reducing sediment from one land use when most of the sediment transported through a river system is contributed by another. An attempt to identify primary sediment sources within a catchment is of importance if appropriate mitigation strategies are to be achieved. By implementing these techniques, small farm dam owners would be able to identify areas of higher contribution of sediment into the dam thereby minimise the amount of money and time spent.

Earlier studies on sediment source identification were based on direct monitoring of potential source areas using erosion pins, runoff plots and other related techniques (Slattery, 1995; Porto and Walling, 2012). According to Collins and Walling (2004) the interpretation of sediment sources was usually based on visual interpretation such as tree root exposure, soil surface crusting, rill or gully size, plant cover and interpretation of aerial photographs using Geographical Information System (GIS) or satellite imagery. Some of these techniques were costly to install and maintain over time coupled with limitations in terms of representativeness of the data obtained, including their spatial and temporal resolution (Collins and Walling, 2004). Additionally, the techniques depended on indirect ways of inferring sediment sources.

An alternative cost-effective approach to the indirect approach of sediment source identification is sediment source fingerprinting or tracing. Sediment source fingerprinting is founded upon the direct link between geochemical, mineralogy, mineral magnetism, radionuclide, biogenic and physical properties of soil and sediment (Martinez-Carreras *et al.*, 2010). It provides a direct method for identifying the sources of sediment and estimating their relative contribution through characterising each potential source soil and comparing with the sediment (Gellis and Walling, 2011). A range of geochemical, mineralogy, mineral magnetism, radionuclides, biogenic and physical properties have been used, either individually (Evrard *et al.*, 2011; Wang *et al.*, 2011; Olsen *et al.*, 2013; Singh *et al.*, 2013), or in combination (composite) (Collins *et al.*, 2010, 2011).

The use of composite fingerprints incorporating several physical and chemical properties selected from a range of different property subsets has proven to be more reliable and provide a most robust, reliable and comprehensive approach to sediment source tracing over the use of a single sediment property (Collins *et al.*, 2010; Mukundan *et al.*, 2012). Most fingerprinting studies have either employed a qualitative or quantitative approach in distinguishing source types within a small catchment (< 50 Km²) or both (Walling and

Woodward, 1992). The quantitative approach is based on robust statistical selection of potential fingerprints and subsequent modelling and sediment source ascription using multivariate models (Rhoton *et al.*, 2011; Collins *et al.*, 2012; D'Haen *et al.*, 2012).

2.6 Environmental radionuclides in sediment source fingerprinting

Environmental radionuclides are some of the most widely used sediment fingerprints (Jenkins *et al.*, 2002; Walling *et al.*, 2011). These include caesium-137 (^{137}Cs), excess-lead-210 ($^{210}\text{Pb}_{\text{ex}}$) and beryllium-7 (^7Be), used individually or in combination (Olley *et al.*, 1993; Collins and Walling, 2002; Walling *et al.*, 2011). Environmental radionuclides are generally assumed to be spatially uniform, at least over a relatively small area, and their behaviour is effectively independent of lithology and soil type (Guzmán *et al.*, 2013).

Caesium-137 with a half-life of 30.2 years is an anthropogenic tracer introduced into the atmosphere as a consequence of above-ground testing of thermonuclear weapons during the period extending from the mid-1950s to the early 1970s. More recently nuclear accidents like Chernobyl, Russia (1986) and Fukushima, Japan (2011) have introduced some ^{137}Cs into the atmosphere. The spatial distribution of ^{137}Cs fallout is determined by the location of the weapon testing and the pattern of distribution shows clear latitudinal zoning with total fallout in the Northern Hemisphere being substantially greater than in the Southern Hemisphere (Mabit *et al.*, 2008). In the Southern Hemisphere the concentrations of ^{137}Cs in the soil is an order of magnitude lower than the Northern Hemisphere (Leslie and Hancock, 2008), because there was a relatively small amount of atmospheric nuclear testing. Thus there are fewer Southern Hemisphere investigations and studies have been confined primarily to Brazil (Sanders *et al.*, 2006) and Australia (Pfitzner *et al.*, 2004; Olley *et al.*, 2013) with very few similar studies in southern Africa (Foster *et al.*, 2009; Boardman *et al.*, 2010; Humphries *et al.*, 2010; Manjoro *et al.*, 2012; Foster and Rowntree, 2012; Rowntree and Foster, 2012).

Caesium-137 reached the ground surface mainly through rainfall whereby it is strongly fixed by the surface soil leading to its concentration generally being much higher in surface soil than in the subsoil. At undisturbed sites, ^{137}Cs concentration in the top layer is relatively higher and decreases with depth. In general, the maximum concentration of ^{137}Cs concentration is slightly displaced few centimetres below the soil surface (Wallbrinks *et al.*, 1999). An analysis of the ^{137}Cs activity in sediment deposits may offer information on the possible sediment source. For example, the presence of detectable ^{137}Cs at depth in a sediment deposit can be interpreted that the sediment was mobilized from a topsoil source

and therefore represents the action of sheet or shallow rill erosion (Wallbrink and Murray, 1993; Walling, 2004). On the other hand, a sediment deposit composed of zero or low ^{137}Cs activity may indicate a subsoil source, mostly mobilized by gully and riverbank erosion. Caesium-137 has also enabled the identification of changing sediment source with different dominant erosion processes (Wallbrink, 2004).

The use of ^{137}Cs as a tracer is restricted to surfaces that existed during the time of fallout (1950s -1970s). It is also dependent on whether there are detectable quantities of the radionuclide in the landscape due to redistribution and radioactive decay leading to a constant reduction in the ^{137}Cs inventory. This often results in some landscapes having very little or undetectable ^{137}Cs concentration especially in landscapes under active erosion. The cessation of the nuclear testing and in-situ decay of ^{137}Cs has necessitated the introduction of alternative isotopes such as unsupported or excess Lead-210 (^{210}Pb). This radionuclide has a half-life of 22.2 years. It is naturally occurring product of the Uranium-238 (^{238}U) decay series. It is constantly replenished due to continuous release of Radon-222 (^{222}Rn) from the soil. Excess Lead-210 settles on the surface of the Earth through dry and wet deposition and has proven to have a strong affinity with soil and sediment particles (He and Walling, 1997).

The use of ^{210}Pb for erosion and sedimentation studies has indicated that the concentration of ^{210}Pb at the top soil layers decreases with respect to depth usually from 10 to 20 cm. For instance, Likuku *et al.* (2006) observed a higher concentration of ^{210}Pb and ^{137}Cs at the top-most 5cm of the soil and demonstrated that its concentration decreased with depth. Also, Moore and Poet (1976) equally asserted that the profile of ^{210}Pb varies from disturbed surface to undisturbed surfaces. Similarly, Walling *et al.* (2003), showed that a clear distinction in ^{210}Pb profile between samples collected from a disturbed and undisturbed soil was as a result of erosion and farming. For inferring sediment source, ^{210}Pb has been used extensively in combination with ^{137}Cs . Simms *et al.* (2008), analysed sediment cores retrieved from reservoirs to determine the source of sediment that has been mobilised from hill slopes, thereby inferring the nature of the erosion processes operating there. Also, Li *et al.* (2003) used ^{137}Cs and ^{210}Pb ratio to determine the main erosion source in the hills of Western China. The authors were able to determine that gully erosion and not surface erosion was the dominant contributor of sediment into the Yellow River.

Beryllium-7 (^7Be) is a natural cosmogenic radionuclide produced in the upper atmosphere by cosmic ray spallation of nitrogen and oxygen (Ayup *et al.*, 2012). Relative to ^{137}Cs and ^{210}Pb ,

^7Be has a half-life of 53 days. It has been successfully used as a sediment tracer with potential for investigating soil erosion processes occurring over a shorter time scale, particularly individual storm events (Matisoff *et al.*, 2002; Walling *et al.*, 2003; Ayub *et al.*, 2012). Typically concentrated in the upper 5 mm of the soil profile, ^7Be can also be used as a good discrimination parameter between surface soil and sediment derived from deeper layers (Zapata, 2003).

These two radionuclides (^7Be and ^{210}Pb) differ from ^{137}Cs in that they are both of natural origin. An analysis of the combinations of these different radionuclide activity concentrations in sediment may be used to define various erosion processes as illustrated in Hancock and Pietsch (2008). It should however, be noted that this study will only assess the use of ^{137}Cs and ^{210}Pb for sediment source tracing. Due to the short half-life of ^7Be and the need to readily collect samples after a storm it is practically not logistically feasible to use as a tracer for this study.

2.7 Environmental magnetism as a sediment source fingerprint

In recent years, magnetic methods have increasingly been applied to fingerprint sediment source (Hatfield and Maher, 2008; Singh *et al.*, 2013; Smith *et al.*, 2013). The fundamental principle of environmental magnetism is that most substances exhibit some form of magnetic behaviour which can be classified as weak, strong and neutral. All substances can be distinguished by their magnetic behaviour and the most important magnetic behaviour is that of iron minerals which are capable of retaining magnetization in the absence of applied magnetic field (remanent magnetisation or remanence). The following remanance properties have been used for sediment tracing: anhysteretic remanent magnetization (ARM), and a stepwise acquisition of isothermal remanent magnetization (IRM) and saturated isothermal remanent magnetization (SIRM) (Hatfield and Maher, 2008). Magnetic minerals in the soil are derived from parent rock (lithogenic origin), soil (pedogenic) or as a result of anthropogenic activities (Alagarsamy, 2009). The principal source of magnetic minerals in fluvial sediment is the eroded soil particles (Ellwood *et al.*, 2006; Oldfield, 2007; Liu *et al.*, 2010).

The most common and easily measured magnetic property is magnetic susceptibility. According to Dearing (1999), susceptibility reflects the magnetizability of samples. It can be measured at low frequency (χ_{lf}) to high frequency (χ_{hf}) susceptibility measurements. The Frequency-dependent susceptibility ($\chi_{fd}\%$) is determined by expressing the difference

between the high and the low frequency measurements as a percentage of χ at low frequency (Dearing, 1999): In addition to susceptibility a number of studies have demonstrated that there is a direct relationship between soil erosion and the concentration of magnetic minerals in deposited sediments (Oldfield, 1991; Eriksson and Sandgren 1999; Foster *et al.*, 2007; Wang *et al.*, 2008; 2011). The relationship is explained by the fact that magnetic minerals such as magnetite are transported and deposited with sediment during high-energy events. Thus peaks in magnetic concentration in the sediment deposit may be linked to high accumulation rates (Wang *et al.*, 2008). Environmental magnetism has been successfully used to elucidate the linkages between sediment sources and sinks (Liu *et al.*, 2010), characterising and distinguishing different source types (e.g. top soil versus subsoil), erosion type (sheet/ rill versus gully) (Wang *et al.*, 2008) and to identify sediment sources in a range of different climate and topography settings (Walling *et al.*, 1979; Oldfield *et al.*, 1985). The ability of the magnetic technique to distinguish between topsoil and subsoil makes it valuable for this current study. Environmental magnetism has previously been exploited to characterise catchment sub-areas on a variety of spatial scales (Caitcheon, 1993). Studies of the magnetic properties of sediment have equally been applied in depositional settings such as lakes and reservoirs (Foster *et al.*, 2007; Foster *et al.*, 2011; Wang *et al.*, 2011) to reconstruct decades of environmental history and change.

Thompson and Morton (1979) investigated the link between sediment in Loch Lomond and its potential sources and found that the magnetic properties were related to rock type. Carcaillet *et al.* (2006) found that magnetic susceptibility or any other proxies cannot be used to reconstruct fire history in lacustrine sediment because the processes leading to the accumulation of sediment in reservoirs and fire history are independent processes. Sheng-Gao and Shi-Qing (2008); Gennadiev *et al.* (2010); Smith *et al.* (2013) investigated magnetic properties of urban and agricultural soils and found that there was a substantial differences in ferrimagnetic behaviour. For example, in different land uses in urban areas ferrimagnetic mineral decreased in the order from industrial areas, road side, residential to commercial and green areas. Different research studies have also noted that magnetic susceptibility of top soil is usually higher than that of subsoil (de Jong, 1998). Smith *et al.* (2013) were able to distinguish between burnt and unburnt soil samples by using environmental magnetism. He observed that unburnt soil samples show a lower χ_f and $\chi_{fd\%}$, values than moderately burnt samples.

2.8 Summary

This chapter has reviewed literature related to small farm dams and sediment source fingerprinting. The study confirmed that little attention has been focused on small farm dams in sediment studies in South Africa and more particularly in the North-West province in South Africa. The following chapter will describe the study sites, field, laboratory measurements and statistical analysis used in the study.

CHAPTER THREE: MATERIALS AND METHODS

3.1 Introduction

The chapter is divided into two sections. The first section describes the study context in which the project was undertaken. The second explains the research techniques used in this study, which include a questionnaire survey, field observation, soil and sediment sampling, laboratory and statistical analysis.

3.2 Study area

The study was undertaken at two spatial scales: a broader spatial scale and a specific catchment. Firstly, the area between the towns of Zeerust and Swartruggens in the North-West province (Figure 3.1) was selected to understand the issues related to the problem of farm dam siltation, the impacts it has on the affected farmers and what strategies were employed to solve the problem. Secondly, it was necessary to investigate the application of environmental radionuclides and magnetism in sediment source fingerprinting in the study area with the objective to understanding sediment source dynamics in terms of the contribution of surface sediment sources (sheet erosion) and subsurface sources (gullies and stream bank erosion).

The broader study area is an undulating plain with hills and small mountain ranges on the north-east of Zeerust. The altitude ranges between 1252 m and 1272 m above sea level and the area is characterised by unpredictable and highly variable rainfall. The region as a whole receives about 439 mm of rainfall per year in summer (Malan and Niekerk, 2005). The soil type is mostly red-yellow-grey latosols (Cowley, 1985; Low and Rebelo, 1996) which are characteristically coarse, sandy and shallow, overlying granite, quartzite, sandstone or shale. Different vegetation types occur in the study area, namely Bakenveld and open savannah (Malan and Niekerk, 2005). The vegetation of the study area consists of bushveld, which occurs mostly in the northern part of Zeerust. Most of the vegetation in the area has been replaced by secondary vegetation and the densities of valuable, productive and soil protecting species has declined (Malan and Niekerk, 2005).

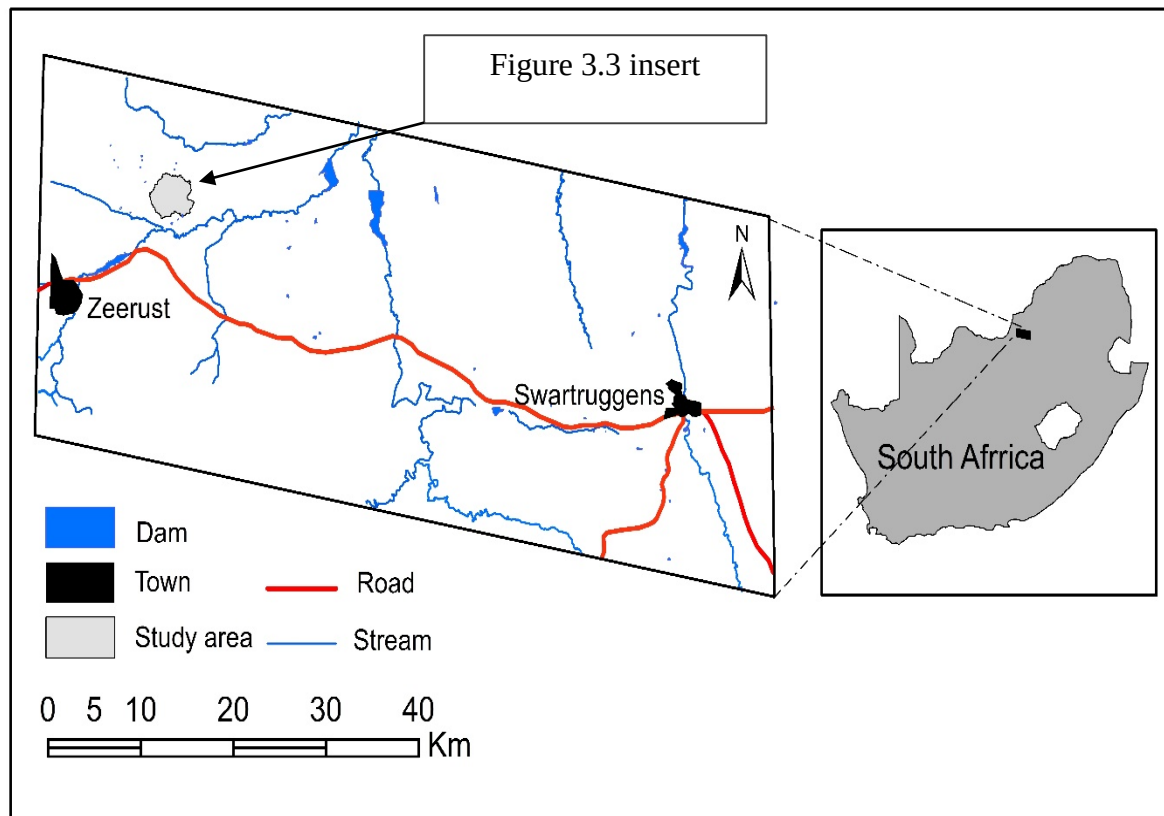


Figure 3.1: Study area. Note that most of the mapped small farm dams were too small to appear in the map at the above scale.

The choice of study area between Zeerust and Swartruggens was motivated by the fact that the study needed a representative area where soil erosion and sediment problems exist. The area had diverse land uses variably affected by land degradation and in particular soil erosion and dam sedimentation.

3.3 Land use

Cattle rearing, cultivation of crops, game farming and ecotourism are the predominant land-use practices along Zeerust-Swartruggens in the North-West Province. The farming activities are mostly dominated by white commercial farmers. In some case, mixed farming system practice is carried out whereby farmers would rear cattle alongside the cultivation of perishable vegetables. A catchment at of 725 ha at the north-east of Zeerust was chosen to fingerprint the dominant source of erosion. The catchment only land-use is cattle rearing and animal game farming. Three artificial dams were created for cattle watering along river channels. The storage capacities of each of the dams were unknown and evidence of wild fire was also seen in the upper slope in the catchment.

3.4 Field observation

Field visits in the study area afforded a valuable opportunity for observing and appraising sediment related problems and to understand the severity of the phenomenon encountered by farmers and the strategies used in order to overcome the problem. Evidence of gully erosion was observed as shown in Figure 3.2. Other forms of erosion such as rills in the form of incised tracks were equally noted in the catchment.



Figure 3.2 Gully erosion

The field visits were conducted using a prepared check-list to identify the silted dams (see Appendix 1), their uses and what strategies were used to solve the problem of siltation. Where possible additional information was obtained from oral testimonies from the farmers. The field visits also offered an opportunity for the identification of a suitable catchment in which more detailed studies would be carried out using sediment source fingerprinting technique. The preliminary stage of sediment source investigation was undertaken during visual observation by identifying potential source areas. The visual appraisal of field evidence for sediment mobilisation, delivery, and potential source of sediment in the catchment enabled the grouping of sediment sources into categories in order to organise and rationalise data collection and interpretation. Collins and Walling, (2004) assert that field observation provides a useful complement to the methods available for documenting catchment suspended sediment sources.

3.5 Documenting small farm dams siltation and sediment management

At this scale the main goal was to understand soil erosion and dam sediment dynamics. This study therefore adopted an exploratory research design. Inventories on the numbers of small farm dams and siltation were gathered through questionnaire administration.

The population of the study was made up of farmers who have small farm dams and face the problem of dam siltation along the farming areas of Zeerust and Swartruggens. The selection of respondents was based on identifying farmers with small farm dams. The objective was to document all the dams that have been silted and those currently experiencing siltation problems. A total of 40 farmers owning small farm dams were chosen using a snowball sampling or chain sampling. Cohen and Arieli (2011) assert that this method is commonly used to locate access and involve people from a specific population where one subject gives the researcher information on the subject and who in turn provides information on the third, and so on.

Questionnaires were one of the main instruments used as data collection tools in this study in order to gather data on sediment management practices. The questionnaire was semi-structured and was administered through the interview technique to farmers who were knowledgeable with the area and its sediment related problems. According to De Vos *et al.* (2002:172), the basic objective of a questionnaire is to obtain facts and opinions about the phenomenon from people who are informed on the particular issue. Marshall and Rossman (2006:125) maintain that, in using questionnaires, researchers rely totally on the honesty and accuracy of participants' responses. The questionnaire used is given in Appendix 2.

3.6 Sediment source tracing

One specific catchment was selected near Zeerust (see Figure 3.2) to implement the sediment source fingerprinting thrust of the study. The catchment was chosen due to a range of factors deemed responsible for different erosive features that were observed during the field visit. The catchment was approximately 725 (ha) in area. The sampling area for sub-catchment 1 (Dam 1) is 219 ha and such-catchment 2 (Dam 2) is 28 ha. A map has been created to distinguish the different source types (topsoil and subsoil) as shown in Figure 3.4

Soil erosion has been identified as causing severe damage by increasing connectivity between land surface and stream channels thereby increasing the transfer of sediment into dams. Road cuts, incised gullies and areas of existing sheet erosion were suspected to be the main sources

of sediment causing the siltation as there was a need to identify those sources of sediment within the catchment. This offered an opportunity to investigate the potentials of using ^{137}Cs , ^{210}Pb and environmental magnetism for sediment source fingerprinting. Two upstream sub-catchments contributing sediment into two small dams were selected for the study.

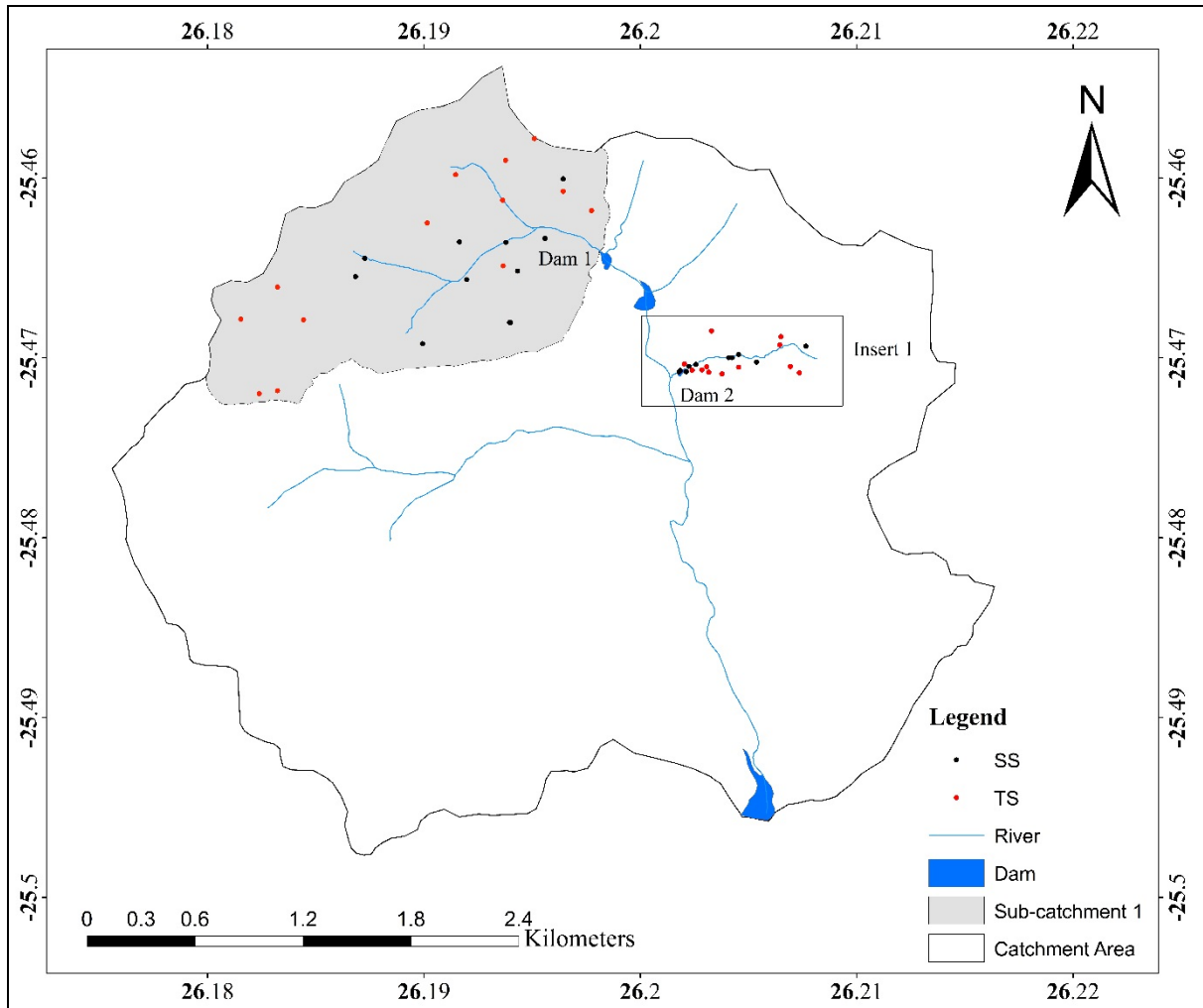


Figure 3.4: Sampling points

3.6.1 Sediment and source material sampling procedures

Consistent with similar sediment tracing studies (Foster *et al.*, 2008; Walling *et al.*, 2008; Kouhpeima *et al.*, 2010), the current study sampled material from potential sediment sources and sediment sinks. Soil samples were collected from two potential sediment sources Figure 3.4: surface and subsurface to enable the identification of the dominant soil erosion mechanism generating sediment in the catchment.

All surface soil samples were collected from eroding areas at a depth of 0-2 cm depth (Walling and Woodward, 1992; Srisuksawad *et al.*, 2015), subsurface sources were collected

from active gully walls and river banks at a depth below 30 cm. All the soil samples were put in labelled plastic bags and taken to the laboratory for analysis. Global Positioning System (GPS) coordinates of all sampling sites were recorded.

In the sub catchment of Dam 1 there were some areas showing signs of recent fires as demonstrated by visible burnt scars and condition of the grass. To enable an assessment of the possible influence of fire on the magnetic signature of the collected surface samples, all samples located in areas with visible burnt scars were subsequently labelled before taking to the lab.

Sediment grab samples were collected from the two uppermost dams and from in-stream sediment deposits at the beginning of the rain season. The sediment samples were collected from the dam where the main stream entered the dam, representing recently deposited sediment.

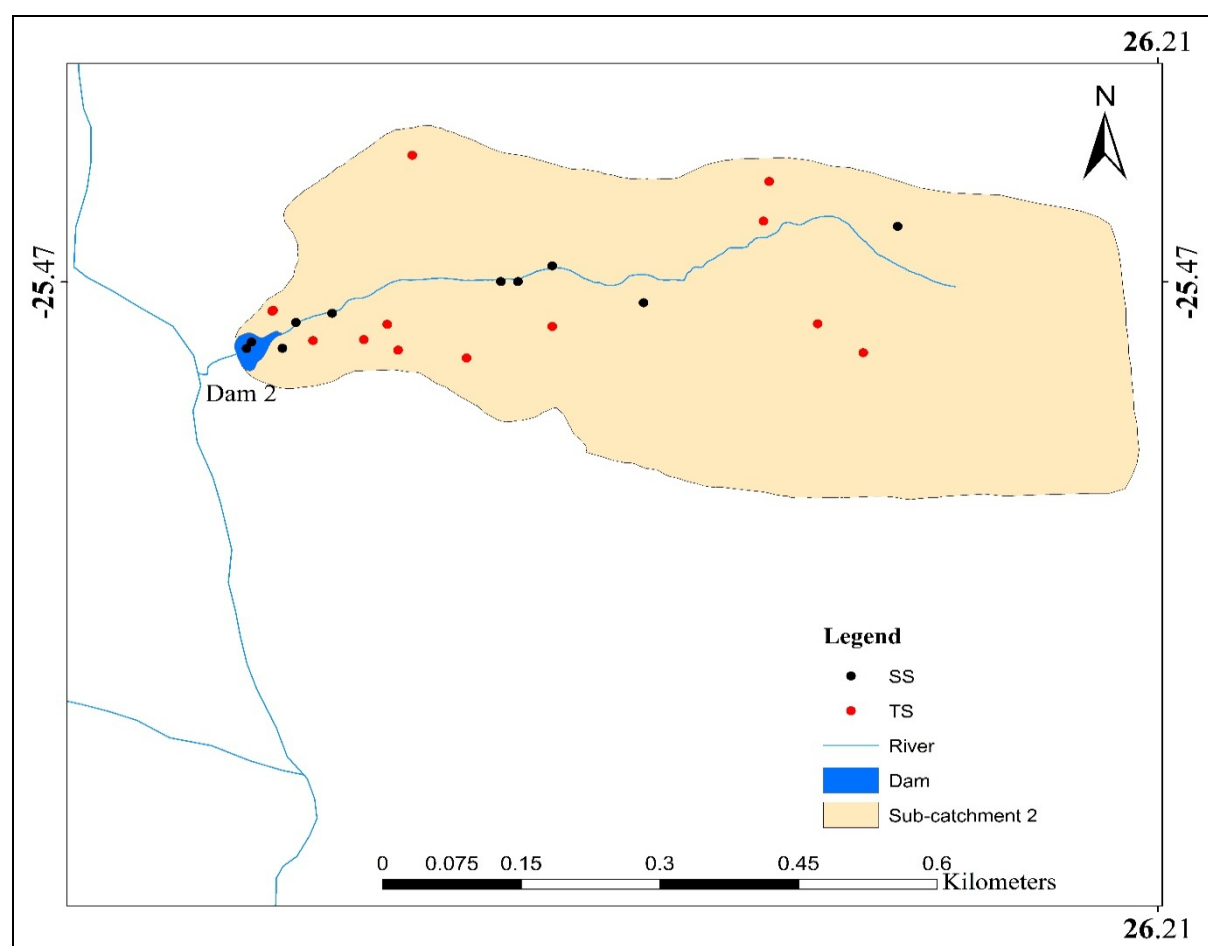


Figure 3.5: Map of sub-catchment of Dam 2

Table 3.1: Number of source and sediment samples collected from each sub-catchment.

Source Area	Dam 1	Dam 2
Surface	11	16
Sub-surface	7	10
In-stream deposition	5	3
Damaged road side	4	6
Dam sediment	2	2
Total	29	37

3.6.2 Laboratory methods

Samples preparation and analysis involved oven drying of the soil at a temperature less than 40 °C to avoid alteration of the magnetic mineralogy of the samples at higher temperatures (Walden *et al.*, 1992). Samples were disaggregated using a mortar and pestle and dry-sieved to collect the fraction below 2 mm for gamma spectrometry analysis. Fallout radionuclides such as ^{137}Cs and unsupported ^{210}Pb are known to have differential adsorption by individual soil particle size fractions (Livens and Baxter, 1988; He and Walling, 1996). He and Walling (1996) investigated grain size effects in the adsorption of ^{137}Cs and unsupported ^{210}Pb by mineral soils through a combination of both laboratory experiments and empirical observations of soils and overbank floodplain deposits. They found significant preferential adsorption of these radionuclides by finer soil particles (< 2mm). Thus the 2 mm threshold is normally used in similar studies to separate the finer soil particles (< 2mm, with preferential adsorption of radionuclides) from rock fragments (> 2mm), (see, Smolders *et al.*, 1997; Zhang *et al.*, 2007; Li *et al.*, 2003; Navas *et al.*, 2007; Marbit *et al.*, 2007).

All samples meant for magnetic measurements were sieved to obtain the fraction less than 63 μm in diameter. This is in line with previous studies using magnetic measurements for sediment source fingerprinting. (Foster *et al.*, 1998; Wang *et al.*, 2012; Smith *et al.*, 2013). Thus the use of two different size fractions for two different measurements was in order.

3.6.2.1 Gamma spectrometry

The study needed a suite of environmental radionuclides to use as sediment tracers. In this study, ^{137}Cs in combination with ^{210}Pb were used to derive additional information on sediment source and to document the relative sediment source types. Humphries *et al.* (2010), and Teramage *et al.* (2013), stated that these two radionuclides are used extensively in sedimentation studies because they have high affinity for soil particles and their half-life are sufficiently long.

Gamma spectrometry was used to measure the activity of ^{137}Cs and ^{210}Pb in all samples using a High Purity Germanium (HPGe) ‘Well’ detector by Canberra (resolution (FWHM) at 122 keV (^{57}Co) is 0.85 keV and at 1332.5 keV (^{60}Co) is 1.86 keV and relative efficiency for energy 1.33 MeV relative to (NaI(Tl) is 36%). Samples were packed into clean, pre-weighted 7 cm long and 9 mm diameter vials. The empty vials were first weighed and the measurements were recorded. The samples were packed to a depth of 4 cm in order to match the geometry of the HPGe ‘Well’ detector. Each of the vials was re-weight before sealing with a rubber seal and paraffin wax to prevent ^{222}Rn gas from escaping and to allow the unsupported ^{210}Pb activity to reach equilibrium with ^{222}Rn (Radon). The sealed vials were kept for approximately three weeks prior to assaying to achieve equilibrium between in situ ^{226}Ra and its daughter ^{222}Rn before measurements. The count times were typically 259 200 seconds on average.

The gamma detector was calibrated for energy using discs of the relevant gamma sources provided by the International Atomic Energy Agency (IAEA). Efficiency calibration was undertaken using multiple radionuclide sediment source (IAEA-385) for natural and artificial in sediments) provided by the IAEA. Activity per samples of the selected radionuclides was obtained from Genie Gamma analysis software.

3.6.2.2 Mineral magnetic measurements

Various magnetic parameters were used for sediment tracing (Table 2). These include: low frequency magnetic susceptibility (χ_{lf}), high frequency susceptibility (χ_{hf}), anhysteretic remanent magnetization (ARM), and a stepwise acquisition of isothermal remanent magnetization (IRM) (Blake *et al.*, 2006; Hatfield and Maher, 2008, Su *et al.*, 2013).

Table 3.2: Magnetic parameters measured or derived in this study (modified from Foster *et al*, 1998)

Symbols	Measured (M) / derived (D)	Instrument	Units
χ_{lf}	M	Bartington MS2B	$10^{-6} \text{ m}^3 \text{ kg}^{-1}$
χ_{hf}	M	Bartington MS2B	$10^{-6} \text{ m}^3 \text{ kg}^{-1}$
χ_{fd}	D	$(\chi_{lf} - \chi_{hf}) / \chi_{lf}$	$10^{-9} \text{ m}^3 \text{ kg}^{-1}$
$\chi_{fd\%}$	D	$[(\chi_{lf} - \chi_{hf}) / \chi_{lf}] \times 100$	%
IRM (-0.1T)	M	Molspin fluxgate magnetometer	$\text{mAm}^2 \text{ kg}^{-1}$
ARM (40 μT)	M	Molspin variac	$\text{mAm}^2 \text{ kg}^{-1}$
S ratio	D	$(\text{IRM}_{(-0.1\text{T})} / \text{IRM}_{(0.8\text{T})}) \chi_l$	Dimensionless
HIRM	D	$(\text{IRM}_{(0.8\text{T})} \times (1 - \text{ratio})) / 2$	$\text{mAm}^2 \text{ kg}^{-1}$

The sample containers were filled to at least half capacity to ensure that the volume did not influence the result. Low frequency susceptibility was first measured followed by the high frequency using a Bartington MS2B Dual Frequency sensor with low (χ_{lf}) 0.47 kHz and high (χ_{hf}) 4.7 KHz frequency following Dearing (1999). The frequency dependent susceptibility (χ_{fd} %), was determined by expressing the difference between the high and low frequency measurements as a percentage of χ at low frequency.

$$\chi_{fd(\%)} = \left[\frac{\chi_{lf} - \chi_{hf}}{\chi_{lf}} \right] \times 100 \quad (\text{Eq 1})$$

A full suite of forward field and back field isothermal remanent magnetization (IRM) measurements were made using a Molspin pulse magnetizer and measured using a Molspin fluxgate spinner magnetometer. All values were expressed on minerogenic basis after correction of the organic matter content (see Appendix 3 and 4 on the magnetic properties of sub-catchment Dam 1 and Dam 2). The interpretation of the different magnetic parameters used in this study is given in Appendix 5.

3.7 Organic matter

Loss on Ignition (LOI) determinations on all samples were undertaken at low temperature (550 °C) for 3 hours following the procedure used by Foster *et al.* (2008) in order to estimate organic matter content of each sample. Precaution was taken so that no humidity remained in the sample before weighing hence the following procedures was performed following the protocol presented by Heiri *et al.* (2001). Empty crucibles were dried at 105°C to a constant weight and cooled in a desiccator before any measurement were made and were heated in a muffle furnace at 550°C for 3 hours. The weight before ignition (W_0) and after ignition (W_1) was determined. The percentage of total organic matter lost is given by Equation 2.

$$\% OM = (W_1 - W_0) \times 100 \quad (\text{Eq 2})$$

The organic matter content was expressed as a percentage weight loss and was used to correct the mineral magnetic parameters.

3.8 Data analysis

Data generated from the questionnaires were coded and subsequently analysed using IBM-SPSS (Statistical Package for Social Science) version 22.1 to generate descriptive statistics. Also, non-parametric tests were used in order to assess the discriminating power of all the properties used. Non-parametric tests are used because fingerprint property data for soils and sediments rarely satisfy the main conditions for adopting parametric tests, that is, the data are uniformly distributed and have equal variances (Collins *et al.*, 1998). Thus the Mann - Whitney U-Test was used. It is one of the most powerful distribution-free tests applicable to small, medium and large data sets where only two groups are involved (Slattery and Walden, 1995). This test was chosen because it involved two sample groups (that is, topsoil and subsoil).

3.8.1 Sediment source modeling

Determining the relative contribution of sediment from topsoil and subsoil in Dam 1 was based on the use of a multivariate mixing model. A two parameter mixing model similar to the one described by Slattery *et al.* (1995) and Collins *et al.* (1996) was used. Dam I was the

only one in which sediment source modelling was undertaken because in the other dam there were no sufficient fingerprints selected and that could distinguish the sediment sources.

3.9 Ethical consideration

The study was cleared by the NWU Ethics Committee (NWU-00016-14-A9). Additional permission was obtained from all the participants and they were fully informed on the nature and outcomes of the research and were assured of anonymity and confidentiality. It was also vital in this project to ensure that those who took part in questionnaire administration were clear about their right and free will to withdraw from the study at any time during the process. Proper explanations of the aim and possible outcomes of this project were clearly explained to each property owner. A clearance form was obtained from the owner of the game park where the dams were selected for sediment source sampling, (see Appendix 6).

3.10 Summary

This chapter has described and justified the choice of the study sites. It explained the research techniques used. The next chapter will present and discuss the results.

CHAPTER FOUR: RESULTS AND DISCUSION

DOCUMENTING SMALL FARM DAMS SILTATION IN THE SWARTRUGGENS-ZEERUST REGION

4.1 Introduction

This chapter presents the results and discussion related to the documentation of small farm dam siltation and sediment management along the farming areas between the towns of Zeerust and Swartruggens in the North West province. The information presented is a result of questionnaires and oral testimonies from farmers and field observations.

4.2 Field survey and census of small farm dams in the study area

Very little is known about siltation and sediment management of small earth dams in the study area. Field surveys and mapping provided the basis for an assessment of the nature and number of the dams in the study area. Forty four (44) dams were mapped and visited in the study area. It was observed that most of the dams vary in age and size. The newest dam was less than 5 years old and the oldest were over 100 years old. Twenty eight of the dams (64 %) are still functional in terms of holding water for a full season but are likely to be completely silted up in the near future judging from the information obtained about the life spans of the dams gleaned from the farmers (Figure 4.1). All the dams visited were built with earth and stones along main streams to capture runoff and provide water for livestock and irrigation. It is also important to note that, during the observation the storage capacities of these dams were unknown and could not be ascertained. Figure 4.2 shows one of the small farm dams visited. One of the dams had been breached as a result of a combination of sediment filling it up and heavy rainstorms resulting in stored sediment being released directly into channels. Foster *et al.* (2009) report about the problem of the delivery of stored sediment in small dams into downstream channels as a result of dam breaching.

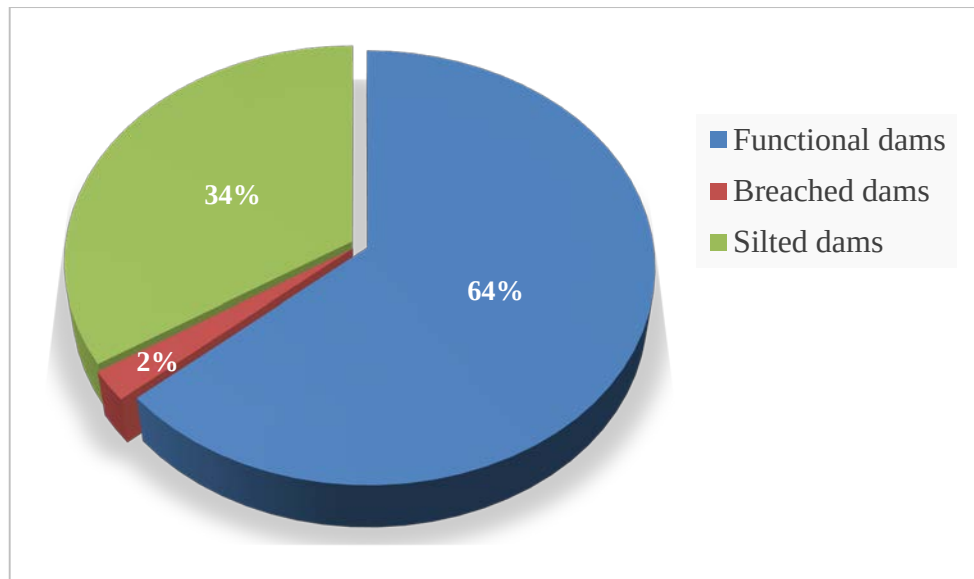


Figure 4 .1: Status of dams in the study area.



Figure 4.2: One of the dams currently experiencing siltation problems

4.3 Purpose of the dams

It was vital to understand the main uses of the dams in the study area. The dams were mainly used for cattle watering, game farming and irrigation and some for dual use such as cattle watering and irrigation (Figure 4.3). Half of the respondents (50%) indicated that the dams were built mainly for livestock watering. About 19% of the respondents indicated that the dams were equally used both for irrigation to water crops and for livestock watering. The least number of respondents (12%) indicated other uses which included domestic uses. The data shows that cattle farming is the main use for the dams and plays a major role in the livelihood of the farmers in the study area. Thus the implications of dam siltation on farmer's livelihoods are most likely serious. It has been observed that small water reservoirs are very important for ensuring water availability and sustenance of livelihood for many rural communities in the developing world (Chihombori *et al.*, 2013; de Fraiture *et al.*, 2013).

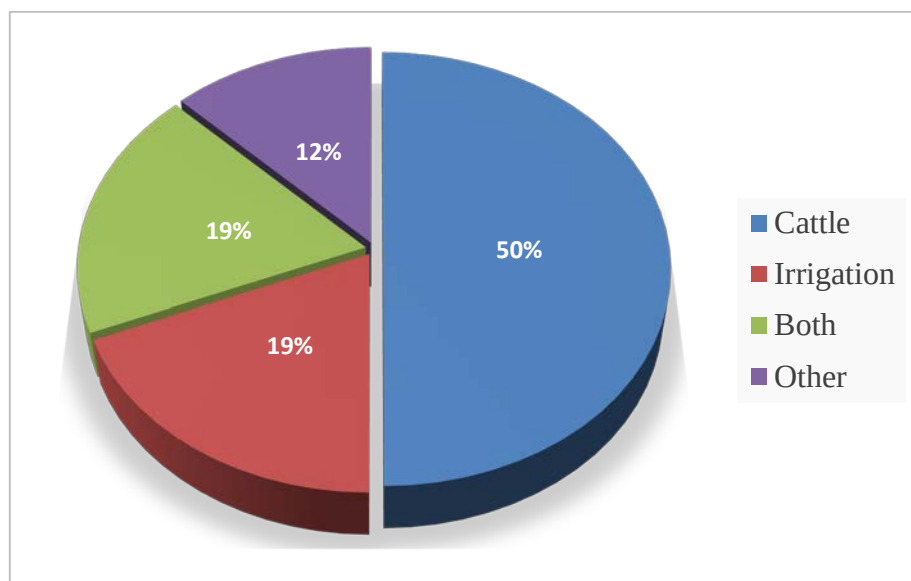


Figure 4.3: Uses of small farm dams in the study area

It has been reported that semi-arid regions are highly dependent on rain fed agriculture as a source of income (Strobl and Strobl, 2011). At a regional scale, changes in water cycles are anticipated due to climate change (Fauchereau *et al.*, 2003), with low mean annual rainfall of 450-550 mm and high annual evaporation of 2000-2500 mm reported in semi-arid areas (Walker and Ogindo, 2005). Since most of the farmers in the study area depend on rain for watering their livestock, without doubt the occurrence of dam siltation can have profound negative impact on cattle farming in the area. The response obtained from field visits and oral

testimonies indicated that some farmers had to abandon their farms (see Figure 4.6) due to lack of water for irrigation resulting from a combination of drought and loss of storage capacity as a result of dam siltation. Most dam structures observed have become less reliable and in the need for alternative sources of water.

4.3.1 Farmers perception and dam siltation

Reservoir siltation is a function of catchment attributes, both anthropogenic and geomorphologic. Each attribute such as slope, poor surface cover and land use whose interaction could result in different types of erosion/ deposition processes and soil siltation. However, being a low risk region to soil erosion, it is widely believe that, the excessive accumulation of sediment into dams is as a result of land use being practiced. Figure 4.3 shows that cattle rearing account for 50% of the main land use in the study area. It is most likely that this type of activity play a predominant role in contributing sediment leading to the siltation of these dams through soil crusting by cattle's and intense grazing thereby exposing the surface soil to be susceptible to erosion. Report by Boardman and foster, (2008) points to the development of Badlands in the Karoo to land use systems introduced by European farming systems through the introduction of large numbers of domesticated sheep and cattle which later on contributed significantly to the development of gully thus destabilising hillslopes and river channels.

4.4 Loss in the storage capacity due to sedimentation and farmer's response

It has been reported that siltation is one of the greatest risks to the success of small dams especially in communal areas (Chihombori *et al.*, 2013). This might be attributed to the fact that small dams fill up with sediment fairly quickly thereby limiting their effectiveness as sources of drinking water for livestock or irrigation. There is a wide-range of direct and indirect causes of rapid siltation of farms dams in the study area. These range from improper soil erosion management within the catchment, overgrazing, and the absence of environmental awareness by the farmers. In this regard it was necessary to know if farmers who were experiencing dam siltation were aware of the problem and its causes. Eighty one percent (81%) of the farmers accepted that siltation poses a threat to the utilization of their dams (Figure 4.4) as opposed to the nineteen percent who did not see siltation as a problem in their dams.

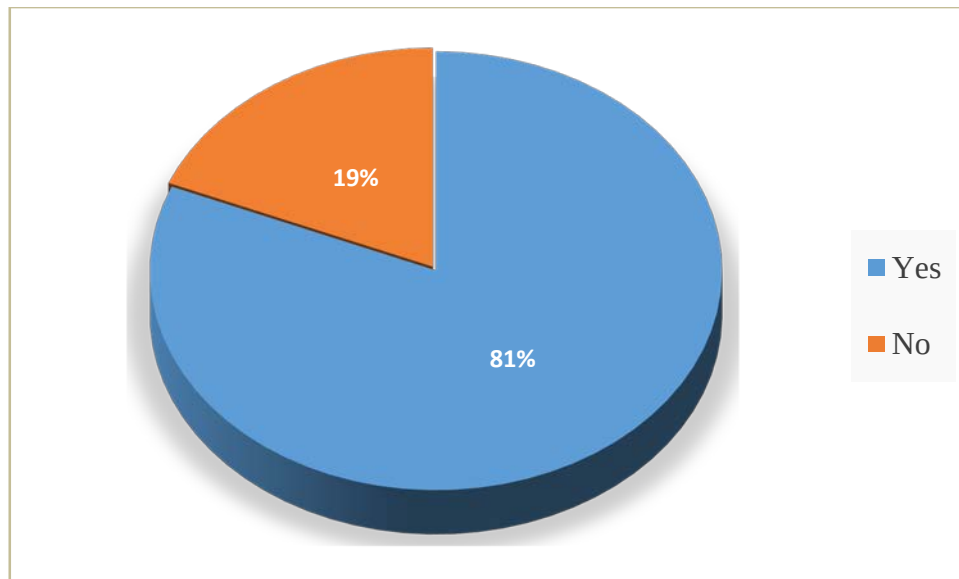


Figure 4.4: Farmer's response to the question whether they consider siltation to be problem on their properties

It is evident from Figure 4.4 that most farmers are highly aware of the problem of siltation. Figure 4.5 shows a dam near Swartruggens facing a serious siltation problem.



Figure 4.5: A silted dam in the Swartruggens area

Having identified that siltation is a real problem faced by most of the farmers in the study area, it was therefore necessary to find out what response strategies they used. It has been

reported that upstream sediment control is one of the best strategies in reducing the amount of incoming sediment within a catchment (Kantouch and Sumi, 2010). However, most of the strategies employed by farmers were not solving the source of the problem whereby upstream sediment control is used to eventually reduce the amount of incoming sediment into the dams. Farmers responded in different ways to the issue of dam siltation (Figure 4.6). The strategies used ranged from the removal of the accumulated sediment using heavy earth moving equipment (dam cleaning), drilling of boreholes as alternative water sources, creating new dams and abandoning the silted dams. Regular dam cleaning to remove the accumulated sediment was the most popular strategy (62 %). 12% identified investment into new dams; 15% drilling boreholes and 8% abandonment of silted dams as a response strategy. It was also noted that all except one (3%) of the farmers did nothing to solve the soil erosion problem. It should be noted however that the degree of siltation varies considerably depending on the condition of the catchment.

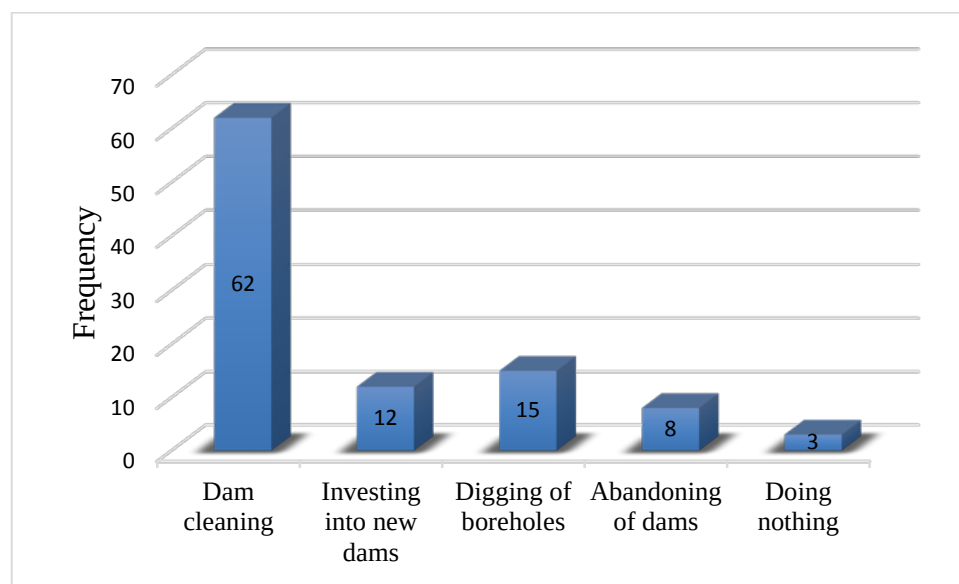


Figure 4.6: Farmer's response to siltation problem

It was observed that dam cleaning is a common measure used by many farmers to remove the excessive sediment accumulating in the dams. Figures 4.7 and 4.8 show aspects of dam cleaning at different stages in various places in the study.



Figure 4.7: Sediment mound waiting to be taken away from a cleaned dam.



Figure 4. Dam recently cleaned of sediment.

The frequency of dam cleaning for those who use this approach was generally every 4 to 5 year. However, some farmers indicated that it depended on availability of funding and whether the dams completely dried up or not (because the cleaning is done during the time when the dams are completely dried). The accumulated sediment was simply piled up as a heap probably to be disposed away as the main reason for cleaning was to create space for drinking water.

4.5 Assessing the economic implications of dam siltation

It was a challenge to estimate the actual cost of dam siltation to the farmers in the study area as many rarely kept records of the actual costs related to dam cleaning. However, it was noted

that one cleaning operation in a 20 000 m² small farm dam could cost about R 10 000 at R500 per hour if the farmer hired dedicated service providers for this operation. However, the cost incurred when the farmer did the work using his own equipment was not easy to estimate. It goes without saying that economic costs of siltation in the study area range from direct costs of dam cleaning to indirect costs related to borehole drilling, building new dams and diversifying livelihood strategies. Investing in small reservoirs has therefore been questioned by some researchers (de Fraiture *et al.*, 2012) for their high maintenance cost, low performance and the collective effort in maintaining these structures.

4.6 Summary

This chapter has reported the result on siltation of small farm dams along the farming areas of Zeerust and Swartruggen. Result from the survey suggests that most of the small farm dam have been silted. Few of the dams are operational but are likely to be silted up within in the near future. Dam cleaning was among the strategies used to remove accumulated sediment into the dam. The next chapter will present the result and discussions on the use of environmental magnetism and environmental radionuclides used for sediment source fingerprinting.

CHAPTER FIVE: RESULTS AND DISCUSSION

SEDIMENT SOURCE TRACING USING MINERAL MAGNETISM AND ENVIRONMENTAL RADIONUCLIDES

5.1 Introduction

This chapter presents the results and discussion on the application of sediment source tracing using mineral magnetism and environmental radionuclides carried out in a small farming catchment near the town of Zeerust. This chapter is divided into three sections, the first one presents the results of the feasibility of using environmental magnetism for sediment source fingerprinting while the second examines the use of environmental radionuclides. The third explains and interprets the sediment source modelling results.

5.2 Tracing sediment source using environmental magnetism

Environmental magnetism has been used as a proxy for sediment source tracing in catchment studies for a very long time (see Dearing *et al.*, 1985; Caitcheon, 1993; Yu and Oldfield, 1993). The potential of the technique to distinguish between topsoil and subsoil (de Jong *et al.*, 1998) and between burnt and unburnt soil (Smith *et al.*, 2014) makes it potentially valuable in this study.

5.2.1 Distinguishing between topsoil and subsoil in the catchment

In order to test the utility of the application for the magnetic parameters of the catchment sediment source tracing, it was necessary to apply robust techniques to assess the ability of each parameter to distinguish the different sediment sources. The Mann–Whitney U test was used to establish which magnetic parameters show significant differences between topsoil and subsoil. The first area of operation was in the sub-catchment of Dam 1 (Table 5.1). A significant difference between the magnetic parameters of the two source groups is indicated by p a value < 0.05 with null hypothesis (H_0) that there is no significant difference in the magnetic parameters of topsoil and subsoil and the alternative hypothesis (H_1) that there is a significant difference in the magnetic parameters of topsoil and subsoil.

Table 5.1: Mann-Whitney results for distinguishing between topsoil and subsoil sources of sediment in the sub-catchment of Dam 1

Magnetic parameters	<i>P</i>- value
χ_{lf}	0.048*
χ_{fd}	0.019*
$\chi_{fd\%}$	0.036*
ARM	0.159
χ_{arm}	0.159
SIRM	0.234
S ratio	0.505
HIRM	0.129
$\chi_{ARM/SIRM}$	0.878
$SIRM/\chi_{lf}$	0.442
$SIRM/\chi_{fd}$	0.574
$HIRM/\chi_{lf}$	0.959
$HIRM/\chi_{fd}$	0.878
$SIRM/ARM$	0.878

* Significant at $p < 0.05$

It was evident from the results that most of the magnetic parameters could not discriminate between the two sediment source types. Only the following magnetic susceptibility parameters; χ_{lf} , χ_{fd} and $\chi_{fd\%}$ showed significant differences between topsoil and subsoil ($p < 0.05$). None of the remanence parameters were capable of distinguishing between topsoil and subsoil. Topsoil generally has a higher magnetic susceptibility than subsoil (Dearing, 1999) because of the formation of secondary ferrimagnetism as a result of the fermentation of

organic matter during decomposition. The mean values of the magnetic parameters that were chosen through the Mann–Whitney U test are shown in Table 5.2

Table 5.2: Summary statistics of soil and sediment samples in the sub-catchment of Dam 1

	Topsoil (TS)	Sub soil (SS)	Instream	Dam
			Deposition (ISD)	sediment (DS)
	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD
χ_{lf}	0.25 ± 0.11	0.11 ± 0.01	0.10 ± 0.04	0.13 ± 0.01
χ_{fd}	29.44 ± 13.90	13.60 ± 7.22	30.18 ± 28.40	16.02 ± 1.50
$\chi_{fd\%}$	12.11 ± 1.84	13.46 ± 1.40	9.28 ± 6.33	12.53 ± 0.53

SD= Standard Deviation

From Table 5.2, it is evident that subsoil $\chi_{fd\%}$ (13.46 ± 1.40) was slightly higher than that of topsoil $\chi_{fd\%}$ (12.11 ± 1.84) and the value for both sources is generally higher than that of the topsoil.

On the other hand, the results of applying the Mann-Whitney U-Test to samples from the sub-catchment of Dam 2 (Table 5.3) showed that none of the susceptibility and remanance magnetic parameters were significantly different (p-values < 0.05) between top soil and subsoil in the sub-catchment. This means that the soil material from topsoil and subsoil (potential sources) were indistinguishable using magnetic parameters.

Table 5.3: Mann-Whitney results for distinguishing between topsoil and subsoil sources of sediment in the sub-catchment of Dam 2

Magnetic parameters	P- value
χ_{lf}	0.057
χ_{fd}	0.578
$\chi_{fd\%}$	0.521
ARM	0.322
χ_{arm}	0.322
SIRM	0.765
S ratio	0.765
HIRM	0.415
$\chi_{ARM/SIRM}$	0.701
$SIRM/\chi_{lf}$	0.701
$SIRM/\chi_{fd}$	0.966
$HIRM/\chi_{lf}$	0.578
$HIRM/\chi_{fd}$	0.765
$SIRM/ARM$	0.638

* Significant at $p < 0.05$

A possible explanation to account for the failure of both magnetic susceptibility and remanance parameters in the sub-catchment of Dam 2 may be the fire history. Most of the sub-catchment had visible signs of burning. According to Peters *et al.* (2001) and Smith *et al.* (2013), burning produces an enhancement in the magnetic signal of soil. Thus the magnetic signal induced by the fire was probably stronger than that brought about by the position of the samples in the profile. This gave the motivation for the testing of the difference between the unburnt and burnt top soil as shown in the next section.

5.2.2 Distinguishing between burnt and unburnt topsoil

All the topsoil samples were re-grouped into burnt and unburnt to investigate if magnetic parameters could discriminate between the two groups. Results of applying the Mann-Whitney U-Test to assess the ability of each magnetic parameter to discriminate between burnt and unburnt topsoil for Dam 2 sub-catchment are shown in Table 5.4.

Table 5.4: Mann-Whitney results for distinguishing between burnt and unburnt topsoil from the sub-catchment of Dam 2

Magnetic parameters	<i>P</i> - value
χ_{lf}	0.040*
χ_{fd}	0.040*
$\chi_{fd\%}$	0.055
ARM	0.701
χ_{arm}	0.701
SIRM	0.701
S ratio	1.000
HIRM	0.898
$\chi_{ARM/SIRM}$	0.701
$SIRM/\chi_{lf}$	0.159
$SIRM/\chi_{fd}$	0.096
$HIRM/\chi_{lf}$	0.306
$HIRM/\chi_{fd}$	0.250
$SIRM/ARM$	0.250

*Significant at $P < 0.05$

The results showed that only magnetic susceptibility parameters (χ_{lf} and χ_{fd}) may be used to discriminate between burnt and unburnt topsoil. Similar to the results from Dam 1 and Dam 2, no remanence properties were able to distinguish the two groups. Fire is known to produce fine-grained ferromagnetic minerals in surface soil during burning (Smith *et al.*, 2013). Soil magnetic properties enhancement might be linked to changes in oxidation status in the surface soil during burning by converting less magnetic iron oxy-hydroxides into more magnetic minerals (Clement *et al.*, 2011; Armstrong *et al.*, 2012). However, this is dependent upon the level of heating and the presence of organic matter. Table 5.5 shows the summary statistics of the magnetic parameters of burnt and unburned topsoil selected by the Mann Whitney U test.

Table 5.5: Summary statistics of burnt and unburnt topsoil samples from the sub-catchment of Dam 2

	Burnt topsoil	Unburnt Topsoil	In stream Deposition	Dam Sediment
	Mean $\pm$ SD	Mean $\pm$ SD	Mean $\pm$ SD	Mean $\pm$ SD
χ_{lf}	0.27 $\pm$ 0.17	0.38 $\pm$ 0.12	0.25 $\pm$ 0.12	0.27 $\pm$ 0.04
χ_{fd}	29.71 $\pm$ 22.91	44.60 $\pm$ 17.01	28.42 $\pm$ 15.82	15.01 $\pm$ 2.83

SD = Standard deviation

The results from Table 5.5 confirmed a difference between the unburnt topsoil samples and the burnt topsoil. This difference is most likely a result of fire. Although fire is known to change the magnetic signature of soils, Gedye *et al.* (2000) suggested that fire intensity also plays a role. Low intensity wild fires below 400°C might not generate significant topsoil magnetic enhancement and as a result produces little or no magnetic enhancement. Although it was difficult to predict if the fire intensity was high or low in sub-catchment Dam 2, the result clearly demonstrate that the fires in the study areas are most likely of high intensity, to produced differentiation between the burnt and unburnt top soil.

5.3 Environmental radionuclides for sediment source tracing

Sixty six soil samples were analysed for ^{137}Cs and ^{210}Pb to investigate whether the soils had ^{137}Cs and ^{210}Pb which could be used as potential fingerprints. The result indicated that only

twenty one of the samples tested positive for ^{210}Pb and only one for ^{137}Cs . The lack of ^{137}Cs in topsoil samples is usually attributed to various factors. Firstly this could be related to the low fallout in the arid areas of the North-West province combined with issues around the generally low ^{137}Cs activities and radioactivity decay in the Southern Hemisphere. According to Wallbrink *et al.* (1998) and Leslie and Hancock (2008), the concentrations of ^{137}Cs in the soil is an order of magnitude lower than the Northern Hemisphere because there was a relatively small amount of atmospheric nuclear testing in the southern hemisphere. This often results in some landscapes having very little and or undetectable ^{137}Cs concentrations. However, the fact that ^{137}Cs was found in sufficient quantity to make it of considerable value in tracing actively transported or very recently deposited sediment in South African landscape by Foster *et al.* (2007) in a study in the Karoo, Eastern Cape, mean that low fallout is not the problem. In an erosive environment as the study area Foster *et al.* (2007) found that it is possible to find no ^{137}Cs as most of the topsoil would have been eroded.

Since only one topsoil sample tested positive for ^{137}Cs , this radionuclide was not used further in the study. On the other hand, $^{210}\text{Pb}_{\text{ex}}$ was found in twenty one samples. Tables 5.6 and 5.7 show the activity concentrations of $^{210}\text{Pb}_{\text{ex}}$ in the two sub-catchments in the study area.

Table 5.6: $^{210}\text{Pb}_{\text{ex}}$ activity for the samples collected in the sub- catchment of Dam 1

Sample ID	$^{210}\text{Pb}_{\text{ex}}$ Bqkg ⁻¹
D1-7X (Topsoil)	112.17 ± 7.68
D1-4X (Topsoil)	235.69 ± 13.69
D1-18X (Topsoil)	138.48 ± 10.48
D1-23X (Topsoil)	33.01 ± 14.6
D1-3X (Subsoil)	83.72 ± 8.34
D1-14X (Subsoil)	69.22 ± 6.42
D1-10X (Subsoil)	12.5 ± 11.05
D1-20X (Subsoil)	54.3 ± 7.6
D-1X (In-stream deposition)	109.60 ± 11.59

D1-9X (Dam sediment)	256.08 ± 11.11
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Table 4.7: $^{210}\text{Pb}_{\text{ex}}$ activity for the samples collected in the sub- catchment of Dam 2

Sample ID	$^{210}\text{Pb}_{\text{ex}}$ Bqkg ⁻¹
D2-19 (Topsoil)	237.78 ± 15.98
D2-27 (Topsoil)	262.71 ± 11.6
D2-22 (Topsoil)	265.94±11.04
D2-2 (Topsoil)	191.97±11.27
D2-4 (Topsoil)	117.56±6.64
D2-3 (Topsoil)	113.05±6.72
D2-17 (Subsoil)	76.58±7.48
D2-25 (Subsoil)	47.91±6.85
D2-21 (Subsoil)	72.61±11.96
D2-5 (Subsoil)	95.42±6.72
D2-23 (Dam Sediments)	367.18±15.66

The samples were subsequently re-grouped into topsoil, subsoil, instream deposition and dam sediment (Table5.8) in order to determine the activity concentration of $^{210}\text{Pb}_{\text{ex}}$ among the potential sources if they could be used as potential fingerprint in the catchment. The activity concentration of $^{210}\text{Pb}_{\text{ex}}$ according to source was calculated and the range and means values ± SD (Standard Deviation) were determine. The units are in Becquerel per kilogram (Bqkg⁻¹)

Table 5.8: Mean values for $^{210}\text{Pb}_{\text{ex}}$ in surface and subsurface samples

Radionuclides	Topsoil	Subsoil	ISD	DS
Pb-210	170.81 ± 10.97	64.03 ± 8.30	237.72 ± 7.68	311.63 ± 13.38
No of samples	10	8	1	2

Key: ISD= In-stream deposition, DS= Dam sediment

A comparison of average concentration values of $^{210}\text{Pb}_{\text{ex}}$ activity in the topsoil (170.81 ± 10.97) and subsoil (64.03 ± 8.30) showed that topsoil sample values were higher than those of the subsoil in the catchment. Studies have demonstrated that the activity concentration of ^{210}Pb on the subsoil tends to be significantly lower than the topsoil (Owen *et al.*, 1997; Caitcheon *et al.*, 2012). Studies have reported that the behaviour of $^{210}\text{Pb}_{\text{ex}}$ in soil is similar to ^{137}Cs hence is of good alternative in areas where ^{137}Cs cannot be used. An analysis of $^{210}\text{Pb}_{\text{ex}}$ and or in combination with ^{137}Cs activity in a sediment deposit may offer information on its possible source. For instance, the presence of detectable ^{210}Pb and ^{137}Cs at depth in a sediment deposit might be interpreted to mean that the sediment was mobilized from a topsoil source and therefore represents the action of sheet or shallow rill erosion (Wallbrink and Murray, 1993; Walling *et al.*, 2003). On the other hand, a sediment deposit composed of zero or low ^{210}Pb activity may indicate a subsoil source, mostly mobilized by gully and riverbank erosion.

5.4 Sediment source modeling in Dam 1

Only Dam 1 was analysed for both environmental radionuclides and magnetism. Thus the estimate of the contribution of topsoil and subsoil was determined for this dam only. The estimate of the proportion of each potential source was undertaken using a 2 parameter multivariate mixing model similar to the one described by Slattery *et al.* (1995) and Collins *et al.* (1996) using ^{210}Pb and χ_{f} as the distinguishing parameters. The model assumes that the concentrations of the selected fingerprint properties in each individual sediment sample directly reflect the corresponding concentrations in the original source materials and the relative proportions of sediment contributed. Within the mixing model, each fingerprint property is represented by a linear equation (Equation 2), comparing the concentration of that

constituent in the sediment sample with the corresponding value based on the sum of the predicted contributions from the sediment sources.

$$\sum_{i=1}^n \left\{ \frac{\left(C_i - \left(\sum_{s=1}^m P_s S_{si} \right) \right)^2}{C_i} \right\} \quad (\text{Eq 3})$$

Where:

C_i = concentration of fingerprint property (i) in sediment sample;

P_s = the optimised percentage contribution from source (s)

S_{si} = mean concentration of fingerprint property (i) in source (s)

m = number of sediment source

n = number of fingerprint properties comprising the optimum composite fingerprint

The model was executed in Excel using a Solver function using Simple Linear Programming (Simple LP) based on the mean values of the selected fingerprints characterising the two potential sediment sources. The following two linear boundary conditions were set to the model: a relative contribution from the two potential sources must be non-negative that is;

$$0 \leq P_s \leq 1 \quad (\text{Eq 4})$$

And the relative contribution from the two potential source must sum to unity that is;

$$\sum_{s=1}^n P_s = 1 \quad (\text{Eq 5})$$

Variants of this sediment modelling procedure have been used by various researchers to trace sediments in diverse environments (Collins *et al.*, 1997b; Walling *et al.*, 1999; Owens *et al.*, 2000; Gruzowski *et al.*, 2003; Motha *et al.*, 2003; Fox and Papanicolaou, 2008; Collins *et al.*, 2010b, 2011).

The results from the analysis suggested that topsoil contributed 100% to the two sediment samples collected from Dam 1. These results only reflect the source of the two sediment samples collected from the entrance of the dam and not all the sediment in the dam. Although unexpected, these results may be a reflection of the complexity of sediment mobilization processes influenced by various factors including the nature and spatial distribution of the rainfall. Studies in the semi-arid Karoo region of the Eastern Cape, have shown that 10 mm of rainfall is sufficient to cause local runoff and at least 20 mm gave rise to widespread soil erosion, sediment transport and improved connectivity between hillslopes and channel networks (Boardman *et al.*, 2010; Foster and Rowntree, 2012). Thus it is possible that one such light storms could have mobilized sediment from only top soil. A more comprehensive depth sampling of the dam sediment could have been more informative in regards to the spatio-temporal dynamics of sediment sources in the investigated sub-catchment.

Although it was expected from field observation that some sediment would come from damaged road tracks and eroding stream banks, the results should be understood within the constraints of limited sediment samples collected.

5.5 Conclusion

The results from this chapter suggest that only magnetic susceptibility has the potential to distinguish between top and subsoil, and between burnt and unburnt soil in the catchment. The application of environmental radionuclides technique has shown that ^{210}Pb has the potential as a sediment tracer for soil erosion and sediment related studies. However the use of ^{137}Cs was detected in only one sample thereby reducing its utility as a tracing method in the study catchment. Sediment modelling indicated that the major source of sediment was topsoil.

CHAPTER SIX: CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This study set out to enhance understanding of dam siltation, sediment management and to test the feasibility of using environmental magnetism and environmental radionuclides in tracing sediment sources in two small sub-catchments in the farming areas between Zeerust and Swartruggens in the North-West province. The following conclusions were reached:

- Farmers in the study area depend on small farm dams for watering cattle and for irrigation purposes.
- Siltation of these dams is a big challenge with huge potential financial and livelihood implications. However, most of the farmers are addressing the source of the problem of dam siltation, with many choosing to manage the sediment mostly through regularly cleaning the sediment from the dams.

With reference to the feasibility of using environmental magnetism and environmental radionuclides for sediment tracing in the two sub-catchments observed that:

- Out of the complete suite of magnetic parameters used only magnetic susceptibility was able to distinguish between topsoil and subsoil sources of sediment in Dam 1 but failed in Dam 2.
- The failure of mineral magnetism in Dam 2 was attributed to the fire history of the sub-catchment. Fire is known to produce a stronger magnetic signature. Magnetic susceptibility was able to distinguish between soil eroded from burnt and unburnt areas than from top and subsoil.
- The absences of detectable ^{137}Cs in almost all the soil samples clearly demonstrate the difficulty of using this radionuclide for erosion and sediment related studies in the area mainly due to lack of ^{137}Cs source.

- $^{210}\text{Pb}_{\text{ex}}$ has the potential as a sediment tracer because of its presence in most of the samples analyzed.

6.2 Limitations

Any research findings need to be contextualized within the specific constraints of the particular research. The following constraints deserve mention:

- The study investigated recently deposited sediment by collecting sediment grab samples at the entrance of each dam. While this approach was suitable for an exploratory study like this one, however, ideally sediment must take into account the spatial variation of sediment deposition within dams by making sure the sampling is representative of the major sediment related processes taking place in the dam. However, due to cost limitations of a widespread sediment sampling program this was not done.
- The long count times of the gamma spectrometry systems (mean of 3 days per sample) and limitations posed by acquisition and set-up of the system meant that it was not possible to count all the available samples. However, the samples analysed gave us an idea of the feasibility of the techniques tested and an exploratory understanding of sediment source dynamics in the investigated dam.
- Lack of ^{137}Cs source from nuclear tests or accidents in the Southern hemisphere limited the detectability of ^{137}Cs in the sediments studied. This made its combinational analysis with ^{210}Pb not possible.
- Various studies (e.g. Walling and Woodward, 1995; Collins et al., 1997b; Walling et al., 1999) have found that to increase the rigour and reliability of the fingerprinting approach multiple fingerprints with differing environmental behaviour must be used to avoid the potential of spurious source sediment linkages (Yu and Oldfield, 1993). The objective of the tracing work in this study was to assess the feasibility of environmental radionuclides and magnetism. Thus the inclusion of other types of fingerprints such as geochemistry was not necessary, although it could have meant a better chance for a more robust modelling of sediment sources.

6.3 Recommendations

- Because the problems of siltation of dams is very severe in the study area and that none of the farmers are addressing the source of the problem of dam siltation (catchment soil erosion), it will be necessary for the agricultural extension officers and natural resources management authorities in the district municipality to embark on an awareness campaigns in relation to soil erosion and land use management so that the sediment issues can be holistically addressed.
- Dam siltation has widespread livelihood impacts in the area. It will be appropriate to the relevant authorities to assist affected farmers to mitigate against the financial losses and livelihood effects of water shortages resulting from dam siltation.

6.4. Recommendation for future research

Below are a number of recommendations for future research:

- Although this study has focused on small farm dam siltation, sediment management and sediment source fingerprinting, it would be necessary for future research to assess the possibility of obtaining information on the application of environmental magnetism, ^{210}Pb and ^{137}Cs on both spatial and source types of larger catchments in the North-west province.
- The reliability of the discrimination afforded by the fingerprinting parameters could be further improved with the inclusion of additional parameters preferably with those from different environmental behaviour to those already employed.
- The result have concluded that unsupported Lead-210 can provide a viable alternative to Caesium-137 as a tracer for soil erosion investigations. Further studies are required to refine and confirm the potential use of unsupported Lead-210 as a tracer in other environmental settings in the North-West Province, South Africa.

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Appendix 1: Observation Checklist

Observation checklist was guided by the need to document small farm dams and sediment management strategies used by farmers along Zeerust-Swartuggens farming area.

The following was observed during the field:

- What materials were used to construct the dams?
- What is the current state of the dam?
- Are the dams filled up with accumulated sediment?
- Dams that had been cleaned due to sediment accumulation?
- Is there any visible sign of erosion leading to the accumulation of sediment into the dams?
- Is there any visible sign of dam breaching due to the accumulation of sediment?
- If the dams have been breached before?
- How do farmers address the problem of siltation?

Appendix 1: Questionnaires schedule on soil erosion and dam siltation for farmers



Department of Geography and Environmental Sciences

1. How many dams do you have in your farm?

.....
.....
.....

2. When were the dam(s) constructed?

.....
.....
.....

3. What materials were used in constructing the dam(s)?

.....
.....
.....

4. What is the purpose of the dam(s)?

.....
.....
.....

5. Are you experiencing any siltation problem in your dam(s)?

.....
.....
.....

6. What strategies do you use to solve the problem of siltation?

.....
.....
.....

7. Is dredging part of your solution to remove accumulated mud in your dam(s)?

.....
.....
.....

8. How often do you dredge your dam(s)?

.....
.....
.....

9. Approximately what is the cost incurred to dredge the dam(s)?

.....
.....
.....

10. What is involved in the above estimate?

.....
.....

Thank you

Appendix 2: Selected mineral magnetic properties of Dam 1

type	Codes	$\chi_{fd}\%$	χ_{lf}	χ_{fd}	IRM	ARM	Xarm	SIRM	SIRM-m	S ratio	IRM@ 1000mT	HIRM	Xarm/SIRM	SIRM/ χ_{lf}	SIRM/ χ_{fd}	HIRM/ χ_{lf}	HIRM/ χ_{fd}	SIRM/ARM
TS	1	11,79	0,31	35,60	57,64	0,08	2,39	0,35	0,36	-0,57	0,20	0,27	6,84	1,17	0,01	0,92	0,01	4,68
TS	1	16,86	0,20	33,38	27,04	0,05	1,53	0,16	0,16	-2,06	0,32	0,24	9,68	0,80	0,00	1,22	0,01	3,29
TS	1	13,13	0,06	7,99	34,71	0,01	0,45	0,07	0,07	-1,19	0,09	0,08	6,19	1,14	0,01	1,25	0,01	5,18
TS	1	13,25	0,43	56,44	-63,64	0,05	1,68	0,05	0,05	-1,13	0,06	0,05	33,61	0,12	0,00	0,13	0,00	0,96
TS	1	10,44	0,32	32,57	29,74	0,10	2,99	0,21	0,21	-2,28	0,47	0,34	14,58	0,66	0,01	1,08	0,01	2,17
TS	1	11,03	0,21	23,02	68,80	0,08	2,64	0,24	0,24	-0,49	0,12	0,18	11,06	1,14	0,01	0,84	0,01	2,86
TS	1	11,69	0,36	41,15	-39,80	0,05	1,62	0,07	0,07	-4,54	0,31	0,19	23,63	0,19	0,00	0,54	0,00	1,34
TS	1	12,05	0,38	44,85	49,18	0,03	0,98	0,17	0,18	-0,62	0,11	0,14	5,63	0,47	0,00	0,38	0,00	5,67
TS	1	12,01	0,22	25,97	27,84	0,02	0,55	0,03	0,03	-0,82	0,03	0,03	16,84	0,15	0,00	0,14	0,00	1,89
TS	1	11,45	0,15	16,96	-36,66	0,03	1,04	0,03	0,04	-1,21	0,04	0,04	30,01	0,23	0,00	0,26	0,00	1,06
TS	1	12,25	0,13	15,79	60,88	0,06	1,82	0,09	0,09	-4,86	0,43	0,26	20,81	0,67	0,01	1,97	0,02	1,54
TS	1	9,35	0,21	19,66	60,88	0,06	1,73	0,08	0,08	-4,86	0,40	0,24	20,81	0,39	0,00	1,15	0,01	1,52
SS	2	12,86	0,09	11,50	-41,35	0,04	1,25	0,07	0,07	-0,94	0,06	0,06	18,80	0,72	0,01	0,70	0,01	1,70
SS	2	12,37	0,16	19,87	45,92	0,04	1,17	0,07	0,07	-1,11	0,08	0,07	17,07	0,42	0,00	0,45	0,00	1,86
SS	2	13,38	0,07	8,75	76,74	0,05	1,46	0,10	0,11	-0,96	0,10	0,10	13,98	1,52	0,01	1,49	0,01	2,28
SS	2	12,87	0,18	22,36	78,76	0,02	0,58	0,07	0,07	-1,38	0,09	0,08	8,57	0,39	0,00	0,46	0,00	3,73
SS	2	15,85	0,04	5,53	15,08	0,03	0,86	0,03	0,03	-0,98	0,03	0,03	27,04	0,83	0,01	0,82	0,01	1,17
ISD	3	1,55	0,14	0,15	18,03	-93,57	0,10	3,20	0,10	0,10	-2,53	0,26	0,18	31,35	0,71	0,01	1,25	0,01
ISD	3	0,74	0,11	0,06	-44,45	-32,58	0,03	0,81	0,05	0,05	-2,23	0,10	0,07	18,09	0,77	0,00	1,23	0,00
ISD	3	1,63	0,12	0,05	-37,44	44,72	0,02	0,76	0,07	0,07	-0,71	0,05	0,06	10,72	1,39	0,00	1,19	0,00
ISD	3	3,43	0,17	0,08	-55,41	79,02	0,04	1,18	0,28	0,29	-0,21	0,06	0,17	4,24	3,63	-0,01	2,20	0,00
ISD	3	3,02	0,08	0,04	-31,67	-79,34	0,02	0,53	0,02	0,02	-1,60	0,03	0,02	32,52	0,39	0,00	0,51	0,00
DS	4	10,42	12,15	0,13	14,83	-32,58	0,03	0,88	0,05	0,05	-2,23	0,11	0,08	18,09	0,39	0,00	0,63	0,01
DS	4	11,26	12,91	0,14	17,22	44,72	0,02	0,63	0,06	0,06	-0,71	0,04	0,05	10,72	0,45	0,00	0,39	0,00

TS = Topsoil; SS = Subsoil; ISD= In-stream deposition; DS= dam sediment

Appendix 4: Selected mineral magnetic properties of Dam 2

Dam2	type	Codes	$\chi_{fd}\%$	χ_{lf}	χ_{fd}	ARM	Xarm	SIRM	SIRM-m	S ratio	IRM @10	HIRM	Xarm/SIRM	SIRM/ χ_{lf}	SIRM/ χ_{fd}	HIRM/ χ_{lf}	HIRM/ χ_{fd}	SIRM/AF
2D-3	TS	2	10,55	0,23	24,12	0,03	0,91	0,08	0,08	-1,67	0,13	0,10	11,91	0,34	0,00	0,45	0,00	2,70
2D-5	TS	2	10,00	0,14	13,79	0,19	6,11	0,17	0,17	-1,52	0,25	0,21	36,76	1,21	0,01	1,52	0,02	0,88
2D-6	TS	2	12,28	0,61	73,90	0,11	3,36	0,18	0,18	-0,63	0,11	0,15	18,86	0,30	0,00	0,25	0,00	1,72
2D-13	TS	2	12,10	0,67	80,03	0,07	2,33	0,13	0,14	-1,07	0,14	0,14	17,72	0,20	0,00	0,21	0,00	1,84
2D-18	TS	2	10,99	0,36	39,31	0,04	1,31	0,13	0,13	-0,35	0,04	0,08	10,42	0,35	0,00	0,24	0,00	3,08
2D-19	TS	2	12,60	0,49	61,77	0,08	2,39	0,10	0,10	-3,46	0,33	0,21	24,94	0,20	0,00	0,44	0,00	1,29
2D-21	TS	2	10,82	0,22	23,12	0,09	2,79	0,15	0,15	-0,50	0,07	0,11	18,93	0,69	0,01	0,52	0,00	1,70
2D-22	TS	2	11,22	0,35	38,99	0,01	0,45	0,04	0,04	-0,32	0,01	0,02	12,83	0,10	0,00	0,07	0,00	2,52
2D-23	TS	2	11,25	0,37	40,96	0,10	3,07	0,05	0,05	-2,15	0,11	0,08	57,63	0,15	0,00	0,23	0,00	0,56
2D-24	TS	2	10,19	0,29	29,23	0,08	2,53	0,15	0,15	-1,37	0,20	0,17	17,22	0,52	0,01	0,61	0,01	1,87
2D-31	TS	2	10,98	0,29	31,44	0,03	0,95	0,04	0,04	-2,35	0,08	0,06	26,53	0,13	0,00	0,21	0,00	1,22
2D-32	TS	2	9,39	0,20	18,13	0,06	1,98	0,22	0,22	-0,36	0,08	0,15	9,06	1,13	0,01	0,77	0,01	3,53
2D-33	TS	2	9,09	0,19	17,35	0,03	0,96	0,07	0,07	-3,20	0,21	0,14	14,31	0,35	0,00	0,73	0,01	2,21
2D-7	SS	1	11,31	0,30	33,32	0,07	2,35	0,04	0,04	-5,13	0,22	0,13	53,55	0,15	0,00	0,46	0,00	0,60
2D-14	SS	1	11,99	0,30	35,61	0,07	2,13	0,21	0,22	-0,23	0,05	0,13	9,97	0,73	0,01	0,45	0,00	3,24
2D-17	SS	1	12,26	0,32	39,12	0,09	2,84	0,32	0,32	-0,38	0,12	0,22	9,00	1,00	0,01	0,69	0,01	3,57
2D-26	SS	1	12,32	0,39	47,08	0,09	2,90	0,08	0,08	-3,27	0,26	0,17	36,42	0,21	0,00	0,45	0,00	0,88
2D-27	SS	1	11,45	0,32	36,14	0,08	2,58	0,11	0,11	-0,53	0,06	0,09	23,21	0,35	0,00	0,27	0,00	1,38
2D-29	SS	1	11,14	0,36	39,26	0,08	2,62	0,08	0,08	-2,92	0,24	0,16	32,44	0,23	0,00	0,45	0,00	0,99
2D-10	ISD	3	11,78	0,35	40,94	0,00	0,05	0,10	0,10	-2,06	0,20	0,15	0,56	0,28	0,00	0,43	0,00	57,11
2D-11	ISD	3	9,73	0,11	10,63	0,11	3,43	0,10	0,10	-3,64	0,36	0,23	34,51	0,89	0,01	2,05	0,02	0,92
2D-20	ISD	3	11,08	0,31	33,71	0,09	2,98	0,16	0,17	-1,46	0,24	0,20	18,27	0,55	0,01	0,67	0,01	1,78
2D-8	DS	4	13,42	0,13	17,02	0,08	2,57	0,16	0,16	-1,42	0,22	0,19	16,49	1,22	0,01	1,47	0,01	1,95
2D-9	DS	4	10,85	0,12	13,01	0,13	4,00	0,31	0,32	-0,20	0,06	0,19	12,74	2,58	0,02	1,54	0,01	2,51

Appendix 5: Magnetic parameters and their interpretations

Magnetic susceptibility It measure the degree to which a substance can be magnetised whilst exposed to a weak magnetic field. The ratio of the magnetisation (M) produced in a sample to the intensity of the magnetic field (H) in which it is placed is the volume susceptibility (called Kappa; κ). Susceptibility can also be measured on a mass specific basis and is referred to as mass specific susceptibility. It can also be measured in the laboratory per unit mass (mass-specific susceptibility designated by the symbol Chi; χ) at different alternating frequencies (e.g. 0.46 and 4.6 kHz in the Bartington MS2 and MS2B dual frequency sensor). From the measurement of low (χ_{lf}) and high (χ_{hf}) frequency susceptibility, the frequency dependent susceptibility can be calculated on a concentration basis (χ_{fd}) or as a percentage ($\chi_{fd\%}$).

χ_{lf} is the most common measurement and gives information about the concentration of ferromagnetic minerals or the total concentration of paramagnetic and antiferromagnetic minerals if ferromagnetic minerals (e.g. magnetite) are only present in low concentrations (Foster et al., 2008). Where samples contain a high proportion of weakly diamagnetic organic matter, measurements can be corrected by determining the organic matter content by loss on ignition and expressing χ_{lf} on a minerogenic basis ($\chi_{lf \text{ min}}$). (Dearing 1999).

Frequency dependent susceptibility is used to detect the presence of very fine-grained magnetic grains, which exhibit viscous, time-dependent behaviour and lose magnetisation very rapidly after removal of the magnetic field. These grains are often produced in soils as a result of weathering and

pedogenesis or by burning. Values of $\chi_{fd\%}$ of less than 2% suggest almost no superparamagnetic (SP) grains, while values of 2–10% suggest a mixture of SP and coarser grains. Values between 10 and 14% suggest that the sample is dominated by SP grains. High $\chi_{fd\%}$ is usually associated with topsoils decreasing values are often associated with subsoil especially in areas of waterlogging and glying (Foster et al., 1998)

Magnetic remanence

Magnetic remanence Magnetic susceptibility is measured while the sample remains in a very weak magnetic field while remanence properties are measured after the sample has been magnetised and removed from the field. The strength of the acquired magnetic remanence is measured in a magnetometer. Several methods exist for imparting the magnetic field but anhysteretic remanent magnetisation (ARM) and isothermal remanent magnetisation (IRM) are often measured routinely

ARM measurements require an a.f. demagnetiser, which generates a large and variable alternating magnetic field while a small constant magnetic field is superimposed parallel to one phase of the alternating field (Walden 1999). Results are reported either as ARM or as the susceptibility of ARM (χ_{arm}). χ_{arm} is selective of true stable single domain ferrimagnetic grains especially those between 0.025 and 0.1 μ m diameter (Maher 1988) and with grains outside this range, χ_{arm} decreases significantly. The parameter is concentration dependent and similar values could be produced by high concentrations of relatively coarse multi-domain grains (Walden 1999).

IRM can also be measured in a magnetometer after exposure of the sample to a magnetic field source such as a pulse magnetiser. A range of forward and reverse fields can be imparted and measurements made immediately afterwards. The purpose of many of these measurements is to obtain a semi-

quantitative description of the shape of part, or all, of the magnetic remanence hysteresis loop that describes the relationship between applied field strength and remanence at increasing and decreasing positive and negative magnetic fields (see Thompson and Oldfield 1986). These measurements can also be used to examine how a sample reacts to fields of gradually increasing field strength up to a maximum of ca. 1 Tesla (T) conventionally used as the field imparting a ‘saturation’ isothermal remanent magnetization (SIRM). (Measurements reported in this paper used a Molspin_ a.f. demagnetiser, and pulse magnetiser with a maximum field of 880 mT, to impart the ARM and IRM respectively) and a Molspin_ slow-speed spinner magnetometer to measure the remanence. The shape of the remanence hysteresis loop varies significantly depending on the type of mineral present and its grain size. At maximum field strengths, pure haematite produces a weaker SIRM at all grain sizes than magnetite, but magnetite usually approaches saturation more rapidly than haematite, which requires higher field strengths to impart a remanence

**Derived remanence
parameters**

The IRM/SIRM ratio at a backfield of 100 mT (the S ratio or HIRM when expressed in concentration units) has received most attention since pure magnetite normally saturates at low fields of ca. 100 m and a pure magnetite would produce a ratio of 1 (Walden 1999). Lower values suggest the presence of more resistant minerals, such as haematite. Higher values of the S ratio denote assemblages in which the magnetic properties are dominated by ‘soft’ (magnetite type) minerals, while lower values denote assemblages in which the magnetic properties are more strongly influenced by ‘hard’ (hematite type) minerals. It is important to distinguish between

dominance of the magnetic properties and dominance of the actual mineral assemblage. Because ferrimagnetic minerals have a much stronger susceptibility, ARM and IRM values per unit volume, they will dominate the magnetic properties even when hematite is many times more abundant.

Magnetic ratios

A large number of ratios can be calculated from the susceptibility and remanence measurements to determine either the magnetic mineralogy or the magnetic grain size. Only those directly related to the interpretation of the Qarun lake sediment sequence are included in this explanation. The ratios $\chi_{\text{arm}}/\text{SIRM}$ and $\chi_{\text{arm}}/\chi_{\text{lf}}$, are both related to changing magnetic grain size and would be expected to decrease as coarser magnetic grains dominate the sample signature. Changes in these ratios in lake sediments is often indicative of dissolution diagenesis which selectively removes the finer magnetic grains from the assemblage (Oldfield 1999). Major declines in all concentration parameters with depth in a sediment sequence may also be indicative of dissolution diagenesis (Foster et al. 1998).

Appendix 6: Ethical Clearance



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2014/05/27

ETHICS APPROVAL OF PROJECT

This is to certify that the next project was approved by the NWU Ethics Committee:

Project title :

Potential application of environmental radionuclides for sediment source fingerprinting in the Ngaka Modiri Molema District, North West Province

Project leader : Manjoro

Student: Nde Che

Ethics number: NWU-00016-14-A9

Status: S = Submission; R = Re-Submission; P = Provisional Authorisation; A = Authorisation

Expiry date: 2019/05/16

The Ethics Committee would like to remain at your service as scientist and researcher, and wishes you well with your project.

Please do not hesitate to contact the Ethics Committee for any further enquiries or requests for assistance.

The formal ethics approval certificate will follow shortly.

Yours sincerely

A handwritten signature in black ink, appearing to read 'Halgryn'.

HM Halgryn