Identification of the sources of nitrate concentrations in Barbados' public water supply

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ABSTRACT

Identification of the sources of nitrate concentrations in Barbados' public water supply

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The degradation of groundwater quality due to nitrate contamination is a global problem, and there has been considerable focus on anthropogenic activities as the potential cause of the accumulation of nitrate in groundwater resources. Barbados relies primarily on groundwater for its potable water supply, and studies have shown that the concentration of nitrate in various public supply wells is approaching the drinking water quality limit of 10 mg/L for Nitrate-Nitrogen (Nitrate-N) set by the World Health Organisation. The health concerns associated with the ingestion of excessive nitrate include methemoglobinemia and stomach cancer. Due to these health concerns it is necessary to identify the sources of nitrate contamination in order to mitigate excessive concentrations of nitrate in potable water sources. Nitrate concentrations in five (5) public supply wells and one (1) agricultural well were monitored for three (3) months, and twenty (20) wells were tested for $\delta^{15}N$ through an analysis of nitrogen isotopes. Geospatial analysis was also carried out using ArcGIS software. Land use patterns and population sizes were spatially analysed and compared with the nitrate concentrations and isotopic nitrogen results to determine the dominant sources of nitrate and the spatial extent of the contribution. Zones of influence based on water pumping rates were calculated and used as the primary areas through which contamination may occur. Additional considerations were made to the basal coral limestone contours of Barbados and features such as sinkholes, which facilitate the directional flow of groundwater. This research identifies domestic wastewater, with influences from agricultural activities, as the dominant source of groundwater contamination in Barbados. The sources were largely attributed to the land use surrounding the wells sampled. Keen management of land use, especially as it relates to residential development and agricultural activities, is necessary to mitigate the occurrence of excess nitrate in groundwater and potable water supplies. Further studies to monitor variation in the sources over time through the analysis of nitrogen isotopes would be useful in determining the consequences of anthropogenic activities to the potable water supply for specified areas.

Keywords: Groundwater; Nitrate; Barbados; Nitrogen isotopes

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1. INTRODUCTION

The health and economic stability of a nation is in part reliant on the provision of and accessibility to safe, potable water. Where there is reliance on groundwater for potable water, it is important to protect groundwater quality to ensure protection of public health, to avoid costs associated with further treatment and to prevent pollution related scarcity.

Globally, the anthropogenic production of nitrogen has altered the nitrogen cycle over the last half century, resulting in a steady accumulation of nitrates in water resources (Ward et al., 2005). Adverse health effects may result when elevated concentrations of nitrate are ingested. Therefore, where groundwater is the main source of potable water, nitrate contamination compromises the safety of potable water supplies. Barbados relies primarily on groundwater for its potable water supply, and studies have shown that the concentration of nitrate in various public supply wells are approaching the drinking water quality limit of 10 mg/L for Nitrate-Nitrogen (Nitrate-N) set by the World Health Organisation (WHO). Previous nitrate studies identified agricultural leachate and runoff, and industrial and domestic wastewater as contributors to nitrate contamination, but the major source of contamination has not been determined. This research seeks to identify the major source(s) of nitrate contamination to the public water supply of Barbados.

1.1. Background

The 166 square mile island of Barbados is located at Latitude 30^{o} North and Longitude 59^{o} 37W. It is the most easterly island in the Caribbean island chain stretching from Florida on the North American mainland to the Guianas on the northern mainland of South America (Government Information Service, 2009). The island is mostly made up of coral limestone, with approximately one sixth of the terrain comprising the sandstones and clays of the Scotland series.

The population in 1990 was recorded as 260,491 and population growth was averaged to be 0.27% between 1990 and 1997 (FAO, 2000a). Residents were mainly found to be concentrated along the west coast, south coast and the capital, Bridgetown. Barbados' economy has been historically dependent on sugarcane cultivation and related activities. More recently, however, tourism and manufacturing have been dominating the economy. A light manufacturing sector and offshore finance and information services are currently significant sources of earned foreign income (Environmental Protection Department, 2007a).

1.1.1. Rainfall

Barbados experiences a "wet season" between July and November, and "dry season" during which the minimum average rainfall is usually recorded in February or March (Government Information Service, 2009). Figure 1 illustrates the occurrence of seasonal rainfall in Barbados by the use of rainfall measurements taken from five (5) stations between 2000 and 2005, each representative of the south, north, west, south-west and centre of Barbados. The "wet season" occurs due to the formation of tropical systems and the occurrence of torrential rains during this time. The mean annual rainfall is between 1000-2000 mm, with the higher levels of rainfall occurring in the central highlands (Mwansa, 2003).

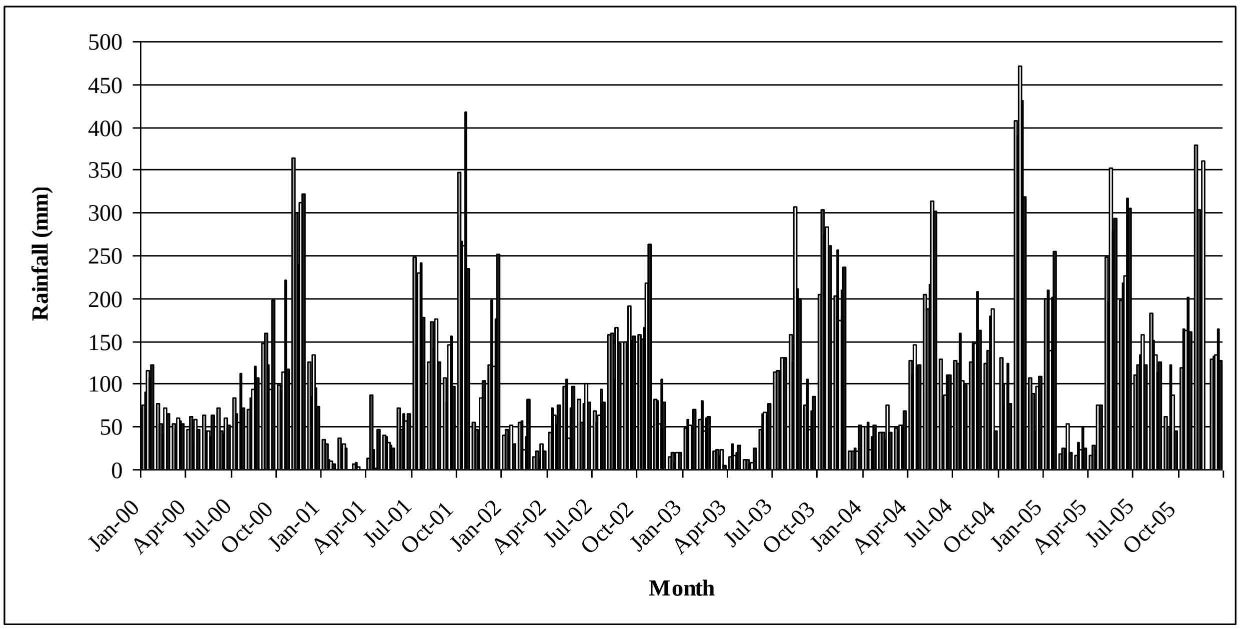


Figure 1 Cumulative rainfall measured at the Grantley Adams International Airport, Stanford, Caribbean Meteorological Institute, Bowmanston and Belle between 2000 and 2005
Source: Grantley Adams International Airport, Caribbean Institute of Meteorology and Hydrology.

1.1.2. Hydrogeology of Barbados

Barbados relies primarily on groundwater for its potable water supply. Groundwater is pumped from the coral limestone aquifers and chlorinated prior to distribution to the public. Coral limestone underlies approximately 85% of Barbados, with the Scotland District as the exception. The Scotland District is underlain by less permeable shales and sandstones, and chalk and siltstone (Delcan, 1995). Due to the poor permeability of the Scotland District, the steep gradients and heavy relief rainfall from the Atlantic, deep gullies and surface streams have developed along the surface causing direct runoff from rainfall with little absorption. Precipitation in the limestone area and runoff from the Scotland District disappear into the ground through cracks, fissures and solution features like sinkholes, to collect in large underground reservoirs (Poole and Barker, 1983). Some of this water may continue to move toward the coastline to join the sheet water. The groundwater flow generally proceeds from the central highlands radially toward the sea. The groundwater table is generally well below the surface and recharge is enhanced through the presence of sinkholes and drainage wells (Mwansa, 2003). The cracks, fissures and sinkholes within the limestone matrix allow for relatively unhindered water flow, thus creating direct pathways for contamination from one region to another.

Alfred Senn (1946) characterised the occurrence and movement of groundwater as being through two main groundwater units in coral limestone, “sheet water” and “stream water”. When water moves downward from higher ground after infiltration through the porous coral limestone, reaches poorly permeable rocks, and flows between the permeable and basal coral rock, this is considered to be stream water. Sheet water is the water that exists just above sea level and is capable of joining a large fresh water lens floating above salt water (Delcan, 1995). Figure 2 shows the delineation between sheet water and stream water in Barbados.

Recharge due to precipitation has been estimated, using many methods. The Tullstrom method, originally used to determine recharge to the aquifer, was primarily based on the geomorphological properties of the island. The soil infiltration fractions shown in Table 1 were derived through the use of the Tullstrom method. This method determined groundwater recharge by catchment area by assigning recharge infiltration attributes for 15 designated soil/terrain units distributed throughout the island (Klohn-Crippen Consultants Ltd., 1997). Table 2 shows the essential catchment areas, the infiltration of precipitation into their soils and the range of the depths to water within each catchment. The table is partially based on Figure 3 which illustrates the soil types as they occur throughout Barbados.

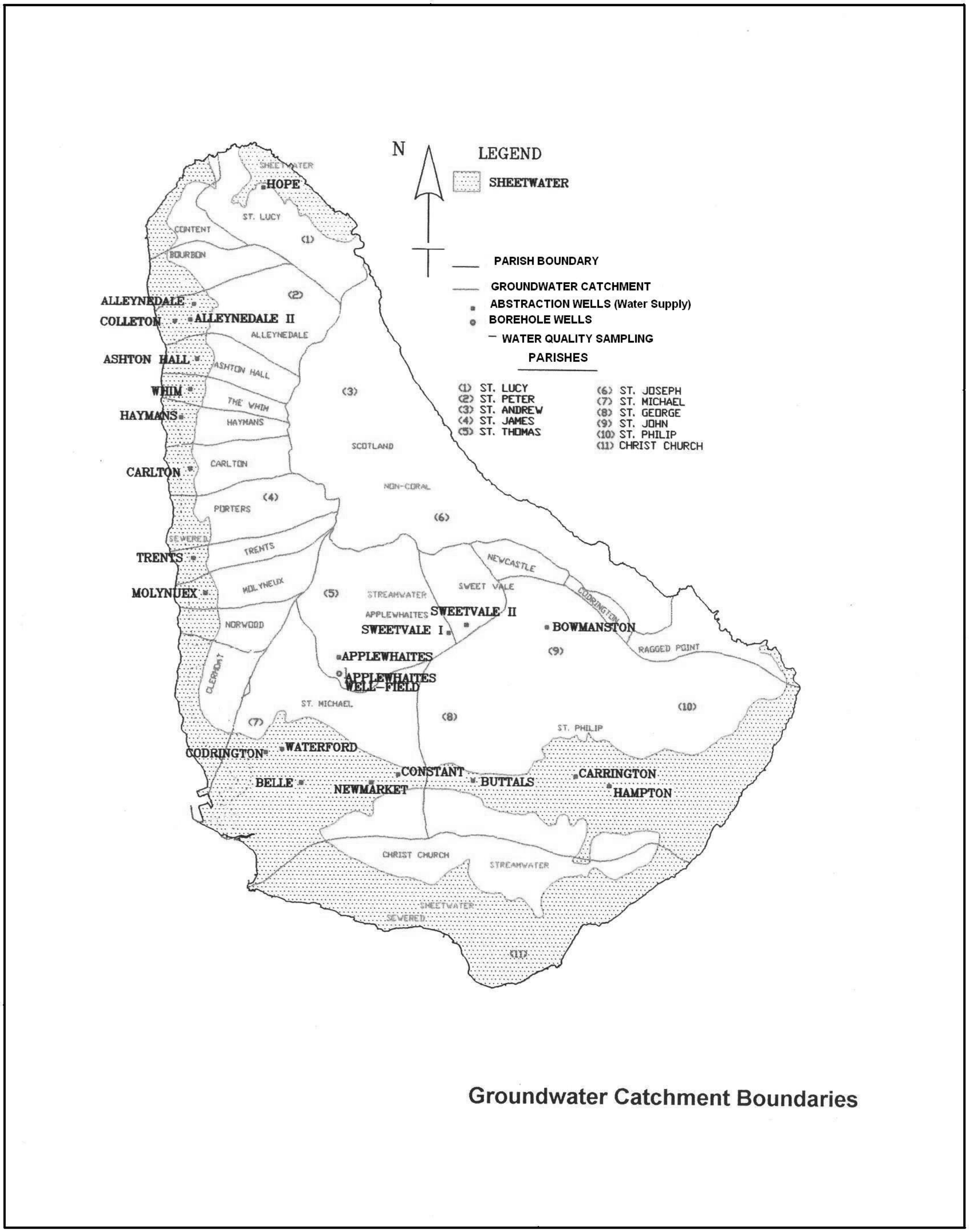


Figure 2 Sheet water and stream water areas relative to ground water catchments
Source: Consulting Engineers Partnership Ltd. et al., 1998

Table 1 Tullstrom infiltration fractions
Source: Tullstrom, 1964

Soil type	Portion of precipitation that infiltrates
Red soil area (except deep red soil in Sweet Bottom)	1/4
Red soil in Sweet Bottom (mainly runoff)	1/10
Brown soil areas with sinkholes and abundant and well developed gulley system, high rainfall	1/4
Brown soil in Sweet Bottom	1/10
Intermediate black soil, higher percentage of gullies and in higher rainfall area	1/7
Intermediate black soil, normal frequency of gullies and sinkholes, moderate rainfall areas	1/8
Intermediate black soil, in flat terrain often over 60 cm (2ft) deep	1/10
Black soil, sloping ground of shallow soil	1/8
Black soil, low rainfall area	1/10
Black soil, on outcropping oceanic formation	1/12
St. Philip soil, low rainfall, almost only surface drainage	1/12
St. George's valley soil, deep clay	1/12
Sandy soil in St. James-St. Peter	1/5
Bridgetown City, mainly road and roof water	1/3
Scotland District, runoff to coral limestone area	1/5

Table 2 Main water catchment areas and their respective infiltration rates and the depth to water in each area
Source: Klohn-Crippen Consultants Ltd., 1997; Tullstrom, 1964

Catchment areas	Soil types	Infiltration rate of precipitation into soil	Range of depth to water (m)
Belle	iba*	1/10	14-55
Hampton	iba*, St. George Valley soil	1/10, 1/12	11-77
Sweet Vale	brown association, St. John association	1/10	45-62
West Coast	iba*, sandy assoc.	1/8, 1/5	2-61

*iba- intermediate black association

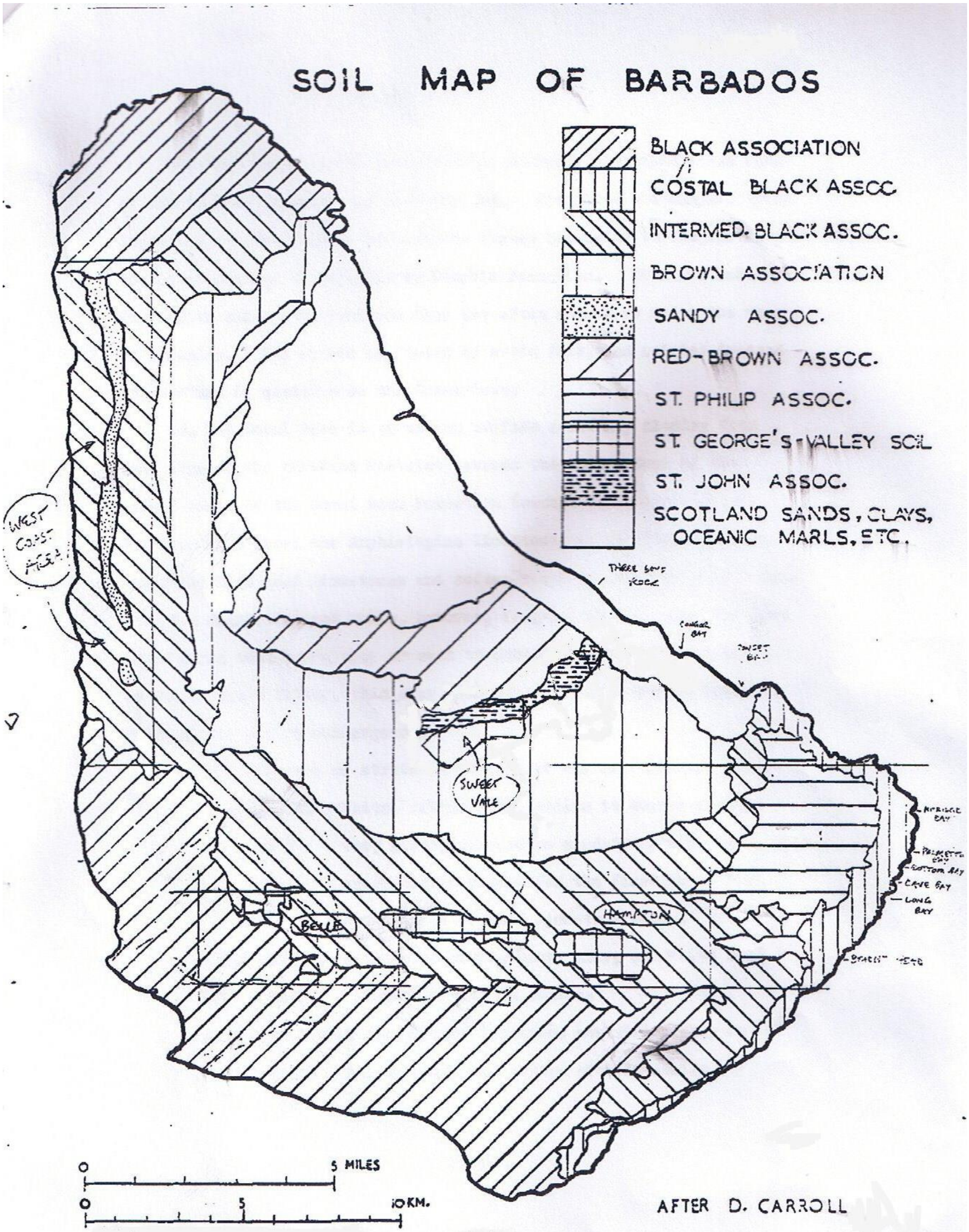


Figure 3 Soil map of Barbados
Source: Tullstrom, 1964

2. RESEARCH GOAL AND OBJECTIVES

The research seeks to identify the sources of nitrate concentration in Barbados' groundwater, with a focus on the public supply wells, in order to assist in addressing the problem of nitrate pollution and in the provision of remedial action.

2.1. Objectives

In order to classify the various sources of nitrate and to identify the dominant source(s), the objectives are to investigate:

the contribution of agricultural activities to nitrate concentration in the groundwater;

the types of agricultural activity that contribute most to nitrate concentration in the groundwater;

the impact of domestic wastewater disposal practices on the nitrate concentration in the groundwater; and

the influence of industrial activities on nitrate concentration in the groundwater.

3. LITERATURE REVIEW

The review seeks to inform readers of nitrate-related literature that have significance to the research. The natural occurrence of nitrogen and nitrate in the environment are discussed in order to emphasise the influence of anthropogenic activities that allow for the accumulation of excess nitrates in water resources. Also, due to the presence of nitrate in potable water sources, the adverse health effects to humans from ingesting excessive amounts of nitrate are described. The use of nitrogen isotopes to determine the dominant sources of nitrate is explained since this method is used in conjunction with land use analysis in the research. Additionally, in select public supply wells in Barbados, the proximity of nitrate concentrations to the WHO drinking water limit of 10 mg/L is highlighted through the review of nitrate studies carried out in Barbados.

3.1. Nitrogen in the environment

Nitrogen is an important compound which naturally occurs in the environment. It is present in various forms such as nitrogen gas (N_2), organic nitrogen, nitrate (NO_3^-) and ammonia (NH_4^+). Organic nitrogen (N) is converted to NH_4^- through a process called ammonification, and NH_4^+ is converted to nitrate by oxidation through a process called nitrification. Nitrate is usually absorbed by plants since it is one of the main nutrients necessary for growth. As shown in Figure 4, naturally occurring processes allow for the conversion of nitrogen to nitrate, ammonium and nitrogen gas. Septic waste, animal manure and nitrogen fertilisers contribute to the production of nitrates. Where the quantity of nitrates produced by any of these methods is greater than plants can uptake, nitrates may be leached into the groundwater. As it relates to groundwater, nitrate concentration is commonly reported as Nitrate-Nitrogen (Nitrate-N) whereby only the nitrogen in the nitrate molecule (NO_3^-) is counted (Townsend and Young, 1999).

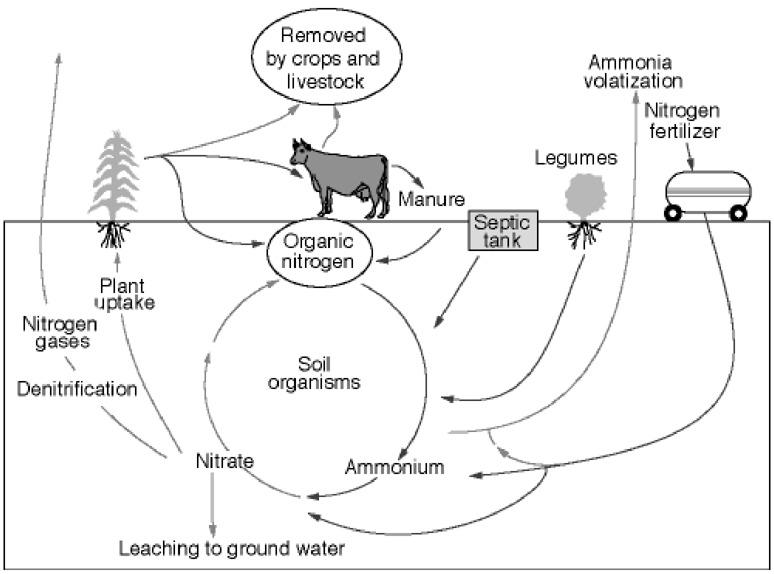


Figure 4 Nitrogen conversion to nitrate in the environment
Source: Townsend and Young, 1999

3.1.1. Nitrate contamination

The most common chemical contaminant in groundwater is excess nitrate (Spalding and Exner, 1993) and large aquifer systems are being threatened by increasing levels of nitrates throughout the world (Freeze and Cherry, 1979). Site-specific determination of the sources of groundwater contamination is therefore an important step in reducing nitrate concentrations and improving groundwater quality. If the source of nitrate is known for specific areas, methods may be employed to manage it in order to protect groundwater quality and the public.

Nitrate present within the groundwater usually originates from nitrate sources on the land in the soil zone or in shallow subsoil zones where nitrogen-rich wastes may be buried (Freeze and Cherry, 1979). These are considered to be direct sources of nitrate. In other circumstances, as shown in Figure 4, nitrate may be converted from organic nitrogen or ammonia through naturally occurring processes, or may be introduced into the soil zone through anthropogenic activities.

Fields (2004) indicated that on a worldwide scale, fertilisers are the largest contributor to anthropogenic nitrogen in the environment.

Fertilisers are usually categorised by the three main nutrients necessary for plant growth, Nitrogen (N), Phosphorous (P) and Potassium (K). Fertilisers are applied to plants and crops at varying rates according to the type of plant and the amount of nutrients required. However, where fertilisers are applied too liberally, infiltration of excess nitrogen into the groundwater may occur. Emphasising the contribution of agricultural nitrate to groundwater contamination is the Nitrates Directive, adopted in 1991 by the European Union (EU), which specifically targets the reduction of pollution in ground and surface waters through the control of agricultural pollution in the EU member states (O'Shea and Wade, 2009). The Directive requires that water bodies are monitored to identify those polluted by fertilisers and requires the designation of "Nitrate Vulnerable Zones" (NVZ). The primary focus on fertilisers highlights the dominance of this source to groundwater nitrate contamination.

Other major contributors to groundwater nitrate include animal and human waste, nitrogen oxides from the combustion associated with automobiles, as well as the generation of electricity, and leguminous crops that fix atmospheric nitrogen. Animal waste and treated domestic wastewater may be applied to infertile land in order to provide nutrients such as nitrogen and phosphorous, and to stimulate the growth of trees and crops. Primary and secondary treated waste has been used for such purposes in many areas around the world including Europe and North America, for centuries. Cities such as Paris, Milan, Fresno and Berlin have been using domestic wastewater for decades to irrigate crops (Freeze and Cherry, 1979). However, if excessive amounts of wastewater are applied to land for irrigation, leaching of nitrate and other nutrients into the groundwater may occur.

3.1.2. Associated health effects

Nitrates, if consumed in large amounts, can be hazardous to infants under six months of age and pregnant women. High levels of nitrate are known to cause a potentially fatal blood disorder called methemoglobinemia, also known as "blue baby syndrome". The illness is caused by the conversion of nitrate to nitrite by the body, which can interfere with the oxygen-carrying capacity of the child's blood. If sufficiently severe, this condition may be life threatening (Behrman et al., 2002). Symptoms include shortness of breath and blueness of the skin. The WHO guideline value of 10 mg/L for Nitrate-N in drinking water was promulgated to protect infants from methemoglobinemia.

Nitrate-N concentrations in excess of 10 mg/L may also be a cause of stomach cancers in adults (O'Riordan and Bentham, 1993). A positive correlation of stomach cancer and nitrate levels in drinking water was found in Spain, Slovakia and Hungary where historical and exposure levels of nitrate were found to be close to or above the maximum contaminant level of 10mg/L (Gulis et al., 2002; Morales-Suarez-Varela et al., 1995; Sandor et al., 2001).

3.1.3. Nitrogen isotopes

The source of nitrate in groundwater may be inferred through the analysis of nitrogen isotopes. Nitrogen has two stable isotopes, ^{14}N and ^{15}N, of which ^{14}N is more abundant. $\delta^{15}N$ is used to express the isotopic signature of nitrogen, where

$$\delta^{15}N = \frac{^{15}N/^{14}N_{sample}}{^{15}N/^{14}N_{standard}} - 1 \times 1000$$ (Kellman and Hillaire-Marcel, 2002)

Point and non-point sources of nitrate have been identified through the analysis of isotopic nitrogen for over 30 years (Townsend et al., 2003). The $\delta^{15}N$ values in groundwater are derived from (1) artificial fertilisers ranging from +2 to +6 permil (‰), and (2) animal or human organic waste greater than +8 permil (‰) (Katz et al., 1999; Bohlke, 2003). According to Bohlke (2003) data from many sites have indicated that nitrate in leachate from manure may have a range from +10 to +25 permil (‰), while nitrate in seepage from septic tank systems may tend towards the lower end of the range +8 to +11 permil (‰). Heaton (1986) and Gromley and Spalding (1979) reported that nitrogen from fertilisers has $\delta^{15}N$ values of 0 ± 4‰ and it was also reported that nitrate from animal waste and septic systems generally has $\delta^{15}N$ values of +8 to +22‰ (Heaton 1986). Due to slight variations in the allocation of nitrate origin based on $\delta^{15}N$ values in the aforementioned literature, land use within the study area appears to be helpful in identifying the origin. This method of determining the source of nitrates has been used in many studies, including southwestern Illinois (Panno et al., 2001), southern Puerto Rico (Rodriguez, 2007), southern Quebec, Canada (Kellman and Hillaire-Marcel, 2003) and France (Mariotti et al., 1988). The study carried out in southern Puerto Rico showed that $\delta^{15}N$ values between +13 to +23‰ were associated with organic-waste sources in the area of poultry farms, and the $\delta^{15}N$ values between +4.3 to +8.8‰ were associated with artificial fertilisers and natural vegetative decay.

3.1.4. Nitrate attenuation in groundwater

Ammonification and nitrification usually occur above the water table where there is an abundance of organic matter and oxygen (Freeze and Cherry, 1979). Nitrate is highly mobile and is the most stable form of nitrogen where there is high oxidation in groundwater— for example, in shallow groundwater with permeable sediment or fractured rock, like limestone, where the dissolved oxygen tends to be high (Freeze and Cherry, 1979). In such an environment, nitrate moves with little or no retardation and can migrate large distances. If there are low oxygen conditions, a process called denitrification may occur, where NO_3^- is reduced to N_2O or N_2. If denitrification occurs, the original isotopic composition of NO_3^- is lost and it would be difficult to identify the source of nitrate, using an analysis of nitrogen isotopes.

Denitrification usually occurs when an electron donor and denitrifying bacteria are present, in addition to low oxygen conditions (Esser et al., 2009). The attenuation of nitrate is controlled by processes which cause nitrate mass removal (Rivett et al., 2008), and denitrification is the process generally recognised as the most significant mass removal process (Korom, 1992; Burt et al., 1999). When low oxygen conditions are present at a watershed or basin scale along with an electron donor such as dissolved organic carbon, denitrification may be occurring (Esser et al., 2009). Rivett et al. (2008) indicated that denitrification is more probable in confined aquifers or near river environments.

3.2. Groundwater protection in Barbados

Two potential sources of aquifer recharge are rainfall and wastewater injection into the ground. Wastewater percolates downward via septic wells or pits, through the unsaturated coral to the groundwater table. The Groundwater Protection Zoning Policy was adopted in 1963 by Cabinet to protect the groundwater, using the following criteria:

Time of travel based on individual well design pumping rates;

Survival rate of enteric bacteria and viruses; and

Protection from “hard to degrade chemicals” (Mwansa, 2003).

Table 3 shows development restrictions for each of the zones, with Zone 1 exhibiting the most stringent restrictions and Zone 5 bearing no restrictions. Figure 5 graphically represents the locations of Zones 1-5 in Barbados.

This method of land zoning was adopted when domestic wastewater was deemed to pose the greatest risk to groundwater quality. Measures based on the policy have been put in place to protect the existing groundwater supply and are still in effect. Agricultural practices were however not factored into this method of groundwater protection, hence the possibility of contamination by pesticides and fertilisers still exists in Zones 1 and 2. Additionally, the karstic nature of coralline limestone allows for conduits within the matrix through which the flow of water can take place relatively unhindered, thus creating direct pathways for contamination from one region to another. These conduits for free flow were not considered in the development of the Groundwater Protection Zoning Policy, thereby presenting a weakness in the use of this policy for adequate protection of the groundwater. A review of the policy commenced in 2009 which seeks to evaluate the potential drawbacks associated with the use of the Groundwater Protection Zoning Policy.

Table 3 Water zones and their accompanying stipulations

<table>
<tr><th>Zone</th><th>Definition of Outer Boundary</th><th>Maximum Depth of Soak-away Pit</th><th>Domestic Controls</th><th>Industrial Controls</th></tr>
<tr><td>1</td><td>300 day travel time</td><td>4.5 m (1973 cabinet decision)</td><td>No new housing or water connections. No changes to existing wastewater disposal except when Water Authority secures improvements. Septic tank and filter bed of an approved design.</td><td>No new industrial development</td></tr>
<tr><td>2</td><td>600 day travel time</td><td>6.5 m</td><td>Septic tank of approved design, discharged to soak away pits. Separate soak away pits for toilet effluent and other domestic waste water No storm runoff to sewage soak away pit. No new petrol or fuel oil tanks</td><td rowspan="4">All liquid industrial wastes to be dealt with as specified by Water Authority

Maximum soakaway pit depths as for domestic waste.</td></tr>
<tr><td>3</td><td>5-6 year travel time</td><td>13 m</td><td>As above for domestic wastewater .Petrol or fuel oil tanks to approved leakproof design.</td></tr>
<tr><td>4</td><td>Extended to all high lands</td><td>No Limit</td><td>No restrictions on domestic wastewater disposal. Petrol or fuel oil tanks to approved leakproof design</td></tr>
<tr><td>5</td><td>Coastline</td><td>No Limit</td><td>No restrictions on domestic wastewater disposal. Siting of new fuel storage tanks subject to approval of Water Authority.</td></tr>
</table>

Source: Environmental Protection Department, 2007

Since the Groundwater Protection Zoning Policy was developed there have also been various changes to the socio-economic structure of Barbados. The economic reliance of Barbados has shifted from the sugar cane industry to the tourism and manufacturing sectors, and since 1960 the population has increased by 61,000 persons (FAO, 2009b) causing the average population density to increase from 494 persons/km^2 to 636 persons/km^2. As can be seen in Figure 6, the population density is greater in the southern and south-western areas of Barbados.

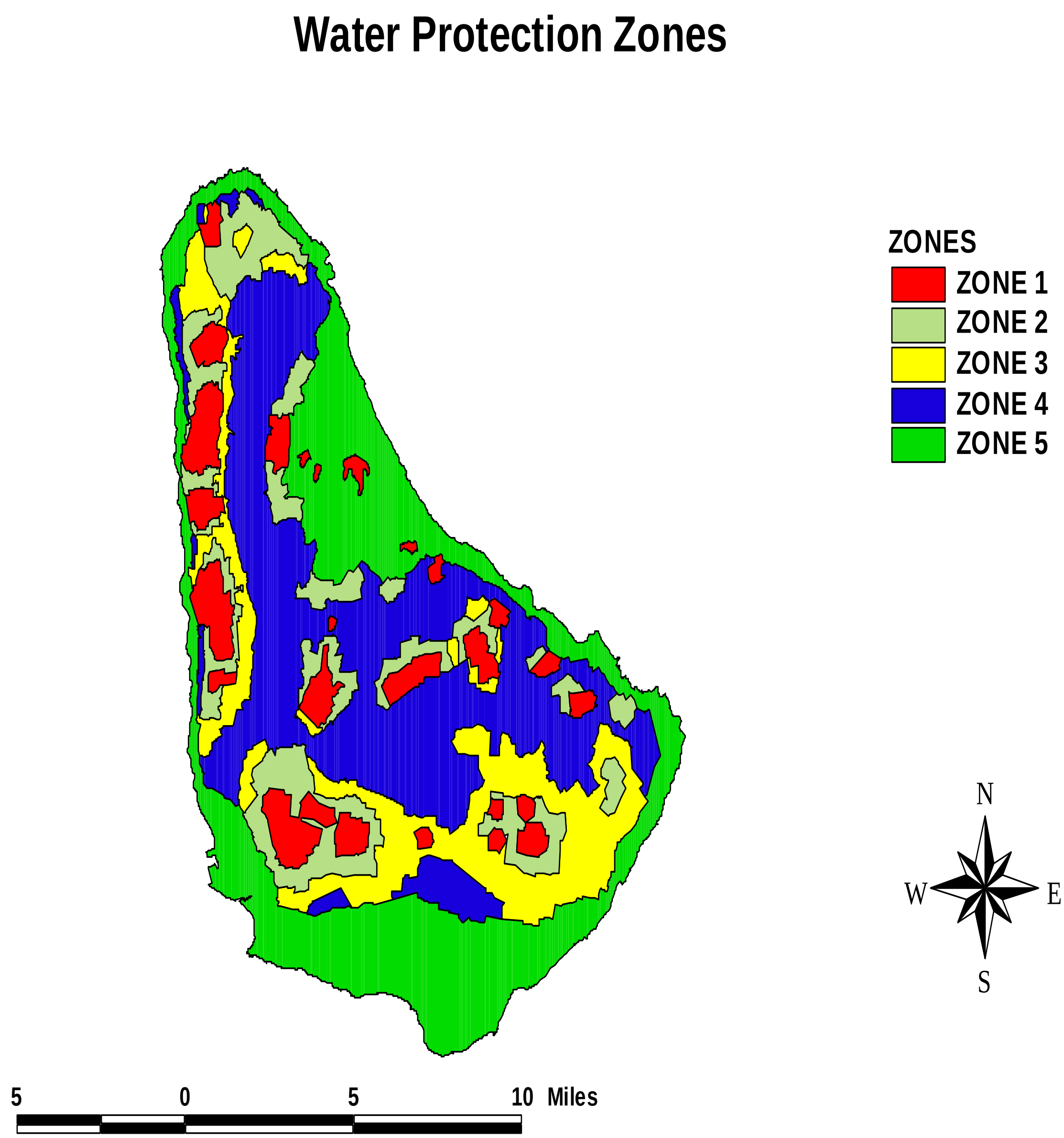


Figure 5 Water protection zones in Barbados
Source: Environmental Protection Department, 2007

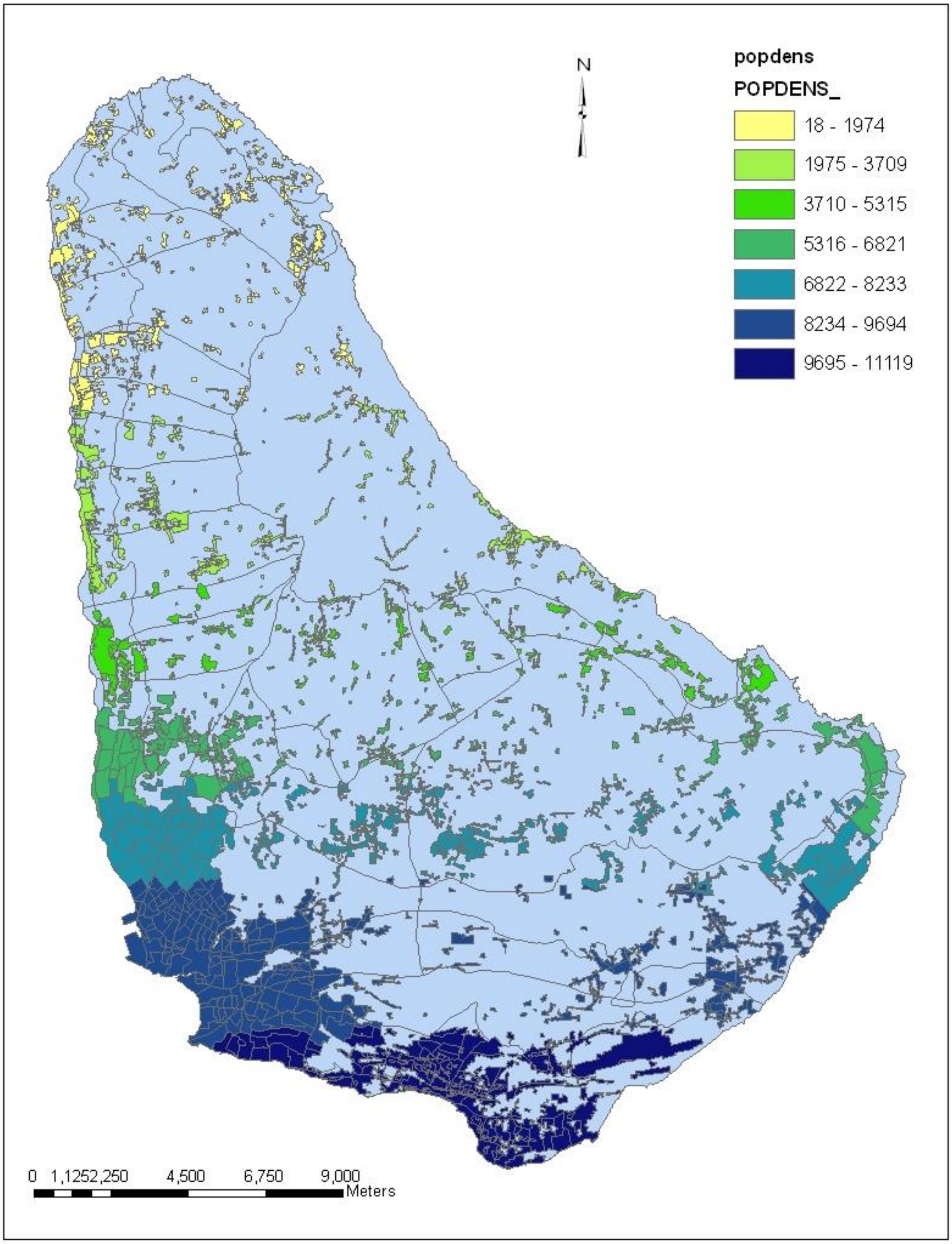


Figure 6 Population density map of Barbados
Source: Ifill, 2000

3.3. Potential for nitrate contamination in Barbados

3.3.1. Nitrate studies

The Environmental Protection Department (EPD) and the Barbados Water Authority (BWA) assess groundwater in Barbados under the Groundwater Monitoring Programme. Twenty-eight parameters are monitored under this programme, including nitrate concentration. There have been growing concerns over the level of nitrate concentrations in the groundwater in Barbados, especially within the Belle, Zone 1 catchment (Nation News, 2008). As was shown in the population density map in Figure 6, the highest density appears to be along the south-western area of Barbados which coincides with the Belle catchment. Nitrate-N concentrations in the water in public supply wells within the Belle catchment are approaching the WHO limit of 10 mg/L for Nitrate-N. Ifill (2000) reported in the Nitrate Vulnerability Assessment, Risk and Exposure Mapping Study that between 1988 and 2000 groundwater quality in Barbados had an average Nitrate-N concentration of 7.6 mg/L. Additionally, it was reported that over 55% of the 25 water sources sampled showed some risk of exceeding WHO drinking water quality limit and the highest nitrate loadings occurred in the Belle catchment and in the south-western area of the West Coast catchment.

Due to the proximity of nitrate concentrations in the wells located in the Belle catchment to the WHO drinking water limit, along with increased density of residential settlement, a feasibility study for the construction and implementation of a sewerage treatment plant was carried out for the Belle catchment. The nitrate concentrations for the public supply wells in the Belle catchment were analysed from March 2000 to May 2002. It was found that the concentrations ranged from 7.7 to 8.7 mg/L (Stantec Consulting International Limited and Social and Environmental Management Services Inc., 2001).

Table 4 Nitrate-N concentrations for wells in the Belle catchment for March 2000-May 2002

Source	Nitrate-N (mg/L)		
	Min	Max	Mean
Belle well	5.9	9.9	8.7
Codrington well	7.5	11.5	8.6
Waterford/Friendship well	7.2	9.1	7.7

Source: Stantec Consulting International Limited and Social and Environmental Management Services Inc., 2001

The Belle study revealed that 64.3% of the residents within the Belle study area had no sewage disposal at the time of the survey— their waste was disposed of around their homes, in the streets and in the gully (Stantec Consulting International Limited and Social and Environmental Management Services Inc., 2001). It was also found that the study area was comprised of 55.3% of land for agricultural purposes, 26.5% of natural landscape which included gullies and marginal lands, 14.6% as suburban Bridgetown, and 3.5% of urban area (Stantec Consulting International Limited and Social and Environmental Management Services Inc., 2003).

The study also indicated that the nitrate concentrations increased from about 5 mg/L upstream of the St. Michael limestone aquifers to about 10 mg/L approximately 2 km downstream of the Belle well. The primary source of contamination in this case was deemed to be applied fertilisers in the sugar cane fields (Stantec Consulting International Limited and Social and Environmental Management Services Inc., 2002).

3.3.2. Domestic wastewater disposal

Domestic wastewater for the purposes of this report refers the waste generated by households, businesses and hotels— primarily bodily wastes from humans. The common method of domestic wastewater disposal in Barbados is via entrance into the ground at a level where absorption naturally occurs, i.e. via suck wells. The Barbados Water Resources Study (Government of Barbados et al., 1978) suggests that 80% of the estimated 16 MGD of discharged wastewater recharges the sheet water downstream of the major water supply wells along the west and south coasts. Increasing populations give rise to increasing quantities of domestic wastewater; the potential to cause nitrate contamination of the groundwater supply due to increased loads therefore exists in the absence of wastewater treatment systems. There are an estimated 80,000 private residences with a growth rate of 8,000–8,500 per decade, and a decreasing average household size of 4 persons in 1971 to 2.8 by 2010 (Government of Barbados, 1998). With these factors being considered, it is likely that the growth of residential areas may encroach upon restricted groundwater zones since the land mass that is Barbados measures 166 square miles. Limited land space and growing needs for housing units thereby create a greater risk of groundwater pollution by nitrates through the potential for disposal of domestic wastewater close to or in Zone 1 areas. In fact, it has been found in the review of the Groundwater Protection Zoning Policy conducted by Burnside International Limited (in prep.) that there are many cases of residential and agricultural activity encroachment into Zone 1 areas.

The contribution of wastewater to groundwater was estimated to be 320,000 kg/year with an assumed average nitrate concentration of 10 mg/L (Delcan, 1995). Additionally, unsewered sanitation and illegal dumping were identified by the British Geological Survey et al. (1989) as potential threats to the groundwater due to the high nitrogen content of domestic wastewater. The 2004 Belle Feasibility Study indicated that the high nitrate and bacteria levels found in the Belle well may be due to the wastewater soakaway pits or suck wells and overland flow that may enter the gully systems upstream of the Belle (Stantec, 2004).

In addition to domestic wastewater disposal into the ground, there are also two municipal wastewater treatment plants that accept sewage waste from areas of Bridgetown and the South Coast, and island-wide waste from septic tanks, i.e. septage. These treatment facilities discharge the treated effluent into the marine environment. The rationale for the discharge into the marine environment lies in the fact that the volume and movement of the sea water allows for adequate dilution. Marine water quality monitoring is carried out in order to ensure the safety of the public in bathing waters. The disposal of waste into the marine environment is however not expected to affect groundwater quality.

3.3.3. Crop cultivation

The economy of Barbados was historically dependent upon its sugar cane production. Today, many of the cane fields have been converted to residential, commercial and industrial developments since the economy has shifted from sugar cane agriculture to tourism, manufacturing and offshore finance (Ministry of Finance, Economic Affairs and Energy, 2008). However, agricultural activity still plays an important part in the lives of many Barbadians, both for foreign exchange and for local use. Sugar cane, cotton, root crops and vegetables are currently the major crops grown in Barbados. The total cultivable land is estimated at 22,472 hectares, of which the cultivated area in 1997 was 17,000 hectares; annual and permanent crops occupied 16,000 and 1,000 hectares respectively (FAO, 2009a). The shift from sugar cane agriculture to cash crops poses a potential threat of groundwater pollution through increased rates of fertiliser and pesticide application (British Geological Survey et al., 1989). Since different types of crops require varying amounts of nutrients for growth, the Ministry of Agriculture advises farmers on the quantity of fertilisers necessary for specific crops through published recommendations (Ministry of Agriculture, 2001).

Farmers may not stringently use these guidelines provided by the Ministry of Agriculture. Therefore, if there is excessive use of nitrate-containing fertilisers, groundwater contamination can result due to leaching of unused nitrate, potentially posing health risks to the public. Records from the Barbados Statistical Services (2009) indicate that fertiliser imports have significantly decreased from the 1980s to the 1990s, but the imports between 2000 and 2008 are greater than between 1990 and 1999.

Table 5 Fertiliser imports to Barbados between 1980 and 2008

Duration	Total fertiliser imports (tonnes)
1980-1989	229,993
1990-1999	51,003
2000-2008	54,308

Source: Barbados Statistical Services, 2009

3.3.4. Poultry and livestock farming

In an effort to reduce the dependence of residents on imported meats, a Livestock Development Project was initiated in Barbados through joint funding from the Government of Barbados and the Commission of European Communities (The Central Bank of Barbados, 2007). The focus of this project was to assist the development of the livestock industry in Barbados through an increase in the production of beef, lamb and pork, in addition to assisting small livestock farmers. In an investigation of the Land Based Sources (LBS) of pollution of the marine environment, the Environmental Protection Department (2008) reported that one of the major impacts from livestock and poultry rearing activities on the marine environment has been observed in increased Nitrogen as Total Kjeldahl Nitrogen (TKN). One marine pollution pathway is via infiltration into the groundwater, indicating that the quality of groundwater may be impacted by livestock and poultry rearing activities. The main source of pollution from poultry and livestock rearing was found to be animal excreta. The report indicated that farmers bury, burn or use animal excreta as manure. The amount of animal excreta produced was reported to be too great for farmers' needs as manure, and since the Sanitation Service Authority no longer accepts animal excreta at the landfill, the methods of burning or burying are employed. Table 6 quantifies the amount of pollutant produced by poultry, beef, mutton and pork in Barbados in 2007. The largest contributor of nitrate pollution was found to be poultry.

Table 6 Total nitrogen contribution of poultry and livestock in 2007

Product	Amount of pollutant produced (kg)	Estimated Quantity of Nitrates (kg)
Poultry	14,934,000	62,722,800
Beef	136,100	16,558
Mutton	72,400	24,488
Pork	2,502,000	405,880
Total pollutant loading	N/A	63,169,726

Source: Environmental Protection Department, 2008

3.3.5. Non-agricultural industry and manufacturing

The non-agricultural and manufacturing industries refer to the tourism and production markets existing in Barbados. This section covers the contribution of these industries to nitrogen pollution in the nation. Currently, its major economic industry is tourism (UN, 2002), a significant user of freshwater resources. The tourism sector is comprised of accommodation, such as hotels and guest houses, the cruise ship industry and their related services, such as catering facilities. Nitrogen-containing wastewater is the main contributor by tourism to groundwater pollution. The wastewater disposal practices within the tourism sector include wastewater treatment facilities, septic tanks and suck wells. According to the Environmental Protection Department (2007b) the estimated pollutant load for the treated effluent from the tourism/service sector utilising wastewater treatment plants is 24.09 kg/day of TKN, indicating that the treatment provided in many cases does not include the removal of nitrogen. Marine outfall, suck wells and storm drains are the methods identified as being used for disposal of effluent, with suck wells utilised most. Where wastewater is disposed via suck wells and storm drains, the potential exists for groundwater pollution due to nitrogen.

Regarding the manufacturing aspect of industry, the Barbados Investment Development Corporation (BIDC) has defined 12 categories. These are: chemicals and chemical products; electronic components and devices; fabricated metal products; food, beverages and tobacco; handicraft; non-metallic mineral products; paper products; precision instruments; textiles, apparel and leather; wood, wooden products and fittings, and other manufacturing (Barbados Private Sector Trade Team, 2003).

Most of the manufacturing facilities are located within the parish of St. Michael, with many being housed within government-owned industrial parks. Privately owned industrial businesses may also be found elsewhere throughout Barbados. In the 1980s a decline in the manufacturing sector was experienced, followed by a rebound within the subsequent decade; growth is, however, slow. (Government of Barbados, 1998). In 2001 and 2002 the food and beverage sub-sector contributed to 50% of the manufacturing sector's output, with paper products and printing being the second largest contributor (Barbados Private Sector Trade Team, 2003).

The type of manufacturing activity governs the constituents within the effluent of manufacturing facilities. The Barbados Water Resources Study (Government of Barbados et al., 1978) indicated that of the industrial developments identified only wastewater or solid waste-generating facilities were deemed to contribute pollution in the form of nitrogen. Some manufacturing facilities that generate Nitrogen-based pollutants are found in Tables 7 and 8, adapted from the pollutant loadings tabulated within the studies carried out on LBS of pollution of the marine environment (Environmental Protection Department, 2007b and 2008) to highlight the contribution of Nitrogen-based pollutants. They show the Total Nitrogen (TN) or Total Kjeldahl Nitrogen (TKN) from the facilities associated with meat and dairy processing, sugar production and bakeries.

Table 7 TKN produced by select manufacturing entities

Activity	Company	Total Nitrogen pollutant load (Kg/yr)
Slaughtering, processing and preservation of meats	Southern Meats	1,122.05
	Hipac Ltd	213.20
Manufacture of dairy products	Pine Hill Dairy (input)	310.65
	Pine Hill Dairy (processed)	2,063.56
	Peaches & Cream Ltd (input)	0.15
Bakeries	WIBISCO	33.50
	Purity Bakery	31.53
	Salisbury Bakery	1.15
	Golden Crust Bakery	0.56
Rendering	CR recycling	5,004
	Sunrise Chick	324.26

Source: Environmental Protection Department, 2008

Table 8 TKN produced by select rum distilleries and sugar factories

Company	Sample Period	Load of TKN kg/day
Portvale Sugar Factory	March-September 2006	2.20
Foursquare Rum Distillery	October 6th 2004 and April 1st 2005	2.23
West Indies Rum Distillery	July 2005- July2006	155

Source: Environmental Protection Department, 2007b

These manufacturing facilities are located downstream of the major public supply wells or in areas that have not been earmarked for exploitation for potable supply purposes. Since this is the case, it is not expected that these facilities have an effect on the potable water supply via groundwater infiltration. However, it may have some implications for the marine environment.

4. METHODOLOGY

4.1. Research approach

There are various sources of nitrates that lend to groundwater contamination. In order to understand the source of contaminants to the groundwater supply, an assortment of parameters were investigated in order to make linkages to its contamination.

Records from the Groundwater Quality Monitoring Programme were reviewed, together with existing land use, zoning, and catchment information in order to identify the sources of nitrate for selected wells within each catchment, and to identify similarities and, where they exist, differences in areas of high and low concentrations. Water samples from five (5) public supply wells and one (1) agricultural well were retrieved and tested for nitrate-nitrogen concentration on a weekly basis for eleven (11) weeks. Twenty (20) sources throughout Barbados were identified and samples were collected over a two-day period for $\delta^{15}N$ analysis.

The five (5) public supply wells selected for nitrate testing are: Hampton, due to its importance as one of the major public supply wells in Barbados and the mixed land use surrounding the well; Bowmanston, due to the fact that it is a streamwater well and the mixed land use surrounding the well; Belle, due to its importance as one of the major public supply wells in Barbados, the attention given to it due to illegal settlements within the area, and the potential for sewering and treatment of waste around the Belle; Molyneux, due to its proximity to a golf course; and Ashton Hall, due to the trend of rising nitrate concentration and mixed land use surrounding the well. The agricultural well, National Hatcheries, was sampled and tested for nitrate concentrations weekly as a comparative well since the land directly surrounding the well is agricultural. Hence, artificial fertilisers and animal manure directly impact this well. Figure 7 shows all the sources sampled for isotopic nitrogen and nitrates. The selected wells for weekly nitrate sampling were chosen as they are widely spread, and can be taken as being representative of the island's catchments.

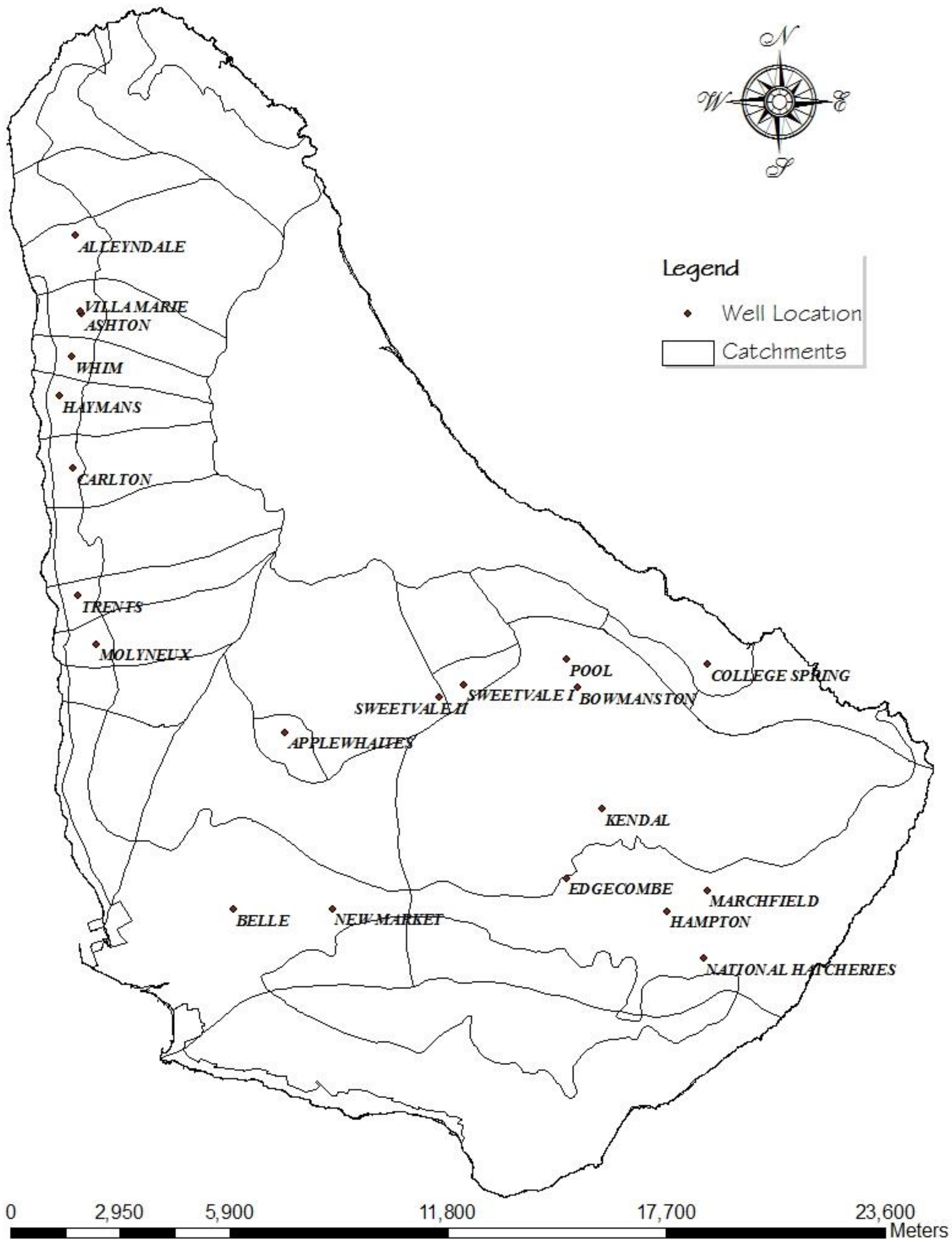


Figure 7 Map of Barbados showing the catchments and the wells sampled in the three-month period

Twenty (20) sources were selected to carry out $\delta^{15}N$ analysis in order to comprehensively ascertain the dominant sources of nitrate contamination throughout Barbados. Public supply wells, agricultural wells and springs were therefore chosen for this analysis. Accessibility to the sources also influenced the choice of the number and types sampled. Cost and availability of the resources for $\delta^{15}N$ analysis played an important role in the number of times this type of analysis was carried out for the research. The following sources were sampled for $\delta^{15}N$ analysis: Applewhaites, Sweetvale 1, Sweetvale 2, Bowmanston, Kendal, Pool, Codrington College spring, National Hatcheries, Marchfield, Hampton, Edgecombe, Newmarket, Belle, Trents, Carlton, Haymans, Whim, Ashton Hall, Villa Marie and Alleynedale.

4.2. Sampling methods and testing

The Standard Operating Procedures used by the Environmental Protection Department (2005) were employed for the collection of groundwater samples. Sanitisation of the taps through use of an instrument to flame the inside of the faucet was not carried out since such an instrument was unavailable. Since bacterial content does not affect nitrate analyses, this procedure was not deemed to be vital to the results of the analysis. Analyses were carried out by the Government Analytical Services (GAS) laboratory in Barbados, hence sample bottles were prepared consistently by this lab for the sampling.

The sampling procedures for isotopic sampling were guided by those set by the International Atomic Energy Agency (IAEA). The amount of sample to be collected was dictated by the analysing laboratory. The Ecosystems Centre, Marine Biological Laboratory located in Massachusetts, U.S.A. analysed the samples for $\delta^{15}N$ and requested approximately 400 mL of sample from each source. In order to preserve the samples, each was filtered with 0.45 μm pore size filters and frozen prior to shipment, as deemed necessary by the IAEA (Kulkarni, n.d.).

4.3. Data collection

The records pertinent to the study were acquired from the various government departments and agencies responsible for the acquisition and storage of the necessary records. Information regarding land use and land zoning in Barbados were obtained from the Town and Country Development Planning Office (TCDPO) to assist in the quantitative and geospatial assessment of land use surrounding the wells sampled. Additionally, information regarding the water catchments and the flow of groundwater were obtained from the Barbados Water Authority

(BWA) since the movement of nitrate in the groundwater may be related to these elements. Existing data and reports regarding nitrate concentrations in public supply wells, agricultural wells and springs throughout Barbados were obtained from BWA and the Environmental Protection Department (EPD). Supplementary information regarding types of agriculture, rate of fertiliser application, crop types, population density, rainfall and applicable GIS datasets for all activities were acquired from the Ministry of Agriculture, the Barbados Meteorological Service and the Barbados Statistical Service.

4.4. Data analysis and limitations

The zones of influence were based on modelled water table elevations using the programme MODFLOW, and reported in the Draft report on Task 2, Reliable Yield Analysis for the Water Resources Management and Water Loss Studies (Klohn-Crippen Consultants Ltd., 1997). After consultation on the method and pumping rates of the wells of interest (A. Ifill, pers. comm.[1]), the zones of influence were calculated. The model used to determine the zones of influence utilised various assumptions since an exact description of the physical aquifer was not possible. Therefore some measure of error is expected in the model; hence the zones of influence are estimates of the areas contributing to groundwater contamination. The water table elevations around the analysed wells indicate where there is radial flow of groundwater to the wells and the extent of such flow into the wells from the surrounding areas. The contours of the basal coral of Barbados were also used to determine the general flow of groundwater from one region to another since the gradient of the basal rock assists gravity flow. There are inherent difficulties in the analysis of the sources of groundwater contamination due to the geologic formations and potential conduits for groundwater flow via cavities that may be unknown in some areas of the island. The zone of influence was therefore used to allow for uniformity in the analysis of each well in the absence of accurate information on the locations of such conduits and cavities, while the use of contours of basal rock was complementary.

Nitrate contribution by human bodily wastes was calculated in order to determine the contribution of residents in the zones of influence to groundwater contamination. The total nitrate eliminated per day per person, 62 mg/day (Mensinga et al., 2003), was used in conjunction with

[1] A. Ifill, The Barbados Water Authority, 15 September, 2009.

the abstraction rates for the wells (L/day) to compare their contribution to the nitrate concentrations, measured in mg/L, of the wells sampled.

Geospatial analysis through the use of ArcGIS software was employed to determine the types of land use, whether agricultural, residential, industrial or other types of activities, within the zone of influence for each of the six (6) wells sampled weekly. It was also used to determine the number of persons residing within each zone of influence to better understand the amount of domestic wastewater being contributed by the area. The primary data set for the analysis consisted of the 2000 Census Map of Barbados, a well location shapefile, the land use map of Barbados updated in 1998, a shapefile of the buildings in Barbados updated in 1998, and a shapefile of the groundwater catchments in Barbados.

The use of GIS analysis and the results of nitrate concentration and isotopic nitrogen were used together to determine the contribution of the types of agricultural activities, domestic wastewater disposal and industrial activities, to the nitrate concentration in the groundwater. Nitrate sampling could only take place once a week over the three (3) month period due to constraints of the Government Analytical Services Laboratory, and isotopic sampling could only be carried out once in the time frame due to the lengthy processing time of samples and shipment to Massachusetts, U.S. The disadvantage of using GIS analysis is the availability of GIS data. Most of the data collected were dated as far back as 1998, and the most recent were created in 2000. All analyses were carried out under the assumption that these factors are similar in 2009; however, it is likely that there have been changes. In an attempt to assist this shortcoming, Google Earth Pro, which presents satellite imagery of 2009, was used as a supplementary tool for land use analysis to check for changes over time.

Additionally, a list of all registered farmers in Barbados was obtained from the Ministry of Agriculture, and this was used to determine the type of agricultural activity carried out within the zone of influence for each well. A limitation of this list is the fact that although it is inclusive of registered farmers, they may not be actively carrying out the types of farming specified. Attempts were made to determine the active farmers and plots of land but were unsuccessful.

Statistical analysis was carried out on the data available from the Groundwater Monitoring Programme. One way ANOVA and the independent t-test were used to determine the difference in mean nitrate concentrations of the public supply and agricultural wells catchment-wide and island-wide using a 95% confidence interval. Scatter plots and linear regression analysis were used to determine whether trends exist between nitrate concentration and rainfall, also using a 95% confidence interval. For each of the analyses, trends were deemed to be significant where $p<0.05$. Where rainfall data was used, the stations closest to the well locations were used for comparison for the specific time period. However, it is not certain whether the rainfall at the rainfall stations was also experienced at the surrounding wells, regardless of proximity.

5. RESULTS AND DISCUSSION

The results of laboratory testing, GIS analysis and data analysis are presented in this section. The potential trends and correlations associated with groundwater nitrate concentrations were also explored and discussed to assist in the determination of the dominant sources of nitrate contamination, and potential contributors to nitrate migration. Among the factors considered in the analysis are rainfall, population density, types of agriculture, soil infiltration characteristics, isotopic nitrogen results, basal coral contours and the presence of gully systems.

5.1. Seasonal trends

The average nitrate concentrations for each well by month for 2000 to 2008 were used to carry out a seasonal trend analysis. There was evidence at the 95% confidence level that the mean nitrate concentrations of the agricultural wells and public supply wells did not differ significantly according to wet or dry seasons ($p > 0.05$). Additionally, linear regression was used for the three-month sampling period and corresponding rainfall data, along with rainfall data and corresponding nitrate concentrations between 2000 and 2005. The period between 2000 and 2005 indicated that rainfall affects nitrate concentration-decreased nitrate concentration with increased rainfall. The rainfall data available were total monthly recordings, and the corresponding nitrate concentrations used for the analysis were monthly averages. Although the scatter plot indicated a general trend, the linear regression analysis proved that the trends were not significant enough ($p > 0.05$) to determine nitrate concentrations based on rainfall data alone. The data may have been too general to allow for any trend to be recognised. This generalised trend was more prominent in the Bowmanston and National Hatcheries wells than in the Belle and Hampton wells, perhaps due to either a greater number of, or physically larger, pathways such as sinkholes into the aquifer.

A similar method was used to determine if any trends existed between rainfall and nitrate concentration for the three-month sampling period. The linear plot indicated decreasing trends; however, there was too little data to carry out an accurate analysis. To supplement the linear plots, graphs of the three-month sampling period were created to determine whether any visual trends could be detected. On the 20th of July 2009 the greatest amount of rainfall was recorded for the three-month period at the rainfall stations at Belle, Bowmanston and a rainfall station north of Ashton Hall. Eight (8) days later on the weekly scheduled day of sampling for nitrates, nitrate concentrations were the lowest recorded for all the wells sampled on that day. It is not certain whether this is a trend, or if there may have been an error at the laboratory. Belle, Bowmanston and Ashton Hall illustrated trends of high rainfall and an eight-day lag time for nitrate concentration response. Rainfall recorded at the station north-east of Hampton and National Hatcheries, however, did not indicate that the greatest amount of rainfall for the three-month period occurred on the 20th of July 2009, but on the 28th of July the nitrate concentrations for both wells were their lowest for the period. The infiltration rates of the soils calculated by Tullstrom (1964), if compared, show that the soils on the West Coast allow for greater infiltration than the Belle and Bowmanston. An eight-day lag time for these wells with different characteristics does not seem plausible unless there are other factors to allow the consistency, such as the presence of similar features in the limestone, such as fissures, cracks and sinkholes. Senn (1946) reported that a large sinkhole north of the Bowmanston well causes silt laden water to appear in the Bowmanston cave two or three days after heavy rainfall. This occurrence was evident after 33 mm of rainfall on 14th September 2009 (Caribbean Institute of Meteorology and Hydrology, 2009) and continued rainfall, to a lesser extent, on the following day of scheduled weekly sampling for nitrates. The pump was shut down due to the high turbidity of the groundwater and a sample could not be retrieved for testing. There was no such problem for any other wells; therefore sinkholes such as that in the Bowmanston region may not be present within the regions affecting the groundwater pumped by the other wells in the sampling schedule. There was no consistency in the trends noticed between rainfall and nitrate concentration. The weekly sampling schedule may not have been of sufficient frequenct to record any recognisable trends.

5.2. Increasing or decreasing trends

Linear regression was used to determine whether nitrate concentrations increased or decreased over time. A general decreasing trend was noticed for the average nitrate concentrations of all groundwater catchments from 1988 to 2008. The decrease was not deemed to be significant enough ($p > 0.05$) to determine future nitrate concentrations.

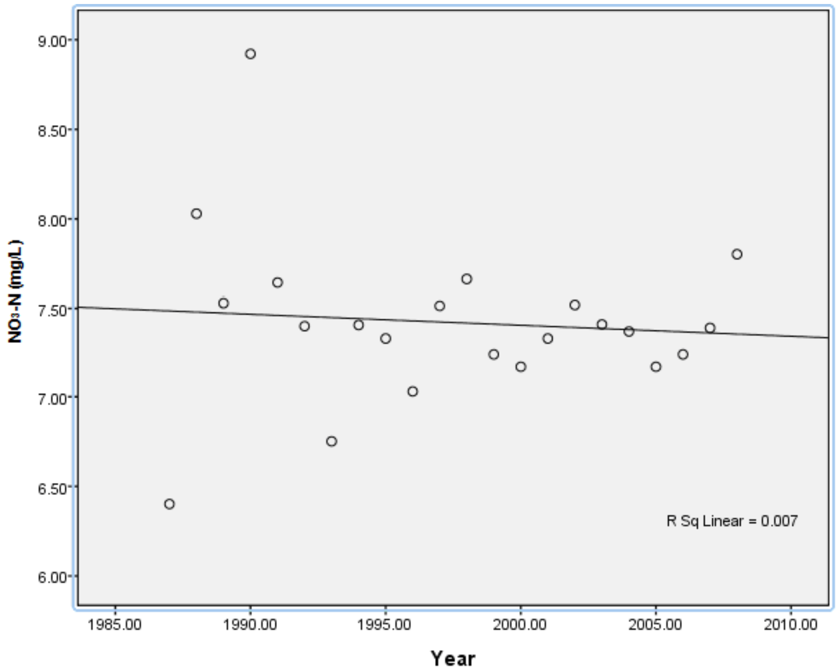


Figure 8 Linear regression illustrating a decreasing trend in average nitrate concentrations for all catchments between 1987 and 2009

The national trend of decreasing nitrates shown in Figure 8 may be rooted in the decrease in fertiliser imports shown in Table 5. Population size has increased, thereby increasing domestic wastewater loading, and lands for sugar cane cultivation are being replaced by residential, commercial and industrial lots and cash crop cultivation. The importation of fertilisers into Barbados has however decreased since 1989, which may indicate that the shift from sugar cane cultivation to the cultivation of cash crops did not increase the use of fertilisers as postulated in the Groundwater Quality Studies for Pollution Risk Assessment in Barbados (British Geological Survey et al., 1989). This would indicate that the dominant sources of nitrate which occurred in the groundwater in the past may have changed on a national scale over time. A redistribution of the population on a countrywide scale may also account for the decrease in nitrate concentration. If populations have moved from areas with high nitrate concentrations to areas with comparatively lesser background nitrate concentrations, the national trend of decrease may result.

5.3. Difference in wells

One way Anova was used to determine whether there were significant differences among the wells in the same catchment, among the wells of all catchments and differences within agricultural wells and public supply wells. The independent t-test was used to determine whether there were significant differences in the nitrate concentrations of agricultural wells versus public supply wells.

5.3.1. Trends in each catchment

There is evidence at the 95% confidence level that there are significant differences in nitrate concentrations among the public supply wells in each catchment ($p < 0.05$). Similarly, there are significant differences in nitrate concentration among the agricultural wells in each catchment. However, in an island-wide analysis, no significant differences were found (1) between agricultural and public supply wells, (2) among all agricultural wells, or (3) among all public supply wells ($p > 0.05$).

On a catchment level, differences were found to be significant, thereby indicating that there are factors, perhaps land use or geophysical properties, within each catchment that cause variations in nitrate concentration for each well. However on the larger island-wide scale, the factors were not deemed to be as significant. Hence it may be assumed that all wells are equally vulnerable to these factors, or may be cancelled out on an island-wide scale. Public supply wells are protected through the Groundwater Protection Zoning Policy whereby land use is restricted in the wells' surrounding areas. But agricultural wells are not protected under the Policy since the wells are not used for drinking water supply so that these wells are not located within protected areas. Agricultural wells may be surrounded by agricultural land where crop cultivation or animal rearing occurs, and there are no restrictions on land use. However, agricultural activities are not restricted under the Policy for areas surrounding the public supply wells and may explain the insignificant difference between the means of the nitrate concentrations of agricultural wells and public supply wells on an island-wide scale.

5.4. Land use

The existing land use throughout Barbados was analysed to determine whether any correlations exist between nitrate concentrations and the type of activities that occur close to the wells sampled. In a general overview of the land use, the residential areas were found to be concentrated along the coastline from the north-west to the south of the island, with the highest concentration located in the south-west region. The pie chart in Figure 9 was produced using GIS analysis and illustrates the existing land use throughout Barbados. Agricultural land use dominates much of the island, while residential land use is the second most dominant land use activity.

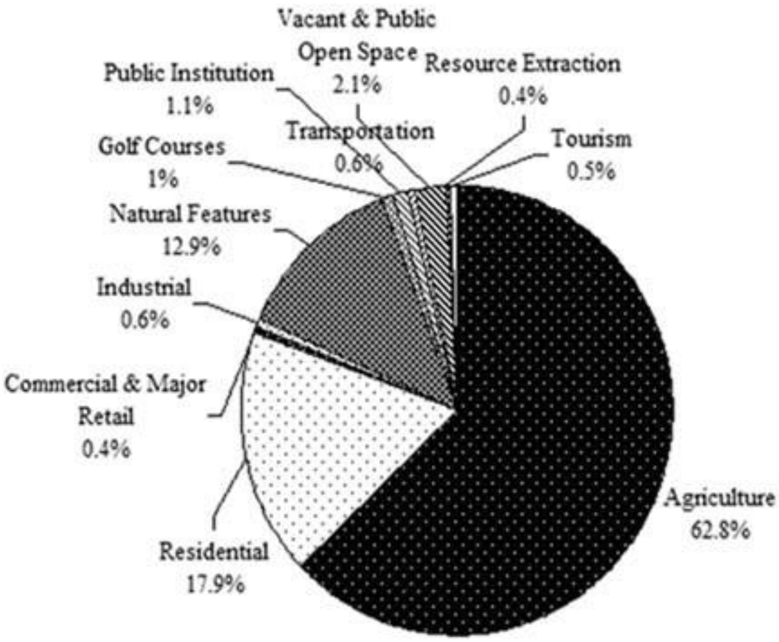


Figure 9 Comparison of land use in Barbados

Tullstrom (1964) indicated that the infiltration factors for precipitation are greater for those areas with higher percentages of gully systems. Therefore the most influential natural features are gully systems that allow for ease in transport of fluids, and provide better infiltration. The basal coral contours together with these gully systems were used to assist in the determination of directional groundwater flow.

The areas considered for analysis are those surrounding each of the six (6) wells sampled weekly and correspond to the respective zone of influence. These areas were analysed for population density, the types of agricultural activity occurring within these areas, and the type of land use for which the areas are earmarked by the Town and Country Development Planning Office.

5.4.1. Ashton Hall

The population density for the 325 m zone of influence around the well in Ashton Hall was calculated to be 569 persons/km^2. The average nitrate concentration for the sample period was 7.78 mg/L and the $\delta^{15}N$ was determined to be 8.7 ‰.

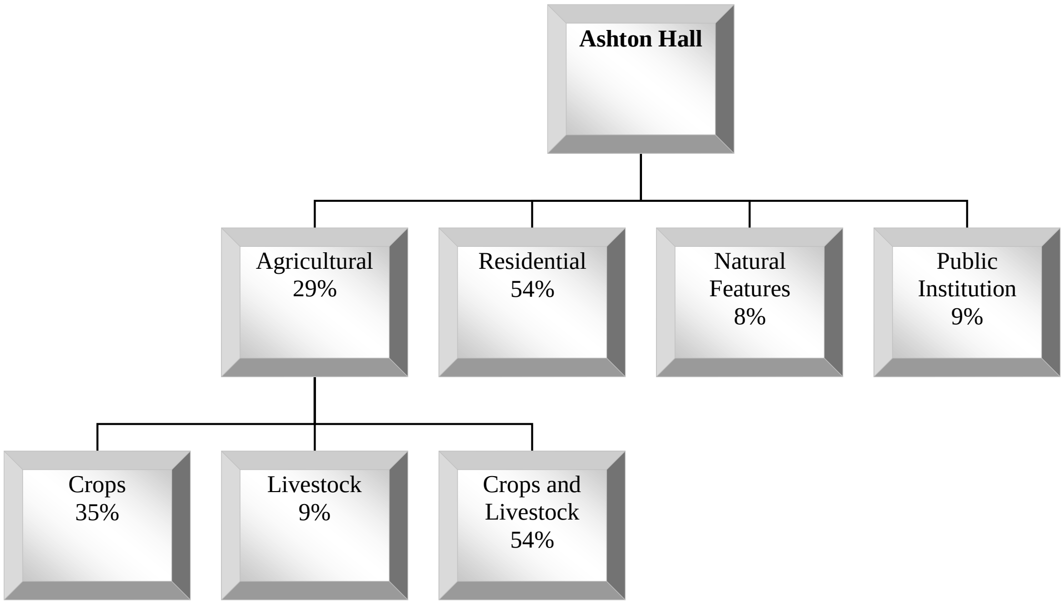


Figure 10 Aerial view of the zone of influence for the Ashton Hall well

Source: Data SIO et al., 2009

The aerial view and map of Ashton Hall shown in Figures 10 and 11 illustrate the proximity of existing houses to the pumping well. The areas closest to the well within Zone 1 are deemed to be the most vulnerable to groundwater contamination. The highlighted area in Figure 10 indicates residential property constructed since 1998, as these buildings were not represented in the GIS data used to produce the map in Figure 11.

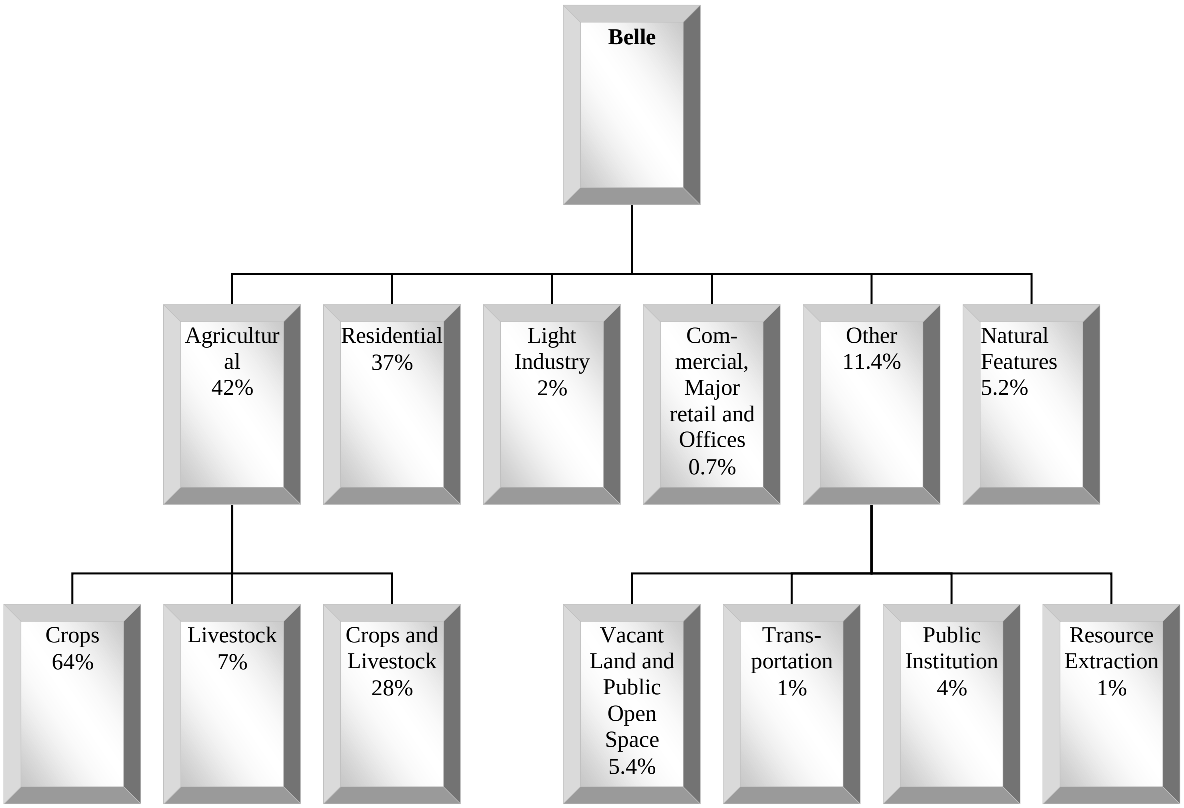
The domestic wastewater emitted from the households surrounding the well is likely to contribute to the resulting nitrate concentrations of the water sampled, due to proximity. The number of persons estimated to live within the zone of influence was calculated to be 188, using the GIS Census map created in the year 2000. As there have been further residential developments since this time the population size may have also changed. Based on 188 persons, the contribution of nitrate from bodily wastes only to the total amount of water abstracted per day was calculated to be 0.0047 mg/L. An increase in residents within the area would explain any increase over time in nitrate concentrations noticed at the Ashton Hall well. The public institution located in Ashton Hall is the St. Joseph Hospital. The hospital has been abandoned and does not actively contribute to sources of nitrate.

The isotopic nitrogen results indicate that the nitrogen in nitrate may be resultant from domestic waste with the potential for contribution from artificial fertilisers. The significantly larger percentage of residential land use, compared with agricultural land use, justifies the hypothesis that domestic waste is more likely to contribute to nitrate concentrations in Ashton Hall. Crop cultivation accounts for 35% of the total agricultural land use and may account for contribution of nitrate from artificial fertilisers since only 9% of the designated agricultural land is strictly used for livestock farming.

Figure 11 Map of Ashton Hall showing the types of land use within the zone of influence of the well

5.4.2. Belle

The population density for the 2 km zone of influence around the well in Belle was calculated to be 2007 persons/km^2. The average nitrate concentration for the sample period was 7.90 mg/L and the $\delta^{15}N$ was determined to be 10.5 ‰.



The area studied for nitrate contribution to groundwater in the Belle illustrates that a larger portion of land is designated to agriculture than residential development. However, the aerial view and map showing the zone of influence for the Belle well, illustrated in Figures 12 and 13, indicate that the residential areas are densely populated. The population for the contributing area was calculated to be 25,221 persons, with a contribution of 0.0297 mg/L of nitrate, due to bodily wastes, to the daily abstracted groundwater. The highlighted areas on the aerial image in Figure 12 indicate where population densities have increased since 1998, noted from the comparison to the prepared GIS map shown in Figure 13. Additionally, domestic wastewater would be generated from the industry, public institution and commercial sectors within the zone of influence.

Figure 12 Aerial view of the zone of influence for the Belle well
Source: Data SIO et al., 2009

The isotopic nitrogen result indicates that the source of nitrogen may be due to domestic waste, animal manure, or both. The land use for the contributing area assists in indicating the most likely contributor, and in this case, due to the high density of population for the area, and the industries, commercial entities and public institutions contributing to domestic waste, the source of nitrates may be mostly attributed to this category of waste. The agricultural portion of the land indicates crop cultivation as the more prominent type of agriculture. However, there is uncertainty regarding application of animal manure to crops and the disposal of animal waste where livestock are reared. Since the $\delta^{15}N$ result is greater than average for domestic waste at 10.5 ‰, it is likely that animal manure is a contributor to nitrate in this area. The summary of the hydrological investigation for the Belle Environmental Study (Stantec Consulting International Limited and Social and Environmental Management Services Inc., 2002) indicated that the primary source of contamination within the study area was found to be applied fertilisers, which indicates that the source of nitrate contamination in the Belle has changed since 2002.

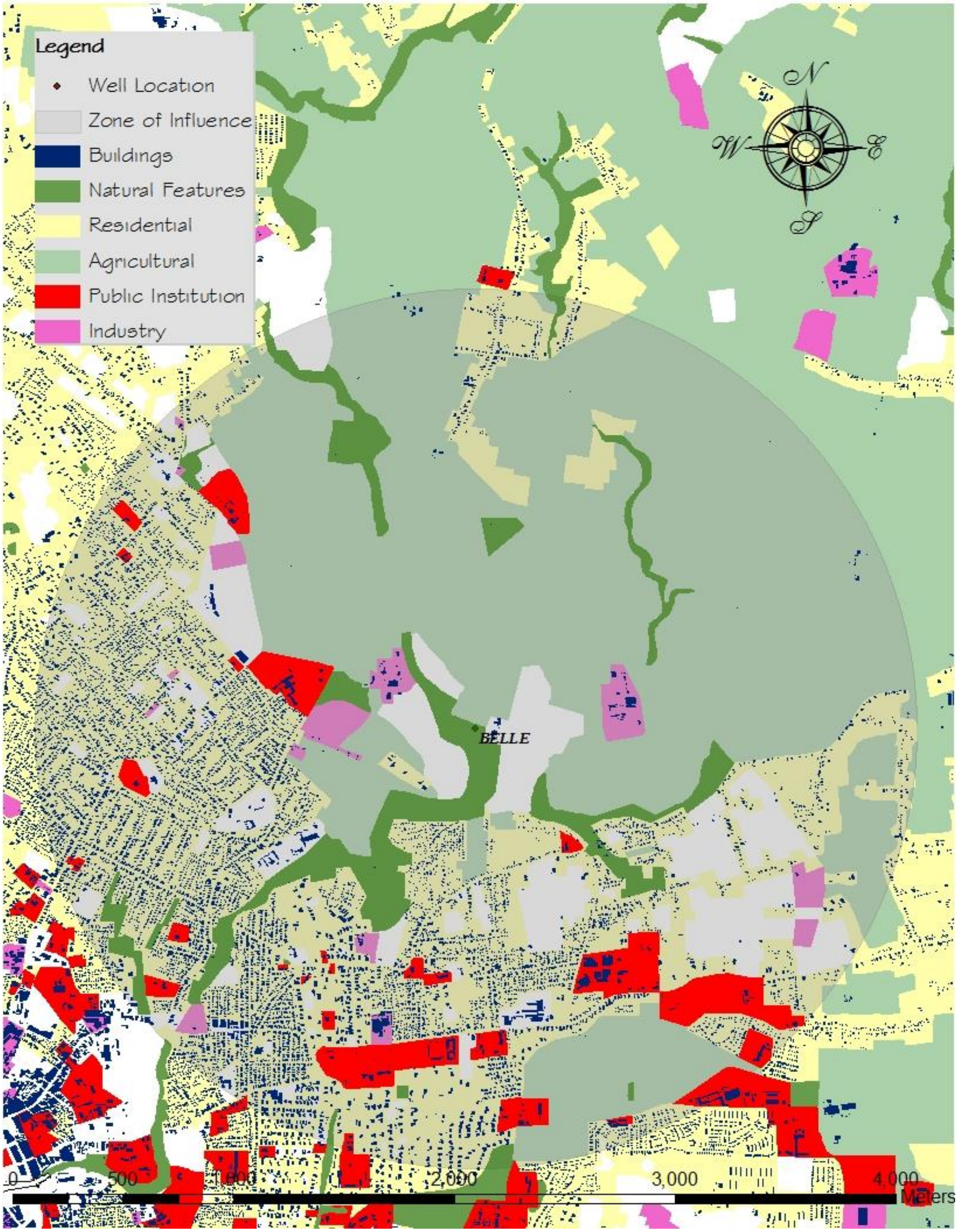
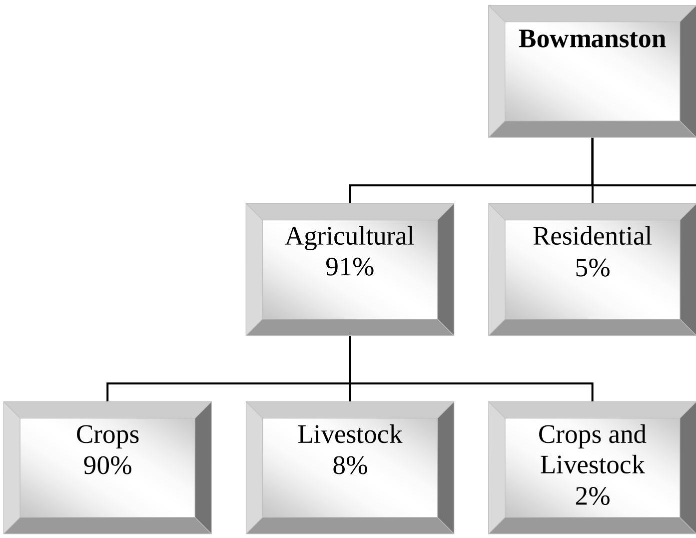


Figure 13 Map of Belle showing the types of land use within the zone of influence of the well

5.4.3. Bowmanston

The population density for the 2 km zone of influence around the well in Bowmanston was calculated to be 266 persons/km^2. The average nitrate concentration for the sample period was 5.42 mg/L and the $\delta^{15}N$ was determined to be 8.3 ‰.



The zone of influence around the Bowmanston well is predominantly devoted to agriculture, with crop cultivation found to be more greatly practised than livestock farming. Nitrate concentrations for samples taken from the Bowmanston well were found to be on average 5.42 mg/L with the highest concentration recorded at 6.22 mg/L for the sampling period. The aerial image shown in Figure 14 does not clearly show any variation from the prepared GIS map shown in Figure 15. A calculated 0.0208 mg/L of nitrate was found to be the contribution from bodily wastes only of the residents within the zone of influence.

Figure 14 Aerial view of the zone of influence for the Bowmanston well
Source: Data SIO et al., 2009

The isotopic nitrogen result indicates that artificial fertilisers and domestic waste may be the sources of nitrogen in the nitrate concentration. The Bowmanston well is a streamwater well, which indicates that the groundwater flow, hence sources of nitrate, may originate from the northern regions of the island. There are many cave-like systems north of Bowmanston, and a large sinkhole located north of the well. These features can facilitate conduit flow of groundwater from the higher regions to the lower areas around Bowmanston.

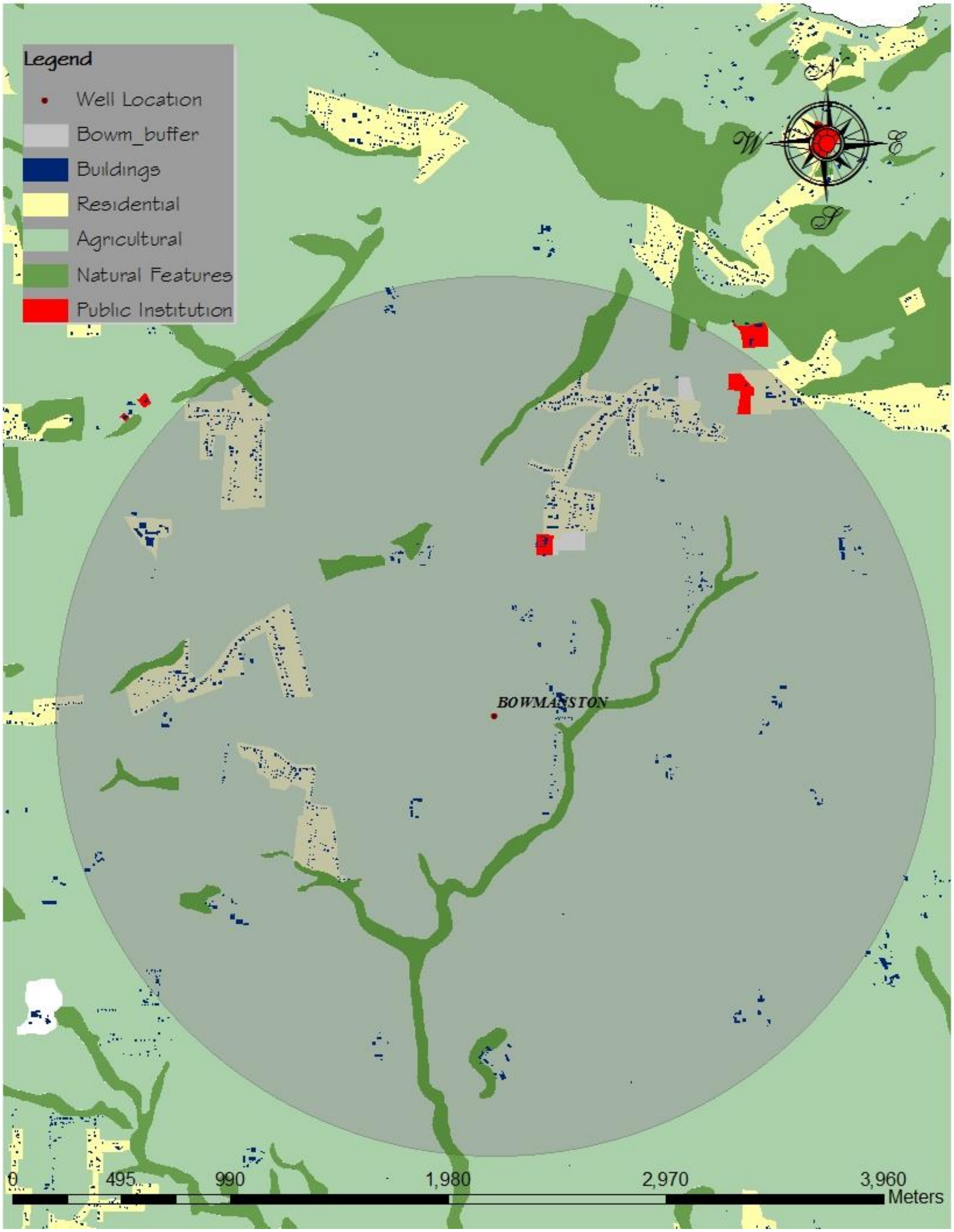
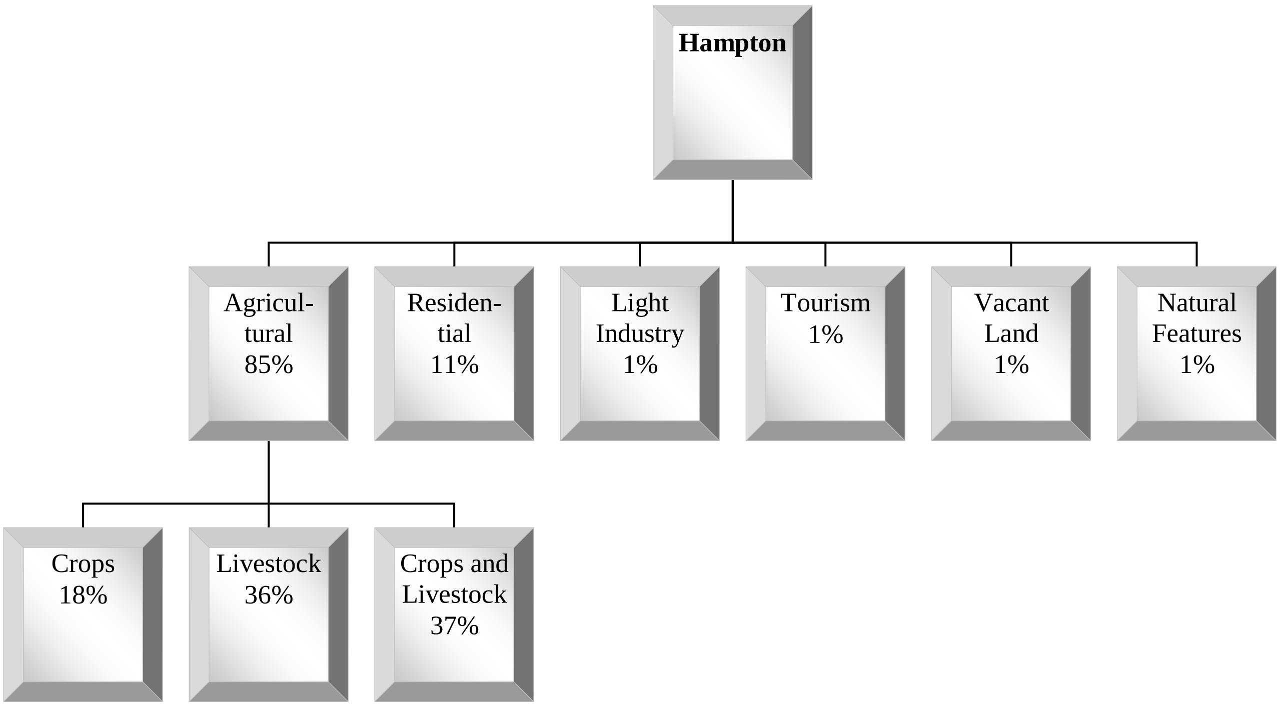


Figure 15 Map of Bowmanston showing the types of land use within the zone of influence of the well

5.4.4. Hampton

The population density for the 2 km zone of influence around the well in Hampton was calculated to be 299 persons/km^2. The average nitrate concentration for the sample period was 6.04 mg/L and the $\delta^{15}N$ was determined to be 9.4 ‰.



The land use in the zone of influence around the Hampton well was found to be predominantly agriculture, with both crop and livestock farming practiced almost equally. Nitrate concentrations from the well were found to be on average 6.04 mg/L, and the highest concentration recorded at 6.72 mg/L. The isotopic nitrogen result indicates that the dominant sources of nitrate occur from domestic wastewater, animal manure, or both. The aerial view of the Hampton shown in Figure 16 indicates that density of residential development is greater than shown on the prepared GIS map in Figure 17, which uses data from 1998. The highlighted areas in Figure 16 indicate where residential development has increased between 1998 and 2000. The contribution of nitrate, due to bodily wastes from residents, to the abstracted groundwater was calculated to be 0.0081 mg/L.

Figure 16 Aerial view of the zone of influence for the Hampton well
Source: Data SIO et al., 2009

Due to the mixed land use within the zone of influence of the Hampton well, it may be concluded that the nitrate concentrations in the groundwater pumped from the Hampton well are being influenced by both domestic wastewater and animal manure, with a greater tendency towards domestic wastewater.

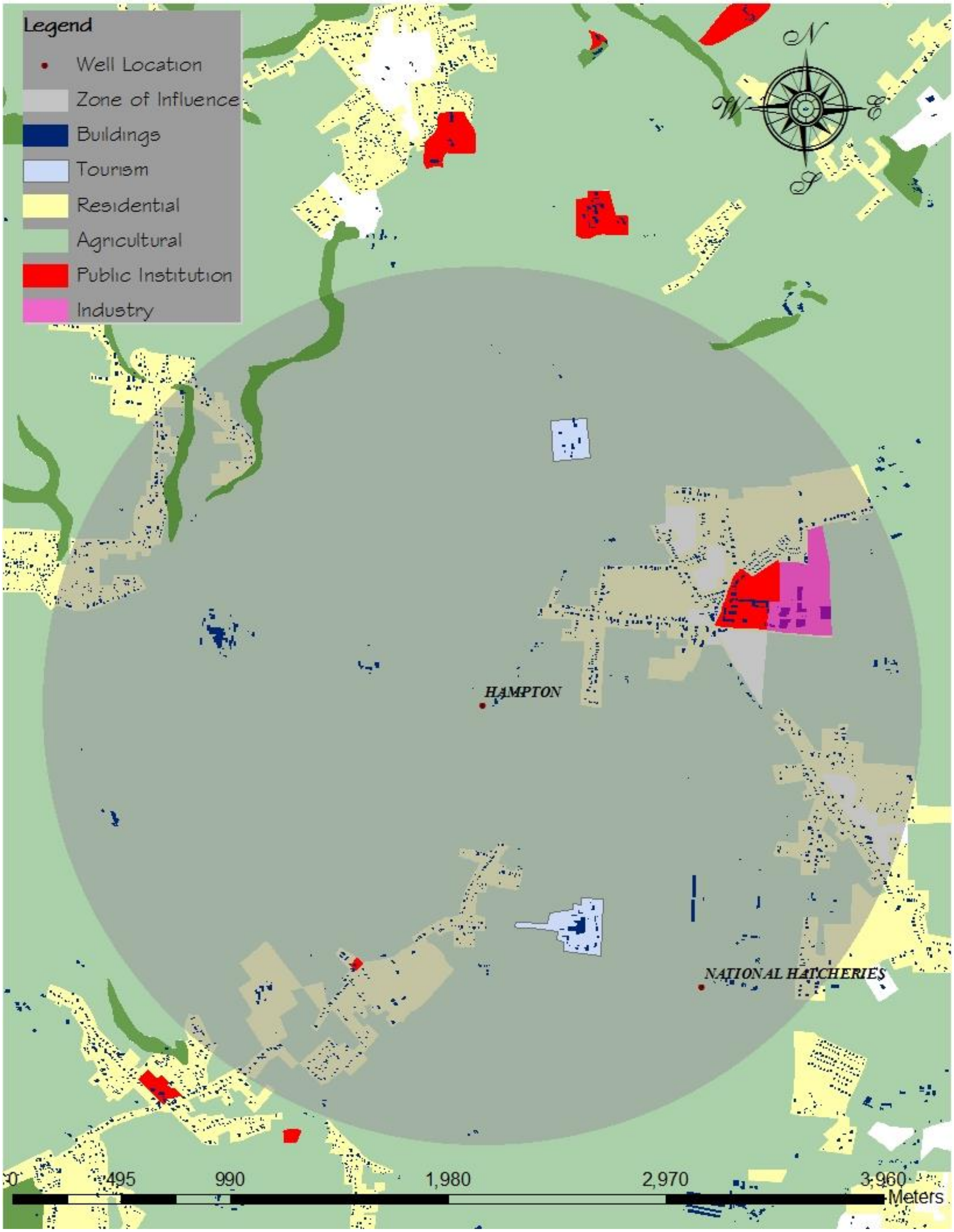
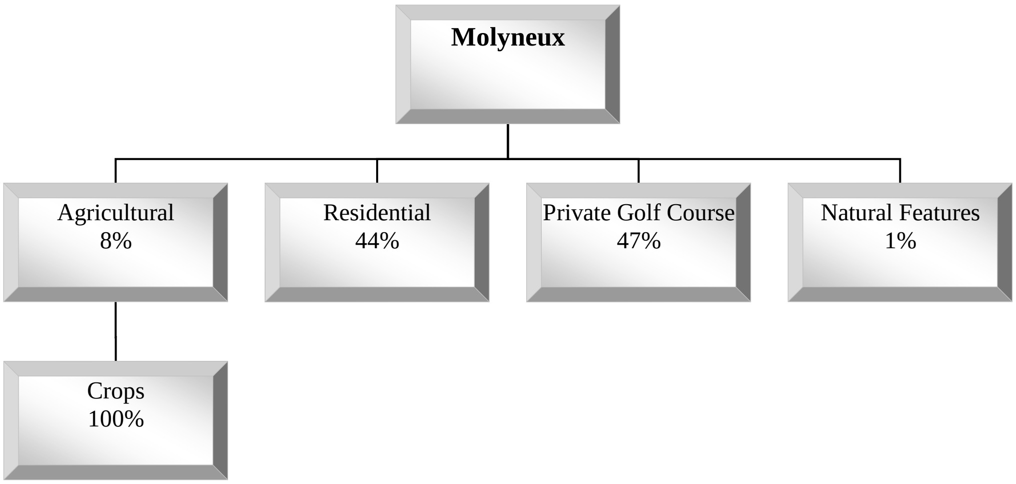


Figure 17 Map of Hampton showing the types of land use within the zone of influence of the well

5.4.5. Molyneux

The population density for the 325m zone of influence around the well in Molyneux was calculated to be 229 persons/km^2. The average nitrate concentration for the sample period was 4.90 mg/L.



The nitrate concentrations of the ground water pumped at the Molyneux well have been found to be consistently low, with an average of 4.9 mg/L and a maximum concentration of 5.66 mg/L. The greatest percentage of land use for this area is attributed to the presence of a golf course, with residential designation occupying much of the remainder of the land. The aerial view of the area shown in Figure 18 however illustrates that there are few residences, though greater than those shown on the prepared GIS map shown in Figure 19, with the majority comprising large, high-end properties. The highlighted areas in Figure 18 indicate where residences have been erected since 1998. The number of persons calculated to be within the zone of influence is 76 and their contribution of nitrate, due to bodily wastes only, to the daily abstracted groundwater was calculated to be 0.0032 mg/L. At the time of sampling for isotopic nitrogen tests, the well at Molyneux was closed for repairs; therefore a value for isotopic nitrogen was not obtained.

Figure 18 Aerial view of the zone of influence for the Molyneux well
Source: Data SIO et al., 2009

The low concentration of nitrate indicates that the use of artificial fertilisers on the golf courses does not impact negatively on the groundwater resources as it relates to nitrate concentration. Additionally, the domestic waste from the residences within the area is considerably less than that in the other areas studied and may be one of the reasons the nitrate concentration of the groundwater pumped from the Molyneux well is low in comparison to the other wells. There is also no livestock farming in the zone of influence, and this may also contribute to the low nitrate concentrations observed at the well.

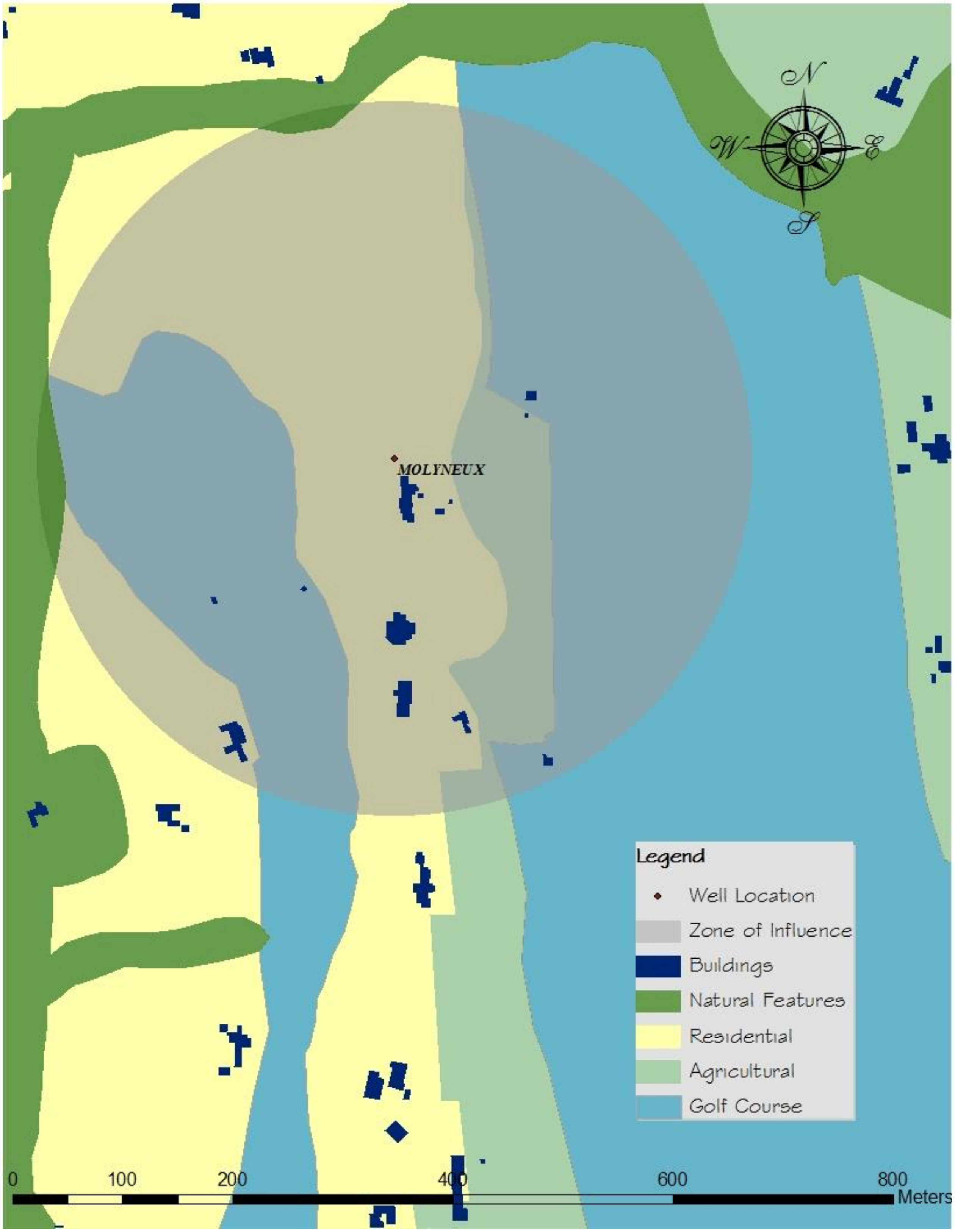
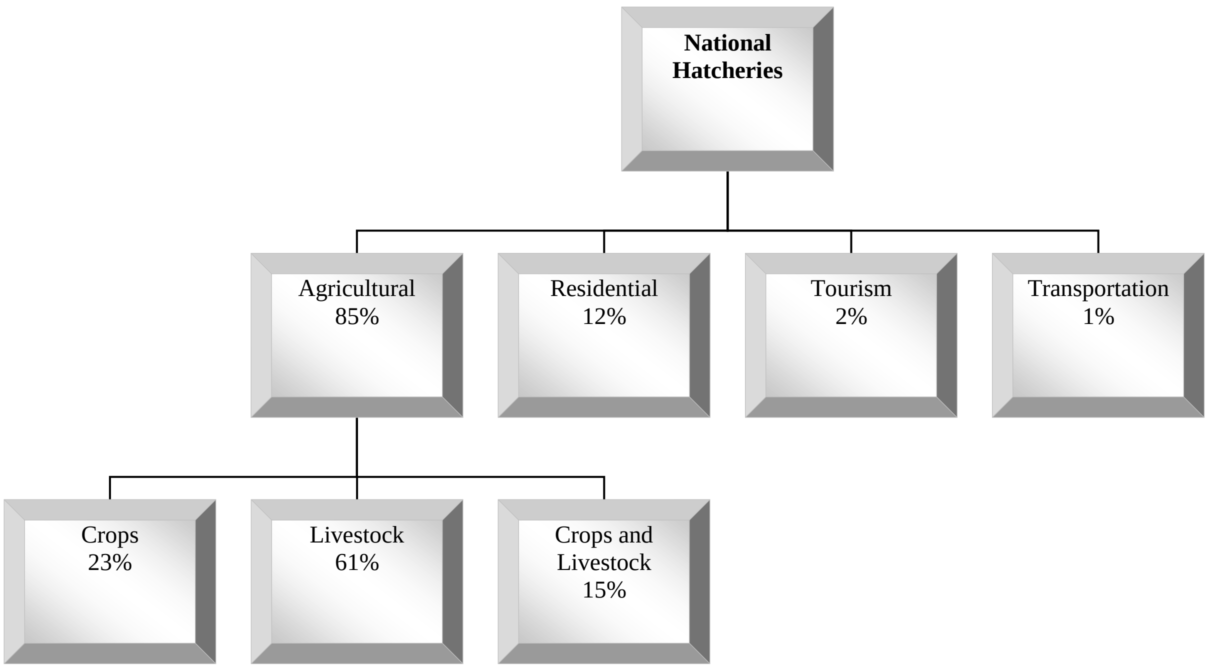


Figure 19 Map of Molyneux showing the types of land use within the zone of influence of the well

5.4.6. National Hatcheries

The population density for the 1 km zone of influence around the well at National Hatcheries was calculated to be 449 persons/km^2. The average nitrate concentration for the sample period was 12.38 mg/L and the $\delta^{15}N$ was determined to be 15.9 ‰



Agriculture was found to be the dominant land use activity within the zone of influence of the well at National Hatcheries. The aerial image in Figure 20 indicates that the land use designated for residential activity is more densely populated than that shown in the prepared GIS map in Figure 21. Thus it may be concluded that the number of residences and the population increased between 1998 and 2009. The highlighted area in Figure 20 indicates where residential development appeared to have increased. The nitrate concentrations were at most times over the WHO drinking water limit of 10 mg/L, and the isotopic nitrogen result indicates that the sources of nitrogen in nitrate are contributed mainly by animal manure. This result is not surprising since National Hatcheries is a chicken farming facility and the surrounding cropland is fertilised through the use of chicken manure and artificial fertilisers. Leaching of nitrates from the manure is expected where there are excess quantities of nitrogen in the soil.

Figure 20 Aerial view of the zone of influence for the National Hatcheries well
Source: Data SIO et al., 2009

5.5. Weekly nitrate sampling

The results obtained from the weekly nitrate sampling indicated that the agricultural well, National Hatcheries, registered the greatest concentration of nitrates compared with the other wells. Alternatively, the well located at Molyneux resulted in the minimum nitrate concentrations compared with the other wells. The golf course located north-east of the Molyneux well can therefore be considered to have little impact on the nitrates present in the groundwater compared with the other wells. The agricultural land use surrounding the well at National Hatcheries may provide evidence that the agricultural practices within this region contribute to high concentrations of nitrate in the groundwater.

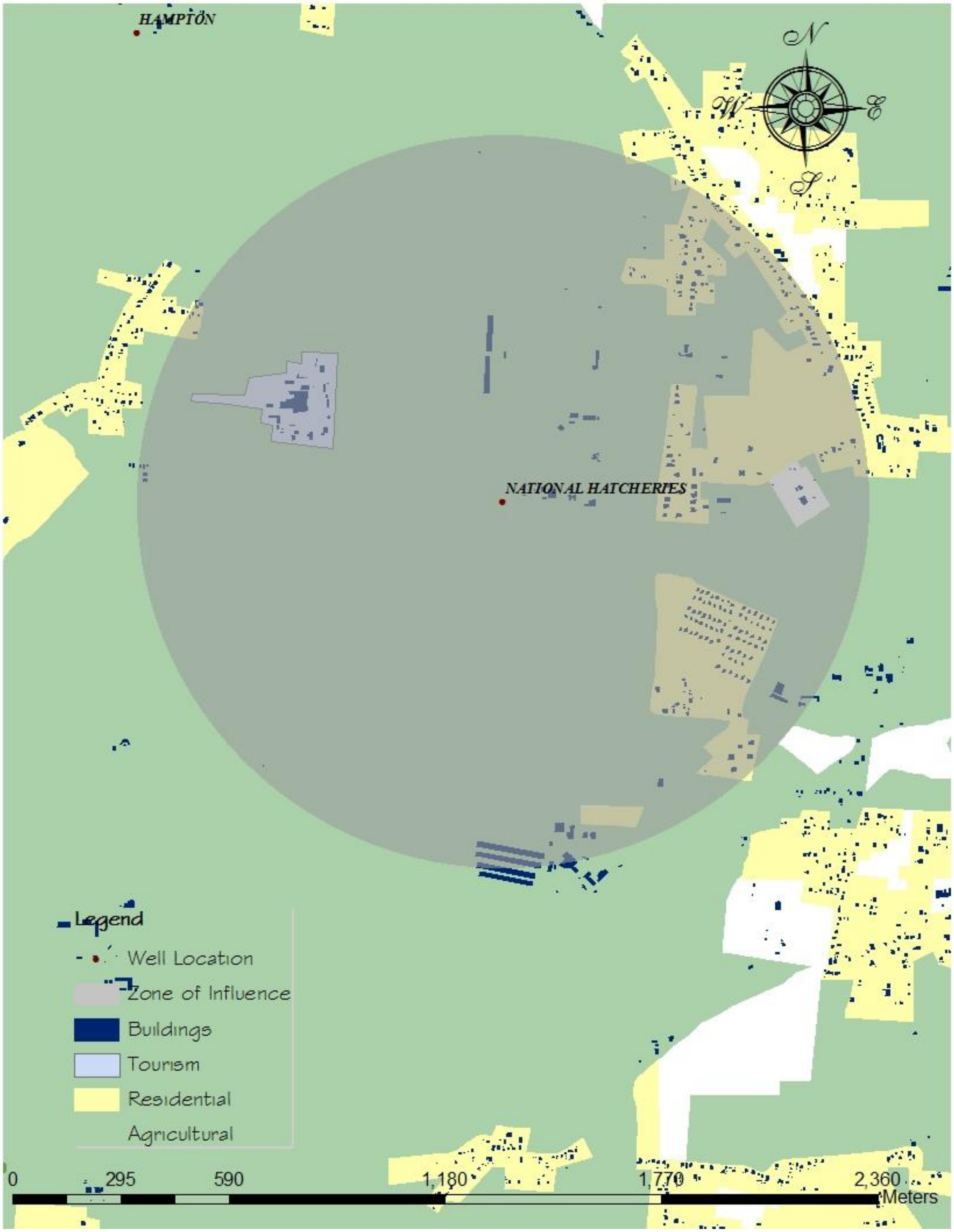


Figure 21 Map showing National Hatcheries and the types of land use within the zone of influence of the well

The results received from the Government Analytical Services Laboratory for the samples taken on July 28th 2009 were significantly lower in nitrate concentrations than those of the other ten (10) comparative weeks. The values were consistently low, however no consistent correlations to rainfall could be made, and no rationale for such an occurrence could be advanced. The samples were handled and preserved as per usual for all (eleven) 11 weeks of sampling. The minimum value obtained for each well was a result of the low results from July 28th 2009; hence the standard deviation for each well is consequently greater without the results from this particular day. The following table shows the averages, maximum and minimum nitrate concentrations, as well as each well's respective standard deviation, inclusive of the results from July 28th 2009.

National Hatcheries, Belle and Ashton Hall are the wells with the greatest standard deviations; no major similarities exist among the wells. It may be postulated that for the well at National Hatcheries, varying application rates of animal manure fertiliser to agricultural land may cause fluctuation in nitrate concentrations. For the well located at the Belle, during the sample period it is not expected that population size would have fluctuated, hence no fluctuation due to domestic wastewater would be expected. However, the agricultural land within the zone of influence may have experienced varying fertiliser application or varying quantities of animal rearing. Rainfall effects may have contributed to variations, however since it was found in the linear trend that rainfall affected National Hatcheries and Bowmanston more greatly than Ashton Hall and Belle, if rainfall were the main contributor to the variations it would be expected that Bowmanston also result in large variations in weekly concentrations, but this was not the case.

Table 9 The average, maximum and minimum nitrate concentrations for each well sampled throughout the 11 weeks, along with their respective standard deviations

Well location	Average (mg/L)	Maximum (mg/L)	Minimum (mg/L)	Standard Deviation (mg/L)
National Hatcheries	12.38	15.70	8.48	2.07
Hampton	6.04	6.72	3.59	0.91
Bowmanston	5.42	6.22	3.33	0.98
Belle	7.90	9.11	4.26	1.79
Molyneux	4.90	5.66	3.27	0.95
Ashton Hall	7.78	8.57	4.19	1.33

5.6. Isotopic nitrogen analysis

The dissolved oxygen for each groundwater sample was measured to determine whether the process of denitrification, the conversion of NO_3^- to N_2O or N_2, occurred prior to sampling. If denitrification had occurred, the source of nitrate in the groundwater would be difficult to identify through the use of the isotopic nitrogen results. The dissolved oxygen values indicated that no denitrification occurred in the aquifer, therefore the $\delta^{15}N$ results can assist in the identification of the sources of nitrate in the groundwater.

The wells sampled resulted in $\delta^{15}N$ values ranging from 7 ‰ to 19.5 ‰. The results in the lower region of this range indicate that the sources of nitrogen are predominantly from artificial fertilisers. Values greater than 12 ‰ indicate dominant contributions from animal manure, while the values from 8 to 12 ‰ indicate contributions primarily from domestic waste. Figure 22 shows the wells that were sampled for isotopic analysis and their respective $\delta^{15}N$ results.

5.6.1. Wells along the west coast

Alleynedale indicates primary contribution from domestic waste with influences from animal manure. From the land use map in Figure 22 it is clear that this well is located within an agricultural land use area. North of Alleynedale are two known chicken farms, Sunrise Chick in Babbs, St. Lucy and Cool Chick in Crab Hill, St. Lucy (Environmental Protection Department, 2008). The waste disposal for Cool Chick was noted to be via the sanitary landfill. The method of waste disposal for Sunrise Chick was not reported. Since the Sanitation Service Authority has discontinued acceptance of animal litter, in many cases it is used as manure or buried, and there may be contributions from animal manure to the groundwater pumped by the well at Alleynedale. The basal coral contours may allow for groundwater flow from Babbs, St. Lucy south-westward toward the Alleynedale area.

There was no $\delta^{15}N$ result for the well located at Villa Marie due to complications encountered in running the analysis at the laboratory. The wells located at Ashton Hall and the Whim exhibit similar $\delta^{15}N$ results and are within close proximity on land. It may be concluded that the dominant source of nitrate are the same, i.e. domestic wastewater. The wells at Haymans and Carlton appear to be influenced most by artificial fertilisers. The land use east of these wells is predominantly agricultural and is higher than the areas in which these wells are located. If the basal coral contours facilitate groundwater flow, it may be inferred that groundwater from the higher geologic regions affect the wells at Haymans and Carlton. Since the infiltration of fluids into the soil is comparatively greater for areas with gulley systems as reported by Tullstrom (1964), the natural features visible on Figure 22 may also lend to the infiltration and movement of water from the higher regions toward Haymans and Carlton.

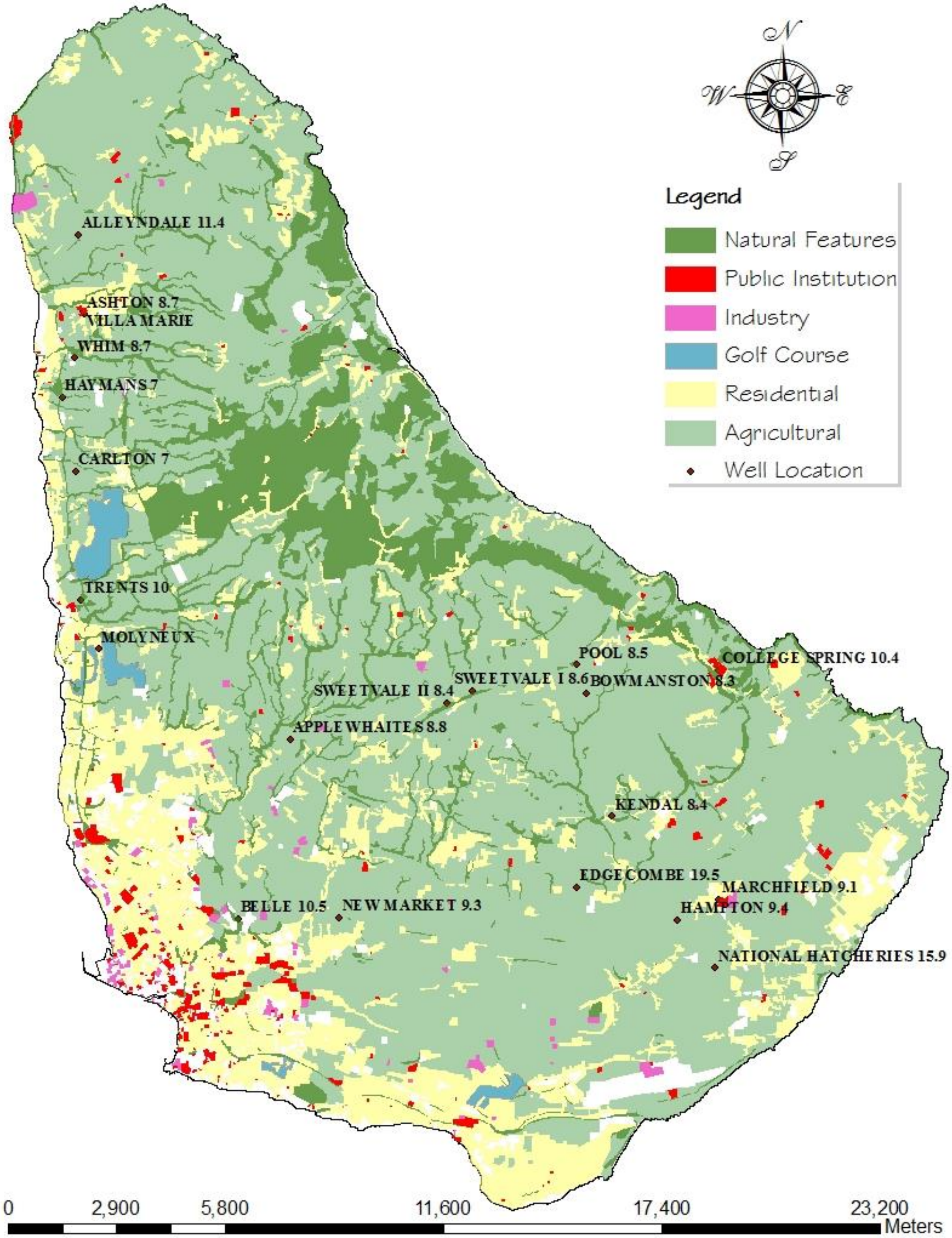


Figure 22 Map of Barbados indicating the major types of land use and the isotopic nitrogen results for the wells sampled

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The well at Trents, on the other hand, appears to be greatly influenced by domestic wastewater with contributions from animal manure. This well is situated west of agricultural land with little residential development. Approximately 3km east of the well at Trents, residential development is evident. The contour of the basal coral allows for a gradual decrease in height from this residential area, westward toward the coast. Groundwater may travel from the higher regions toward the west coast, thereby carrying sources or nitrate from the higher north-eastern regions. Crop and livestock agriculture is recorded by the Ministry of Agriculture in Trents and the surrounding area; therefore contributions from animal manure may be present.

5.6.2. Centrally located wells

The wells located Applewhaites, Sweetvale 1 and 2, Pool Plantation and Bowmanston exhibit similar $\delta^{15}N$ results and are within close proximity on land. It is expected that due to large amounts of land designated for agricultural activity with scattered regions of residential land use, artificial fertilisers may contribute to the dominant source of domestic wastewater. The $\delta^{15}N$ value indicates that the source of nitrate is domestic wastewater, while the land use patterns illustrate that agriculture also plays an important role. The Inventory of Selected Land Based Sources of Pollution and Estimation of Land Based Pollutant Loads into the Marine Environment (Environmental Protection Department, 2008) accounts for three (3) poultry farms within this central area which reportedly dispose of litter via dumping or use as manure. The locations where dumping and use as manure are carried out are unclear. These farms are located south of all the centrally located wells, and if the basal coral contours within these areas are considered, litter from the farms would not affect these wells since the farms are downstream of the wells. Since the $\delta^{15}N$ results do not point to animal manure as a dominant source of nitrate, it is assumed that the operation of these farms do not significantly affect the centrally located wells. Additionally, runoff from the Scotland District into the coral limestone areas where the centrally located wells are may also contribute to groundwater constituents in these wells. The land use within the Scotland District appears to be mostly agricultural, but there are residential areas along the southern border where the geologic formations meet that can influence nitrate concentrations due to domestic wastewater.

5.6.3. Codrington College Spring

The result at College Spring varied slightly from the aforementioned centrally located wells, and this is attributed to the residential development north-west of the sampling point. The basal coral contours allow for the movement of water from the north-west and west toward the eastern coastline. The spring is a surface water body and would be expected to receive sources of nitrates from higher regions.

5.6.4. South-eastern wells

The well at Kendal is located in an agriculturally designated area, with its surroundings a mixture of both agricultural and residential land use. The $\delta^{15}N$ results indicate primary contributions from domestic wastewater, while the agricultural nature of the surroundings indicates some contribution from artificial fertilisers.

The wells located at Marchfield and Hampton exhibit similar $\delta^{15}N$ results, both indicating domestic wastewater as the primary source of nitrate. A light industry facility is located next to the Marchfield well. However, the industry is one of furniture manufacture and would not contribute greatly to nitrates other than domestic waste produced by employees. A public farm market facility is also located close to the Marchfield well and animal manure may contribute to the 9.1 ‰ result for Marchfield and 9.4 ‰ result for Hampton.

The wells at National Hatcheries and Edgecombe have definitive contributions from animal manure due to the heavy weighting of their $\delta^{15}N$ results. Each of these wells is located on farm land where livestock rearing occurs, and although the pumping rates may allow for groundwater pumpage from areas other than those immediately surrounding the well, the $\delta^{15}N$ results indicate that the dominant source of nitrate is animal manure.

5.6.5. South-western wells

The well located at New Market points to domestic waste as the dominant source of nitrate. New Market is in the midst of agricultural land, primarily that of crop cultivation. Horse stables are located north-west of the well and horse manure may contribute to the $\delta^{15}N$ result. North of the well at New Market is residential land use, and if the contours of the basal coral influences the groundwater movement, the domestic wastewater from this area contributes to the well at New Market.

The well at the Belle was found to be influenced primarily by domestic wastewater, yet the heavy weighting of the $\delta^{15}N$ result also indicates that there may be contributions from animal manure. If the basal coral contours are considered in addition to the zone of influence, groundwater may flow from north and south of the Belle well, thus allowing these areas to contribute to the sources of nitrate. Although domestic waste seems to be the greatest contributor of nitrates, based on population density of the zone of influence and groundwater flow, activities in the agricultural lands north of the well may allow for contributions from animal manure.

5.7. Overview and limitations

While there are mixed sources of nitrate for various areas, domestic wastewater appears to be the dominant source of nitrates throughout Barbados. Since the zone of influence delineates the respective areas that contribute to groundwater contamination based on abstraction rates, the hydrogeologic flows due to basal coral contours are also expected to contribute to contamination. The extent of this contribution is unknown. Comparison of the research results and previous studies indicate that the sources of nitrate vary according to land use; therefore, isotopic testing over a longer period of time and with greater frequency would assist in determining how large this variation can be and in what time frame it occurs. It may also identify activities, that are detrimental to groundwater safety, those persons potentially responsible for such activities and the spatial extent of the contribution of hydrogeologic flows.

Where there is mention of contribution of nitrates from bodily wastes to the daily abstracted groundwater, it should be noted that while these values are small in comparison to the nitrate concentrations of the samples, residents also use the pumped groundwater for household purposes. The water supplied to the public is constantly being recycled. The abstraction rates indicate the demand for water. Thus, after this water is used, much of nitrate contained within this water re-enters the ground via suck wells, creating a background level of nitrates in the groundwater. The original sources of nitrate therefore re-enter the groundwater along with new sources according to land use activities. The contribution of bodily wastes, artificial fertilisers and animal manure can therefore be considered an additional load that may accumulate in the groundwater over time.

Consistent and significant seasonal trends were not found using the weekly nitrate sampling schedule. Trends may be better noticed if nitrate sampling could be done on a schedule that allows for sampling more than once a week, since the lag time for response after rainfall is unknown. An assessment of the lag time can also assist in locating geologic features, such as sinkholes, and further inform the movement of contaminated groundwater.

6. CONCLUSION AND RECOMMENDATIONS

The effect on average nitrate concentration for each well is considered to be peculiar to the land use and geophysical properties of the contributing areas. The sources of nitrate throughout Barbados were found to vary from artificial fertilisers to domestic wastewater and animal manure. Agricultural activities were the dominant sources of nitrate for four (4) of the nineteen (19) sources for which results were obtained, where two (2) sources were predominantly due to artificial fertilisers, and the other two (2) due to animal manure. In many cases however, due to the mixed land use within relatively small areas, there is a combination of sources contributing to nitrate concentrations in the groundwater. Domestic wastewater was the main contributor for the other fifteen (15) sources although there may have been contributions to a lesser extent from agricultural land use. Industrial wastes were not found to contribute greatly to the nitrate concentrations for the wells sampled.

The wells at National Hatcheries, Belle and Ashton Hall showed considerable variation in their respective weekly results in comparison to the other wells sampled. It is hypothesized that the agricultural lands within the zones of influence for these wells may contribute to the fluctuation in nitrate concentrations through variations in fertiliser or manure application to agricultural lands, or burial of manure. Some correlation between nitrate concentration and rainfall was found, using historic rainfall and nitrate concentration data, as well as the weekly sampling data. As rainfall increased, nitrate concentrations showed a general trend of decrease. However, it was not deemed to be significant enough for use in the prediction of nitrate concentrations. The variations in the wells at National Hatcheries, Belle and Ashton Hall may also be attributed to the small fluctuations in nitrate concentrations as a result of rainfall. In order to further the investigation of rainfall contributions to nitrate concentrations in the groundwater, the sampling schedule may be modified to increase the number of sampling days per week.

The research has shown that the dominant source of nitrate throughout Barbados is domestic wastewater but agricultural activities also contribute to nitrate concentrations depending on the land use surrounding, or upstream, of the well. A continued schedule of isotopic testing is recommended on a regular basis in order to monitor any variations that may occur in the sources of nitrates. The management of land use as it relates to residential and agricultural activities is also necessary for the protection of groundwater and public health. Residential developments are encroaching upon Zone 1 lands— those areas deemed to be critical to groundwater protection. Alternatives to the disposal of untreated domestic wastewater into the ground should be highly considered, especially within the restricted zones. Additionally, farmers should be offered education on the testing of soils for nutrients in order to better determine the application rates of manure or fertilisers for specific crops. The disposal of animal excreta is also a critical issue that needs to be addressed since the Sanitation Service Authority no longer allows for the disposal of these wastes into the landfill. Farmers are left with few alternatives when there are no designated disposal methods for their waste, and are more likely to pose a risk of groundwater contamination.

The need for safe, potable water in Barbados is the driving force behind the requirement of sustainable management of water resources. Since ground water is the primary source for potable water, it is of utmost importance to protect it. Knowledge of the dominant sources contributing to nitrate concentrations in the groundwater can therefore guide management decisions in safeguarding the future of Barbados.

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8. APPENDICES

8.1. Appendix 1 Isotopic nitrogen results received from Marine Biological Laboratory

Sample	□^{15}N-NO3 of sample (o/oo vs. AIR)	Comments
Pool Plantation	8.5	
Sweetvale #1 P.S	8.6	
Sweetvale #2 P.S	8.4	
Kendal	8.4	
Bowmanston P.S	8.3	
Carlton P.S	7.0	
Hampton P.S	9.4	
Trents P.S	10.0	
Applewhaites P.S	8.8	
New Market P.S	9.3	
Hayman P.S	7.0	
Alleynedale P.S	11.4	
Codrington College	10.4	
Marchfield	9.1	
Edgecombe	19.5	
Villa Marie	----	No value obtained. Problem with diffusion process, most likely.
Belle P.S	10.5	
Whim P.S	8.7	
Ashton Hall P.S	8.7	
National Hatcheries	15.9	

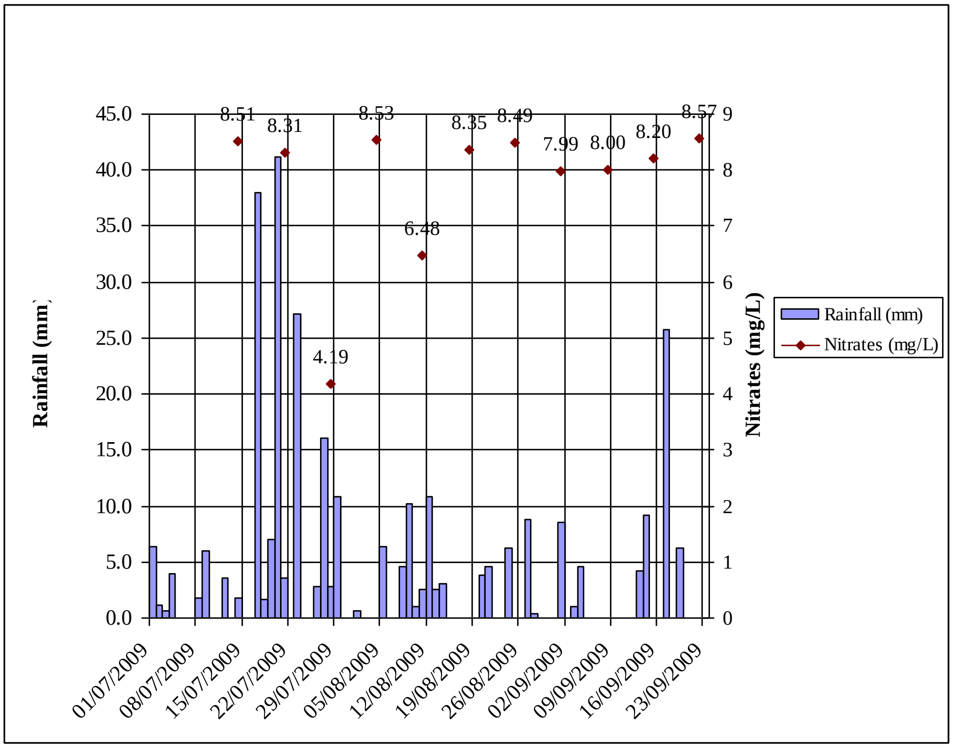
8.2. Appendix 2 Weekly sampling results for nitrate concentrations

Well Location	NO3-N (mg/L)										
	14-Jul-09	21-Jul-09	28-Jul-09	04-Aug-09	11-Aug-09	18-Aug-09	25-Aug-09	01-Sep-09	08-Sep-09	15-Sep-09	22-Sep-09
National Hatcheries	12.2	15.7	8.48	11.6	9.9	13.5	13.5	12.4	12.2	11.7	15
Hampton	6.41	6.41	3.59	6.54	5.12	6.42	6.52	6.13	6.22	6.36	6.72
Bowmanston	6.22	5.81	3.88	6.1	3.33	5.55	5.85	5.75	5.7		6.01
Belle	9.09	8.73	4.71	8.72	7	8.91	8.95	4.26	8.57	8.89	9.11
Molyneux		4.98	3.27	5.35						5.26	5.66
Ashton Hall	8.51	8.31	4.19	8.53	6.48	8.35	8.49	7.99	8	8.2	8.57

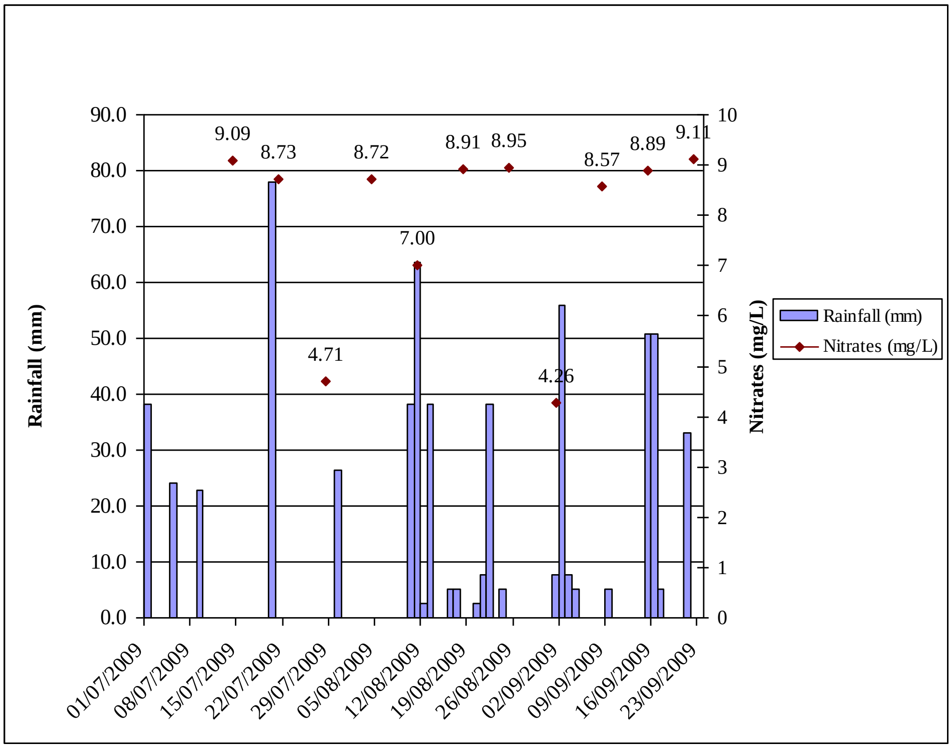
8.3. Appendix 3 Table showing the calculation of nitrate loading by residents from bodily wastes, using 62 mg/day as the amount of nitrate expelled from the body of one person.

Area	Population	Abstraction rate (L/day)	NO_3-N load (mg/day)	NO_3-N load (mg/L)
Ashton Hall	188	2,463,910.00	11,656.00	0.0047
Belle	25,221	52,733,100.00	1,563,702.00	0.0297
Bowmanston	3,344	9,969,280.00	207,304.44	0.0208
Hampton	3,758	28,639,520.00	233,022.66	0.0081
Molyneux	76	1,454,710.00	4,712.00	0.0032

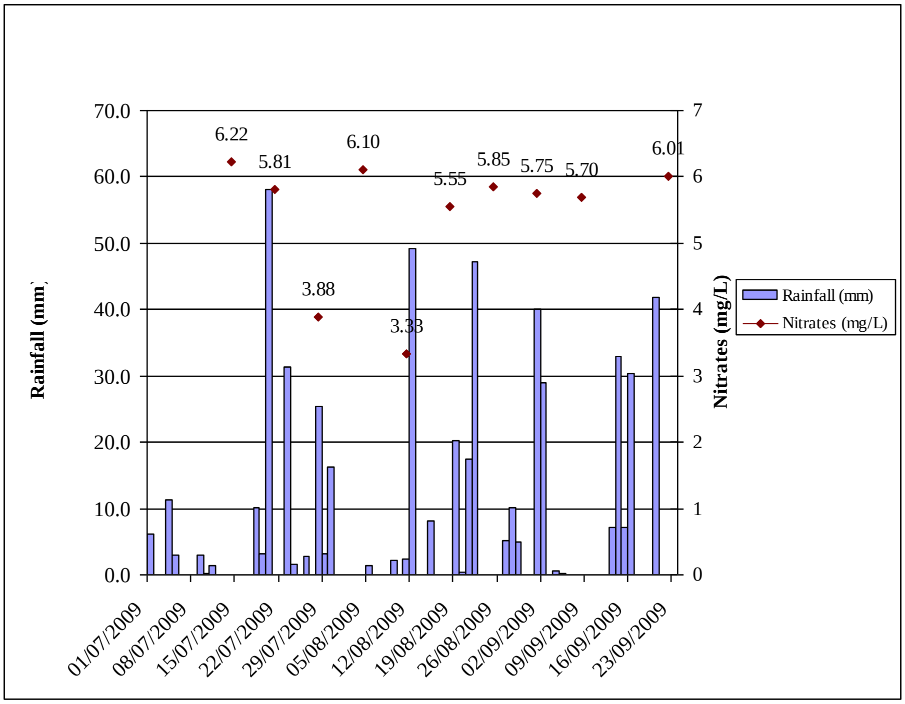
8.4. Appendix 10 Figure showing the rainfall occurrences and nitrate concentrations applicable to Ashton Hall for the sample period between July and September 2009.



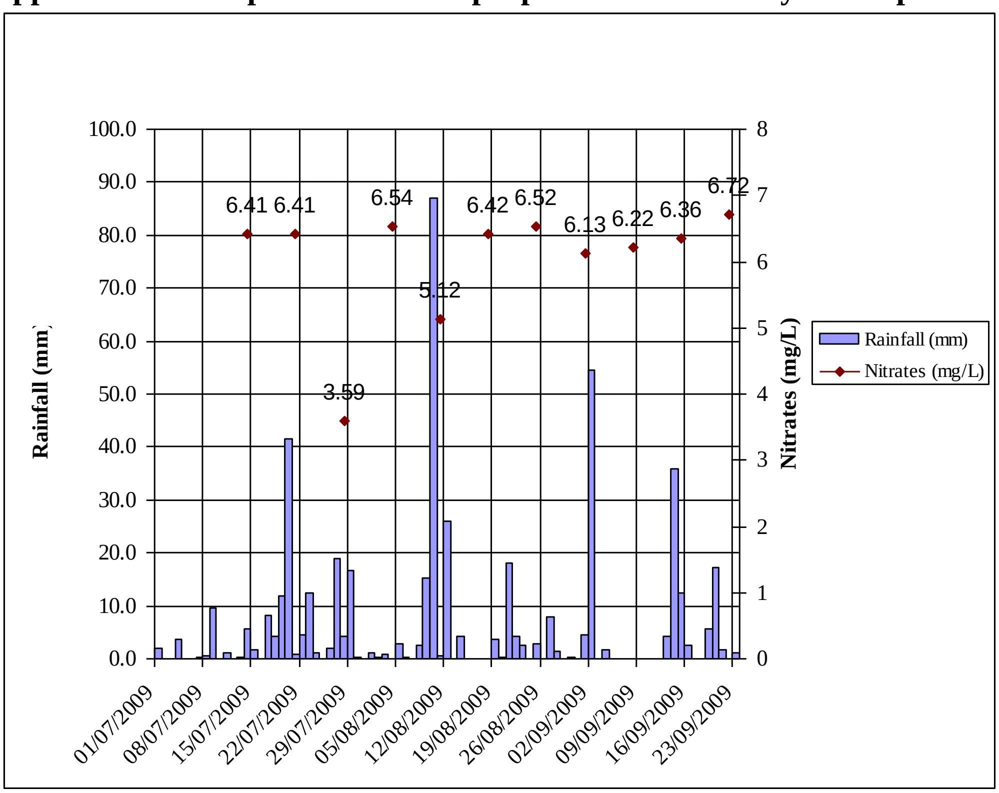
8.5. Appendix 11 Figure showing the rainfall occurrences and nitrate concentrations applicable to Belle for the sample period between July and September 2009.



8.6. Appendix 12 Figure showing the rainfall occurrences and nitrate concentrations applicable to Bowmanston for the sample period between July and September 2009.



8.7. Appendix 13 Figure showing the rainfall occurrences and nitrate concentrations applicable to Hampton for the sample period between July and September 2009.



8.8. Appendix 14 Figure showing the rainfall occurrences and nitrate concentrations applicable to National Hatcheries for the sample period between July and September 2009.