Drinking water quality and farming practices on dairy farms in the greater Mangaung Metro, South Africa

By

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Submitted in partial fulfillment of the academic requirements for the degree of Doctor Technologiae: Environmental Health in the Department of Life Sciences, Central University of Technology, Free State.

Bloemfontein

December

2014

PREFACE

The experimental work described in this thesis was carried out in the Department of Life Sciences of the Faculty of Health and Environmental Sciences at the Central University of Technology, Free State, under the supervision of Professor Annabel Fossey and the co-supervision of Doctor Elsa Potgieter.

I hereby certify that this statement is correct, and as the candidate's promoters we agree to the submission of this thesis.

Professor Annabel Fossey

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Doctor Elsa Potgieter

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DECLARATION

I, **Leana Esterhuizen**, declare that

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(ii) This thesis has not been submitted for any degree or examination at any other university.

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ACKNOWLEDGEMENTS

I wish to thank the following people and organisations for their contribution to this thesis:

- My promoter, Professor Annabel Fossey, thank you for great leadership and mentorship. With you it is always less complicated.
- My co-promoter, Dr Elsa Potgieter, for being a friend and mentor and thank you for all those mugs of coffee. Thank you for keeping me on the right track.
- The Department of Life Sciences at the Central University of Technology, Free Sate, for support and use of the laboratory facilities and equipment.
- The Mangaung Metro Municipality, the environmental health practitioners for their assistance in identifying the dairy farms and the Microbiological laboratory for their guidance and support.
- The NRF for the Sabbatical grant that made my study leave possible and for funding the research project through a Thutuka grant.
- My friends for their encouragement and understanding over the duration of my period of study.
- Bev, my dear friend, I appreciate all your love and support.
- Thank you to my family. You all assisted in so many ways, thanks for all the meals, support, editing and assisting with the girls.
- To Christine and Ezeth, I love you both my angels, thank you for trying to understand my work and hectic schedule.
- Johnny, I am grateful for the support and motivation received from you.

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List of Abbreviations

AIDS	acquired immune deficiency syndrome
BOD	biological oxygen demand
COA	certificate of acceptability
COD	chemical oxygen demand
CCME-WQI	Canadian Council of Ministers of the Environment Water Quality Index
DAEA	Department of Agriculture and Environmental Affairs
DoH	Department of Health
DWA	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry
EC	electrical conductivity
EU	European Union
EHP	Environmental Health Practitioner
EPA	Environmental Protection Agency
FAO	Food and Agriculture Organisation of the United Nations
FDC	Free State Development Corporation
GPS	global positioning system
HIV	human immunodeficiency virus
HPC	heterotrophic plate count
IDF	International Dairy Federation
IGS	Institute of Groundwater Studies
ISO	International Organisation for Standardisation
IWRM	integrated water resource management
MDG	Millennium Development Goals
MPN	most probable number
MUG	4-methylumbelliferyl-β-D-glucuronide
NIST	National Institute of Standards and Technology

nse	normalised sum of excursions
NSF	National Sanitation Foundation
ONPG	ortho-nitrophenyl-β-D-galactopyranoside
SANS	South African National Standards
STATS SA	Statistics South Africa
TDS	total dissolved solids
UN	United Nations
USA	United States of America
UV	ultraviolet
VIP	ventilated improved pit latrine
WFD	Water Framework Directive
WISA	Water Institute of Southern Africa
WQI	Water Quality Index (Indexes)
W-WQI	Weighted Water Quality Index
WA-WQI	Weighted Arithmetic Water Quality Index
WHO	World Health Organisation

Abstract

Dairy farms produce large volumes of animal waste comprising of manure, urine and dairy wash water. In South Africa, dairy waste is usually discharged onto pastures and land by irrigation or flooding which has been known to pollute groundwater with faecally derived microorganisms and nitrates. This study was undertaken to assess groundwater quality on dairy farms in the greater Mangaung area of the Free State. Secondly, the minor aim was to investigate factors that may influence groundwater quality on the farms. These included farming management practices, dairy farm infrastructure and dairy farm waste disposal. Groundwater quality data was collected on 75 dairy farms in 2009. A follow-up study was undertaken in 2013, however, because many farms had ceased production, only 34 farms were included in this round.

The groundwater quality data of the 75 farms assessed in 2009 revealed that many farms were compliant with the South African National Standard for Drinking Water. However, 49% of the farms exceeded the limit for nitrates, 60% for total coliforms and 29% for *Escherichia coli*. When the data gathered on the 34 farms in 2013 were compared to the same farms' data of 2009, it was found that 45% of the farms in 2009 and 57% in 2013 demonstrated hardness levels that could pose a risk to sensitive consumer groups, such as infants, the aged and the immune compromised. The groundwater on many farms tested as hard or very hard, while the water on a few farms tested extremely hard. Since water is used in all dairy cleaning operations, these levels of hard water could add an additional cost to the running of a dairy by reducing the life span of equipment and increasing the amount of soap used.

On 18.9% of the farms in 2009 and 5.6% in 2013, the counts of coliforms exceeded 1 000 per 100 mℓ groundwater, posing a serious health risk for all consumers. Groundwater with counts of 10 – 100 coliforms per 100 mℓ could result in clinical infections in consumers, but counts of 100 – 1 000 coliforms could cause infections, even with once-off consumption. In this study, three of the 2013 farms (8.8%) demonstrated counts of *E. coli* greater than 100 per 100 mℓ, posing a serious health risk to the consumers. Counts in the region of 10 – 100 per 100 mℓ were observed in groundwater of 17.6% of the 2009 farms and 29.4% on the 2013 farms. Therefore, consumers on these farms are at risk of clinical infections. Furthermore, when such poor quality water is used in a dairy, the quality of raw milk and products may be affected. Moreover, the number of farms that presented a health risk increased from 41.2% in 2009 to 50.0% in 2013.

One of the most effective ways to communicate water quality information is through the use of an index which aggregates all water quality data into a single value. Through a review of literature, three prominent water quality indexes were selected, evaluated and modified; the Canadian Council of Ministers of the Environment (CCME-WQI), the Weighted (W-WQI) and the Weighted Arithmetic (WA-WQI). Environmental health limits were assigned to eight selected water quality parameters and Water Quality Index (WQI) values calculated using 2013 data. WQI values were categorised into five classes ranging from excellent to unacceptable. When these results were compared with a manual rating of the data, the versatile W-WQI provided the most accurate description of data. The index was then applied to the 2009 and 2013 groundwater quality data of 34 farms. Results revealed an improvement from 2009 to 2013, however, the change was not significant (p = 0.110). Overall, the quality of groundwater on these dairy farms is poor and could pose a health risk to consumers, farm animals and the quality of raw milk and products.

During 2013, management practices and infrastructural data were recorded on 34 dairy farms. All farms in this study depend on untreated groundwater for domestic and dairy activities. More than two thirds of the farms (85.3%) disposed of the dairy effluent by means of flooding or collection in shallow soil dams, while only five farmers re-used dairy effluent as fertiliser. The results also indicate that, although dairy farms vary in milk yield and size, they are designed and managed to prevent obvious groundwater contamination by dairy effluent. Possible correlations between farm management practices, infrastructure and the poor water quality revealed a weak negative correlation between the number of cows on a farm and the coliform values in the groundwater (R^2 = 0.0023). Also, no correlation existed between the number of cows on a farm and the *E. coli* values or the number of cows and the nitrate values in the groundwater. These results suggested that the link between groundwater pollution and farm management practices and infrastructure are not clear and in need of further investigation.

This study supports the findings that groundwater is vulnerable to pollution. In particular, the microbiological quality of the groundwater on the dairy farms was poor. The high levels of coliforms and *E. coli* in the groundwater confirm faecal pollution that could be indicative of poor sanitary conditions. This water contains high concentrations of microbial organisms and nitrates. Vulnerable groups on the farms are therefore at risk of becoming ill. Furthermore, the use of poor quality groundwater in dairy activities and other agricultural activities, such as the irrigation of crops, may further impact produce quality and could ultimately impact the health of consumers.

Chapter 1
Introduction

1.1 Introduction

Water is an important resource for all living organisms. Currently, water resources are under pressure (Bogardi *et al*., 2012). Climate change and the pollution of the environment are two major factors affecting water resources and the quality of the water (Sivakumar, 2011). Other activities impacting on water availability and quality include mining, industrial, recreational, domestic and agricultural practices. In the agricultural sector water is central to many activities; from crop and dairy production to animal husbandry, and is also used in domestic activities.

Water usage on dairy farms is twofold. Besides what is used by the cattle, water is used throughout the milking process. The milking process involves the extraction of milk from cows and the storing of it in bulk refrigerated tanks. Milk is then collected by milk buyers or transferred into smaller containers for further processing for the market. After milking, dairy parlours and all its equipment are thoroughly washed.

Dairy farm effluent, which refers to manure and urine deposited by cows during milking, is diluted during washing down of a milking dairy floor (Williamson *et al*., 1998; Hooda *et al*., 2000). Animal waste in dairy effluent is a major source of pollution through nutrient enrichment of streams and groundwater, which may in turn, have a significant impact on the environment (Wilcock *et al*., 1999; Ali *et al*., 2006; Atalay *et al*., 2008; Kay *et al*., 2008; Van der Schans *et al*., 2009). In South Africa, dairy farm effluent is discharged onto pastures and land by irrigation or flooding (Strydom *et al*., 1993) and has been proven to pollute groundwater (Tredoux *et al*., 2000). The direct impact on groundwater quality from dairy waste and manure management operations is not well-known nor studied. Due to the lack of data, there is not much guidance on the prevention of pollutant leaching into groundwater and groundwater monitoring on dairy farms (Harter *et al*., 2002). As a result, minimal guidance is available on how to effectively prevent groundwater leaching and how to monitor groundwater quality within dairy farming operations.

Dairy effluent contains a high bacteriological load (Fenton *et al*., 2011). Dairy effluent is released into the surrounding environment, either as a source of fertiliser or as a waste product. Faecally derived pathogens in the enriched water, such as *Escherichia coli*, reduce the water quality, which when used in a dairy parlour could reduce milk quality (Oliver *et al*., 2009b). Also, when bacterial enriched water is consumed, it could impact human health.

Animal manures are known to contain pathogenic bacteria, viruses and parasites (Pell, 1997) and pose a significant threat to human health through the consumption of water polluted by these organisms (Skerrett and Holland, 2000; Oliver *et al*., 2009b). An Environmental Protection Agency (EPA) report highlighted that the application of dairy waste onto the land is the main source of microbial pathogens in groundwater (Fenton *et al*., 2011). Organisms found in polluted water typically lead to gastrointestinal symptoms, such as nausea, diarrhoea and stomach cramps. The most common organisms include non-typhoidal *Salmonella*, *Giardia*, *Shigella*, *Campylobacter, Microsporidium* and *Cryptosporidium* (Lund and O'Brien, 2011).

The harmful effects of agricultural activities on groundwater (Gillingham and Thorrold, 2000; Dahiya *et al*., 2007; Monaghan *et al*., 2009) are becoming more and more of a concern worldwide (Santhi *et al*., 2006). Currently, manure handling and disposal practices in dairy enterprises are undergoing critical revision in order to reduce their impact on groundwater quality (Goss and Richards, 2008). The use of best management practices has been introduced in New Zealand and Australia (ARMC, 1999), while in the USA, the EPA developed the Agricultural Management Practices for Water Quality Protection (EPA, 2003). In Europe, the Water Framework Directive was developed with a specific section addressing water pollution from agricultural sources and how to protect water resources from agricultural pollution (WFD, 2000).

The water quality used in a dairy operation in South Africa must meet a set of minimum standards in order to comply with the conditions set out in Regulation R961 under the Foodstuffs, Cosmetics and Disinfectants Act, No. 54 of 1972. Clean, safe water is a requirement to obtain the certificate of acceptability (COA) under the Foodstuffs, Cosmetics and Disinfectants Act. The quality of water used in a food premises and dairy operation must meet the required standard, as prescribed in the South African National Standards 241 for Drinking Water Quality (SANS 241, 2011). Without a COA, farmers are not permitted to sell milk to bulk buyers nor to operate a dairy other than for private use.

Water used in urban settings is extensively monitored by public health officials to assure compliance with the SANS 241 requirements (SANS 241, 2011). The development of the Blue Drop scoring system in 2008 is to evaluate the water quality management of municipalities (DWAF, 2009a; DWAF, 2009b). The Blue Drop system is an incentive based programme, aiming to improve the water quality management throughout South Africa (DWAF, 2009b). This system is based on compliance to all water related legislation and regulations (National Water Act, No. 36 of 1998; Water Services Act, No. 108 of 1997 and SANS 241, 2011) and enforces a sampling plan with a specified sampling strategy. All municipalities and towns are scored biannually according to the criteria of the Blue Drop system by trained assessors representing Department of Water Affairs and Sanitation.

In rural and farming communities of South Africa, groundwater is the main source of potable water. These communities often have no other water source available (Van Tonder, 2009). In the Free State, the majority of the dairy farms is not within the municipal water supply network and thus do not have access to treated water. Instead, these farms utilise groundwater as their only drinking water source, as well as for all dairy related activities. Currently, rural water supply is not included in the Blue Drop municipal assessment and is thus not routinely monitored. Consequently, rural and farming communities are consuming groundwater without knowledge of its quality, possible health impacts and associated risk to milk products produced on dairy farms.

Long term impacts from dairy farming on groundwater quality are a concern because of the impact it has on drinking water quality (Van der Schans *et al*., 2009). This study was conducted because dairy farming was identified as a significant source of domestic groundwater contamination.

1.2 Aims and objectives

The main aim of this study was to assess groundwater quality on dairy farms in the greater Mangaung area of the Free State. The secondary aim was to investigate factors that may influence groundwater quality on dairy farms. These factors included dairy farming management practices, dairy farm infrastructure and dairy farm waste disposal.

More specifically, the project was broken down into the following objectives:

- to select dairy farms in the greater Mangaung area;
- to determine borehole drinking water quality on the selected dairy farms;
- to determine dairy farm management practices;
- to determine dairy farm infrastructure;
- to develop and calculate water quality index (WQI) for the dairy farm groundwater sources; and
- to derive appropriate recommendations to mitigate and control groundwater pollution.

1.3 Structure of thesis

This thesis comprises of eight chapters.

Chapter 1: Introduction

In chapter 1 the research project, together with the rationale, is introduced. The aims and objectives are also presented in this chapter.

Chapter 2: Literature Review

In chapter 2 a review of the literature pertaining to groundwater quality, with specific reference to dairy farming, is presented.

Chapter 3: Materials and Methods

In this chapter the study area is defined and the various methods are briefly described.

Chapter 4: Groundwater Quality on Dairy Farms Sampled in 2009

In 2009, the groundwater of 75 dairy farms in the Free State was sampled. Groundwater quality was assessed in terms of chemical, physical and microbiological parameters. The results of this study are presented in Chapter 4 as they were published in the journal *Water SA* in 2012:

> *Esterhuizen L, Fossey A and Lues JFR. 2012. Dairy farm borehole water quality in the greater Mangaung region of the Free State Province, South Africa. Water SA Vol. 38: 803-806.*

Chapter 5: Comparison of Groundwater Quality on Dairy Farms Sampled in 2009 and 2013

In 2013, the groundwater of the original 75 dairy farms was resampled. However, it was found that only 34 of them were still in business. Groundwater quality of these 34 dairy farms was reassessed, similar to the 2009 sampling season. During this sampling round, supplementary information of farming management practices and infrastructure was also gathered. In chapter 5 a comparison between the two sampling seasons is presented.

Chapter 6: A Water Quality Index for Groundwater on Dairy Farms

Water quality data comprises measurements of many parameters, making it difficult to interpret. The development of a single value that incorporates all relevant parameters into an index facilitates the understanding of the water quality. This chapter presents a water quality index that is suitable for groundwater measurements. The index is demonstrated using the water quality data generated in this study.

Chapter 7: Farm Management Practices and Infrastructure

In this chapter, the farm management practices and infrastructure data gathered for 34 dairy farms in 2013 are used in an attempt to explain the groundwater quality results from the dairy farms in this study. This chapter sets out to link the groundwater quality to the farm management practices and infrastructure.

Chapter 8: Conclusion and Recommendations

In chapter 8 the findings of this study are highlighted and discussed. Potential future studies are also presented.

Chapter 2
Literature Review

2.1 Introduction

South Africa is a moderately dry country and is listed as one of the 20 most water-scarce countries in the world (Levy, 2011). Mean annual precipitation is in the order of 450 mm (Claassen, 2010). In South Africa, freshwater sources, surface water as well as groundwater, are under pressure because of a growing population and expanding economy (Oberholster and Ashton, 2008). It is estimated that by 2025, South Africa's water demand will exceed its supply (Levy, 2011). Groundwater in South Africa has not been fully developed, where only 6% of the estimated available groundwater potential is currently being utilised. It is therefore reasonable to assume that in the near future, groundwater will be used to supplement current water supplies in South Africa (Levy, 2011).

Groundwater is central to domestic, industrial, agricultural and mining water supply, and currently contributes about 13% of the total water use in South Africa (Strydom, 2010). In many parts of South Africa, groundwater is the sole water supply with, for example, as many as 68% of the towns in the Free State are reliant on groundwater (Kotze *et al*., 2013). This is mostly attributable to financial constraints experienced by rural local water service authorities to provide water from other water sources (Rajkumar and Xu, 2011). The mean annual rural domestic and agricultural groundwater use in South Africa in 2004 has been estimated as being 1 389 million cubic litres per year (Strydom, 2010).

It is widely recognised that modern agriculture affects the wider environment, causing concern for various reasons (Delfs *et al*., 2013). Increasing use of fertilisers, size of farms, intense production practices, manure handling and disposal practices on animal farming operations, are currently undergoing critical revision to reduce their impact on water quality (Harter *et al*., 2002). Intensive agriculture is known to emit significant amounts of nutrients, particularly nitrogen and phosphorus, faecal bacteria and sediment (Hooda *et al*., 2000; Monaghan *et al*., 2007).

Contaminated groundwater poses a risk to consumers (Böhlke, 2002). Although groundwater used domestically is increasing worldwide, typically it is not treated to ensure the quality (Graham and Polizzotto, 2013). Groundwater sources in the agricultural set-up are known to contain faecally derived bacteria that cause disease and infections in sensitive groups, such as infants, the elderly and the immune compromised (DWAF *et al*., 1998; Dzwairo *et al*., 2006). Therefore, polluted water is not only a health concern, but may also impact on economic development and social prosperity (Vasanthavigar *et al*., 2010; Obilonu *et al*., 2013).

Groundwater is gaining importance in rural communities in the drier regions of South Africa, mostly because of the growth in agricultural activities, industrial development and mining, which significantly influence the quality of water (Adams *et al*., 2001). In the absence of appropriate sanitation measures, untreated water used as drinking water, can act as a passive way of transporting nutrients and harmful microorganisms into the body thereby posing a serious environmental and health risk (Ayodele, 2012).

2.2 Dairy farming in South Africa

Dairy farming is a major role-player in the agricultural sector in South Africa, contributing to economic development and sustainability of the country (DAFF, 2012). Farm configurations are diverse, composed of small enterprises with a few milk producing cows to large industrialised farms consisting of more than a thousand cows. When comparing the gross value of agricultural production, dairy farming is the fourth largest in South Africa, after poultry, cattle and cattle products, and maize production (Mkhabela and Mndeme, 2010). The South African dairy industry comprised of more than 4 000 milk producers in 2010, employing 60 000 farm workers and providing a further 40 000 indirect jobs within the dairy value chain (Mkhabela and Mndeme, 2010).

Dairy farming in South Africa has shown a steady decrease in the number of active smaller dairy farms since 2006, from 3 899 active producers to 2 083 in 2013 (Milk SA, 2013). This trend towards smaller dairy cow herds has also been identified in other parts of the world, for example in Ireland (Ruane *et al*., 2011). The high price of animal feed and the relatively low price for fresh milk have been put forward as the major reasons for this trend. In the period from 2006 to 2013, the reduction in the number of dairy farms in South Africa was 41.8% (Milk SA, 2013). Table 2.1 indicates the provincial distribution of dairy farms for the period from 2006 to 2013 showing the reduction of dairy farms in all provinces. In 2006, the Free State had the largest number of milk producers, followed by the Western Cape. In 2011, however, the Western Cape had overtaken the Free State to become the province with the largest number of producers. The province of Mpumalanga demonstrated the highest drop in number of active dairy farms, followed by North West and Free State (Milk SA, 2013).

All provinces in South Africa produce milk. Approximately 200 million litres of milk are produced per month, translating into 2 757 billion litres of milk per year (Milk SA, 2013). The provinces of Western

Table 2.1 Provincial distribution of milk producers, indicating a decrease over time (Milk SA, 2013)

Province	Jan 2006	Jan 2007	Jan 2008	Jan 2009	Jan 2011	Jan 2012	Sept 2013	% change 2007–2013
Western Province	878	827	815	795	683	647	573	–31
Free State	1 067	987	919	884	601	535	423	–57
KwaZulu-Natal	402	385	373	373	323	322	294	–24
Eastern Cape	422	420	407	387	314	283	271	–35
North West	649	596	549	540	386	352	253	–58
Mpumalanga	407	357	302	286	201	164	143	–67
Gauteng	275	245	228	217	127	126	121	–56
Northern Cape	39	37	34	37	28	21	21	–46
Limpopo	45	45	38	32	23	24	18	–53

* 2010 — Results not published

Cape, Eastern Cape and KwaZulu-Natal are responsible for approximately 75% of the total milk production of the country (Table 2.2) (Milk SA, 2013). The Eastern Cape and KwaZulu-Natal also boast as having the largest dairy farms in the country, while the farms in the Western Cape are comparatively smaller. The Free State is the fourth largest dairy producer with relatively small farms when compared to the major milk producing provinces.

Table 2.2 Provincial distribution of milk production and number of cows per producer in February 2012

Province	% Distribution of milk production	Number of cows in milk per producer	
		Mean	Median
Western Province	27.4	246	180
Free State	10.5	111	79
KwaZulu-Natal	23.5	425	315
Eastern Cape	24.3	536	365
North West	3.5	78	52
Mpumalanga	3.6	116	75
Gauteng	5.5	248	151
Northern Cape	1.0	188	112
Limpopo	0.7	207	105

(Table modified from MPO statistics, Milk SA, 2012)

Dairy farmers use a number of different dairy breeds. In South Africa, the major dairy breeds are Holstein-Friesland, Jersey, Guernsey and Ayrshire, of which Holstein-Friesland is the most popular, followed by Jersey (Gertenbach, 2005). Holstein-Friesland produces more milk per cow but Jerseys produce milk higher in protein and butterfat (Esterhuizen, 2013 personal communication).

The Holstein-Friesland breed are large animals and could be considered as dual purpose as the sale of cull cows can contribute to the income of the dairy enterprise (Gertenbach, 2005). The distinguishing aspects of this breed are the high yields of milk and good temperament facilitating ease of milking. Jerseys are the smallest breed, characterised by its leanness and very good udder and are known for their suitable temperament for dairying. Jersey milk is rich, high in butterfat, which influences the milk price of the producer as high butterfat content receives an incentive (KZN DAEA, 2013). Ayrshires are bigger than Jerseys but smaller than Holstein-Friesland, and also produce milk with higher butterfat than Holstein-Friesland breed (Gertenbach, 2005). Aspects to consider in selection of dairy breeds include heat resistance, sensitivity to stockmanship and their foraging ability. Jerseys are more resistant to heat than Holstein-Friesland. Ayrshire are good foragers but more sensitive to poor stockmanship than the other two breeds (KZN DAEA, 2013).

The Free State province has the second most dairy farms in South Africa. However, the dairy operations are relatively small, with the mean number of milk producing cows in the order of 100 per producer (Milk SA, 2013). Over the period 2006 to 2013, the Free State demonstrated a reduction of more than 50% in dairy production, declining from 1 067 in 2006 to 423 dairy farms in 2013 (Milk SA, 2013). The percentage of lactating cows in the Free State dropped from 18% to approximately 10% per farm of the total number of lactating cows in the country (Milk SA, 2013).

Milk production in the Free State is based on self-produced forage and grain, fed with concentrates in a mixed ration diet (Ndambi and Hemme, 2009). Few farms use pasteurisation and other processes to treat the milk on the farm. The majority of the Free State farms sell milk to bulk buyers, who process and distribute the products to retailers. Few dairy farms are located within the municipal boundaries and serviced with treated municipal water, therefore, most farms utilise mainly groundwater for all dairy operations, as well as for domestic use.

2.3 Factors influencing dairy production

Food safety is a major challenge in the African region. Factors contributing to this challenge include unsafe water, poor environmental hygiene, inadequate food-borne disease surveillance and inability of small and medium scale producers to provide safe food (Belli *et al.*, 2013). Milk and dairy products are considered as a high-risk category for food safety. Particular risk to food safety on dairy farms include microbial contamination, poor control of herd health, inadequately trained farmers and farm workers, and weaknesses in the processing chain (Belli *et al*., 2013).

2.3.1 Environmental hygiene

Poor hygienic practices in dairy productions can result in unsafe milk products. Through the application of microbiological hygiene practices consumers are protected against pathogenic agents. Milk has on many occasions been identified as a source of food-borne disease, even when pasteurised milk has been used (Adesiyun *et al*., 1995; Altekruse *et al*., 1998; De Buyser *et al*., 2001; Heuvelink *et al*., 2009). Four major areas are responsible for contamination of milk and dairy products on dairy farms:

- udder hygiene;
- hygiene of milking environment;
- hygiene of the equipment; and
- herd health.

Milk is a nutritious medium for many microorganisms. In the absence of mastitis, milk is secreted free of microorganisms. Milk quality is subjective to the microbial loading of the milk. Milk is sterile when aseptically drawn but is contaminated after secretion and during the milk production and processing operations (Gleeson *et al*., 2013). Milk is subjected to contamination from microorganisms moving up the teat canal, referred to as udder commensals. These commensals are present in small numbers and are mostly lactic acid bacteria (Frank and Hassan, 2003). Udders can also harbour pathogenic microorganisms (e.g. streptococci, staphylococci, enteric bacteria), especially in the case of clinical or subclinical mastitis (Belli *et al*., 2013). Milk can further be contaminated from the udder skin and hide, emphasising the need for udder hygiene.

Microbial contamination of surface areas, milking equipment and bulk tanks in dairies is mostly harmful and consequently affects milk and products (Salo *et al*., 2005; Nada *et al*., 2012). Microbial contaminants commonly found on contact surfaces include enterobacteria, lactic acid bacteria, micrococci, streptococci, pseudomonas, bacilli and fungi (Salo *et al*., 2006). Biofilm development might occur in the dairy when hygiene procedures are inadequate (Austin and Bergeron, 1995). Biofilms develop particularly in cooling systems, milk transfer lines, bulk tanks and other equipment, on floors and in drains (Salo *et al*., 2005). Bulk tank contamination occurs through contamination from the external surface of the udder and teats, milking equipment surfaces and from mastitis organisms within the udder (Jayarao *et al*., 2004; Elmoslemany *et al*., 2010). Milk-borne pathogens occurring in bulk tanks include *Campylobacter jejuni*, Shiga toxin producing *E. coli*, *Listeria monocytogenes*, *Salmonella* spp. and *Yersinia enterocolitica* (Jayarao *et al*., 2006). Microorganism counts in bulk tank milk provide information on the hygienic conditions of the various steps in milk production (Jayarao *et al*., 2004).

2.3.2 Dairy waste

The large volumes of solid waste and effluent generated by dairy farms present a serious environmental and human problem. Dairy waste pollutes surface water and groundwater and causes soil degradation (Sims *et al*., 2005; Barba-Gutiérrez *et al*., 2009; Bouma, 2011). The volume of waste and effluent generated on a farm depends on factors, such as the frequency of milking and the herd size (Healy *et al*., 2007). Dairy effluent comprises a diluted mixture of cattle faeces and urine, milk spillages, detergent and disinfectant residues, as well as chemicals that may have been dosed to the herd (Williamson *et al*., 1998; Hooda *et al*., 2000). Effluent is further characterised by:

- its high biological oxygen demand and chemical oxygen demand;
- high levels of dissolved or suspended solids, including fats, oils and grease; and
- nutrients, such as ammonia or minerals, phosphates and pathogens (Sarkar *et al*., 2006; Rodríguez *et al*., 2012).

The physical, chemical and biological characteristics of dairy effluent are highly variable between farms because of contrasting management of effluent, feed pads, wash down waters, chemicals, age and size of dairy herd breed, and stock management (Houlbrooke, 2008).

The land application of animal manure is cited as a major source of pathogenic microorganisms in surface water and groundwater systems (Jamieson *et al*., 2002). The application of dairy waste on land may result in pollution of water sources and impact soil quality (Ruane *et al*., 2011). Soil quality is defined as the capacity of a soil to function within an ecosystem, sustaining biological productivity, maintaining environmental quality and promoting plant and animal health (Zalidis *et al*., 2002). Excessive deposition of dairy waste may cause the alteration of soil properties and could result in soil malfunction and eventually to soil degradation (Zalidis *et al*., 2002).

To protect the environment and increase sustainability, all waste products on a dairy farm must be handled in a proper manner. The principles of waste management should be applied, namely reduce, re-use, recycle and dispose of waste products in an environmental friendly manner. All animal and human waste generated on the farm must be stored, managed and treated appropriately to reduce the risk of environmental pollution, such as pasture, feed and water contamination (SAI, 2009).

2.3.3 Water quality

Dairy effluent disposal practices impact surface water and groundwater quality (Harter *et al*., 2002). Dairy waste run-off pollutes streams and other surface water sources with sediment, nutrients, such as phosphorus and nitrogen and faecally derived microorganisms (Pell, 1997). Dairy waste ponds are point sources of groundwater pollution, contaminating groundwater with chemicals and microorganisms (Baram *et al*., 2014). Particularly in South Africa, groundwater is at risk of being contaminated since land and pasture application of dairy waste is the common disposal method employed by most dairy farmers (Strydom *et al*., 1993). The land application of animal manure is cited as a major source of pathogenic microorganisms in surface and groundwater systems (Jamieson *et al*., 2002). Dairy waste can create a number of pollution problems, including the loss of phosphates and nitrates in run-off, as well as the subsurface leaching of nitrates and faecal material into soil and groundwater (Ruane *et al*., 2011).

Raw milk is consumed on most dairy farms in South Africa and is also used for the production of homemade dairy produce. Washing with high quality water is essential to reduce the microbial contamination of raw milk (Rodríguez *et al*., 2012). When contaminated water is used for cleaning purposes in the dairy, the quality of raw milk may become compromised (Oliver *et al*., 2005; DSA, 2013). The presence of *E. coli* in washing water has been identified as a risk factor associated with poor quality raw milk (Perkins *et al*., 2009). High bacterial content of raw milk negatively impacts raw products, as well as the products' shelf-life (Millogo *et al*., 2010; Molineri *et al*., 2012). Thus, raw milk with a high bacterial count increases the probability of contamination of raw dairy products, which may pose a health risk to consumers, as well as impact on the pasteurisation process.

The domestic use of polluted water on dairy farms also poses a health risk to consumers and farm animals. High concentrations of *E. coli* and faecal coliforms in drinking water affect human and animal health and can cause gastrointestinal diseases (Pell, 1997). Animal health and weight gain may be impaired by poor water quality through diseases transferred by water.

Groundwater used on many South African farms exhibits particularly high levels of hardness (DWAF *et al*., 1998). Hard water generally poses no health risk for consumers, however, water that is very hard or extremely hard could result in chronic health effects in sensitive groups, such as the aged and immune compromised (DWAF *et al*., 1998). Furthermore, hard water causes scale deposition, particularly in heating appliances on the farm. The use of hard water in dairies could have a substantial economic impact because of an increased use of soap, electricity and appliance maintenance (Rubenowitz-Lundin and Hiscock, 2005).

2.3.4 Herd health

Nutritional management is the most important determinant of herd productivity (Roche, 2006). The relationship between nutrition and productivity begins at birth. The feeding system must deliver the necessary nutrients to each cow at the correct stage of lactation to maintain optimal productivity. Cows need a variety of macro- and micro-nutrients to maintain healthy growth. If any nutrients are lacking in the feed, there will be adverse consequences if essential nutrients cannot be provided by other means (EFSA, 2009).

Maintaining a healthy herd is essential to produce high quality, safe milk and to ensure optimal production and profitability. Unhealthy dairy cows produce milk that is lower in quality and less wholesome. It is therefore vitally important for dairy farmers to maintain healthy herds, which means reducing the prevalence of endemic diseases such as mastitis, Johne's disease, bovine viral diarrhoea and bovine tuberculosis (NFU, 2010). Mastitis is considered a disease that has the greatest financial impact on a dairy enterprise (Spanua *et al*., 2011). Mastitis is defined as inflammation of the mammary gland. It presents either as subclinical or clinical mastitis. Mastitis results in an increase in the number of somatic cells in milk, which is used as an indicator of udder health in the dairy herd. The symptoms of clinical mastitis are clearly visible. The causative microorganisms of clinical mastitis are *Streptococcus* bacteria, including *E. coli*, *Klebsiella* spp. and *Pseudomonas* spp., while microorganisms associated with subclinical mastitis include *Staph. aureus* and *Streptococcus agalactiae* (Borneman and Ingham, 2014).

2.3.5 Dairy farm infrastructure and management

There is a wide range of infrastructural designs commonly used on dairy farms. Some of the factors of importance determining the most suitable design include:

- herd health management;
- milk processing;
- waste collection and disposal;
- water quality; and
- hygiene systems (Baumgart-Getz *et al*., 2012).

Important physical factors to consider are:

- water sources and drainage;
- slope and topographic features of the area; and
- local meteorological conditions, such as wind patterns and rainfall data (Rogers, 2008).

To prevent groundwater pollution, it is recommended that a dairy should not be constructed in areas with a shallow water-table or in an area where there is a connection between the surface water and groundwater sources. Any design tends to be a compromise between many factors, as no single solution can be optimal for all farms (Andrews and Davison, 2002).

Milk produced on dairy farms can easily become contaminated from food spoilage bacteria due to unhygienic conditions during the handling, storage, cooling and transport of milk. Contamination of milk with bacteria can come from different sources, such as air, milking equipment storage, feeding, soil, faeces and animal health (Bytyqi *et al*., 2013). Therefore, care should be taken to prevent the contamination of raw milk. The structural design of a dairy should thus ensure the hygienic and safe production of milk. The structural design of the milking parlour should provide for smoothly finished, non-absorbing and corrosion-resistant material and must be free of any open seams and cracks and should facilitate easy and effective cleaning (DSA, 2013). All equipment used in the dairy should be adequately resistant to cleaning and disinfecting agents.

The quality of the animal housing plays an important role in animal health and performance. Attention should be paid to the space allowances in lying areas, access routes, feeding and watering areas and the overall ventilation (Bord Bia, 2013). Poor ventilation results in the build-up of toxic gases, which may lead to serious health problems.

2.4 Groundwater as resource

Groundwater is the largest water supply source for domestic water use in the South African Development Community (SADC) (Braune and Xu, 2008). Groundwater is a water resource, particularly in rural areas of South Africa, the mining industry, and is also used to supplement domestic water supply in urban areas. Groundwater contributes 13% of the total water consumption in South Africa, with more than 300 towns and approximately 65% of the population dependent upon groundwater for their water supply (Strydom, 2010). Groundwater, as a water source, has not been well exploited because of a lack of reliable hydro-geological information, as well as negative community perceptions and beliefs based on poor understanding of this resource (Colvin *et al*., 2008; Knüppe, 2011; Du Toit *et al*., 2012).

Groundwater is part of the hydrological cycle. During rainfall, some of the water is absorbed by the soil, which infiltrates deeply and accumulates in underground reservoirs known as *aquifers* (DWA, 2010). Between the soil surface and an aquifer is an unsaturated zone containing air and water. The upper level of the unsaturated zone is called the water-table. Aquifers vary in diameter, from a few centimetres to hundreds of metres, below the soil surface and are determined by geological and geo-hydrological factors. Groundwater occurs in fractures in the water-table (fractured aquifers) as well as in aquifers where interconnected openings are filled with water (DWA, 2010). Hard rock aquifers found inland contain groundwater in cavities that occur in the rock after the formation of the rock and are known as secondary aquifers (DWA, 2010).

In the Free State, groundwater abstraction is a common occurrence. It is well-known that many towns and villages in the rural areas are dependent on groundwater (Viles, 2007). In geological terms, the Free State is an extension of the Karoo Super Group. The common geology of the area includes shale, sandstone and mudstone ridges of the Beaufort Group, located in the Main Karoo Basin. The Main Karoo Basin overlies the central and eastern parts of South Africa (DWA, 2012; Gomo *et al*., 2012). The sedimentary geology of shale and mudstone is regularly associated with saline groundwater (Usher *et al*., 2007; DWA, 2012; Figure 2.1).

2.4.1 Composition and pollution

Groundwater contains natural contaminants arising from the geological strata. Groundwater chemistry is determined by the geology, topography, landscape and climate of the region, as well as

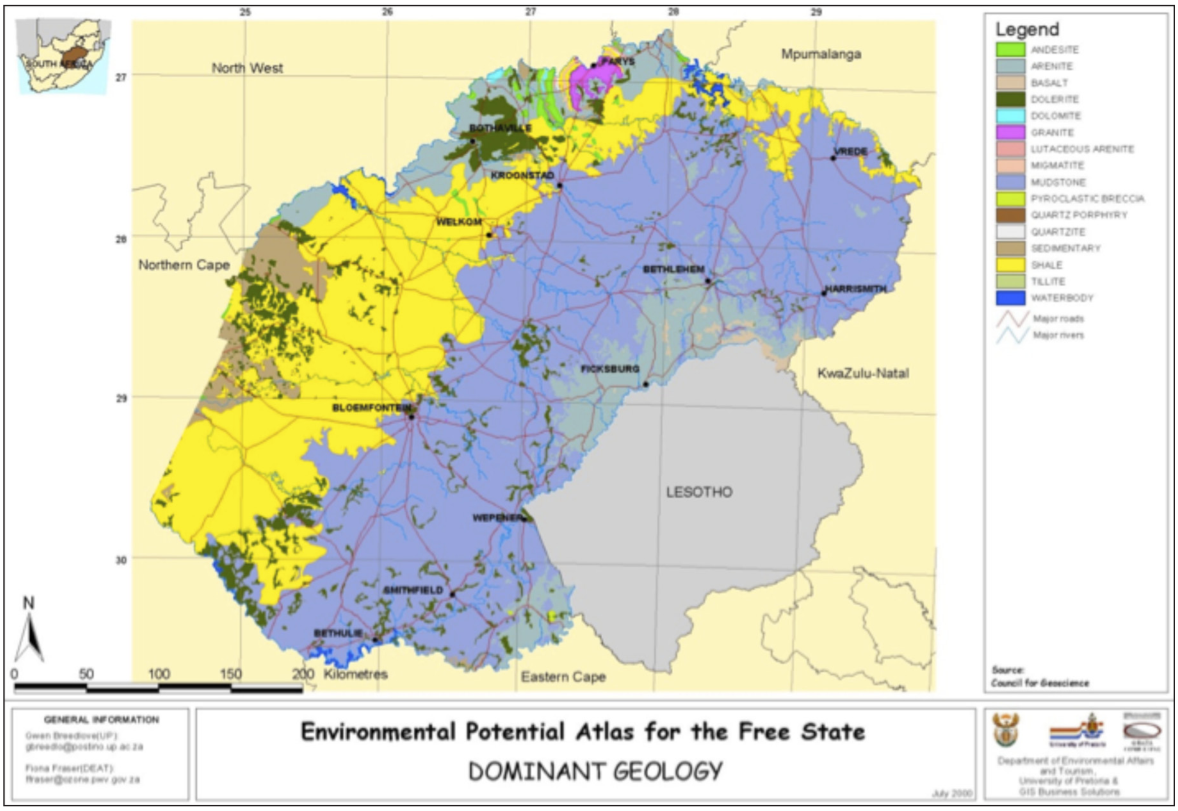

Figure 2.1 Dominant geology of the Free State (DEA, 2000)

anthropogenic activities (Fawell and Nieuwenhuijsen, 2003; Seth *et al*., 2014). Since groundwater occurs in association with geological materials containing soluble minerals, higher concentrations of dissolved salts are normally expected in groundwater relative to surface water. The type and concentration of salts depends on the geological environment and the source and movement of the water. Groundwater flows through almost all rocks and sediments below the water-table, at different speeds. The quality of groundwater is dependent upon the soluble products of rock weathering, duration of water in contact with rocks, the amount of dissolved carbon dioxide and also on the differences in the permeability and porosity of the rock formations (Seth *et al*., 2014). These conditions influence groundwater quality resulting in elevated concentrations of inorganic compounds, such as arsenic, fluoride and iron (MacDonald *et al*., 2012). The quality of groundwater is further dependent on the quality of recharge water, precipitation and surface water (Vasanthavigar *et al*., 2010). Resulting from the geology of the area, the chemistry of groundwater may give rise to unacceptable chemical concentrations rendering the water unfit for human consumption, for example, high sulphate in some parts of the weathered basement and mudstones and hardness in limestone aquifers or sandstones cemented with carbonate material (MacDonald and Davies, 2000; Mpenyana-Monyatsi and Momba, 2012).

Groundwater is also contaminated through anthropogenic activities, such as industrial chemical spills, agriculture spills, waste products, mining activates, as well as waste and effluent from intensive farming enterprises. Illegal dumping and improper disposal of industrial wastes lead to an increase in contamination of groundwater (Fawell and Nieuwenhuijsen, 2003). Once polluted, groundwater quality cannot be restored by preventing or stopping the pollution at the source (Dave *et al*., 2012). Organic chemical pollution of groundwater derives from leachate, organic compounds and chlorinated compounds, such as trihalomethans. Inorganic compounds impacting on groundwater quality include substances resulting from water treatment processes and pesticides or polluting products containing amounts of cadmium, barium, mercury, molybdenum and boron (Al-Khatib and Arafat, 2009). Other sources impacting groundwater quality include wastewater from treatment plants, abattoirs and industry; overuse of fertilisers and agricultural pesticides; and improperly managed landfill sites (Al-Khatib and Arafat, 2009).

Pit latrines and septic tanks are also sources of groundwater contamination, especially when the site selection is poor or when shallow pits are situated close to a borehole (Fawell and Nieuwenhuijsen, 2003). Other factors influencing groundwater contamination by pit latrines include the permeability of the soil and depth of the water-table (Ahaneku and Adeoye, 2014). Soil also plays an important role in the prevention of groundwater contamination by pathogenic organisms. The soil type and type of sanitation facility determine the effectiveness of the removal of pathogenic organisms by the soil (Ahaneku and Adeoye, 2014).

Guidelines for the construction of pit latrines aim to protect groundwater. These include:

- to locate the borehole at an area that is topographically higher than the site of the pit latrines;
- to dig the borehole more than 15 m away from the pit latrine; as well as
- to ensure the pit bottom of the latrine is more than 2 m above the water-table (Ahaneku and Adeoye, 2014).

Areas with shallow groundwater are more susceptible to pollution from pit latrines and septic tanks than areas with a deeper water-table (Graham and Polizzotto, 2013). Environmental factors play a role in governing groundwater pollution from latrines. Hydrogeological conditions are strong predictors of the threat of nitrate contamination of groundwater.

Dairy farming, in particular, is known to affect groundwater quality through inappropriate dairy waste disposal (Hudak, 2000). During the past two decades, various agricultural activities have shown to have a negative effect on groundwater in South Africa (Böhlke, 2002). In particular, faecal pathogenic microorganisms and nitrates are responsible for groundwater deterioration (Douagui *et al*., 2012). Nitrate leaching stem from agricultural sources, such as dairy yards, dairy effluent, waste ponds and fertiliser usage (Huebsch *et al*., 2013). Nitrate is regarded as the most widespread contaminant of groundwater, since nitrate is both soluble and mobile; it is inclined to leach through soils infiltrating groundwater (Nolan and Hitt, 2006). High nitrate levels are prevalent in groundwater throughout South Africa (Maherry *et al*., 2009; Figure 2.2).

Microbial contaminants, such as faecal coliforms adenoviruses, rotaviruses, and enteroviruses, have been identified in groundwater (Jamieson *et al*., 2002; De Oliveira *et al*., 2012). The presence of faecal pathogens in groundwater suggests that microorganisms penetrate groundwater and aquifers in rates of days and weeks, which is faster than recharging of groundwater (Taylor *et al*., 2004). The vulnerability of groundwater to microbial contamination is important because of the associated health risk, as the ingestion of low quantities ($<10^2$) of microbial pathogens and viruses may cause water-borne diseases (Taylor *et al*., 2004).

Changes in the physico-chemical parameters may have a major influence on biochemical reactions that occur within the groundwater. The electrical conductivity is a good indication of the amount of total dissolved salts in groundwater and indicates levels of salinity of the water (Usher *et al*., 2007).

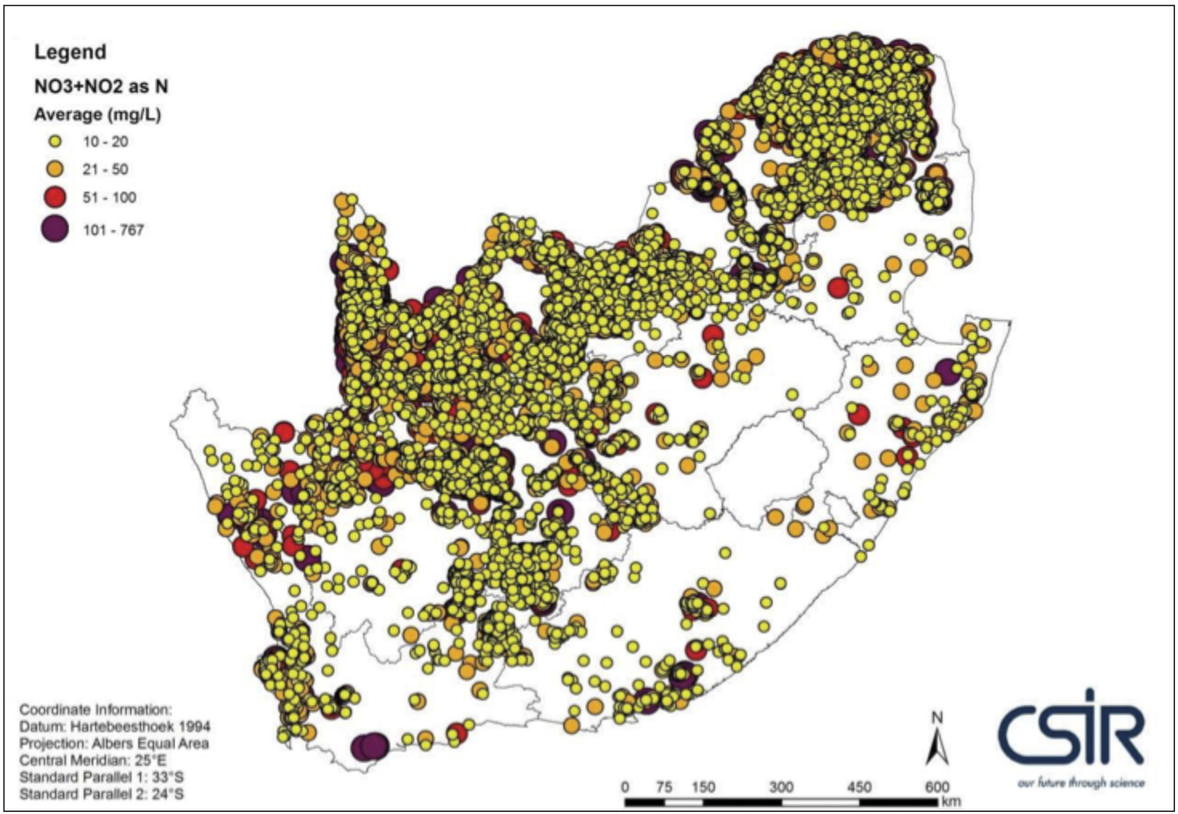

Figure 2.2 Average nitrogen greater than 10 mg/ℓ per sampling station (Maherry *et al*., 2009)

Thus, electrical conductivity is used as a measure of salinity, which measures the ability of water to conduct electricity.

2.5 Drinking water quality

The former United Nations (UN) Secretary General, Kofi Annan stated that: "*Access to safe water is a fundamental human need and, therefore, a basic human right. Contaminated water jeopardizes both the physical and social health of all people. It is an affront to human dignity*" (Ahmed 2010). Water quality is described by physical, chemical and biological characteristics of water in relationship with a set of standards (SANS 241, 2011; Obilonu *et al*., 2013).

Drinking water supply and quality have been the focus of numerous discussions and forums. These forums include:

- the 1977 World Water Conference in Mar del Plata, Argentina, which launched the water supply and sanitation decade of 1981–1990;
- Rio de Janeiro, 1992 Earth summit, (Biswas 2001);
- the Millennium Development Goals adopted by the General Assembly of the United Nations in 2000;

- the Johannesburg World Summit for Sustainable Development in 2002 (Rahaman and Varis, 2005); and
- the International Decade for Action, “Water for Life” from 2005 to 2015, declared by the UN General Assembly (WHO, 2008).

Many of the challenges faced by civilisation in the current century are related to water, specifically its quality and its quantity (Schwarzenbach *et al*., 2010). The importance of supplying safe drinking water has led to the establishment of regulations or guiding documents for the monitoring of the quality of water by different countries (Ongoley, 1999). These regulatory guidelines describe reasonable minimum requirements of safe practice to protect consumers from water-borne diseases (WHO, 2011).

The World Health Organisation (WHO) published the first and second editions of the Guidelines for Drinking-Water Quality in 1984 and 1997 and recently updated them in 2008 (WHO, 2008). These guidelines describe requirements to ensure drinking water safety, minimum procedures and the intended use. They are intended for countries to develop their own standards, regulations and mandatory limits (WHO, 2008). Consideration of these guidelines needs to be made in the context of local or national environmental, social, economic and cultural conditions in a particular country (WHO, 2008). They further describe guideline values and provide fact sheets on significant microbiological and chemical hazards (WHO, 2008).

The provision of drinking water of safe and acceptable quality is secured in most countries by a series of mandatory standards or advisory guidelines, using the WHO Guidelines for Drinking-Water Quality as a reference (Roccaro *et al*., 2005; WHO, 2008). The Safe Drinking Water Act of 1974 in the USA governs and regulates contaminants in drinking water. This act introduced the implementation of water safety plans (Blackburn *et al*., 2002). In the USA, this act is used in combination with the standards for drinking water quality set by the Environmental Protection Agency (EPA), that is responsible for overseeing compliance with the standards (EPA, 1999). The European Union countries have developed the EU Drinking Water Directive, 98/83/EC (EC, 1998). This directive prescribes standards for the most common physical, chemical and microbiological parameters that are used to determine water quality at point of use. The Drinking Water Standards of Australia are subject to the Australian Drinking Water Guidelines of 1996, which were developed by the National Health and Medical Research Council, together with the Agriculture and Resource Management Council of Australia and New Zealand. These documents are used along with relevant WHO’s 1993 guidelines (Stein, 2001). In Africa, Botswana implemented the National Conservation

Strategy (1990) and the Water Master Plan of 1991 to safeguard natural water resources (UNDP, 2003). The Botswana Standards, which were developed by the Bureau of Botswana Standards, describe the water quality standards and associated penalties for the breach of these standards. Water Quality in South Africa is regulated by legislation, as well as the South African Drinking Water Quality Guidelines (DWAF, 1996) and the South African National Standards for Drinking Water (SANS 241, 2011).

2.5.1 South African drinking water legislation and standards

The South African Water Act was promulgated in 1998 (Act 36 of 1998) and recognises that water is a resource that must be protected and managed. Government has a responsibility to provide water but also to ensure that it is protected and effectively managed. The aim is:

- to achieve sustainable use where communities will have access to water in terms of quantity as well as quality; and
- that there is provision for the day to day use of water, as well as for future needs.

The Act sets out to protect water quality by addressing pollution and to regulate bulk water consumption by licensing water use. Water must be managed in an integrated way, which will allow for delegation, in order to be more effective (National Water Act, 1998).

The Water Services Act, No. 108 of 1997 regulates the structure and the supply of drinking water in the country (Water Services Act, 1997). The purpose of this act is to provide national norms, standards and an institutional framework for the provision of water services (Water Services Act, 1997). This act addresses important issues such as:

- national standards and norms;
- the right of access to basic water supply and sanitation;
- a regulatory framework for water service institutions; and
- the collection and development of a national information system.

Various South African documents, specifically the Compulsory National Standards for the Quality of Potable Water taken up in Regulation 5 of the Water Services Act of 2001, have resulted in the development of the South African National Standards 241 for Drinking Water (SANS 241, 2006 and 2011). The SANS 241 (2006) was aligned with the WHO (2008) standards and was amended in 2011, resulting in the publication of SANS 241: Part 1 and Part 2 (SANS 241, 2011). The SANS 241 (2011) is a conclusive reference of acceptable limits for drinking water quality parameters at the point of delivery.

SANS 241 (2011) specifies the quality of acceptable drinking water in terms of physical, chemical, microbiological and aesthetic parameters at the point of delivery. According to SANS 241 (2011), drinking water quality at the point of use must show a 95% compliance with the standard over a twelve month period. Water that complies with SANS 241: Part 1 (2011) presents an acceptable health risk for lifetime consumption (average consumption of 2ℓ of water per day for 70 years). Water services institutions and water services intermediaries must ensure that water that they supply complies with the numerical limits provided by Part 1 of SANS 241 (2011), as prescribed in the Water Services Act of 1997. Water services institutions and water services intermediaries are required to monitor and maintain monitoring programmes, informed by the routine monitoring programme and risk assessment processes described in Part 2 of SANS 241 (2011).

2.5.2 Drinking water quality parameters

Drinking water quality is assessed according to the physical, chemical and microbiological parameters. The physical properties of water may affect the aesthetic quality of water and include taste, colour, odour, clarity (turbidity) and temperature of the water. The pH of water is also regarded as a physical property of water. On-site measurements are frequently used to measure the physical parameters, whereas the chemical and microbiological parameters are analysed in chemical and microbiological laboratories.

The chemical quality of drinking water is a result of the concentration of dissolved substances, such as salts, metals and organic chemicals (DWAF *et al*., 1998). The different chemical constituents present in water originate from natural sources, as well as from anthropogenic activities (Table 2.3).

Table 2.3 Sources of chemical constituents in water (modified from WHO, 2011)

Source of chemical constituents	Typical sources
Naturally occurring	Rocks, soils and the effects of the geological setting and climate
Industrial sources and human communities	Mining, manufacturing, processing, sewage, solid waste, run-off, fuel leakages
Agricultural activities	Manures, fertilisers, intensive animal practices and pesticides
Water treatment or materials in contact with drinking water	Coagulants, disinfection by-products, piping materials
Pesticides used in water for public health	Larvicides used in the control of insect vectors of disease
Cyanobacteria	Eutrophic surface waters

Most chemicals found in drinking water may become a health risk after many years of continuous exposure; the exception being nitrates (WHO, 2011).

The analytical methods used for inorganic and organic chemicals differ greatly. Some of these methods are more complex than others in terms of equipment and operation. Chemical analyses range from volumetric to more complex methods including spectrometry (Table 2.4). The chemical pollutants associated with agricultural sources are analysed at dedicated chemical laboratories that employ colorimetric methods, electrothermal atomic absorption spectrometry and gas chromatography methods (Table 2.4).

Table 2.4 Ranking of complexity of analytic methods for inorganic and organic chemicals from less complex to more complex (modified from WHO, 2011)

Ranking	Examples of analytical methods
Inorganic chemicals	
1	Volumetric method, colorimetric method
2	Electrode method
3	Ion chromatography
4	High-performance liquid chromatography (HPLC)
5	Plane atomic absorption spectrometry (FAAS)
6	Electrothermal atomic absorption spectrometry (EAAS)
7	Inductivity coupled plasma (IPC) / atomic emission spectrometry (AES)
8	Inductivity coupled plasma (IPC) / mass spectrometry (MS)
Organic chemicals	
1	High-performance liquid chromatography (HPLC)
2	Gas chromatography (GC)
3	Gas chromatography / mass spectrometry (GC / MS)
4	Headspace gas chromatography / mass spectrometry
5	Purge-and-trap gas chromatography, purge-and-trap gas chromatography / mass spectrometry

In drinking water, disease-causing pathogens are predominantly of faecal origin and therefore known as enteric pathogens (Ashbolt, 2004). Traditionally, microorganisms are removed from drinking water by filtration and chlorination. Pathogens responsible for cholera (*Vibrio cholerae*) and typhoid fevers (*Salmonella typhi* and *S. paratyphi*) are indicated by the common faecal indicator bacterium *E. coli*, which is excreted in the faeces of all warm-blooded animals and some reptiles (Ashbolt, 2004). In contrast, there are many enteric pathogens that behave differently to the indicator microorganism *E. coli* with respect to their resistance to disinfectant chemicals and their persistent occurrence in the environment. Chlorine-resistant microorganisms of concern include oocysts of the resistant parasitic protozoa *Cryptosporidium parvum* and various enteric viruses (Li *et al*., 2002). In the treatment of drinking water, it is imperative to match suitable indicators for particular groups of pathogens (Ashbolt, 2004).

It is not practical and also very costly to test for the presence of all potentially water-borne pathogens. Therefore, it is more practical to identify and use indicator organisms that represent these groups of pathogens. Different indicator organisms will thus represent bacteria, viruses, protozoa and helminths. The WHO proposes the following criteria for the selection of indicator organisms (WHO, 2011):

- water-borne transmission as a route of infection must be established;
- sufficient data should be available to enable a quantitative microbiological risk assessment;
- must occur in water;
- must persist in the environment;
- must be sensitive to removal or inactivation by treatment processes; and
- its infectivity, incidence and severity of disease known.

Different methods for pathogen detection measure different properties. Living microorganisms are detected by methods based on infection or growth, such as culture methods, broth cultures or agar-based bacterial media, whereas cell cultures are used for viruses and phages. Detection methods of the physical presence of a pathogen or its components, irrespective if it is alive or infectious, include microscopy, the presence of nucleic acids determined through amplification (for example, applying the polymerase chain reaction) and immunological assays (for example, enzyme-linked immunosorbent assays).

International methods have been established for the detection of microorganisms in drinking water. Before the adoption of these methods by a country, it is recommended that they are tested under local circumstances. Established methods, such as those of the International Organisation for Standardisation (ISO), can be tested and modified for local use by a country (Table 2.5).

2.6 Dairy standards

South Africa and many countries in the world have established regulations or minimum requirements for dairy production to ensure the safety of dairy products (CAC/RCP, 2004; NZFSA, 2009; Regulation 961, 2012). The purpose for developing and implementing minimum standards is to

Table 2.5 International Organisation for Standardisation (ISO) standards for the detection and enumeration of faecal indicator organisms in water (modified from WHO, 2011)

ISO standard	Title
6461–1: 1986	Detection and enumeration of the spores of sulphite-reducing anaerobes (clostridia) Part 1: Method by enrichment in a liquid medium
6461–2: 1986	Detection and enumeration of the spores of sulphite-reducing anaerobes (clostridia) Part 2: Method by membrane filtration
7704:1985	Evaluation of membrane filters used for microbiological analyses
9308–1: 2000	Detection and enumeration of *Escherichia coli* and coliform bacteria Part 1: Membrane filtration method
9308–2: 1990	Detection and enumeration of coliform organisms, thermotolerant coliform organisms and presumptive *Escherichia coli* Part 2: Multiple tube (most probable number) method
9308–3: 1998	Detection and enumeration of Escherichia coli and coliform bacteria Part 3: Miniaturised method (most probable number) for the detection and enumeration of *E. coli* in surface and wastewater
10705–1: 1995	Detection and enumeration of bacteriophages Part 1: Enumeration of F-specific cRNA bacteriophages
10705–2: 2000	Detection and enumeration of bacteriophages Part 2: Enumeration of somatic coliphages
10705–3: 2003	Detection and enumeration of bacteriophages Part 3: Validation of methods for concentration of bacteriophages from water
10705–4: 2001	Detection and enumeration of bacteriophages Part 4: Enumeration of bacteriophages infecting *Bacteroides fragilis*

prevent or minimise the contamination of raw milk and milk products. These hygiene standards should be uniformly adopted by all dairy farms and industries to ensure quality of milk and dairy products. To ensure ease of implementation, compliance measurements should be uncomplicated and easily executed (Ruegg, 2003). Dairy farm standards cover aspects such as: milk handling, herd health, milk composition and quality, and the presence of antibiotics (Hillerton and Berry, 2004). Contaminated water, pests in the dairy, chemicals such as cleaning agents and veterinary products, as well as the environment where the animals are kept or milked, may contaminate the feed, milking equipment or raw milk (CAC/RCP 2004).

Regulations Relating to Hygiene Requirements for Milking Sheds and Transport of Milk and Related Matters (Regulation 961, 2012) prescribe that all dairy farmers in South Africa should obtain a certificate of acceptability (COA) in order to supply raw milk to local consumers and bulk buyers. Dairy hygiene and hygienic milking practices are prescribed in the requirements of the COA under the headings:

- milking shed;
- milk containers and milking machine;
- handling of milk;
- health status of dairy stock;
- personnel hygiene; and
- milk handlers (Regulation 961, 2012).

Dairy farmers obtain a COA by firstly submitting an application to the local authority, after which an environmental health practitioner (EHP) will inspect the dairy and issue a certificate, if the farm complies with the requirements. Monitoring of compliance to the requirements of the COA is through inspection and sampling by EHP.

2.6.1 Infrastructure

In South Africa, according to Regulation R961 (Regulation 961, 2012), dairy farmers are required to have a dedicated dairy shed. Such a milking shed should consist of a milking parlour, a milk room, a change room and a scullery (DSA, 2013). The walls and floors of the shed should be constructed of material that is easily cleaned and the building is required to have a ceiling to limit dust and rodents. Flooring should allow for efficient drainage and cleaning (Regulation 961, 2012). The milk room should have a basin providing hot and cold water for cleaning equipment. A change room with a shower for staff, a hand wash basin with hot and cold water, soap and disposable towels should be supplied.

Specific guidelines have been developed for the protection of boreholes from pollution from sanitation facilities. Therefore, when groundwater is used in a dairy, the borehole head must be sealed to prevent contaminates entering the borehole and the area surrounding the borehole must be sustained to reduce and prevent groundwater contamination. Water storage tanks must have a cover to protect the water from contaminants entering the tank (Bord Bia, 2013).

Solid waste and effluent should be handled in such a manner to prevent contamination of raw milk and the herd. Dairy cows should be kept away from areas where waste is stored to minimise exposure to harmful contaminants and faecal material. Storage facilities of waste should be designed in such a manner as to prevent pest and rodent infestation (DSA, 2013). All waste generated in the milking shed must be removed by means of a pipeline or a cement ditch (Regulation 961, 2012).

2.6.2 Water quality

Specific guidelines prescribe the cleaning of a dairy shed and equipment with water of a specific quality and standard (SAI, 2009; Regulation 961, 2012; Bord Bia, 2013). According to Regulation R961 (Regulation 961, 2012), water used during the milking process must be of the same quality as for human consumption; complying with the South African National Standards for Drinking Water Quality (SANS 241, 2011), thus it must be free of harmful contaminants, such as faecal bacteria and other pathogens. Furthermore, the milking equipment, bulk tank, milk transportation truck and protective clothing of workers in a dairy must be cleaned and disinfected to ensure good hygiene practices, as well as to prevent potential contamination of raw milk.

The equipment used in the dairy, as well as the effectiveness of the chemicals used in the dairy, may deteriorate because of poor water quality (Corkal *et al*., 2004). Some of the equipment that could be affected in the dairy includes the nozzles and the boilers and geysers that could clog up because of the hardness of the water (Rubenowitz-Lundin and Hiscock, 2005).

2.6.3 Dairy herd health

According to Regulation R961 (Regulation 961, 2012), all aspects pertaining to herd health should be recorded to allow traceability. To promote and maintain herd health, the regulation prescribes that all dairy animals be distinctively marked and a complete medical record of each cow be kept. All veterinary treatments and dates thereof, as well as the drugs used, should be recorded. Good record-keeping will alert the herd manager or handlers on any action to be taken to maintain a healthy herd, thereby ensuring the production of safe raw milk. The regulation (Regulation 961, 2012) also states that, before-milking continues, the fore-milk of a cow must be visually examined to determine its health status, after which the fore-milk is discarded.

Milk should only be abstracted from animals in good health, ensuring the end product is safe (CAC/RCP, 2004). Cows suffering from tuberculosis, mastitis or brucellosis must be kept separate from the herd and the milk may not be used for human consumption (Regulation 961, 2012). It is advised that milk producers follow a regular inspection routine of all animals in the dairy herd, and these inspections should be increased during periods of calving and other vulnerable periods (Bord Bia, 2013). Milk from unhealthy cows or animals treated with veterinary drugs should be properly discarded until the withdrawal period of the drugs has been achieved (CAC/RCP, 2004; Regulation 961, 2012).

2.7 Water quality management

In 2000, the leaders of 189 member nations of the United Nations adopted the Millennium Declaration at the Millennium Summit in New York. This declaration included a series of collective priorities for poverty eradication, development and protecting the environment. This declaration resulted in the formulation of eight Millennium Development Goals (MDG) supported by 18 targets (UN, 2000). Target 10, which is part of the Environmental Sustainability goal, MDG no. 7, states that the world's population lacking access to safe drinking water and basic sanitation, will be reduced by half by 2015 (Schwarzenbach *et al*., 2010). Achieving this target may also positively impact child mortality, major infectious diseases, maternal health, as well as quality of life of people in poor communities (Hutton and Bartram, 2008). Between 1990 and 2010 more than two billion people gained access to improved drinking water, and the proportion of people using improved water increased from 76% in 1990 to 89% in 2010 (UN, 2013b). This progress is also true for South Africa with 90.8% of the population with access to safe water in 2012 (STATS SA, 2013). Although target 10 has been met ahead of time, there still is concern about the quality and safety of the water of a large number of improved water sources (UN, 2013b).

2.7.1 Integrated water resource management

Freshwater must be acknowledged as a limited and valuable resource, crucial to the sustainability of human life and the environment, but is also necessary for social and economic development. Thus, the goal of integrated water resource management (IWRM) is to manage and control water of a catchment, ensuring quality and quantity of water resources. It is the approach of IWRM to holistically manage water resources and to promote an organised awareness of all resources (Foster and Ait-Kadi, 2012). For IWRM to succeed, a multi-disciplinary approach should be followed involving water users and policy makers in the planning process (Foster and Ait-Kadi, 2012).

IWRM is based on the principal of vulnerability and loss. Vulnerability represents the potential for contamination or impact on the water resource caused by contamination hazards. Loss represents the economic, environmental or health impact resulting from the contamination of a water resource (Simpson *et al*., 2012). Therefore, municipalities need to implement water safety plans as part of their IWRM in the provision of safe drinking water (WRC, 2010).

2.7.2 Blue and Green Drop certification

In South Africa, the Blue Drop and Green Drop certification programmes were developed to improve water quality and water management. The Blue Drop and Green Drop certification programmes are flagship innovations by the Department of Water Affairs and Forestry (DWAF, 2009a). During 2008 these programmes were introduced as incentive-based regulation systems. The Blue Drop programme strives to improve the quality of municipal drinking water, while the Green Drop programme aims to improve wastewater management (Molewa, 2011). Municipalities and water service providers are scored according to set criteria. To obtain a Blue Drop, a score of 95% or more must be obtained (DWAF, 2009b). These scoring criteria encompass the current South African water legislation and the drinking water standard. By meeting the set criteria for a Blue Drop grading, the water service providers and municipalities are complying with the current legislation and meeting the drinking water quality standards.

Water used in urban settings is extensively monitored to assure compliance with the South African National Drinking Water Quality (SANS 241, 2011). The recent development of the Blue Drop scoring system to evaluate the water quality management of municipalities enforces a sampling plan with a specified sampling strategy (DWAF, 2009b). The majority of farms and many rural communities in South Africa do not have access to municipal water supply networks. Many of these communities utilise groundwater as their only source of drinking water, which is typically untreated and is not included in the municipal Blue Drop assessment (Graham and Polizzotto, 2013). Therefore, these water sources are rarely monitored and seldom treated (Knüppe, 2011).

The Green Drop certification programme scores municipalities on their ability to manage and treat wastewater. A Green Drop assessment focuses on the entire business of a municipal wastewater service. The risk analysis specifically addresses the wastewater treatment function (DWA, 2011). Poor wastewater treatment not only threatens the health of surrounding communities, but also the receiving water systems that supply water to communities and ecosystems (Van Vuuren, 2014). The success rate of Green Drop certification is currently less than that of the Blue Drop certification (Munnik, 2013). This may be because of the infrastructural maintenance backlog and need to train plant operators.

2.7.3 Water quality index

Water quality of any source is assessed using a variety of parameters, which include physical, chemical and biological parameters. A problem with water quality assessments is the complexity related to analysing and interpreting a large number of measured parameters together with their variability (Khan *et al*., 2005; Alobaidy *et al*., 2010; Zali *et al*., 2011). There is no single measurement that can describe water quality (Nasirian, 2007; UNEP, 2007; Alobaidy *et al*., 2010). Thus, a water quality index (WQI) uses all the data of a water quality assessment and reduces it into a single value (Štambuk-Giljanović, 1999; Nasirian, 2007; González *et al*., 2012; Tyagi *et al*., 2013). A WQI is one of the most effective methods to describe the quality of water. The use of a single value describing water quality, facilitates the understanding of water quality issues by non-water professionals, policy makers and the general public (Tyagi *et al*., 2013).

The first WQI was developed in the United States by Horton (1965) and applied in Europe since the 1970s, initially in the United Kingdom. It has also been used in Africa and Asia (Liou *et al*., 2004; Saeedi *et al*., 2010). Since Horton (1965) proposed the first WQI, several arithmetical methods to calculate an index have been developed. These methods include the aggregation of quality assessment data to produce an overall quality index. Some of the major examples include:

- the weighted averaging methods of Brown *et al*. (1970) and Štambuk-Giljanović (1999);
- weighted geometric means (Dinius, 1987); and
- hybrid methods (Dojlido *et al*., 1994; Swamee and Tyagi, 2000).

These indexes define a unique rating curve for each parameter, by which its values are interpreted, using a questionnaire, in terms of conceptual quality units, or some set of standards (Liou *et al*., 2004).

An index is a number that is dimensionless, expressing the relative magnitude of the collective water quality data. The WQI concept is based on the comparison of the water quality parameters with respective regulatory standards (Khan *et al*., 2005). An index is developed following four general steps (Boyacioglu, 2007).

- selection of the set of water quality parameters;
- development of sub indexes;
- weighting of the water quality parameters based on their relative importance; and
- the formulation of overall water quality index.

The Canadian water quality index is one of the few indexes that consider microbiological parameters in combination with physical and chemical parameters (CCME, 2001).

Some of the advantages of a WQI include:

- easy to understand by non-water professional;

- more emphasis on the status of water quality than on individual parameters; and
- an average of various parameters combining different measurements into a single value.

The main disadvantage of WQI is that some information of individual parameters and their interactions may be masked. The choice of the WQI method is dependent on the water to be assessed, which determines the number of parameters to be included in the calculation (Camejo *et al*., 2013). A WQI has also been successfully applied to assess groundwater, particularly in India. The WQI values of groundwater in Tumkur taluk were relatively high, mainly because of the high incidence of iron, nitrate, total dissolved solids, hardness, fluorides, bicarbonate and manganese (Ramakrishnaiah *et al*., 2009), while groundwater from the Kurmapalli Vagu basin was of poor quality because of high fluoride values detected (Srinivas *et al*., 2011).

The use of a WQI as a management tool in water quality assessment is a recent introduction (Muthulakshmi *et al*., 2013). Water managers and policy makers need precise and concise information about water sources for decision making purposes, which are provided by a WQI (Darko *et al*., 2013).

2.8 Water quality and health effects

The UN reaffirmed the importance of water to human health and wellbeing in the Human Right to Water and Sanitation, which entitles everyone to ‘‘sufficient, safe, acceptable, physically accessible and affordable water for personal and domestic uses’’ (UN, 2010). A step towards universal access to safe water is enshrined in the Millennium Development Goals (MDGs) Target 7c, which aims “to halve the proportion of the population without sustainable access to safe drinking water …’’ (UN, 2013a).

Water contamination is a major source of health problems, particularly in the developing world, where drinking water quality is poorly managed and monitored (Ul-Haq *et al*., 2011). Exposure to water-borne contaminants through ingestion of contaminated drinking water may pose a health risk to particularly high-risk population groups, such as infants, the elderly, pregnant women and immune compromised (Burkholder *et al*., 2007).

2.8.1 Chemical effects

Effects of agricultural activities and run-off increase the risk of nitrate pollution of surface water and groundwater (Hooda *et al*., 2000). High levels of nitrate in drinking water, in excess of 10 mg/ℓ, have been associated with a number of different health effects. There is an increased risk for methaemoglobinaemia (blue baby syndrome) in infants under six months of age, when nitrate-rich water is used in the preparation of infant formula (Burkholder *et al*., 2007). Other health factors associated with nitrate-rich water include diarrhoea and respiratory disease (Ward *et al*., 2005); increased risk of hyperthyroidism (Burkholder *et al*., 2007); insulin-dependent diabetes (Kostraba *et al*., 1992); and increased risks for adverse reproductive outcomes, including central nervous system malformations (Arbuckle *et al*., 1988).

Heavy metal pollution of the natural environment is a worldwide problem because these metals are indestructible and most of them have toxic effects on living organisms when they exceed acceptable limits in water (Batayneh, 2012). Heavy metals cannot be degraded, biologically or chemically, and thus may accumulate in water sources. Heavy metals in groundwater originate from the weathering of soils and rocks and a variety of anthropogenic activities. Water pollution by heavy metals is very prominent in areas of mining sites, although heavy metals of terrestrial origin could come from industry and urban development and other human practices (Saunders *et al*., 2005; Riekert, 2007).

Arsenic is a naturally occurring element found in groundwater (Saunders *et al*., 2005; Riekert, 2007), however, arsenic contamination also may result in industrial processes, such as metal refining and timber treatment (WHO, 2012). The health effects as a result of the consumption of arsenic-rich water include skin problems, such as colour changes, hard patches on the palms and soles and skin cancer (Carr and Neary, 2008). Other diseases known to be caused by arsenic exposure are cancers of the bladder, kidney and lung; and diseases of the blood vessels of the legs and feet; and possibly also diabetes, high blood pressure and reproductive disorders (Abernathy *et al*., 2003; WHO, 2008).

Excess lead in drinking water is a threat to the health of a population. Lead contamination of drinking water may have deleterious effects on multiple organs, including the nervous, haematopoietic, renal, endocrine and reproductive organs, especially in children (Ul-Haq *et al*., 2011). Lead exposure could result in developmental damage to a foetus, while acute exposure can cause vomiting or death (Palaniappan *et al*., 2010). Low-level ingestion of cadmium over a long period of time has been associated with kidney damage and can cause bones to become fragile and break easily (ATSDR, 2008). Copper, while also an essential mineral, in high concentrations can cause stomach irritation, nausea, vomiting, and diarrhoea (ATSDR, 2004). Fluoride is also a natural mineral with beneficial effects on teeth at low concentrations in drinking water, but excessive exposure to fluoride in drinking water can give rise to a number of adverse effects, such as mild dental fluorosis and crippling skeletal fluorosis, as the level and period of exposure increases (Fawell *et al*., 2006).

2.8.2 Microbiological effects

Infectious diseases caused by pathogenic bacteria, viruses and parasites are the most common and widespread health risk associated with drinking water (WHO, 2011). The burden of disease is determined by the severity and incidence of the illnesses associated with pathogens, their infectivity and the population exposed. Unlike many chemical agents, a once-off exposure can result in disease. Other typical properties of water-borne pathogens are listed in Table 2.6.

Table 2.6 Properties of water-borne pathogens (modified from WHO, 2011)

Properties of water-borne pathogens
Pathogens can cause acute and also chronic health effects.
Some pathogens can grow in the environment.
Pathogens are discrete.
Pathogens are often aggregated or adherent to suspended solids in water, and pathogen concentrations vary in time, so that the likelihood of acquiring an infective dose cannot be predicted from their average concentration in water.
Exposure to a pathogen resulting in disease depends upon the dose, invasiveness and virulence of the pathogen, as well as the immune status of the individual.
If infection is established, pathogens multiply in their host.
Certain water-borne pathogens are also able to multiply in food, beverages or warm water systems, perpetuating or even increasing the likelihood of infection.
Pathogens do not exhibit a cumulative effect.

Water related diseases caused by pathogens can be categorised into four major groups based upon epidemiological considerations: water-borne diseases, water-washed diseases, water-based diseases and water-vectored diseases. Water-borne diseases are those transmitted by the ingestion of contaminated water; and water-washed diseases are related to poor hygienic habits and sanitation. Water-based diseases is where pathogenic organism spends part of its life cycle in water or in an intermediate host, which lives in water; and water-vectored diseases are spread by insects, which breed or feed near water (Table 2.7).

Serious water related outbreaks of diseases have occurred in many regions of the world. Contaminated drinking water, along with inadequate supplies of water for personal hygiene and poor sanitation, are the main contributors to an estimated 4 billion cases of diarrhoea each year causing 2.2 million deaths, mostly among children under the age of five (WHO, 2000). The largest water-borne disease outbreak in the history of the United States occurred in 1993 in Milwaukee,

Table 2.7 Examples of water related diseases (modified from WRC, 2003)

Water relationship group	Water-borne disease
Water-borne	Cholera
	Giardiasis
	Infectious hepatitis
	Leptospirosis
	Paratyphoid
	Tularaemia
	Typhoid
Water-borne or water-washed	Amoebic dysentery
	Bacillary dysentery
	Gastroenteritis
Water-washed	Ascariasis
	Conjunctivitis
	Diarrhoeal diseases
	Leprosy
	Scabies
	Skin sepsis and ulcers
	Tinea
	Trachoma
Water-based	Dracunculiasis
	Schistosomiasis
	Malaria
	Onchocerciasis
	Sleeping sickness
	Yellow fever

when over 400 000 people became ill with diarrhoea because of *Cryptosporidium* in the drinking water (CDC, 2013). Cholera is endemic in many African countries, leading to recurring epidemics (Mintz and Tauxe, 2013). In Senegal, West Africa, a series of cholera outbreaks resulted in 31 719 cases with 458 deaths between 2004 and 2005 (De Magny *et al*., 2012). In South Africa, data from 2005 statistics indicate that 16 060 deaths per year (3.6%) can be linked to contaminated water (Nel *et al*., 2009). In September 2005, typhoid and diarrhoea outbreaks claimed 49 lives in Delmas, South Africa (Momba *et al*., 2009).

"Disinfection will remain the major technique of ensuring drinking water is free from water-borne microorganisms, but it must be seen as part of a larger integrated approach to water resource protection which will become increasingly difficult as global warming continues to create uncertainties in our climate" (Gray, 2014).

Chapter 3
Materials and Methods

3.1 Study area

The Free State is the third largest province in South Africa, with an area of approximately 129 825 km^2 (Gandure *et al*., 2013). The Free State province has an estimated population of 2.7 million and is estimated to grow at an growth rate of approximately 0.23% (FDC, 2014). The Motheo district municipality has the largest share of the province's population (FDC, 2014). Farming dominates the Free State's landscape with 3.2 million hectares of cultivated land, natural veld and grazing land. Agriculture can thus been seen as a key role-player in the province's economy. Agricultural produce includes, among others, maize, wheat, potatoes, sunflower, red meat, vegetables, cherries and dairy (FDC, 2014). Industrial development, agricultural activities and population growth are driving the increase water demand of the province (Woyessa *et al*., 2006).

The area is dry and has a typical Highveld climate with warm summers, low summer rainfall and cold winters. The calculated mean annual rainfall for the region is 545 mm and, because of the typical climatic conditions, the region is described as a semi-arid area (Akwensioge, 2012). High intensity thunderstorms in the summer months promote run-off in this region (Woyessa *et al*., 2006). The topography is diverse with lower altitudes in the southern and western parts and relatively high altitudes in the northeast and eastern parts of the province (Mokhele and Walker, 2012).

The Free State is located within the Karoo Super Group with most of the province composed of subdivided Ecca and Beaufort Groups. These groups are dominated by sedimentary rocks including sandstone, shale and mudstone (DWA 2012). The Beaufort Group is mainly characterised by sedimentary rocks deposited from the Middle Permian to the Middle Triassic Period. The Reddersburg area consists of sandstone, shale and mudstone deposited during the middle stage of the Beaufort Group, whilst the Dewetsdorp and Thaba 'Nchu areas consist of purple and green shale, and sandstone deposited during the upper stage. Geology around Bloemfontein includes sandstone, shale and mudstone of the lower stage of the Beaufort Group. An intensive array of dolerite dykes and sills can be found in Reddersburg, Dewetsdorp and Thaba 'Nchu, as well as the area to the northwest of Bloemfontein (DWA, 2012). During formation, extremely hot dolerite intruded into the sedimentary host rock, resulting in a baked contact zone. These baked zones are fractured and groundwater accumulates in these areas, making these zones the main target during groundwater exploration because it can easily be abstracted (DWA, 2012). Areas, including Dealesville, Bainsvlei and Petrusburg, are characterised by sandstone and shale from the Ecca and Beaufort Groups (DWA, 2012). In sedimentary areas with little or no intrusive dolerites, most groundwater is found in fractures and changes in lithology. This water is hard but usually low in natural nitrates (Usher *et al*., 2007).

In this study, 75 farms were identified in the central Free State with the assistance of Mangaung environmental health practitioners. In the 2013 follow-up study, many of the original 75 dairy farms have ceased dairy production and thus only 34 farms were included in this component of the study. When the comparative study was done later, only the 34 farms that had been sampled twice were used.

3.2 Study design

This study comprises two sampling seasons. During the first season in 2009, groundwater was sampled on 75 dairy farms in central Free State. Water quality was analysed in terms of 15 physical, chemical and microbiological parameters (Figure 3.1). During the follow-up study in 2013, 17 water quality parameters were studied.

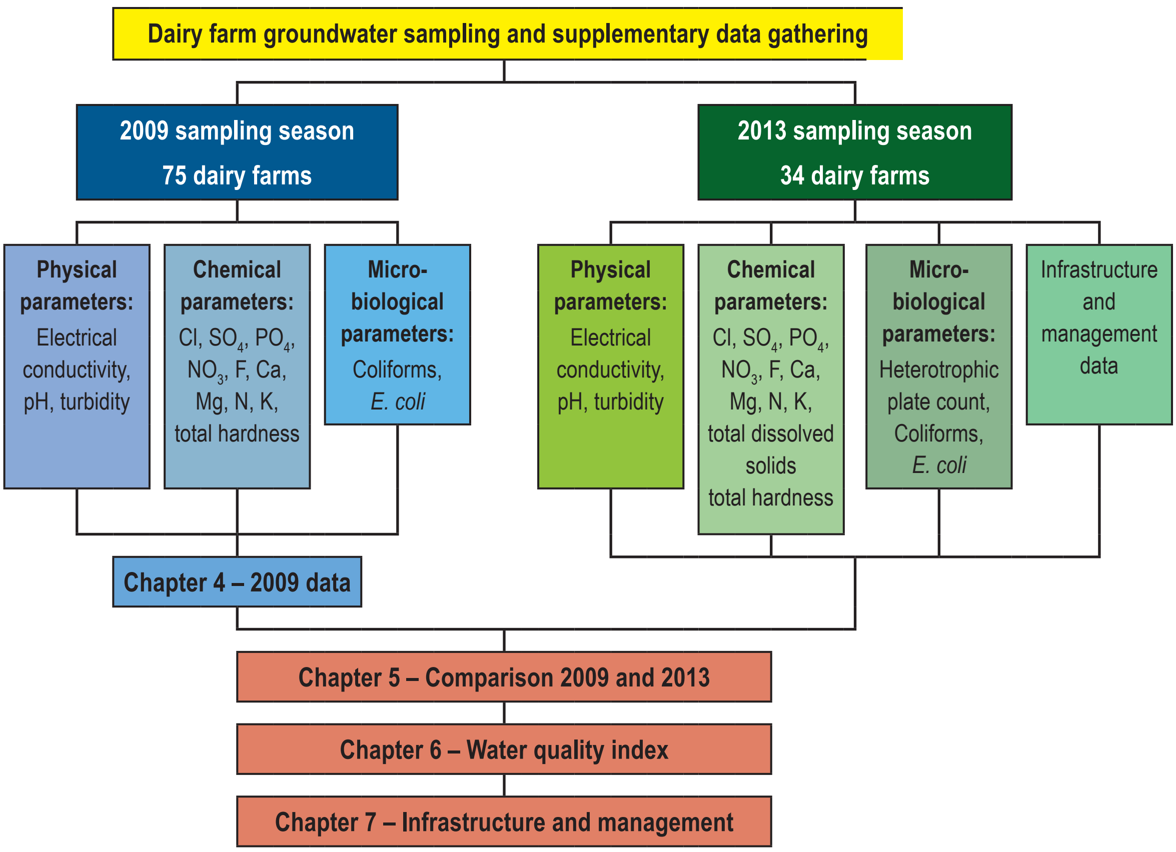

Figure 3.1 Study design

The measurements of the parameters of both years were compared to the South African National Standard 241 for Drinking Water Quality (SANS 241, 2011). The water quality data of 2009 were also compared to the water quality data of the follow-up study in 2013. The 2013 data were used to develop a water quality index (WQI) that is suitable to describe, in particular, groundwater quality. This WQI was then used on both the 2009 and 2013 data to compare the overall status of the groundwater quality on the participating dairy farms. The infrastructural and management information collected in 2013 was used in an attempt to explain the groundwater quality results.

3.3 Location of sampling sites

The dairy farms were selected with the aid of the Mangaung municipal health services division. Only farms in the area utilising groundwater were included in the study. The geographical positioning of the participating farms was recorded in 2009. The geographic positions of the 75 farms in the central Free State are depicted on the maps in Figure 3.2 and Figure 3.3. The farms are located mostly north of Dewetsdorp, but south of Dealesville.

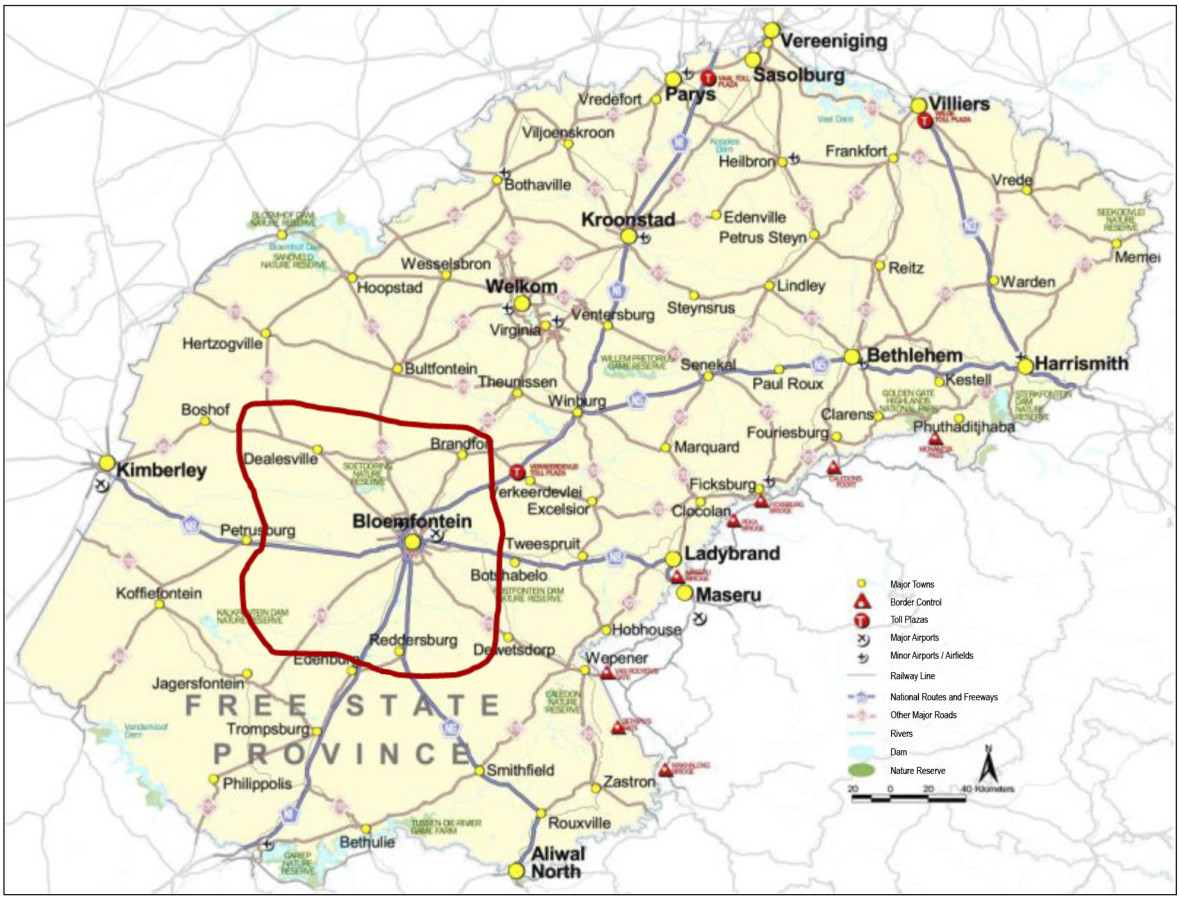

Figure 3.2 Free State map indicating the general location of the 75 farms sampled in 2009

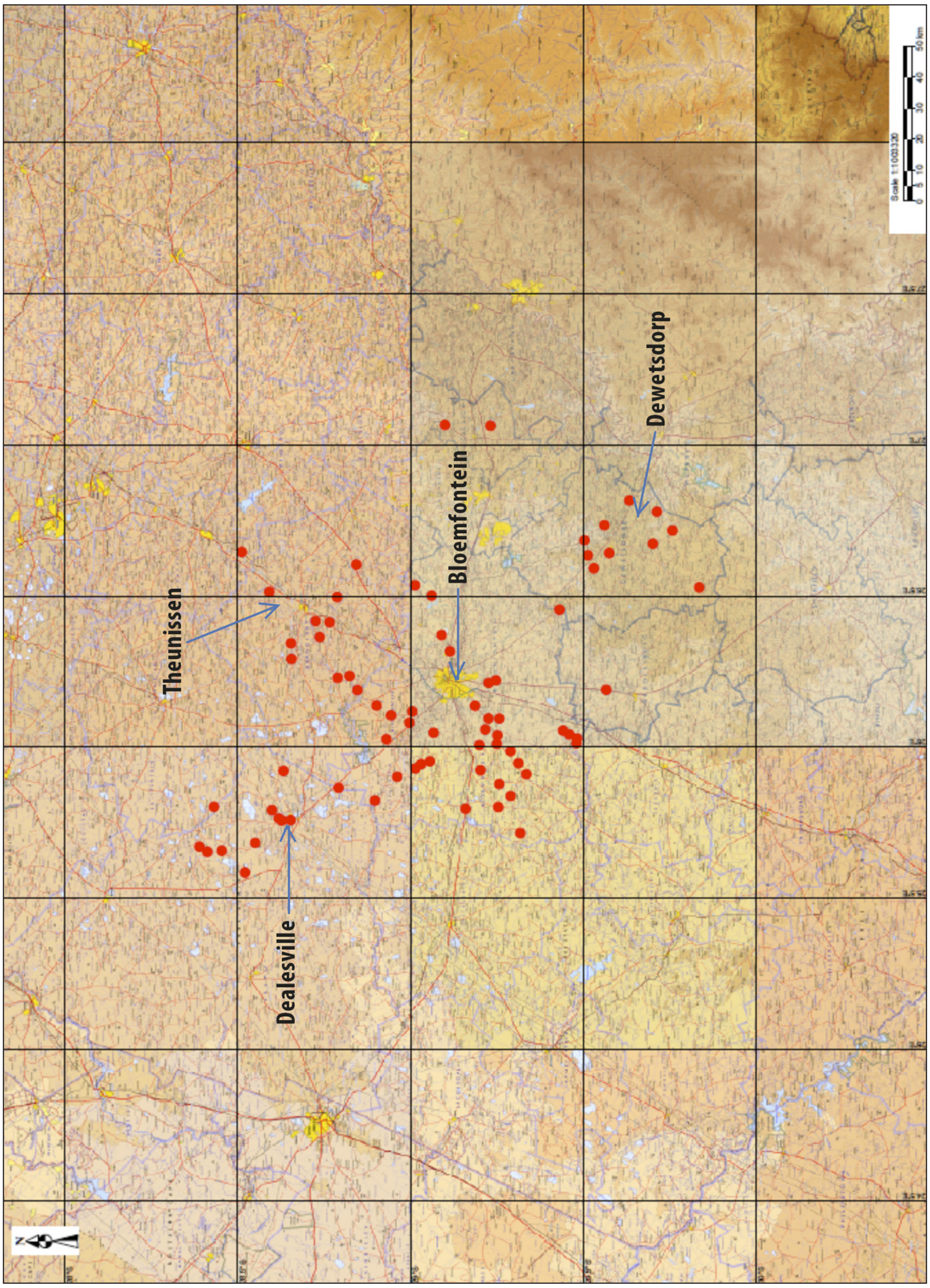

Figure 3.3 Map indicating the detailed positions of the farms with red dots

During the follow-up study in 2013, only 34 of the original 75 farms sampled in 2009 were still in production. Therefore, the number of the participating farms in 2013 was 34. Farm numbers and GPS coordinates of the participating farms in this study are listed in Table 3.1.

Table 3.1 Farm numbers and farm GPS coordinates of the 75 farms with the 34 farms in the follow-up study marked with an asterisk (*)

Farm number	GPS coordinates		Farm number	GPS coordinates	
	South	East		South	East
1	29.2499	26.0115	39*	28.5120	26.6464
2*	28.5914	26.5141	40	29.7134	26.7795
3*	29.0668	26.0483	41*	29.1596	25.7969
4	29.0902	26.3716	42	29.4803	26.0134
5*	29.3353	25.9114	43	28.5992	25.7927
6	29.3124	25.9475	44	28.6193	25.7652
7	29.8356	26.5289	45	29.2541	25.8026
8*	29.0141	25.9303	46	28.9969	26.0812
9	29.2573	26.0952	47	29.5308	26.5923
10	28.6534	25.7593	48*	29.5131	26.6354
11*	29.1141	26.3178	49*	29.2897	25.9870
12	28.6324	25.9222	50*	29.4312	26.4552
13	29.1867	26.1378	51	28.8434	26.6049
14	28.6540	26.3447	52*	29.6331	26.8164
15*	28.9615	25.9024	53	28.7658	26.4141
16*	29.2519	26.0398	54	28.8239	26.2358
17*	28.3891	25.6716	55*	29.2570	25.8786
18	28.8464	26.1896	56	29.4415	26.0555
19*	29.4595	26.0427	57	29.5611	26.7347
20*	29.0562	25.9537	58*	28.5209	25.5859
21*	28.6275	25.7584	59*	29.2166	26.0589
22*	29.7582	26.7174	60	29.2260	26.2132
23*	28.9017	26.1386	61	28.4538	25.6584
24	29.3176	25.7165	62*	29.0609	26.5022
25*	29.0056	26.1187	63*	29.0131	26.5362
26	28.8969	25.8239	64	29.2256	26.0959
27*	28.9439	26.1059	65	29.2896	25.8390
28	29.0308	25.9446	66	28.6555	26.2923
29*	29.5037	26.6851	67*	28.7920	25.8662
30	29.5750	26.6427	68	28.7895	26.2297
31	28.5504	25.6842	69*	29.4823	26.0294
32	29.7015	26.6738	70	28.7256	26.4182

Farm No.	GPS coordinates		Farm No.	GPS coordinates	
	South	East		South	East
33	29.0997	27.0664	**71***	29.5664	26.1907
34	28.7372	26.3649	**72***	28.7879	26.4974
35	28.9018	26.1386	**73**	28.4121	25.6546
36	29.2315	27.0639	**74**	28.4315	25.8033
37	29.2029	25.9245	**75**	29.2474	26.2214
38	29.0308	25.9446			

3.4 Methods

Standard sampling and analytical procedures were followed as prescribed by SANS 241 (SANS 241, 2011) and Department of Water Affairs (DWAF, 2006) for the physical and chemical parameters. For the microbiological analyses, the instructions of the manufacturers of Petrifilm® and Colilert®-18 were followed. Procedures are discussed in brief.

3.4.1 On-site sample collection and measurements

On-site water samples were analysed for physical determinants (turbidity, electrical conductivity, temperature and pH) at the tap. The taps were first sterilised by flaming with a portable gas burner for approximately one minute. After sterilisation, the tap was opened and left to run freely for approximately one minute, after which the sample was collected. For laboratory chemical analyses, sterile 500 mℓ bottles were used, while for microbiological analyses, sterile 100 mℓ bottles were used to collect water samples. All samples destined for the laboratory were labelled appropriately and placed in an icebox for transportation. For the on-site measurements, a battery operated HACH 2100Q turbidity meter was used to measure turbidity and a battery operated MARTINI MI 806 pH/EC/Temperature multi probe was used to measure temperature, pH and electrical conductivity (EC) (Figure 3.3).

Calibration and measurement of turbidity with the HACH 2100Q turbidity meter:

1. Water was collected at the source using a 250 mℓ beaker, after which water was poured into a cuvette and filled up to the 10 mℓ line.
2. The HACH 2100Q turbidity instrument was calibrated on-site using a calibration standard.
3. Immediately after calibration, the sample cuvette was inserted into the instrument and the turbidity reading recorded.
4. Between sample readings, the sampling cuvette was rinsed using distilled water.

(a) (b)

Figure 3.4 On-site measuring instruments: (a) HACH 2100Q turbidity meter; (b) MARTINI MI 806 multi probe

Calibration and measurement of pH, EC and temperature with the MARTINI MI 806 multi probe:

1. The MARTINI MI 806 multi probe was calibrated in the laboratory prior to departing on the sampling trip.
2. For pH calibration, the two point calibration procedure was followed. Buffer solution pH 7.00 (NIST) and pH 4.01 (NIST) were used in the calibration process.
3. For EC calibration, M10000 solution and MA9030 calibration solution were used.
4. On-site the appropriate mode was selected and the measurements for pH, EC and temperature were recorded.
5. At each sample site the sensor probe was rinsed using distilled water prior and after taking the measurements.

3.4.2 Laboratory measurements

All chemical parameters were analysed at the Institute for Groundwater Studies (IGS) of the University of the Free State in Bloemfontein, while the microbiological parameters were analysed in the laboratories of the Mangaung Metropolitan Municipality in Bloemfontein.

The chemical analyses that were conducted at the IGS laboratory included spectrophotometric analysis and ion-exchange chromatography. A spectrophotometer measures the amount of light at specific wavelengths while passing through a medium or chemical (Jones and Hemmings, 1989). A spectrophotometer operates at a specific wavelength range and a halogen lamp is used as the light source. The absorption rate of the medium or chemical is unique to each substance and therefore this instrument can be used to identify the substance and concentration values present. Ion-exchange is used to separate charged molecules to detect ionic compounds in water (Cummins *et al*., 2011). The IGS laboratory is not currently accredited but they do take part in proficiency testing as part of their internal quality control.

Measurement of coliforms and E. coli using the IDEXX (Colilert18) Quanti-Tray™ method:

The IDEXX (Colilert18) Quanti-Tray™ method is a biotechnological detection approach, which uses the multi-well most probable number (MPN) method. It incorporates a defined substrate medium, which contains *θ*-nitrophenyl-*β*-D-galactopyranoside (ONPG) and 4-methylumbelliferyl-*β*-D-glucuronide (MUG). After incubation at 37°C for 18 to 22 hours, coliform bacteria produce a yellow colour due to the production of *β*-galactosidase and *E. coli* produces blue fluorescence as a result of the action of *β*-glucuronidase under UV light (HPA, 2004). The MPN is calculated from the number of positive wells.

1. A Colilert 18 medium was added to the 100 mℓ water sample, gently shaken then left to stand for a few minutes allowing the medium to dissolve.
2. The 100 mℓ medium containing water sample was then poured into the Quanti-Tray®/2000, sealed and incubated for 18 to 22 hours at 37°C.
3. After incubation, the number of yellow wells was counted and MPN tables used to quantify coliforms.
4. After exposing the Quanti-Tray®/2000 to UV light, the blue fluorescent wells were counted and MPN tables used to quantify *E. coli*.

Measurement of total aerobic count using the Petrifilm® method:

The Petrifilm® method is used to enumerate total aerobic bacteria. Each plate contains nutrients; a coloured dye called triphenyl tetrazoliumchloride, which colours bacterial colonies red, and a cold water soluble gelling agent (Petrifilm™, 1989). The indicator dye and built-in grid allows for fast accurate identification of colonies within 48 hours. For each water sample, two aerobic plate counts were performed using the Petrifilm Aerobic Count plate method. One plate was used on an undiluted sample and the other on a 10 × dilution:

1. A Petrifilm Aerobic Count plate was placed on a flat surface.
2. The top film of the plate was lifted, after which a pipette was used to carefully dispense 1 mℓ of sample onto the centre of the bottom film.
3. The top film was then placed onto the sample.
4. The sample was then distributed evenly with a spreader using a gentle downward pressure and left undisturbed for approximately one minute to permit solidification of the gel.

5. Plates were then incubated in a horizontal position at 37°C for 48 + 3 hour, after which all red dots, regardless of size or intensity, were counted as colonies using a standard colony counter.

Chapter 4
Groundwater Quality on Dairy Farms Sampled in 2009

4.1 Introduction

An adequate supply of safe drinking water is one of the critical prerequisites for a healthy life. People's lives and livelihoods depend on water. Water of good quality and quantity is paramount to sustain life. The demand for clean water increases continuously with population growth. Many areas of the world lack fresh, drinkable water essential to the survival of humankind. It has now become evident that groundwater is one of the most valuable natural resources, which supports human health, economic development and ecological diversity (Ahmed, 2010).

Groundwater is an essential water resource for rural communities, providing for domestic, agricultural and industrial needs. It is estimated that groundwater provides 15% of all available water in South Africa (Mpenyana-Monyatsi *et al*., 2012). Groundwater is defined as the water that percolates into the ground and accumulates in both unconsolidated sediments and hard rock formations (aquifers) (Harter *et al*., 2002). Most groundwater occurs in the folded zones of the African platform (Xu and Usher, 2006). Groundwater sources include springs, wells and boreholes (Harter, 2001).

The lack of information on the groundwater quality in South Africa, as well as the geohydrological information, is well documented (DWAF, 2000; Knüppe, 2011; Pietersen *et al*., 2012; Owen, 2011). The situation in the Free State province is not different from the rest of the country (DWA, 2012). The quality of groundwater on farms is infrequently sampled, which results in the usage being of an unknown quality.

Globally, the dairy industry is expanding rapidly and the consequential impact on water quality has only recently been identified and studied. Effects of liquid waste, nitrates and pathogens from dairy activities on the environment and human health, have been investigated. These water constituents have all indicated elevated levels and a possible health impact to consumers (Chomycia *et al*., 2008). Dairy farming activities and waste have been identified as significant sources of domestic groundwater contamination (Van der Schans *et al*., 2009).

Dairy farms are inspected by environmental health practitioners (EHP) during health and hygiene inspections. Water samples from dairy farms are occasionally sampled for microbiological analyses by the EHP or the milk buyer. The sampling schedule is annually or as permitted by a particular municipal budget. Poor record-keeping, lack of data and infrequent sampling leaves the farming community, especially the infants, elderly and immune compromised, vulnerable to potential health impacts from poor water quality.

The data collected during 2009 was used to describe the quality of groundwater on 75 dairy farms. An article composed of this work was published in 2012 by Esterhuizen *et al*., (2012). "Dairy farm borehole water quality in the greater Mangaung region of the Free State, South Africa". Water SA. Vol 38 (5): 803-806. A copy of this article is presented in this chapter. These data were also used to produce a peer reviewed conference paper that was delivered at the WISA 2012 conference in Cape Town by Esterhuizen *et al*., 2012: "Pollution index for dairy farm borehole water quality in the Free State, South Africa". This conference paper is included as Appendix A.

4.2 Article

Abstract

Most dairy farm effluent is discharged onto pastures and land by irrigation and poses a risk on enriching groundwater, including borehole drinking water. Nitrate, coliforms and Escherichia coli (E. coli), in particular, may cause disease in humans and animals when drinking contaminated water. The aim of this study was to obtain an understanding of the status of borehole drinking water quality, including physical, chemical and microbiological properties, on 75 dairy farms in the greater Mangaung region of the Free State, South Africa. Borehole drinking water samples were collected during autumn and spring of 2009 and the physical, chemical and microbiological parameters analysed and compared to the required standards of South African National Standards 241 of 2006. Most farms were compliant; however for combined nitrate and nitrite,N, 37 of the farms exceeded the prescribed limit. Similarly, for total coliforms, 45 and for E. coli, 22 of the farms exceeded the acceptable limit. Nine of the farm boreholes were contaminated by N and E. coli. On one farm, the bacteriological parameters and four of the chemical parameters exceeded limits. Two farms presented similar chemical data, except for the E. coli being compliant. These data suggest further studies into water and waste management on dairy farms in the Mangaung region of the Free State.

Keywords: *water quality; borehole drinking water; water standards; E. coli; coliforms; nitrate*

Introduction

Dairy farming is a major contributor in the agricultural sector of South Africa, making a significant contribution to the economic development and sustainability of the country. Farm configurations are diverse; from small enterprises with a few milk producing cows to large industrialised farms consisting of more than a thousand cows.

All dairy enterprises utilise water for all the steps of the dairy industry, including cleaning, sanitisation, heating, cooling and floor washing. Dairy wastewater, or dairy effluent, is characterised by physical, chemical and microbiological parameters (Danalewich *et al*., 1998). In particular, it is known to have high biochemical and chemical oxygen demand; high levels of total dissolved solids, including fats, oils and grease; and nutrients, such as ammonia phosphates. As such, it must be treated (stabilised) appropriately before being discharged into the aquatic environment or re-used by disposal to land.

Faecally derived pathogens, such as the *Escherichia coli* (*E. coli*) strain O157:H7, can impact water quality and also human health, especially when the water is consumed without prior treatment (Oliver *et al*., 2009). It is well-known that surface run-off from land during excessive periods of rainfall or discharge from dairy farms, can pollute groundwater drinking water sources and have a significant adverse environmental impact on receiving surface waters (Atalay *et al*., 2008; Kay *et al*., 2008; Van der Schans *et al*., 2009). The harmful effect of agricultural activities on groundwater and surface water (Monaghan *et al*., 2009) is becoming more of a concern worldwide (Santhi *et al*., 2006). For example, elevated concentrations of ammoniacal nitrogen and phosphate found in receiving watercourses from farm effluent, are harmful to both farm animals and the indigenous wildlife, if used as drinking water sources and the aquatic micro- and macro-fauna within such water bodies. Equally of concern is the potential for groundwater sources to become contaminated, such as water is consumed as drinking water often without any further treatment. Therefore, it is important that farm effluent is adequately treated and stabilised before being allowed to discharge into water or disposed of onto land (Wilcock *et al*., 1999).

South Africa is a water-scarce country and the central region, which includes the Free State, is an arid area. In the Mangaung area of the Free State, surface water is limited to a few seasonal streams and the low flowing Modder River. The majority of dairy farms in this area are not close to any surface water sources and utilise groundwater (borehole water) for all dairy activities and for drinking water. Groundwater is the main source of potable water for the majority of rural and farming communities in South Africa. These communities often have no other available water source (Van Tonder, 2009). A study on the handling practices of dairy effluent in South Africa by Strydom *et al*. (1993) showed that most farm effluent was discharged onto pastures and land by irrigation. With the increasing growth of the dairy industry, together with the risk posed by dairy effluent, there is no doubt that measures to protect groundwater sources should be instituted. However, information about the impact of the dairy effluent on groundwater is limited (Harter *et al*., 2002), particularly so in South Africa.

The aim of this study was to obtain an understanding of the status of borehole drinking water quality, including physical, chemical and microbiological properties, on 75 dairy farms in the Mangaung region of the Free State, South Africa.

Materials and Methods

One borehole water sample was collected from 75 farms in the greater Mangaung region during autumn and spring of 2009. This central region of the Free State covers a surface area of 6 263 km^2 and hosts approximately 850 000 people. Samples were collected using the prescribed sampling methods of the Department of Water Affairs (DWAF, 2006), and standard sampling and analytical procedures as prescribed by South African National Standards (SANS) 241 of 2006. Fourteen parameters were analysed, namely, pH, electrical conductivity, total hardness ($CaCO_3$), chloride (Cl), sulphate (SO_4), phosphate (PO_4), combined nitrate and nitrate (NO_3), fluoride (F), calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), *E. coli* and total coliforms.

Summary statistics were calculated for the different parameters and correlations established between N and *E. coli* concentrations, NO_3 and coliform bacteria, as well as between coliform and *E. coli* concentrations. A water quality index (WQI) was calculated for each borehole to summarise the borehole water quality data. The WQI formula was devised by the Canadian Council of Ministers of the Environment (Saffran *et al*., 2001). The WQI were used to rank the boreholes according to excellent (values 95 – 100), good (values 80 – 94), fair (values 65 – 79), marginal (values 45 – 64) and poor (values 0 – 44).

Results

Generally, the physical and chemical properties of the borehole water of the 75 farms were within the prescribed SANS 241 (2006) limits, except for NO_3 (Table 4.1). The 10 mg/ℓ limit for N was exceeded by 49.3% of the farm boreholes, also demonstrated by the mean value, as well as the median value, being greater than the SANS 241 (2006) limit. When the N concentrations were compared to WHO (2008) standards, only two farms exceeded the limit of 50 mg/ℓ with values of 65.05 and 68.00.

Boreholes on 22 farms (29.3%) were found to be contaminated with *E. coli*, while more than half (60%) of the boreholes exceeded the prescribed SANS 241 (2006) and WHO (2008) limits for total coliform bacteria (<10 cfu/100 mℓ) and *E. coli* (0 cfu/100 mℓ), collectively (Table 4.2).

Table 4.1 Physical and chemical variables indicating statistics of borehole water quality of the 75 farms

Variable	(SANS 241 standard)	WHO standard **	Max	Min	Mean ± standard deviation	Median	No. farms exceeding
pH	(5.0–9.5)		8.30	7.10	7.64 ± 0.3	7.68	0
EC	(< 150 mS/m)		353.00	30.00	95.4 ± 48.6	81.50	6
Ca	(< 150 mg/ℓ)		406.00	24.00	90.7 ± 67.2	72.00	3
Mg	(< 70 mg/ℓ)		237.00	9.50	43.4 ± 35.8	33.00	7
Na	(< 200 mg/ℓ)		740.00	15.70	71.8 ± 85.7	57.40	2
K	(< 50 mg/ℓ)		158.00	0.30	10.5 ± 23.6	4.30	0
$CaCO_3$	(< 150 mg/ℓ)		1 314.00	3.60	304.2 ± 145.7	301.00	0
F	(< 1.0 mg/ℓ)	1.5 mg/ℓ	1.43	0.02	0.44 ± 0.3	0.40	3
Cl	(< 200 mg/ℓ)	5 mg/ℓ	533.00	10.50	80.3 ± 100.6	47.00	6
N	(< 10 mg/ℓ)	50 mg/ℓ	68.00	0.20	11.2 ± 11.7	9.60	37
PO_4	(0.1 mg/ℓ)*		5.46	0.04	1.5 ± 1.6	1.00	0
SO_4	(<400 mg/ℓ)		376.00	10.80	55.5 ± 54.1	43.50	0

EC = Electrical conductivity

( ) = SANS limit of variable not to exceed

* = United States Public Health Standard Limit

** = WHO Guidelines for drinking water quality (2011); standards of health concern

Table 4.2 Borehole bacteriological water quality statistics

Variable	Number of farms	Total coliforms* (10)	Total *E. coli* (0)
Maximum	75	>2 419**	1 414
Minimum		0	0
Mean ± standard deviation (sd)		171.11 ± 704.5	62.83 ± 323.9
No. of non-compliant farms		45	22

* Farms non-compliant because *E. coli* burden excluded from the Total coliforms

( ) = number of organisms not to be exceeded

** = values exceeding 2 419 were recorded as >2 419

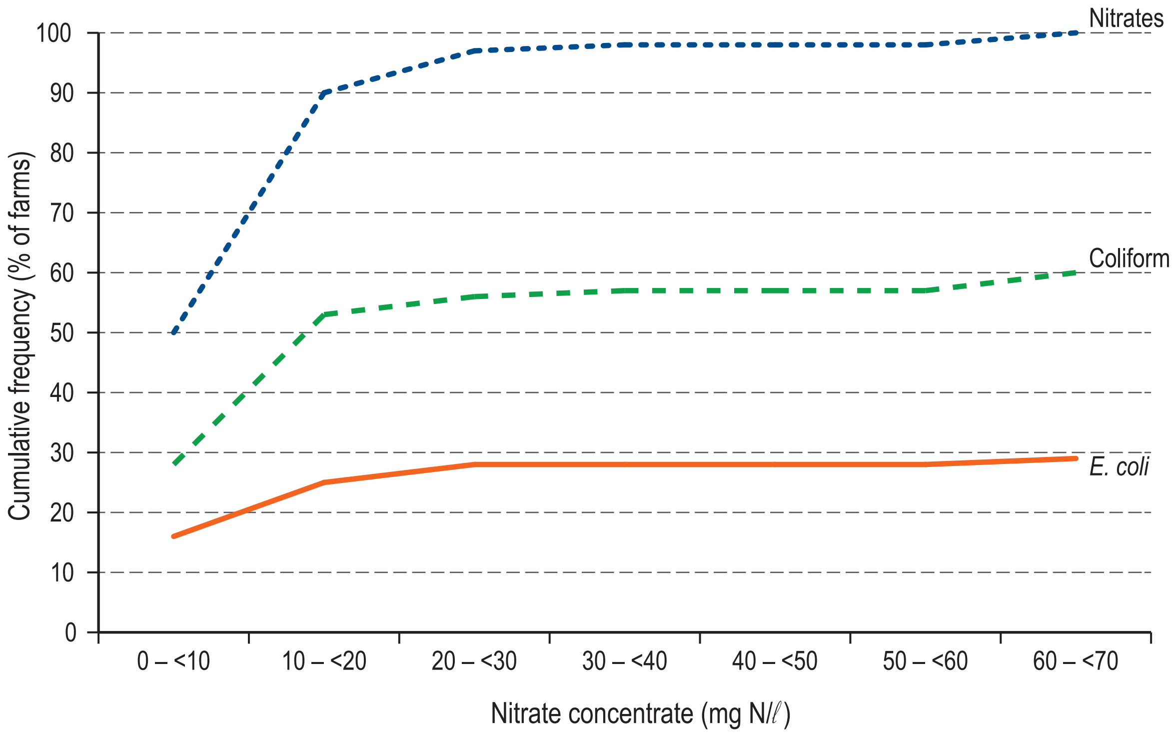

Figure 4.1 Cumulative frequencies for the two major groups of bacterial contamination (*E. coli* and coliform) and nitrates

Nine of the farm boreholes were found to contain elevated levels of N and *E. coli*, beyond the recommended SANS 241 (2006) standards. All the bacteriological parameters and four of the chemical parameters, including N, were exceeded by one of the 75 farms. Two farms presented similar chemical data, except for the *E. coli* being compliant; one farm with exceeding levels of Ca, Mg, Cl and NO_3; the other farm with exceeding levels of Mg, Na, F, Cl, and N.

There was a moderate positive correlation between N and *E. coli* concentrations ($r = 0.33$, $r^2 = 0.11$, $p = 0.004$), N and coliform bacteria ($r = 0.5$, $r^2 = 0.25$, $p = < 0.001$), as well as between coliform and *E. coli* ($r = 0.59$, $r^2 = 0.35$, $p < 0.001$) (Figure 4.1).

WQI of the boreholes ranged from 91.9 to 100, of which 68% of the boreholes were ranked as excellent and 32% as good.

Discussion and Conclusions

Dairy farm effluent, which refers to the dung and urine deposited during milking, is subsequently diluted during washing down of the milking shed floor polluting groundwater, drinking water sources and streams (Hooda *et al.*, 2000). Animal wastes are a major source of nutrient enrichment of streams from run-off from dairies (Wilcock *et al.*, 1999), and therefore groundwater quality has become a major concern, particularly because of salt and nitrate leaching, often demonstrated by heavy agricultural activities (Mohammad and Kaluarachchi, 2004). Therefore, manure handling and disposal practices in dairy enterprises are currently undergoing critical revision to reduce their impact on groundwater quality (Goss and Richards, 2008).

As dairy farming is a contributor of anthropogenic nitrogen worldwide, it was not surprising that some of these dairy farms displayed high N levels in the borehole drinking water. In this study, the enrichment of groundwater maybe attributed mostly to animal waste and run-off from the dairies. On some of the farms the NO_3 levels were exceptionally high, up to seven times greater than the specified health limit. These high toxic levels of nitrate are of concern for the expression of methaemoglobinaemia ("blue baby syndrome") in infants less than 6 months of age (Ward *et al*., 2005). Acute toxicity has been documented at concentrations of >50 mg/ℓ (Spalding and Exner, 1993) but methaemoglobinaemia has never been recorded at levels lower than 6 mg/ℓ (Kempster *et al*., 1997).

Although the WQI of all the farms were greater than 91, categorising the farms as either being excellent or good, it should be noted that nearly 30% of the farm boreholes displayed non-compliance to the national standard (SANS) 241 of 2006 for *E. coli*. *E. coli* numbers of six of the boreholes were between 10 and 100 organisms per 100 mℓ, which can be considered as being high-risk, whereas five of the boreholes were above 100 organisms per 100 mℓ, posing a severely high-risk to the users. Since these boreholes are the sole drinking water sources on these farms, humans and animals are therefore at risk for contracting gastrointestinal diseases (Pell, 1997).

The contaminated water could further contribute to the decrease of the quality of dairy products and other farming produce (Jones, 1999; Schneider *et al*., 2010). It can therefore be concluded that this baseline study strongly suggests that further studies should be undertaken to provide insights into water and wastewater management strategies on dairy farms in the Mangaung region.

Acknowledgements

The authors wish to thank Mr. Barns (Manager, Environmental Health) from the Mangaung Metropolitan for making the water quality data available for the study.

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Chapter 5
Comparison of Groundwater Quality on Dairy Farms Sampled in 2009 and 2013

5.1 Introduction

Due to the invisible nature of groundwater, this resource can easily be neglected or poorly managed. Changes in groundwater quality transpire over time and not as rapidly as in surface water (DWAF, 2000). To restore groundwater quality is challenging and very expensive. It has been reported that groundwater resources are poorly managed because of a lack of information regarding pollutants and information about the occurrence of groundwater pollution (DWAF, 2000). The quality of groundwater reflects inputs from the atmosphere, soil and water rock reactions as well as pollutant sources such as agriculture, domestic and industrial wastes (Odonkor and Addo, 2013). It has been stated that groundwater quality is currently deteriorating at a fast rate, mostly because of anthropogenic pollution, including septic tanks, landfill leachates, domestic sewage, waste produced in agricultural activities and from agricultural run-off (Odonkor and Addo, 2013). This pollution is mostly attributed to nutrient, chemical and pathogen loadings into groundwater as a result of point source and non-point source activities (EPA, 2003).

5.2 Methods

Of the 75 dairy farms sampled in 2009, 34 were still in production in the follow-up study in 2013. Therefore, to compare the groundwater quality data of the dairy farms, the 2009 data of the 34 productive dairy farms together with their 2013 data, were used in this comparison. The data of fifteen groundwater quality parameters were used, namely, electrical conductivity (EC), pH, total hardness, chloride (Cl), sulphate (SO_4), phosphate (PO_4), nitrate (NO_3), fluoride (F), calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), heterotrophic plate count (HPC), total coliforms and *Escherichia coli*. The TDS values, that were estimated by multiplying EC by the factor of 6.5, were included as the sixteenth parameter (DWAF *et al*., 1998). A *t-test* was used to determine if any significant change in groundwater quality occurred over time.

5.3 Results

Of the sixteen water quality parameters that were assessed, four parameters in 2009 and six in 2013 exhibited 100% compliance with the standard (Table 5.1). The three parameters, namely,

Table 5.1 Summary statistics of the water quality parameters measured in 2009 and 2013

Parameters	Limit standard (SANS 241)	Minimum		Maximum		Median		Mean (standard deviation)		% Compliance	
		2009	2013	2009	2013	2009	2013	2009	2013	2009	2013
EC	(170 mS/m)	54.00	44.50	231.00	282.00	79.15	96.66	98.69 (48.82)	96.66 (48.47)	89.19	97.05
TDS	(1 200 mg/ℓ)	351.00	289.25	1 501.50	1 833.00	516.10	541.45	635.89 (307.01)	620.40 (303.45)	89.19	89.19
pH	(5 – 9.7)	7.12	7.04	8.34	8.09	7.70	7.51	7.64 (0.33)	7.49 (0.25)	100.00	100.00
Total hardness*	(100 mg/ℓ)	3.59	10.00	471.00	1 544.77	294.00	309.85	281.10 (106.98)	375.53 (272.26)	8.82	5.88
Chloride (Cl)	(300 mg/ℓ)	12.00	19.83	462.00	474.10	45.00	54.30	91.56 (116.73)	88.71 (98.71)	91.10	97.05
Sulphate (SO_4)	(500 mg/ℓ)	15.00	14.60	194.00	266.19	42.00	45.94	55.19 (45.95)	60.26 (52.58)	94.59	100.00
Phosphate (PO_4)	(0.1 mg/ℓ)	0.10	<1.00	5.46	<0.10	0.25	<0.10	1.75 (2.47)	<0.32 (0.40)	97.05	100.00
Nitrate (NO_3)	(11 mg/ℓ)	0.39	0.65	68.00	79.18	10.76	12.79	13.79 (15.54)	15.02 (14.17)	58.82	41.17
Fluoride (F)	(1.5 mg/ℓ)	0.13	0.08	1.43	0.96	0.38	0.35	0.41 (0.25)	0.38 (0,19)	100.00	100.00
Calcium (Ca)	(150 mg/ℓ)	38.40	10.70	406.00	295.71	72.95	67.41	107.90 (94.09)	81.61 (50.89)	85.29	94.11
Magnesium (Mg)	(70 mg/ℓ)	11.10	3.94	152.00	196.46	34.25	35.46	47.23 (33.89)	44.58 (34.30)	100.00	97.05
Sodium (Na)	(200 mg/ℓ)	15.70	21.23	142.00	162.91	53.60	63.69	66.49 (33.89)	66.22 (32.77)	100.00	100.00
Potassium (K)	(50 mg/ℓ)	0.33	0.19	158.00	10.65	4.09	3.97	14.62 (34.72)	4.47 (3.00)	94.11	100.00
Heterotrophic plate count	(1 000 counts/100 mℓ)	0.00	3.00	9 500.00	21 000.00	87.00	90.00	594.59 (1.00)	984.82 (3 592.77)	82.35	97.41
Total coliforms	(<10 counts/100 mℓ)	0.00	0.00	720.00	2 419.00	21.00	11.60	354.70 (720.44)	272.02 (596.11)	23.52	44.12
E. coli	(not detected in 100 mℓ)	0.00	0.00	415.00	45.00	0.00	0.00	84.50 (399.13)	4.15 (10.18)	32.43	58.88

( ) = Standard limit according to SANS 241 (2011); EC = electrical conductivity; TDS = total dissolved solids; * slightly hard (DWAF, 1996) nitrate, *E. coli* and total coliforms showed relatively low compliance across the farms and years. Approximately 33% of the farms were non-compliant for *E. coli* and more than 50% for total coliforms in both sampling years. For hardness, almost all the farms were non-compliant in both sampling years. *T-tests* revealed that only three of the parameters demonstrated a significant change from 2009 to 2013, namely:

- pH (t = 3.165; p = 0.002);
- hardness (t = 2.113; p = 0.021); and
- potassium (t = 1.743; p = 0.0453).

The results demonstrated that the pH value and potassium levels of the water reduced during the study period, while the harness levels increased. From this study and available analyses, it is difficult to ascertain the origin for the change in the water quality. It can be concluded that the increase of hardness is as a result of another chemical and not from the potassium.

5.3.1 Health and economic implications

Hard water generally poses no health risk to consumers; however, water that is very hard or extremely hard could result in chronic health consequences for sensitive groups, such as infants, the aged and immune compromised (DWAF *et al*., 1998). In this study approximately 45% of the farms in 2009 and 57% in 2013 demonstrated hardness levels that pose a risk to the sensitive consumer groups (Figure 5.1).

Hard water used for domestic purposes results in scale deposition, particularly in heating appliances, and also increases the use of soap (Rubenowitz-Lundin and Hiscock, 2005). The groundwater on many farms tested as hard or very hard, while the water on a few farms tested extremely hard (Figure 5.1). Since water is used in all dairy cleaning operations, these levels of hard water could add an additional cost to the running of a dairy by reducing the life span of equipment and increasing the amount of soap used.

More than 50% of the farms studied in both years demonstrated levels of nitrates that could pose a health risk. Of particular concern were the few farms with levels of nitrates exceeding 40 mg/ℓ which poses an acute risk for babies (DWAF *et al*., 1998) (Figure 5.2). Drinking water containing nitrate at levels that exceed 50 mg/ℓ will be the major source of total nitrate intake, especially for bottle-fed infants (WHO, 2011). Furthermore, nitrate poisoning of livestock could result in animal losses (Tredoux *et al*., 2000). Other adverse health effects in animals include increased incidences of abortions and stillborn calves, lower milk production and reduced weight gains (Tredoux *et al*., 2004).

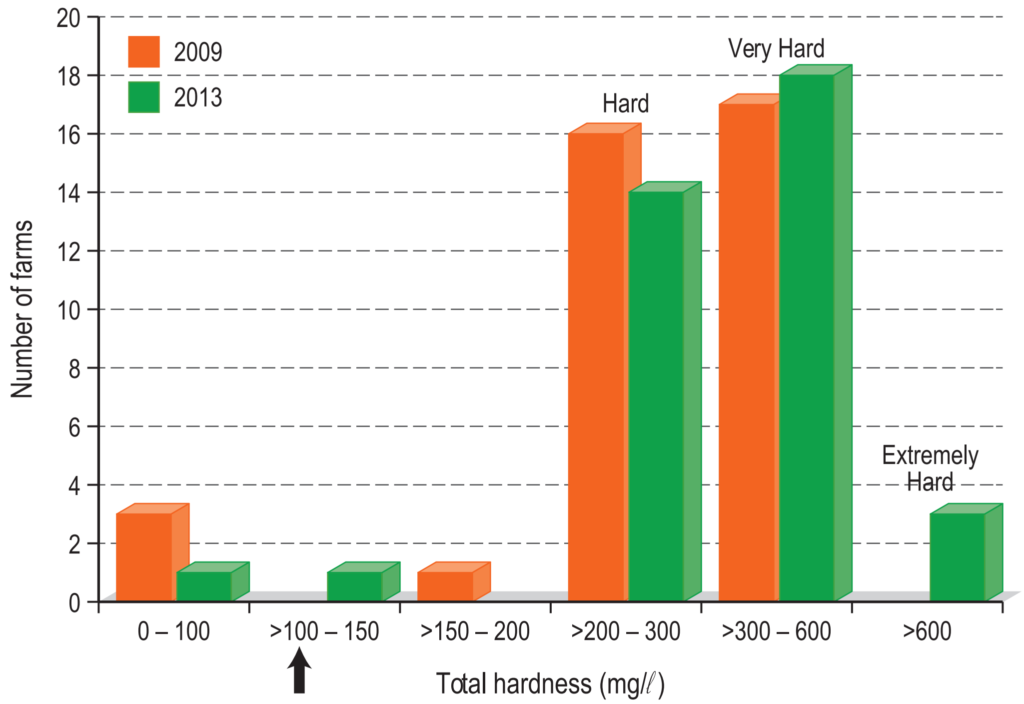


Figure 5.1 Distribution of measurements for total hardness (arrow indicates the limit of the South African standard (DWAF *et al.*, 1998))

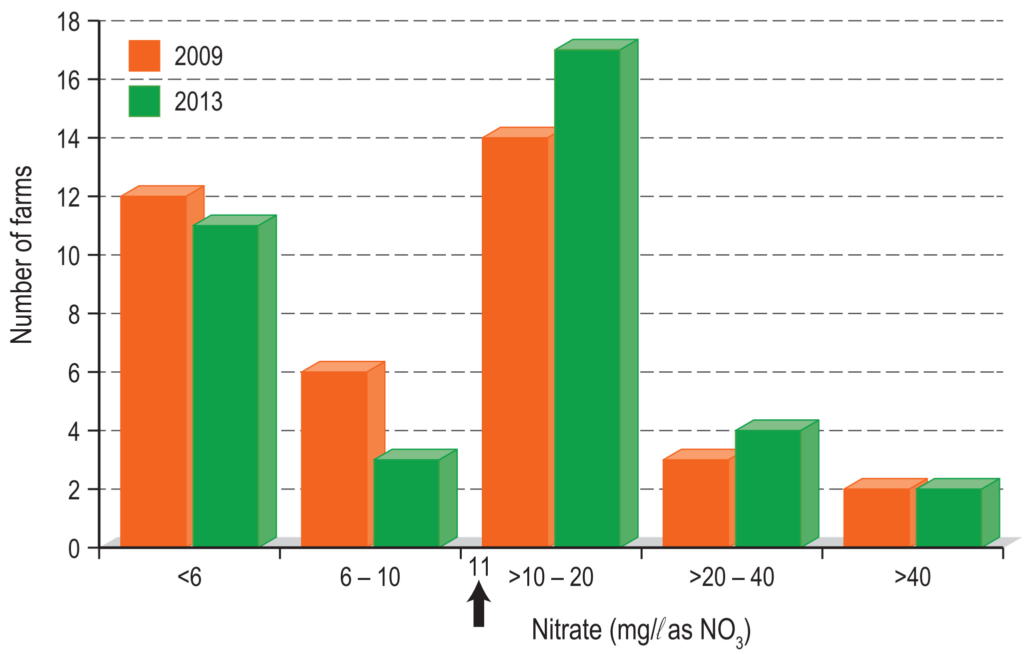


Figure 5.2 Distribution of measurements for nitrate (arrow indicates the limit of the South African standard (SANS 241, 2011))

The high levels of coliforms found in the groundwater on many of the farms may affect sensitive groups adversely. Water with counts of 10 – 100 coliforms per 100 mℓ could result in clinical infections in consumers, but counts of 100 – 1 000 coliforms could cause infections, even with once-off consumption (DWAF *et al.*, 1998). On 18.9% of the farms in 2009 and 5.6% in 2013, the counts of coliforms exceeded 1 000 per 100 mℓ groundwater, posing a serious health risks for all consumers on the farms (DWAF *et al*., 1998) (Figure 5.3).

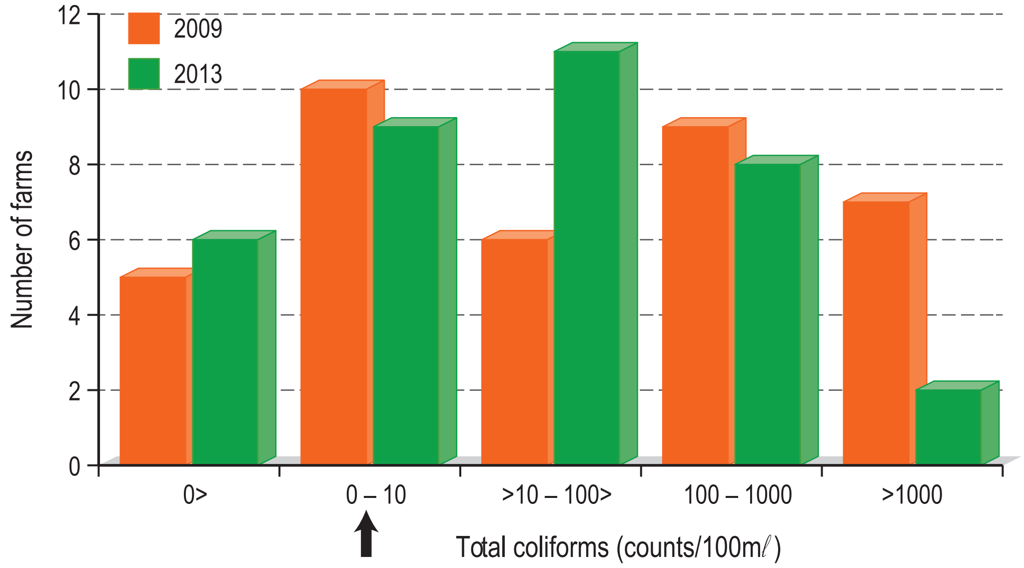


Figure 5.3 Distribution of measurements for total coliforms (arrow indicates the limit of the South African standard (SANS 241, 2011))

E. coli, contrary to coliforms, poses a health risk to consumers at much lower levels, particularly for sensitive groups (DWAF *et al*., 1998). Clinical infections are common, even with once-off consumption, at counts of 10 – 100 per 100 mℓ and serious health effects are common for all users at counts greater than 100 per 100 mℓ (Figure 5.4). These risks are equally prevalent when untreated polluted

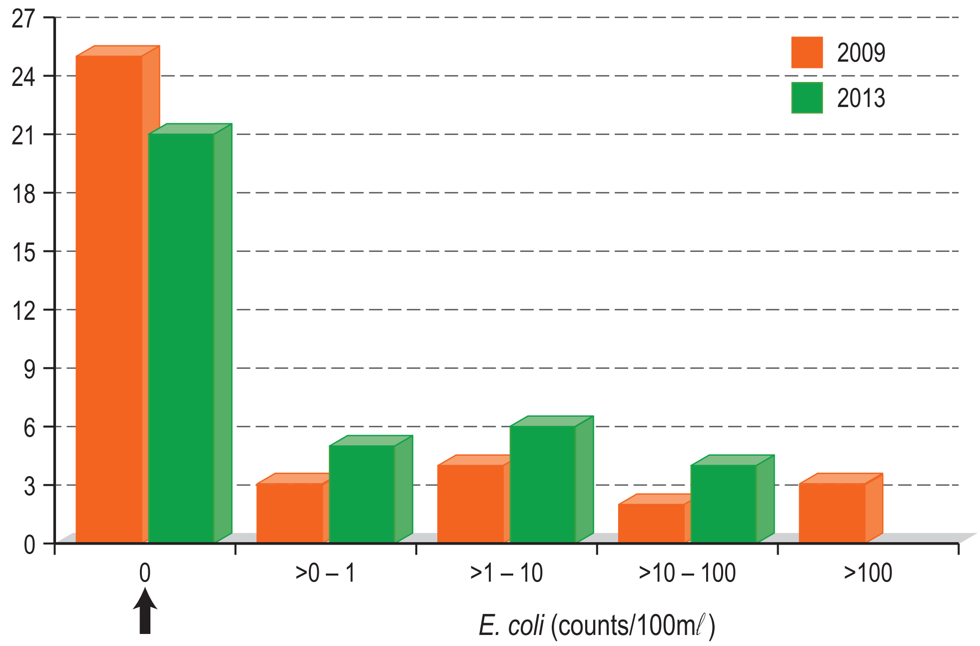


Figure 5.4 Distribution of measurements for *E. coli* (arrow indicates the limit of the South African standard (SANS 241, 2011))

groundwater is used in food preparation (DWAF *et al*., 1998). In this study, three of the 2013 farms (8.8%) demonstrated counts of *E. coli* greater than 100 per 100 mℓ, posing a serious health risk to consumers. Counts in the region of 10 – 100 were observed in groundwater of 17.6% of the 2009 farms and 29.4% of the 2013 farms. It is therefore expected that consumers on these farms are at risk of clinical infections. Furthermore, when water of such poor quality is used in dairy cleansing processes, the quality of raw milk and milk products may be affected.

A major concern in this study was the prevalence of three or more parameters with values exceeding the limit in a single sample. Some farms displayed values of total hardness, nitrates, total coliforms and *E. coli* at levels that were a health risk to consumers. Moreover, the number of farms that presented a health risk increased from 41.19% in 2009 to 50% in 2013.

5.4 Discussion and conclusions

The region in which this study was undertaken is known for its hard water, caused mainly by the natural geology of the region. Nitrate enrichment of water can mostly be attributed to animal waste and run-off from the dairies (Wilcock *et al*., 1999). On some of the farms the nitrate levels were exceptionally high; up to seven times greater than the South African specified health limit of 11 mg/ℓ (SANS 241, 2011), which is less stringent than the latest limits used by the EU of 6 mg/ℓ specified for nitrates (Tredoux *et al*., 2004; Tredoux *et al*., 2012). On two farms in 2009 and one in 2013, the nitrate measurements exceeded the toxic levels of greater than 50 mg/ℓ (Spalding and Exner, 1993; Savci, 2012; Mingzhu *et al*., 2014). A groundwater study conducted in the rural areas of South Africa indicated that increasing nitrate levels in groundwater are hazardous to bottle-fed infants, as well as to livestock (Tredoux *et al*., 2000). A result of high nitrate concentration is methaemoglobinaemia in young infants, which results in their death. When infants ingest nitrate, it can be reduced to nitrite before the nitrate is absorbed in the bloodstream and combined with haemoglobin. This process produces anoxia, which can lead to the death of infants by asphyxia (Ayodele, 2012).

A further concern was the high levels of coliforms and *E. coli* that were detected in the water used for domestic purposes and dairy activities. The amount of total coliform and *E. coli* found in the drinking water suggest that poor sanitation conditions and practices are potential reasons for the high presence of microbial contaminants (Gwimbi, 2011). With the high levels found in this study, coliforms could pose a health threat even with once-off consumption (DWAF *et al*., 1998). *E. coli* contamination in drinking water at more than 55% of the farms fell into the intermediate to very high-risk categories, as defined by the World Health Organisation (1997). The *E. coli* presence indicates faecal contamination and therefore poses a health threat to humans and animals residing on the farms (Pell, 1997). Exposure to high levels of *E. coli* and other coliforms, which may include other pathogens, could result in serious illness in these sensitive groups. The immune compromised patients suffering from HIV and AIDS are particularly vulnerable to diseases. The 32.5% prevalence of HIV and Aids in the Free State province is the third largest in South Africa (DoH, 2011), emphasising the possible health risk to the community in this study area.

A noteworthy concern is the use of poor quality groundwater in dairy activities. Water is used in many cleansing processes in a dairy (Altalhi and Hassan, 2009). If these processes are incomplete, the potential for milk to be contaminated will increase. Although the process of pasteurisation is responsible for the improvement of the safety and the lengthening of the shelf-life of dairy products, it does not eliminate all microorganisms and their enzymes, spores and toxins. The thermal destruction process is logarithmic and eliminates bacteria at a rate that is proportional to the number of bacteria present in raw milk (LeJeune and Rajala-Schultz, 2009). In instances where the bacterial count is high in raw milk, pasteurisation will not be able to kill all bacteria within the short period of its application (Lund *et al*., 2002). Milk buyers in South Africa apply a sliding scale for good quality milk and a penalty system for milk with low bacteriological quality when determining the value of the raw milk (Clover, 2013). Furthermore, the high bacterial content in groundwater could compromise the quality of dairy products and other farming produce (Jones, 1999). This study strongly suggests a revision of wastewater management strategies on dairy farms in the Free State and continuous monitoring of groundwater quality.

Chapter 6
A Water Quality Index for Groundwater on Dairy Farms

6.1 Introduction

One of the most effective ways to communicate the information with respect to water quality and water quality trends is through the use of a suitable index. The suitability of a water source for domestic use can best be described in terms of a water quality index (WQI). A WQI reduces the bulk of information into a single value, by expressing water quality information in a logical and simplified form (Nasirian 2007; González *et al*., 2012; Tyagi *et al*., 2013). This simplified form of water quality data increases the level of understanding of water quality issues by non-water professionals, policy makers and the general public (Tyagi *et al*., 2013).

The use of a WQI was initially proposed by Horton (1965) and Brown *et al*. (1970). Since that time, many different methods for calculating a WQI have been developed. Generally, WQI consider physical and chemical parameters but calculate the index in different ways (Štambuck-Giljanović, 1999).

A WQI can be defined as a rating scale that describes the composite impact of different water quality parameters. It is usually dimensionless and expresses the relative magnitude of the composite components of water quality (Muthulakshmi *et al*., 2013). Most WQI determine water quality from the standpoint of suitability as a drinking water source (Yisa and Jimoh, 2010). The intention of a WQI is to assess the general state of water depending on a range of predetermined water quality parameters, which are then compared to a regulatory standard (González *et al*., 2012).

Few WQI consider microbiological parameters in combination with physical and chemical parameters, and thus do not provide a holistic understanding of the health risk that water may pose on consumers. The data in this study (captured in previous chapters) revealed that some of the farms demonstrated high nitrate, coliform and *E. coli* values in the groundwater; making this water unsuitable for domestic use and posing a health risk. Therefore, this study was undertaken to develop a suitable WQI for groundwater, whilst also considering the potential health impact the parameters may pose on humans at levels above the recommended standard. Existing WQI calculation methods were reviewed for their potential use for groundwater; then modified and tested to include physical, chemical and microbiological parameters using suitably chosen health limits.

6.2 Methods

A review of the literature was undertaken to select a number of WQI that could be tested for their potential use on groundwater measurements in South Africa, and that can also be applied by non-professionals. Three prominent indexes were selected, namely the Weighted Arithmetic WQI (WA-WQI) (Brown *et al*., 1972), the Weighted WQI (W-WQI) (Tiwari and Mishra, 1985; Jerome and Pius, 2010) and the Canadian Council of Ministers of the Environment WQI (CCME-WQI) (CCME, 2001). Both the WA-WQI and the CCME-WQI (CCME, 2001) are widely used to assess water quality (Brown *et al*., 1972; Tyagi *et al*., 2013; CCME, 2001; UNEP, 2007), while the W-WQI has been applied in various groundwater studies (Tiwari and Mishra, 1985; Ramakrishnaiah *et al*., 2009; Jerome and Pius, 2010). The widely used National Sanitation Foundation (NSF) WQI was excluded from this study (Brown *et al*., 1970; Kumar and Alappat, 2009), because of the complexity of its mathematical calculations.

The three selected WQI were critically reviewed and compared for their suitability of use for groundwater measurements. Eight WQI characteristics were devised to score the three selected WQI. The characteristics included:

- which parameters are used in the WQI calculation;
- the required number of sampling rounds;
- the ease of implementation; and
- mathematical formulations used.

The characteristics for evaluation of a WQI were based upon previous experience of the author and supervisors and the critical evaluation of WQI by Tyagi *et al*. (2013).

The water quality parameters that were used in the calculations of WQI values were selected by first listing those commonly used to monitor drinking water in the Free State. For example, parameters such as arsenic, cadmium and lead were excluded from this list as they have not been associated with the drinking water assessments in the study area. Parameters that may pose a health risk or are of economic importance in this region were identified through consultation with two water quality experts of the Mangaung Metropolitan Municipality, Dr Elsa Potgieter, the chief microbiologist and Mr Piet Wagener, the chief chemical analyst. A health related limit was assigned to each of these parameters using the water quality limits for marginal water quality described by DWAF *et al*. (1998). According to DWAF *et al*. (1998), *marginal water quality* implies that negative effects may occur in some sensitive groups, such as people with medical conditions, babies, young

Table 6.1 WQI rating scale

Water quality rating	CCME-WQI	W-WQI	WA-WQI
Excellent	> 95 – 100	≤ 50	0 – 2 5
Good	> 80 – ≤ 95	> 50 – 100	> 25 – 50
Poor	> 65 – ≤ 80	> 100 – 200	> 50 – 75
Very poor	> 45 – ≤ 65	> 200 – 300	> 75 – 100
Water unsuitable for drinking	0 – 45	> 300	> 100

children, the elderly and the immune compromised. Other negative effects considered included economic factors such as increased soap consumption, scaling and corrosion of pipes.

The groundwater data collected on the 34 farms in 2013 were used to test and compare the three selected WQI. These WQI values were rated using the five point scale as proposed by Ramakrishnaiah *et al*. (2009) (Table 6.1). A manual rating of the raw farm data was also conducted through inspection taking into account health risks and economic factors. The ratings of the respective WQI values were then compared with the manual inspection ratings to ascertain how accurately the calculated WQI values reflected the water quality by applying a *chi-square* test of independence at an alpha of 0.05. The guideline used for rating the raw groundwater data through inspection has been taken up in Appendix B. Based on the performance of the three tested WQI, one was selected as the most suitable and used to also calculate WQI values for the 2009 groundwater data of the same 34 farms. The WQI values of the two sampling years were then compared statistically by applying a *t-test*.

6.3 Review of WQI

6.3.1 Weighted Arithmetic WQI (WA-WQI)

The WA-WQI (Brown *et al*., 1972) incorporates multiple water quality parameters that can be used to rate the quality of a water source. This WQI classifies the water source according to the level of purity. The WQI value is computed with the following formula:

$$\mathrm{WA-WQI} = \frac{\sum Q_i W_i}{\sum W_i} \quad \text{...} \quad (7)$$

Where, Q_i is the water quality rating and W_i is the unit weight of each water quality parameter

The quality rating scale for each parameter is calculated by using the following:

$$Q_i = 100 \left\{ \frac{V_i - V_0}{S_i - V_0} \right\} \quad \text{..........} \quad (8)$$

Where, V_i is the estimated concentration of the i^{th} parameter of the water sample, V_i is the ideal value of the parameter in pure water, V_0 = 0 (except pH = 7.0) and S_i is the recommended standard value of the i^{th} parameter.

The unit weight (W_i) for each water quality parameter is calculated by using the following formula:

$$W_i = \frac{K}{S_i} \quad \text{..........} \quad (9)$$

Where, K is the proportionally constant.

It can also be calculated by using the following equation:

$$K = \frac{1}{\sum \left[\frac{1}{S_i} \right]} \quad \text{..........} \quad (10)$$

6.3.2 Weighted WQI (W-WQI)

The W-WQI (Tiwari and Mishra, 1985) computes a WQI value by applying a weighted index method. Three steps are followed to calculate the WQI value (Tiwari and Mishra, 1985). In the first step, the parameters are assigned a weight (w_i) from one to five according to their relative importance in the overall quality of water. A maximum weight of five is assigned to the most important parameters, for example, in this study nitrate and *E. coli* were assigned a five. In the second step, the relative weight (W_i) is computed from the following equation:

$$W_i = \frac{w_i}{\sum_{i=1}^{n} w_i} \quad \text{..........} \quad (11)$$

Where, W_i is the relative weight, w_i is the weight of each parameter and n is the number of parameters.

In the third step, a quality rating scale (q_i) for each parameter is assigned by dividing its concentration in each water sample by its respective standard and the result multiplied by 100:

$$q_i = \frac{C_i}{S_i} \times 100 \quad \text{..........} \quad (12)$$

Where q_i is the quality rating, C_i is the concentration of each chemical parameter in each water sample in mg/ℓ, and S_i is standard for each parameter.

For computing the WQI, the Sl_i is first determined for each parameter, which is then used to determine the WQI of a water source using the following equations:

$$\mathrm{Sl}_i = \mathrm{W}_i \times \mathrm{q}_i \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (13)$$

$$\mathrm{WQI} = \sum \mathrm{Sl}_i \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (14)$$

where Sl_i is the sub index of i th parameter; q_i is the rating based on concentration of i^{th} parameter and n is the number of parameters.

For the calculations of the W-WQI values the following weights and relative weights were applied (Table 6.2).

Table 6.2 Weights and relative weight of selected water quality parameters

Parameter	Weight (w_i)	Relative weight (W_i)
Chloride	3	0.094
Nitrate + Nitrite	5	0.156
Sulphate	4	0.125
Total hardness	2	0.063
Turbidity	4	0.125
pH	4	0.125
Total coliforms	5	0.156
E. coli	5	0.156

6.3.3 Canadian Council of Ministers of the Environment WQI (CCME-WQI)

The Canadian water quality index (CCME-WQI) (CCME, 2001) was developed to provide a consistent method conveying water quality information for managers and the public. The water quality parameters used in this index include physical, chemical and microbiological parameters. The CCME-WQI (CCME, 2001) provides a mathematical framework to assess the current water quality relative to specific water quality objectives. The CCME-WQI compares observations (measurements) to a benchmark or standard. It is a requirement to have at least four different sampling locations where a minimum of four variables were sampled four times; also referred to as the 4 × 4 rule (CCME 2001; UNEP 2007). In a later study it was suggested that a minimum of seven parameters should be used (Hurley *et al.*, 2012).

The WQI value is computed with the following formula:

$$\text{CCME}-\text{WQI} = 100 - \left\{\frac{\sqrt{F_1^{\,2} + F_2^{\,2} + F_3^{\,2}}}{1.732}\right\} \quad \ldots\ldots\ldots\ldots \quad (1)$$

Where F_1 is the *Scope*: the percentage of parameters that exceeds the standard:

$$F_1 = \left\{\frac{\text{number of parameters not complying}}{\text{total number of parameters}}\right\} \times 100 \quad \ldots\ldots\ldots \quad (2)$$

Where F_2 is the *Frequency*: the percentage of individual tests within each parameter that exceeds the standard:

$$F_2 = \left\{\frac{\text{number of failed tests}}{\text{total number of tests}}\right\} \times 100 \quad \ldots\ldots\ldots\ldots \quad (3)$$

Where F_3 is the *Amplitude*: the extent (excursion) to which the failed test exceed the guideline. This is calculated in three steps:

$$excursion_i = \left\{\frac{\text{failed test value}_i}{\text{objective}_i}\right\} - 1 \quad \ldots\ldots\ldots\ldots \quad (4)$$

Second, the normalised sum of excursions (nse) is calculated as follows:

$$nse = \frac{\sum_{i=1}^{n} \text{excursion}_i}{\text{number of tests}} \quad \ldots\ldots\ldots\ldots \quad (5)$$

F_3 is then calculated using the formula that scales the nse to range from 1 and 100:

$$F_3 = \left\{\frac{nse}{0.01 \times nse + 0.1}\right\} \quad \ldots\ldots\ldots\ldots \quad (6)$$

6.4 Critique of WQI

The devised WQI characteristics were used to score and compare the three selected WQI. The scores of all three indexes exceeded 60% (Table 6.3). The W-WQI (Tiwari and Mishra, 1985) and the WA-WQI (Brown *et al.*, 1972) were identical for all eight characteristics. Of particular interest was the CCME-WQI (CCME, 2001) that includes microbiological parameters, but this index requires multiple sampling rounds. The calculations of the CCME-WQI (CCME, 2001) are also scientifically complex and therefore make it more challenging for non-professional officials to use.

6.5 Assessment of WQI

Eight specific health related water quality parameters were identified for use in WQI calculations for groundwater using the *marginal water quality* limits described by DWAF *et al.* (1998). Each water

Table 6.3 Scores of the reviewed WQI

WQI characteristics	CCME-WQI (2001)	W-WQI (1985)	WA-WQI (1972)
Includes physical properties	Yes	Yes	Yes
Includes chemical properties	Yes	Yes	Yes
Includes microbiological properties	Yes	No	No
Includes different sampling rounds	Yes	No	No
Can be adapted to include additional parameters	No	Yes	Yes
Can be calculated using a single round of measurements	No	Yes	Yes
Simple formula or equation (ease of use for non-professionals	No	Yes	Yes
Ease of interpretation	Yes	Yes	Yes
Score out of 8	**5**	**6**	**6**

quality parameter was described in terms of drinking water and food preparation qualities at the specified health limit (Table 6.4). The SANS 241 (SANS 241, 2011) limits were also included in the table as a reference.

The different WQI were compared with one another and with the manual inspection rating to identify the most appropriate WQI for groundwater in the Free State. The WQI values of the CCME-WQI (CCME, 2001) were biased towards acceptable water revealing that 94% of the farms had either *excellent* or *good* water (Table 6.5). The WQI values of W-WQI (Tiwari and Mishra, 1985) and WA-WQI (Brown *et al*., 1972) were similar and spread more evenly over the categories. However, the W-WQI (Tiwari and Mishra, 1985) appeared to be more stringent than the WA-WQI (Brown *et al*., 1972).

A graphical perspective clearly shows the bias that the CCME-WQI presents towards *excellent* water quality (Figure 6.1). This result is contrasted by the other WQI showing a spread of WQI values over the different rating categories.

Chi-square tests of independence were performed on the data comparing the different WQI with the manual inspection rating. Taking into account the assumption of the limit on class sizes, namely, that no more than 20% of the expected counts should be less than five and all individual counts

Table 6.4 Water quality limits and effects for specified health parameters (DWAF *et al.*, 1998)

Water quality parameter	SANS 241	Health limit	Drinking water	Food preparation
Chloride	≤ 300	200 – 600 (mg/ℓ)	Increasing health risk to sensitive groups	Increasing effects in sensitive groups
Nitrate + Nitrite	≤ 11	10 – 20 (mg/ℓ as N)	Slight chronic risk to some babies	Slight chronic risk to some babies
Sulphate	≤ 500	400 – 600 (mg/ℓ)	Slight chance of initial diarrhoea in sensitive groups, but disappears with adaptation	Slight chance of initial diarrhoea in sensitive groups, but disappears with adaptation
Total hardness	NS	300 – 600 (very hard)	Possible chronic effects in sensitive groups only	Severe scaling of kettles and geysers
Turbidity	≤ 5	1 – 20 (NTU)	Possibility of secondary health effects	Slight risk, e.g. salads
pH	≥ 5 to ≤ 9.7	≥ 4 and ≤ 10	Irritation of mucous membranes	Irritation of mucous membranes
Total coliforms	10 – 100 counts/100 mℓ	10 – 100 counts/100 mℓ	Clinical infections unlikely in healthy adults, but may occur in some sensitive groups	Clinical infections unlikely in healthy adults, but may occur in some sensitive groups
E. coli	Not detected	1 – 10 counts/100 mℓ	Clinical infections unlikely in healthy adults, but may occur in some sensitive groups	Clinical infections unlikely in healthy adults, but may occur in some sensitive groups

NS = not specified for drinking water quality

NTU = Nephelometric Turbidity Units

Table 6.5 WQI values calculated for farms using the three different indexes

Farm No.	CCME-WQI	W-WQI	WA-WQI	Manual Inspection Rating
1	96.8	73.9	25.0	
2	96.8	130.8	37.1	
3	94.3	385.8	347.2	
4	94.8	285.6	167.0	
5	96.1	152.7	29.8	
6	92.1	768.7	674.5	
7	96.7	158.0	124.7	
8	96.8	127.1	40.0	
9	84.3	1 603.9	1 822.7	
10	96.1	132.0	47.4	
11	97.7	85.2	14.7	
12	97.7	225.5	28.2	
13	97.7	114.0	87.5	
14	97.7	50.7	6.8	
15	89.4	1 058.6	1 154.6	
16	60.2	4 057.1	4 460.6	
17	96.8	91.1	51.5	
18	96.8	71.5	44.8	
19	96.8	105.5	33.3	
20	89.9	1 035.2	1 014.6	
21	83.3	1 839.9	989.9	
22	97.7	38.4	10.0	
23	92.3	781.5	856.0	
24	96.4	225.5	27.8	
25	97.7	94.3	75.6	
26	56.0	4 432.6	1 845.0	
27	95.0	264.6	40.0	
28	95.0	286.9	1 162.0	
29	96.0	222.9	91.0	
30	100.0	35.4	35.0	
31	100.0	34.8	12.0	
32	98.0	53.3	14.0	
33	98.0	59.3	39.0	
34	90.0	996.4	459.0	
Excellent	23	3	6	3
Good	9	8	11	10
Poor	0	7	1	8
Very poor	2	6	3	2
Unacceptable	0	10	13	11

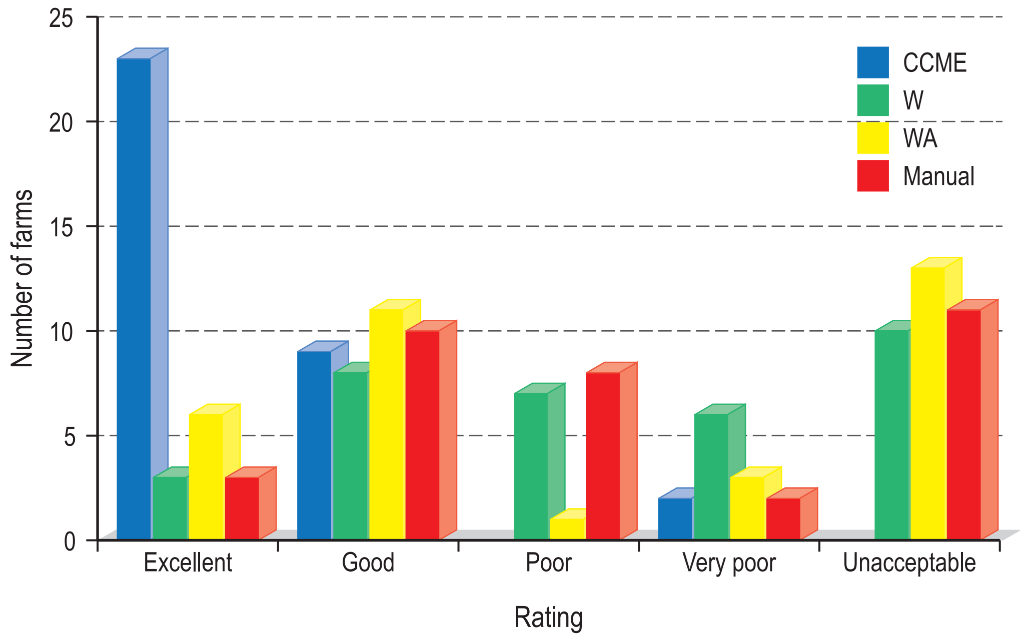


Figure 6.1 Comparison of the WQI ratings of the different WQI

should be one or greater, the rating categories were grouped. Group *acceptable* (A) comprises the *excellent* and *good* categories, while group *unacceptable* (U) comprises the categories *poor*, *very poor* and *unacceptable*. The *chi-square* test revealed that the WQI values of the CCME-WQI differed significantly from those of the manual inspection rating (Table 6.6). However, the tests revealed that the WQI values of the W-WQI and WA-WQI did not differ from the manual inspection rating.

Table 6.6 Contingency tables of the *chi-square* tests comparing each WQI value with the manual inspection rating, showing observed values and expected values parentheses

Class	CCME-WQI	Man. inspect	Total	W-WQI	Man. inspect	Total	WA-WQI	Man. inspect	Total
A	32 (22.5)	13 (22.5)	45	11 (12.0)	13 (12.0)	24	17 (15.0)	13 (15.0)	30
U	2 (11.5)	21 (11.5)	23	23 (22.0)	21 (22.0)	44	17 (19.0)	21 (19.0)	38
Total	34	34	68	34	34	68	34	34	68
	x^2 = 23.7; DF = 1; p = 0.000			x^2 = 0.258; DF = 1; p = 0.612			x^2 = 0.954; DF = 1; p = 0.329		

A = acceptable water comprising of categories excellent and good

U = unacceptable water comprising of categories poor, very poor and unacceptable

Man. inspect = Manual inspection rating; x^2 = *chi-square* value; DF = degrees of freedom; p = probability

6.6 Application of selected WQI

This study indicated that both the W-WQI (Tiwari and Mishra, 1985) and the WA-WQI (Brown *et al*., 1972) were reflections of the results obtained from the manual rating. However, the formulations of the WA-WQI (Brown *et al*., 1972) do not accommodate zero limits in the standard with ease, therefore the W-WQI (Tiwari and Mishra, 1985) was chosen for application on the groundwater quality data collected in 2009 and 2013. The WQI values showed a substantial improvement from 2009 to 2013, which is clearly demonstrated in the change of the mean values of the two years (approximately 20% improvement) (Table 6.7). The overall deterioration of the WQI values was less than 15% when 2009 and 2013 values were compared. However, when the WQI values were categorised and grouped as *acceptable* (A) and *unacceptable* (U), it was found that all the 2009 samples fell in the U category, while for the 2013 samples 32.4% of the samples were of the A type. However, the *t-test* revealed that the overall quality of the two years did not display a significant change from 2009 to 2013 (p = 0.113).

Table 6.7 WQI values and description of change from 2009 to 2013 sorted on 2009 values

Farm No.	Rating scale	2009	2013	Change description	Change difference
1		168.0	73.9	Improved	94.1
5		195.9	152.7	Similar*	43.2
15		332.3	1 058.6	Deteriorated	– 726.3
19		355.8	105.5	Improved	250.3
22		357.5	38.4	Improved	319.1
29		357.7	222.9	Improved	134.8
23		364.4	781.5	Deteriorated	–417.1
17		376.7	91.1	Improved	285.6
24		392.1	225.5	Improved	166.6
26		423.9	4 432.6	Deteriorated	–4 008.7
3		432.9	385.8	Similar	47.1
33		437.8	59.3	Improved	378.5
25		440.9	94.3	Improved	346.6
31		443.1	34.8	Improved	408.3
2		460.2	130.8	Improved	329.4
16		472.9	4 057.1	Deteriorated	–3 584.2
14		486.3	50.7	Improved	435.6
8		501.2	127.1	Improved	374.1
20		546.9	1 035.2	Deteriorated	–488.3
18		552.0	71.5	Improved	480.5

Farm No.	Rating scale	2009	2013	Change description	Change difference
32		644.8	53.3	Improved	591.5
13		691.0	114.0	Improved	577.0
11		729.4	85.2	Improved	644.2
27		963.3	264.6	Improved	698.7
28		1 659.9	286.9	Improved	1 373.0
10		1 836.7	132.0	Improved	1 704.7
9		2 002.5	1 603.9	Improved	398.6
4		2 216.0	285.6	Improved	1 930.4
34		3 401.1	996.4	Improved	2 404.7
12		5 876.9	225.5	Improved	5 651.4
7		6 008.9	158.0	Improved	5 850.9
6		6 070.0	768.7	Improved	5 301.3
30		9 586.9	35.4	Improved	9 551.5
21		47 616.0	1 839.9	Improved	45 776.1
Mean		2 864.76	590.55		2 274.21
Standard Dev		8 202.1484	1 034.2628		
Excellent	≤ 50	0	3	Similar (5.9%)	3
Good	> 50 – 100	0	8	Improved (79.4%)	10
Poor	> 100 – 200	2	7	Deteriorated (14.7%)	8
Very poor	> 200 – 300	0	6		2
Unacceptable	> 300	32	10		11

* = values are regarded as being similar if the difference is less than 50, Standard Dev = standard deviation

6.7 Conclusion

This study indicated that both the W-WQI (Tiwari and Mishra, 1985) and the WA-WQI (Brown *et al*., 1972) are suitable indexes to adapt for the use of groundwater quality assessments in the Free State. However, because the WA-WQI (Brown *et al*., 1972) does not accommodate zero values in a limit, it is therefore recommended that the W-WQI (Tiwari and Mishra, 1985) is adapted and used for groundwater quality assessments in the Free State. The W-WQI (Tiwari and Mishra, 1985) successfully demonstrated differences in the groundwater quality of the participating farms of the two sampling years. Through statistical comparison, the data revealed that the overall quality of the groundwater did not change significantly. The testing phase of the adapted W-WQI (Tiwari and Mishra, 1985) further showed that its ease of implementation will be useful for adoption by professionals and decision makers to determine the status of the groundwater quality and where intervention is needed.

Chapter 7
Farm Management Practices and Infrastructure

7.1 Introduction

Dairy activities substantially impact the environment (Battini *et al*., 2014). Milking shed effluent contains cow faeces, urine, chemicals, and wash water used in cleaning the milking units, pipelines, bulk tanks, the floor and wall surfaces (Alveraz *et al*., 2011). Disposal of dairy effluent onto pastures could result in an increased risk of contaminating waterways and groundwater. For example, it has been shown that high levels of faecal coliforms have been detected in groundwater (Jiang *et al*., 2010), which was the case with the farms in this study. Contaminated groundwater used without being treated poses a public health risk for consumers (Collins *et al*., 2007).

Dairy effluent contains high concentrations of chloride, nitrates, as well as microbial contaminants, which may include pathogens. Chloride originates from salts added to the cows' feed, while nitrates originate from natural mineral sources and anthropogenically as a by-product of agriculture, animal and human wastes (Masetti *et al*., 2008). Pathogenic microorganisms that are found in manure can cause serious illness and death in humans (Cotruvo *et al*., 2004).

Environmental considerations demand that dairies are sustainably managed. Farm management practices and infrastructural design contribute to the load of the nutrient and faecal bacterial transfer from dairy effluent in the soil to water sources (Monaghan *et al*., 2009). It is therefore important that dairy managers consider potential farm management options and infrastructural designs to protect their resources and consider the impact on the environment with more rigour (Ullman and Mukhtar, 2007). Best management practices can ensure that dairy operations become environmentally more sustainable, reduce the generation of waste and avoid the degradation or contamination of environmental resources such as soil and water (FAO and IDF, 2011).

Many activities on a dairy farm have the potential to affect groundwater quality (Van der Schans *et al*., 2009). The amount of manure generated on the farm is determined by the number of cows. Other influencing factors include, the distance from the collected manure to the borehole; the slope from farm waste and sanitation facilities to the borehole; run-off; and the moistness of the soil (Hooda *et al*., 2000; McLay *et al*., 2001; Collins *et al*., 2007; Gourley *et al*., 2012).

The placement of a borehole and the protection of the head are key mechanisms to protect groundwater (DWAF, 2004a). Boreholes are at risk of pollution by the accumulation of stagnant water around the borehole head. By sealing the head of a borehole, run-off water and waste are prevented from entering the borehole. Furthermore, pollution sources should be located downstream from the borehole and measures should be taken to prevent the flow of waste and run-off in the direction of a borehole (DWAF, 2004a; DWAF, 2004b).

The data in this study revealed that some farms demonstrated high nitrate, coliform and *E. coli* values in the groundwater, making this water not suitable for domestic or dairy use. A data gathering checklist was thus developed to gain insight into dairy farm management practices and dairy farm infrastructure in an attempt to explain how the groundwater may become polluted.

7.2 Materials and methods

Of the original 75 farms from the 2009 sampling round, the 34 dairy farms that were still productive in 2013, were used in this investigation. These farms were visited and data collected about dairy farm management practices and infrastructure. A data gathering tool was developed and was used to gather the data.

7.2.1 Development of the data gathering tool

Farm management practices and infrastructure on active dairy farms were investigated by means of a data gathering checklist. Management aspects, such as the age of the dairy, number of milking's per day and handling of the dairy effluent, were investigated together with infrastructural information, such as the number of boreholes used and the size of the bulk milk tanks.

The checklist was developed in six steps using national and international informing documents (Figure 7.1)

- ***Step 1:*** Information on farm management practices and dairy farm infrastructure, of interest to this study, was obtained.
- ***Step 2:*** The requirements for the COA (certificate of acceptability), as described in the Regulations Relating to Hygiene Requirements for Milking Sheds, The Transport of Milk and Related Matters (Regulation 961, 2012), was used as the primary guiding document to construct the first draft of the checklist. This document is used by all environmental health practitioners in South Africa. This draft checklist was then elaborated upon by adding specific information specified in other documents namely, The Code of Hygienic Practice for Milk and Milk Products developed by Codex (CAC/RCP, 2004), Sustainable Dairy Assurance Scheme

Producer Standard developed by the Irish Food Board, 2013 (Bord Bia, 2013), as well as similar studies conducted by Strydom *et al*. (1995), Meyer *et al*., (1997 and 2011).

- ***Step 3:*** This draft was then reviewed by Dr J. Van der Merwe and Ms Y. Kotze, groundwater specialist researchers at the Institute of Groundwater Studies (IGS) at the University of the Free Sate and Mr J. Esterhuizen, a local dairy farm advisor.
- ***Step 4:*** Revision of the draft checklist.
- ***Step 5:*** After the revision, the second draft was reviewed by professors P. Fourie and C. Van der Westhuizen from the Department of Agricultural Management at the Central University of Technology, Free State and Ms Y. Kotze (IGS).
- ***Step 6:*** The final document was prepared, taking into account feedback from the reviewers, as well as the information from the informing documents.

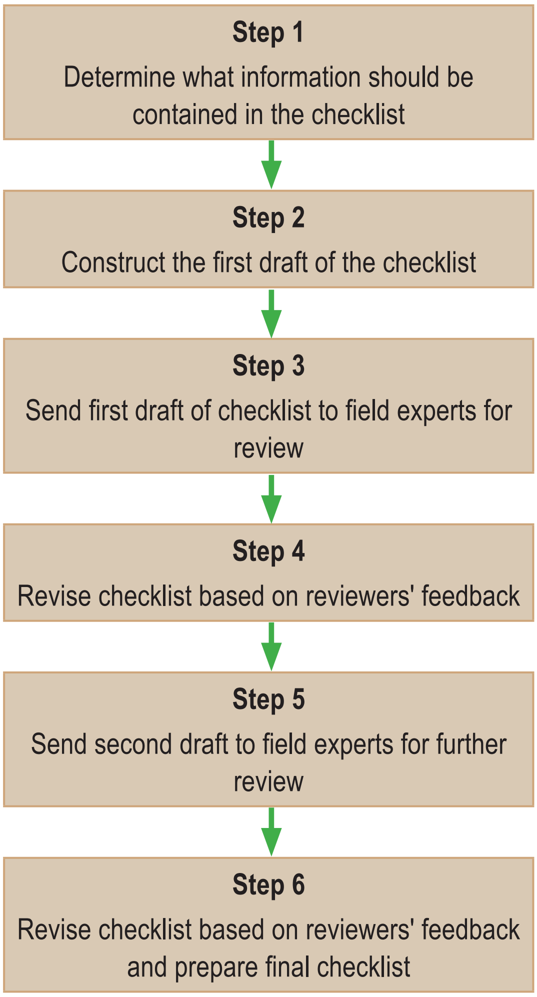


Figure 7.1 Steps followed to develop the checklist

Initially questions regarding the herd health and use of antibiotics were included in the checklist, but these questions were not well received by the farmers, who were unwilling to reveal information on herd health and medication. This information was therefore excluded from the checklist. A copy of the data gathering checklist has been included in Appendix C.

7.2.2 Data collection and analyses

During the sampling round in 2013, the checklist was completed on the 34 participating farms. The data gathering process followed these subsequent steps:

1. Owners of the 34 participating farms were telephonically briefed on the details of the follow-up study and a suitable time for a visit was arranged to gather the data.

2. During a farm visit, the checklist was completed on-site by interviewing the farmer or the dairy manager. At some farms the farmer or dairy manager was not available at the time of the scheduled visit and thus only accessible data could be collected. The outstanding data were then collected telephonically. All information was treated as confidential.
3. The data were captured and analysed using Microsoft Excel spreadsheets.

7.3 Results and discussion

Most of the participating dairy farms have been in operation for more than 20 years (33 of the 34 farms). Only one dairy farm was recently established; approximately five years ago. The major dairy breeds in South Africa are Holstein-Friesland, Jersey, Guernsey and Ayrshire, of which the Holstein-Friesland is the most popular followed by Jersey (Gertenbach, 2005). In this study, many of the participating farms use Holstein cows for milk production (76%). The breeds on the remaining farms included Jersey (14.7%), mixed herds (5.8%) and Ayrshire (2.9%).

Many activities on a dairy farm have the potential to affect groundwater quality. In particular, the amount of manure generated on the farm is determined by the number of cows. Other influencing factors include, the distance from the collected manure to the borehole; the slope from farm waste and sanitation facilities to the borehole; and the moistness of the soil (Hooda *et al*., 2000; McLay *et al*., 2001; Collins *et al*., 2007; Gourley *et al*., 2012).

Dairy practices on the participating farms varied substantially. All farmers confirmed that they had obtained a COA (Table 7.1). The majority of the dairy farms sold raw milk to local Bloemfontein buyers, while a few supplied raw milk to a bulk buyer in Gauteng. The sizes of the dairy herds ranged from a few (< 10) to many (> 2 000) lactating cows. The milking frequency in the majority of the dairies is twice per day. However, farms with large herds (> 300) milked three times a day and therefore produced the largest volumes of raw milk. These farms also owned the largest bulk tanks.

Three of the large farms in this study also exhibited a large number of consumers (including farm workers) (Table 7.2). This could be attributed to other extensive agricultural activities. On farm 4, the dairy activities were complemented by extensive crop production and vegetable farming; farm 8 by a dairy processing plant; and farm 33 by crop production and a sheep farming operation. Although farm 23 could be regarded as being large because the dairy operation was the main agricultural activity on the farm, there were relatively few consumers residing on the farm.

Table 7.1 Dairy practices on participating dairy farms

Farm No.	No. of cows	Daily milking frequency	Quantity of milk per day (litres)	Storage capacity (litres)	Bulk buyer	Certificate of acceptability (COA)	Dairy design
1	180	2	2 000	4 500	Dairy Corporation	Yes	Fishbone
2	220	2	2 280	5200	Dairy Corporation	Yes	Fishbone
3	8	1	70	650	Private	Yes	Tandem
4	300	2	3 000	7 000	Homsek	Yes	Fishbone
5	80	2	800	2 400	Dairy Corporation	Yes	Tandem
6	200	3	3 300	11 000	Dairy Corporation	Yes	Tandem
7	100	2	1 400	8 400	Dairy Corporation	Yes	Tandem
8	2 000	3	26 000	100 000	Homsek	Yes	Tandem
9	220	2	3 200	8 200	Dairy Corporation	Yes	Tandem
10	100	2	2 000	6 000	Dairy Corporation	Yes	Tandem
11	190	2	5 130	6 100	Dairy Corporation	Yes	Tandem
12	65	2	845	3 200	Dairy Corporation	Yes	Tandem
13	200	2	2 400	6 300	Homsek	Yes	Fishbone
14	120	2	1 200	3 350	Homsek	Yes	Fishbone
15	210	2	400	2 400	Homsek	Yes	Tandem
16	23	1	260	1 500	Dairy Corporation	Yes	Tandem
17	30	2	500	1 500	Dairy Corporation	Yes	Fishbone
18	70	2	800	1 500	HANCOR	Yes	Tandem
19	300	3	3 900	5 200	Dairy Corporation	Yes	Tandem
20	140	2	2 100	2 450	Joburg buyer	Yes	Fishbone
21	26	2	338	1 250	Homsek	Yes	Tandem
22	80	2	2 400	4 300	Joburg buyer	Yes	Tandem

Farm No.	No. of cows	Daily milking frequency	Quantity of milk per day (litres)	Storage capacity (litres)	Bulk buyer	Certificate of acceptability (COA)	Dairy design
23	400	2	6 000	20 000	Dairy Corporation	Yes	Tandem
24	250	2	7 500	8 000	DairyBelle	Yes	Tandem
25	70	2	1 000	3 000	DairyBelle	Yes	Fishbone
26	128	2	720	3 400	DairyBelle	Yes	Tandem
27	85	2	2 000	6 000	HANCOR	Yes	Fishbone
28	50	2	1 300	30 000	HANCOR	Yes	Fishbone
29	170	2	5 000	10 000	HANCOR	Yes	Tandem
30	187	2	2 400	3 000	Joburg buyer	Yes	Crate
31	100	2	1 200	2 400	Joburg buyer	Yes	Fishbone
32	250	2	3 250	5 000	Joburg buyer	Yes	Fishbone
33	500	3	7 500	5 000	Homsek	Yes	Fishbone
34	50	2	300	2 800	Private – fresh milk	Yes	Tandem
Mean	208.8		8 558.8	3 014.5			
Maximum	2 000		100 000.0	26 000.0			
Minimum	8		650.0	70.0			
Std Dev	335.1		17 112.6	4 513.9			

Std Dev = standard deviation; Crate = hand milking method

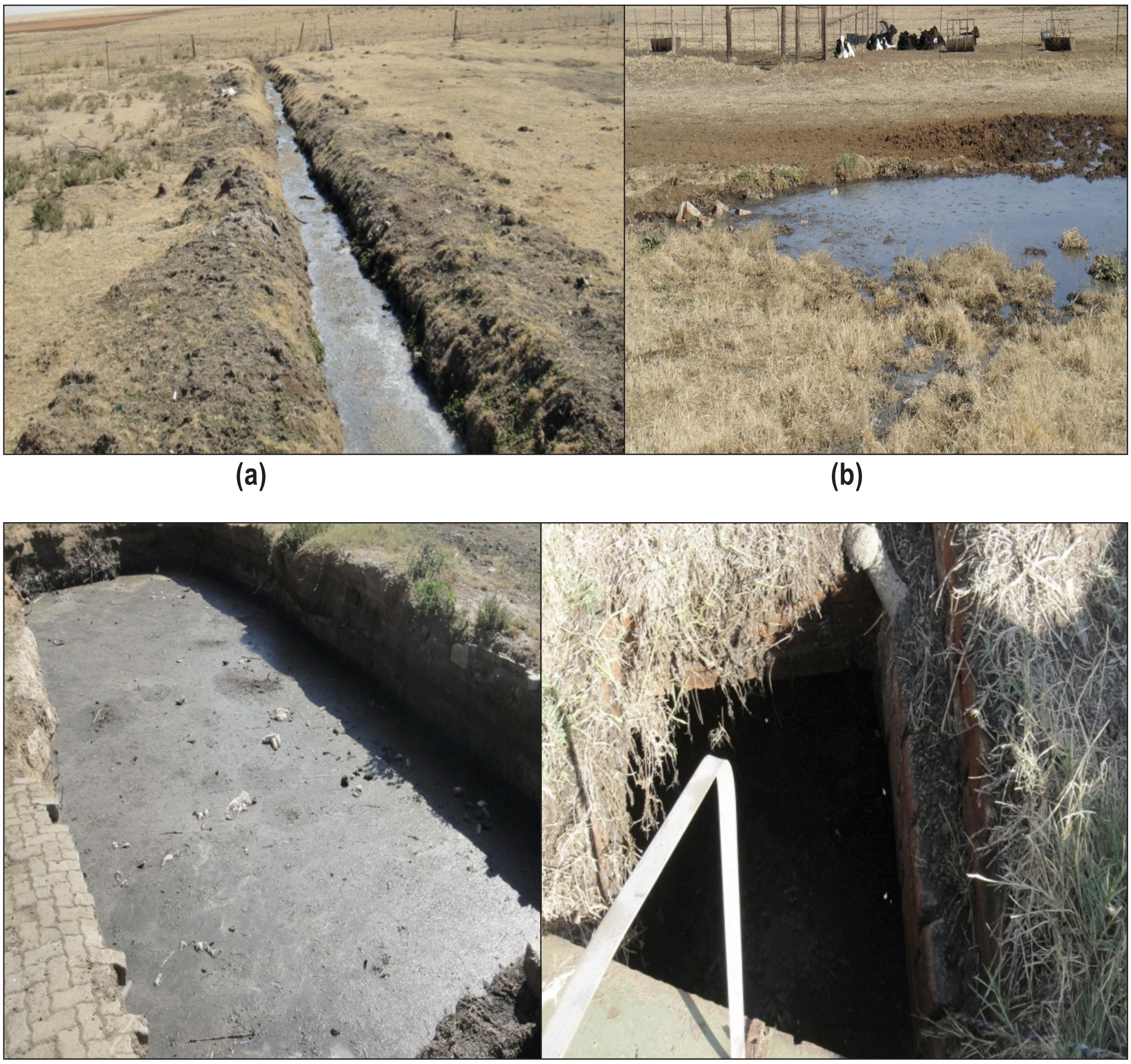
Table 7.2 Water use and waste management practices on participating dairy farms

Farm No.	No. of consumers	Type of sanitation on farm		Method of discharging effluent
		Household	Farm workers	
1	20	Septic tank	Ventilated improved pit	Dam collection and irrigation
2	17	Septic tank	Ventilated improved pit	Flood
3	10	Septic tank	Ventilated improved pit	Flood
4	100	Septic tank	Ventilated improved pit	Dam
5	17	Septic tank	Ventilated improved pit	Flood
6	0	NA	Septic tank	Dam collection and irrigation
7	15	Septic tank	Ventilated improved pit	Dam collection and irrigation
8	200	Septic tank	Ventilated improved pit	Dam collection and irrigation
9	40	Septic tank	Ventilated improved pit	Flood

Farm No.	No. of consumers	Type of sanitation on farm		Method of discharging effluent
		Household	Farm workers	
11	30	Septic tank	Ventilated improved pit	Dam
13	0	Municipal supply	Municipal supply	Flood
14	8	Septic tank	Ventilated improved pit	Flood
15	4	Septic tank	Ventilated improved pit	Flood
16	6	Septic tank	Ventilated improved pit	Flood
17	23	Septic tank	Ventilated improved pit	Flood
19	10	Septic tank	Ventilated improved pit	Flood
20	17	Septic tank	Ventilated improved pit	Flood
21	18	Septic tank	Ventilated improved pit	Flood
22	9	Septic tank	Ventilated improved pit	Flood
23	15	Septic tank	Ventilated improved pit	Flood
24	25	Septic tank	Ventilated improved pit	Flood
25	12	Septic tank	Ventilated improved pit	Flood
26	20	Septic tank	Ventilated improved pit	Dam
27	20	Septic tank	Ventilated improved pit	Flood
28	4	Septic tank	NA	Flood
29	8	Septic tank	Ventilated improved pit	Dam
30	100	Septic tank	Ventilated improved pit	Dam
31	7	Septic tank	Ventilated improved pit	Flood
32	20	Septic tank	Ventilated improved pit	Dam collection and irrigation
33	17	Septic tank	Ventilated improved pit	Flood
34	10	Septic tank	Ventilated improved pit	Flood
Mean	25			Total flood = 23
Maximum	200			Total dam = 6
Minimum	0			Total dam & irrigation = 5
Std Dev	38			

Std Dev = standard deviation; NA = no longer residing on the farm

Dairy wash water containing waste from the floor and other cleaning activities was discarded from the dairy through pipes or by means of a trench. More than two thirds of the farms (85.3%) disposed of dairy effluent by means of flooding or collection in shallow soil dams, which supports the findings of Strydom *et al*. (1993) who studied dairy effluent discharge in South Africa (Table 7.2). Only five farmers in this study re-used dairy effluent as a source of fertiliser (Figure 7.2 (c) & (d)). The type of



(a) (b)

(c) (d)

Figure 7.2 Effluent disposal: (a) and (b) flooding of effluent; (c) storing of effluent in dam; (d) storing of effluent in a pit

breed used in the dairy and the number of animals residing on the farm determines the volume of manure produced on the farm. It was reported by Knowlton (2010) that the Holstein-Friesland dairy breed, the most prevalent breed in this study, generates more dairy waste than the Jersey breed.

All farms in this study depended on groundwater for dairy activities. Most farms had more than one borehole, whereas one farm had 13 boreholes (Table 7.3). On 27 farms (79.4%), the main household and the dairy shared the same borehole. Although groundwater was generally used for domestic use on farms, farm 14 had access to municipal water, which was used in the household for domestic needs, but not in the dairy. Most borehole heads are well protected from direct environmental contamination (Figure 7.3).

(a) (b)

Figure 7.3 Borehole protection: (a) protected borehole head; (b) borehole head not elevated and not protected from stagnant water

Table 7.3 Infrastructural design on participating dairy farms

Farm No.	No. of boreholes	Borehole protection	Distance (m) from borehole to:				Slope from borehole
			Dairy	Dairy effluent	Kraal	Septic tank	
1	2	Yes	< 50	100 – 200	> 300	> 300	Down
2	1	Yes	100 – 200	> 300	> 300	100 – 200	Down
3	6	Yes	< 50	< 50	< 50	< 50	NV
4	4	Yes	> 300	> 300	> 300	> 300	Down
5	13	Yes	> 300	> 300	> 300	> 300	Down
6	1	Yes	100 – 200	100 – 200	100 – 200	100 – 200	Down
7	4	Yes	100 – 200	100 – 200	> 300	> 300	NV
8	4	Yes	> 300	> 300	> 300	> 300	Down
9	4	Yes	100 – 200	100 – 200	100 – 200	100 – 200	Down
10	2	Yes	100 – 200	> 300	> 300	> 300	Down
11	3	Yes	> 300	> 300	> 300	> 300	NV
12	2	Yes	100 – 200	100 – 200	> 300	> 300	NV
13	1	Yes	> 300	> 300	> 300	> 300	NV
14	3	Yes	> 300	> 300	> 300	> 300	NV
15	2	Yes	> 300	> 300	> 300	> 300	Down
16	2	Yes	> 300	> 300	> 300	> 300	Down
17	1	Yes	> 300	> 300	> 300	> 300	NV

Farm No.	No. of boreholes	Borehole protection	Distance (m) from borehole to:				Slope from borehole
			Dairy	Dairy effluent	Kraal	Septic tank	
19	6	Yes	> 300	> 300	> 300	> 300	NV
20	1	No	> 300	> 300	> 300	> 300	Down
21	2	Yes	> 300	> 300	> 300	> 300	Up
22	3	Yes	> 300	> 300	> 300	> 300	NV
23	2	Yes	100 – 200	> 300	> 300	< 50	Down
24	2	Yes	100 – 200	100 – 200	> 300	> 300	NV
25	6	Yes	> 300	> 300	> 300	100 – 200	NV
26	2	No	> 300	< 50	> 300	> 300	NV
27	1	Yes	100 – 200	100 – 200	> 300	> 300	NV
28	4	Yes	> 300	> 300	> 300	> 300	NV
29	1	Yes	> 300	> 300	> 300	> 300	NV
30	2	Yes	> 300	> 300	> 300	> 300	Down
31	1	Yes	> 300	> 300	> 300	> 300	Down
32	3	Yes	> 300	> 300	> 300	> 300	Down
33	3	Yes	> 300	> 300	> 300	> 300	NV
34	5	Yes	< 50	> 300	> 300	> 300	Down
Mean	3	Protected = 32	< 50 = 3	< 50 = 2	< 50 = 1	< 50 = 1	Downslope = 16
Maximum	13.0		100 – 200 = 10	100 – 200 = 8	100 – 200 = 2	100 – 200 = 4	Upslope = 1
Minimum	1	Not protected = 2	> 300 = 21	> 300 = 24	> 300 = 31	> 300 = 29	Not visible = 17
Std Dev	3.2						

Std Dev = standard deviation; NV = slight or no slope with direction indeterminable

It is recommended that pollution sources, such as pit latrines, animal kraals and milking sheds are located from 10 to 15 m away from a borehole as well as being down slope from the water source (DWAF, 2004a). Household sanitation facilities in this study mostly comprises septic tanks, while the majority of farm workers had access to ventilated improved pit latrines (VIP), which is typical of South African rural conditions (DWA, 2012) (Table 7.2). The sanitation infrastructural design on all the farms conformed to the recommended pollution prevention distances, for example, the borehole on most farms was further than 100 m from the dairy, the collection point of the dairy effluent, the kraal and the septic tank. On 16 farms the pollution sources were clearly downslope from the borehole, while on one farm, the pollution source was located upslope from the borehole, increasing the pollution risk of the borehole.

The checklist was also used to probed the knowledge of farm owners and dairy managers on various aspects of water quality. The data revealed a distinct lack of knowledge of all aspects pertaining to the prevention of groundwater pollution (Table 7.4). The majority of farmers used the groundwater without it being treated, probably because of the perception among the rural communities and farmers that groundwater is safe and without any health risks (Chitanand *et al*., 2008). Furthermore, all farmers in this study had never received training on groundwater protection and water quality issues.

Table 7.4 Farm owners and dairy managers knowledge of water issues

Water knowledge	Yes	No
Do you know the water quality of your water supply?	3	31
Do you treat your drinking water	5	29
Have you tested the quality of your water in the past year?	1	33
Have you received any training on water quality issues?	0	34

The perception that untreated groundwater is safe for human consumption is contradicted by the poor water quality as measured on these farms (Chapter 4). Summary statistics revealed the presence of high levels of nitrates, coliforms and *E. coli* in the water used on these farms (Table 7.5). Of particular interest are the high levels of *E. coli*, which is indicative of pollution from dairy manure.

Hard water in this region results in scale deposition, particularly in geysers and dairy appliances and also increases the use of soap (Rubenowitz-Lundin and Hiscock, 2005). Since groundwater is used in all dairy farms, the hardness of the water probably adds to the running costs of the dairies.

Table 7.5 Summary statistics of important water quality parameters

Statistic	Nitrate (11 mg/ℓ)	Hardness (100 mg/ℓ)	Coliforms (≤10 counts/100 mℓ)	*E. coli* (not detected/100 mℓ)
Mean	15.02	386.86	343.12	75.30
Maximum	79.18	1 544.77	2 419.20*	2 419.20*
Minimum	0.65	42.89	0	0
Standard Deviation	15.56	264.49	698.31	414.28

* = maximum detection limit of the test

( ) = SANS 241 limit (SANS 241, 2011)

Possible correlations between farm management practices, infrastructure and the poor water quality were investigated. A weak negative correlation existed between the number of cows on a farm and the coliform values in the groundwater (R^2 = 0.0023). Also, no correlation existed between the number of cows on a farm and the *E. coli* values or the number of cows and the nitrate values in the groundwater. These results suggested that the link between groundwater pollution and farm management practices and infrastructure are not clear.

7.4 Conclusion

The challenge to increase production as well as to protect the environment and to ensure product safety is an international challenge faced by all dairy farmers. To protect and ensure groundwater quality in agricultural areas requires an integrated approach to farming (Schwarzenbach *et al*., 2010). The results obtained from the study indicate that, although dairy farms vary in milk yield and size, they are designed and managed in such a way as to prevent obvious groundwater contamination by dairy effluent. The boreholes are protected and the distance from the borehole to the dairy and waste collection area meet the criteria suggested by the Department of Water Affairs (DWA, 2004a). The poor groundwater quality on the dairy farms is a health risk to all water consumers and a revision of the current management practices is suggested. The extent of groundwater contamination largely depends on the environmental context of an area, mostly hydrological and soil conditions (Graham and Polizzotto, 2013). It is often difficult to isolate the source of groundwater pollution and therefore, groundwater flow assessments will aid in the identification of dominant contamination sources of the water (Graham and Polizzotto, 2013). The lack of knowledge and awareness of the farmers is a concern and training and information sessions are needed to address this aspect. An in-depth groundwater flow study will probably reveal some link between the dairy waste and groundwater pollution because *E. coli* was present in the groundwater on 15 out of the 34 farms studied.

Chapter 8
Conclusion and Recommendations

8.1 Introduction

Only 2.5% of the earth's water is suitable for human consumption, the other 97% is in oceans and seas (Chaudhary *et al*., 2011). Approximately 13% of the available freshwater is groundwater, an essential source of drinking water for many people worldwide (Mahvi *et al*., 2005). More than 50% of the world's population depends on groundwater as drinking water. Many rural and farming communities are solely dependent on groundwater as their only source of drinking water (Mahvi *et al*., 2005).

Although only about 13% of all water used in South Africa is from groundwater, it plays a major role in South Africa, as millions of people are dependent on groundwater in rural and farming areas (Colvin *et al*., 2008; Hay *et al*., 2012). Water quality at the source is dependent on the natural geology of the area and the soils of the catchment, as well as anthropogenic factors such as land use and disposal of waste in various forms.

Groundwater quality is described in terms of physical, chemical, and biological qualities. Naturally, groundwater contains mineral ions. These ions originate from the surrounding geological structures and slowly dissolve in the groundwater and are referred to as dissolved solids, which may be either positively charged or negatively charged (Harter, 2003). The total mass of dissolved solids is referred to as the total dissolved solids concentration and influences the electrical conductivity of the water. Besides the naturally occurring inorganic constituents, organic matter originating from topsoil, may affect the quality of groundwater. Complications arise where this water source becomes contaminated and unfit for use because of high concentrations of chemicals and organic matter.

Intensive agriculture is one of the major anthropogenic sources of groundwater pollution. Dairy farming, in particular, has been identified as an important source of domestic groundwater contamination (Van der Schans *et al*., 2009). Contamination of groundwater occurs mainly through inappropriate disposal of solid waste and effluent, land application of manure, fertiliser application in mixed farming operations, as well as dairy wash water containing detergents and soaps. Typical dairy contaminants include nitrates, phosphorus, faecal bacteria and sediment (Monaghan *et al*., 2008). In this study, the quality of groundwater was investigated over two sampling years on dairy farms in the Free State. The results revealed concentrations of nitrates and faecal contaminants well above acceptable limits, as well as high levels of hardness.

8.2 Nitrate pollution of groundwater

The manifestation of high nitrate levels in groundwater is a widespread phenomenon. Nitrate pollution on dairy farms occurs via a variety of sources (Van der Schans *et al*., 2009). Typical dairy farm nitrate pollutant sources include animal waste storage ponds, animal holding areas, crop fields receiving animal waste and chemical fertiliser, surface run-off and waste from farm sanitation facilities (Hooda *et al*., 2000; Smith *et al*., 2013).

Several studies focusing on groundwater quality have revealed elevated levels of nitrates, similar to this study. In Ghana, 14% of 75 groundwater samples from the Densu Basin exceeded the WHO limit of 10 mg/ℓ (Amoako *et al*., 2011). Measurements of nitrate concentrations of groundwater samples from the basement complex of south western Nigeria reached levels up to 30.8 mg/ℓ (Ayodele, 2012). In Chikhwawa, Malawi significantly high nitrate concentrations of up to 200 mg/ℓ were recorded (Grimason *et al*., 2013). In this study, the highest measurements recorded in 2009 were 65.05 and 68.00 mg/ℓ, while in 2013 a measurement of 79.18 mg/ℓ was recorded.

When the mean nitrate measurements of the two years were compared (mean in 2009 = 13.7 mg/ℓ; mean in 2013 = 14.7 mg/ℓ), data indicated that nitrate levels in groundwater in the study region could be increasing. This result is similar to the outcomes of a groundwater study in the Susa plain of Khozestan-Iran, where data indicated an increase from a mean value of 6.3 mg/ℓ in 1998 to an mean value of 10.4 mg/ℓ in 2004 (Mahvi *et al*., 2005).

When the state of pollution of the 2009 and 2013 groundwater samples of the participating farms was compared, the data revealed minor differences in the overall nitrate pollution. The percentage of non-compliant samples (n = 75) for 2009 was 49%, while for the non-compliant samples (n = 34) for 2013 was 59%. In a similar dairy farm groundwater study in north eastern Mexico, 34% of the samples were non-compliant (Pastén-Zapata *et al*., 2014), while in a groundwater study on dairy farms in the San Joaquin Valley in California, all groundwater samples were non-compliant (Van der Schans *et al*., 2009).

In South Africa, high nitrate levels in groundwater is the single most important reason for groundwater sources to be declared unfit for drinking (Clarke *et al*., 2004; Colvin *et al*., 2008). Tredoux reported, as early as 1993, that 27% of groundwater abstraction points (approximately 5 000) in South Africa exceeded the current safe drinking water standard of 10 mg/ℓ (Colvin *et al*., 2008). This study supports this early finding that nitrate is a concern on dairy farms in the Free State, particularly to the vulnerable members of the farming communities. Vulnerable members include infants, pregnant woman, the elderly and the immune compromised. It was estimated in 2012 that 12.2% of the South African population (6.4 million persons) were HIV positive, of which the Free State together with Mpumalanga, had the second highest prevalence of all nine provinces (Shisana *et al*., 2014). The Free State province had a HIV prevalence of 32.5% in 2011 (DoH, 2011).

The vulnerable communities on farms and other rural communities that rely upon groundwater could be exposed to the widespread occurrence of high nitrate levels in South Africa. For example, all but one of the groundwater samples at rural schools in the Greater Giyani Municipality exceeded the recommended nitrate limit (Samie *et al*., 2013). Excessive consumption of water with high levels of nitrate may result in the death of young infants as a result of methaemoglobinaemia or “blue baby” disease. Because infants lack acidity in gastric juice, nitrate reducing bacteria can grow in their upper intestinal tracts (Ayodele, 2012). When nitrate is ingested, it can be reduced to nitrite before the nitrate is completely absorbed in the bloodstream and combine with haemoglobin to form methaemoglobinaemia, which is ineffective as an oxygen carrier. The infant develops anoxaemia and eventually dies by asphyxia (Ayodele, 2012). Other health effects associated with excessive nitrate ingestion include cancer of gastrointestines and urinary tracts (Chaudhary *et al*., 2011) and nitrate poisoning in animals (Pastén-Zapata *et al*., 2014).

In the environment, nitrates may be exported to surface water, which could lead to eutrophication, thereby affecting biodiversity of mammals, birds, and fish populations by producing toxins and reducing oxygen levels (Pastén-Zapata *et al*., 2014).

8.3 Microbiological pollution of groundwater

Groundwater is perceived as being less vulnerable to contamination than surface water given the natural filtering ability of the soil subsurface (Graham and Polizzotto, 2013). Sanitation facilities such as pit latrines and septic tanks are often presented as the most obvious sources of faecal contamination of groundwater. Poor maintenance of boreholes, uncapped boreholes and poor sanitary design, as well as subsurface leaching of microbial contaminants further contribute to the microbial load of groundwater (Howard *et al*., 2003). Additional typical sources of microbial contamination on dairy farms include inadequate manure and dairy effluent disposal.

Depending on the source, groundwater may contain a wide variety of harmless heterotrophic microorganisms such as *Flavobacterium* spp., *Pseudomonas* spp., *Acinetobacter* spp., *Moraxella* spp., *Chromobacterium*, *Achromobacter* spp. and *Alcaligenes* spp., as well as numerous unidentified or unidentifiable bacteria (Aydin, 2007). Many microbial pathogens are known to contaminate groundwater and include viruses, bacterial pathogens and protozoa, such as *Cryptospiridium* and *Giardia*. These pathogens are frequently transmitted via drinking water and are predominantly of faecal origin (Ashbolt, 2004). The presence of microbial contaminants in groundwater indicates a rapid movement from the soil surface to the water-table because most pathogenic microorganisms have only limited persistence; bacteria for example typically have survival times measured in days or months (Howard *et al*., 2003).

Groundwater quality studies mostly constitute assessing the chemical and physical properties and exclude microbiological analyses. Studies that do include microbiological quality assessments have shown that microbial contamination of groundwater is relatively common. A groundwater study in the Gaza Strip showed a number of non-compliant samples for coliforms and *E. coli* (16% and 7% respectively). Similar results were found in a study conducted in Turkey (25% and 15% respectively) (Aydin, 2007).

In Southern Africa, the prevalence of coliforms and *E. coli* in groundwater appeared to be higher than in other studies. Gwimbi (2011) recorded that of the groundwater samples studies in Lesotho, 97% were non-compliant for coliforms and 71% for *E. coli*. In this study, the overall compliancy was marginally better. In the 2009 sampling year, 60% of the samples were non-compliant for coliforms and 29% for *E. coli*. In the 2013 round, 55% of the samples were non-compliant for coliforms and 41% for *E. coli*. The presence of coliforms and *E. coli* in so many samples in this study can probably be attributed to poor sanitary conditions and unhygienic handling of solid waste and effluent, which supports the view of Adekunle *et al*. (2007) that high coliform levels appear to be characteristic of groundwater used for domestic purposes in rural and farming communities.

Faecal contamination of groundwater is a serious environmental health concern and has been linked to outbreaks of various water-borne infections (Krolik *et al*., 2013). There were 288 documented confirmed water-borne outbreaks of infectious enteric diseases caused by contaminated groundwater in Canada over a 27-year period, with the most common pathogens being *Giardia intestinalis*, *Campylobacter* sp., *Salmonella* and rotavirus (Krolik *et al*., 2013). Acute gastrointestinal illness is the most recognised illness associated with poor microbiological water quality, presenting symptoms such as fever, nausea, diarrhoea, and/or vomiting (Macler and Merkle, 2000). The relatively high levels of coliforms and *E. coli* found in the groundwater on many of the farms in this study are of concern, particularly for sensitive groups. Clinical infections from coliforms are common even with once-off consumption of water containing 100 – 1 000 coliforms per 100 mℓ (22% of farms in 2009; 23% of farms in 2013) and serious health effects are indicated at levels > 1 000 per 100 mℓ (12% of farms in 2009; 5.6% of farms in 2013) (DWAF *et al*., 1998). Similarly, clinical infections are common with once-off consumption of water containing 10 – 100 *E. coli* per 100 mℓ (8% of farms in 2009; 44% of farms in 2013) and serious health effects could result for users at counts greater than 100 per 100 mℓ (6.7% of farms in 2009) (DWAF *et al*., 1998). Furthermore, poor microbiological water quality can also impact the quality of the dairy products and crops irrigated with such water, which in turn could have a negative impact on the health of consumers of such produce (Perkins *et al*., 2009; Elmoslemany *et al*., 2010; Hanjra *et al*., 2011).

8.4 Hardness of groundwater

Hardness levels in groundwater are determined by the geological structures of the underground rock and soil (Deshmukh, 2013). Generally, hard water originates where the topsoil is thick with limestone formations. The presence of cations of calcium and magnesium in groundwater is predominantly responsible for groundwater hardness (Dave *et al*., 2012).

Most farms in this study presented hard water. In both sampling years, more than 90% of the farms exceeded the limit of 100 mg/ℓ. The majority of the farms presented groundwater with very hard water levels, more than 300 mg/ℓ. The maximum levels recorded in this study were 471 mg/ℓ (2009) and 1 544 mg/ℓ (2013). These results are similar to that of a study conducted in the different municipalities of Limpopo, where most of the samples presented with hard to very hard water (Du Toit *et al*., 2012).

Health effects of hard water are generally indicated in sensitive groups, causing possible chronic effects. Particularly infants under the age of one year and individuals with a history of kidney or gall-bladder stones (DWAF *et al*., 1998). Exposure to hard water has also been suggested to be a risk factor that could aggravate eczema (WHO, 2011).

Hardness may have substantial financial implications for dairy farmers. Hard water prevents soap lathering and increases the boiling point of water. Furthermore, hardness results in the accumulation of scale (magnesium, manganese, iron, and calcium carbonates) in water delivery equipment (Singh *et al*., 2012; Deshmukh, 2013). These effects impact the running cost of a dairy because of exacerbated maintenance and electricity costs, as well as the increased soap use during cleaning processes (Dave *et al*., 2012; Singh *et al*., 2012).

8.5 Water quality index

Water quality indexes play a major role in the assessment and management of water quality. The application and use of a WQI has increased across the world and is applied by water quality professionals in USA, Canada, Europe, Iran, India and Nigeria (González *et al*., 2012; Yisa *et al*., 2012; Mohebbi *et al*., 2013; Tyagi *et al*., 2013). The United Nations also applies a WQI to assess the status of water quality worldwide (UNEP, 2007). The application of a WQI is a relatively recent introduction and is used to communicate water quality information by water professionals to the general public (Darko *et al*., 2013; Muthulakshmi *et al*., 2013; Tyagi *et al*., 2013).

In this study, various WQI were scrutinised and used to develop a suitable WQI that can be applied to groundwater. Because of the versatility of the weighted WQI (Tiwari and Mishra, 1985; Jerome and Pius, 2010), it was adapted, modified and extended for dairy farm groundwater. This modified WQI includes, in particular, microbiological water quality parameters, which are conspicuously absent from most other indexes. Other attributes of the modified WQI comprises the inclusion of physical and chemical water quality parameters, adaptability to include additional parameters, ease of interpretation, use of single sampling round measurements and simple to calculate.

The inclusion of the microbiological parameters as part of the modified WQI used in this study revealed that the overall status of groundwater quality on the dairy farms was poor. The modified WQI classified the groundwater as unsuitable for drinking of 35% of the farms in the 2009 sampling season. In the 2013 sampling season, the groundwater quality had improved, showing only 11% of the farms within an unsuitable for drinking classification, however this improvement was not significant. In Nigeria, similar WQI results were obtained from a groundwater study, where poor microbiological water quality was measured (Yisa *et al*., 2012).

8.6 Conclusion

This study supports the findings that groundwater is vulnerable to pollution from various sources on dairy farms. These include waste disposal, sanitation practices and the use of fertiliser. In particular, the microbiological quality of the groundwater on the dairy farms was poor. The high levels of coliforms and *E. coli* in the groundwater confirm faecal pollution that could be indicative of poor sanitary conditions. The farming communities residing on these farms consume the poor quality groundwater on a daily basis. This water contains high concentrations of microbial organisms and nitrates. Vulnerable groups on the farms are therefore particularly at risk of becoming ill. Furthermore, the use of poor quality groundwater in dairy activities and other agricultural activities, such as the irrigation of crops, may further impact produce quality and could ultimately impact the health of consumers.

A better understanding of the overall quality of groundwater in the Free State province is needed. Limited data are available on groundwater quality, particularly in areas of agricultural activities and mining. Further studies are thus needed for a more in-depth study of the groundwater quality in the area and the reasons for change. Due to the inherent health impact that poor quality groundwater holds in this region, it is imperative that farmers are made aware of the implications of using poor quality groundwater in all operational and domestic activities, and how to undertake remedial action. The versatility of the modified WQI has the potential to become a key tool in the study of groundwater quality in the province and because of its simplicity of data interpretation, it could be of great value to non-professionals such as farmers.

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Appendix A
Supplementary Information to Chapter 4

WISA 2012 PRESENTATION: POLLUTION INDEX FOR DAIRY FARM BOREHOLE WATER QUALITY IN THE FREE STATE, SOUTH AFRICA

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Abstract

In South Africa, many dairy farms depend on borehole water as the only source of drinking water. Generally, dairy wastewater is discharged onto pastures and land, posing a risk of polluting groundwater. Pollutants, such as nitrates, may cause diseases in humans and animals and adversely affect the environment. A pollution index will assist in the rating of boreholes according to drinking water quality standards. In this study, borehole drinking water quality of 75 dairy farms in the Free State, was assessed for physical, chemical and microbiological parameters. Standard sampling procedures were followed, the water analysed and the data compared to the drinking water quality standards of South Africa, South African National Standards, 241 of 2006. A water quality index and rating was determined for each farm borehole. The nitrogen content for 49.3% of the farms exceeded the prescribed limit. Similarly, for total coliforms, 68%, and for E. coli, 30.6%, of the farms exceeded the acceptable limits. Some 10.7% of the farm boreholes exceeded the limits for all three the major pollutants, namely, nitrates, coliforms and E. coli. Farming communities rely upon borehole water as the sole drinking water source. Currently, data on borehole water quality of South Africa dairy farms is limited. Those boreholes that are monitored are sampled infrequently. Because of the potential for pollution of groundwater from activities on dairy farms, polluted water may pose a health risk to all water consumers on the farm. A pollution index, generated from water *quality data, provides a means to rate borehole water quality and to identify farms posing the highest health risk to the consumers. This risk assessment tool has the potential to facilitate farming management decisions, thereby reducing or eliminating the exposure of farming communities to poor quality drinking water.*

Keywords: *water quality index; borehole drinking water quality; E. coli; coliforms; nitrate*

INTRODUCTION

Dairy farming is a major role-player in the agricultural sector of South Africa and contributes to economical development and sustainability in the country. All dairy enterprises utilise water for all the steps of the dairy industry, including cleaning, sanitization, heating, cooling and floor washing. Dairy wastewater is characterised by the high biological oxygen demand (BOD) and chemical oxygen demand (COD) contents, high levels of dissolved or suspended solids including fats, oils and grease, nutrients, such as ammonia or minerals and phosphates, and therefore require proper attention before disposal (1).

Dairy farm wastewater, which refers to manure and urine deposited during milking, is diluted during washing down of a milking shed floor (2; 3). Animal waste in dairy run-off is a major source of pollution and nutrient enrichment of streams and groundwater, and may have significant environmental impacts (4; 5; 6). The harmful effects of agricultural activities on groundwater (7; 8; 9) is becoming more and more of a concern worldwide (10), for example, high concentrations of ammoniacal nitrogen are harmful to stream animals if not adequately diluted (4).

It has been demonstrated that groundwater quality becomes affected, particularly through salt and nitrate leaching, during heavy agricultural activities (11). Therefore, manure handling and disposal practices in dairy enterprises are currently undergoing critical revision to reduce their impact on groundwater quality (12).

South Africa is a water-scarce country and the central region, which includes the Free State, is an arid area. Many of the dairy farms in the Free State are not close to any surface water sources and utilise borehole water for all dairy activities and for drinking water.

A study by Strydom *et al*. (13) on the handling practices of dairy wastewater in South Africa, showed that most farm wastewater was discharged onto pastures and land by irrigation, and has not changed since that time (personal communication C. Louw, 2010). With the increasing growth of the dairy industry together with the risk posed by dairy wastewater, there is no doubt that practices to protect groundwater sources should be instituted. According to WHO organisation, about 80% of all the diseases in human beings are caused by water (14). Once the groundwater is contaminated, its quality cannot be restored by stopping the pollutants from the source (15).

Little is known about direct groundwater quality impacts from the many elements of dairy manure management operations (16). A water quality index (WQI) is one of the most effective tools to communicate information on the quality of water to the consumers and concerned citizens. It, thus, becomes an important parameter for the assessment of groundwater (17, 18, 19, 14). The use of a WQI to communicate water quality is used since the seventies as documented by Saeedi (20). WQI is defined as a rating reflecting the composite influence of different water quality parameters. WQI is calculated from the point of view of the suitability of groundwater for human consumption. Therefore, the objective of the present work was to study groundwater quality of 75 dairy farms in the Free State and to discuss the suitability of groundwater for human based consumption based on computed water quality index values (WQI). The Free State is the third largest province, comprising 10.6% of South Africa's land area, and accommodates most of the dairy farms in South Africa in the eastern and northern regions.

STUDY AREA AND METHODS

The 75 farms studied are located in the three districts of Motheo, Xhariep and Lejweleputswa of the Free State (Figure 1). Groundwater samples were collected from the 75 dairy farms during 2009. Each of the groundwater samples was collected at the point of use in the dairy on the farm. Fourteen parameters were analysed, namely, pH, electrical conductivity, total hardness, chloride, sulphate, phosphate, nitrate, fluoride, calcium, magnesium, sodium, potassium, total coliforms and *E. coli*. Standard sampling and analytical procedures as prescribed by South African National Standards 241 (21) and Department of Water Affairs (22) were applied.

WQI was calculated from the point of view of suitability of groundwater for human consumption. Three steps were followed to compute the WQI (14). In the first step, each of the fourteen parameters was assigned a weighting (w_i) of relative importance in the overall quality of drinking water. In step 2 the relative weight (W_i) was calculated with the following calculation:

$$\mathrm{W}_i = \frac{\mathrm{w}_i}{\sum_{i=1}^{n}\mathrm{w}_i} \quad \ldots\ldots \quad (1)$$

Where, W_i is the relative weight, w_i is the weight of each parameter and n is the number of parameters.

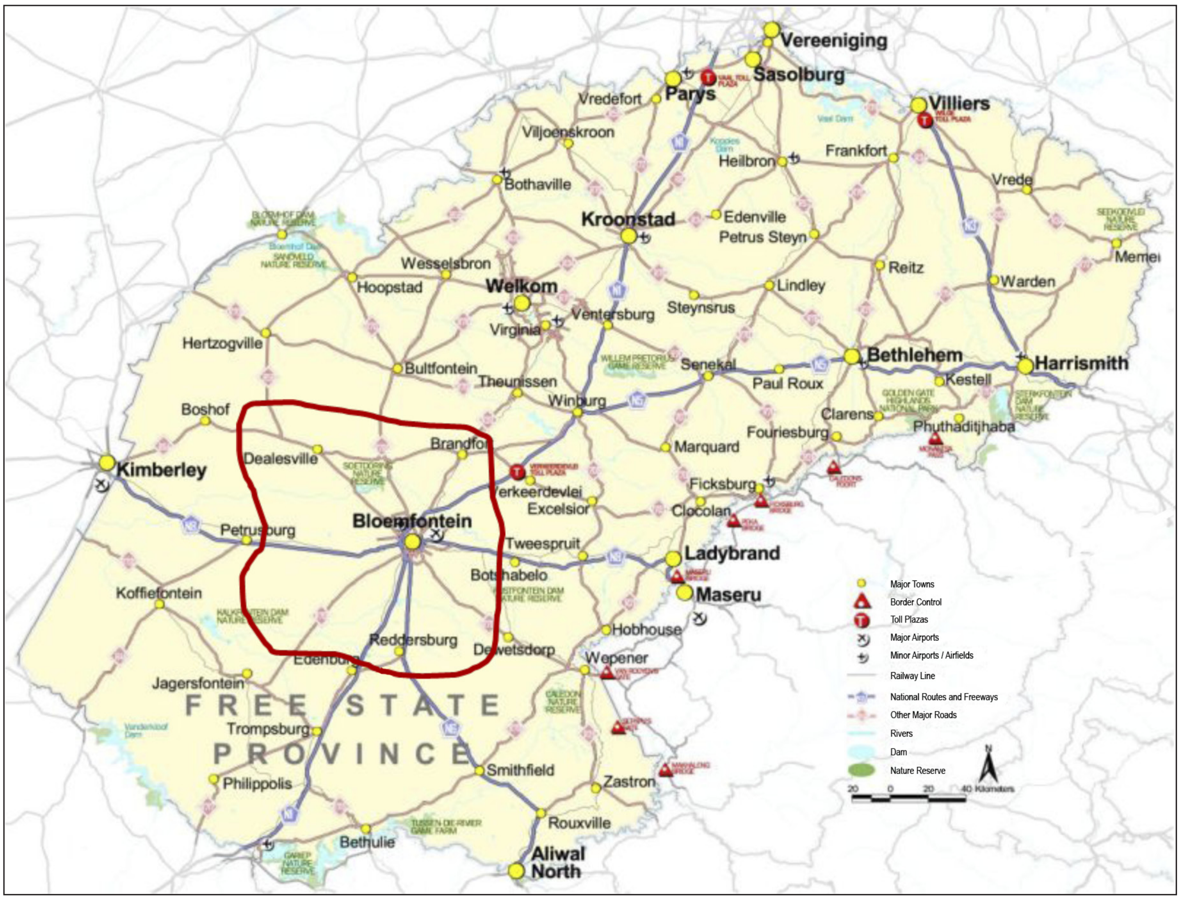

Figure 1 Study area in the Free State

In the last step, a quality rating scale (q_i) was calculated for each parameter by dividing its concentration in the water sample by its respective standard as prescribed by SANS 241 (21). This value was then multiplied by 100:

$$q_i = \frac{C_i}{S_i} \times 100 \quad \ldots\ldots \quad (2)$$

Where q_i is the quality rating, C_i is the concentration of each parameter in each water sample, and S_i the SANS 241 (21) standard.

The WQI was computed, by just calculating the Sl_i for each parameter, which was then used to determine the WQI as follows:

$$\mathrm{Sl}_i = W_i \times q_i \quad \ldots\ldots \quad (3)$$

$$\mathrm{WQI} = \sum \mathrm{Sl}_i \quad \ldots\ldots \quad (4)$$

where Sl_i is the sub index of i^{th} parameter; q_i is the rating based on concentration of i^{th} parameter and n is the number of parameters.

The WQI values were classified into five types, ranging from “excellent water” to “unsuitable for drinking” (15).

RESULTS

Generally, the physical and chemical properties of the borehole water of the 75 farms tested were within the prescribed SANS 241 (21) limits, except for a few parameters (Table 1). The borehole water on the majority of the farms displayed high levels of hardness and, on approximately half of the farms, the nitrogen level in the borehole water exceeded the SANS 241 (21) standard.

More than 60% of the boreholes tested indicated faecal pollution (Table 2). *E. coli* was present in approximately one third of the farms.

Table 1 Summary statistics of chemical water quality parameters of borehole water samples

Variable	Standard	Median	Mean	Max	Min	Standard deviation	% farms non-compliant
pH	(5.0–9.5)	7.7	7.6	8.3	7.1	0.3	0.0
EC	(< 150 mS/m)	79.5	94.7	353.0	30.0	48.6	6.6
Ca	(< 150 mg/ℓ)	71.0	87.7	406.0	24.0	67.2	6.6
Mg	(< 70 mg/ℓ)	33.0	42.7	237.0	9.5	35.8	10.6
Na	(< 200 mg/ℓ)	57.4	72.6	740.0	15.7	85.0	2.6
K	(< 50 mg/ℓ)	4.3	9.1	158.0	0.3	23.6	0.0
$CaCO_3$	(< 150 mg/ℓ)	301.0	307.0	1 314.0	3.6	145.7	96.0
F	(< 1.0 mg/ℓ)	0.4	0.4	1.4	0.0	0.3	4.0
Cl	(< 200 mg/ℓ)	44.0	78.8	533.0	10.5	100.6	8.0
N	(< 10 mg/ℓ)	9.9	11.5	68.0	0.2	11.7	49.3
PO_4	(< 0.1 mg/ℓ)*	1.2	1.6	5.5	0.1	1.6	14.6
SO_4	(< 400 mg/ℓ)	41.0	54.7	376.0	10.8	54.1	0.0

EC = electrical conductivity

Standard = SANS 241 standard value

% farms non-compliant displayed one or more water quality parameter that exceeded the SANS 241 limits

Table 2 Summary statistics of microbiological water quality parameters of borehole water samples

Variable	Total coliforms	*E. coli*
Standard		
Median	79	0
Mean	169.0	67.5
Maximum	1 230.0	2 419.0
Minimum	0	0
Standard deviation (SD)	252.85	326.12
% farms non-compliant	68.0	30.6

% farms non-compliant displayed one or more water quality parameters that exceeded the SANS 241 limits

For computing the WQI, weights were allocated to the different chemical water quality parameters as suggested by (15) and (23). For microbiological parameters, weights were selected based upon their importance as water quality parameters. The maximum weight of five was assigned to parameters such as nitrate and *E. coli* (Table 3)

Table 3 Weight, relative weight and compliance of water quality parameters

Parameter	Weight (w_i)	Relative weight (W_i)
pH	4	0.08510
Electrical conductivity	5	0.10638
Calcium	2	0.04255
Magnesium	2	0.04255
Sodium	4	0.08510
Potassium	2	0.04255
Total hardness as $CaCO_3$ mg/ℓ	2	0.04255
Fluoride	4	0.08510
Chloride	3	0.06382
Nitrate	5	0.10638
Phosphate	2	0.04255
Sulphate	5	0.10638
Total coliforms	2	0.04255
E. coli	5	0.10638
Total 14	47	1.00000

Table 4 Water quality classification based upon WQI value

WQI value	Water quality	Percentage farms
< 50	Excellent	16.00
> 50 – 100	Good water	37.33
> 100 – 200	Poor water	8.00
> 200 – 300	Very poor water	1.33
> 300	Water unsuitable for drinking	37.33

The WQI computed for the 75 farms revealed that less than 50% of the boreholes were suitable for human consumption (Table 4). The WQI further indicated that the water quality of approximately 40% of the boreholes should not be used for human consumption.

DISCUSSION AND CONCLUSIONS

As fertilizer is the largest contributor of anthropogenic nitrogen worldwide, it was not surprising that some of these dairy farms displayed high nitrate levels in the borehole drinking water. This enrichment of the water can be attributed mostly to animal waste and run-off from the dairies (4). On some of the farms the nitrate levels were exceptionally high, up to seven times greater than the South African specified health limit (21) of 10 mg/ℓ, which is more stringent that the 50 mg/ℓ specified for nitrates by the World Health Organisation (24). These high toxic levels of nitrates are a major concern as acute toxicity has been documented at a concentrations > 50 mg/ℓ (25). Ingestion of nitrates in drinking water may cause methaemoglobinaemia ("blue baby syndrome") in infants less than 6 months of age (26).

A further concern is the large number of farm boreholes in which *E. coli* was detected. Because these boreholes are the sole drinking water sources on these farms, humans and animals are at risk for contracting gastrointestinal diseases (27). The contaminated water could further contribute to the decrease in quality of dairy products and other farming produce (28). It can therefore be concluded that this baseline study strongly suggests that further studies should be undertaken to provide insights into water and wastewater management strategies on dairy farms in the Free State.

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Table A.1 Raw data and summary calculations of WQI

Farm No.	pH	EC	Ca	Mg	Na	K	$CaCO_3$	F	Cl	N	PO_4	SO_4	Coli	*E. coli*
1	8.03	78.8	64.1	24.9	57.9	7.150	281.0	0.46	40.0	10.18	<0.1	47.0	6	0
2	7.76	74.5	62.4	26.6	65.4	3.929	327.0	0.37	27.7	3.88	<0.1	29.2	50	1
3	7.84	79.4	76.0	41.9	41.8	1.850	313.0	0.13	48.0	11.66	<0.1	18.0	4	0
4	7.70	63.4	53.0	19.0	66.0	1.400	238.0	0.94	33.1	5.43	<0.1	28.0	2419	73
5	7.15	66.9	57.7	32.1	35.0	2.530	223.0	0.14	22.0	18.13	<0.1	36.0	0	0
6	7.93	75.2	59.0	25.2	57.4	4.450	271.0	0.35	46.0	10.01	<0.1	29.0	2	0
7	7.38	56.0	54.3	13.5	51.9	2.530	226.0	0.45	33.0	1.98	<0.1	24.0	3	0
8	7.22	145.0	331.0	53.0	61.0	158.000	14.7	0.54	197.0	13.79	<0.1	98.0	1	0
9	7.97	93.1	79.0	28.8	62.9	7.580	319.0	0.33	56.0	10.61	<0.1	65.0	770	0
10	7.44	67.6	60.0	36.0	16.0	4.520	232.0	0.13	29.0	14.72	<0.1	40.0	26	2
11	7.23	227.0	263.5	115.0	94.7	4.400	395.0	0.27	462.0	12.55	<0.1	194.0	0	0
12	7.05	94.2	71.0	37.0	56.0	7.610	278.0	0.39	79.0	16.74	<0.1	57.0	9	0
13	7.27	112.0	107.0	43.8	85.0	2.650	341.0	0.38	107.0	10.96	<0.1	82.0	276	0
14	7.43	81.5	75.0	35.0	45.0	6.000	302.0	0.36	49.0	9.56	<0.1	45.0	12	0
15	7.33	163.0	406.0	138.0	73.0	93.000	11.0	0.22	245.0	10.90	<0.1	87.0	1	0
16	8.11	69.6	57.7	21.2	41.8	7.180	238.0	0.37	29.0	13.33	<0.1	37.0	21	9
17	7.68	226.0	161.0	138.0	142.0	14.900	462.0	0.58	412.0	65.05	4.32	189.0	237	0
18	7.72	168.0	71.0	49.0	230.0	0.750	515.0	0.46	211.0	2.91	<0.1	86.0	0	0
19	7.68	67.0	62.9	34.5	42.7	1.050	308.0	0.31	23.0	1.79	<0.1	30.4	0	0
20	8.34	124.0	96.0	64.0	70.0	7.100	369.0	0.44	105.0	19.58	5.46	49.0	722	2

Farm No.	pH	EC	Ca	Mg	Na	K	$CaCO_3$	F	Cl	N	PO_4	SO_4	Coli	*E. coli*
21	7.80	56.4	54.0	28.6	27.0	9.010	238.0	0.39	14.3	7.65	0.39	21.0	12	0
22	7.75	73.0	70.0	27.0	34.0	3.100	185.0	0.20	65.0	14.74	< 0.1	51.0	1334	0
23	7.36	102.0	85.0	32.0	77.0	4.320	269.0	0.22	106.0	17.37	< 0.1	50.0	42	0
24	7.89	79.0	63.0	32.0	52.0	3.700	247.0	0.42	34.0	20.67	< 0.1	51.0	2419	461
25	7.91	142.0	125.0	70.0	73.3	5.572	279.0	0.40	176.0	36.98	< 0.1	70.0	2419	0
26	8.04	353.0	101.0	110.0	740.0	1.787	1314.0	1.27	533.0	17.88	< 1.0	376.0	37	0
27	8.00	91.6	76.0	25.8	67.7	6.710	331.0	0.42	52.0	16.43	< 0.1	23.0	2419	0
28	7.42	108.0	95.0	41.0	96.0	6.900	315.0	0.42	89.0	17.95	< 0.1	60.0	1	0
29	7.15	65.0	53.7	19.0	55.7	1.750	308.0	0.47	20.0	1.31	< 0.1	20.9	112	0
30	7.29	55.0	49.1	23.6	25.6	3.100	232.0	0.27	27.0	3.64	< 0.1	19.8	0	0
31	7.40	143.0	131.0	76.0	56.0	6.750	310.0	0.24	171.0	29.23	2.48	112.0	10	0
32	8.02	65.5	41.2	11.3	106.4	1.177	285.0	1.37	26.0	1.12	< 0.1	26.0	118	0
33	7.68	60.6	55.0	13.7	64.0	5.500	278.0	0.02	10.5	6.45	< 0.1	16.7	86	0
34	7.53	80.4	24.0	237.0	117.0	3.040	420.0	0.50	23.0	0.37	< 0.1	11.4	0	0
35	7.54	102.0	84.5	30.0	93.9	6.760	303.0	0.63	139.0	14.93	> 0.1	51.0	2	0
36	7.63	57.0	44.6	17.5	53.2	3.700	209.0	0.44	20.0	6.95	1.7	32.0	2	0
37	7.90	131.0	81.0	45.0	137.0	8.940	346.0	0.56	116.0	25.20	< 0.1	96.0	479	10
38	7.49	231.0	220.0	152.0	84.0	1.610	471.0	0.25	381.0	68.00	< 0.1	191.0	2419	2419
39	7.52	64.9	69.8	19.3	59.9	1.457	295.0	0.59	23.0	0.56	< 0.1	31.0	137	0
40	7.98	78.9	72.0	45.0	28.0	4.170	282.0	0.30	36.0	14.07	< 0.1	50.0	687	1
41	7.71	67.3	84.8	29.9	36.3	3.670	349.0	0.79	18.0	0.25	0.04	13.1	7	0

Farm No.	pH	EC	Ca	Mg	Na	K	$CaCO_3$	F	Cl	N	PO_4	SO_4	Coli	*E. coli*
42	7.37	86.9	70.0	38.0	58.0	7.750	320.0	0.46	49.0	12.94	0.79	28.4	47	0
43	7.34	118.0	110.0	46.5	75.0	6.800	324.0	0.36	111.0	20.18	0.35	62.9	7	0
44	7.99	85.6	58.0	33.0	75.0	6.200	328.0	0.68	56.0	8.08	<0.1	30.0	2149	291
45	7.26	84.6	72.0	29.0	85.0	5.900	316.0	0.39	44.0	12.05	<0.1	25.1	13	0
46	7.64	30.0	25.1	9.5	19.6	4.390	127.0	0.27	16.4	0.17	<0.1	14.2	0	0
47	7.30	75.0	73.9	29.1	42.3	0.630	360.0	0.26	28.0	1.99	<0.1	20.4	1	0
48	7.15	89.1	75.9	33.5	78.9	3.810	326.0	0.55	54.0	10.61	<0.1	47.0	11	0
49	7.77	54.0	38.4	12.1	55.4	3.370	221.0	0.42	31.0	1.64	<0.1	19.3	2419	219
50	7.51	75.1	58.0	26.0	56.0	8.160	287.0	0.58	49.0	6.98	<0.1	31.0	6	0
51	7.78	83.4	60.7	11.1	128.9	1.200	337.0	1.43	53.0	1.54	<0.1	33.0	1	0
52	7.47	74.8	62.0	36.0	39.0	1.800	356.0	0.18	26.0	5.93	<0.1	14.0	5	0
53	7.76	108.0	90.0	42.0	74.0	5.360	336.0	0.40	88.6	15.18	1.04	53.0	2419	1414
54	7.86	88.8	56.0	33.0	91.0	4.630	394.0	0.57	43.0	4.12	<0.1	30.0	112	0
55	7.46	135.0	116.0	51.8	154.8	1.180	465.0	0.47	87.0	2.39	0.16	169.0	21	0
56	7.78	59.1	70.5	23.0	38.4	1.170	292.0	0.40	13.5	0.48	<0.1	23.0	93	5
57	7.68	78.8	61.0	42.0	33.0	7.240	294.0	0.54	47.0	9.98	<0.1	42.0	231	1
58	7.63	61.3	45.4	26.5	51.8	2.490	282.0	0.18	21.0	5.75	<0.1	15.0	1	0
59	8.03	115.0	84.8	33.8	80.2	10.400	301.0	0.32	114.0	22.94	<0.1	50.0	0	0
60	7.70	96.9	77.0	43.0	67.0	7.720	302.0	0.57	89.0	17.94	1.29	58.0	231	0
61	8.24	91.0	359.0	55.0	23.0	112.000	3.59	0.61	41.0	6.52	<0.1	46.0	99	0
62	7.78	83.0	75.0	55.0	32.0	0.330	340.0	0.19	34.0	0.44	<0.1	73.0	13	2

Farm No.	pH	EC	Ca	Mg	Na	K	$CaCO_3$	F	Cl	N	PO_4	SO_4	Coli	*E. coli*
63	7.94	85.7	77.3	30.9	49.9	5.760	283.0	0.27	63.0	9.57	< 0.1	49.0	210	96
64	8.04	85.7	75.0	24.6	66.6	3.470	303.0	0.56	54.0	8.06	< 0.1	50.0	49	5
65	7.46	71.0	83.2	34.8	32.6	0.990	337.0	0.18	21.5	3.98	< 0.1	24.5	179	20
66	8.11	71.0	56.0	32.0	53.0	4.700	281.0	0.48	29.0	8.17	< 0.1	31.0	194	11
67	7.88	79.5	74.0	29.0	56.0	7.3800	293.0	0.58	35.0	12.36	< 0.1	41.0	113	0
68	7.54	62.4	59.6	34.5	25.1	4.000	202.0	0.25	23.0	14.41	< 0.1	56.0	32	0
69	7.34	67.5	76.2	21.6	44.0	2.420	283.0	0.86	29.0	3.30	< 0.1	36.0	6	3
70	7.66	76.0	42.0	27.0	82.0	1.342	377.0	0.38	22.0	1.51	< 0.1	10.8	99	4
71	7.90	64.6	65.5	26.7	32.9	1.110	257.0	0.26	24.0	7.91	< 0.1	30.0	4	0
72	7.12	56.6	55.0	34.0	15.7	0.500	279.0	0.18	12.0	0.39	< 0.1	25.0	3	0
73	7.87	90.8	63.0	38.0	77.0	6.450	258.0	0.59	60.0	16.11	1.37	78.0	104	10
74	7.72	69.6	60.0	37.0	22.0	5.000	261.0	0.25	21.0	7.29	< 0.1	68.0	1112	0
75	7.31	111.0	108.0	61.6	48.6	3.050	373.0	0.17	89.0	14.88	< 0.1	75.0	0	0
Limit		(< 150 mS/m)	(< 150)	(< 70)	(< 200)	(< 50)	(< 150)	(< 0.1)	(< 200)	(< 10)	(– 0.1)	(< 400)	(< 10)	Not detected
Total	75	75	75	75	75	75	75	75	75	75	75	75	75	75
Exceed limit	0	4	6	3	0	9	73	3	5	35	8	0	51	23
Median	7.68	79.50	71.00	33.00	57.40	4.32	301.00	0.40	44.00	9.98	1.165	41.00	23.50	0
Mean	7.6488	94.71467	87.744	42.70413	72.576	9.06672	307.0439	0.435067	78.82133	11.484	1.615833	54.69467	336.027	67.45333
Max.	8.34	353	406	237	740	158	1 314	1.43	533	68	5.46	376	2 419	2 419
Min.	7.05	30	24	9.51	15.7	0.33	3.59	0.02	10.5	0.17	0.04	10.8	0	0
Std Dev	0.294962	48.56167	67.18541	35.79022	84.9981	23.64841	145.6938	0.25489	100.6379	11.73005	1.626138	54.07504	704.1146	323.9405

Table A.2 WQI data

Farm No.	Elec. Cond.	Ca	Mg	Na	F	Cl	N	PO_4	Coli	*E. coli*	F_1	F_2
1	79	64	25	58	0	40	10	< 0.1	6	0	7	7
2	75	62	27	65	0	28	4	< 0.1	50	1	14	14
3	79	76	42	42	0	48	12	< 0.1	4	0	7	7
4	63	53	19	66	1	33	5	< 0.1	2 419	73	14	14
5	67	58	32	35	0	22	18	< 0.1	0	0	7	7
6	75	59	25	57	0	46	10	< 0.1	2	0	7	7
7	56	54	14	52	0	33	2	< 0.1	3	0	0	0
8	145	331	53	61	1	197	14	< 0.1	1	0	7	7
9	93	79	29	63	0	56	11	< 0.1	770	0	14	14
10	68	60	36	16	0	29	15	< 0.1	26	2	21	21
11	227	264	115	95	0	462	13	< 0.1	0	0	36	36
12	94	71	37	56	0	79	17	< 0.1	9	0	7	7
13	112	107	44	85	0	107	11	< 0.1	276	0	14	14
14	82	75	35	45	0	49	10	< 0.1	12	0	7	7
15	163	406	138	73	0	245	11	< 0.1	1	0	21	21
16	70	58	21	42	0	29	13	< 0.1	21	9	21	21
17	226	161	138	142	1	412	65	4.0	237	0	50	50
18	168	71	49	230	0	211	3	< 0.1	0	0	21	21
19	67	63	35	43	0	23	2	< 0.1	0	0	0	0

Farm No.	Elec. Cond.	Ca	Mg	Na	F	Cl	N	PO_4	Coli	*E. coli*	F_1	F_2
20	124	96	64	70	0	105	20	5.0	722	2	29	29
21	56	54	29	27	0	14	8	0.0	12	0	7	7
22	73	70	27	34	0	65	15	<0.1	1 334	0	14	14
23	102	85	32	77	0	106	17	<0.1	42	0	14	14
24	79	63	32	52	0	34	21	<0.1	2 419	461	21	21
25	142	125	70	73	0	176	37	<0.1	2 419	0	21	21
26	353	101	110	740	1	533	18	<1.0	37	0	50	50
27	92	76	26	68	0	52	16	<0.1	2 419	0	14	14
28	108	95	41	96	0	89	18	<0.1	1	0	7	7
29	65	54	19	56	0	20	1	<0.1	112	0	7	7
30	55	49	24	26	0	27	4	<0.1	0	0	0	0
31	143	131	76	56	0	171	29	2.0	10	0	29	29
32	66	41	11	106	1	26	1	<0.1	118	0	14	14
33	61	55	14	64	0	11	6	<0.1	86	0	7	7
34	80	24	237	117	1	23	0	<0.1	0	0	7	7
35	102	85	30	94	1	139	15	>0.1	2	0	7	7
36	57	45	18	53	0	20	7	2.0	2	0	7	7
37	131	81	45	137	1	116	25	<0.1	479	10	21	21
38	231	220	152	84	0	381	68	<0.1	2 419	2 419	50	50
39	65	70	19	60	1	23	1	<0.1	137	0	7	7

Farm No.	Elec. Cond.	Ca	Mg	Na	F	Cl	N	PO_4	Coli	*E. coli*	F_1	F_2
40	79	72	45	28	0	36	14	<0.1	687	1	21	21
41	67	85	30	36	1	18	0	0.0	7	0	0	0
42	87	70	38	58	0	49	13	1.0	47	0	14	14
43	118	110	47	75	0	111	20	0.0	7	0	7	7
44	86	58	33	75	1	56	8	<0.1	2 149	291	14	14
45	85	72	29	85	0	44	12	<0.1	13	0	14	14
46	30	25	10	20	0	16	0	<0.1	0	0	0	0
47	75	74	29	42	0	28	2	<0.1	1	0	0	0
48	89	76	34	79	1	54	11	<0.1	11	0	14	14
49	54	38	12	55	0	31	2	<0.1	2 419	219	14	14
50	75	58	26	56	1	49	7	<0.1	6	0	0	0
51	83	61	11	129	1	53	2	<0.1	1	0	7	7
52	75	62	36	39	0	26	6	<0.1	5	0	0	0
53	108	90	42	74	0	89	15	1.0	2 419	1 414	29	29
54	89	56	33	91	1	43	4	<0.1	112	0	7	7
55	135	116	52	155	0	87	2	0.0	21	0	7	7
56	59	71	23	38	0	14	0	<0.1	93	5	14	14
57	79	61	42	33	1	47	10	<0.1	231	1	14	14
58	61	45	27	52	0	21	6	<0.1	1	0	0	0
59	115	85	34	80	0	114	23	<0.1	0	0	7	7

Farm No.	Elec. Cond.	Ca	Mg	Na	F	Cl	N	PO_4	Coli	*E. coli*	F_1	F_2
60	97	77	43	67	1	89	18	1.0	231	0	21	21
61	91	359	55	23	1	41	7	<0.1	99	0	7	7
62	83	75	55	32	0	34	0	<0.1	13	2	14	14
63	86	77	31	50	0	63	10	<0.1	210	96	14	14
64	86	75	25	67	1	54	8	<0.1	49	5	14	14
65	71	83	35	33	0	22	4	<0.1	179	20	14	14
66	71	56	32	53	0	29	8	<0.1	194	11	14	14
67	80	74	29	56	1	35	12	<0.1	113	0	14	14
68	62	60	35	25	0	23	14	<0.1	32	0	14	14
69	68	76	22	44	1	29	3	<0.1	6	3	7	7
70	76	42	27	82	0	22	2	<0.1	99	4	14	14
71	65	66	27	33	0	24	8	<0.1	4	0	0	0
72	57	55	34	16	0	12	0	<0.1	3	0	0	0
73	91	63	38	77	1	60	16	1.0	104	10	29	29
74	70	60	37	22	0	21	7	<0.1	1 112	0	7	7
75	111	108	62	49	0	89	15	<0.1	0	0	7	7

Table A.3 WQI calculations

Farm No.	F_1	F_2	excursion cforms	excursion E. coli	excursion N	excursion PO_4	excursion Cl	excursion F	excursion Na	excursion Mg	excursion Ca	excursion Elec. Cond	*nse*	F_3	$F_1 + F_2 + F_3$	$\sqrt{F_1 + F_2 + F_3}$	WQI
1	7	7			0								0	0	14	4	98
2	14	14	3	–1									0	100	129	11	93
3	7	7			0								0	1	15	4	98
4	14	14	241	–1									0	13	41	6	96
5	7	7			1								0	5	20	4	97
6	7	7			0								0	0	14	4	98
7	0	0											0	0	0	0	100
8	7	7			0								0	3	17	4	98
9	14	14	76		0								5	84	113	11	94
10	21	21		–1	0								0	–4	39	6	96
11	36	36			0		1			1	1	1	0	20	91	10	94
12	7	7			1								0	5	19	4	97
13	14	14	27		0								2	66	94	10	94
14	7	7	0										0	1	16	4	98
15	21	21			0		0						0	3	46	7	96
16	21	21	1	–1	0								0	3	46	7	96
17	50	50	23		6	42	1			1	–1	1	5	84	184	14	92
18	21	21					0		0			0	0	2	45	7	96

Farm No.	F_1	F_2	excursion cforms	excursion E. coli	excursion N	excursion PO_4	excursion Cl	excursion F	excursion Na	excursion Mg	excursion Ca	excursion Elec. Cond	*nse*	F_3	$F_1 + F_2 + F_3$	$\sqrt{F_1 + F_2 + F_3}$	WQI
19	0	0											0	0	0	0	100
20	29	29	71	−1	1	54							9	90	147	12	93
21	7	7	0										0	1	16	4	98
22	14	14	132		0								9	90	119	11	94
23	14	14	3		1								0	22	51	7	96
24	21	21	241	−1	1								17	95	137	12	93
25	21	21	241		3					0			17	95	137	12	93
26	50	50	3		1		2	0	3	1		1	1	42	142	12	93
27	14	14	241		1								17	95	123	11	94
28	7	7			1								0	5	20	4	97
29	7	7	10										1	42	56	8	96
30	0	0											0	0	0	0	100
31	29	29	0		2	24				0			2	65	122	11	94
32	14	14	11					0					1	44	73	9	95
33	7	7	8										1	35	49	7	96
34	7	7								2			0	15	29	5	97
35	7	7			0								0	3	18	4	98
36	7	7				16							1	53	68	8	95
37	21	21	47	−1	2								3	77	120	11	94

Farm No.	F_1	F_2	excursion cforms	excursion E. coli	excursion N	excursion PO_4	excursion Cl	excursion F	excursion Na	excursion Mg	excursion Ca	excursion Elec. Cond	nse	F_3	$F_1 + F_2 + F_3$	$\sqrt{F_1 + F_2 + F_3}$	WQI
38	50	50	241	–1	6					1	0	1	18	95	195	14	92
39	7	7	13										1	48	62	8	95
40	21	21		–1	0								0	–4	38	6	96
41	0	0											0	0	0	0	100
42	14	14	4		0								0	22	51	7	96
43	7	7			1								0	7	21	5	97
44	14	14	241	–1									17	94	123	11	94
45	14	14	0		0								0	3	32	6	97
46	0	0											0	0	0	0	100
47	0	0											0	0	0	0	100
48	14	14	0		0								0	1	30	5	97
49	14	14	241	–1									17	94	123	11	94
50	0	0											0	0	0	0	100
51	7	7						0					0	3	17	4	98
52	0	0											0	0	0	0	100
53	29	29	241	–1	1	9							18	95	152	12	93
54	7	7	10										1	42	56	8	96
55	7	7											0	0	14	4	98
56	14	14	8	–1									1	34	63	8	95

Farm No.	F_1	F_2	excursion cforms	excursion E. coli	excursion N	excursion PO_4	excursion Cl	excursion F	excursion Na	excursion Mg	excursion Ca	excursion Elec. Cond	nse	F_3	$F_1 + F_2 + F_3$	$\sqrt{F_1 + F_2 + F_3}$	WQI
57	14	14	22	–1									2	60	89	9	95
58	0	0											0	0	0	0	100
59	7	7			1								0	8	23	5	97
60	21	21	22		1	12							2	71	114	11	94
61	7	7	9										1	39	53	7	96
62	14	14	0	–1									0	–5	23	5	97
63	14	14	20	–1									1	58	86	9	95
64	14	14	4	–1									0	17	46	7	96
65	14	14	17	–1									1	53	82	9	95
66	14	14	18	–1									1	55	84	9	95
67	14	14	10		0								1	43	72	8	95
68	14	14	2		0								0	16	44	7	96
69	7	7		–1									0	–8	7	3	99
70	14	14	9	–1									1	36	65	8	95
71	0	0											0	0	0	0	100
72	0	0											0	0	0	0	100
73	29	29	9	–1	1	13							2	61	118	11	94
74	7	7	110										8	89	103	10	94
75	7	7			0								0	3	18	4	98

Appendix B
Supplementary Information to Chapter 6

Inspection guide to assess raw water data and compare it with WQI scores as used in chapter 6.

Table B.1 Inspection criteria

Categories	
Excellent	100% compliance / and slight increase for coliforms
Good	Slight increase in *E. Coli* / just exceeding turbidity + nitrates / just exceeding coliforms + nitrates (values slightly exceeding limit of 1 or 2 parameters)
Poor	Exceeding coli + *E. Coli* / nitrates+ hardness /nitrates + total hardness + coliforms (values of 2 parameters exceeding limits, micro very high)
Very poor	Nitrates + total hardness + *E. Coli* / chlorine + nitrates + total hardness (3 parameters exceeding with 1 very high)
Unacceptable	Nitrates + total hardness + *E. Coli* + coliforms / nitrates + turbidity + total hardness + coliforms + *E. Coli* / nitrates + total hardness + coliforms / chlorine + hardness + turbidity + coliforms + *E. Coli* (4 or more parameters exceeding limits as well as 3 parameters exceeded limits excessively)

Table B.2 Categories described in Table B.1 applied to raw data obtained from the dairy farms

Farm No.	pH	EC	Ca	Mg	Na	K	F	Cl	N	PO_4	SO_4	Tur	Total Hard	Coli	E. coli	Rate
Limit	5 – 9.7	170	150	170	200	50	1.5	300	11	0.1	500		100	10	0	
1	7.5	75.4	67.5	35.8	45.6	1.5	0.5	58.8	11.2	– 0.1	24.5	0.7	315.3	0.0	0	Good
2	7.4	129.0	105.7	60.8	87.1	10.7	0.4	148.0	14.8	– 1.0	80.1	0.6	513.5	3.1	0	Poor
3	7.6	96.1	78.2	35.4	76.3	6.0	0.5	72.0	20.0	– 0.1	56.4	2.7	340.5	160.7	1	Unsuitable
4	7.4	171.0	133.0	99.6	86.4	8.0	0.4	203.0	49.7	– 1.0	87.4	1.5	740.6	40.4	0	Very poor
5	7.3	167.0	110.1	54.5	162.9	10.2	0.8	202.0	11.9	– 1.0	131.4	1.0	498.4	0.0	0	Poor
6	7.7	137.0	113.4	68.7	68.2	4.7	0.4	184.0	39.5	– 1.0	64.0	1.8	565.2	325.5	4	Unsuitable
7	7.6	85.3	67.3	23.0	67.5	5.7	0.6	48.5	15.3	– 0.1	20.4	1.3	262.8	48.9	0	Poor
8	7.3	118.0	97.0	36.9	88.2	6.2	0.3	138.0	19.2	– 1.0	69.4	0.5	393.9	2.0	0	Unsuitable
9	7.8	83.3	78.5	52.5	39.4	3.9	0.3	55.2	13.1	– 0.1	64.4	0.4	411.4	980.4	0	Unsuitable
10	7.5	125.0	68.5	43.7	154.7	8.8	0.4	122.4	21.6	– 1.0	93.7	1.3	350.3	1.0	0	Poor
11	7.7	86.4	57.8	35.6	99.4	4.3	0.5	46.6	4.9	– 0.1	28.4	0.2	290.2	2.0	2	Good
12	7.5	84.1	60.4	35.3	85.2	6.4	0.6	61.6	8.7	– 0.1	31.8	0.2	295.9	9.8	2	Good
13	7.3	199.0	218.6	107.6	93.9	3.7	0.1	348.8	10.6	– 1.0	213.5	0.4	987.6	0.0	0	Very poor
14	7.5	77.4	73.2	58.5	35.1	0.2	0.2	48.1	0.6	– 0.1	63.5	0.3	422.8	0.0	0	Good
15	8.0	100.0	91.6	47.8	74.0	6.0	0.3	70.3	16.0	– 1.0	49.1	0.5	425.3	613.1	1	Unsuitable
16	7.3	82.0	65.4	34.3	73.7	3.4	0.6	53.4	14.2	– 0.1	50.9	0.5	304.4	2419.2	13	Unsuitable
17	7.2	60.3	52.4	33.8	32.5	2.4	0.2	19.8	19.6	– 0.1	42.8	2.4	269.7	1.0	0	Good
18	7.6	63.2	57.6	25.3	44.0	6.9	0.5	25.1	12.5	– 0.1	37.2	0.2	247.7	12.2	0	Good

Farm No.	pH	EC	Ca	Mg	Na	K	F	Cl	N	PO_4	SO_4	Tur	Total Hard	Coli	E. coli	Rate
Limit	5 – 9.7	170	150	170	200	50	1.5	300	11	0.1	500		100	10	0	
19	7.6	60.9	45.8	31.7	51.2	2.5	0.2	20.4	6.7	− 0.1	14.6	0.2	244.4	10.9	3	Good
20	7.6	73.4	63.5	22.2	86.7	4.4	0.3	38.1	3.8	− 0.1	32.5	0.5	249.9	547.5	9	Unsuitable
21	7.1	282.0	295.7	196.5	98.0	1.9	0.2	474.1	79.2	− 1.0	266.2	1.6	1544.8	461.1	45	Unsuitable
22	7.2	69.2	69.0	46.2	21.2	0.9	0.1	20.0	1.0	− 0.1	37.2	0.3	361.7	2.0	0	Good
23	7.5	66.1	61.4	27.4	28.9	1.1	0.3	32.8	9.4	− 0.1	37.1	0.3	265.9	456.9	1	Poor
24	7.1	67.1	64.6	29.8	27.2	1.1	0.3	22.5	2.2	− 0.1	32.2	0.3	283.6	11.0	11	Poor
25	7.3	64.8	60.9	19.1	34.4	2.3	1.0	24.4	3.2	− 0.1	31.5	0.2	230.6	36.9	0	Good
26	7.0	62.1	50.3	29.5	23.8	4.0	0.3	20.7	14.5	− 0.1	58.9	0.6	246.8	2419.2	38	Unsuitable
27	7.6	101.0	72.6	50.4	45.8	7.9	0.5	94.0	15.7	− 0.1	69.5	0.3	388.0	13.0	10	Unsuitable
28	7.4	104.0	60.6	43.7	79.5	9.1	0.5	94.6	17.0	− 0.1	74.2	15.6	330.8	0.0	0	Poor
29	7.3	98.9	77.9	37.7	55.6	8.6	0.3	90.3	26.7	− 0.1	42.6	0.2	349.4	73.8	0	Poor
30	8.1	50.5	10.7	3.9	102.9	1.7	0.4	21.0	2.0	− 0.1	20.6	0.4	42.9	2.0	0	Excellent
31	7.6	61.0	66.9	26.9	40.8	0.6	0.2	22.4	2.3	− 0.1	23.0	0.1	277.8	0.0	0	Excellent
32	7.5	63.3	58.0	21.2	59.9	2.1	0.4	27.9	2.0	− 0.1	22.3	0.2	232.1	1.0	1	Good
33	7.9	44.5	38.0	8.3	55.1	1.0	0.2	26.8	2.1	− 0.1	20.1	0.4	129.0	14.8	0	Excellent
34	7.8	78.2	82.7	32.2	35.5	3.6	0.2	80.6	19.7	− 0.1	57.4	0.2	338.7	579.4	0	Unsuitable

Appendix C
Supplementary Information to Chapter 7

Infrastructural data

Farm: .... Farm Owner: ....

GPS: .... Date: ....

	M/I				Remark
Farm information					
# of water consumers	**M**				
# of cows & dairy animals	**M**				
Age of dairy & dairy history	**M**	1 – 4 years	5 – 10 years	More than 10 years	
Type & no. of sanitation (MH)	**M**	Spectic tank	VIP/Pit		
Type of sanitation (WH)	**M**	Septic tank	VIP/Pit		
Breed		Holstein	Ayrshire	Jersey	
Dairy management					
COA	**M**	Yes	No		
# of milkings per day	**M**				
# of bulk tanks & size	**I**				
# of litres per day on average per cow	**M**	≤ 10	11 – 21	More than 21	
# of litres per day	**M**				
Milking cow arrangement	**M**	Fishbone	Tandem	Rotary	
SOP cleaning of dairy	**M**	Hot water	Soap & detergent	Rinse	
Bulk buyer	**M**				

Other products	**M**	Yoghurt/ flavoured milk	Dairy juice	Pasteurisation	UHT
Other processes					
Antibiotics used		Past month	2 – 3 months ago	4 – 6 months ago	
Equipment – manual/ automated	**I**				
Dairy wastewater handling	**M**	Dam & irrigate	Dam	Flooding	
Borehole information					
# of boreholes used	**I**				
# used for HH & DP	**I**				
Borehole protection	**M**	Yes	No		
Dist. from borehole to dairy	**M**	less than 50 m	50 – 100 m	More than 100 m	Slope
Dist. from borehole to DW outlet/pond	**M**	less than 50 m	50 – 100 m	More than 100 m	Slope
Dist. from borehole to kraal	**M**	less than 50 m	50 – 100 m	More than 100 m	Slope
Dist. from borehole to septic tank/PL	**M**	less than 50 m	50 – 100 m	More than 100 m	Slope
Water use					
Estimated use per day	**M**				
Do you treat your water?	**M**	Yes	No		
If Yes, treatment plan formula	**I**				
Do you test your WQ?	**M**	Yes	No		
Water tank management					
Previous test date	**M**				

Dairy farm layout