ON-SITE SANITATION IMPACTS ON WATER RESOURCES NEAR TAYLORS HALT, KWAZULU-NATAL, SOUTH AFRICA

BN Wickham

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Supervisor: Prof. SA Lorentz

ABSTRACT

As many as 2.5 billion people worldwide lack basic sanitation, where every year millions suffer from diarrhoea, cholera and other related illnesses as a result. On-site sanitation is a practical and viable solution, but the growing number of on-site sanitation systems pose a risk of lateral movement of contaminants during intense rainfall and threaten precious water resources. The aim of the study was to determine the lateral movement of on-site sanitation contaminants in the near surface hillslope through-flow, from Pour-flush and Ventilated Improved Pit latrine systems. This was done by observing the nitrate, phosphate, ammonium, sulphate, chloride, calcium, magnesium, sodium and potassium electrical conductivity and *Escherichia coli* values in the near-surface hillslope through-flow at different study sites. The results indicate that the on-site sanitation systems periodically impact the near surface groundwater, where the maximum values for nitrate, phosphate and *Escherichia coli* were 1656.5 mg/l, 206.2 mg/l and 241920 MPN/100 ml, respectively. On numerous occasions, several of the hillslope through-flow samples exhibited values well above the drinking water limits defined by the WHO and SANS. The presence of a near surface semi-pervious layer, water table depth and soil texture had a significant impact on the movement of contaminants in the groundwater. The results of this study will contribute to the improvement of existing scientific knowledge, and the development of guidelines for on-site sanitation suited to rural and peri-urban areas in developing nations.

PREFACE

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LIST OF ACRONYMS

OSS - Onsite Sanitation System

VIP - Ventilated Improved Pit latrine

PF - Pour-flush toilet

WFD - Wetting Front Detector

SG - Surface Gutter

FC - Faecal Coliforms

SP - Slangspruit

CR - Crèche

AZ - Azalea

TH - Taylors Halt

THC - Taylors Halt Control

WHO – World Health Organisation

UNICEF – United Nations International Children's Emergency Fund

ORP – Oxidation Reduction Potential

SANS – South African National Standards

1. INTRODUCTION

As many as 2.5 billion people worldwide lack basic sanitation (UNICEF and WHO, 2012), where every year millions suffer from diarrhoea, cholera and other related illnesses as a result (UN-Water, 2012). While conventional full water-borne sewage treatment systems are a preferred option, it is costly, requires an uninterrupted source of water and an existing sewerage infrastructure. For many in poor urban and rural regions, particularly in developing nations, full waterborne sewerage is not feasible (Kalbermatten *et al*., 1980). Other more practical solutions, such as on-site sanitation systems, are vital for improving the poor sanitation status of many, and minimising the impact of water related diseases. However the faecal material, *viz*. pathogens, nitrate and phosphate, stored in the leach pit(s) of an on-site sanitation system, has the potential to contaminate groundwater and surface water resources (Adejuwon and Adeniyi, 2011; Carodona, 1998; Fourie and Van Ryneveld, 1995).

There have been numerous studies conducted to improve the understanding between on-site sanitation systems and water contamination. However many of these studies have been based in developed countries, particularly the USA (Lewis *et al*., 1982), where much of the focus is directed towards the contamination of deep groundwater resources. The few that were conducted in developing nations, were predominantly under tropical climates, which left a small number of studies based in semi-arid areas.

Hundreds of millions of people from developing nations still rely on on-site sanitation systems as the primary form of sanitation. In 2010 56 % of the people in developing nations utilised improved sanitation facilities, which includes VIP's and Pour-flush systems (UNICEF and WHO, 2012). Thus many people in the developing nations are yet to benefit from studies conducted in their environment, which will be more relevant and representative of their setting, climate, soil and geology. This emphasises the need for more field based studies situated in developing nations where it will be of more benefit to the people in such nations.

Several on-site sanitation studies *viz*. Adejuwon and Adeniyi (2011); Pujari *et al*. (2012); Pujari *et al*. (2007), have reported high concentrations of pathogens and nitrates in drinking water sources, which exceed the maximum limit defined by WHO and SANS. In some events, unacceptably high values of the above contaminants were measured beyond several of the recommended lateral safe spacing for an on-site sanitation systems. In these cases, the validity of several existing on-site sanitation guidelines and their representation in these situations, is questionable, and highlights the need for further scientific research in the relevant environmental setting.

Classically in the vadose zone, the contaminants from an on-site sanitation system move predominantly in a vertical direction towards the deeper underlying groundwater, where they are transported laterally in the direction of the water flow (Lewis *et al*., 1982). However if the deeper groundwater flow is the primary factor responsible for the lateral movement of the relevant contaminants, it is more than likely that the concentration of contaminants at the minimum recommended safe distances, would be below the maximum drinking water limits set by the WHO and SANS, considering (i) the classical slow water movement in the unsaturated zone which promotes the natural attenuation processes that act upon the contaminants (Lewis *et al*., 1982), and (ii) the dilution and denitrification effects that are present in the groundwater (Fourie and Van Ryneveld, 1995; Godfrey *et al*., 2005). Unfortunately this is not always the case, and it is possible that other subsurface characteristics such as semi-pervious layers and preferential flow paths, may be playing a larger role in the relatively fast lateral movement of the contaminants in the subsurface.

There is still much to be understood about the processes occurring within the vadose zone. Looney and Falta (2000) have highlighted the lack of scientific understanding of vadose zone processes, while Carodona (1998) has emphasised the need for further research on on-site sanitation contaminants moving in the subsurface. Lewis *et al*. (1982) has remarked that there is a lack of information pertaining to the relationship between groundwater pollution and on-site sanitation systems. Lastly Fourie and Van Ryneveld (1995) have highlighted the need for more field based studies that investigate the movement of on-site sanitation contaminants in the vadose zone, particularly from dry or low flush systems in rural and informal settlements.

The research question posed here is: To what extent do on-site sanitation system contaminants travel in the vadose zone, in the presence of a near surface semi-pervious layer, in a rural and peri-urban housing environment, under a semi-arid climate. In order to answer the research question the following objectives were followed:

(a) Review existing literature highlighting (i) the major findings of on-site sanitation contaminants, (ii) the impact from rainfall on the contaminants, (iii) the effects of preferential flow paths and semi-pervious layers in the vadose zone, and (iv) reporting the lateral distance and concentration of nitrate and faecal coliform results from several relevant case studies. This objective is covered throughout chapter 3.

(b) Develop a methodology to observe *in-situ* the lateral movement of on-site sanitation contaminants in the near surface groundwater, in a rural and peri-urban area, during the rainfall season. This objective is covered throughout chapter 4.

(c) Present the results of the study in a series of figures, diagrams, tables, and basic statistical analyses, which describe the subsurface characteristics of the study sites, the lateral spread of contaminants from the on-site sanitation systems under investigation, and the effect of rainfall on the contaminants. This objective is covered in chapter 5.

(d) Evaluate the results of the study, and discuss the lateral spread of contaminants from an on-site sanitation system and provide explanations for the results. Finally, answer the research question and draw a conclusion and make recommendations. This objective is covered in chapters 6 and 7.

2. BACKGROUND OF ON-SITE SANITATION

2.1. South Africa

The South African Water Services Act [No. 108 of 1997] stipulates that every South African has the right to access basic water supply and basic sanitation (Water Services Act, 1997). Furthermore, the Local Government Municipal Systems Act [No. 32 of 2000] outlines that it is the responsibility of a municipality to ensure that all members of a local community have access to the minimal level of basic municipal services (i.e. sanitation) (Municipal Systems Act, 2000). While the necessary legislation is in place to promote sanitation services and ensure that everyone may benefit from this basic need, sadly there are still many in South Africa who have yet to do so. At the end of 2010, approximately 25.00% of South Africans used unimproved sanitation systems or had no sanitation facilities (Lehohla, 2011). The South African Government has set a target of 100.00% access to basic sanitation by 2014 (DWAF, 2012), while on a Global scale the Millennium Development Goal (MDG) sanitation target is aimed at 75.00% by 2015 (UNICEF and WHO, 2012). If these targets are to be achieved, it is inevitable that the number of on-site sanitation systems used in South Africa and around the world will grow, which may exacerbate current water quality issues.

There are several different types of on-site sanitation systems available to the public, each with its own pros and cons, enabling the user to choose a suitable system based on the needs of the user in his/her living environment. Statistics from the General Household Survey Volume III report suggested that in 2010, 58.70% of South Africans utilised full waterborne sewerage systems, while 3.40%, 12.50%, 0.40% and 25.00% comprised of septic tanks, VIP latrines, chemical toilets and unimproved or no sanitation facilities, respectively (Lehohla, 2011). Furthermore between 2002 and 2010, VIP latrine systems were the fastest growing form of sanitation, rising from 4.40% to 12.50%, while the number of full waterborne sewerage systems used, remained relatively static throughout the eight years (Lehohla, 2011). In South Africa the three most commonly used systems are VIP latrines, low flush toilets and septic tanks (Van Ryneveld and Fourie, 1997). Clearly on-site sanitation systems are a popular option and are likely to become as common as full waterborne sewerage in the years to come. However there is concern about the potential water pollution issues associated with leachate from such systems.

2.2. Water Quality Impacts and Human Health

In the context of water quality, the primary chemical species of concern are nitrates and phosphates (Carodona, 1998; Fourie and van Ryneveld, 1995; Lewis *et al*., 1982). Prolonged ingestion of water containing nitrate (> 45 mg/l) may lead to methaemoglobinaemia in infants (WHO, 2008) as well as gastric cancer in adults (Lewis *et al*., 1982). From an environmental prospective, high levels of phosphorus > 0.10 mg/l (i.e. 0.30 mg/l phosphate) and nitrogen in water resources, has been known to induce eutrophication, which may have several ecological, social, health and financial ramifications (DWAF, 2002).

While chemical nutrients from on-site sanitation systems may pose a threat to water quality, it is typically the microbiological components of human faecal matter (i.e. pathogens) that have the greatest impact on human health (Ashbolt, 2004; Esrey *et al*., 1991; Fourie and Van Ryneveld 1995). Every year, waterborne pathogens infect approximately 250 million people (Nsubuga *et al*., 2004), resulting in the death of millions due to cholera, diarrhoea and other related diseases (Adejuwon and Adeniyi, 2011; Ashbolt, 2004). In South Africa, this problem is exacerbated for those living with life threatening illnesses, such as HIV/AIDS and tuberculosis. In 2011 it was estimated that 5.3 million South African were living with HIV (Lehohla, 2011), while 500 000 cases of tuberculosis were reported, with 73.00% testing positive for HIV (Department of Health, 2012).

Human excreta comprise numerous chemical nutrients and biological species, which pose a risk to water resources and human health. This is particularly relevant to South Africa, and the study of the movement of onsite sanitation contaminants below the surface, will aid in the development of better guidelines, policies and system designs, and ultimately lead to the better protection of water resources and human health. However, knowing that a contaminant may reach a drinking water resource, does not necessarily mean the water there will be contaminated (Fourie and Van Ryneveld, 1995). There are numerous physical, chemical and biological processes in the subsurface which act upon these contaminants, which may change their concentration or composition, and inhibit or promote their movement into nearby water resources. This next section will briefly describe some of the main scientific findings that are relevant to the concentration, composition and movement of on-site sanitation contaminants in the subsurface.

3. REVIEW OF ON-SITE SANITATION IMPACTS RESEARCH

The primary on-site sanitation contaminants of concern are nitrates, phosphate and pathogens. This chapter describes the main processes governing the mobility and transformation of the contaminants. Furthermore several on-site sanitation related case studies will be briefly described to lend support to the main process discussed, as well as provide lateral distances and concentrations of nitrate and faecal coliforms in the groundwater under different environmental settings.

3.1. Nitrate

The nitrogen from human excreta does not remain in one form but changes, depending upon numerous environmental factors. Starting with ammonium, approximately 95% of the nitrogen in human excreta is in the urine component, in the form of an ammonium ion (Jack *et al*., 1999). Studies on septic tank systems reveal that 76 – 95% of the nitrogen in the effluent derived from human excreta leaves the tanks as ammonium ions (Gerritse *et al*., 1995; Robertson *et al*., 1991 and Walker *et al*., 1973). Robertson *et al*. (1991) reported NH_4–N and NO_3–N concentrations of 59.00 mg/l and 0.10 mg/l, respectively, from the effluent in a septic tank weeping tile. Thus it is likely that the leachate closest to the leach pit of an on-site sanitation system will have a high ammonium content and a relatively low nitrate value in anaerobic soil conditions. However, as the ammonium in the leachate from an on-site sanitation system moves further away through the soil, it may be exposed to aerobic conditions and undergo nitrification.

In the presence of oxygen and a sufficient supply of carbon, the ammonium in the leachate from an on-site sanitation system is oxidised through microbial driven nitrification, to produce an intermediate nitrite and more stable nitrate compound (Carodona, 1998; Robertson *et al*., 1991). Robertson *et al*. (1991) reported a 67% and 100% conversion efficiencies of ammonium to nitrate, within the first few meters of the unsaturated soil below a septic tank leaching tile. Weiskel and Howes (1992) reported similar results of *ca.* 70% conversion efficiencies of ammonium to nitrate in the leachate from septic tanks moving towards the groundwater. Walker *et al*. (1973) observed significant nitrification of ammonium within the first few centimetres of unsaturated soil interfacing with the leachate from a septic tank, after a few hours. In another study, Cogger and Carlile (1984) describe nitrate and ammonium fluctuations in the leachate from septic tanks systems constructed on seasonally and continuously flooded soils. In the constantly saturated soils the ammonium concentration was higher than the nitrate, but in the seasonally saturated soils the nitrate values were higher than the ammonium (Cogger and Carlile, 1984). The reason for the differences was that, under the continually saturated condition there was little nitrification taking place, but in the seasonal condition, the water table fluctuated enough to allow alternating aerobic/anaerobic conditions. This promoted the nitrification process and thus the production of nitrate (Cogger and Carlile, 1984). In the context of pit latrines, Dzwairo *et al*. (2006) reported clear nitrification in the leachate, where NH_4–N and NO_3–N concentrations ranged from 0.00 mg/l and 2.20 – 5.60 mg/l, respectively, in the groundwater. Nitrification is not the final process which acts upon nitrogen. Under the right conditions, the nitrate in the groundwater may undergo denitrification to produce nitrogen gas.

The denitrification of nitrate requires the presence of anaerobic conditions, denitrifying bacteria and an adequate supply of available organic carbon (Fourie and Van Ryneveld, 1995; Robertson *et al*., 1991). Robertson *et al*. (1991) observed rapid denitrification in the groundwater 20 m downslope of a septic tank and 0.5 m below a river bed. Within a few meters from this point, the nitrate concentration (NO_3–N) dropped from 20.00 mg/l to 0.60 mg/l, while the ammonium (NH_4–N) remained unchanged at approximately 0.5 mg/l (Robertson *et al*., 1991). The anaerobic conditions and the presence of a higher organic carbon content from the river bed, made an ideal setting for the denitrification process and promoted the gaseous losses of nitrogen from the system. Fourie and Van Ryneveld (1995) remarked that denitrification is not limited to the saturated zone, but may also occur in the vadose zone, where there are pockets of saturation and a sufficient amount of available organic carbon present in the soil.

There are other processes responsible for the loss of nitrogen from human excreta in an on-site sanitation system. Ammonium ions in the leachate may absorb and desorb on the exchange sites of the soil interfacing with the leachate until an equilibrium is reached (Carodona, 1998). Furthermore, ammonium ions may undergo ammonia volatilization where it is lost to the atmosphere (Jacks *et al*., 1999). In addition, plants can take up nitrate and ammonium ions, as well as soil microbes when the C: N ratio > 25:1, and effectively immobilise the nitrogen into their biomass until they die and release it back into the system (Brady and Weil, 2008). However in the context of on-site sanitation systems, the above nitrogen removing processes are considered insignificant and temporary (Carodona, 1998; Jacks *et al*., 1999).

A study by Jacks *et al.* (1999) established a nitrogen budget surrounding several VIP latrines located in rural Botswana villages. From the study, four major pools of nitrogen were defined, monitored and assigned a respective nitrogen fraction. (i) ammonia volatilization 1 %, (ii) deep leaching of nitrate 1 – 50%, (iii) denitrification 30 – 70% and (iv) residual nitrogen in pit contents 17 – 19% (Jacks *et al.*, 1999). From this study, denitrification and nitrate leaching were highlighted as the largest pools of nitrogen regarding VIP latrine systems (Jacks *et al.*, 1999).

Nitrogen undergoes several transformations in a soil, and exists in several pools, which is largely governed by nitrifying and denitrifying bacteria, presence of oxygen and available carbon, and pH conditions. Figure 3.1 depicts an overall summary of the main processes acting upon the nitrogen in the subsurface, as described by the literature, starting with the ammonium ion present in human excreta, which proceeds to ammonia or nitrate or nitrogen gas.

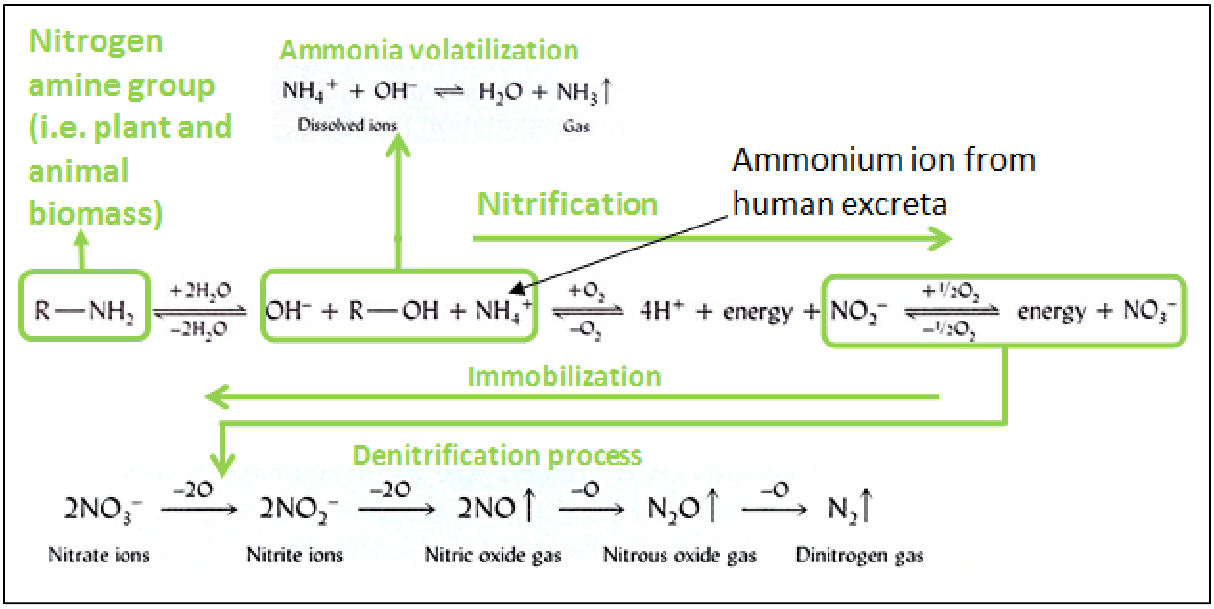

Figure 3.1 Nitrogen transformations in the soil (adapted from Brady and Weil, 2008)

From the literature, nitrogen in the groundwater, which leached from an on-site sanitation system, will primarily be in the ammonium or nitrate form, depending upon the presence of nitrifying bacteria and oxygen. The nitrate ion is negatively charged (figure 3.1) and will travel freely through the soil with water drainage, unlike the ammonium ion which is positively charged (figure 3.1) and is attracted to the predomination negatively charged colloidal surfaces in the soil. Thus the presence on nitrate in the groundwater (contaminated by leachate from on-site sanitation) will classically occur at greater distances from the on-site sanitation system, compared to the ammonium ion. If the nitrate in the groundwater encounters prolonged anaerobic conditions (and the presence of available carbon and denitrifying bacteria), then the nitrate will be subjected to denitrification and be transformed into nitrogen gas (figure 3.1). Thus the measurement of ORP, and ammonium and nitrate compounds in the groundwater below an on-site sanitation system, is essential to this study, in order to gain a holistic view on the nitrogen process occurring below the soil surface

3.2. Phosphate

Similar to nitrogen, the phosphorus from human excreta does not remain unchanged, but undergoes several reactions depending upon the prevailing environmental factors. Approximately 65.00% of the total phosphorus in human excreta is in the urine component in the form of the phosphate ion (Jack *et al*., 1999). A study on septic tank systems by Wilhelm *et al*. (1994) revealed that as much as 76.00% of the total phosphorus in the effluent derived from human excreta in the tank, is in the form of the phosphate ion.

The phosphate in the leachate moving through the soil surrounding an on-site sanitation system is affected by adsorption/desorption process as well as being removed by precipitation reactions. The soluble phosphate ions in the leachate are initially subjected to adsorption/desorption reactions onto hydrous oxides of iron, aluminium, manganese and carbonate surfaces (Carodona, 1998; Brady and Weil, 2008). In addition, the adsorbed phosphate may become occluded by subsequent adsorption reactions of the soluble phosphate and the above metals, resulting in insoluble precipitation complexes (Brady and Weil, 2008). The pH of the soil solution determines which metal ion reacts with the phosphate ions in solution. Phosphate ions react with aluminium and iron ions under acidic conditions and calcium ions under basic conditions (Carodona, 1998; Brady and Weil, 2008). The significance of all this, is that usually there is a relatively small amount of soluble phosphate in the soil solution, where any added phosphate (i.e. leachate from and on-site sanitation system) to the soil system is rapidly fixed within the soil matrix. However, the phosphate bound to iron oxides become more soluble under prolonged anaerobic conditions, as the iron ion is reduced and releases the phosphate ion into the soil solution (Brady and Weil, 2008).

A study by Reneau *et al*. (1989) investigated the reaction of phosphate ions in leachate from on-site sanitation systems, in the presence of aluminium and iron ions in acidic soils. The study revealed a significant increases in aluminium and iron complexes with phosphate within the first 0.15 m of soil compared to the control soil profile (Reneau *et al*., 1989). Weiskel and Howes (1992) noted a 60.00% removal of phosphate ions in the leachate from a septic tank within 1 m of aluminium and iron rich soils. Moreover, at a greater distance the phosphate ions in the leachate was reduced to background levels (i.e. < 0.02 mg/l PO_4^{3-}–P) before reaching the groundwater (Weiskel and Howes, 1992). A study by Robertson *et al*. (1991) reported similar findings at two different sites *viz.* Cambridge and Muskoka. At the Cambridge site, there was little phosphate attenuation noted in the unsaturated zone. However in the groundwater the average pH was 7.10 and the phosphate concentrations were reduced from > 5.00 mg/l to < 0.02 mg/l (PO_4^{3-}–P) after several meters down gradient of the septic tank tile bed. The reason for this was due to the high calcium content and basic conditions present in the groundwater which facilitated the formation of calcium-phosphate precipitates. At the Muskoka site, there was a 99 % phosphate reduction within the first 2 m of unsaturated soil below the tile bed, and the phosphate concentrations in the groundwater was < 0.02 mg/l (PO_4^{3-}–P). At this site groundwater pH values ranged from 6.00 – 5.20 and the calcium content was half that of the first site. At this site the aluminium and iron reactions with the phosphate ions played a large role in the decrease of phosphate concentration in the groundwater. Unfortunately there was no mention of information on aluminium, iron or calcium reactions in the unsaturated zone at both sites.

Carodona (1998) remarked that saturated conditions may dissolve phosphate precipitations that were formed under acidic conditions, and allow for new adsorption and precipitation reactions at a later stage. In most cases the phosphate ions, from on-site sanitation systems, do not usually reach the groundwater (Jack *et al*., 1999), as most soils (excluding coarse, clean gravels) immobilize (*via* adsorption) the phosphate within a small distance from the on-site sanitation system (Fourie and Van Ryneveld, 1995).

Phosphorus (as phosphate) in a soil mainly exists in two pool of low solubility products (figure 3.2). Under high pH conditions and calcareous soil, it is fixed in a calcium-phosphate compound, and at low pH it is fixed in iron and aluminium compounds (figure 3.2). Classically only a small portion of the total soil phosphate is in the soluble pool, which is subjected to leaching (figure 3.2). Figure 3.2 depicts the dominant pools of inorganic phosphate in a soil, as well as the main processes acting upon phosphate, as described by the literature. The arrows indicated the pathways between the different pools, with the thick arrows depicting the dominant process (i.e. adsorption and fixation).

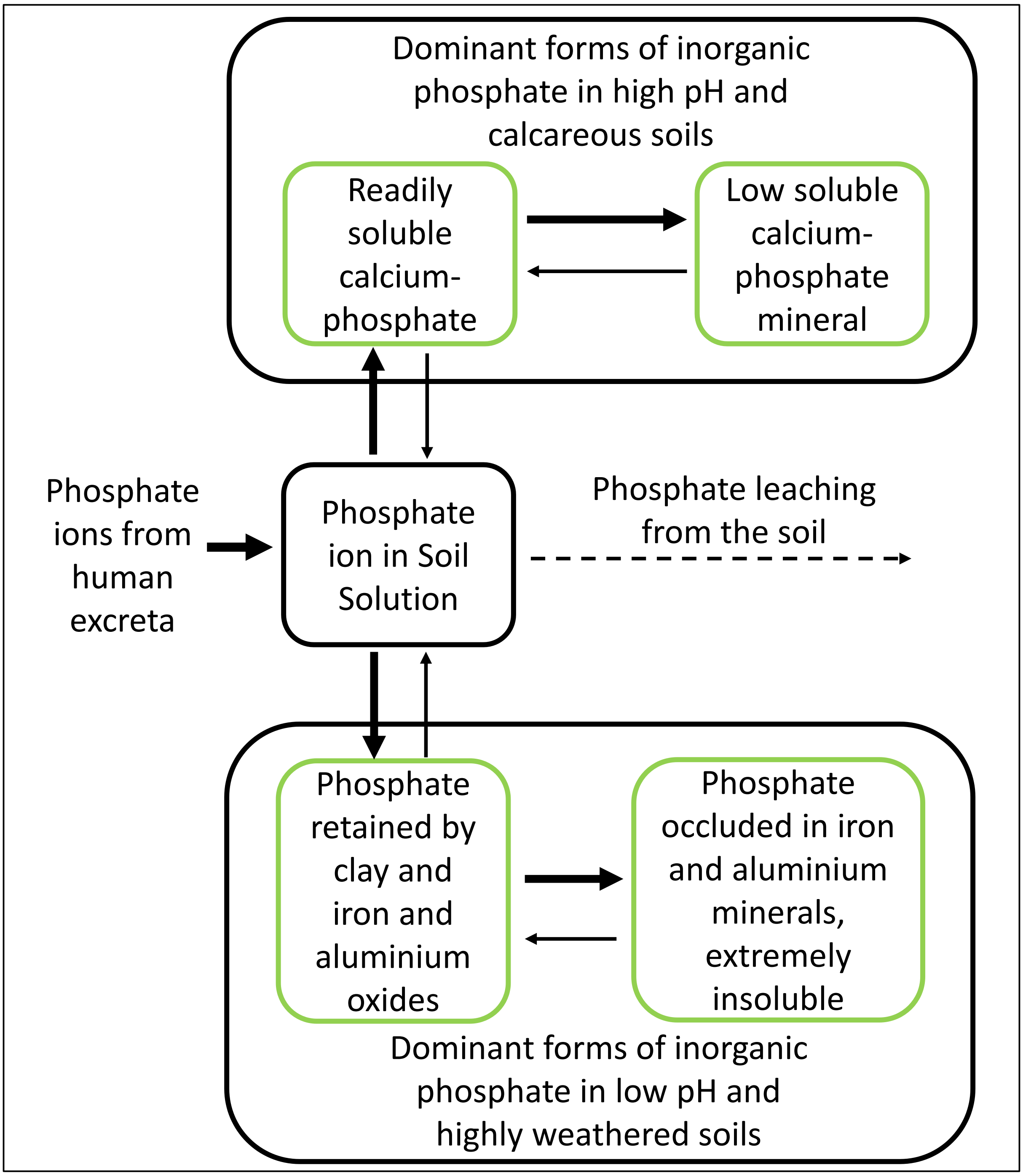

Figure 3.2 The different pools and transformations of inorganic phosphate in the soil (adapted from Brady and Weil, 2000)

From the literature, phosphate ions leached from an on-site sanitation system, are rapidly adsorbed and fixed within the soil adjacent to the leach pit. Thus phosphate leachate from an on-site sanitation system, is unlikely to travel far from the leach pit, and may not even reach the groundwater in most cases. The type of soil (i.e. clay, loam or sand), the pH and aerobic/anaerobic conditions, largely determines the amount of soluble phosphate in a soil which is subjected to leaching and entering the groundwater. Thus the measurement of pH, ORP and phosphate in the groundwater below an on-site sanitation system, is essential to this study, in order to gain a holistic view on the phosphorus process occurring below the soil surface.

3.3. Pathogens

Human excreta contains four classes of microbial contaminants *viz*. helminths, protozoa, bacteria and viruses. There are several means of transmittance for these pathogens, such as contaminated food, physical contact to hands, or insects (Franceys *et* al., 1992; Lewis *et al*., 1982). However the movement *via* the subsurface will be the focus in this section. The extent to which the pathogens move is largely determined by the physical size of the pathogen, and other relevant chemical, physical and biological processes occurring in the soil (Fourie and Van Ryneveld, 1995; Lewis *et al*., 1982).

The relatively large helminths and protozoa are larger in size when compared to silt particles (i.e. >2 μm) and are usually filtered out effectively by the soil adjacent to the leach pit, except in coarse soils or fissured settings (Figure 3.3) (Fourie and Van Ryneveld, 1995; Franceys *et* al., 1992; Lewis *et al*., 1982). The smaller sized bacteria and viruses are affected by other processes such as adsorption onto soil particles and natural die-off, which play a significant role in the attenuation of these pathogens in a soil (Carodona, 1998; Fourie and Van Ryneveld, 1995). The adsorption of viruses onto clay particles is due to electrostatic double layer interaction and van der Waal forces (Fourie and Van Ryneveld, 1995). Sobsey *et al.* (1980) report a 99.00% reduction of viruses in clayey soil, whereas sandy and organic soils were less effective. Whilst viruses may have a greater potential of mobility in a soil, they generally have a low survival time and cannot reproduce outside of a host, unlike bacteria (Fourie and Van Ryneveld, 1995). Consequently, it is often bacteria that are responsible for many of the waterborne illnesses reported globally.

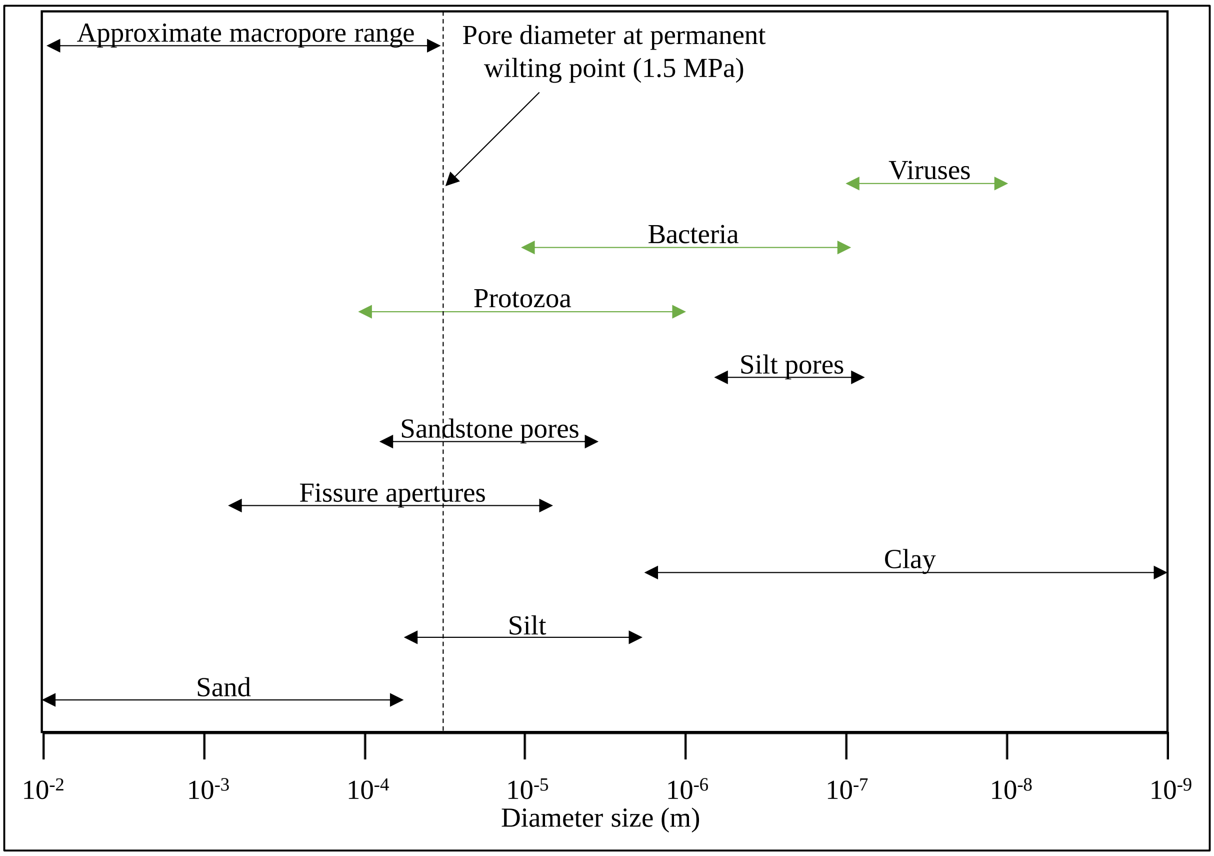

Figure 3.3 The approximate sizes of protozoa, bacteria and viruses from human excreta relative to sand, silt and clay particle sizes and fissure apertures, sandstone and silt pore sizes (after Buchan and Flury, 2004 and Taylor *et al*., 2004)

Crane and Moore (1984) describe filtration, adsorption onto clay and organic colloids and die-off as the three primary processes responsible for the removal of bacteria from a liquid effluent in the soil. The physical filtration of bacteria comprise three processes acting simultaneously or independently (i) retention by the soil matrix, (ii) sedimentation onto soil pores and (iii) "bridging" or "clogging" where previously filtered bacteria build up, and effectively reduce the soil pore diameter which improves the filtering action (Crane and Moore, 1984).

The clogging effect has been recognised in several studies *viz*. (Caldwell and Parr, 1937; Krone *et al*., 1958; Kropf *et al*., 1974; Lewis *et al*., 1982), and is known to change in a soil depending on the nutrient availability, moisture content and temperature conditions (Kropf *et al*., 1974). Caldwell and Parr (1937) reported the detection of faecal coliforms up to 10.00 m from a pit latrine in sandy clay soils. Three months after the installation of the pit latrine, a scum bio mat developed around the soil particles near the sanitation system, and after seven months the bacteria spread had retreated back to the latrine. In a similar study, Brown *et al*. (1979)

investigated the vertical movement of faecal coliforms from a septic tank line in a sandy clay soil, over a two year period. Initially 0.10 m below the line, the faecal coliform concentration was 30.00 coliforms/g soil. Seven months later this increased to 35 000.00 coliforms/g soil, however after one year the count was < 2 coliforms/g soil (Brown *et al*. 1979).

Several studies have reported a significant reduction of bacteria within the first few centimetres of the soil surrounding a leach pit, due to the filtration and adsorption processes. Crane and Moore (1984) remark that 60.00 – 98.00% of bacteria in an effluent applied to a soil are adsorbed onto the soil particles > 1.00 µm in diameter. Gerba *et al*. (1975) report a 92.00 – 97.00% removal of bacteria in an effluent within the first 0.01 m of the soil and the almost complete removal within the first 0.05 m of soil. Similarly, Butler *et al*. (1954) report the formation of a "limiting zone" in a fine sandy loam soil, from 0.10 – 0.50 m. In the study, the initial coliforms count of 1.10×10^8 MPN/100 ml was reduced to 230.00 MPN/100 ml after passing through 0.60 m of soil (Butler *et al*., 1954). Furthermore, clayey soils have a greater reduction of bacterial effluent leaching through a soil compared to sandy or gravel soils (Crane and Moore, 1984; Brown *et al*., 1979). Experiments demonstrate that leachate containing *Escherichia coli* is affected by the soil type, as depicted in Figure 3.4.

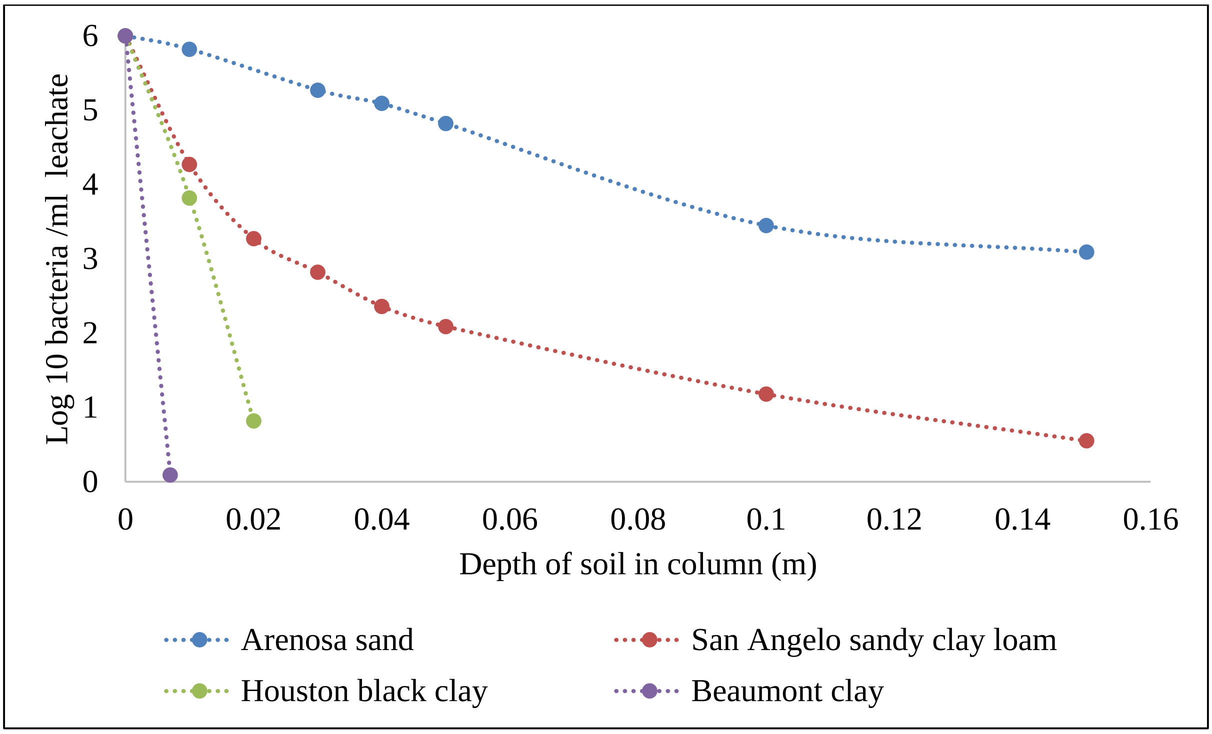

Figure 3.4 *Escherichia coli* count reduction as a function of depth for different soil textures (after Crane and Moore, 1984)

The die-off of bacteria plays a significant role in the residence time of the pathogen in the soil. There are several factors which influence the survival time of bacteria in a soil *viz.* nutrient availability, temperature, moisture and pH being the primary factors. Crane and Moore (1984) describe the effect of these variables in detail, but is beyond the scope of this study. Generally, moderate temperatures, with increasing soil moisture content and nutrient availability and neutral pH conditions favour the survival of bacteria (Carodona, 1998; Crane and Moore, 1984).

Ideally the best conditions for minimising groundwater contamination from on-site sanitation, is to maximise the residence time in the unsaturated zone. This increases the duration of the various natural attenuation processes to act upon the contaminants of concern. However in the event of rainfall, contaminants in the vadose zone may experience saturated flow conditions, resulting in a greater spread and concentration of contaminants in the groundwater.

3.4. Rainfall

Several on-site sanitation studies have investigated the relationship between rainfall and the contamination of nearby water resources *viz*. Ahmed *et al*. (2002); Barrell and Rowland (1979); Godfrey *et al*. (2005) and Howard *et al*. (2002). The impact that rainfall may have on mobilizing on-site sanitation contaminants and the subsequent potential contamination of water resources, is not always consistent. On the one hand, rainfall is seen to promote the spread of contaminants towards the groundwater, resulting in a higher concentration of contaminants in the water resource (Ahmed *et al*., 2002; Bordalo and Savva-Bordalo, 2007; Dillion, 1997; Reneau *et al*., 1989, Howard *et al*., 2002). Fourie and Van Ryneveld (1995) remark that nitrates may accumulate in a soil during a dry period and be flushed out following a significant rainfall event. In terms of pathogens, significant rainfall events may also lead to desorption and further mobilization of bacteria and viruses in the soil (Reneau *et al*., 1989; Goldshmid *et al*., 1973; Crane and Moore, 1984).

Ahmed *et al*. (2002) studied the contamination of groundwater in Bangladesh from on-site sanitation at 2 sites *viz.* Dattapara & Keraniganj. Table 3.1 provides the results for the wet and dry months at both sites, describing the highest faecal coliform counts in the sampling wells during high rainfall months compared to the drier months. In this study the rainfall promoted desorption and mobilization of faecal coliform in the groundwater, which resulted in the highest values during the wet months.

Table 3.1 Faecal coliform concentrations in sampling wells for a wet and dry month (from Ahmed *et al*., 2002)

	Rainfall	Faecal coliform at Dattapara	Faecal coliform at Keraniganj
Wet months	May, 236 mm	1000.00 FC/100ml	6000.00 FC /100ml
	June, 423 mm	1000.00 FC /100ml	2300.00 FC /100ml
Dry months	January, 0 mm	3.00 FC /100ml	18.00 FC /100ml
	April, 7 mm	29.00 FC /100ml	310.00 FC /100ml

In a similar study, at 2 sites in India *viz*. Karod and Kaichi Cola, Pujari *et al*. (2007) observed nitrate and faecal coliform contamination of the groundwater. There were higher nitrate and faecal coliform values observed during the wet monsoon period compared to the drier summer period (Table 3.2). In this study the rainfall flushed out the nitrate and encouraged desorption and mobilization of the faecal coliforms in the groundwater.

Table 3.2 Nitrate and faecal coliforms concentrations in summer and monsoon periods (from Pujari *et al*., 2007. Note: Coliform Forming Unit (CFU) is not the same as faecal coliform counts (FC))

		Karod	Kaichi Cola
Wet monsoon	Nitrate (as Nitrate)	46.00 mg/l	141.00 mg/l
	Faecal coliforms	130.00 CFU/100ml	360.00 CFU/100ml
Drier summer	Nitrate (as Nitrate)	10.00 mg/l	28.00 mg/l
	Faecal coliforms	0.00 CFU/100ml	44.00 CFU/100ml

Barrell and Rowland (1979) studied the faecal coliform concentration at 6 village wells in Gambia, before, during and after the rainy season. In the study, the faecal coliform counts remained around 20 000.00 FC/100 ml prior to the rainy season. However, during the onset of the rainy season, the concentration in the wells remained around 500 000.00 FC/100 ml or more. Towards the end of the rainy season, the faecal concentrations decreased slowly and irregularly. In this study the rainfall encouraged desorption and mobilization of the faecal coliforms in the groundwater.

On the other hand, there are incidences where higher levels of on-site sanitation contaminants have been measured during the dry season as opposed to the wet. In these cases, rainfall is assumed to have a dilution effect on the contaminants in the groundwater, resulting in a lower concentration (Godfrey *et al*., 2005; Lewis *et al*., 1982; Lu *et al*., 2008; Wright, 1986). Nsubuga *et al*. (2004) studied the movement of on-site sanitation contaminants in Uganda at 2 sites *viz*.

Kwaempe and Makindye, during the wet and dry season. There were higher nitrate and faecal coliform values during dry season compared to the wet season, except in one case (Table 3.3). In this study the uncontaminated rainfall during the wet season had a diluting effect on the contaminated water resource.

Table 3.3 Nitrate and faecal coliforms concentration in the wet and dry seasons (from Nsubuga *et al*., 2004)

		Kawempe	**Makindye**
Wet season	Nitrate (NO_3–N)	11.10 mg/l	21.00 mg/l
	Faecal coliforms	229.00 FC/100ml	645.00 FC/100ml
Dry season	Nitrate (NO_3–N)	31.10 mg/l	50.00 mg/l
	Faecal coliforms	303.00 FC/100ml	495.00 FC/100ml

Dzwairo *et al*. (2006) studied the movement of on-site sanitation contaminants in shallow wells in the wet and dry season at Kamangira village in Zimbabwe. The nitrate values remained relatively static throughout the study period, but there were higher faecal coliform values during the dry months (Table 3.4). While there was no mention of rainfall having a diluting effect in this study, the results suggest that there may have been.

Table 3.4 Nitrate and faecal coliforms concentration in the wet and dry months (from Dzwairo *et al*., 2006).

		Shallow well 1	**Shallow well 3**
Wet month (7 March)	Nitrate (NO_3–N)	3.00 mg/l	3.80 mg/l
	Faecal coliforms	33.00 CFU/100ml	32.00 CFU/ 100ml
Dry month (4 April)	Nitrate (NO_3–N)	-	3.50 mg/100ml
	Faecal coliforms	-	820.00 CFU/100ml
Dry month (5 May)	Nitrate (NO_3–N)	0.70 mg/l	-
	Faecal coliforms	488.00 CFU/100ml	-

The impact of rainfall on the contamination of groundwater from on-site sanitation remains undecided. Whether or not rainfall causes an increase or decrease in the contaminants concentration in the groundwater, is dependent upon site specific characteristics and whether there is connectivity between the on-site sanitation system and rain induced flows that reach the groundwater. Further study of the contaminants during the rainfall season in areas where a semi-pervious layer are present in the vadose zone, may reveal deeper insight on the effect rainfall has on on-site sanitation contaminants in the groundwater. In the presence of a semi-pervious layer in the vadose zone, the infiltrating water from the rainfall may accumulate above the impeding layer and create temporary zones of saturation. In these areas, processes such as denitrification, dilution and desorption may occur, as well as an increases in flow velocities resulting in a greater spread of contaminants.

3.5. Near Surface Water Movement below On-site Sanitation System

The movement of pollutants will not exceed the rate of movement of the contaminated water in the subsurface (Fourie and Van Ryneveld, 1995). Typically the flux of water in the unsaturated zone is slower than in the saturated zone (Brady and Weil, 2008; Jury and Horton, 2004; Looney and Falta, 2000). This is essential to maximise the residence time of on-site sanitation contaminants in the vadose zone, allowing more time for the natural attenuation process to act upon the contaminants before they reach a nearby stream or groundwater resource (ARGOSS, 2001; Carodona, 1998; Franceys *et al*., 1992; Fourie and Van Ryneveld 1995; Lewis *et al*., 1982).

For a typical pit latrine installed above the groundwater, Harvey *et al*. (2002) describes the pollution pathway from the leach pit in a homogenous soil, primarily in the vertical direction towards the ground water, with minimal lateral movement (Figure 3.5). In this example, the leach pit is resting in 2.00 m or more of unsaturated sand or loam soil above the water table. The leachate from the leach pit spends a sufficient amount of time in the unsaturated zone to prevent the contamination of the underlying groundwater (Harvey *et al*., 2002).

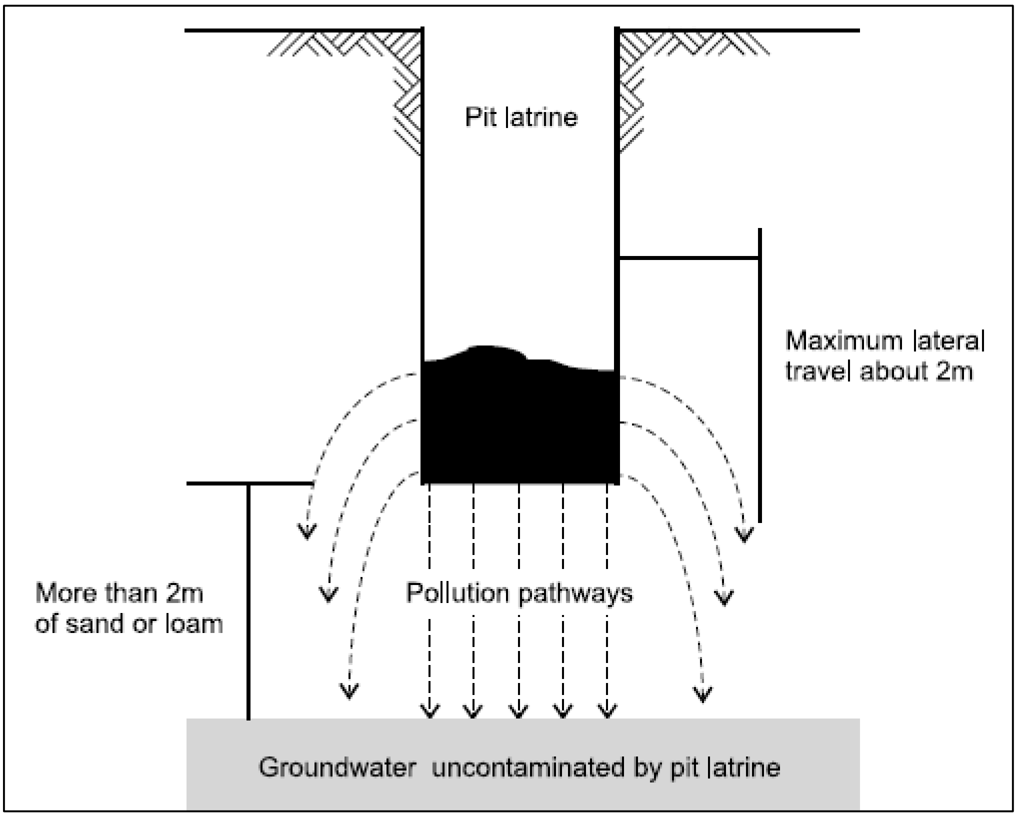

Figure 3.5 Pit latrine contaminant movement in the unsaturated zone (Harvey *et al*, 2002)

While the water movement in the vadose zone is regarded as slower compared with that in groundwater, there are unique situations where this may not hold true. The existence of a semi-pervious layer in the vadose zone will impede the vertical infiltration of water, and create a zone of saturation above this layer. Furthermore the presence of macropore-like structures such as clay shrinkage cracks, worm holes, animal burrows, decaying root channels and fractures in bedrock may lead to preferential flow conditions (Abu-ashour *et al.*, 1994; Brady and Weil, 2008; Miyazaki, 2006). Along these flow paths, the water bypasses the bulk of the porous media and travels faster than the surrounding unsaturated flow (Brady and Weil, 2008; Miyazaki, 2006). Lal and Shukla (2004) remark that 80.00% of the total water percolating through a soil profile can be conducted *via* preferential flow pathways. This may have a significant impact on the concentration and spread of on-site sanitation contaminants.

Several studies have shown that bacteria may migrate at a fast rate in the subsurface *via* preferential flow paths. Skilton and Wheeler (1988) studied the movement of bacteriophages in groundwater, where the bacteriophages were injected in to the aquifer exhibiting preferential flow characteristics. In the study, water samples were taken from boreholes located 366.00 m and 122.00 m away from the injection point, and were analysed. The results revealed the fastest migration of the bacteriophages was 2419.20 m/day (Skilton and Wheeler, 1988). Champ and Schroeter (1988) reported *Escherichia coli* travelling through a fractured granite aquifer exhibiting preferential flow characteristics. In the study *Escherichia coli* migrated at a velocity of 90.00 m/day over 12.70 m (Champ and Schroeter, 1988). Potentially, the contaminants from an on-site sanitation system which move in preferential flow paths, may be transported rapidly to the groundwater (ARGOSS, 2002; Buchan and Flury, 2004; Howard *et al.,* 2002; Pujari *et al*., 2012; Pujari *et al*., 2007).

Abay (2010) remarked on the enhanced percolation of effluent down a soil profile up to 3.00 m, due to large surface cracks from cyclic shrinking and swelling of clays. Howard *et al*. (2002) studied the impact of on-site sanitation contaminants in the groundwater at Uganda. The study concluded that there was rapid groundwater contamination of nitrates and faecal coliforms after rainfall *via* preferential flow pathways in a shallow aquifer of a highly weathered, poorly sorted muddy sand material with root channels (Howard *et al*., 2002). Pujari *et al.* (2012) studied the movement of on-site sanitation contaminants under two different geological settings. The first setting *viz*. Ahilya Nagar, consisted of a shallow vadose zone of 4.00 m underlain by fractured and vesicular basalt lava flow (i.e. preferential flow paths), with the water table varying between 5.00 – 20.00 m. The second setting *viz*. Palpara, comprised a 250.00 m thick alluvium deposit over basaltic geology, consisting of sandy aquifers in the first 6.00 m and between 90.00 – 150.00 m (were the water is drawn from). Between these two sandy aquifers, was a series of semi-permeable clay lenses. The shallow vadose zone at Ahilya Nagar exhibited high nitrate and faecal coliform values, reaching 75.00 mg/l and 1600.00 CFU/100ml, respectively, at 150.00 m away from the nearest pit latrine (Pujari *et al*., 2012). In comparison, the nitrate and faecal coliform values did not exceed 0.50 mg/l and 2.00 CFU/100ml respectively, within 150.00 m away from the nearest pit latrine at the Palpara site (Pujari *et al*., 2012). Rapid lateral movement of the contaminants within the first few meters at the Ahilya Nagar site occurred *via* the preferential flows in the basalt, which accounted for the higher values at the site (Pujari *et al*., 2012).

In addition to preferential flows, the presence of semi-pervious layers in the vadose zone, such as saturated clay lenses and rock strata, impede the vertical movement of infiltrating water and may lead to temporary zones of saturation along this layer (Figure 3.6) (Brady and Weil, 2008; Jury and Horton, 2004). In a layered soil, the leaching of soil materials accumulates lower down in the soil profile, resulting in the formation of clay lenses. Typically this will result in a higher hydraulic conductivity in the lateral direction (above the clay lens) compared to the vertical direction (Zaslavsky and Rogowski, 1969).

In the context of on-site sanitation, the contaminants leaching from these systems which reach a semi-pervious layer, will travel in a lateral direction along this layer in the direction of groundwater flow (Figure 3.6) (Caldwell, 1937; Dawes and Goonetilleke, 2003; Engel *et al*., 1974; Wells, 2001).

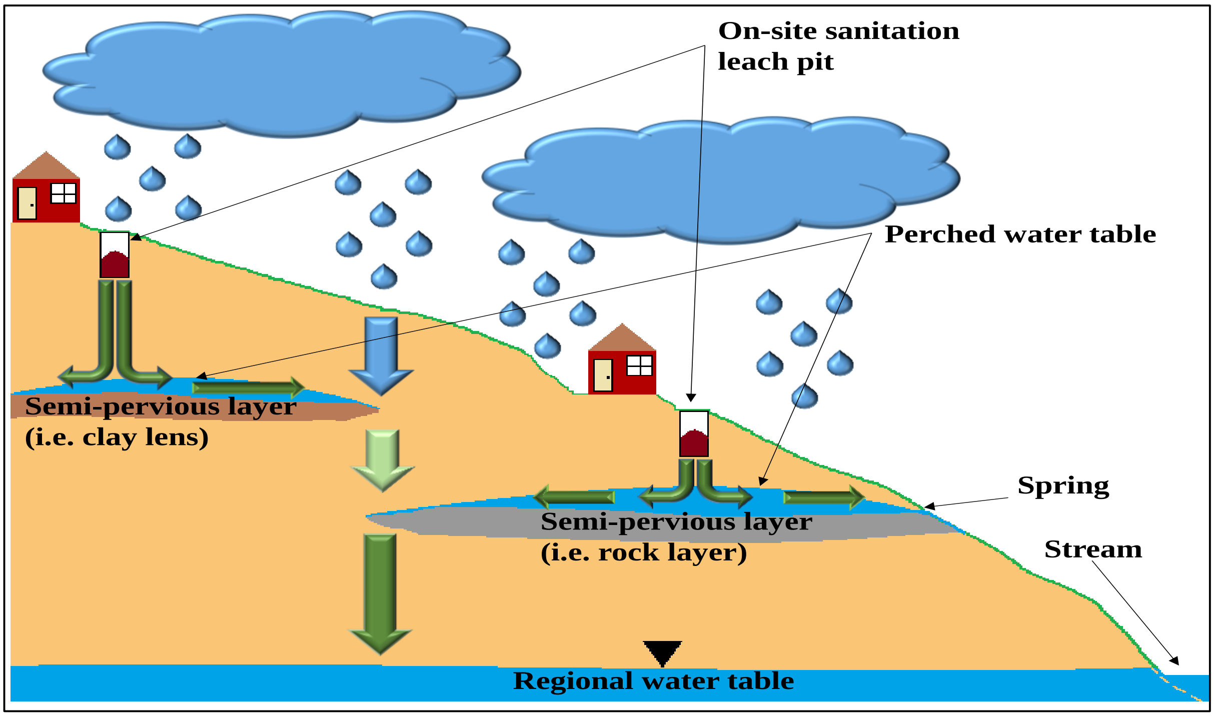

Figure 3.6 Semi-pervious layers leading to the formation of a perched water table and lateral spread of on-site sanitation contaminants

The lateral movement of on-site sanitation contaminants along semi-pervious layers has been observed in few studies. Caldwell (1937) studied the movement of on-site sanitation contaminants in a shallow, sandy, unconfined aquifer, approximately 8.00 m thick overlying a calcareous impervious layer. During the wet season, the water table was at its highest and experienced high flow velocities of 4.00 m/d in the sandy aquifer. At a horizontal distance of 24.00 m or more downslope of the leach pit, a high abundance (i.e. 100.00% of source abundance) of *B. coli* (i.e. *E. coli*) bacteria was measured. Dawes and Goonetilleke, (2003) observed substantial lateral movement from a septic tank drain field in a shallow 1.00 m thick sandy soil underlain by an impermeable clay layer, especially during periods of high rainfall.

Robertson *et al*. (1991) observed fast lateral movement of leachate from an on-site sanitation system, in a shallow sandy unconfined aquifer underlain by a silt till of low permeability. At a horizontal distance of 90.00 m downslope of the system, the nitrate values remained high, reaching 230.20 mg/l (Robertson *et al*. 1991). Clearly the near surface hillslope water movement has a direct response on the lateral spread of on-site sanitation contaminants. Thus studying the interaction between the precipitation and subsurface hillslope water processes, is important to understanding the impact that an on-site sanitation system may have on nearby water resources.

3.6. Isotopes and pH Oxidation Reduction Potential Conditions in the Natural Environment

Natural stable isotopes of water, O^{18} and H^2, have been used to determine the contribution of different water sources to nutrient transportation (Kollongei and Lorentz, 2014), and to investigate the interaction between groundwater and surface waters (Baskaran *et al*. 2009). The fractionation process between the oxygen and hydrogen isotopes creates a natural signature for different pools of water within the global hydrological cycle (Figure 3.7). This has been applied successfully in a wide range of hydrological and climatic processes, at varying scales (Kollongei and Lorentz, 2014).

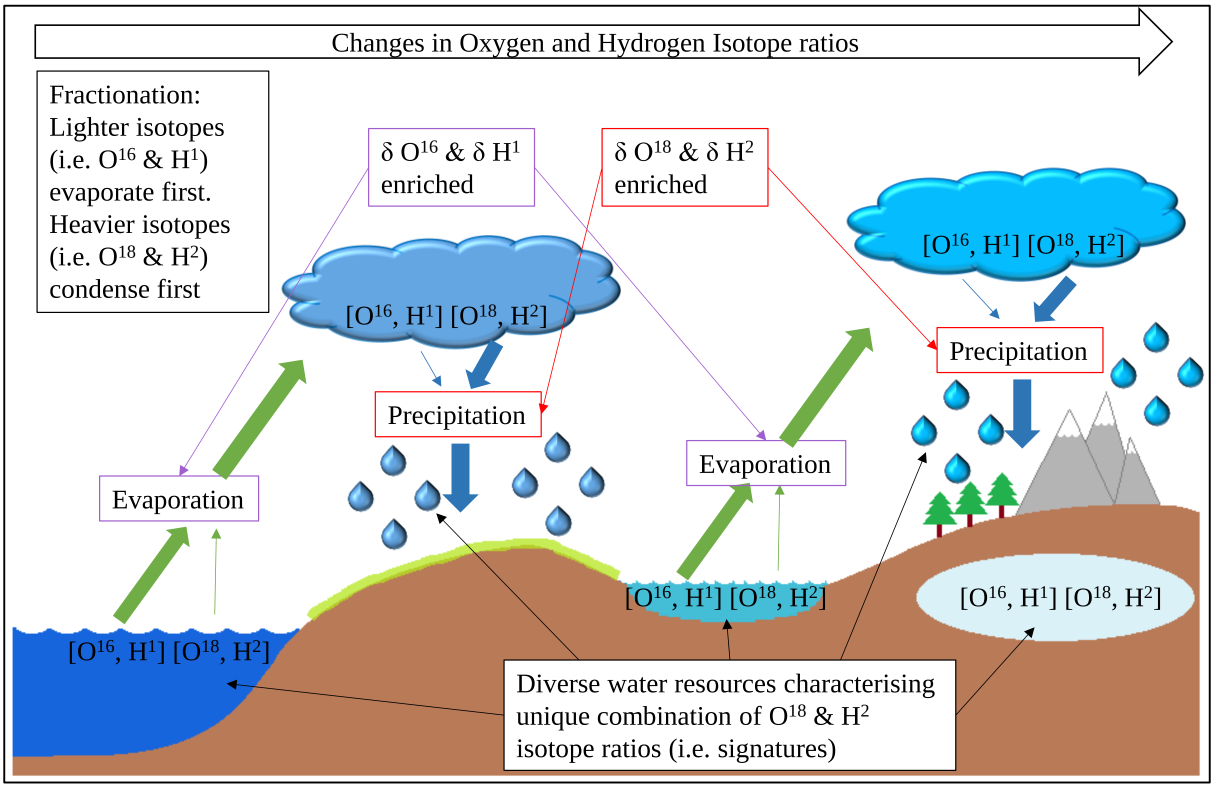

Figure 3.7 Fractionation of natural isotopes of hydrogen and oxygen in different water bodies

The natural stable isotopes of water, O^{18} and H^2 are plotted as differences (i.e. δ value) between the measured value and a standard, in this case the Vienna Standard Mean Ocean Water (VSMOW), and are expressed as a part per thousand (‰) (Lorentz *et al.*, 2008). Typically the natural O^{18} and H^2 values from the ocean follow along the global meteoric water line, yet the local rainfall in an area may exist above or below this line (Figure 3.8). Lorentz *et al.*, (2008) used the fractionation of natural isotopes, O^{18} and H^2, to discern the rainfall and hillslope components in the Weatherley catchment and their individual contributions which made up the stream discharge in the catchment (Figure 3.8). The isotope results revealed a mix contribution from the different water sources, where individual contribution varied between the wet and dry seasons.

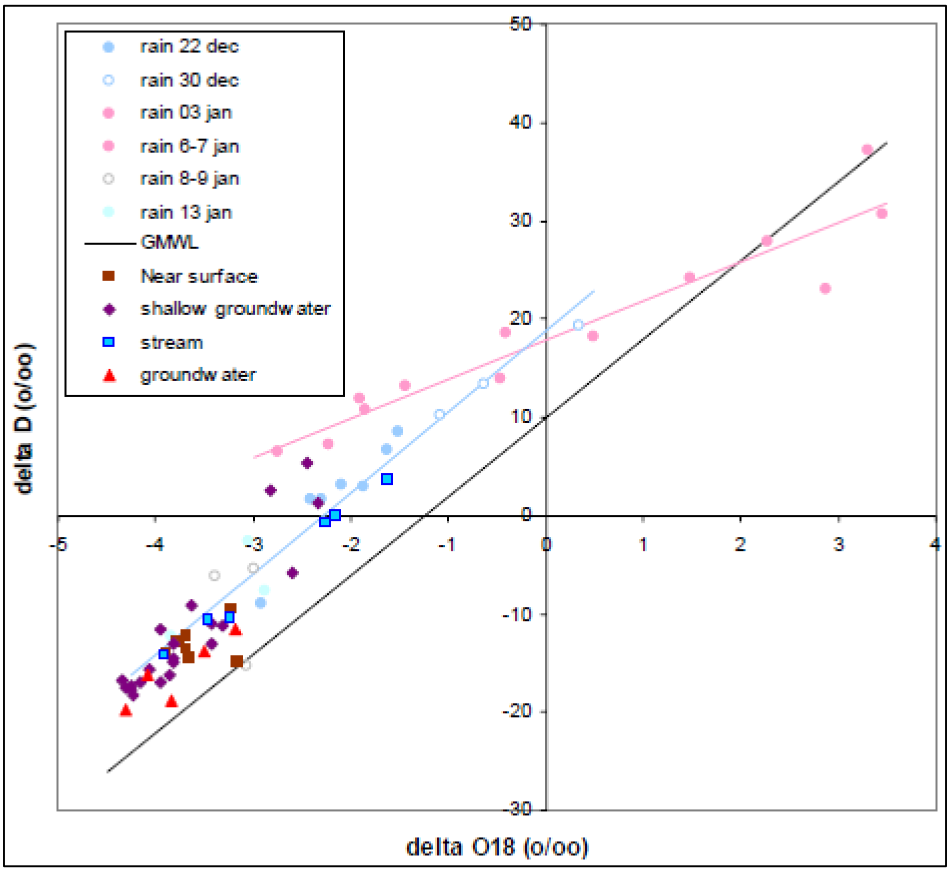

Figure 3.8 Natural isotope values for different hillslope components in the Weatherley catchment (Lorentz *et al.*, 2008)

While natural isotopes are useful for discerning the connectivity of hillslope water processes, they do not provide a measure of the anaerobic/aerobic status of the water below the soil surface. DeLaune and Reddy (2005) produced a range of redox values which described the anaerobic/aerobic status in a soil and the sequence of electron acceptors (Table 3.5). While the redox value of the water in the subsurface provides an indication of the anaerobic/aerobic status, it is not a sufficient measurement to discern the status of the electron acceptors, particularly nitrate. Many of the redox reactions in the soil are related to the pH condition (Brady and Weil, 2008), and the Eh value is dependent upon the pH. Baas-Becking *et al*. (1960) incorporated redox and pH values into a series of Eh–pH diagrams for a variety of environments, based on numerous scientific studies of redox and pH values from numerous natural settings. From these values, a generic Eh–pH diagram for soils was derived, which described the likelihood of a soil setting being water logged or normal, based on a range of redox and pH values (Figure 3.9).

From the information presented in Table 3.5 and Figure 3.9, it is possible to define whether a sample came from an aerobic or anaerobic environment, based on the redox and pH values of the water sample. This will be important for interpreting the nitrate and phosphate data from the water samples collected in this study.

Table 3.5 Anaerobic and aerobic environments in the soil (adapted from DeLaune and Reddy, 2005)

Sediment conditions	Aerobic	Anaerobic		
Redox condition	Oxidised	Moderately reduced	Reduced	Highly reduced
Electron acceptor sequence	O_2	NO_3^- Mn^{4+}	Fe^{3+} SO_4^{2-}	CO_2
Eh (mV)	≥ + 400	+ 399 to + 100	+ 99 to - 199	≤ - 200

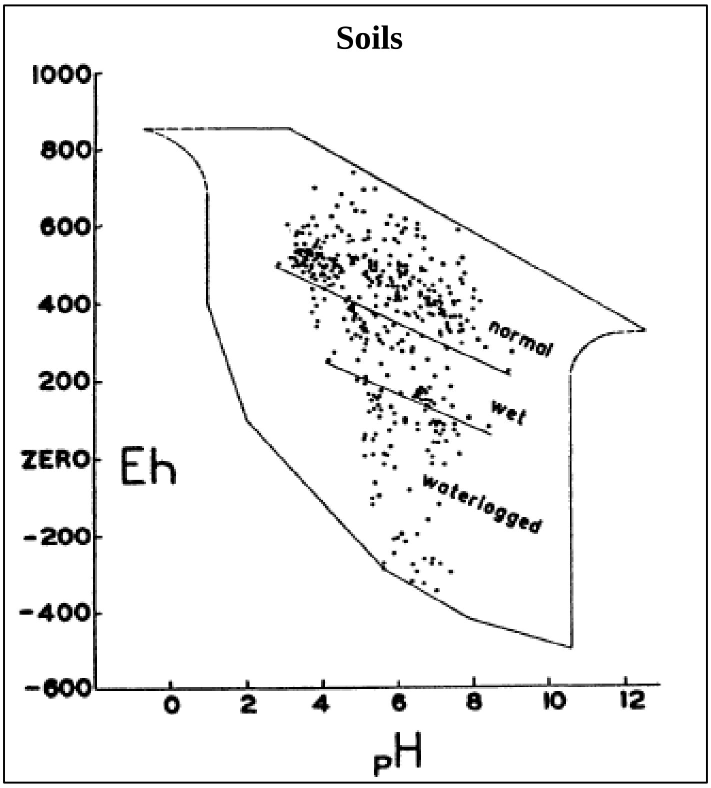

Figure 3.9 Generic Eh-pH value range for normal, wet and waterlogged soils (from Baas-Becking *et al*., 1960)

3.7. Nitrate and Faecal Coliform Case Studies

The review of on-site sanitation case studies revealed areas in current literature which are lacking. Firstly, there are relatively few number of on-site sanitation studies conducted in developing nations where the data were derived from *in-situ* field based measurements. Secondly, many of the studies are focused on septic tank systems in developed nations such as USA, and tropical climates for majority of the few studies in developing nations, with the focus centered on the impact of permanent groundwater resources. Thirdly, there are few studies which report the lateral distances and concentrations of the contaminants from on-site sanitation systems, especially in the near surface hillslope through-flow along semi-pervious layers. Lastly there are a limited number of studies which describe the subsurface conditions at the study site(s), with even fewer investigating the effect of different soil textures on the mobility and concentration of on-site sanitation contaminants.

With this being said several on-site sanitation case studies, mostly based in developing nations, have been selected and studied to produce a set of graphs depicting the concentration of nitrate and faecal coliform values at varying lateral distances from their respective on-site sanitation systems, under varying soil characteristics (i.e. Figures 3.10 and 3.11). In addition, the study site characteristics have been summarised, with comments on the major findings of the respective case studies (i.e. Table 3.6). Lastly several on-site sanitation guidelines and studies were examined to produce a range of recommended safe lateral distances for installing an on-site sanitation system away from nearby drinking water point(s) (i.e. Table 3.7). From this investigation, 15.00 m, 30.00 m and 50.00 m were identified as the most commonly accepted safe lateral spacings for on-site sanitation systems. Furthermore, if the system is located up-slope of a water source, or in a fissured rock geology, highly permeable soil or in high water table setting, the value of the original recommended safe lateral spacing of the on-site system should be increased.

The analysis of the case studies reveals several key points. Firstly many of the nitrate and faecal coliform values fall within the most common recommended safe distances of 15.00 m, 30.00 m and especially 50.00 m. This is expected considering that many of these safe lateral spacings were derived from field based studies, some of which are in this review. Furthermore, 75.00% of the nitrate values from the case studies are within the acceptable drinking water level defined by the WHO and SANS. However 86.00% of the faecal coliforms values from the case studies were above the acceptable drinking water limit, defined by the WHO and SANS. Thus, more often than not an on-site sanitation system will have a limited nitrate impact on the nearby groundwater, especially beyond the recommended safe distances. However it is almost guaranteed that the nearby groundwater will be impacted by faecal coliforms.

In the case of nitrate and faecal coliforms values that were above the acceptable drinking level, 38.00% and 41.00% of the nitrate and faecal coliform values originate from pit latrine systems, respectively, with the balance coming from septic tanks. Thus pit latrines pose a marginally smaller risk than septic tanks do to nearby groundwater resources, but they deserve as much attention as septic tanks in terms of groundwater contamination.

Furthermore there were several cases where, the nitrate and faecal coliform values were above the acceptable drinking water limit and were measured in the groundwater beyond several of the recommended safe distances. This was the case for Tandia *et al*. (1999); Pujari *et al*. (2012): Ahilya Nagar; Pujar *et al*. (2007): Karod; Adejuwon and Adeniyi (2011); Dzwario *et al*. (2006): TW1 – TW4; Dzwario *et al*. (2006): Shallow wells and Robertson *et al*. (1991). In these events, the study sites displayed characteristics of either shallow sandy soils of high transmission, a high water table or preferential flow-paths, or combination of the above. Additionally, the studies which covered the wet and dry seasons, indicated higher contaminants values in the wet season, where the infiltrating rainfall lead to the faster movement of contaminants through the unsaturated zone, which minimised the residence time and attenuation processes acting upon them before they reached the groundwater.

Another observation from the case studies, was the occurrence of higher nitrate and faecal coliform values at lateral distances further away as opposed to closer to the respective on-site sanitation system. In the case of nitrate, the subsurface environment nearest to the on-site sanitation system was anaerobic and the ammonium ion was the major form of nitrogen. However further away from the on-site sanitation system, the subsurface conditions became more aerobic where the ammonium underwent nitrification, resulting in a higher nitrate value in the groundwater at this point. As to the faecal coliforms values, the changing of a bio-mat surrounding the leach pit over time, depending upon nutrient availability, moisture content and temperature conditions, affected the mobility of the bacteria and accounted for the higher values further away from the on-site sanitation system. In some cases there were preferential flow pathways, which rapidly transported the contaminants from the on-site sanitation systems. In these cases some observation wells may not have intersected these preferential flow pathways near the on-site sanitation systems, but only at distances further away, and may have led to the higher values.

Lastly most of the case studies were conducted in sandy soils, making it difficult to perceive the effect of different soil textures on the mobility of on-site sanitation contaminants. Only three studies *viz.* Pujari *et al.* (2012), Banerjee (2011) and Adejuwon and Adeniyi (2011) show the effect that clayey soils have on the mobility and concentration of on-site sanitation contaminants. In Pujari *et al.* (2012) the nitrate and faecal coliforms values in the groundwater did not exceed 0.50 mg/l and 2.00 CFU/100ml respectively, where it was observed that the clay lenses in the subsurface significantly retarded the infiltrating leachate from the on-site sanitation system. In Banerjee (2011), several pit latrines in sandy soils were compared to a pit latrine surrounded by a 0.50 m clay envelope in a sandy soil, in the pre monsoon and monsoon periods. From the study, the sandy sites showed the greatest movement of faecal coliforms during the monsoon period where they travelled a lateral distance of seven meters (Banerjee, 2011). However at the site where the clay envelope was present, it was noted that the faecal coliforms could not penetrate through the clay barrier (Banerjee, 2011). Similarly Adejuwon and Adeniyi (2011) studied the movement of nitrate and total coliforms in the groundwater moving through sandy and clayey soils. In this study, the sandy soils exhibited higher nitrate and total coliform values in the shallow observation wells compared to the clayey soil sites. Furthermore, the clayey soil sites did not show any presence of faecal coliforms in the shallow observation wells (Adejuwon and Adeniyi, 2011). In these three cases the clay soils retarded the water movement through the soil profile, resulting in a longer residence time in the unsaturated soil which promoted the natural attenuation processes acting upon the contaminants.

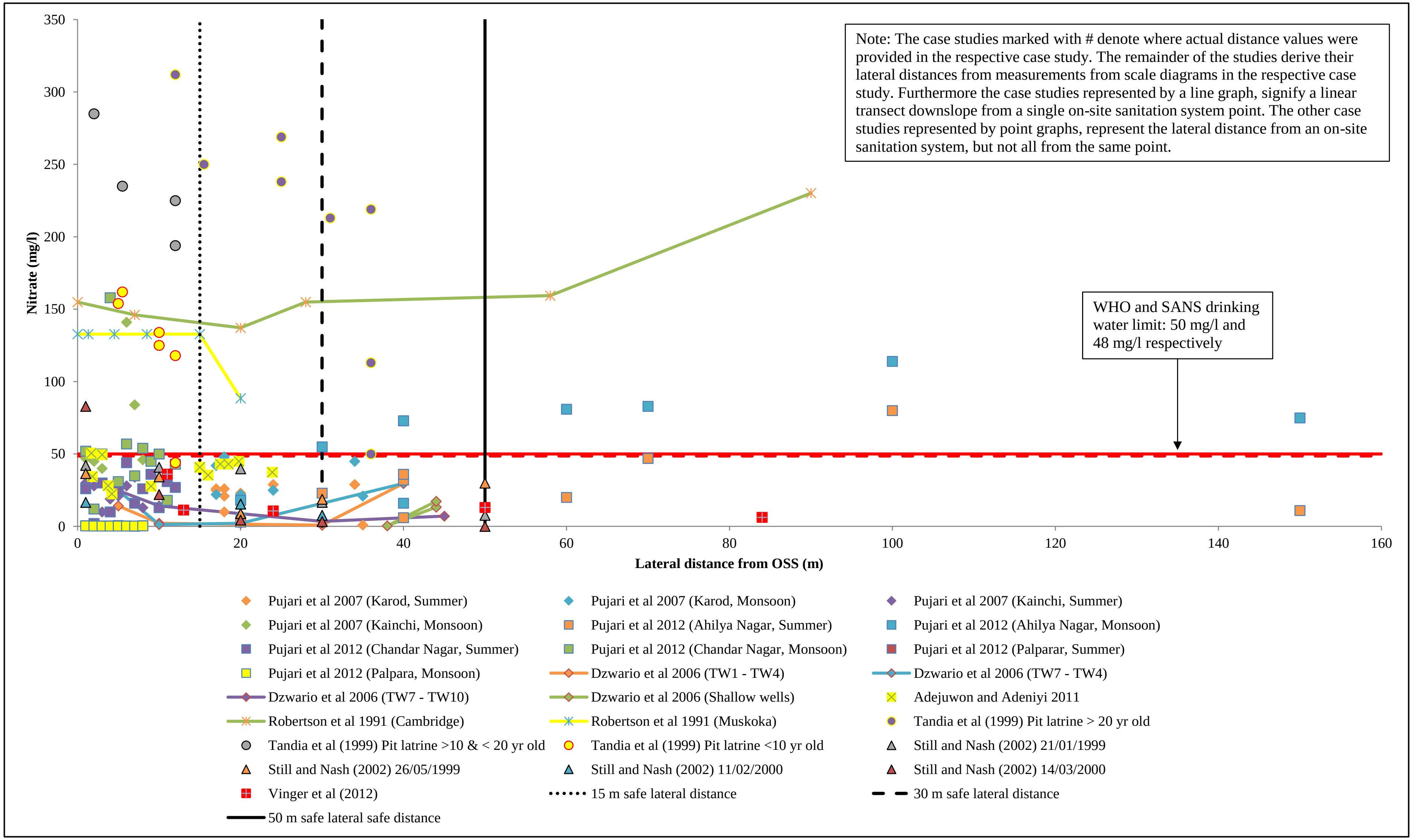

Figure 3.10 Reported lateral distances of nitrate concentration from several case studies

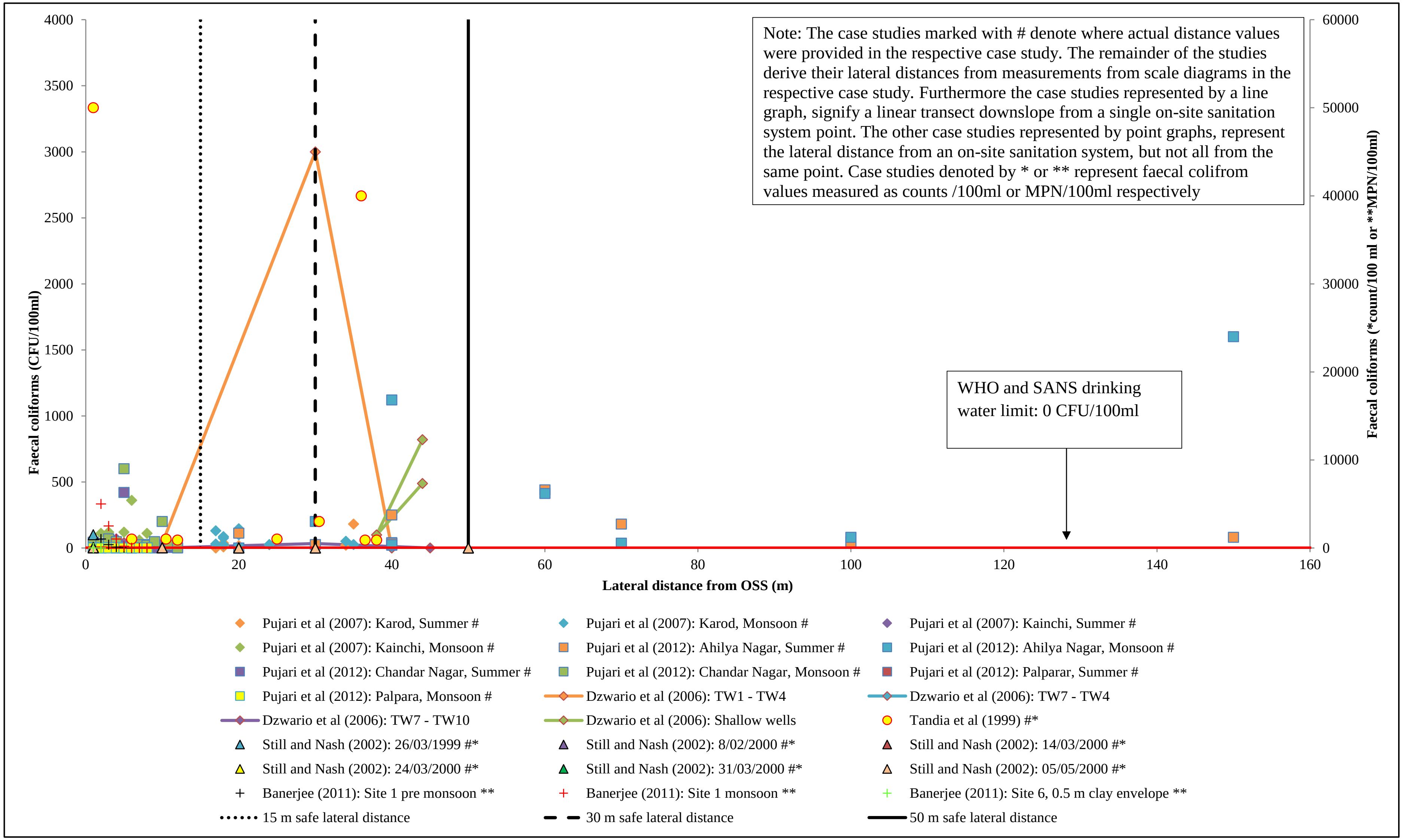

Figure 3.11 Reported lateral distances of faecal coliform concentrations from several case studies

Table 3.6 Summary of the study sites characteristics from the reported case studies

Reference	Sanitation system	Study area	Population	MAP (mm)	Soil	Geology	Water Sampling Point	Comments
Pujari *et al.* (2007)	Septic tank	Karod, Bhopal city, India	1, 454, 830	1260	Alluvium	Deccan basalts with fractures and joints underlain by sandstone and shale	10 Hand pumps dug wells	On average, groundwater contamination was higher during the wet season (monsoon) compared to summer. This was due to the greater recharge during the monsoon, which encouraged the contaminants to move faster through the unsaturated zone. Joints and fractures in the basalt were viewed to be the potential pathway for contaminants. Contaminant concentration was greater in areas of high density of on-site sanitation systems.
Pujari *et al.* (2007)	Septic tank	Kainchi, Bhopal city, India	1, 454, 830	1260		Deccan basalts with fractures and joints underlain by sandstone and shale	8 Hand pumps dug wells	
Pujari *et al*. (2012)	Septic tank	Ahilya Nagar, Indore city, India	170	1050	Black cotton soil, 2 -3 m thick	Hard basaltic lava flow, with fractures and vesicular units	9 Open wells and hand pumps	Water table varied between 5 – 10 m & 10 – 20 m for the monsoon and summer periods, respectively. On average, groundwater contamination was higher during the wet season (monsoon) compared to summer. The higher rainfall during the monsoon promoted faster movement of contaminants through the vadose zone. The fractures and vesicular units in the bedrock, served as preferential flow pathways and encouraged the rapid movement of contaminants. Furthermore, anaerobic conditions occurred in summer with the lowering of the water table, resulting in the reduction of nitrate into nitrogen.
Pujari *et al*. (2012)	Septic tank	Chandan Nagar, Indore city, India	300	1050		Hard basaltic lava flow, with fractures and vesicular units	6 Open wells and hand pumps	

Continuation of table 3.5

Pujari *et al*. (2012)	Septic tank	Mathpara, Kolkata city, India	-	1580	250 m alluvium deposit, consisting of shallow 6m sandy aquifers, followed by a 76 m clay layer, overlying a confined sandy aquifer at 90 m. where water is abstracted from	-	6 Open wells and hand pumps	Water samples were extracted from the confined aquifer at 90 m. On average, groundwater contamination was higher during the dryer season (summer) compared to the monsoon. Significant decrease of the contaminant values occurred when passing through the clay layer, where they were retarded and absorbed.
Pujari *et al*. (2012)	Septic tank	Palpara, Kolkata city, India	-	1580		-	8 Open wells and hand pumps	
Dzwario *et al*. (2006)	3 Pit latrines	Kamangira village, Zimbabwe	100	-	Sandy, with high transmission of water	Faulted granitic rocks	14 Boreholes and 3 shallow wells (SW)	The pit latrine base for TW1-TW4 was above the water table throughout the study, ranging from 0.2 – 1.8 m. However the latrine base for TW7-TW4 & TW7-TW10, intersected the water table, ranging from 0.6 – 1.7 below the water table. Similarly the latrine base for SW3 ranged from 3.2 – 1.2 m below the water table. The water demand at SW1 & SW3 is higher than at SW2, which explained the higher nitrate and faecal coliform concentrations at SW1 & SW3. Faecal coliforms values decreased significantly after 5 m from the pit latrines. All samples were within the WHO guidelines values of 45mg/l, however all the shallow wells located at 38 m and 44 m from the nearest pit latrine, indicated faecal contamination.
Adejuwon and Adeniyi (2011)	Pit latrines	Isale-Igbehin district, Abeokuta, Nigeria	-	1156	Mostly sandy, with some sites of clayey soil	-	12 Shallow wells	High nitrate and total coliform counts were measured in the sandy soils. At approximately 20 m nitrate concentrations reach 45 mg/l and total coliforms were 2100 CFU/100ml. Higher nitrate and total coliforms values were measured in sandy soils compared to clayey soils.

Continuation of table 3.5

Robertson *et al*. (1991)	Septic tanks	Cambridge, Canada	4		Fine sand to a depth of 4 – 8 m, overlying a silt till of low permeability	-	41 Piezometers, installed to depth of 4- 6 m.	Water table depth varied around 3.5 m. There was a distinct contaminated plume in the groundwater with a low vertical dispersion of contaminants, and significant lateral movement above the silt layer of low permeability. At 90 m the nitrate concentration was 230.2 mg/l. However agricultural practices were present in the area, where background concentrations of nitrate ranged from 75 – 150 mg/l. The long residence time (>7 days) of the effluent in the unsaturated zone allowed for near complete transformation of ammonium to nitrate before entering the groundwater.
Robertson *et al*. (1991)	Septic tanks	Muskoka, Canada	2		Fine fluvial sand to depth of 10 m	Granitic bedrock	20 Piezometers installed to a depth of 3 -5 m.	Water table depth varied around 3.5 m. There was a distinct contaminated plume in the ground water with low vertical dispersion of contaminants, and significant lateral movement within the sand aquifer. At 20 m the nitrate concentration was 88 mg/l. There was a distinct decrease in the nitrate concentration beyond 20 m, where the plume intersected a river bed, rich in labile organic carbon. Within 1 m the nitrate dropped to 0.5 mg/l, due to denitrification. The long residence time (>7 days) of the effluent in the unsaturated zone allowed for near complete transformation of ammonium to nitrate before entering the groundwater.
Tandia *et al*. (1999)	Pit latrines	Yeumbeul, Dakar, Senegal	7000 houses	480	Fine to coarse sand	-	Unspecified number of existing wells	Water table depth varies between 0 – 11 m. Increases in the electrical conductivity was observed in the groundwater, following rainfall events that washed out the salts in the overlying soil. Distinct nitrate concentrations in the groundwater grew from 20 mg/l to > 200 mg/l in less than 20 years, due to development of pit latrines from human settlements in the area. Nitrate concentration in the groundwater decreased from 7000 mg/l at 1 m to 1000 mg/l at 5 m, due to the presence of reducing bacteria, carbonaceous organic substrate and diminishing oxygen values. The concentration of nitrate in the groundwater decreased with the increasing lateral distance from the pit latrine. There was no clear relationship between faecal coliform concentration and distance from pit latrine.

Continuation of table 3.5

Still and Nash (2002)	Pit latrines	Mbazwana, South Africa	-	-	Fine sand	-	Unspecified number of public and private wells	Water table depth varies between 5 – 20 m. There was a clear pattern of nitrate and faecal coliform concentrations in the groundwater decreasing with the increasing lateral distance from the pit latrine. There was little correlation between the wells with high nitrates and those indicating the presence of faecal coliforms. Fine sand appeared to be an effective filter for bacteria, and nitrate values above the acceptable drinking water level were limited to the first few meters from the pit latrine.
Vinger *et al*. (2012)	Pit latrines	North West Province, South Africa	-	-	-	-	9 Boreholes	Water table depth varied between 6 – 9 m. There was a clear pattern of nitrate concentration in the groundwater decreasing with increasing the lateral distance from the pit latrine. The nitrate pollution from the pit latrines were unlikely to impact the groundwater beyond 12 m.
Banerjee (2011)	Pour-flush latrine	Site 1, West Bengal, India	-	-	Sandy silt	-	35 Observation wells	Water table depth varied between 1.08 – 2.08 m. The greatest lateral travel of faecal coliforms was near 6 m, which occurred in sandy soils and during the monsoon period. The minimum safe distance between the pit latrine and a water source was 10 m, except in a fissured rock environment.
Banerjee (2011)	Pour-flush latrine	Site 6, West Bengal, India	-	-	Sand with 0.5 m clay envelope surrounding leach pit	-	8 Observation wells	Water table depth varied around 2.33 m. There was a clay envelope surrounding the leach pit, which completely arrested the movement of faecal coliforms. The minimum safe distance between the pit latrine and a water source was 10 m, except in a fissured rock environment.

Table 3.7 Recommended safe distances for siting an on-site sanitation system near a drinking water source

Suggested safe horizontal distance (m)	Conditions	On-site sanitation contaminants (i.e. nitrate, phosphate and pathogens)	Reference
6	For sandy soils	Chemical and microbial	Dyer and Bhaskaran (1945)
10	For sandy or clay soils, except fissured rock environments	Microbial	Banerjee (2011)
15	Provided that the water abstraction rates do not cause the water gradient to change significantly	Chemical and microbial	Franceys *et al*. (1992)
15	Provided that the water abstraction point is in an area that is higher than the latrine, and that the base of the pit has at least 2 m of unsaturated soil above the water table	Chemical and microbial	Kimani-Murage and Ngindu (2007)
15	-	Chemical and microbial	Amadi *et al*. (2013)
20	For fine sandy soil where the water table varies between 5 - 20 m below the ground level	Chemical and microbial	Still and Nash (2002)
30	-	Chemical and microbial	Dzwario *et al* 2006; Adejuwon and Adeniyi (2011)
30	The bottom of the leach pit should be at least 1.5 m above the water table	Chemical and microbial	Sphere project (2006)
30	For VIP toilets only, sited downslope of a drinking water source on slightly raised ground, on firm soil	Chemical and microbial	Bester and Austin (2000)
30	Downslope and not in coarse or fissured ground	Chemical and microbial	Harvey et al. (2002)
50	For fine to coarse sand where the water table varies between 0 - 11 m below the ground level	Chemical and microbial	Tandia et al. (1999)
50	-	Chemical and microbial	WaterAid (2011)
10 - 90	30 m distance is not recommended for highly permeable soils, with a shallow and fluctuating water table	Viruses	Dillon, 1997
15 - 50	Dependent upon the depth of the water table, soil composition and aquifer characteristics	Chemical and microbial	Xu and Braune (1995)
15 - 50	-	Chemical and microbial	Lewis et al (1982)
8	The pit latrine is in a low permeable soil and is downslope of a drinking water point	Chemical and microbial	McCarthy *et al*. (1994)
30	The pit latrine is on level ground, above the highest point of the water table or in high permeable soil, or toilet system upslope of a drinking water point	Chemical and microbial	McCarthy *et al*. (1994)
7.5	If the highest water table level is more than 5m below the bottom of pit or soak-away	Chemical and microbial	CSIR (2005); Devilliers (1987)
15	If the highest water table level is between 1- 5m below ground	Chemical and microbial	CSIR (2005); Devilliers (1987)
30	If the highest water table level is less than 1m	Chemical and microbial	CSIR (2005); Devilliers (1987)
No safe distance	Area comprises of coarse soil, fissured rock or limestone	Chemical and microbial	CSIR (2005)

The review of the literature has described some of the major process governing the mobility and concentration of the on-site sanitation contaminants. While the case studies generally support the legitimacy of the several recommended safe distances mentioned by various studies and guidelines, it does however reveal certain gaps and concerns which need attention *viz.*:

(a) Majority of the studies focus on the contamination of permanent groundwater resources, and the spread of contaminants in this zone, while overlooking the water movement in the vadose zone which is vital for minimizing groundwater contamination,

(b) Majority of the studies focus on septic tank systems where many were conducted in developed nations, while pit latrines may pose as much of a threat to the water quality, and is one of the most commonly used form of sanitation in many developing nations,

(c) Majority of the studies have been conducted in sandy textured soils, while only a few have investigated the movement through clayey soils and

(d) Several studies observe higher concentrations of contaminants in groundwater resources during the wet season, yet other studies reveal higher values in the drier season and

(e) Many of the existing on-site sanitation studies that were based in developing nations were conducted under tropical climates, while relatively few studies have been carried out under semi-arid (.i.e. non-tropical) areas.

As a result, it is the purpose of this study to investigate the lateral movement of on-site sanitation contaminants in (i) clayey soils, (ii) in the vadose zone, (iii) in the presence of a near surface semi-pervious layer, (iv) in a rural and peri-urban housing environment, (v) in a semi-arid area. Furthermore, this study was conducted before and during the wet season to describe the effect that rainfall had on the contaminants in the near surface hillslope lateral through-flow. The next section will introduce the methodology adopted in this study, and outline the approach used to answer the research question.

4. METHODOLOGY

The methodology presented in this chapter was designed to answer the research question. Here, suitable study sites were identified, where various instrumentation and equipment were installed to describe the subsurface hillslope water movement, and to collect numerous water samples. The water samples were analysed to obtain information on the distance and concentration of the contaminants in the near surface. The overall methodology is described in Figure 4.1. This chapter will be broken down into three sections *viz.* (i) Study sites, (ii) Water sample collection and (iii) Water sample analyses.

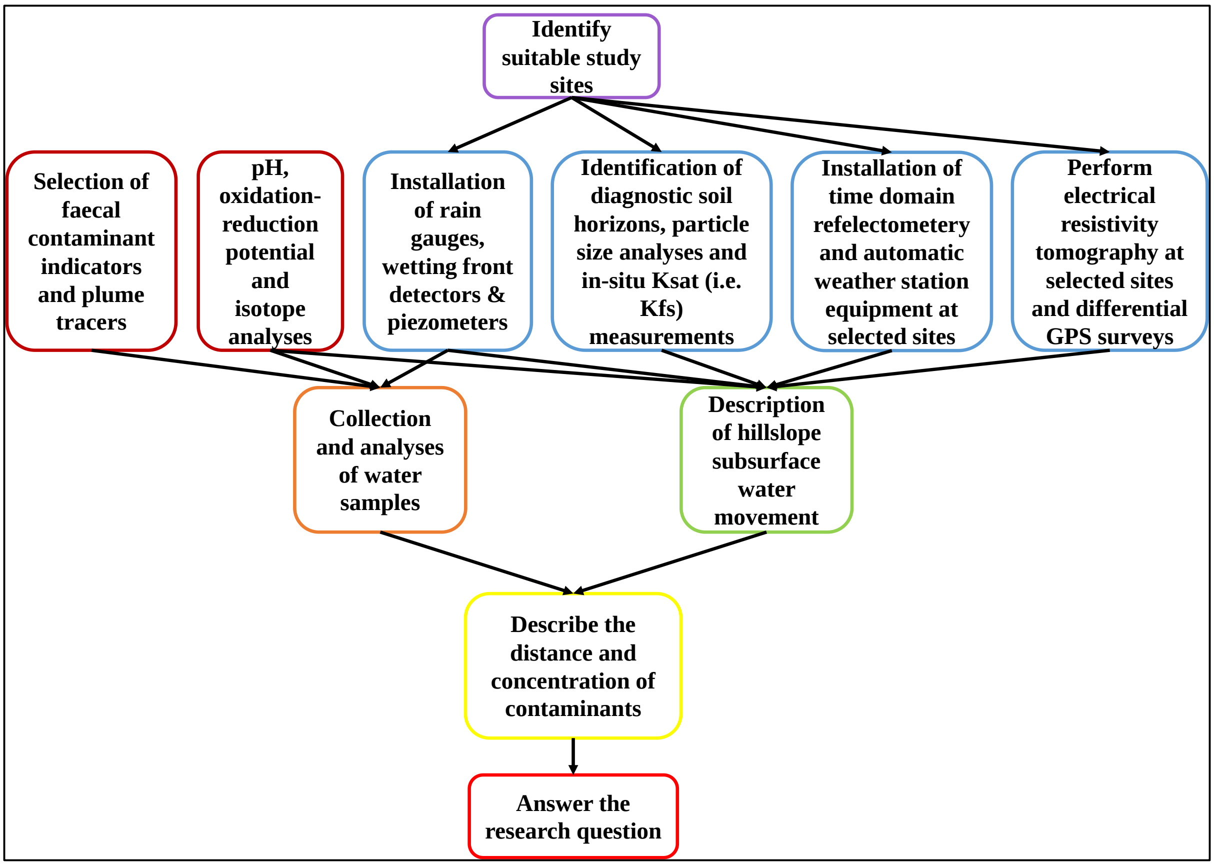

Figure 4.1 Overview of methodology

4.1. Site Characterisation

The study consisted of 5 study sites *viz*. Slangspruit, Crèche, Azalea, Taylors Halt, and Taylors Halt Control, located around the city of Pietermaritzburg in KwaZulu-Natal (Figures 4.2 and 4.9). The first 3 study sites are located in a peri-urban housing environment in Edendale on the western peripheral of the city of Pietermaritzburg. The Taylors Halt and Taylors Halt Control sites are located further west in the rural area of Taylors Halt. These sites are located in a subtropical climate, where the daily temperature ranges from 1.9 °C to 32.7 °C and the mean annual precipitation fluctuates around 1200 mm (Schulze, 1997). The start of the wet season begins in October and extends to the end of April.

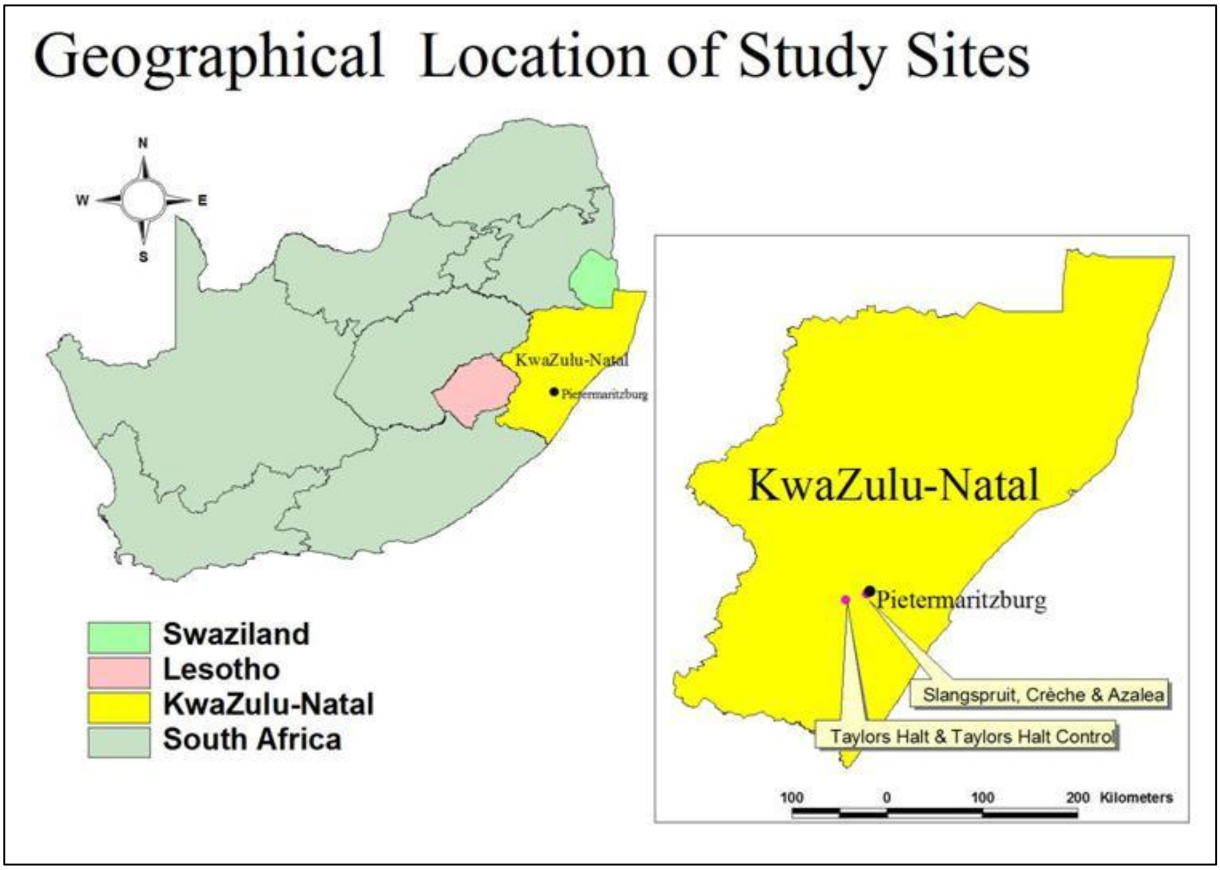

Figure 4.2 Map of study sites in relation to South Africa

The selection of the study sites were based on several criteria, as described below:

(a) In a rural or informal area where VIP latrines and Pour-flush systems are the main or only form of sanitation in the area,
(b) Minimal or no interference from other sanitation systems, including faecal waste from domestic animals,
(c) Minimal soil disturbance, with the presence of a semi-impervious layer in the vadose zone,
(d) Large enough areas of open space to accommodate transects of piezometers and
(e) Permission from the homeowner to install the necessary study equipment on his or her premises.

At the study sites, transects of piezometers, wetting front detectors and plastic rain gauges were installed, as well as several other instrumentation at selected sites. Figures 4.3 – 4.7 describe the outlay of instrumentation at each of the study sites.

The Slangspruit site was located in an informal housing setting, with a Pour-flush system that is four years old and serves a family of four (i.e. two adults, two teenagers). The depth of the leach pit extended to 1.52 m into the ground where Pietermaritzburg Formation Shale was the dominant geology for the area. Unfortunately there were several other on-site sanitation systems situated throughout in the area, as well as domestic pigs, goats, chickens and dogs that were unrestrained. Several of the piezometers closest to the on-site sanitation system under study were located within a secure fenced off property, while the remaining were open to the public. There were relatively few open areas with minimal soil disturbance. Figure 4.3 describes the instrument layout of the Slangspruit study site.

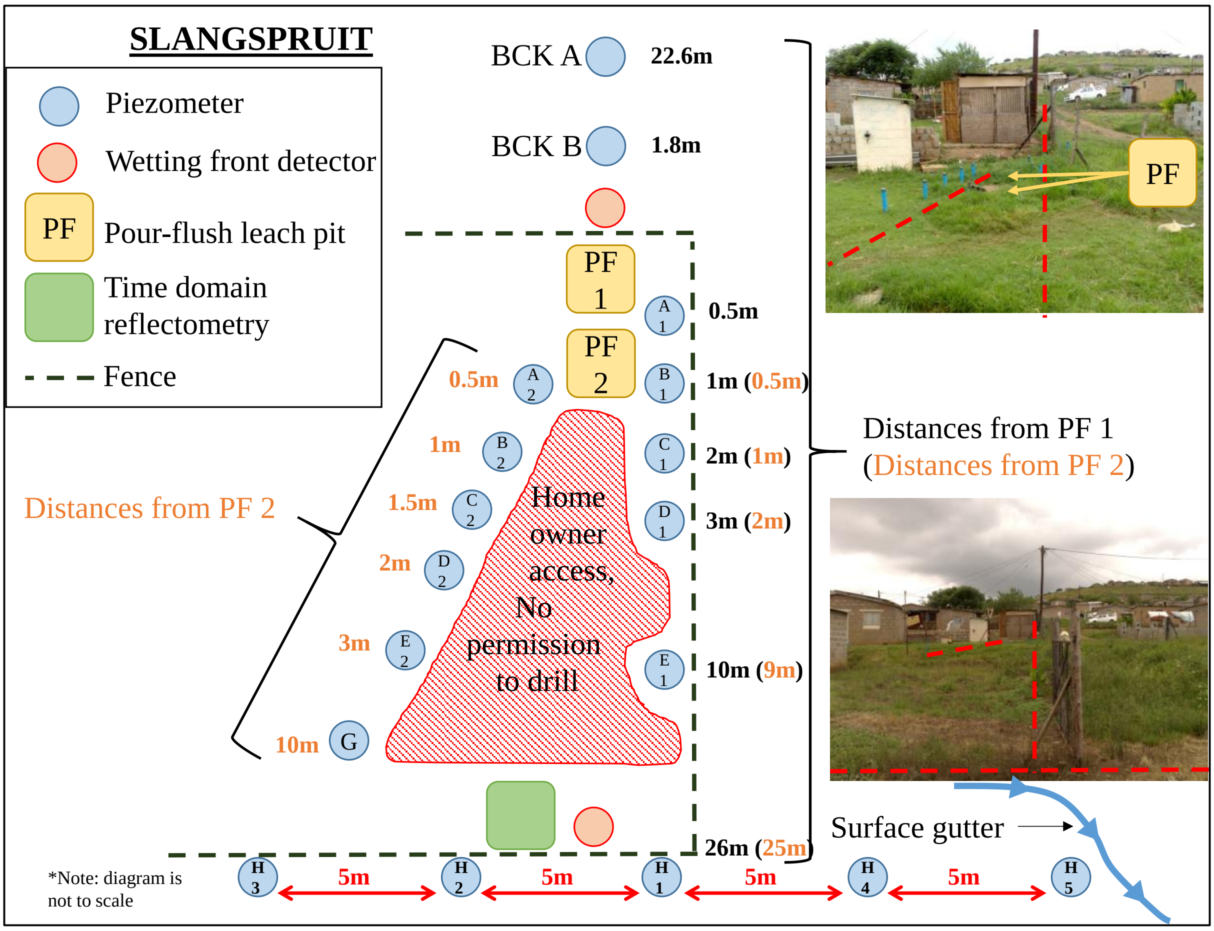

Figure 4.3 Slangspruit study site

The Crèche site was located approximately 150 m downslope of the Slangspruit site and was in the same environmental setting. A four year old pour-flush system served a crèche of approximately 60 children and several adults. The depth of the leach pit extended to 1.52 m into the ground where PMB formation shale is the dominant geology for the area. Similar to the Slangspruit site, there was a secure fence surrounding the property, which prevented the various domestic animals in the area from entering the study site, except for the background piezometers which was open to the public. Furthermore, there was substantial soil disturbance, where the soil profile was excavated, mixed and dumped, presumably to create level surfaces for houses. Figure 4.4 describes the instrument layout of the Crèche study site.

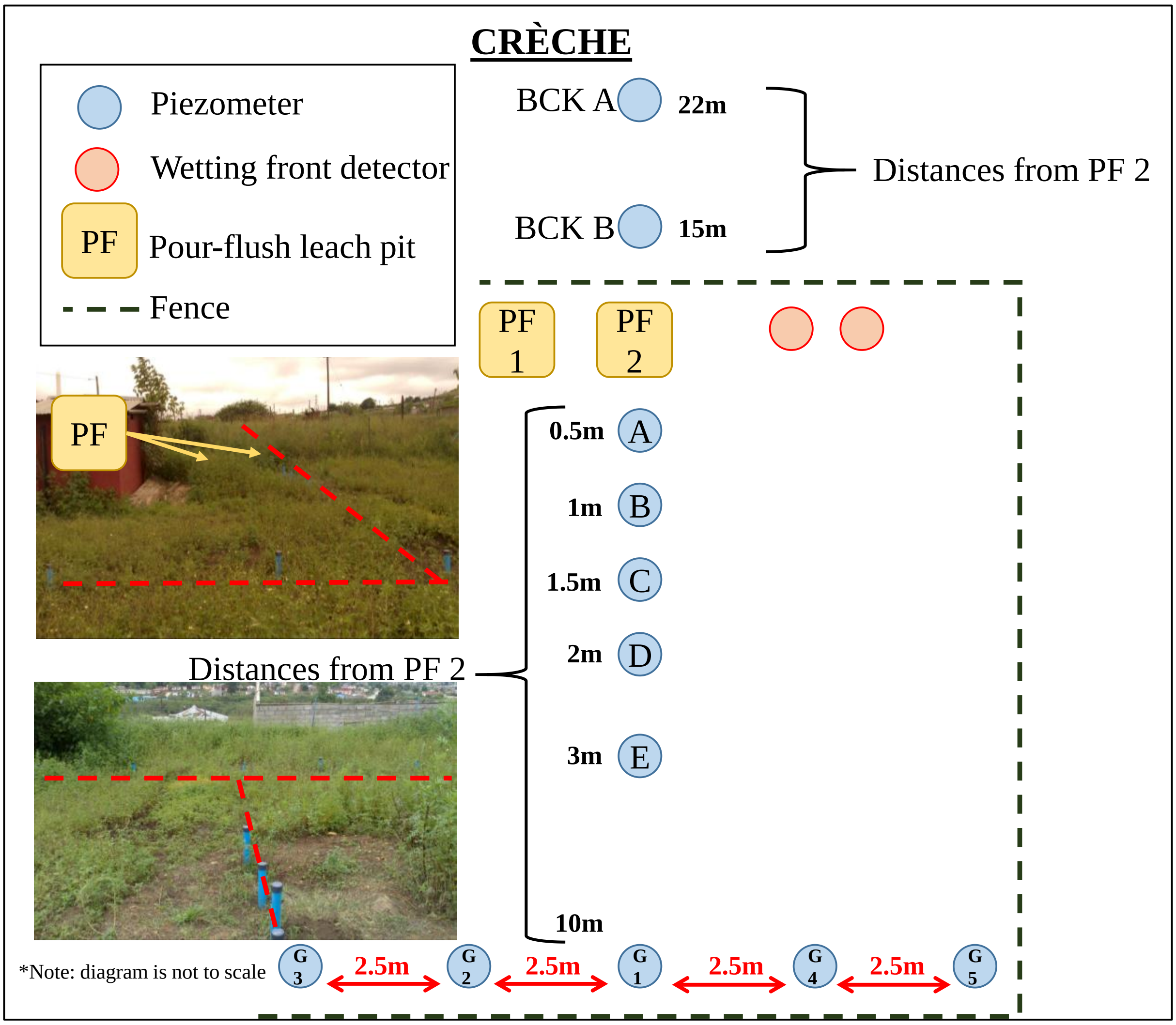

Figure 4.4 Crèche study site

The Azalea site was located approximately 8.5 km from the previous two sites, where a four year old pour-flush system served a family of three (i.e. two adults and one teenager). The depth of the leach pit extended 1.52 m into the ground where dolerite was the dominant geology for the area. The housing in the area was a mixture of informal and formal settlements, and was less densely populated than the previous sites. In addition, there was municipal sewerage in the area and a stream. Similar to the Crèche site, there was a secure fence surrounding the piezometers nearest to the leach pit, which prevented nearby cattle, dogs, goats and chickens from entering the property. Furthermore, there was clear soil disturbance, where soil had been excavated and dumped to create a level surface for building on, and where the sewage pipe was installed. Figure 4.5 describes the instrument layout of the Azalea study site.

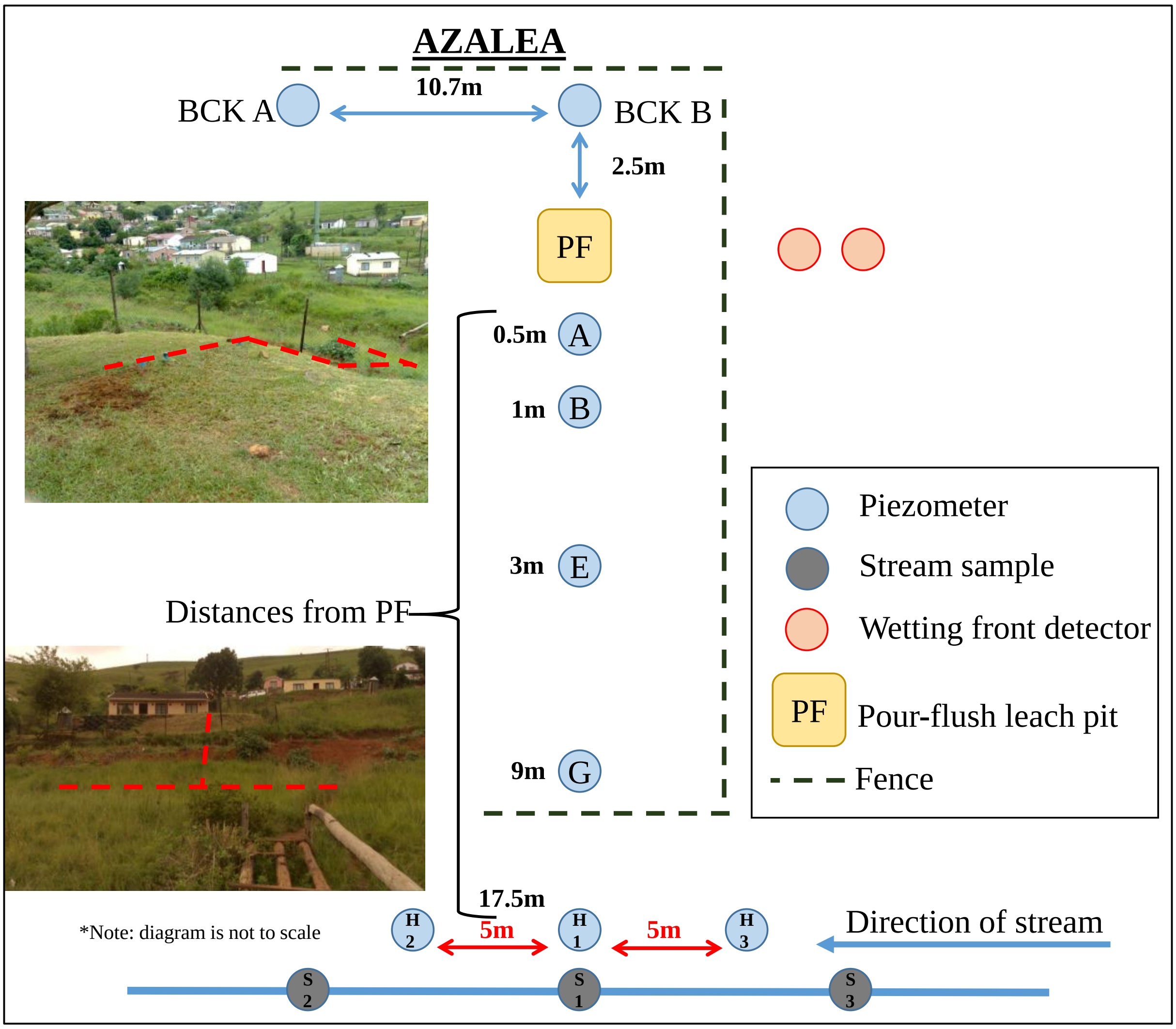

Figure 4.5 Azalea study site

The Taylors halt study site was located approximately 35 km outside of Pietermaritzburg, in the area of Taylors Halt. The area is rural and is made up of a mixture of informal and formal housing. Unlike the previous study sites, this site comprised numerous Ventilated Improved Pit latrine systems located on the side of a hill, with more open spaces of veld grass than the previous study sites. The ages of the VIP systems varied, most were around five years old, and the leach pit extended 1.75 m into the ground. Dolerite was the dominant geology for the area. Furthermore, several houses did not have fences surrounding the respective premises, and numerous cattle, dogs, goats, pigs and chickens were free to roam throughout the area. In addition, there was also a stream where the head waters reside in the study site. Similar to the Azalea site, there was evidence of soil disturbance along the hillslope where the soil was excavated and dumped to create a level surface for building houses. Figure 4.6 describes the instrument layout of the study site.

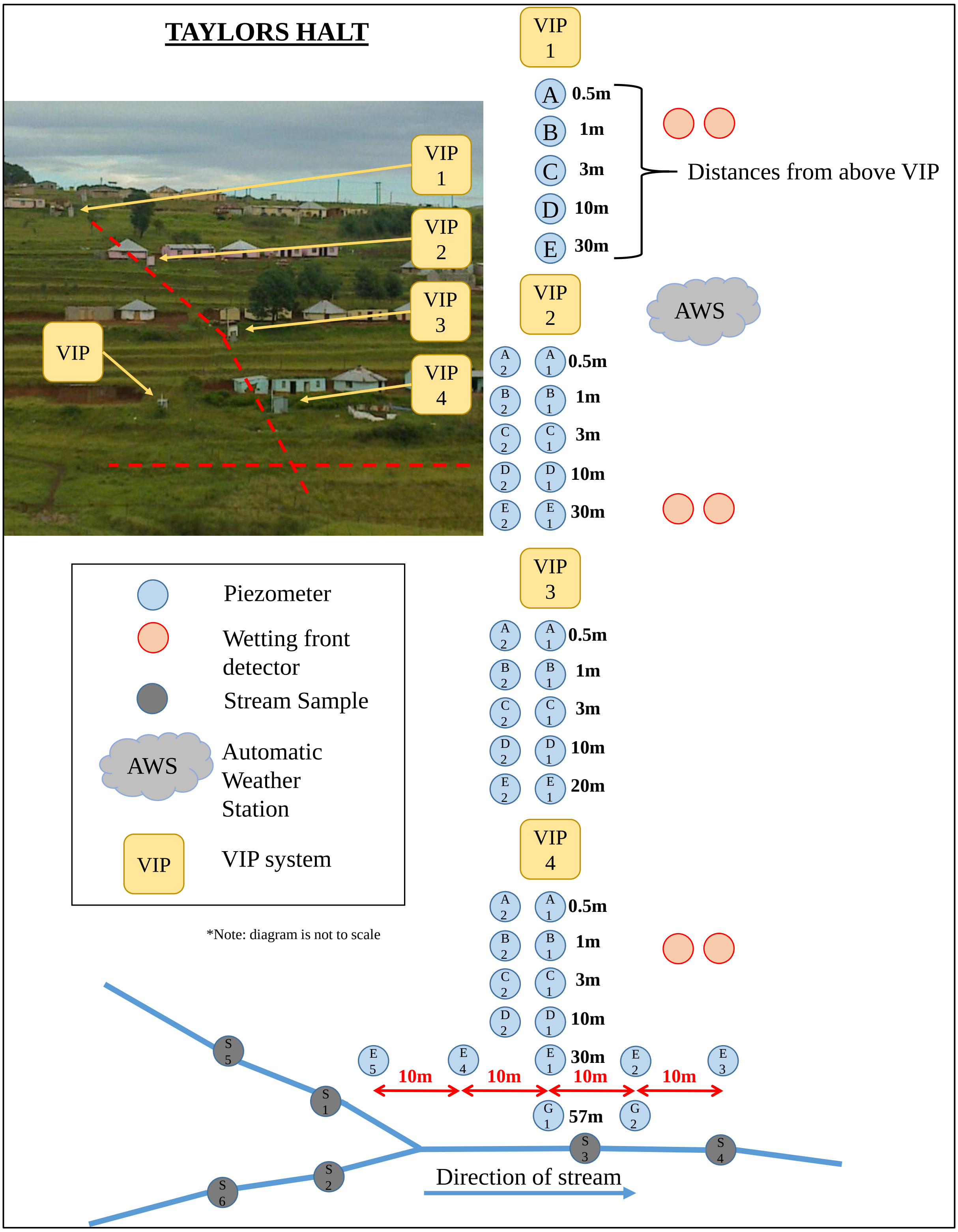

Figure 4.6 Taylors Halt study site

Lastly, the Taylors Halt Control site was located approximately 1.5 km from the Taylors Halt site. This site had identical hillslope characteristics to the Tyalors Halt site. This site was selected to represent undisturbed conditions (or as close as possible) and served as a control site to the Taylors Halt site. Unfortunately there were a few VIP systems located nearby, however the number of these systems was far less than that at the Taylors Halt site. Figure 4.7 describes the instrument outlay of the study site.

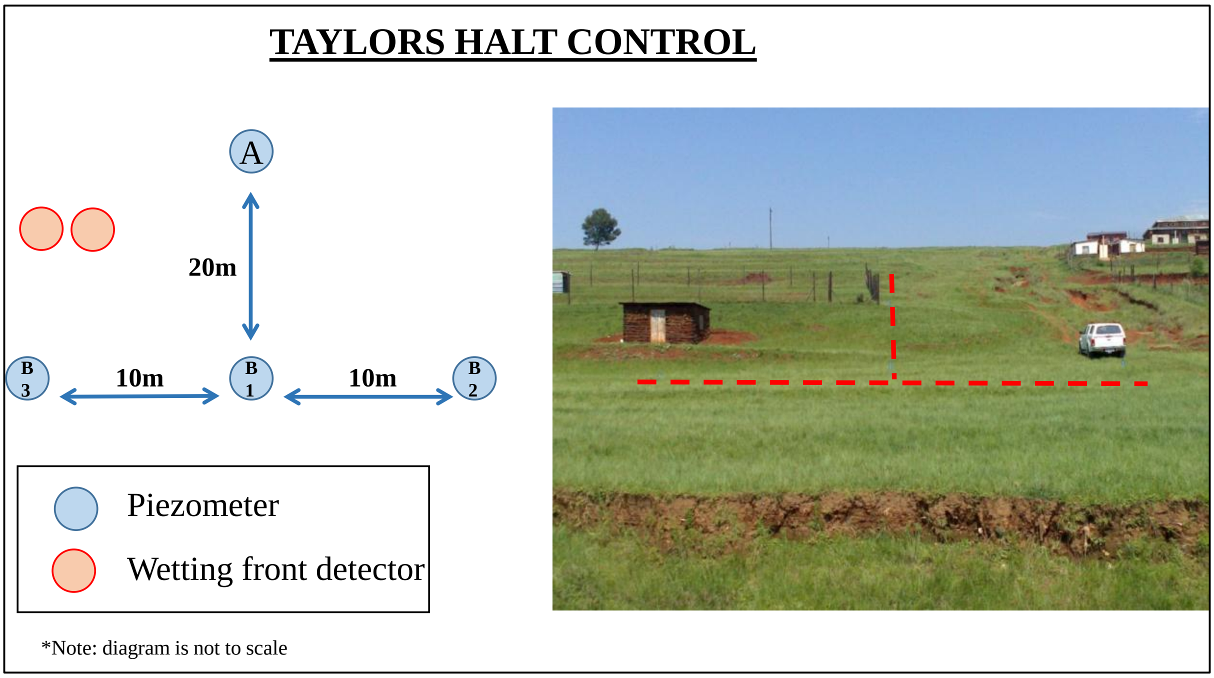

Figure 4.7 Taylors Halt Control study site

The depth of the soil profile and diagnostic horizons were recorded during the installation of the piezometers throughout the study sites. The near surface water table depth was measured in the piezometers using a dip meter, during a sampling event.

4.2. Water Sample Collection

The water samples were collected from a variety of sources on the hillslope, *viz.* rainfall, infiltration, through-flow and streams where applicable. The assessment of the impact from the on-site sanitation systems on the near surface hillslope through flow was achieved by cross-examining the different hillslope components. Surface run-off troughs and boreholes were originally part of the study, to collect surface run-off and deeper groundwater samples respectively, however due to financial, time and practical constraints, this was not possible. Figure 4.8 describes the layout of the instrumentation at the study sites. At a study site a plastic rain gauge (a), wetting front detectors (installed 0.3 m deep) (b) and PVC piezometers (installed to depth of parent material) (c) were installed, to capture the rainfall, surface run-off and infiltration, and near surface hillslope through-flow samples, respectively. A stream sample (d) was collected where applicable. The water samples were collected in clean, sterilised 250 ml polyethylene terephthalate (i.e. QPET) plastic bottles. Water samples that were turbid, were filtered using Whatman filter paper No. 1. The samples intended for *E.coli* analyses were collected in 500 ml clean and sterilised polycarbonate plastic bottles, which were supplied by Umgeni Water laboratories.

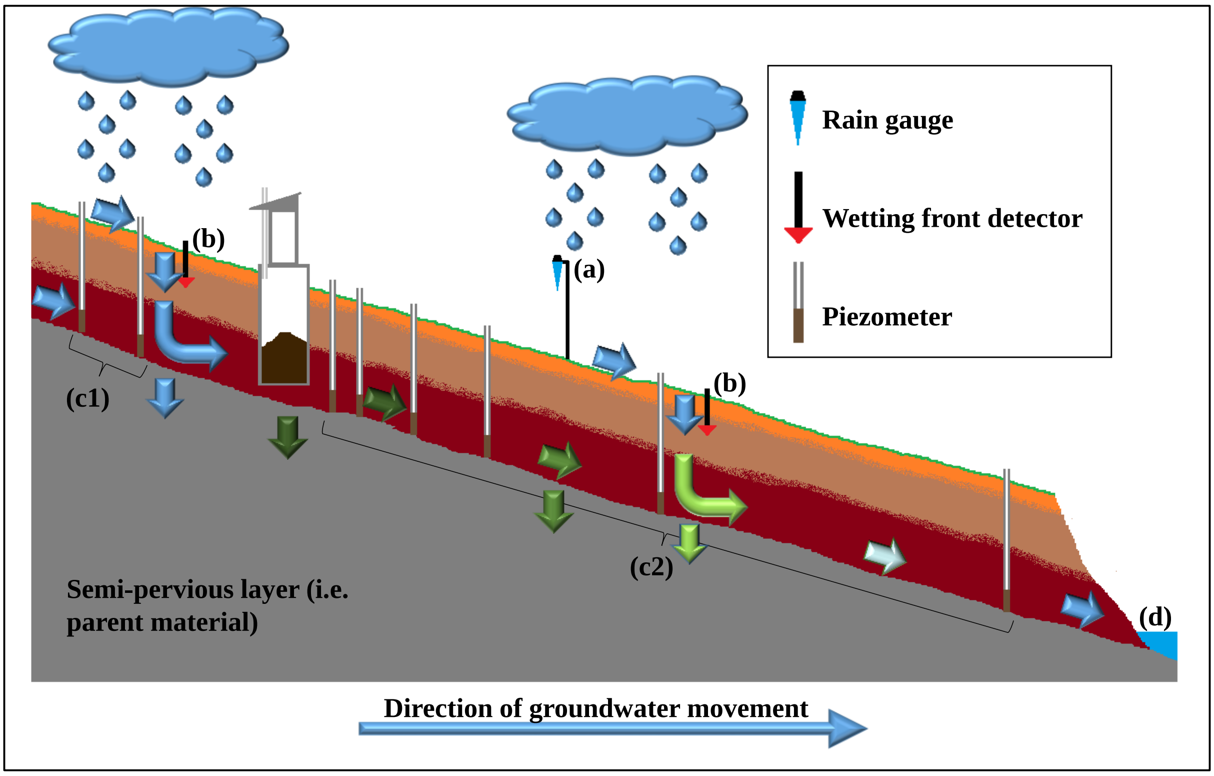

Figure 4.8 Generic layout of water sampling instrumentation

A standard plastic manual rain gauge was used to collect rainfall samples which fell over the study site (Figure 4.8). The rain gauge was installed 2.00 m above the ground on a wooden pole, 2.00 m away from any obstructions such as trees or buildings which would have interfered with the collection of the rainfall samples. This method of collecting rainfall sample was chosen, based on its practical aspects, such as its ease of use, robustness and minimal financial cost. The plastic rain gauges were emptied and cleaned between sampling events.

The samples from the surface run-off and infiltration were collected from two or more full-stop wetting front detectors which were installed 0.30 m into the top soil (Figure 4.8). Multiple wetting front detectors were used to get a representative sample of the study area. A spade was used to dig a 0.30 m deep hole, in which the wetting front detectors were installed. The excavated soil was carefully backfilled on top of the instrument, to ensure minimal soil disturbance. This method was selected based on its practical aspects, such as its ease of use, robustness and minimal financial cost. This method of collecting surface run-off and infiltration is described in Van der laan *et al*. (2010). The wetting front detectors were purged prior to every sampling event.

The near surface hillslope through-flow was collected *via* a series of piezometers which were installed above and below the on-site sanitation system under investigation (Figure 4.8). A plastic bailer was used to collect a water sample from the piezometers, which was rinsed three times with the water sample to minimise cross-contamination between piezometers. Prior to every sampling event, the piezometers were purged, and a fresh water sample was collected. The piezometers consisted of a 63 mm Ø PVC pipe, with a 450 mm slotted section at the bottom end. This allows the ingress of water from the soil (i.e. under a positive pressure), into the piezometer to collect a water sample. The piezometers were installed to the depth of the semi-pervious layer (i.e. parent material). Once in place, they were backfilled with Umgeni coarse sand, to prevent clogging or sealing around the slotted section of pipe, and were then firmly sealed at the soil surface with the *in situ* soil material which was excavated during the augering process.

The background piezometers (c1) were installed upslope of the on-site sanitation system under investigation and were used to collect background near surface through-flow water samples (Figure 4.8). A series of piezometers (c2) were installed downslope of the on-site sanitation system and were used to collect water samples which describe the near surface hillslope through-flow contamination from the on-site sanitation system (Figure 4.8). These piezometers were installed at increasing lateral distances from the leach pit, as described in Figures 4.3 – 4.7. The length of the piezometer transects was limited to the size of open spaces available at the different study sites. This method of capturing the near surface hillslope through-flow *via* piezometers was selected based on its practical aspects, such as its ease of use, robustness and minimal financial cost. This method has been used in several studies *viz*. Dzwario *et al*. (2006); Nyenje *et al*. (2013) and Robertson *et al*. (1991). Small plastic bottles attached to a nylon string were lowered to the bottom of several piezometers which experienced rapid fluctuation of the water table, to capture the intermittent through-flow water samples.

The collection of water samples was carried out over a two year period, primarily during the wet season where the rainfall was at its highest, resulting in a greater travel distance and concentration of the contaminants, compared to the dry months. Sampling events started on the 15 March 2012 and ended on the 18 March 2014. During this time period, there were 4 sampling campaigns; (1) 15 March 2012 – 10 December 2012, (2) 12 February 2013 – 2 April 2013, (3) 25 September 2013 – 3 December 2013 and (4) 22 January 2014 – 18 March 2014. A total of 1404 samples were collected throughout the entire study period.

4.3. Water Analyses

The water samples from the study sites were analysed for several chemical parameters *viz*. NH_4^+, NO_3^-, PO_4^{3-}, SO_4^{2-}, Cl^-, Ca^{2+}, Mg^{2+}, Na^+, K^+ and electrical conductivity, as well as *Escherichia coli* (*E.coli*). The ammonium, nitrate, phosphate and *E.coli* analyses represented the primary contaminants of concern, and were measured to describe their lateral extent in the near surface hillslope through-flow from an on-site sanitation system. Chloride, calcium, magnesium, sodium, potassium and electrical conductivity were measured in the water samples and used as tracers which described the chemical plume from the on-site sanitation system. The sulphate analyses were used to describe highly reduced areas in the near surface hillslope through-flow. The above chemical ions (along with carbon) are recognised as the major ions found in human excreta (Polprasert, 2007; Kirchmann and Pettersson; 1995; Schouw *et al*., 2002) and were used to describe the impact from on-site sanitation systems on nearby water resources in several studies (i.e. the case studies described in this document).

The NH_4^+, NO_3^-, PO_4^{3-}, SO_4^{2-} and Cl^- ions were analysed *via* the Thermo Scientific Gallery photometric analyser, based on the colorimetric method. In water samples prior to February 2013, the analyses for NO_3^- and PO_4^{3-} only, were measured using the HACH DR/2000 Direct Reading Spectrophotometer, which was also based on the colorimetric method. A comparison between the 2 instruments for NO_3^- and PO_4^{3-} was performed *via* a calibration curve. This was done to determine whether both analysers produced the same value for a known concentration, and thus whether the results from both instruments could be used together in the same dataset. In all cases both instruments functioned well and provided accurate results. Appendix 1 - 12 describe the calibration curves used for the analyses of NH_4^+, NO_3^-, PO_4^{3-}, SO_4^{2-} and Cl^-. Water samples analysed by the Gallery instrument were measured within 12 hours after collection.

The Ca^{2+}, Mg^{2+}, Na^+, K^+ ions were analysed *via* the Varian 730-ES Inductively Coupled Plasma-Optical Emission Spectrometer (ICP-OES), using the Optical Emission Spectrometry method. Water samples analysed for Ca^{2+}, Mg^{2+}, Na^+, K^+ ions started in February 2013. The calibration of the ICP-OES analyser was different to the Gallery instrument. Here the suitable wavelength(s), representing the different ions were selected, based on a set of criteria described by Boss and Fredeen (1997):

(a) The wavelength must be accessible for the analyser,
(b) The wavelength must be appropriate for the concentration of the element,
(c) The wavelength must be free from spectral interferences, or otherwise only have an interference with elements that are not present in the water samples and
(d) At least 2 wavelengths for each element should be identified, from which the best wavelength for a particular element should be selected, based on the previous criteria and its closeness or similarity to the known standards of the respective element.

Eight suitable wavelengths were initially selected, which was then narrowed down to four wavelengths. These final 4 wavelengths *viz* Ca^{2+} (422.673 nm), Mg^{2+} (280.270 nm), Na^+ (588.995 nm) and K^+ (766.491 nm), were used in the final analysing of the water samples. The calibration standards used were a mixed combination of Ca^{2+}, Mg^{2+}, Na^+, K^+ at concentrations of 0, 10, 20, 50 and 100 mg/l. Appendix 13 describe the ICP–OES analysers and a screen-shot of the calibration curves used in particular analyse event. The water samples analysed by the ICP–OES instrument were carried out once a month, due to the limited availability of the instrument. Water samples were refrigerated during the time period between sample collection and analysing.

When a sample concentration exceeded the range of the respective calibration curve, for the HACH, Gallery and ICP–OES analysers, the samples were diluted manually by a factor of five, 10, 20 or 40, and reanalysed until the sample fell within the calibration range. The Gallery analyser had a reflex action programmed into its tests, where it automatically diluted the sample when the initial analyses exceed the respective test calibration range. This reflex dilution action was taken into account during the manual dilutions steps. The calibration for the Gallery was performed prior to every sampling campaign, while the ICP-OES was calibrated after every 50 samples.

Water samples from selected piezometers and streams were analysed for *E.coli via* the Colilert ™ method. Only a selected number of water samples from the different study sites were sent in for analysis to the Umgeni Water water testing laboratory in Pietermaritzburg, due to time and financial restraints. For routine screening of water samples, it was impractical to analyse for the presence of each specific pathogen in the water sample. As a practical solution, the Colilert ™ method was used, and it is a relatively simple and rapid bacteriological test for intestinal bacteria *viz*. *E.coli*, which are present in human faeces. The Colilert ™ method gave an approximate concentration of *E.coli* (i.e. Most Probable Number (MPN) /100ml). In this method the water samples were mixed with a substrate containing σ-nitrophenyl-β-D-galactopyranoside and 4-methylumbelliferyl-β-D-glucoronide, which reacted with the enzymatic activities of the total coliforms and *E.coli* bacteria respectively. The samples were then analysed under a UV light to distinguish which samples tested positive for *E.coli* (Appendix 14).

In addition to the water sample analyses for chemical ions and *E.coli,* the pH and ORP values were measured to describe the anaerobic or aerobic status of the subsurface environment from where the water samples were taken. The pH, ORP and EC values were measured using the Hanna Instruments testers: HI 98121 Combo pH/ORP/Temperature tester and the HI 98312 DiST®6 EC/TDS/Temperature Tester. The pH and EC were calibrated prior to every sampling event. A 2 point calibration was performed for the pH test, using the known buffer solutions of 7.01 and 4.01. Similarly, the EC was calibrated using a 1 point calibration on a 12.88 mV solution. The ORP measure was factory calibrated and was checked against a known ORP 240 mV solution regularly for quality control purposes. The pH, ORP and EC measurements were performed *in-situ.*

The pH, ORP, EC testers and the pipette used to transfer water samples during the Gallery, HACH and ICP-OES analysing, were rinsed four times with deionised water between measurements, to minimise cross-contamination during the analysing process.

Lastly, the analyses of natural isotopes *viz*. O^{18} and H^{2}, was performed on the water samples to identify the connectivity between the rainfall, near surface through-flow and streams at the different study sites. The isotopes were analysed using the LGR DLT-100 Liquid-Water Isotope Analyser Automated Injection instrument. Post-processing of the data was performed by Mr C. Pretorius at UKZN using the LGR LWIA Post Analysis programme (LGR, 2007), where the results were reported as the differences (i.e. δ value) between the measured value and VSMOW standard, as part per thousand (‰).

4.4. Daily Rainfall Weather Stations

The daily rainfall was recorded by a meteorological weather station located at or near the study sites. The Ukulinga automatic meteorological weather station recorded the daily rainfall values, which was used for all the study sites. The meteorological weather station was located approximate 3.60 km, 3.70 km, 9.40 km and 19.80 km away from the Slangspruit, Crèche, Azalea and Taylors Halt study sites, respectively (Figure 4.9). In September 2013 a Davis Vantage Pro 2 automatic weather station was installed at the Taylors Halt site, to obtain daily rainfall values and compared them to the meteorological weather station values at Ukulinga, prior to September 2013. The rainfall tipping bucket unit was calibrated in a laboratory to 0.20 mm/tip, using a known volume of water dispensed from a burette (Appendix 15). The Ukulinga daily rainfall records were compared to the values from the Davis weather station at Taylors Halt, over the time period 25 September 2013 to 18 March 2014 (i.e. 175 days). The Ukulinga daily values were then adjusted by a rainfall adjustment factor (RAF) which was calculated by Equation 4.1. The accumulated daily rainfall for the weather stations at Taylors Halt and Ukulinga, for the 175 day period is depicted in Appendix 16.

$$\text{RAF} = \frac{\text{Sum Taylors Halt daily rainfall for 175 days}}{\text{Sum of Ukulinga daily rainfall for 175 days}} \qquad (4.1)$$

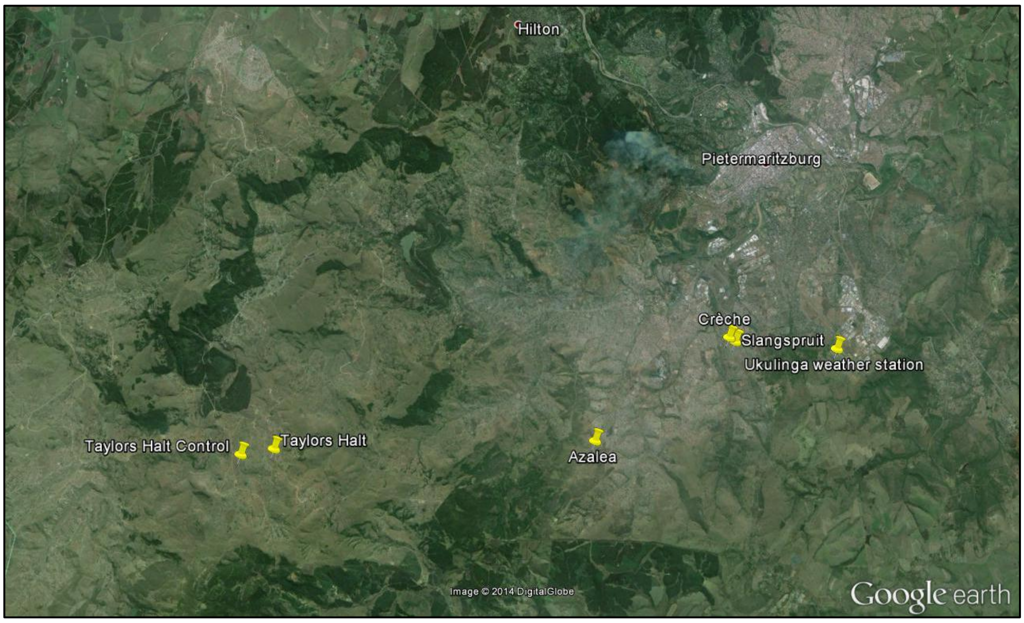

Figure 4.9 Geographical location of daily rainfall weather stations and study sites

4.5. Soil Particle Size Analyses

At all 5 study sites an in-depth analyses of the soil characteristics was performed. The depth and diagnostic soil horizons were identified where the saturated hydraulic conductivity measurements were performed. Soil samples were collected from the different soil horizons and were used in the particle size analyses step.

The particle size analyses was based on the Hydrometer methods described by Bouyoucos (1962) and Dane and Topp (2002), where the clay, silt and sand fractions were derived. This method was selected based on its accuracy and practicality (i.e. its ease of use, availability of required equipment and minimal financial cost). For each of the soil samples collected, a portion was passed through a 2.00 mm sieve, where approximately 250.00 g of sample was gathered. This step removed any gravels, large aggregates and organic matter such as plant roots and leaves. The soil sample was then placed into an oven to dry for 24 hours at 105 °C. Fifty grams of the oven dry sample was measured out accurately using an electronic scale, and transferred to a mixing cup. Fifty millilitres of dispersing agent (i.e. Calgon: 40.00 g sodium hexametaphosphate and 9.10 g sodium carbonate dissolved in one litre of hot deionised water) and 500 ml of deionised water was added to the cup. The mixture was stirred for five minutes on a stirring machine, after which it was checked to see if any soil aggregates remained in the mix. If any were identified, they were crushed against the side of the mixing cup using a glass rod, and the mixture was stirred for another three minutes on the stirring machine.

Once thoroughly mixed, all the suspension was transferred to a one litre glass sedimentation cylinder, and was then brought up to one litre volume using deionised water. A one litre blank (i.e. deionised water with 50.00 ml Calgon solution only) sedimentation cylinder was also established at this point, and was used to provide a blank hydrometer reading. The temperature of the soil solution in the sedimentation cylinder was measured using a standard mercury thermometer. This temperature value was used to provide the time required for the sand fraction to settle out of suspension (i.e. silt and clay particles remain in suspension) (Appendix 17). Following this, the thermometer was removed and the soil solution was mixed by hand using a stirring plunger for a minute. The plunger was then removed and a stopwatch was started, recording the time that was necessary for the sand to fall out of suspension (i.e. the silt + clay fraction only in suspension). At the predetermined point in time, the density of the soil solution and blank solution were measured using a hydrometer. After the silt + clay fraction measurement was performed, both the blank and soil solution cylinders were mixed again for one minute using the stirring plunger, and the temperature was recorded in each solution to determine the time required for the sand and silt particles to fall out of solution (i.e. clay fraction only in suspension). Immediately after mixing, a stop-watch was started, recording the time, and the open top of the respective measuring cylinders was covered using a glass disk. When the desired time had passed, the density of the blank and soil solutions were measured again using the hydrometer. The density of the soil solutions were corrected using the density values measured from the blank solution. The stirring plunger was rinsed with distilled water between stirs. The clay, silt and sand fractions for a soil sample was calculated using Equations 4.2, 4.3 and 4.4, respectively.

$$\% \text{ clay} = [(\rho_{s2} - \rho_{b2}) \times 100 / m_{so}] \quad (4.2)$$

$$\% \text{ silt} = [(\rho_{s1} - \rho_{b1}) \times 100 / m_{so}] - \% \text{ clay} \quad (4.3)$$

$$\% \text{ sand} = 100 - (\% \text{ clay} + \% \text{ silt}) \quad (4.4)$$

Where:

m_{so} = mass of oven dry soil sample (g),

ρ_{s1} = density of solution for silt + clay fraction (g/cm^3),

ρ_{b1} = density of blank during silt + clay fraction determination (g/cm^3),

ρ_{s2} = density of solution for clay fraction (g/cm^3) and

ρ_{b2} = density of blank during clay fraction determination (g/cm^3)

The results of the particle size analyses was used to determine the texture of the soil sample, based on the USDA texture triangle described in Appendix 18. The soil texture values were used to describe the characteristics of the soil profile at the study sites, and for the calculation of the *in-situ* field saturated hydraulic (K_{fs}) conductivity measurements.

4.6. *In-situ* Saturated Hydraulic Conductivity

Field saturated hydraulic conductivity (i.e. K_{fs}) at different depths in the soil profile were measured using a combination of a double ring infiltrometer and Guelph permeameter (Table 4.1). The *in-situ* field saturated values were measured rather than the laboratory saturate hydraulic conductivity methods, in an attempt to acquire a better representation of the site conditions (with minimal soil disturbance). The saturated hydraulic conductivity values were used to describe the water movement through the soil profile at the study sites, and indicate the presence of a water impeding layer(s) in the profile. The saturated hydraulic conductivity values were not measured at the Taylors Halt Control site, as this site was only used to compare the water quality samples to that of the Taylors Halt site. Methods described by Reynolds *et al*. (2002) and Reynolds (1993) were followed regarding the use of the double ring infiltrometer and Guelph permeameter, respectively. These methods were selected for practical reasons (i.e. ease of use, availability of required equipment and minimal financial cost).

Table 4.1 Depth of field saturated hydraulic conductivity measurements and soil particle size samples

	Slangspruit	**Crèche**	**Azalea**	**Taylors Halt**
Double ring infiltrometer	Soil surface	Soil surface	Soil surface	Soil surface
	0.50 m	0.45 m	0.50 m	0.50 m
Guelph permeameter	1.30 m	1.30 m	1.50 m	1.50 m

The double ring infiltrometer comprised of two concentric rings of different inside diameters (i.e. 9.80 cm and 22.00 cm) that were inserted 3.00 cm into the soil, at the required depth in the soil profile (Appendix 19). The outer ring was filled with water first to a specified water head (i.e. the top of the rim) followed by the inner ring to the same water level. Throughout the experiment, it was ensured that the water level in the outer ring never went above the level in the inner ring, in order to prevent a biased effect acting upon the dropping water level in the inner ring. The time was recorded for a 1.00 cm or 2.00 cm water level drop in the inner ring, using a stopwatch and a section of measuring tape glued to the inside of the smaller ring. After the water level had dropped to the predetermined point in the inner ring, both rings were filled with water again to their original specified water heads, and the time was measured again for the water level to drop to the previous predetermined point. This step was repeated until a steady infiltration rate was reached. The K_{fs} was calculated using Equation 4.5 as described in Reynolds *et al*. (2002):

$$K_{fs} = q_s/[(H/(C_1 d + C_2 a)) + (1/(\alpha^*(C_1 d + C_2 a))) + 1] \tag{4.5}$$

Where:

K_{fs} = field saturated hydraulic conductivity ($cm.s^{-1}$),
q_s = quasi-steady infiltration rate ($cm.s^{-1}$),
H = depth of water ponding (cm),
C_1 = quasi-empirical constant = 0.9927,
C_2 = quasi-empirical constant = 0.5781,
d = cylinder insertion depth (cm),
a = measuring cylinder radius (cm) and
α^* = soil macroscopic capillary length parameter, obtained from Figure 5.11 (cm^{-1})

This equation for calculating the K_{fs} from the double ring infiltrometer was selected, because it took into account the biased effect from a ponded head of water that rested above the infiltrating surface. An example calculation of K_{fs} derived from the double ring infiltrometer is shown in Appendix 20. The final K_{fs} value for the soil at the specified depth was taken as the average between of the two K_{fs} values at the specified depth.

The Guelph permeameter was inserted into an 8.50 cm diameter hole that was augured by hand to the required depth in the soil profile. A tripod was placed around the hole to support the

Guelph permeameter when it was functioning in the hole. Once the hole was excavated, the Guelph permeameter was filled with water and inserted into the hole and fixed at a depth where the bottom of the instrument was resting 5.00 cm above the soil surface in the hole. The water level in the Guelph permeameter was recorded and a stopwatch was used to record the time for 1.00 cm drop interval in the water level, until a steady infiltration rate was reached. The Guelph permeameter was then refilled with water and set to a new depth (i.e. its bottom rested 10.00 cm above the soil surface in the hole), and the processes was repeated until a steady infiltration rate was reached. The K_{fs} was calculated from Equation 4.6 as described in Reynolds (1993). An example calculation for the K_{fs} by means of the Guelph permeameter is shown in Appendix 21.

$$K_{fs} = CAR/[2\pi H^2 + C\pi a^2 + (2\pi H/\alpha^*)] \quad (4.6)$$

Where:

K_{fs} = field saturated hydraulic conductivity ($cm.s^{-1}$),

C = dimensionless shape factor obtained (Appendix 22),

A = cross sectional area of the Guelph permeameter (cm^2),

R = steady state rate of fall of water in the Guelph permeameter reservoir ($cm.s^{-1}$),

H = steady depth of water in the well (i.e. set by the height of the air tube) (cm),

a = the radius of the well (cm) and

α^* = soil macroscopic capillary length parameter, based on the soil texture properties (Appendix 23) (cm^{-1})

The Taylors Halt site was considerably longer than the other study sites (i.e. approximately 240.00 m). Thus three locations along the study transect were selected for saturated hydraulic conductivity measurements (Figure 4.10). However at location three, it was not possible to use the Guelph permeameter, given that the groundwater was near the surface (i.e. 0.70 m) which made it problematic for the instrument to function properly at depths below that water level.

4.7. Geophysics at Azalea and Taylors Halt

The geophysical surveys, in the form of Electrical Resistivity Tomography (ERT), were performed at selected sites *viz*. Taylors halt and Azalea. The Taylors Halt Control site was not surveyed, as only the water quality results were required for comparison with the Taylors Halt site. The other sites *viz*. Slangspruit and Crèche, were not surveyed for several reasons:

(a) Limited time available for the ERT instrumentation,
(b) Lack of sufficient open surface areas at the sites to accommodate a straight transect, due to houses, roads, etc. and
(c) Unpredictable presence of metal debris and objects, such as fences, pipes and gates, buried below the ground, which would have affect the ERT results.

The ERT images were compared to typical resistivity values of subsurface water (Table 4.2), which identified areas of groundwater (i.e. highlighted in bold green text). This was used to define the near subsurface hillslope through-flow at the Taylors Halt and Azalea sites.

Table 4.2 Typical resistivity values of different types of water (from ABEM, 2009)

Type of water	Resistivity (Ωm)
Precipitation	30 - 1000
Surface water, in areas of igneous rock	30 - 500
Surface water, in areas of sedimentary rock	10 - 100
Groundwater, in areas of igneous rock	**30 - 150**
Groundwater, in areas of sedimentary rock	**> 1**
Sea water	≈ 0.2
Drinking water (max. salt content 0.25 %)	> 1.8
Water for irrigation and stock watering (max. salt content 0.25 %)	> 0.65

The method described in ABEM (2009) was used for the ERT surveys. The Schlumberger short and long protocols were used in all the surveys. The electrodes were inserted approximately 0.25 m into the soil medium, at 2.00 m and 4.00 m intervals for the Schlumberger short and long protocols, respectively. This electrode spacing ensured that the resistivity values were measured up to 8.00 m and more, down the soil profile. The electrodes which gave a connecting error during the electrode checking step, were identified and watered with a solution of water + table salt, which improved the contact of the probe with the surrounding soil medium. The

GPS coordinates for each electrode inserted into the soil, were recorded using the Trimble differential GPS system. This data were differentially corrected to the nearest reference station, (i.e. Pietermaritzburg) and was used to fit the resistivity data to the topography of the selected site during the ERT image process step.

The data from the ERT surveys were imported from the ABEM terrameter SAS 1000 to a PC, using the Terrameter SAS 1000 / SAS 4000 Utility software. The respective .s4k file was then converted to a RES2DINV file, through the S4KCONV programme. The ERIGRAPH software was then used to produce a 2D graphical representation of the topographically corrected resistivity values for the respective sites, using the corresponding RES2DINV file and differentially corrected GPS data. The step of importing the ERT data and using the relevant software to produce a set of topographically corrected resistivity images, was performed by Dr. Eddie Riddell (A Water resources manager, SANPARKS), and Honorary Research Fellow at Centre for Water Resources Research, University of KwaZulu-Natal.

The apparatus used for the ERT surveys is listed below. The layout of the ERT equipment used during surveys at Taylors halt and Azalea sites, is shown in Appendix 24.

(a) ABEM Terrameter SAS 1000,
(b) ABEM LUND resistivity Imaging System ES10-64,
(c) ABEM instrumentation connecting cables,
(d) 4 × 250 m long sounding cables,
(e) 100 × 0.75 m long connecting cables,
(f) 1 × 12 volt car battery,
(g) 100 × 0.4 cm Ø 0.3 m long stainless steel,
(h) 1 × 4 pound hammer
(i) 1 × 100 m roll-up measuring tape and
(j) 1 × Trimble differential GPS

At the Taylors Halt site 2 ERT transects were performed. Transect one occurred down the length of the hillslope and the other across the hillslope near the bottom (Figure 4.10). Transect one started at the bottom of the hillslope, and consisted of 1 roll-along to cover the required distance. Transect two started from right to left, several meters above the seepage face, and did not require a roll-along (Figure 4.10). At the Azalea site, only one ERT transect was performed, which started at the middle of the hillslope and extended down the slope, towards the stream at the bottom (Figure 4.11). All the ERT transects were performed in April 2013, near the end of the wet season where the water table was near its highest level.

Lastly the topography of the study transects at all the study sites, was surveyed using the Trimble differential GPS apparatus. A simplified cross-sectional soil profile of the respective study transects was created using the differentially corrected GPS data and the soil profile information collected during the installation of the piezometers.

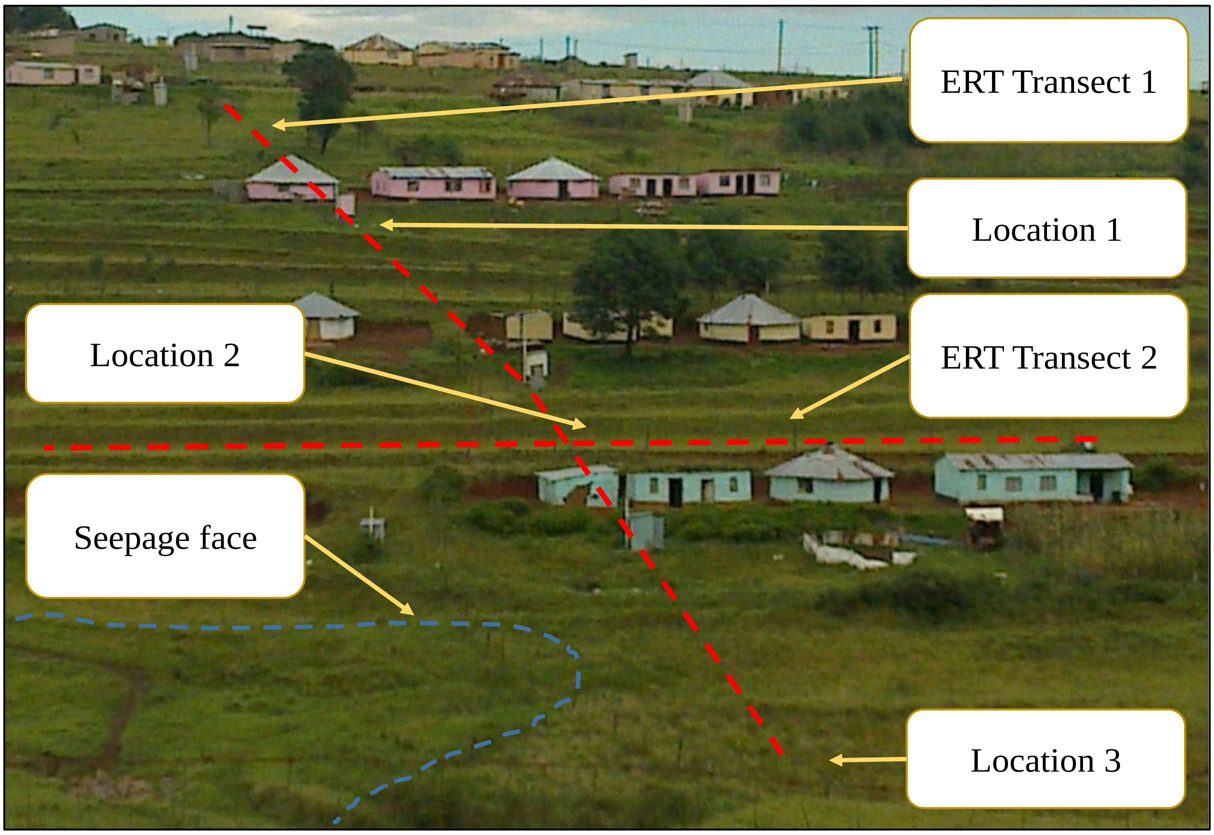

Figure 4.10 Location of saturated hydraulic conductivity measurements and layout of ERT transects at the Taylors Halt site

Figure 4.11 Layout of ERT transect at the Azalea site

4.8. Time Domain Reflectometry at Slangspruit Site

The Time Domain Reflectometry (TDR) was used only at the Slangspruit site. This described the water content down the soil profile throughout a rainfall event(s). The TDR system used at the Slangspruit was installed in September 2013, just before the start of the wet season. At the time of the study, there was only enough TDR instrumentation (i.e. TDR 100, multiplexer, logger and 8 TDR probes) available for one study site. The Slangspruit site was selected for the reasons listed below:

(a) Compared to the other sites, this was the only site which had a noticeable semi-pervious clayey layer near the soil surface. This clay layer acted as a key water partitioning point in the subsurface. The TDR probes were inserted above, within and below this clay layer, to show the effect it has on the infiltrating rainfall.

(b) Out of all the five study sites, Slangspruit was one of the safest (i.e. protection against theft and vandalism) to install the expensive TDR equipment. It was installed on a secure premises, where a fence surrounded the entire property. This kept unwanted animals and individuals away from the instrumentation. It was also one of 2 sites where permission was given by the home owner to install the equipment on their property.

The methods described by Ferrè and Topp (2002), Campbell Scientific (2010) and Campell Scientific (2009) were used for the TDR calibration and installation. Prior to the installation of the TDR equipment, the probe off-set for each probe was derived. This was achieved by connecting the TDR apparatus in the correct arrangement and connecting it to a PC to run the PCTDR software. One at a time, the TDR probes were inserted into a large plastic container filled with deionised water, ensuring a minimum of 5.00 cm of clearance between the probe rods and the sides of the container at all times. At the same time the water temperature was measured using a standard mercury thermometer. Once a TDR probe was immersed into the deionised water, the PCTDR programme was opened and the required parameters were entered into the programme (Appendix 25).

The cable propagation velocity (Vp), waveform average and waveform points, was set to values of 1.00, 4.00 and 251, respectively, as recommend by Campell Scientific (2009). The waveform start and waveform length values was selected to capture the section of the waveform where the start and end inflection points were visible. The actual probe rod length was measured and entered into the PCTDR programme, and the probe offset was set to 0 as this needed to be calculated. After the relevant parameters were entered in, the waveform and water content were generated (Appendix 25). The terminal emulator, under the options tab, was opened where the $start_{index}$ and end_{index} values were generated 3 time to provide a representative average. These values were then used to calculate the probe off-set for the respective TDR probe, using Equations 4.7 to 4.10. The relevant parameters used to calculate the probe off-set for each of the 8 TDR probes is shown in appendix 26.

$$La = L \times \sqrt{[\varepsilon(T)]} \tag{4.7}$$

Where:

La = Apparent length (m),
L = Actual probe rod length (m) and
ε(T)] = Dielectric permittivity of water corresponding to the water temperature (Appendix 27).

$$Start_{dist} = [Start_{index} / (\text{waveform points} - 1)] \times \text{Window length} \tag{4.8}$$

$$End_{dist} = [End_{index} / (\text{waveform points} - 1)] \times \text{Window length} \tag{4.9}$$

$$\text{Probe off-set} = [(La \times Vp - End_{dist} + Start_{dist}) / Vp] \times -1 \tag{4.10}$$

The derived TDR probe offsets were used to calibrate the TDR probes. TDR probes were inserted into four 20 litre plastic buckets containing a mixed soil sample from the Slangspruit site. The initial volumetric water content of the soil in each bucket was measured three times, using three identical stainless steel rings of a known mass and volume. Each stainless steel ring was inserted into the soil material, ensuring that the soil sample occupied the entire volume of the steel ring. The sample and ring were weighed and placed into an oven to dry at 105 ° C for 24 hours. The oven dry sample was then weighed again, to determine the initial water mass in the soil, where the initial volumetric water content was calculated using Equation 4.11.

$$\Theta_V = [(m_{as} - m_{os})/\rho_w]/V_{os} \quad (4.11)$$

Where:

Θ_V = Volumetric water content,
m_{as} = mass of air dry soil (g),
m_{os} = mass of oven dry soil (g),
ρ_w = density of water (g/cm^3) and
V_{os} = volume of oven dry soil sample (cm^3)

The initial water content values in each bucket provided an indication as to how much water was required to make the soil, in the respective bucket, to the desired known volumetric water content: 0.35, 0.45 and 0.55 (Appendix 28). The volumetric water content in each of the buckets was verified by the same steps used in determining the initial soil volumetric water content. TDR probes were inserted into the soil of each bucket with a known volumetric water content, up to the base of the probe. The TDR apparatus was connected to a PC and the PCTDR programme was opened to measure the volumetric water content in each of the corresponding 20 litre buckets of wet soil. Three readings were recorded for each bucket. The volumetric water content from the TDR probes was calculated using the Ledieu equation (i.e. 4.12) as describe in Campbell Scientific (2010). The calibration results are shown in Appendix 29.

$$\Theta_V = [0.1138 \times (\sqrt{K_a})] - 0.1758 \quad (4.12)$$

Where:

Θ_V = Volumetric water content ($cm^3 . cm^{-3}$) and
$\sqrt{K_a}$ = La / L

The TDR apparatus at the Slangspruit site (Figure 4.12), was installed in a pit that was dug to the depth of the parent material, approximately 1.3 m deep. Eight TDR probes were inserted horizontally into the soil profile, upslope of the excavated hole, at 4 different depths: Probes 1 & 2 at 0.20 m, probes 3 & 4 at 0.50 m, probes 5 & 6 at 0.80 m and probes 7 & 8 at 1.30 m (Figure 4.13). The programme for TDR apparatus was compiled using the Loggernet software, and the data was downloaded from the logger every week. The first programme used, recorded the Θ_V, La/L, battery voltage and console temperature every hour. However after analysing the data for the first few months, it was discovered that the volumetric water content values that the TDR 100 produced were either unrealistic or unusable. The programme was then altered to record the 251 waveform points for each TDR probe, in addition to the previous variables. For every hour of data, the waveform for each TDR probe was plotted in Excel, where the start and end index values were determined. The start and end index values were then converted into distance values using Equations 4.8 and 4.9, which were used to determine the La value using Equation 4.13. The volumetric water content was then calculated using the derived La/L value, from Equation 4.13, which was then corrected to the true volumetric water content based on the calibration curve (Appendix 29). The final volumetric water content at the soil depths of 0.20 m, 0.50 m, 0.80 m and 1.30 m was calculated as the average corrected volumetric water content values between the TDR probes at their respective soil depths.

$$La = End_{distance} - Start_{distance} - \text{Probe offset} \quad (4.13)$$

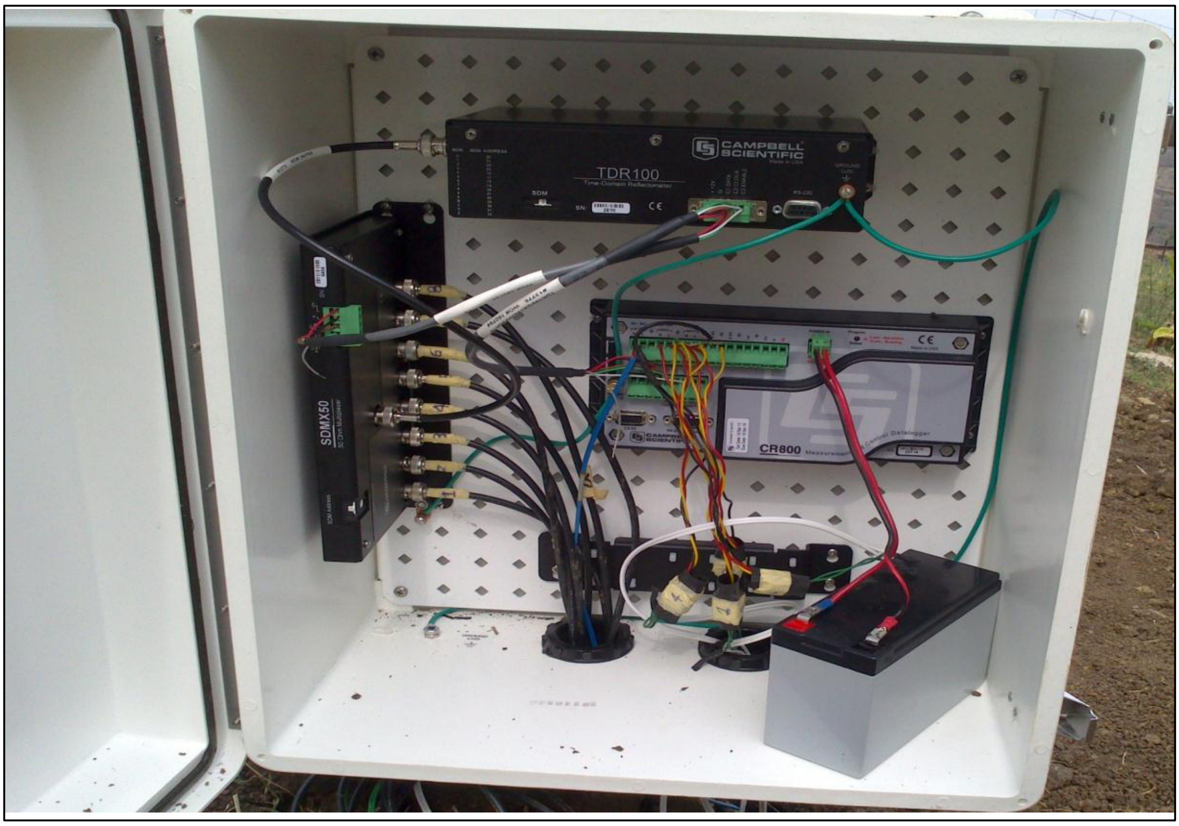

Figure 4.12 Configuration of TDR apparatus used at the Slangspruit site

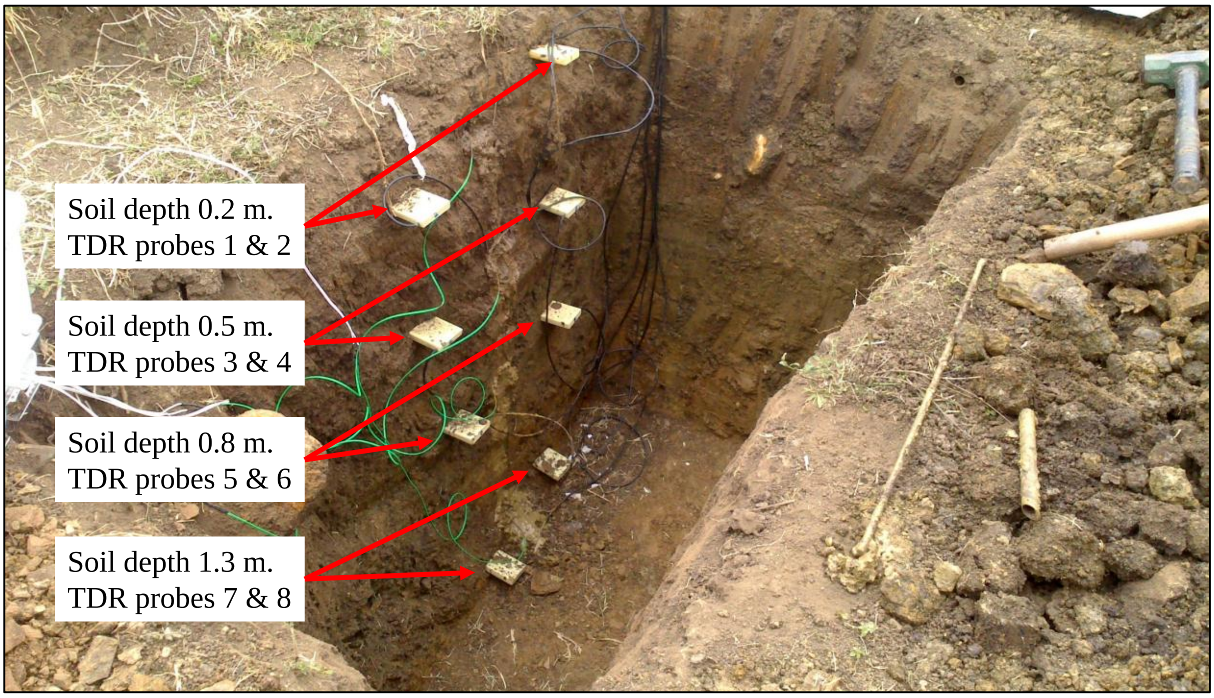

Figure 4.13 Installation of TDR probes at the Slangspruit site

5. RESULTS

There were difficulties in the collection and assembly of the all the data collected over the two year study period. On numerous occasions the wetting front detectors, piezometers and plastic rain gauges at the study sites, had to be replaced due to vandalism and theft. Piezometers H2 and H3 at the Slangspruit site and G and H3 at the Azalea site, all had to be replaced twice. All the wetting front detectors at the Azalea and Taylors Halt Control sites were also replaced twice. The plastic rain gauges at the Azalea and Crèche sites were broken twice, which resulted in the use of the rainfall samples from the Slangspruit site for the Crèche and Azalea sites. In addition, TDR probes 5 and 6 encountered unresolvable electronic or connectivity problems and were not able to produce a single set of waveform point values that were useable. Lastly there were several occasions where the home owner(s) at the respective study sites, were not present to provide access to their premises during a sampling event.

The amount of data that was collected over the two year study period was substantial and difficult to present it all in the results chapter. Thus the data was summarised into informative diagrams and graphs, where selected figures that demonstrated the main findings and processes at the study sites, were presented in the result chapter. The results were presented in two sections: (i) description of the soil profile and near surface hillslope water movement (ii) water sample analyses. The entire data set is presented the Appendices chapter (Appendices 36 – 55).

5.1. Soil Profile Description and Near Surface Hillslope Water Movement

At each of the study sites the soil profile was studied, where the soil texture, *in-situ* saturated hydraulic conductivity and the near surface water table levels were measured. In addition, natural isotope, pH and ORP values were measured in all the water samples. All this data was used to produce a set of graphs describing the near surface hillslope water movement at each of the study sites.

5.1.1. Slangspruit

The soil profile at the Slangspruit site was shallow, on average 1.50 m thick. The soil form was identified as a Sepane according to the Taxonomic soil classification system for South Africa. The top soil, subsoil and parent material were identified as an Orthic A, Pedocutanic B, Unconsolidated material with signs of wetness and Shale, respectively (Figure 5.1). The soil texture throughout the soil profile was clayey, where the clay percentage values ranged from 44 % - 58 %. The K_{fs} values at the soil surface, 0.50 m and 1.30 m were 0.46 cm/h, 0.03 cm/h and 0.10 cm/h respectively. The low K_{fs} values indicated slow water movement down the soil profile, especially at 0.50 m where a distinct clay layer started. Cutans in the soil profile were present at 0.25 m – 0.50 m and overlaid the distinct clayey layer at 0.50 m, which indicated a significant decrease of the infiltration rate of water at this layer. The profile description and properties are summarised in Figure 5.1, where the diagnostic soil horizons are clearly defined.

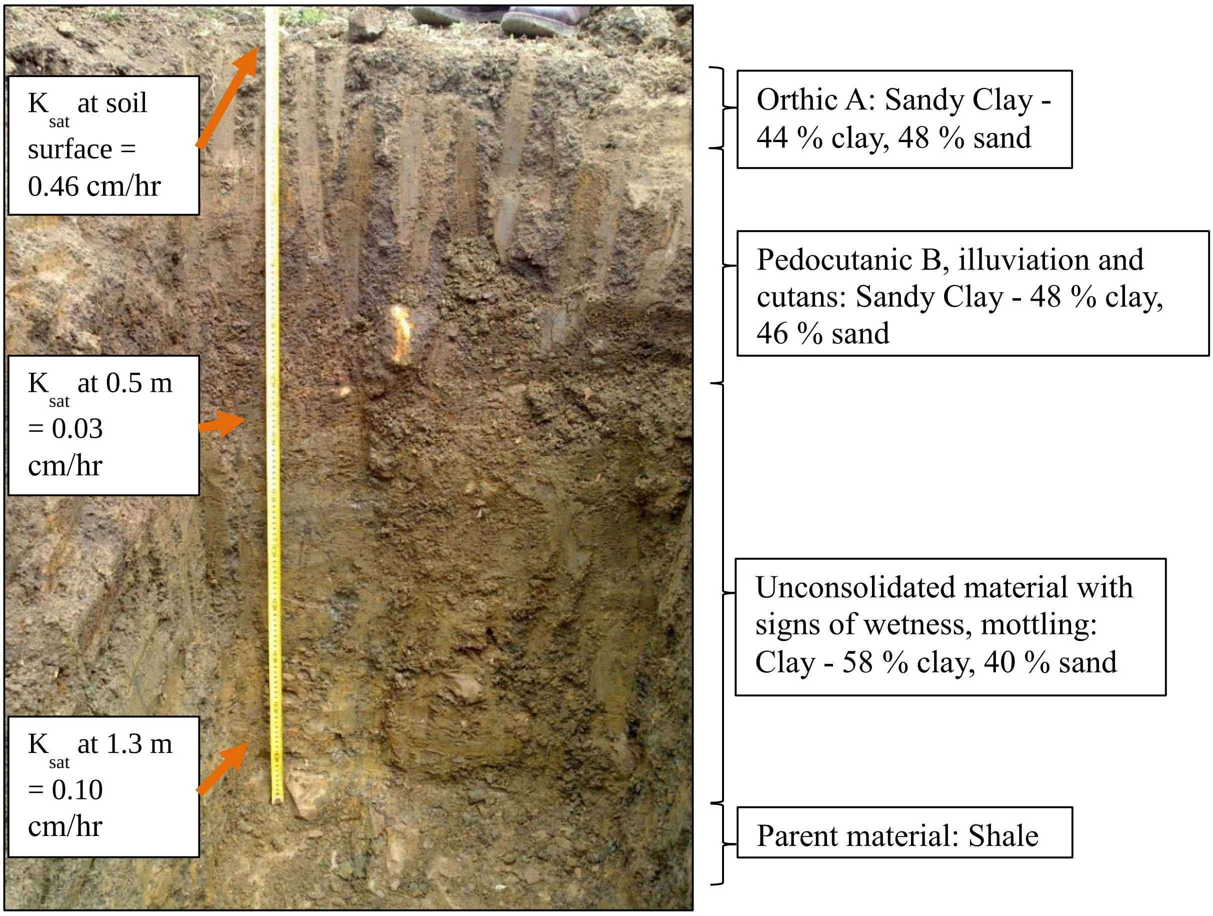

Figure 5.1 Slangspruit soil profile

The TDR data at the Slangspruit site revealed the change in the volumetric water content at different depths in the soil profile (Figures 5.2. 5.3 and 5.4). The soil profile remained moderately saturated near the end of the wet season. From 14 January 2014 to 18 March 2014, the average volumetric water content increased down the soil profile to the start of the clayey layer: 0.38 to 0.54 at depths of 0.20 m and 0.50 m, respectively. The TDR probes 5 & 6 which were installed at 0.80 m (i.e. in the middle of the clay semi-pervious layer) failed to produce a usable water volumetric result. Below the clayey layer, the average volumetric water content was slightly lower than in the top soil: 0.46 at 1.30 m. This highlighted the semi-pervious nature of the clay layer within the soil profile. The gap in the data from the 28-02-2014 to 11-03-2014 refers to a period of data that was over-written, due to a collection error. Furthermore, there were several high rainfall events which caused a visible increase in the volumetric water content in the soil (i.e. red circles in Figures 5.2, 5.3 and 5.4). These rainfall responses were more prominent at 0.20 m and became less noticeable at deeper depths. The TDR data down the soil profile indicated that the water content in the soil was sensitive to high rainfall events, and that the clayey layer had a significant impact retarding the movement of the infiltrating water.

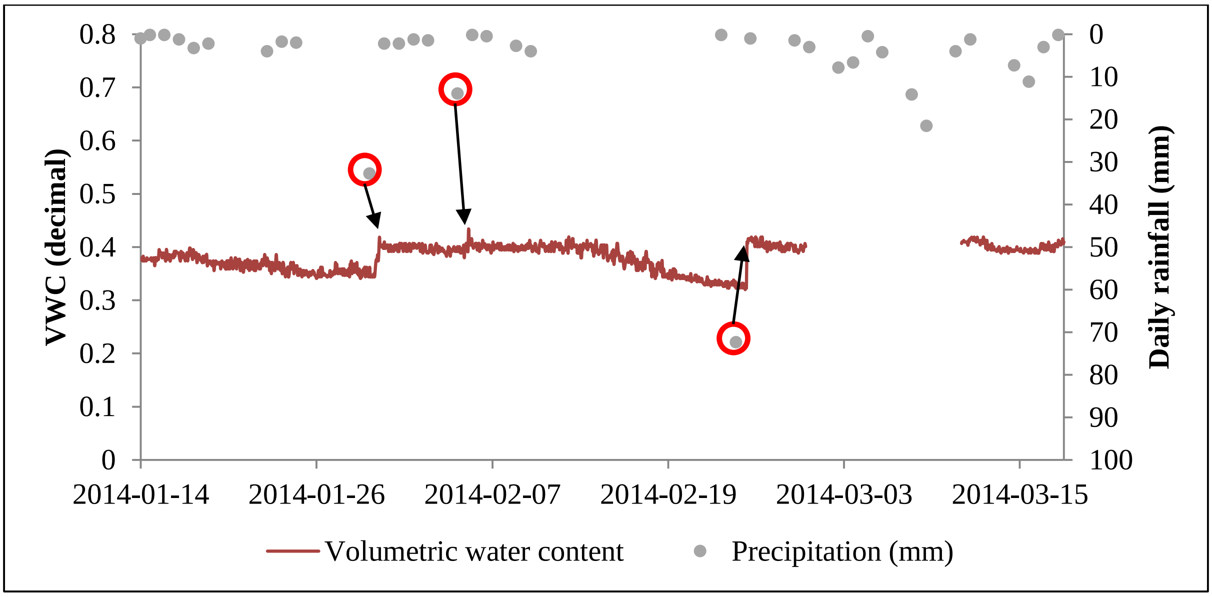

Figure 5.2 Volumetric water content (VWC) at 0.2 m below the soil surface at the Slangspruit site

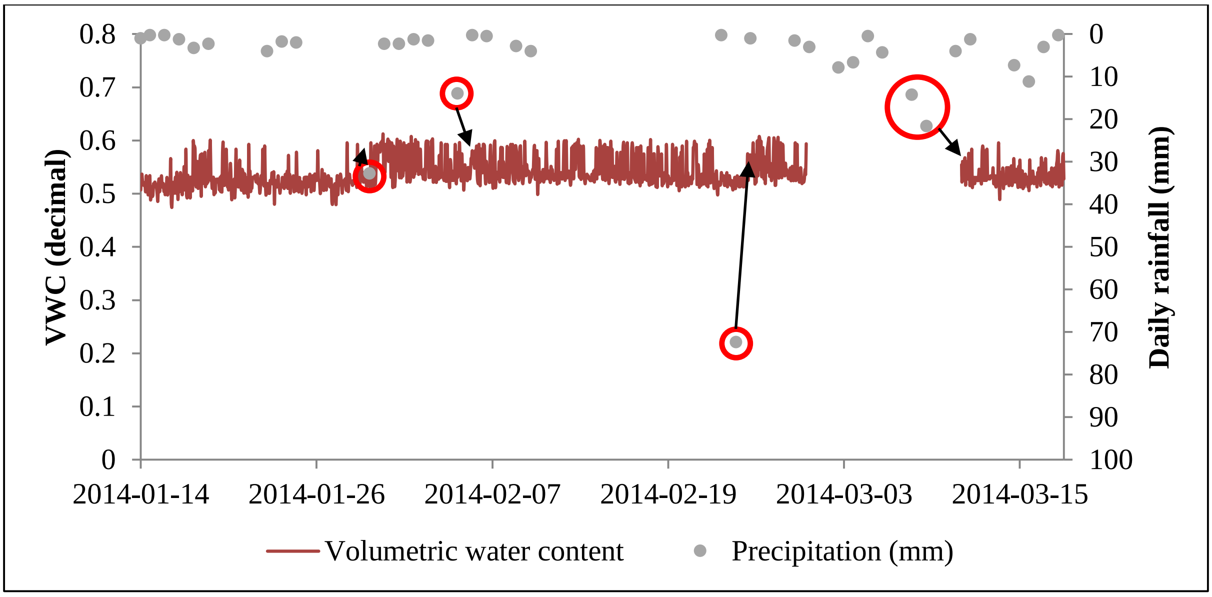

Figure 5.3 Volumetric water content (VWC) at 0.5 m below the soil surface at the Slangspruit site

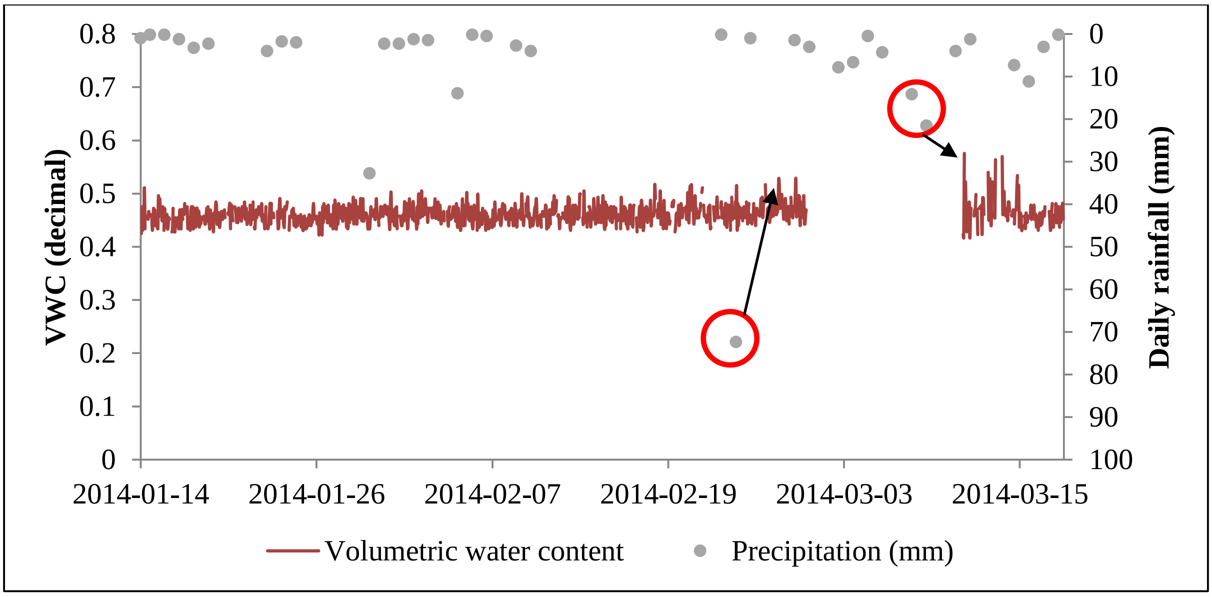

Figure 5.4 Volumetric water content at (VWC) 0.13 m below the soil surface at the Slangspruit site

The isotope data at the Slangspruit site fell consistently along the meteoric water line (Figures 5.5 and 5.6). The isotope values from the rainfall, surface gutter, wetting front detectors, and piezometers, overlapped consistently with each other and indicated similar isotope signatures. This revealed that there was connectivity between the rainfall and the near surface hillslope through-flow. Furthermore, the near surface hillslope through-flow was primarily supplied by water from the rainfall and not from deeper groundwater resources.

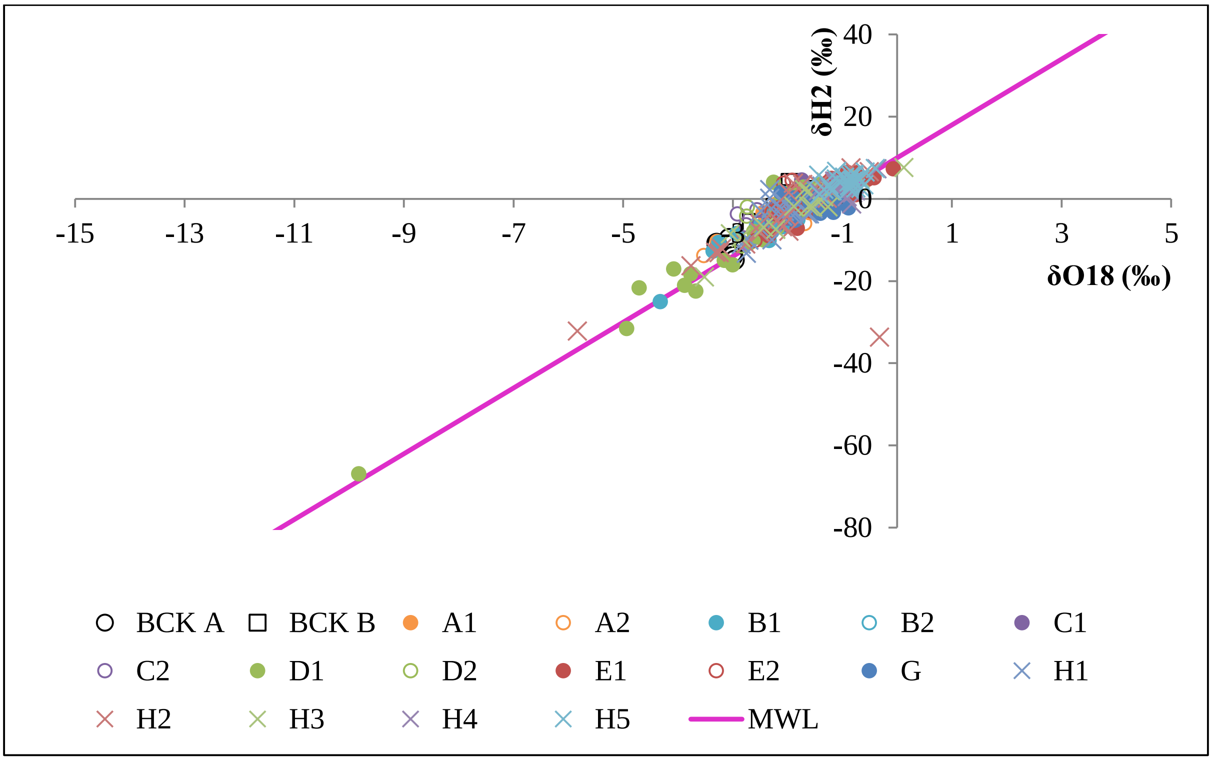

Figure 5.5 Isotope values for the piezometers BCK A - G at the Slangspruit site

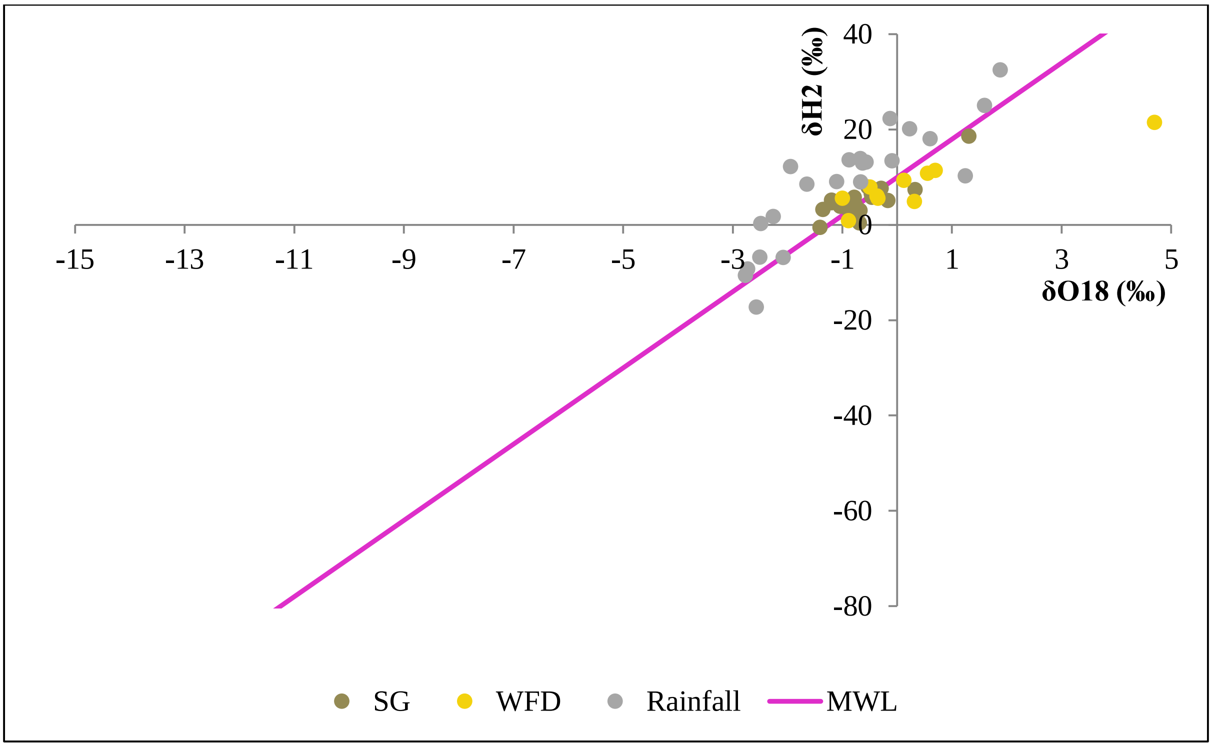

Figure 5.6 Isotope values for the surface gutter, wetting front detectors and rainfall at the Slangspruit site

The pH and ORP values in the near surface hillslope through-flow ranged from 6.51 to 8.29 and -236.00 mV to 370.00 mV, respectively. The soil below the on-site systems, fluctuated between a wet and waterlogged soil environment, based on the pH-ORP soil diagram from Baas-Becking *et al.* (1960) (Figure 5.7). Furthermore, the water in the near surface hillslope through-flow remained in anaerobic soil conditions, where piezometer C1 experienced high reducing conditions for a majority of the time.

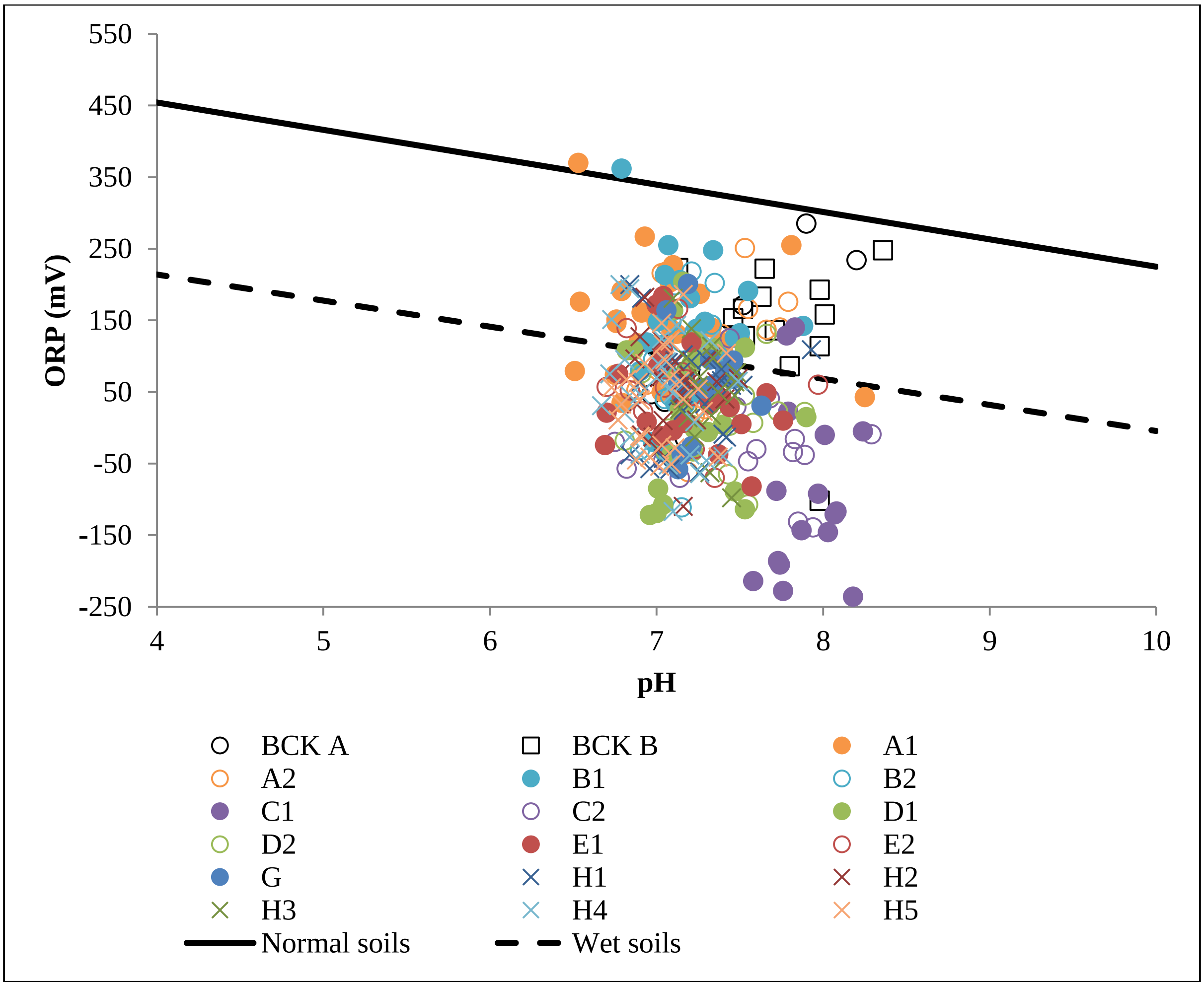

Figure 5.7 pH-ORP values for piezometers BCK A – H5 at the Slangspruit site

The water table remained near the soil surface throughout the study period (Figure 5.8). In October 2012 and March 2014 it breached the soil surface after periods of high rainfall (Appendix 30). In these cases the soil water content was high and the high rainfall event(s) resulted in saturated conditions above the clay layer (i.e. low K_{sat} values at 0.50 m), which caused the water table to breach the soil surface. The pour-flush leach pits and surface gutter supplied water to the soil and caused an increase in the water table. This was evident in piezometers B2 and C1, given their close proximity to the leach pits, and at H4 and H5, given their close proximity to the surface gutter (i.e. < 3 m).

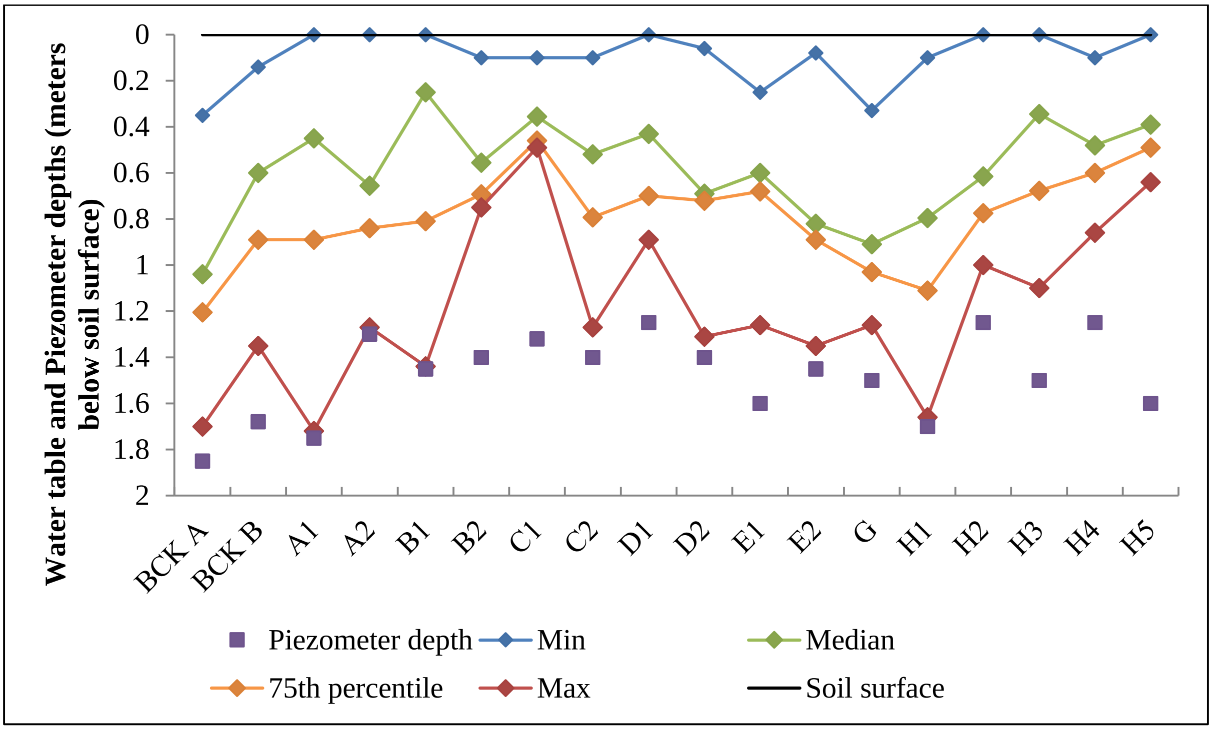

Figure 5.8 Water table and piezometer depths at the Slangspruit site

5.1.2. Crèche

The soil profile at the Crèche site was shallow, on average 1.30 m thick, except near the bottom of the study transect where it reached down to 2.00 m. The soil form above the pour-flush was identified as a Mispah, while the soil at the pour-flush was a Sepane, according to the Taxonomic soil classification system for South Africa. The Sepane top soil, subsoil and parent material were identified as an Orthic A, Pedocutanic B, Unconsolidated material with signs of wetness and Shale, respectively (Figure 5.9). The soil texture throughout the soil profile was clayey, where the clay percentage values ranged from 40 % - 56 %. The K_{sat} values at the soil surface, 0.45 m and 1.30 m were 2.38 cm/h, 0.05 cm/h and 0.10 cm/h, respectively. Similar to the Slangspruit site the low K_{sat} values indicated slow water movement down the soil profile, except in the top soil. Cutans in the soil profile were present at 0.20 m – 0.45 m and overlaid a distinct clayey-rocky layer at 0.45 m, which indicated a noteworthy decrease of the infiltration rate of water at this layer. The profile description and properties are summarised in Figure 5.9, where the diagnostic soil horizons are clearly defined.

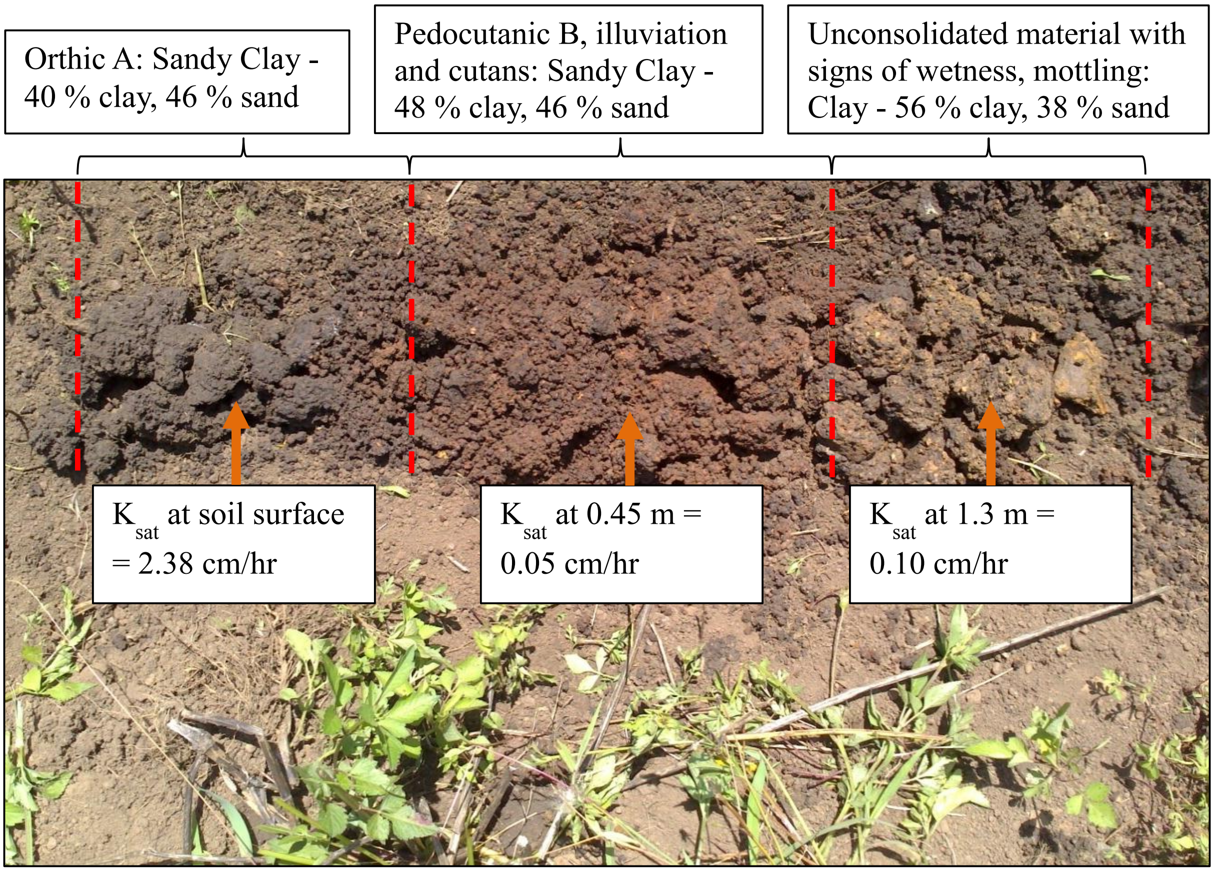

Figure 5.9 Crèche soil profile

The isotope data at the Crèche site fell consistently along the meteoric water line (Figures 5.10 and 5.11). The isotope values from the rainfall, wetting front detectors, and piezometers, overlapped consistently with each other and indicated similar isotope signatures. This revealed that there was connectivity between the rainfall and the near surface hillslope through-flow. Furthermore, the near surface hillslope through-flow was primarily supplied by water from the rainfall and not deeper groundwater resources.

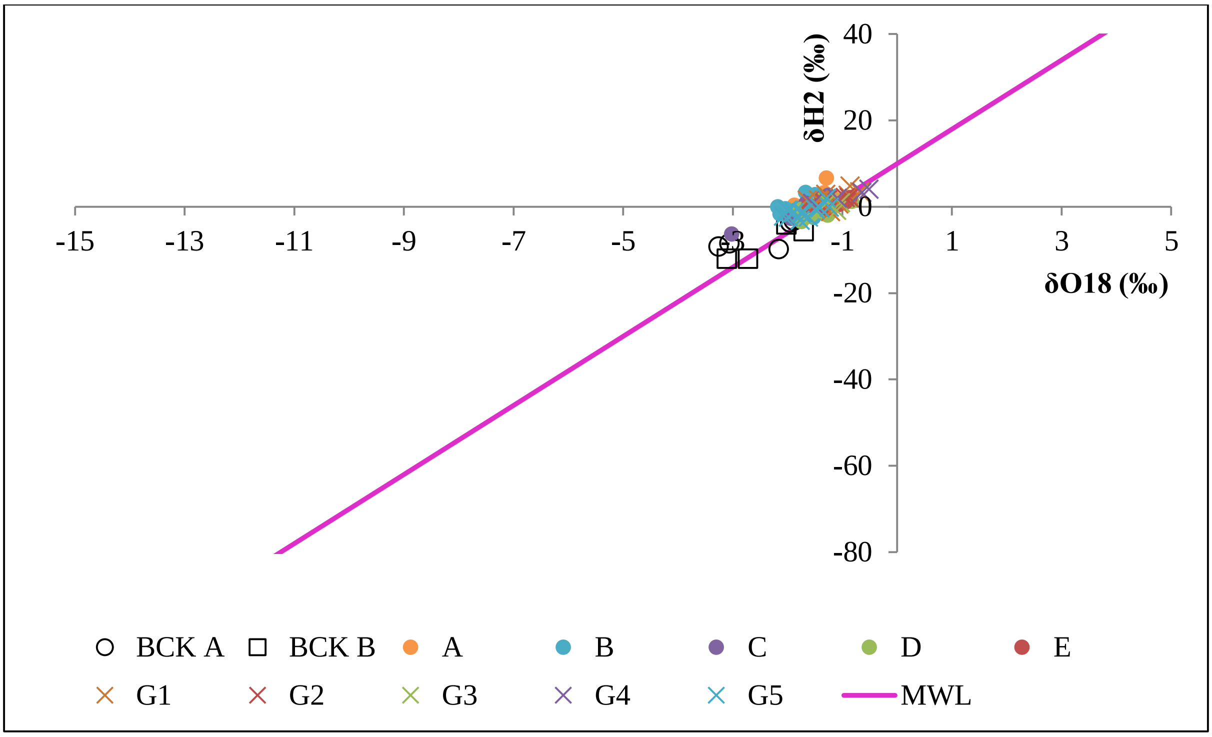

Figure 5.10 Isotope values for the piezometers BCK A – G5 at the Crèche site

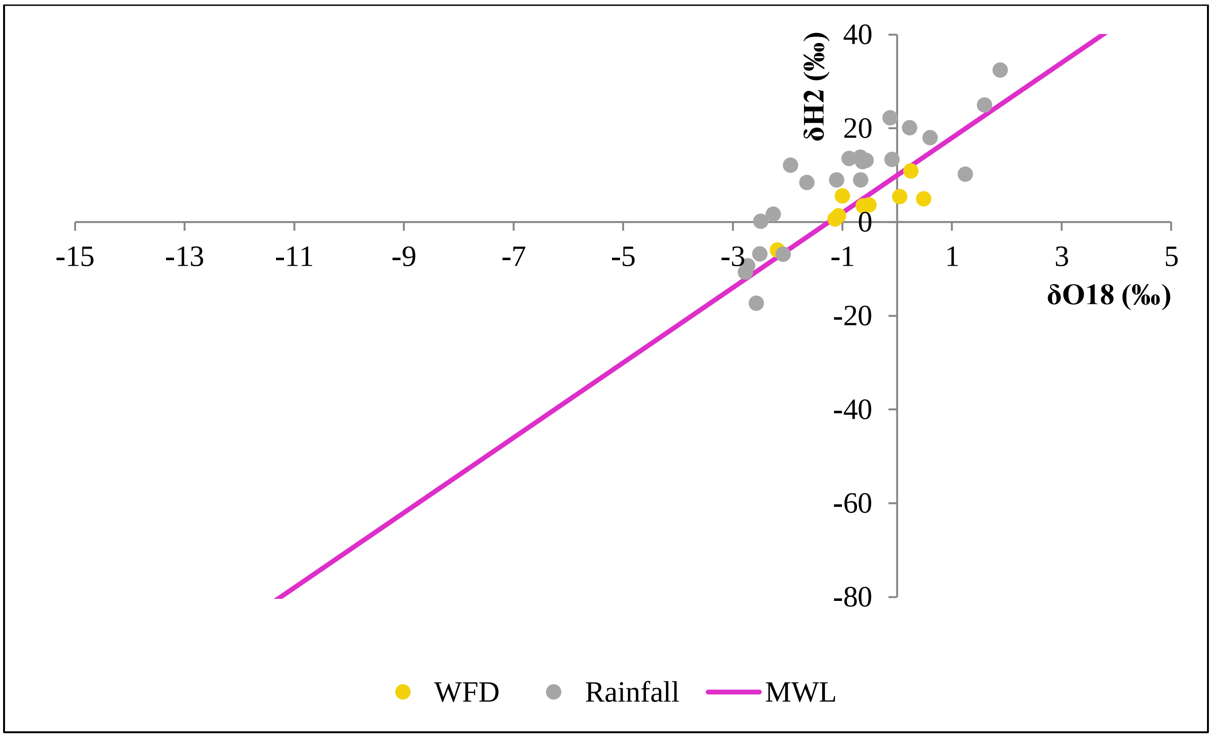

Figure 5.11 Isotope values for the wetting front detector and rainfall at the Crèche site

The pH and ORP values in the near surface hillslope through-flow ranged from 6.44 to 7.59 and -147.00 mV to 252.00 mV, respectively. The soil below the on-site system, fluctuated between a wet and waterlogged soil environment, based on the pH-ORP soil diagram from Baas-Becking *et al*. (1960) (Figure 5.12). Furthermore, piezometers BCK B and B experienced moderate reducing conditions for the majority of the time.

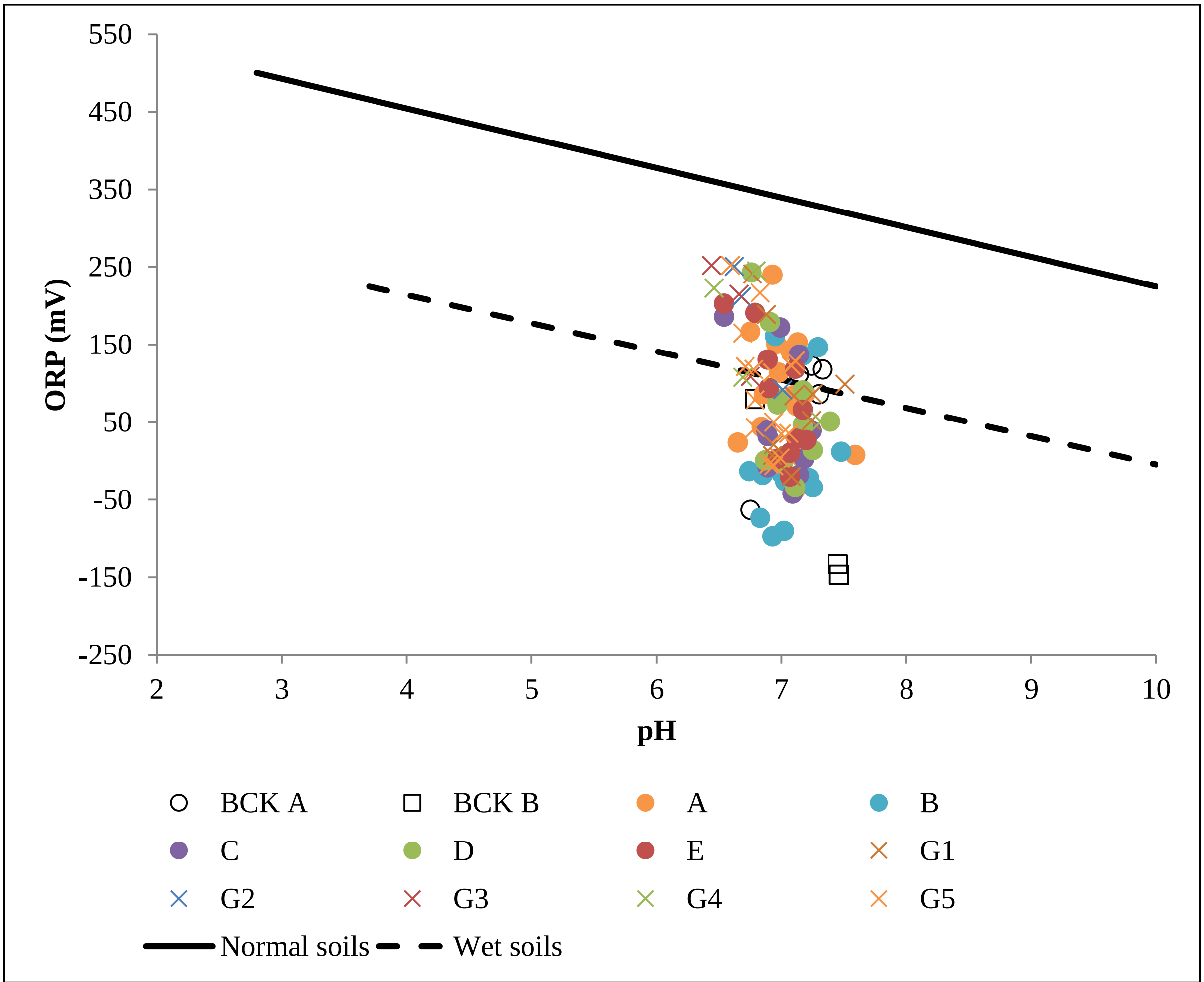

Figure 5.12 pH-ORP values for piezometers BCK A – H5 at the Crèche site

The water table fluctuated along the study transect throughout the study period, but never breached the soil surface (Figure 5.13). Upslope of the leach pits the intermittent water table remained just above the depth of the parent material, due to the intersection of the hillslope through-flow by the storm water drain located upslope. However downslope of the leach pits, the water table rose, due to the addition of water from the pour-flush system to the soil, which resulted in an increase in the water table. This was evident in piezometers A to E, given their close proximity to the leach pits. At piezometers G1 – G5, the soil profile was disturbed where the soil was mixed to create a level surface for future housing. As a consequence there were large dolerite and shale rocks brought near the soil surface (i.e. 0.90 m below the surface, as shown in Appendix 31) which limited the depth to which piezometers G1 to G4 could be installed. However there was a gap between the disturbed rocky material, where only piezometer G5 was installed to the original depth of the parent material at 2.00 m. Thus piezometers G1 and especially G2 – G4 often missed the near surface hillslope through-flow due to their limited depth, and only intercepted the near surface water movement after periods of prolonged high rainfall events.

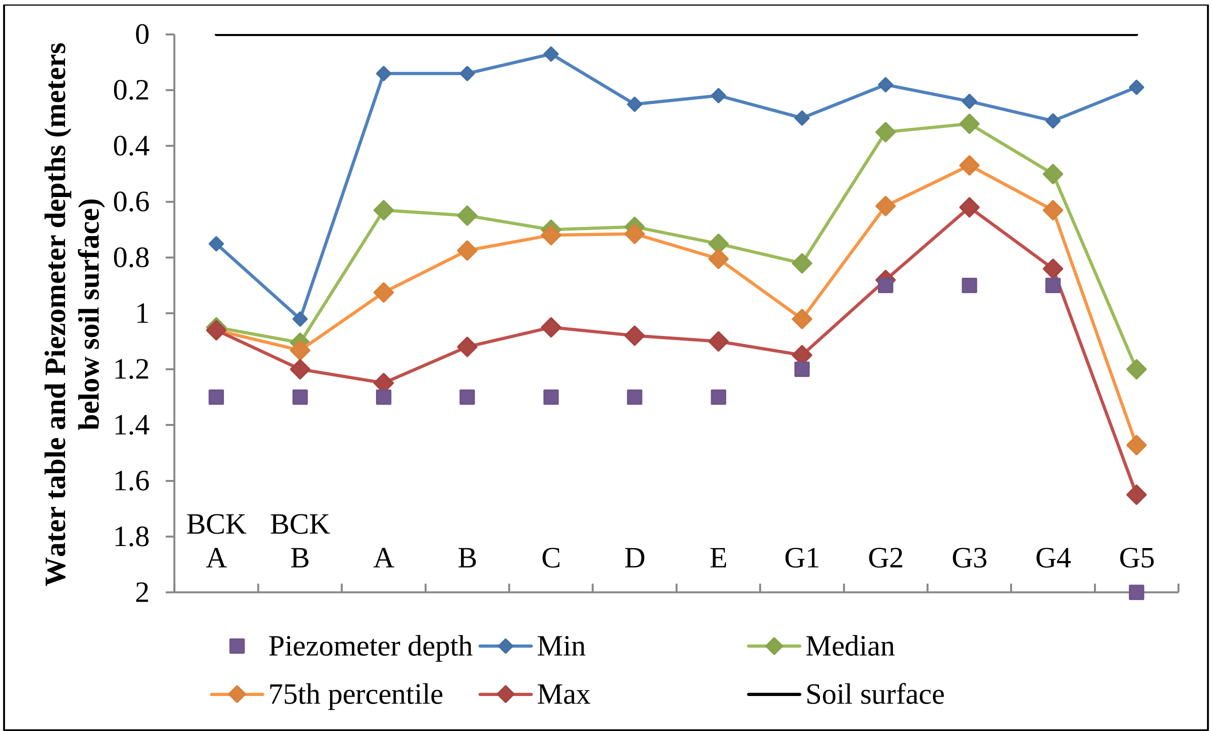

Figure 5.13 Water table and piezometer depths at the Crèche site

5.1.3. Azalea

The soil profile at the Azalea site was deep, which ranged from 6.10 m near the top of the study transect, to 1.60 m near the stream at the bottom. The soil form was identified as a Bloemdal according to the Taxonomic soil classification system for South Africa. The top soil, subsoil and parent material were identified as was an Orthic A, Red apedal B, Unspecified material with signs of wetness and Dolerite, respectively (Figure 5.14). The soil texture throughout the soil profile was clayey, where the clay percentage values ranged from 36 % - 62 %. The K_{sat} values at the soil surface, 0.50 m and 1.50 m were 1.65 cm/h, 0.46 cm/h and 0.41 cm/h, respectively. The distinct red colour in the Red apedal horizon indicated well drained conditions. However the underlying yellow mottling colour in the Unspecified material with signs of wetness material, indicated intermitted or prolonged saturation with water. The profile description and properties are summarised in Figure 5.14, where the diagnostic soil horizons are clearly defined.

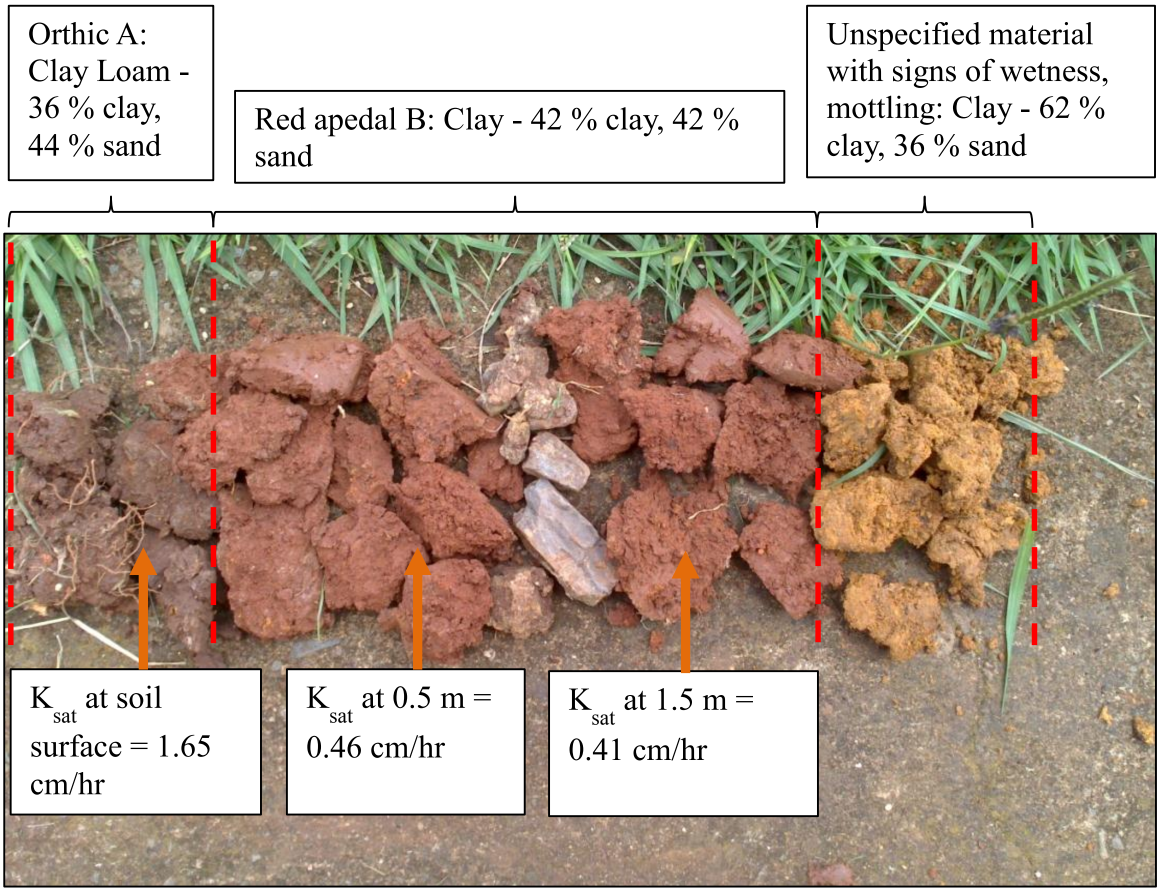

Figure 5.14 Azalea soil profile

The ERT data at the Azalea site revealed several areas of low resistance (i.e. 1.00 – 150.00 Ωm) which indicated groundwater (Figure 5.15). There was a clear zone of wet soil within the first 7 meters of soil between electrode positions 0 – 77 (i.e. from the top of the hillslope to stream 1). The continuous region of wet soil indicated near surface hillslope through-flow in which the pour-flush leach pits were located. There was a distinct plume of groundwater immediately downslope of the pour-flush leach pits (i.e. red dashed circle), which indicated a clear supply of water to the surrounding soil (Figure 5.15). There was also a sewerage pipe running across the bottom of the hillslope. Lastly there was a small wetland located between the bottom of the study transect and stream 1, which acted as a buffer zone for the pour-flush contaminants traveling towards the stream *via* the near surface hillslope through-flow (Figure 5.15).

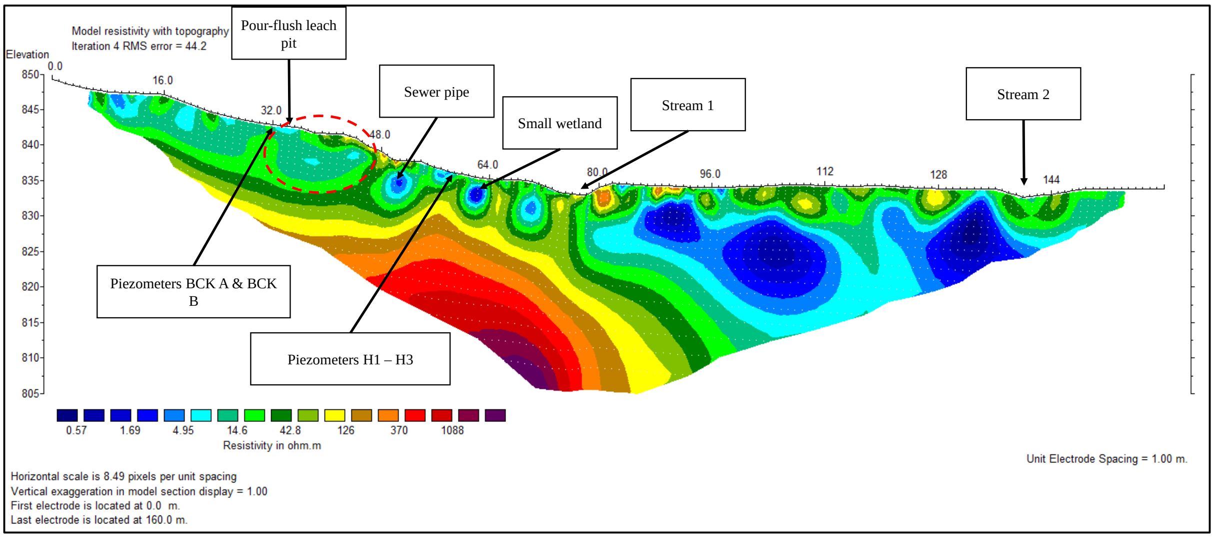

Figure 5.15 ERT image for the Azalea site

The isotope data at the Azalea site fell consistently along the meteoric water line (Figures 5.16 and 5.17). The isotope values from the rainfall, wetting front detectors, piezometers and stream samples overlapped consistently with each other and indicated similar isotope signatures. This revealed that there was connectivity between the rainfall, the near surface hillslope through-flow and the nearby stream. Furthermore, the near surface hillslope through-flow was primarily supplied by water from the rainfall and not deeper groundwater resources.

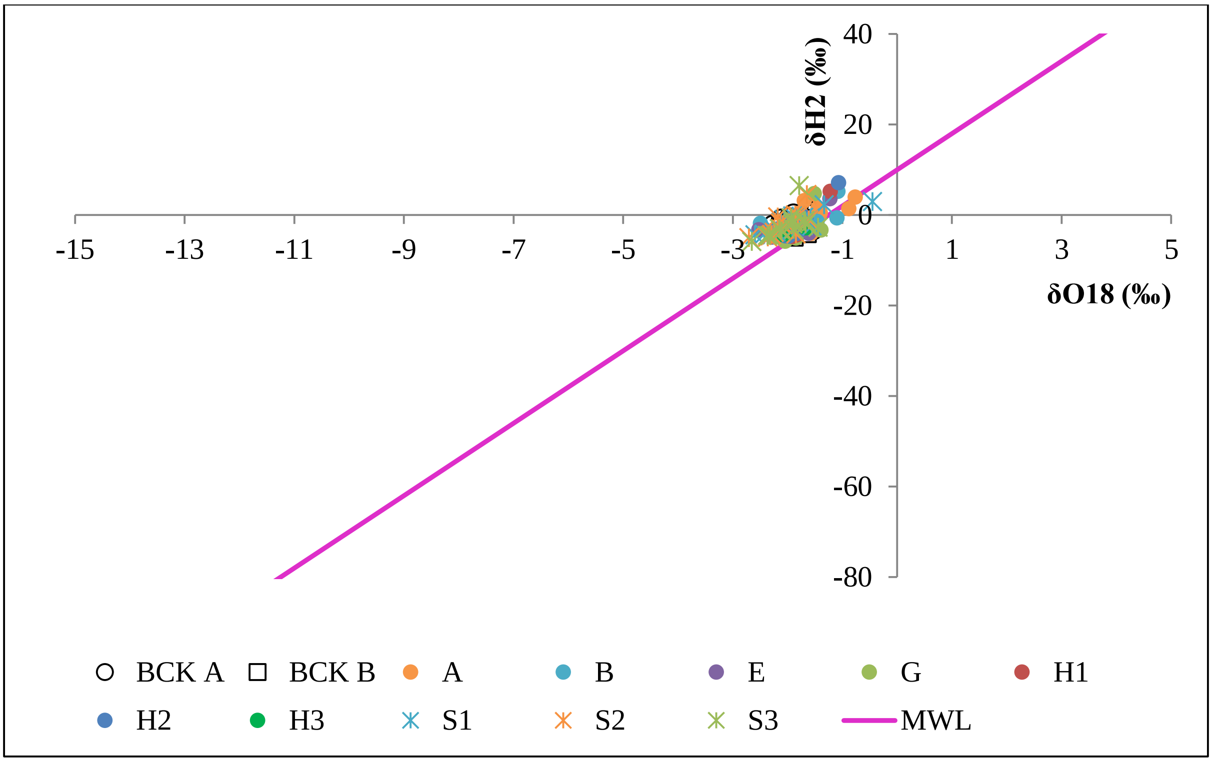

Figure 5.16 Isotope values for the piezometers BCK A – H3 and stream samples at the Azalea site

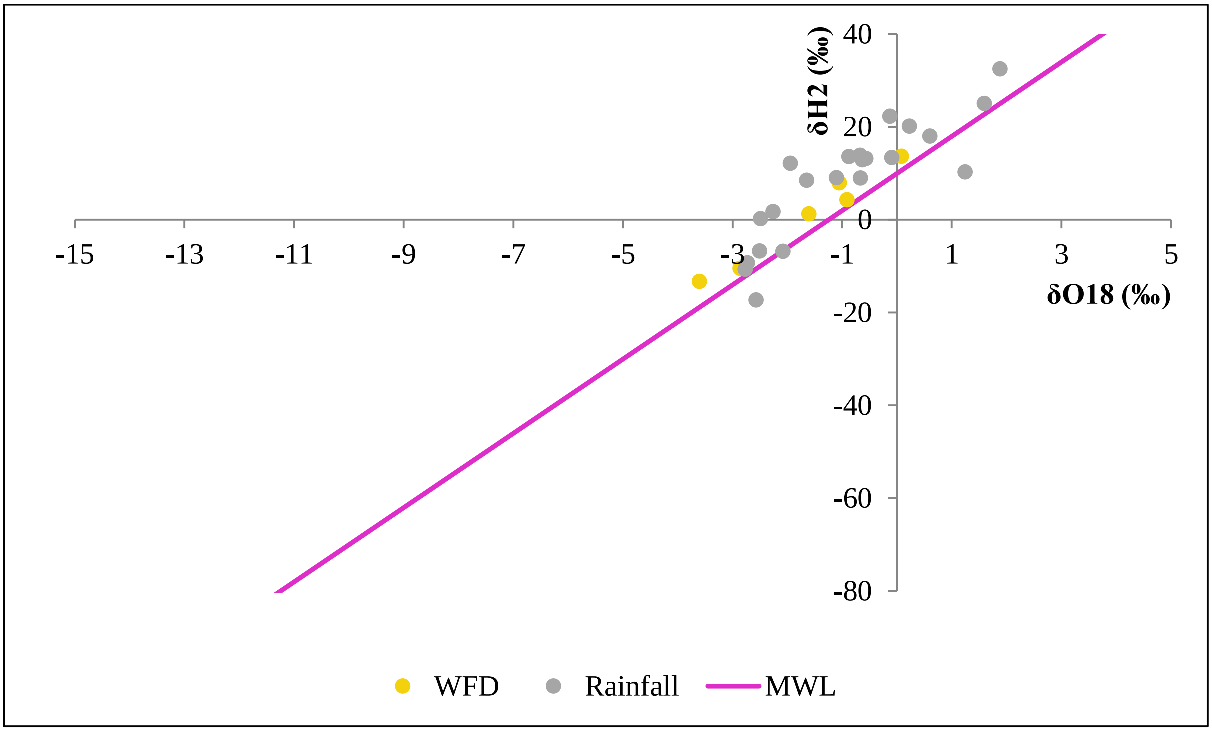

Figure 5.17 Isotope values for the wetting front detectors and rainfall at the Azalea site

The pH and ORP values in the near surface hillslope through-flow ranged from 5.66 to 7.39 and -33.00 mV to 300.00 mV respectively. The soil below the on-site system, fluctuated between a wet and waterlogged soil environment, based on the pH-ORP soil diagram from Baas-Becking *et al*. (1960) (Figure 5.18). The near surface hillslope through-flow was less anaerobic compared to the Slangspruit and Crèche sites, where only on two occasions the ORP values were slightly negative (i.e. -5.00 mV and -33.00 mV at piezometers H1 and G respectively).

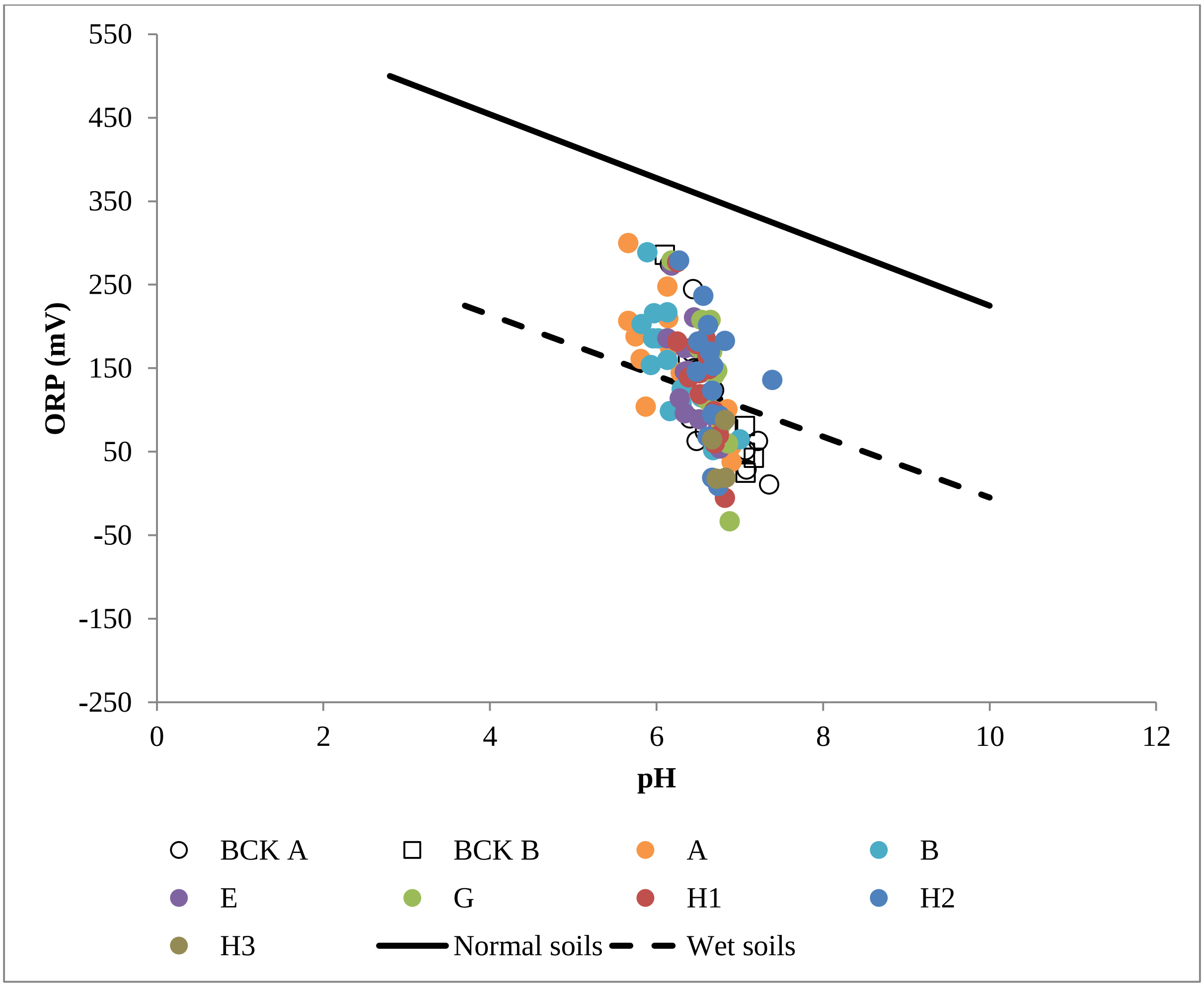

Figure 5.18 pH-ORP values for piezometers BCK A – H3 at the Azalea site

The water table remained low throughout the study period and never breached the soil surface, given the *.ca* 6 m of soil above the water table (Figure 5.19). The leach pits supplied water to the soil and caused a minor increase in the water table level (Figure 5.19). This was evident in piezometers A and B, given their close proximity to the leach pits. However the water table level at piezometer H3 remained low and seldom exhibited any water (Figure 5.19.

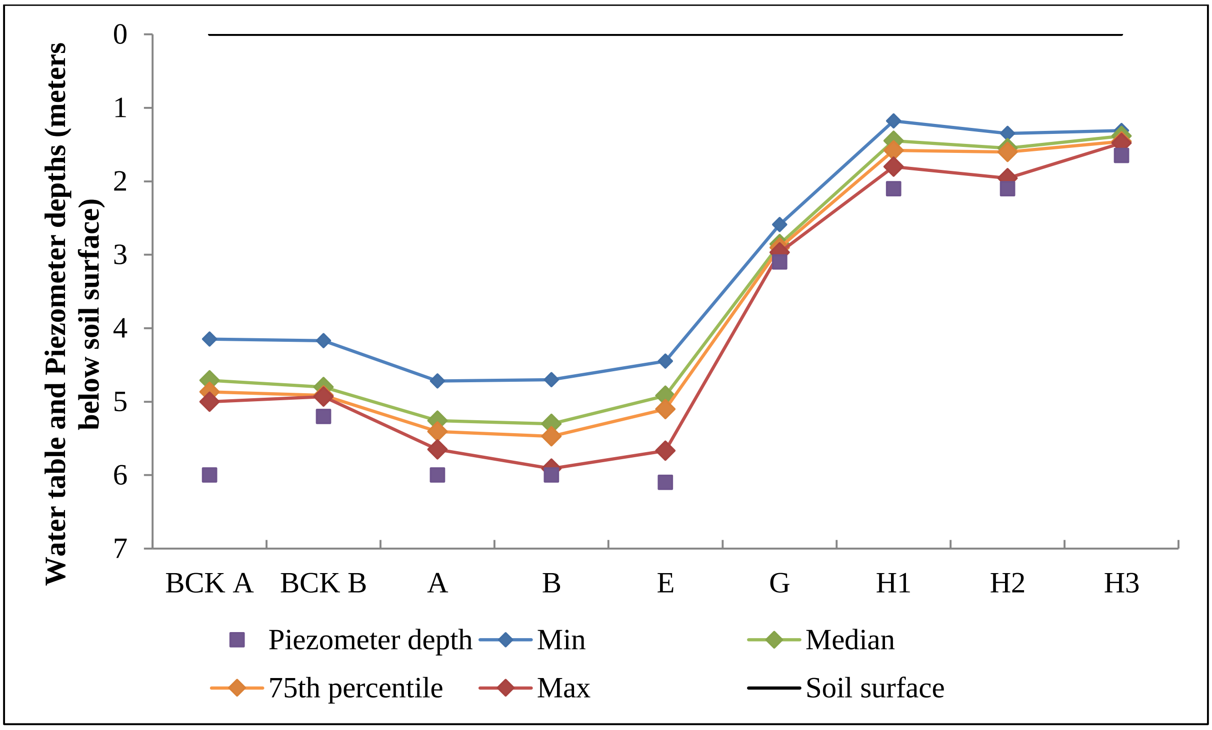

Figure 5.19 Water table and piezometer depths at the Azalea site

5.1.4. Taylors Halt and Taylors Halt Control

The soil profile at the Taylors Halt site was deep, which consisted of 1.00 m, 8.50 m and 1.50 m thick soil profile at the top, middle and bottom of the hillslope respectively. Furthermore, the study transect occupied the entire hillslope from the crest to the toe, where the soil form changed down the hillslope. At the crest, the profile consisted of an Orthic A top soil, Yellow-brown apedal B and Unspecified sub soils, and was identified as a Clovelly soil form according to the Taxonomic soil classification system for South Africa. Further down from the crest, the soil form was a Hutton and consisted of an Orthic A top soil, Red apedal B and Unspecified (i.e. saprolite) sub soils (Figure 5.20). Near the bottom of the hillslope, the soil form was a Bloemdal and consisted of an Orthic A top soil, Red apedal B and Unspecified material with signs of wetness sub soils (Figure 5.20). At the toe of the hillslope, the soil form was a Katspruit and consisted of an Orthic A top soil, Dark brown G and Gleying G sub soils (Figure 5.20).

Soil texture throughout the hillslope was clayey, where the clay percentage values ranged from 32 % - 60 %. The K_{sat} values throughout the hillslope ranged from 0.68 cm/h – 0.87 cm/h, 0.11 cm/h – 1.01 cm/h and 0.51 cm/h – 1.04 cm/h at the soil surface, 0.50 m and 1.50 m depths respectively (Figure 5.20). The distinct red colour in the Red apedal b soil horizon indicated well drained conditions throughout the hillslope. However near the bottom of the hillslope there were signs of wetness in the soil layer resting on the parent material, which indicated intermitted or prolonged saturated conditions. At the toe of the hillslope there was completely reduced subsoil horizon in the soil near the stream, where the water table was near the soil surface. The profile description and properties are summarised in Figure 5.20, where the different diagnostic soil horizons are clearly defined.

The Taylors Halt Control site exhibited a similar clayey soil profile to the Taylors Halt site near the bottom of the hillslope. The soil profile was shallow (i.e. 1.50 m) from the top to the near bottom of the hillslope, which extended down to 3.00 m. The soil form was classified as a Bloemdal, and consisted of an Orthic A top soil, Red apedal B and Unspecified material with signs of wetness sub soils, underlying a Gleying G Horizon (Figure 5.21). The profile description and properties are summarised in Figure 5.21, where the different diagnostic soil horizons are clearly defined.

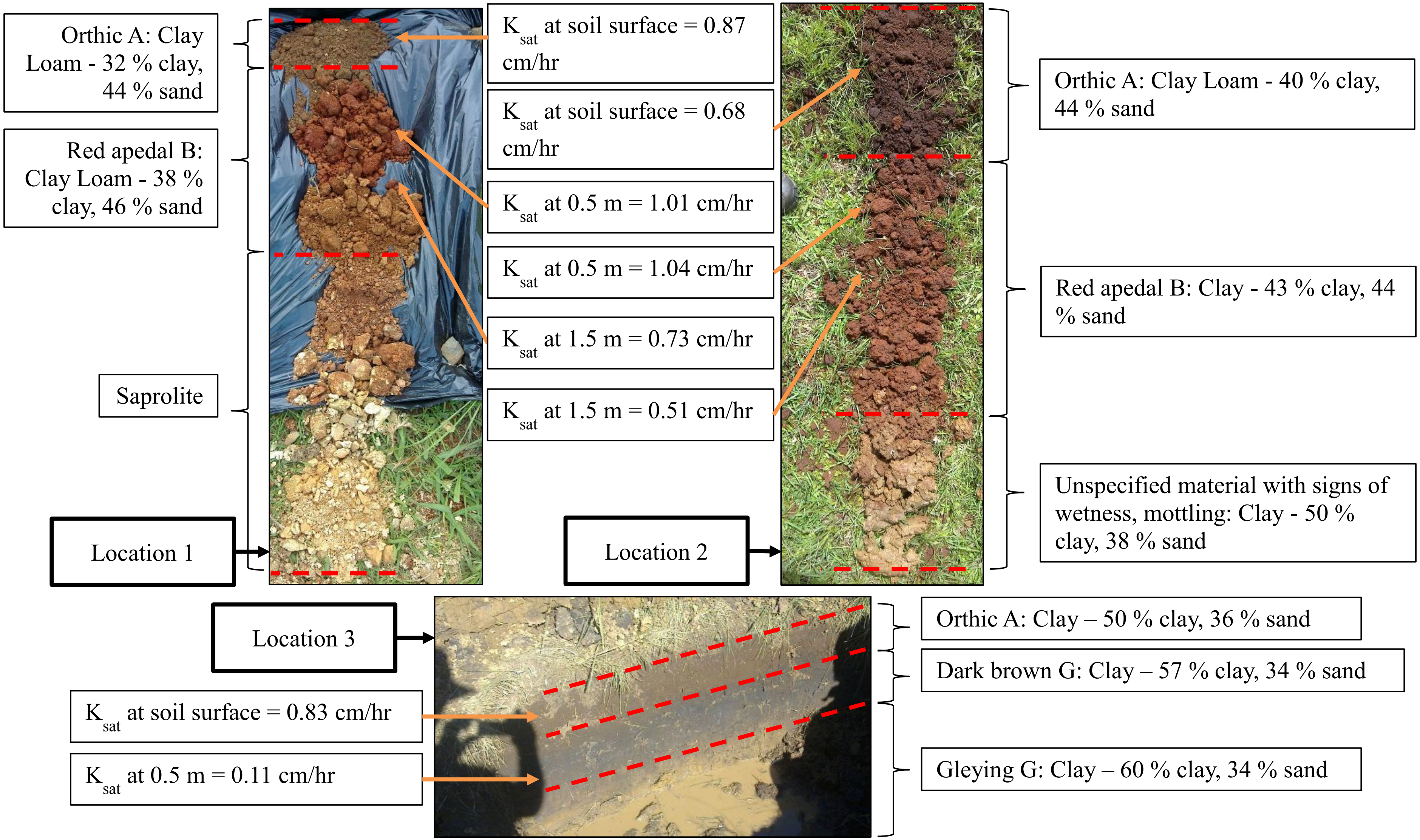

Figure 5.20 Taylors Halt soil profile

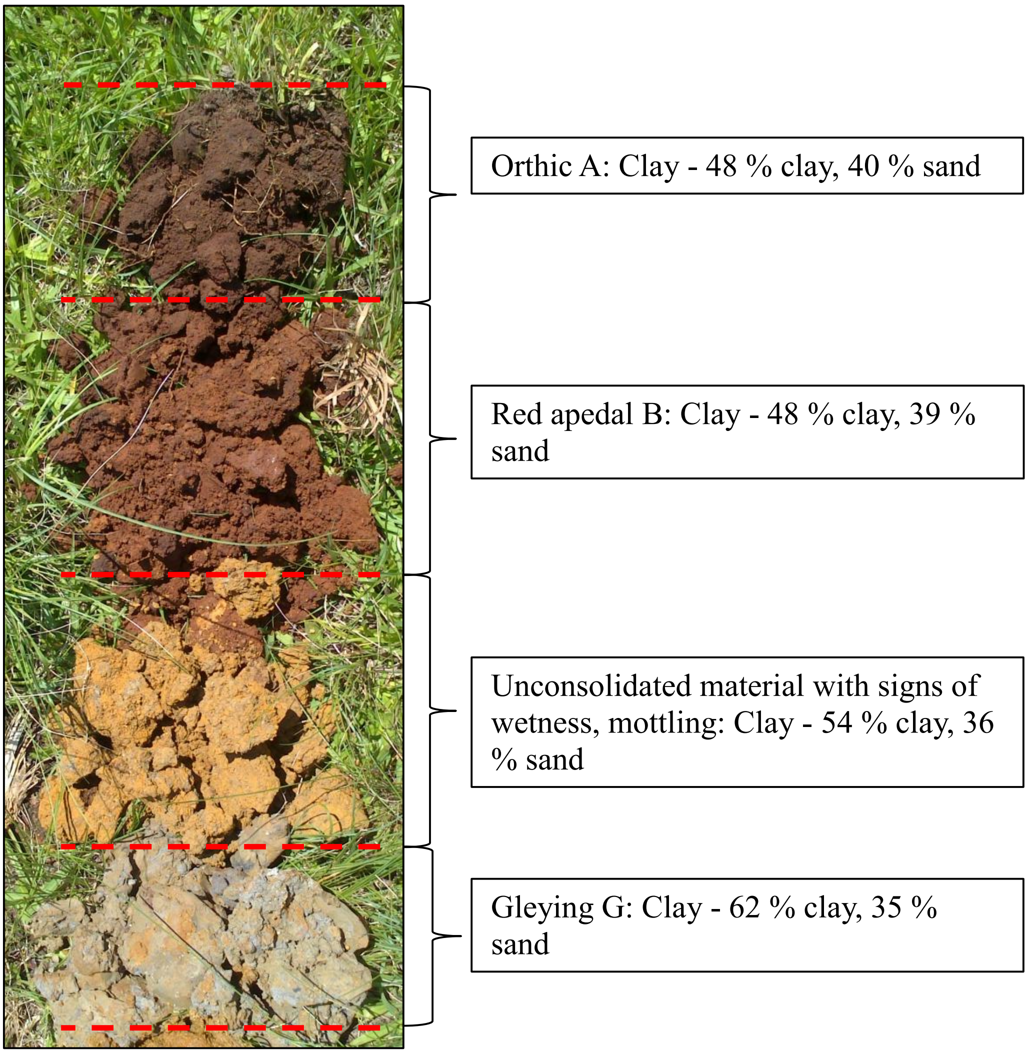

Figure 5.21 Taylors Halt Control soil profile

The ERT data at the Taylors Halt site revealed several areas of low resistance (i.e. 1 – 150 Ωm) which indicated the presence of groundwater (Figures 5.22 and 5.23). With regards to Transect 1 (Figure 5.22) there was a clear region of wet soil at 8.00 m or more between electrodes 50 - 194. Piezometer VIP3 E2 was the highest piezometer up the hillslope to intercept the hillslope through-flow between electrodes 50 – 194. The remainder of the piezometers upslope of VIP3 E2 failed to a produce a single water sample, which indicated that they were not deep enough to intercept the through-flow. At the toe of the hillslope (i.e. electrodes 12 – 50) there was a shallow region of unsaturated soil approximately 3.00 m thick, which rested upon a section of dolerite rock. This section of soil was occasionally partially saturated after prolonged periods of high rainfall. The dolerite intrusion at electrodes 12 – 50 inhibited the downslope movement of the groundwater, and was forced to travel across the hillslope (i.e. towards the reader) and surface at the seepage face. Furthermore, there was a small region of wet soil (i.e. low Ωm resistance) around the VIP leach pits, which indicated the movement of effluent from the systems, into the surrounding soil. However this region of wet soil was not as large and distinct as the wet soil surrounding the pour-flush leach pits at the Azalea site. This was due to the typical higher water use in the pour-flush systems, compared to the VIP systems which do not require water to function. Transect 2 (Figure 5.23) described the inhibited groundwater at the toe (i.e. by the dolerite intrusion) which travelled across the hillslope and surfaced at the seepage face further down.

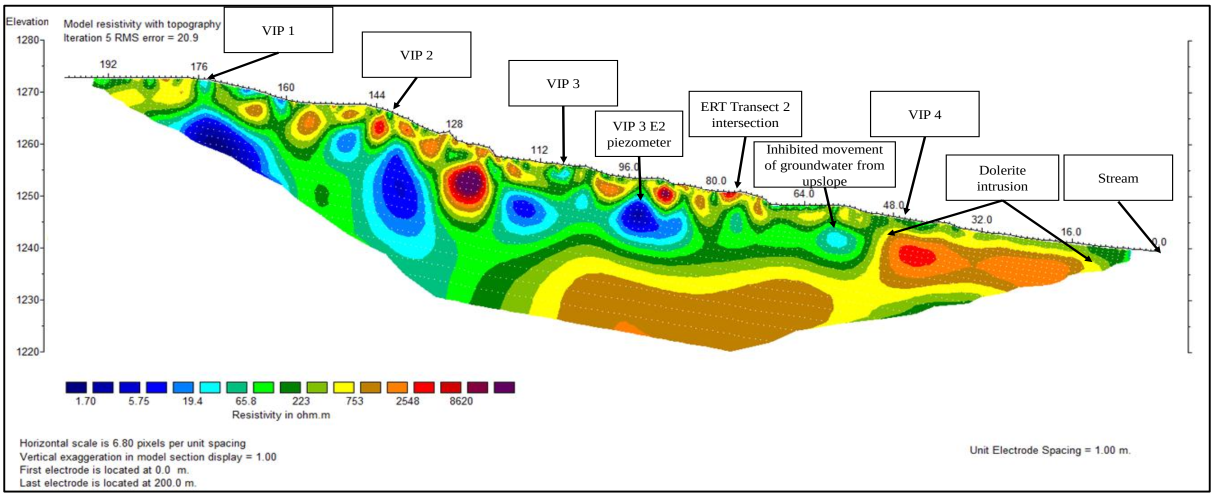

Figure 5.22 ERT image of Transect 1 at the Taylors Halt site

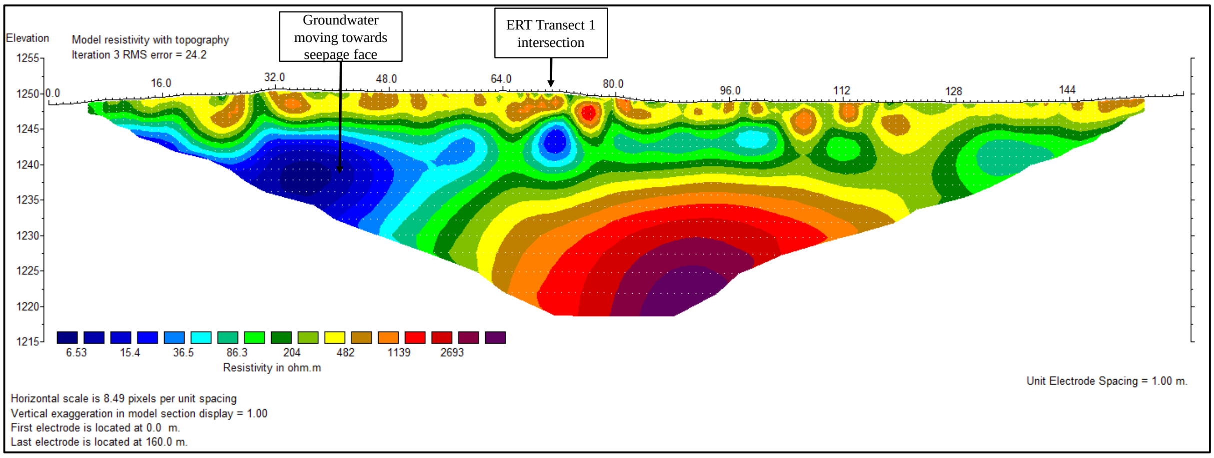

Figure 5.23 ERT image of Transect 2 at the Taylors Halt site

The isotope data at the Taylors Halt and Taylors Halt Control sites site fell consistently along the meteoric water line (Figures 5.24 and 5.25). The isotope values from the rainfall, wetting front detectors, piezometers and stream samples overlapped consistently with each other and indicated similar isotope signatures. This revealed that there was connectivity between the rainfall, the near surface hillslope through-flow and the nearby stream. This showed that the near surface hillslope through-flow was supplied by the rainfall.

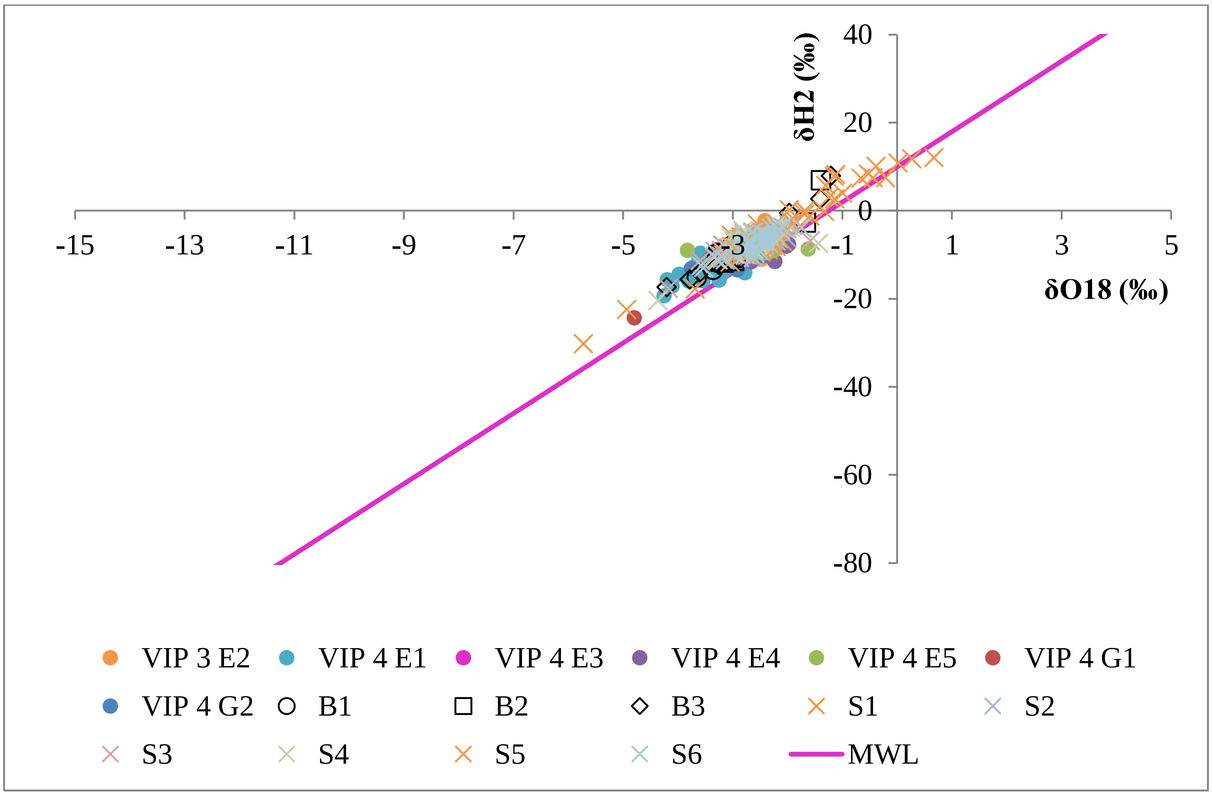

Figure 5.24 Isotope values for the piezometers and stream samples at the Taylors Halt and Taylors Halt Control sites

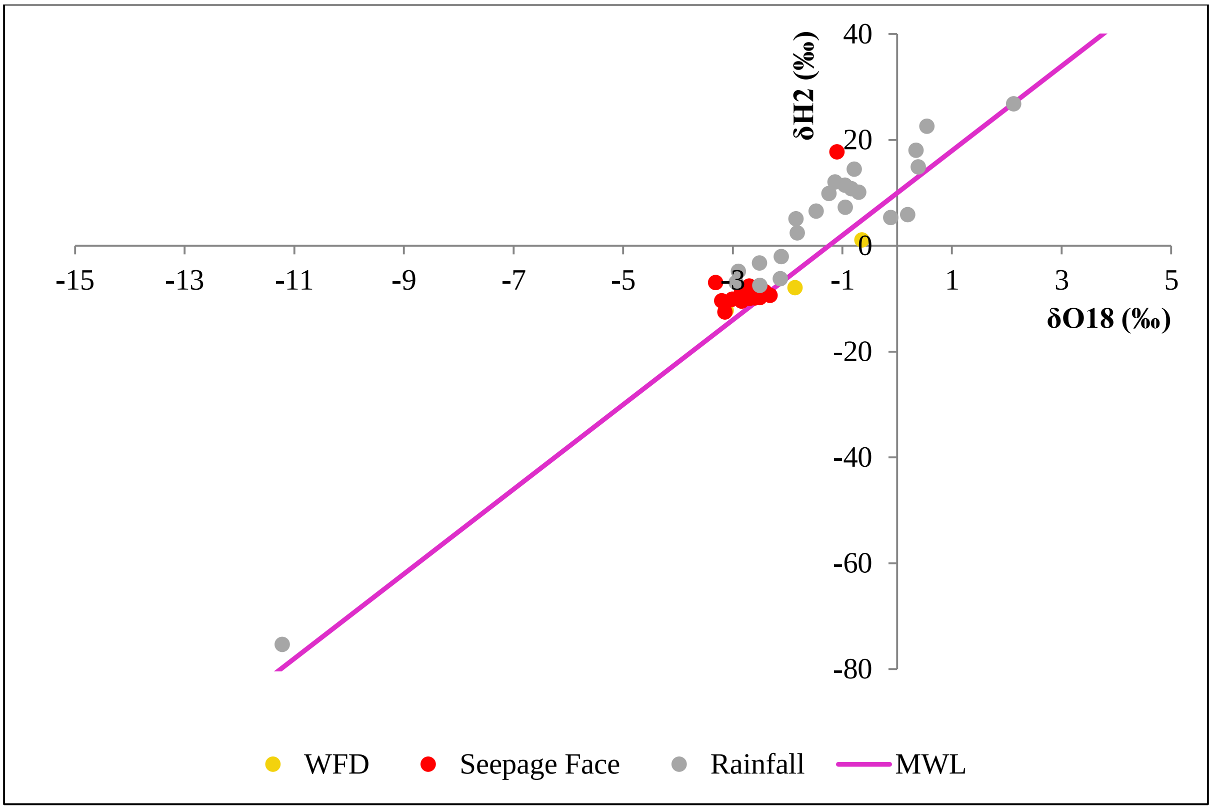

Figure 5.25 Isotope values for the rainfall, wetting front detector and seepage face at the Taylors Halt and Taylors Halt Control sites

The pH and ORP values in the near surface hillslope through-flow ranged from 5.81 to 7.74 and -65.00 mV to 267.00 mV respectively. The soil below the on-site systems, fluctuated between a wet and waterlogged soil environment, based on the pH-ORP soil diagram from Baas-Becking *et al*. (1960) (Figure 5.26). Similar to the Azalea site, the near surface hillslope through-flow was less anaerobic compared to the Slangspruit and Crèche sites, where all the piezometers exhibited a positive ORP value for the majority of the time. Occasionally piezometers B2, B3, VIP4 E4, VIP4 E5 and VIP4 G2 exhibited a negative value, but no more than -65 mV.

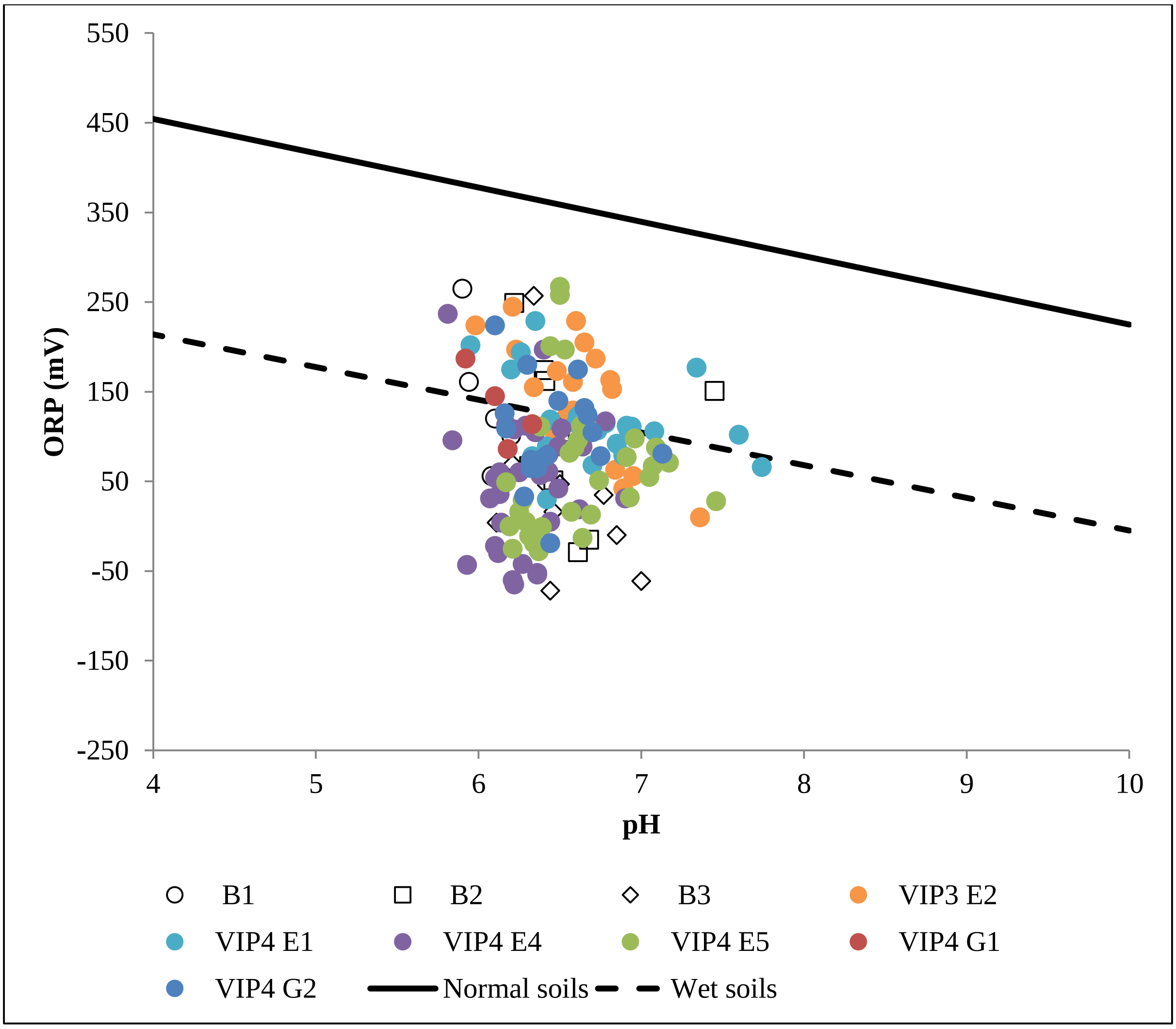

Figure 5.26 pH-ORP values for piezometers B1 – H3 at the Taylors Halt and Taylors Halt Control sites

The water table was only present at piezometer VIP3 E2 and several piezometers downslope of that position (Figure 5.27). Piezometers VIP4 E4 and VIP4 E5 (which intercepted the through-flow at the seepage face) had water at every sampling event, however VIP4 E1, VIP4 G1 and VIP4 G2 exhibited intermitted water samples, which indicated the water shedding impact caused by the dolerite intrusion as described in the ERT images. There was no impact from the VIP systems on the water table level, which was expected considering the vast soil depth between the VIP latrine leach pits and the top of the water table. The water table levels in the piezometers near the toe of the hillslope remained relatively unchanged throughout the study period (Figure 5.27).

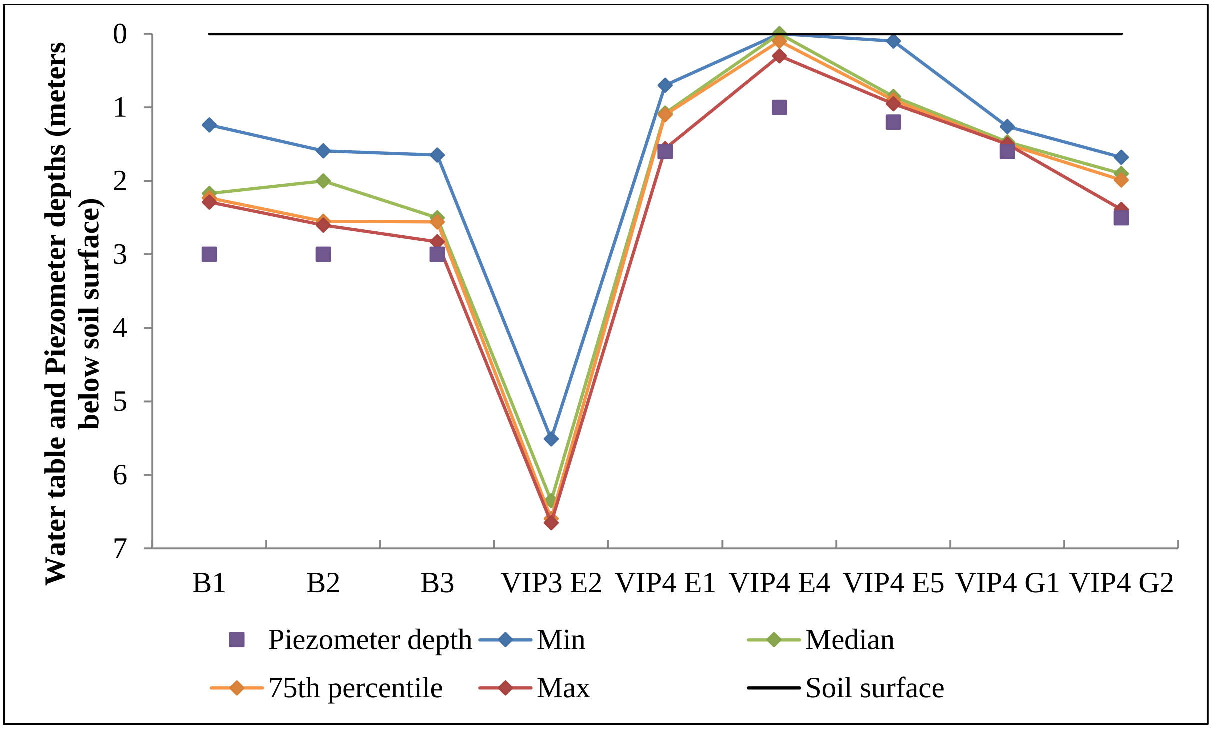

Figure 5.27 Water table and piezometer depths at Taylors Halt and Taylors Halt Control

5.2. Water Sample Analyses

The water samples collected from all the study sites were analysed for several chemical parameters *viz*. NH_4^+, NO_3^-, PO_4^{3-}, SO_4^{2-}, Cl^-, Ca^{2+}, Mg^{2+}, Na^+, K^+ and electrical conductivity, as well as *Escherichia coli* (*E.coli*). All this data was used to produce a set of graphs which described the lateral extent of the on-site sanitation contaminants and the chemical plume in the near surface hillslope through-flow. Figure 5.28 describes the components of the box and whisker plot graphs used to present the water sample analysis data. The mean and standard deviation for the water analyses at each sampling location is presented in Appendices.

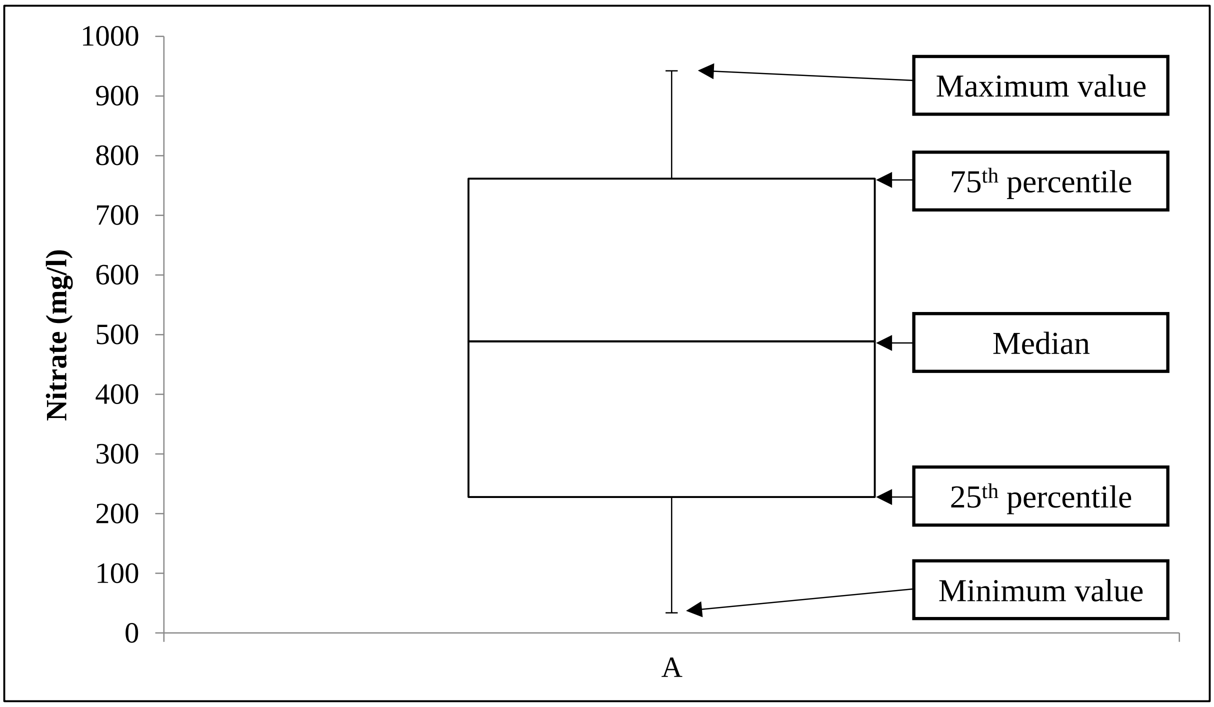

Figure 5.28 Nitrate example for box and whisker plot graph

5.2.1. Slangspruit

At the Slangspruit site, piezometers BCK A, A1, A2, B1, C2, D1, H1, H2 and H3 all exhibited high maximum nitrate values, above the 48 mg/l acceptable drinking water limit (Figure 5.29). Piezometers B2 and C1 exhibited relatively low nitrate values (i.e. < 20 mg/l) but high maximum ammonium values of 240.29 mg/l and 990.64 mg/l, respectively (Figure 5.29 and Figure 5.30). The low sulphate (Figure 5.31) and ORP values at B2 and especially C1 indicated a highly reduced environment at these piezometers which prevent any significant nitrification from occurring. It was speculated that the localised high nitrate value at BCK A was from the close proximity of a chicken pen installed after the installation of piezometer BCK A (Figure 5.29). Similarly it was speculated that the high nitrate values at H1, H2 and H3 was from the frequent defecation of pigs, goats and other domestic animals around the respective piezometers (Appendix 32). In both these cases, the wetting front detectors were unable to capture the animal waste suspended in the surface run-off at piezometers BCK A, H1, H2 and H3, and it was speculated that a portion of the localised contaminated run-off infiltrated the surface between the soil and the pipe wall of affected piezometer, during periods of high rainfall. Nevertheless by comparison to the background values and wetting front detectors, there was a clear nitrate impact from the pour-flush system, in the near surface hillslope through-flow (Figure 5.29). The impact was consistently high up to piezometer B1 (i.e. 75 % of the values were > 333.59 mg/l), and extended infrequently to piezometer D1. There was no clear nitrogen impact from the pour-flush system beyond piezometer D1 (Figures 5.29 and 5.30).

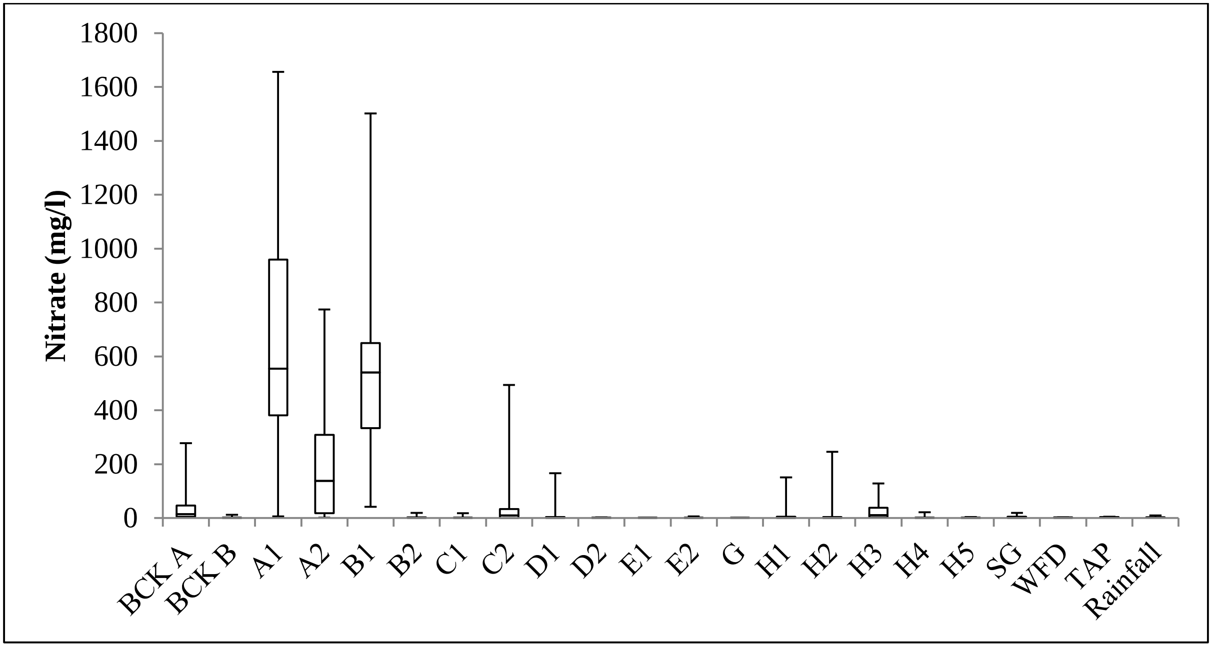

Figure 5.29 Nitrate (NO_3^-) values for the Slangspruit site

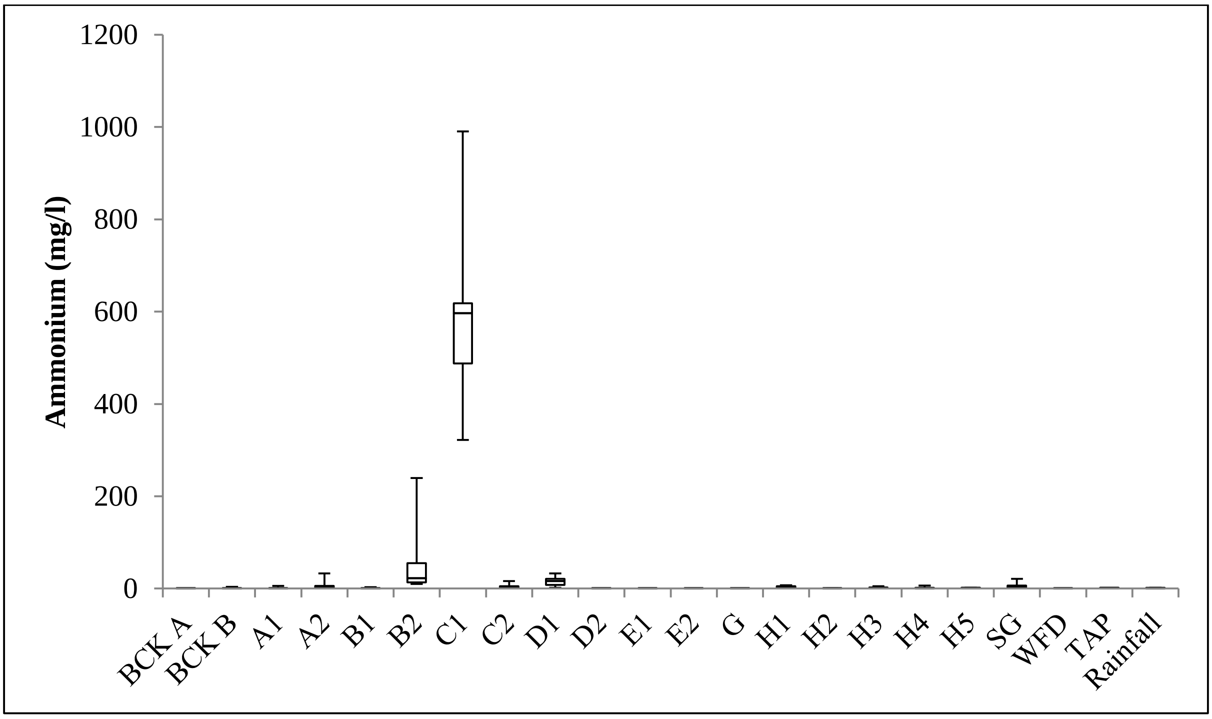

Figure 5.30 Ammonium (NH_4^+) values for the Slangspruit site

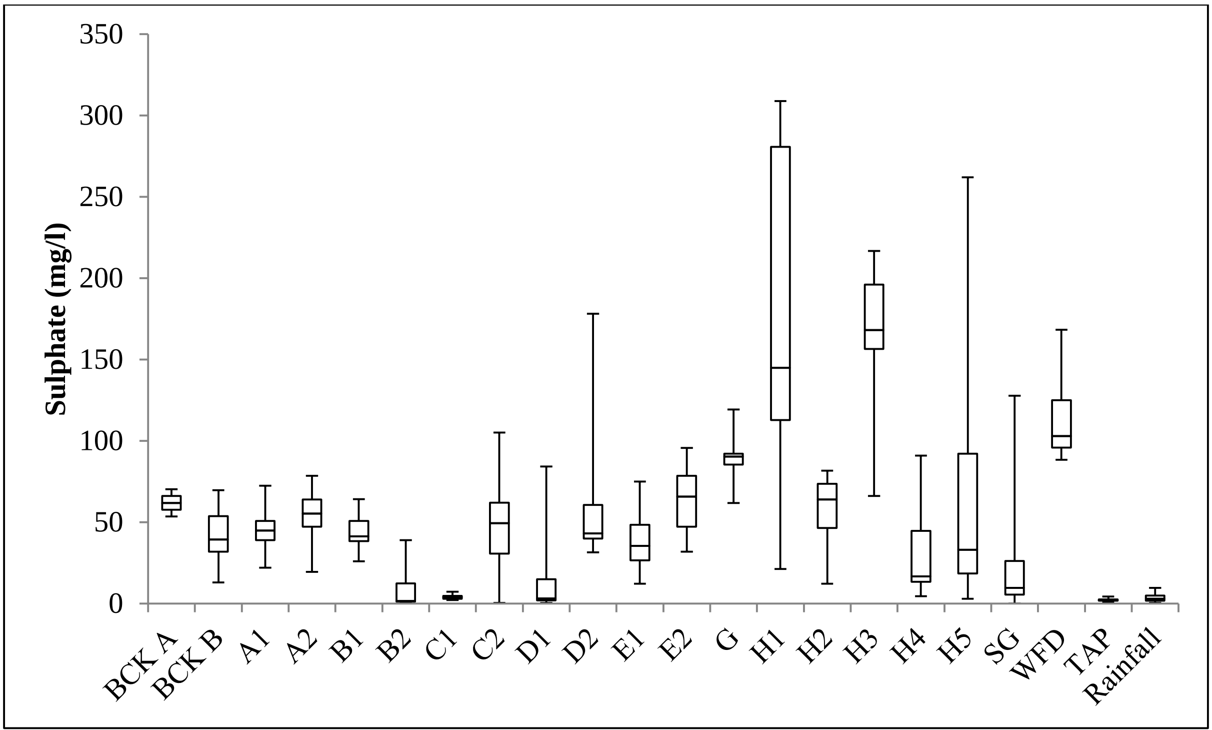

Figure 5.31 Sulphate (SO_4^{2-}) values for the Slangspruit site

At the Slangspruit site, all the piezometers (except G) exhibited maximum phosphate values above the 0.30 mg/l limit for eutrophication (Figure 5.32). Piezometers B1, B2, C1, D1, H1, H3, H4, H5 all exhibited high maximum phosphate values, relative to the other piezometers (Figure 5.32). Piezometer C1 exhibited consistently high phosphate values (i.e. 75 % of the values were above 26.62 mg/l), due to its close proximity to the leach pit and its highly reduced environment. At this piezometer, there were low sulphate and ORP values, where the iron, in iron bonded phosphate compounds, became reduced under prolonged anaerobic conditions and released phosphate ions into the surrounding soil solution. This was also the case for the high phosphate values at piezometers B2 and D1. It was speculated that the high maximum phosphate values at H1 and H3 was attributed to the defecation of domestic animals around these piezometers, given the significantly low phosphate values between piezometers D1 and H1 (Figure 5.32). The high maximum values at piezometers H4 and H5 was due to their close proximity to the surface gutter (i.e. SG) which was regularly used for the disposal of grey water that contained phosphate from washing detergents and the like (Figure 5.32). Furthermore, it was speculated that the slightly high phosphate value in the rainfall was due to the occasional defecation of birds into the plastic rain gauge. Nevertheless by comparison to the background values and wetting front detectors, there was a clear phosphate impact from the pour-flush system, in the near surface hillslope through-flow (Figure 5.32). The impact was consistently high up to piezometer C1 (i.e. 75 % of the values > 26.62 mg/l), and extended infrequently to piezometer D1. There was no clear phosphate impact from the pour-flush system beyond piezometer D1.

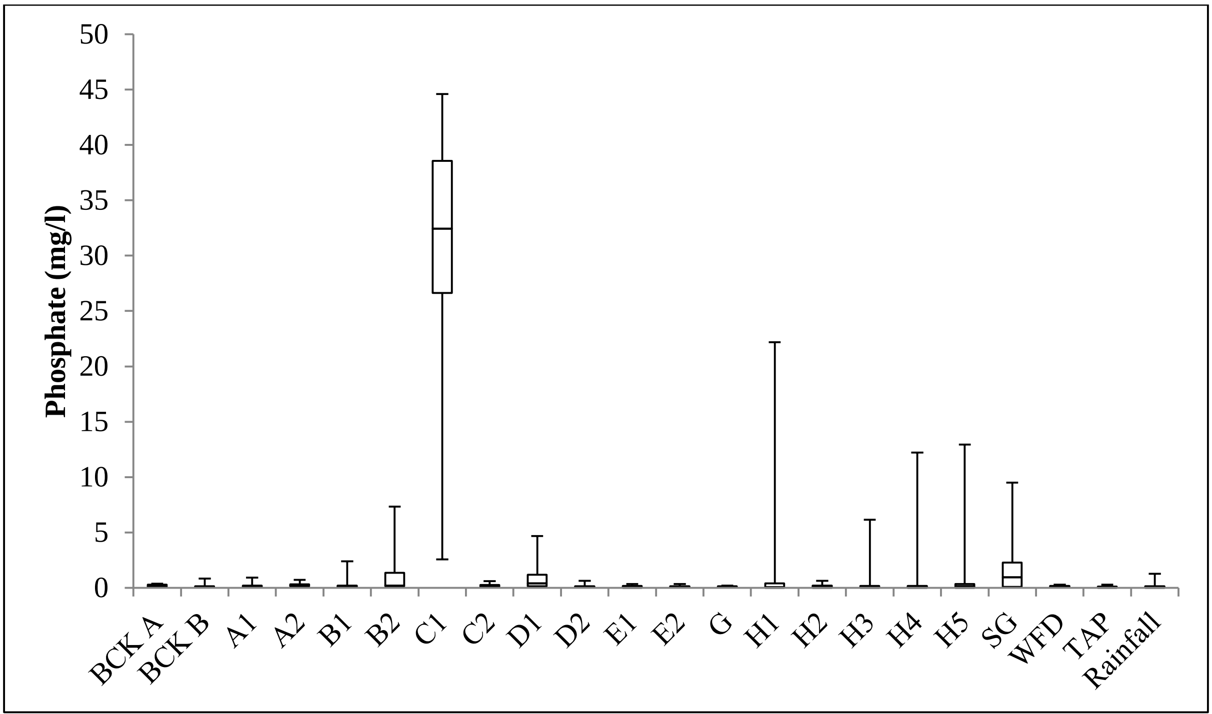

Figure 5.32 Phosphate (PO_4^{3-}) values for the Slangspruit site

At the Slangspruit site, all the piezometers exhibited maximum values above the 0 bacteria/100ml limit (Figure 5.33). Piezometers BCK A, BCK B, C1, D1, E1, E2, G, H1, H2, H4 and H5 all exhibited high maximum *E.coli* values, relative to the other piezometers (Figure 5.33). Piezometers BCK A, BCK B, H1, H2, H4 and H5 were all located outside of the fenced-off property where the pour-flush system was installed, and it was speculated that the defecation from the domestic animals resulted in the localised high *E.coli* values at these piezometers, during periods of high rainfall. This masked any *E.coli* values which originated from the pour-flush system at piezometers H1, H2, H4 and H5. On the other hand piezometers C1, D1, E1, E2 and G were located within the fenced-off property, and the high *E.coli* values at these piezometers were from the pour-flush system. Piezometer E1 exhibited consistently high *E.coli* values (i.e. 75 % of the values were > 3120.80 MPN/100ml), due to its close proximity to the leach pit, yet piezometer G exhibited consistently lower values (i.e. 75 % of the values were < 909.75 MPN/100ml). The *E.coli* impacted the near surface hillslope through-flow consistently up to piezometer E1, and extended infrequently to piezometer G or further (Figure 5.33).

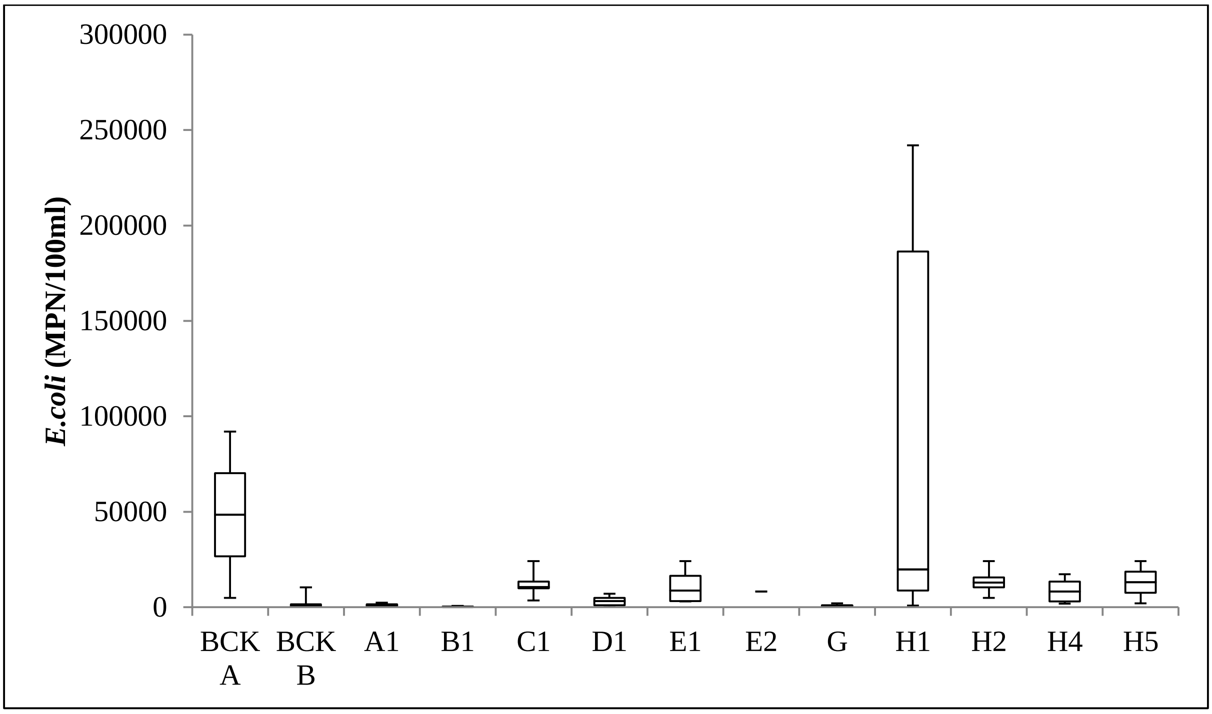

Figure 5.33 *E.coli* values for the Slangspruit site

At the Slangspruit site, the EC, SO_4^{2-}, Cl^-, Ca^{2+}, Mg^{2+}, Na^+ and K^+ analyses of the water samples revealed that the study site was noisy, however there was a noticeable pattern which was summarised by the electrical conductivity values (Figure 5.34). The highest median values for these analyses were observed in the piezometers near the leach pits of the pour-flush system (i.e. piezometers A1 – D2), and generally decreased in the piezometers at greater distances downslope of the system (Figure 5.34). Piezometers H1 – H5 were the exception, as it was speculated that they were contaminated by localised domestic animal defecation and the grey water in the surface gutter. In summary, by comparison to the background values and wetting front detectors, these water analyses indicated that there was a chemical plume in the near surface hillslope through-flow, which originated from the pour-flush system. Furthermore, piezometer E1 exhibited relatively low median values for EC, Cl^-, Mg^{2+}, Na^+ and K^+ compared to the remaining piezometers upslope, which indicated that the chemical plume was reduced noticeably at piezometer E1 (Figure 5.34).

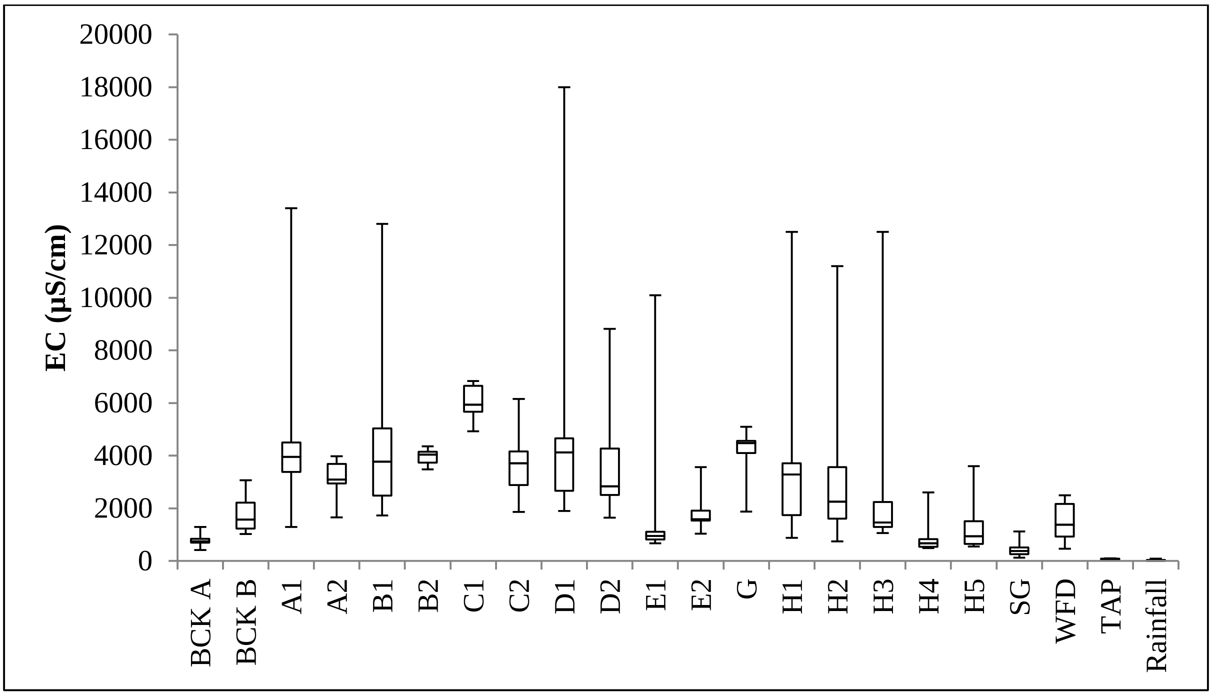

Figure 5.34 Electrical conductivity (EC) values for the Slangspruit site

5.2.2. Crèche

At the Crèche site, piezometers A, G1, G2, G3 and G4 all exhibited high maximum nitrate values, above the 48.00 mg/l acceptable drinking limit (Figure 5.35). Piezometer A exhibited consistently high nitrate values (i.e. 75 % of the values were > 123.46 mg/l), given its close proximity to the pour-flush leach pits (Figure 5.35). However piezometers B to E only exhibited intermitted high nitrate values after periods of high rainfall (i.e. 75 % % of the values were < 1.26 mg/l) (Figure 5.35). Similarly, piezometers G1 to G4 yielded a limited number of water samples, and only after periods of high rainfall, during which their elevated levels of nitrate were recorded. Piezometers BCK A, BCK B, A and B exhibited high maximum ammonium values relative to the remainder of the piezometers (Figure 5.36). The high ammonium values at piezometers BCK B and B was attributed to their low ORP values which indicated a moderately reduced environment, and prevented any significant nitrification from occurring. Furthermore, there was an unforeseen unimproved pit latrine leach pit built near piezometer BCK B (i.e. 1.50 m) after the piezometer was installed. This accounted for the relatively high ammonium values at piezometer BCK B. In addition, the relatively high nitrate values in the wetting front detectors indicated the suspension of domestic animal excreta and inorganic fertilizers in the surface run-off, however this had no apparent impact on the near surface hillslope through-flow at the site (Figure 5.35). Nevertheless by comparison to the background values, there was a clear nitrate impact from the pour-flush system, in the near surface hillslope through-flow (Figure 5.35). The impact was consistently high up to piezometer A (i.e. 75 % of the values were > 123.46 mg/l), and extended infrequently to piezometer G4 after periods of high rainfall.

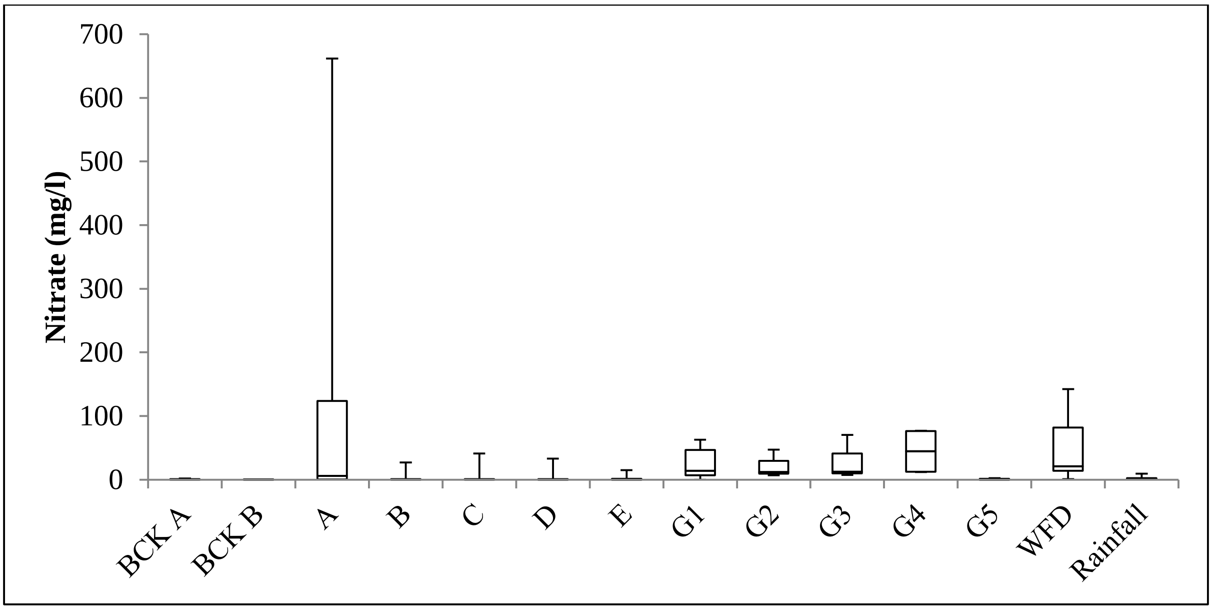

Figure 5.35 Nitrate (NO_3^-) values for the Crèche site

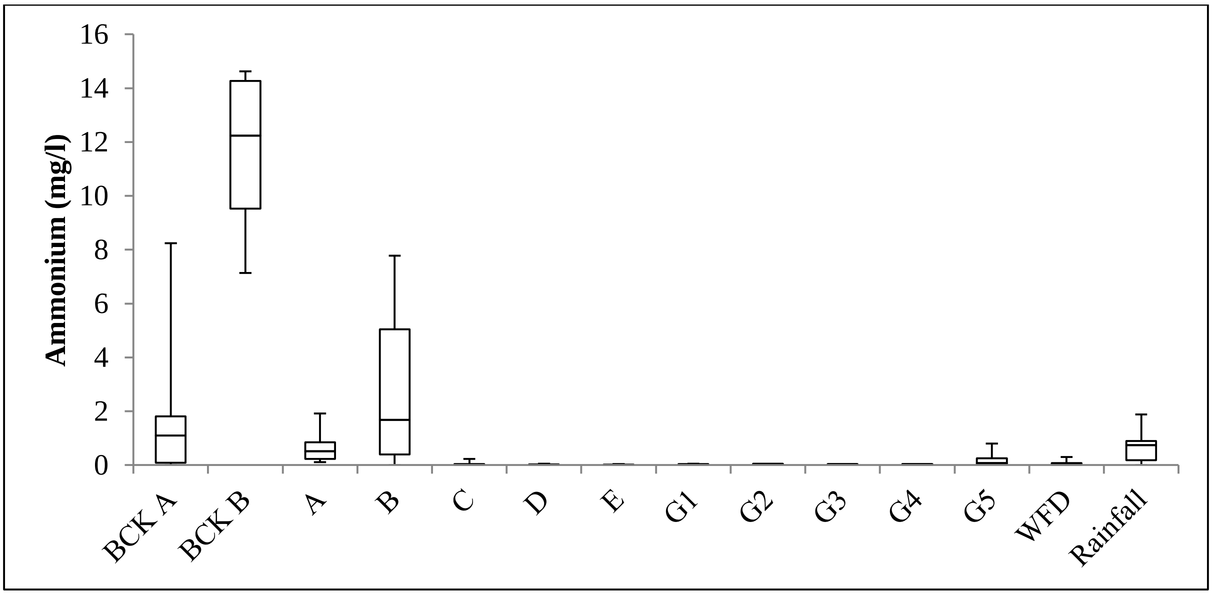

Figure 5.36 Ammonium (NH_4^+) values for the Crèche site

At the Crèche site, all the piezometers (except BCK A, G1, G2, G4 and G5) exhibited maximum phosphate values above the 0.30 mg/l limit for eutrophication (Figure 5.37). However none of the piezometers exhibited high phosphate values relative to the Slangspruit site (i.e. none of the piezometers exceeded 0.72 mg/l). The relatively high phosphate values at piezometers BCK B, A and B was attributed to their close proximity of the unimproved pit latrine and pour-flush system respectively. The relatively high phosphate values in the wetting front detector, indicated the suspension of domestic animal excreta and inorganic fertilizers in the surface run-off, however this had no apparent impact on the near surface hillslope through-flow at the site, except at piezometer BCK A (Figure 5.37). It was speculated that the relatively high phosphate value in the rainfall was due to the defecation from birds into the plastic rain gauges. Nevertheless, by comparison to the background values and wetting front detectors, there was no clear phosphate impact from the pour- flush system, in the near surface hillslope through-flow (Figure 5.37). There was a minor increase in the maximum phosphate values in piezometers A and B compared to the remaining downslope piezometers (Figure 5.37). This was due to their close proximity to the pour-flush leach pits.

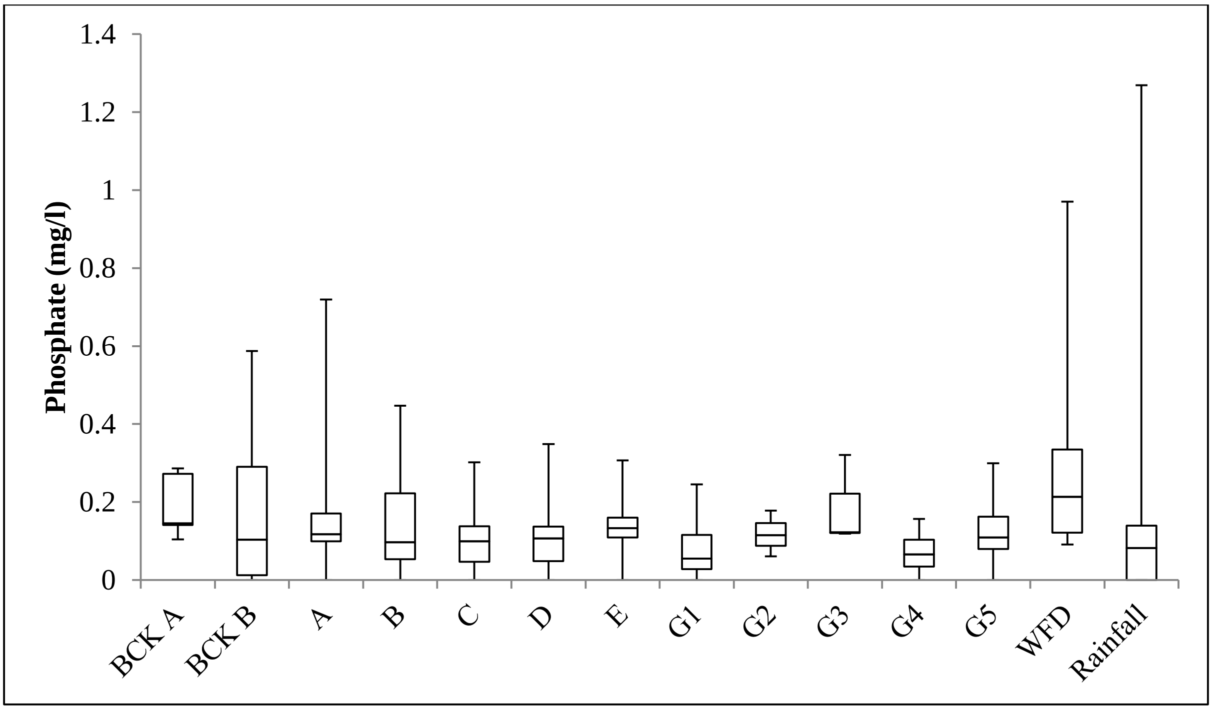

Figure 5.37 Phosphate (PO_4^{3-}) values for the Crèche site

At the Crèche site, all the piezometers exhibited maximum *E.coli* values above the 0 bacteria/100ml limit (Figure 5.38). Piezometers BCK A, BCK B, A and E exhibited relatively high maximum *E.coli* values (Figure 5.38). Piezometer A exhibited consistently high *E.coli* values (i.e. 50 % of the values were > 515.00 MPN/100ml), due to its close proximity to the pour-flush leach pit (Figure 5.38). The consistently high values at piezometer BCK B was attributed to its close proximity to the leach pit from the unimproved pit latrine. The once-off high value at piezometer E (i.e. 3106 MPN/100ml) may have been from the leach pit, but was more than likely from cross contamination, given that none of the piezometers from B to D exhibited a *E.coli* value anywhere near that measurement (i.e. none of the values were > 922MPN/100ml) (Figure 5.38). By comparison to the background values, there was no clear *E.coli* impact from the pour-flush system, in the near surface hillslope through-flow (Figure 5.38). However piezometer A exhibited consistently higher values compared to the piezometers downslope, which indicated a limited *E.coli* impact from the pour-flush system up to piezometer A, in the near surface hillslope through-flow (Figure 5.38).

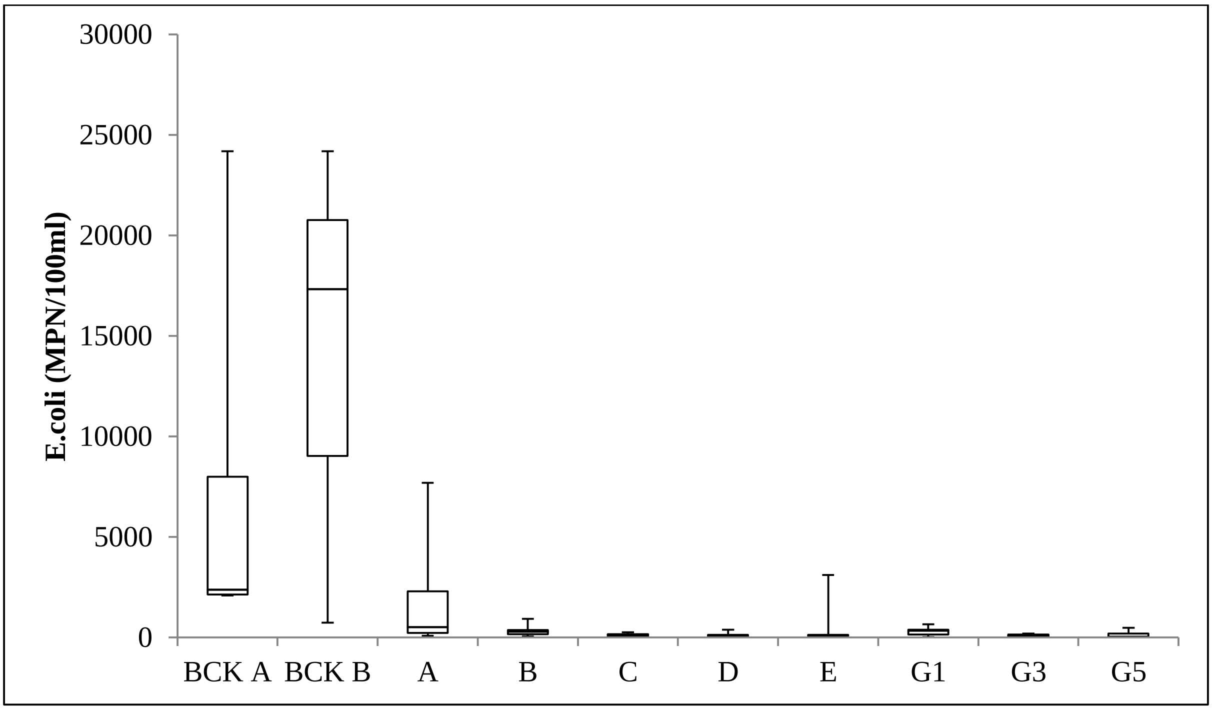

Figure 5.38 *E.coli* values for the Crèche site

At the Crèche site, the EC, SO_4^{2-}, Cl^-, Ca^{2+}, Mg^{2+}, Na^+ and K^+ analyses of the water samples revealed that the study site was noisy, however there was a noticeable pattern which was summarised by the electrical conductivity values (Figure 5.39). This pattern was more distinct compared to the Slangspruit site, which indicated that it was less noisy. The highest median values for these analyses were observed in the piezometers near the leach pits of the pour-flush system, and decreased in the piezometers at greater distances downslope of the system (Figure 5.39). This indicated that there was a chemical plume in the near surface hillslope through-flow, which originated from the pour-flush system. Furthermore, piezometer G5 exhibited higher EC, Cl^-, Ca^{2+}, Mg^{2+}, Na^+ and K^+ values, compared to G1 – G4, which indicated that the chemical plume from the leach pits extent to G5, where the deeper piezometer intercepted the near surface hillslope through-flow (Figure 5.39). In summary, by comparison to the background values and wetting front detectors, these water analyses indicated that there was a chemical plume in the near surface hillslope through-flow, which originated from the pour-flush system. Furthermore this plume expanded consistently up to piezometer G5 (Figure 5.39).

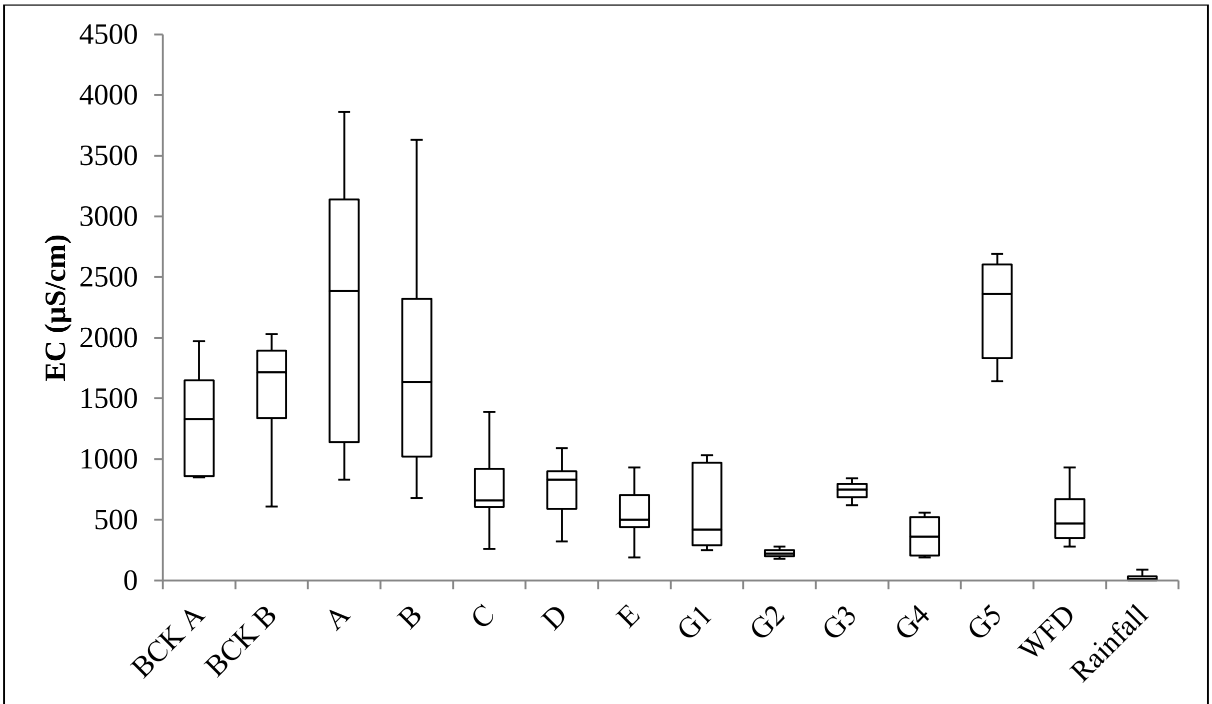

Figure 5.39 Electrical conductivity (EC) for the Crèche site

5.2.3. Azalea

At the Azalea site, piezometers BCK A, BCK B, A, B, E, G and H2 all exhibited high maximum nitrate values, above the 48 mg/l acceptable drinking limit (Figure 5.40). Piezometers A and B exhibited consistently high nitrate values (i.e. 75 % of the values were > 227.91 mg/l), due to their close proximity to the pour-flush leach pits (Figure 5.40). The remainder of the piezometers exhibited intermittent high values (i.e. 75 % of the values were < 24.38 mg/l)

(Figure 5.40). The ammonium values for all the piezometers was low (i.e. all the values were < 1.10 mg/l) (Figure 5.41), due to the consistently positive ORP values (i.e. minor reducing conditions) which allowed for significant nitrification to occur. The relatively high ammonium values in the wetting front detector indicated the suspension of ammonium fertilizers and animal excreta in the surface run-off, however this had no apparent impact on the near surface hillslope through-flow at the site (Figure 5.41). Nevertheless, by comparison to the background values and wetting front detectors there was a clear nitrate impact from the pour-flush system, in the near surface hillslope through-flow (Figure 5.40). The impact was consistently high up to piezometer B and extended infrequently to piezometer H2 (Figure 5.40). There was no clear nitrogen impact from the pour-flush system on the stream: the low nitrogen values indicated the dilution of any nitrogen that may have originated from the leach pit.

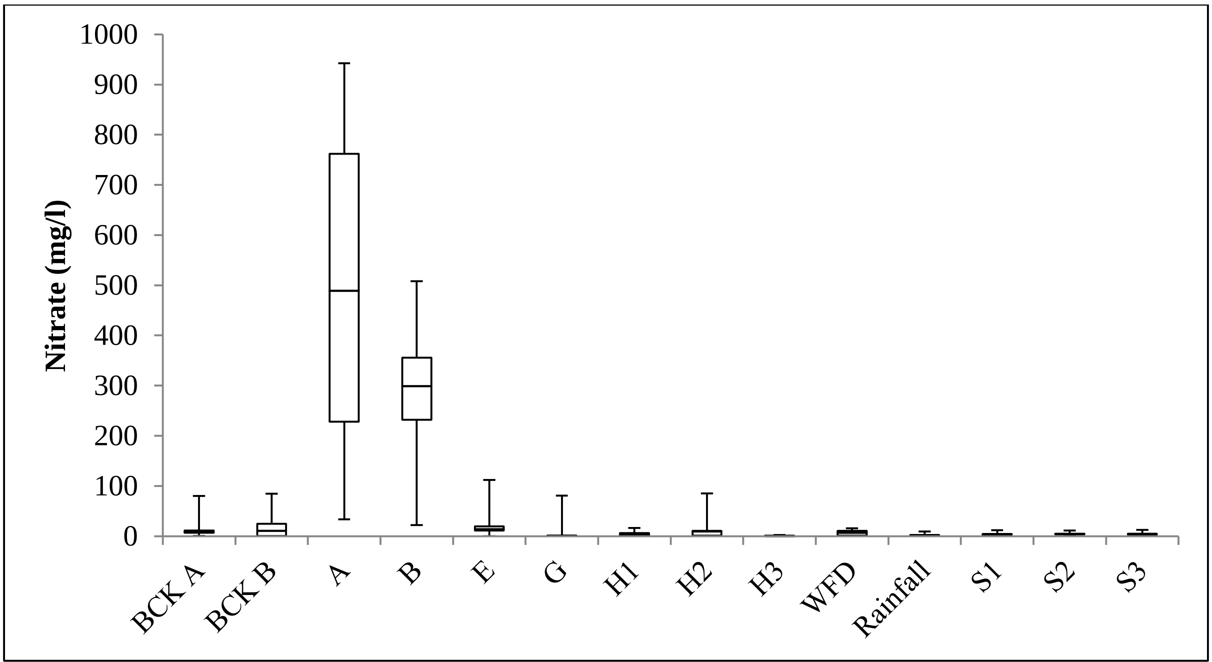

Figure 5.40 Nitrate values for the Azalea site

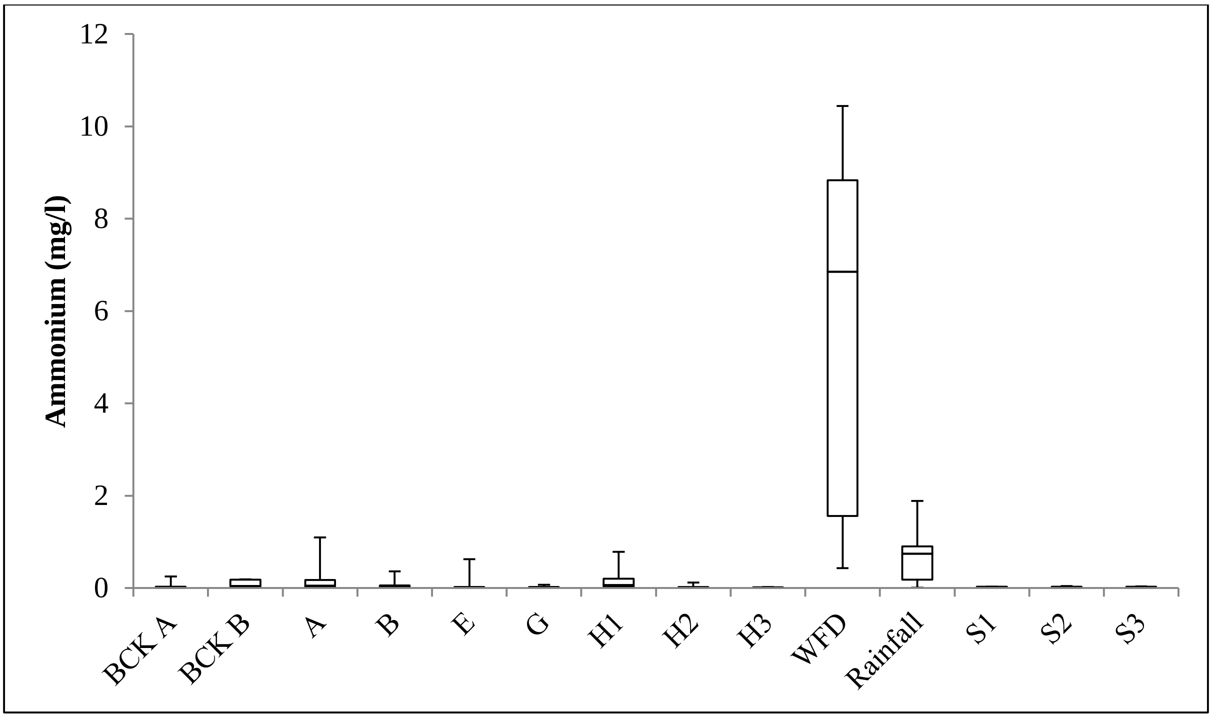

Figure 5.41 Ammonium values for the Azalea site

At the Azalea site, only piezometers BCK A, BCK B, A, B and E exhibited maximum phosphate values above the 0.30 mg/l limit for eutrophication (Figure 5.42). However none of the piezometers exhibited high phosphate values relative to the Slangspruit site (i.e. none of the values were > 0.50 mg/l) (Figure 5.42). Piezometers A, B and E exhibited the highest values compared to the remaining piezometers, and this was attributed to their close proximity to the pour-flush leach pits (Figure 5.42). The relatively high phosphate values in the wetting front detector, indicated the suspension of domestic animal excreta and inorganic fertilizers in the surface run-off. However this had no apparent impact on the near surface hillslope through-flow at the site (Figure 5.42). It was speculated that the relatively high phosphate value in the rainfall was due to the defecation of birds into the plastic rain gauges. Nevertheless, by comparison to the background piezometers, there was a minor phosphate impact from the pour-flush system, in the near surface hillslope through-flow (Figure 5.42). This minor impact extended to piezometers A, B and E, but not beyond.

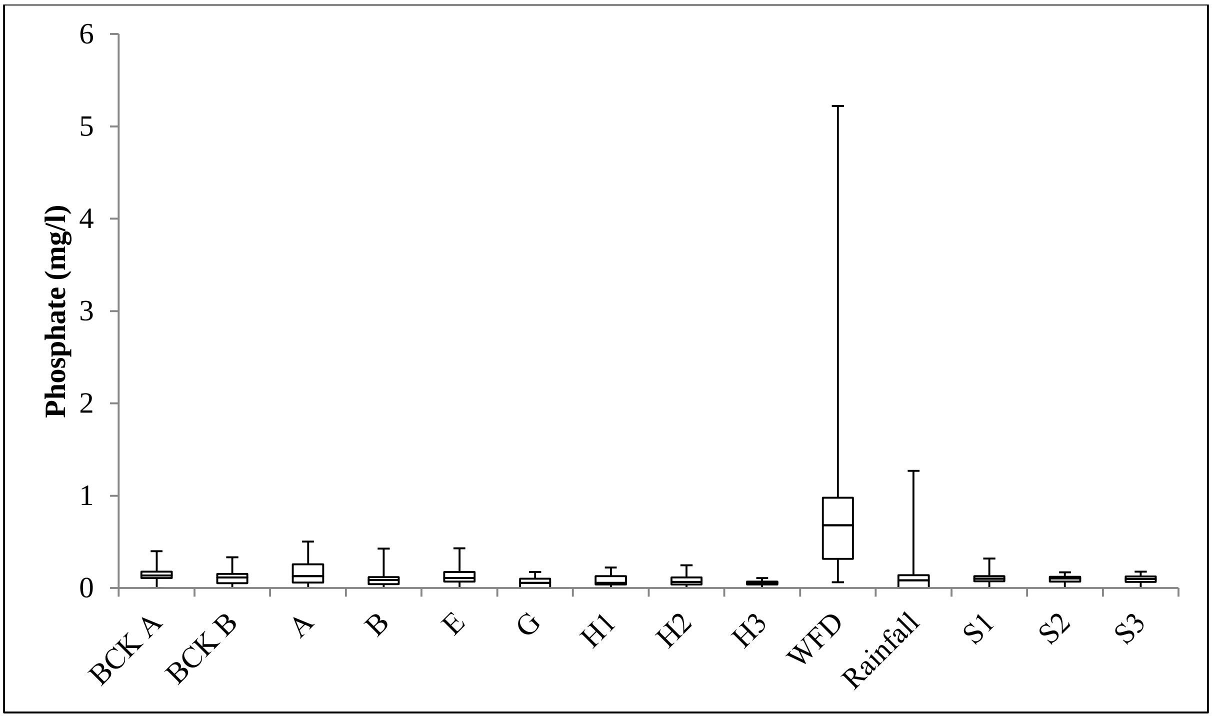

Figure 5.42 Phosphate values for the Azalea site

At the Azalea site, all the piezometers exhibited maximum *E.coli* values above the 0 bacteria/100 ml limit (Figure 5.43). Piezometers BCK A, A and B exhibited high maximum *E.coli* values (Figure 5.43). Piezometers A and B exhibited consistently high *E.coli* values (i.e. 50 % of the values were >1012.50 MPN/100ml), due to their close proximity to the pour-flush leach pits (Figure 5.43). The outlier value at piezometer BCK A was likely to have come from cross contamination, as this piezometer was located within a secure premises and was not subjected to any form of vandalism from human or domestic animal activities. By comparison to the background values, there was a clear *E.coli* impact from the pour-flush system, in the near surface hillslope through-flow (Figure 5.43). However the *E.coli* impact was limited up to piezometer E, where background values were reached (Figure 5.43). There were higher *E.coli* values in the nearby stream compared to several of the piezometers (Figure 5.43). However it is unlikely that the *E.coli* from the pour-flush system reached the stream, given that piezometers E – H2 exhibited lower *E.coli* values than the stream (Figure 5.43), which would dilute any contaminants that reached the stream. Thus the higher *E.coli* values were attributed to the regular defecation of domestic animals in the area, either directly into the stream or *via* suspension of the material in the surface run-off after a rainfall event in the area upstream.

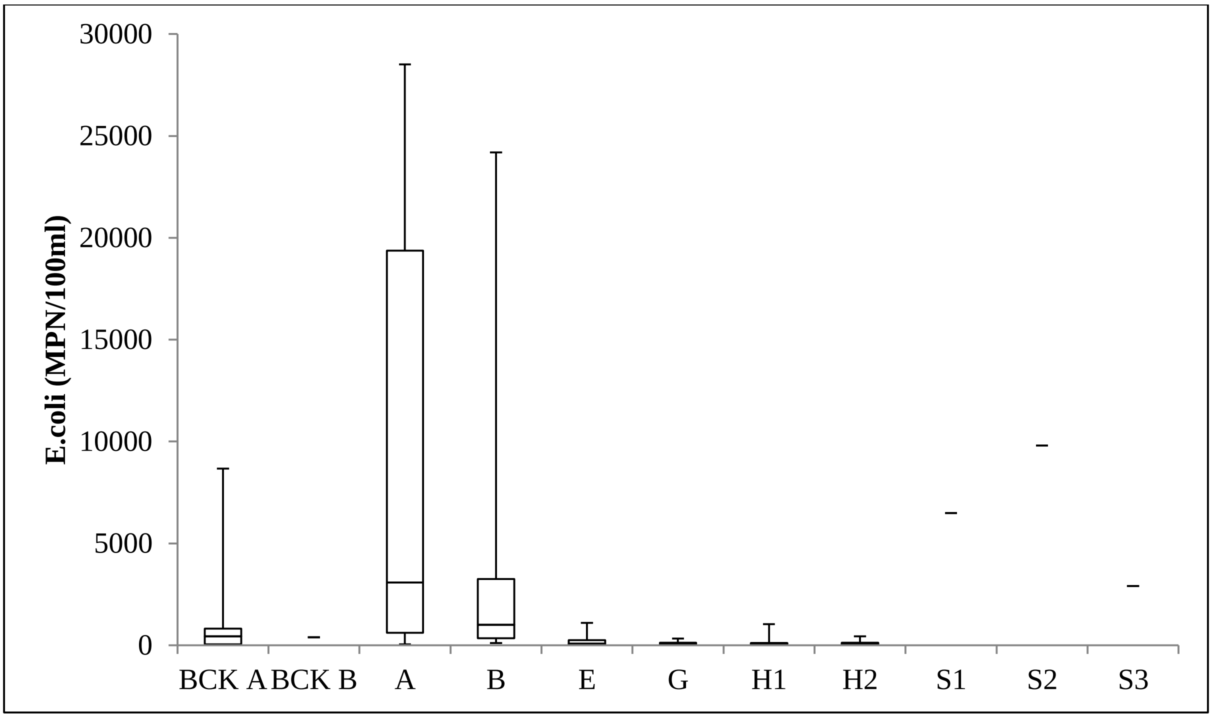

Figure 5.43 *E.coli* values for the Azalea site

At the Azalea site, the EC, SO_4^{2-}, Cl^-, Ca^{2+}, Mg^{2+}, Na^+ and K^+ analyses of the water samples revealed that the study site was considerably less noisy than the previous 2 study sites. At this site there was a distinct pattern in the values which was summarised by the electrical conductivity values (Figure 5.44). High median values for these analyses were observed in the piezometers near the pour-flush system, which decreased in the piezometers at greater distances downslope of the system (Figure 5.44). This indicated that there was a chemical plume in the near surface hillslope through-flow, which originated from the pour-flush system. Furthermore, the chemical plume only extended to piezometer E, where background values were reached (Figure 5.44). The stream samples exhibited low EC, SO_4^{2-}, Cl^-, Ca^{2+}, Mg^{2+}, Na^+ and K^+ values, and indicated a diluting effect on any chemical species that may have reached the stream.

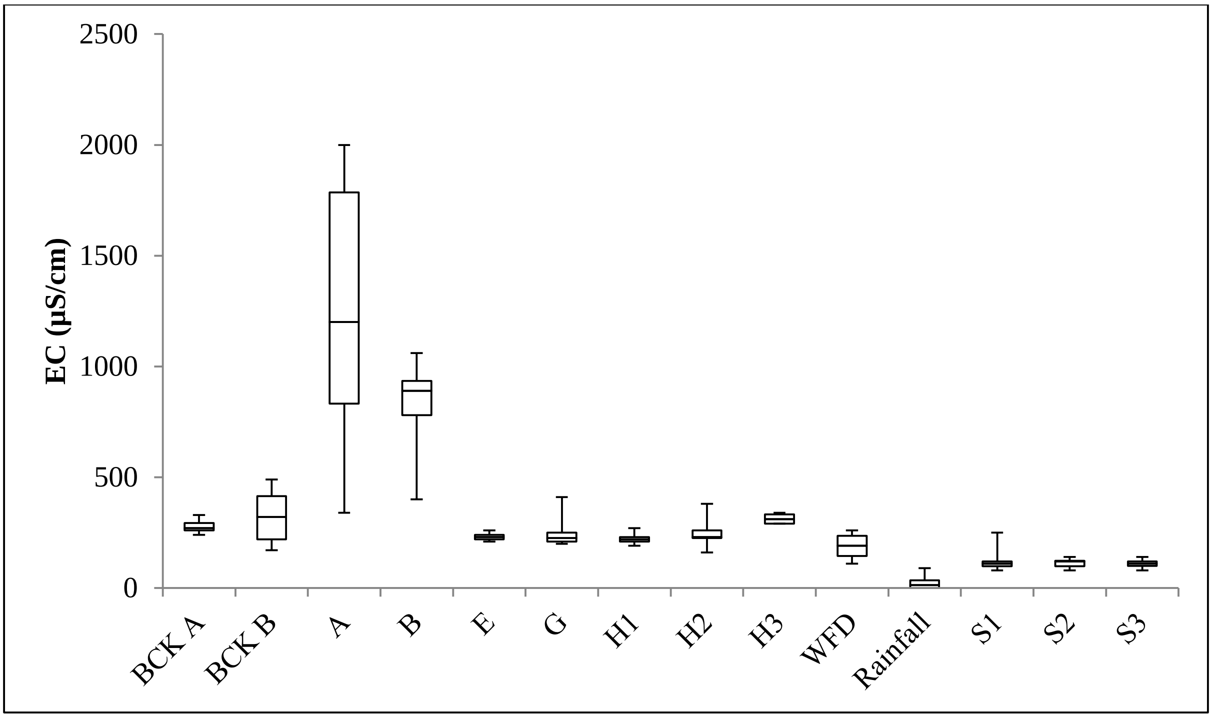

Figure 5.44 Electrical conductivity values for the Azalea

5.2.4. Taylors Halt and Taylors Halt Control

At the Taylors Halt and Taylors Halt Control sites, piezometers VIP4 E1, VIP4 E5 and VIP4 G1 exhibited intermittent high maximum nitrate values, above the 48 mg/l acceptable drinking water limit (Figure 5.45). None of the piezometers exhibited consistently high nitrate values (i.e. 75 % of the values were < 35.89 mg/l) (Figure 5.45). The ammonium values for all the piezometers, except B3, were low (i.e. all the piezometer values were < 1.55 mg/l), and was attributed to the consistently positive ORP values (i.e. minor reducing conditions) which allowed for significant nitrification to occur (Figure 5.46). The elevated ammonium value at B3 was attributed to the close proximity of an unimproved pit latrine (< 4.00 m), which was built after the installation of the piezometer. The elevated ammonium values in the rainfall was due to occasional defecation of birds into the plastic rain gauge. Throughout the hillslope, there was no consistent nitrate impact from the VIP systems, in the near surface hillslope through-flow (Figure 5.45). However by comparison to the background values (i.e. piezometers B1 to B3) and the wetting front detectors, there was intermittent high nitrate values in piezometers VIP4 E1, VIP4 E5 and VIP4 G1, several days after high rainfall events, which indicated an intermittent nitrate impact from the VIP systems (Figure 5.45). Considering that the streams exhibited elevated nitrate values after the same rainfall events, and that the nitrate values were low in the wetting front detectors, this indicated that the nitrate from the VIP system reached the stream *via* the near surface hillslope through-flow moving along the preferential flow pathways.

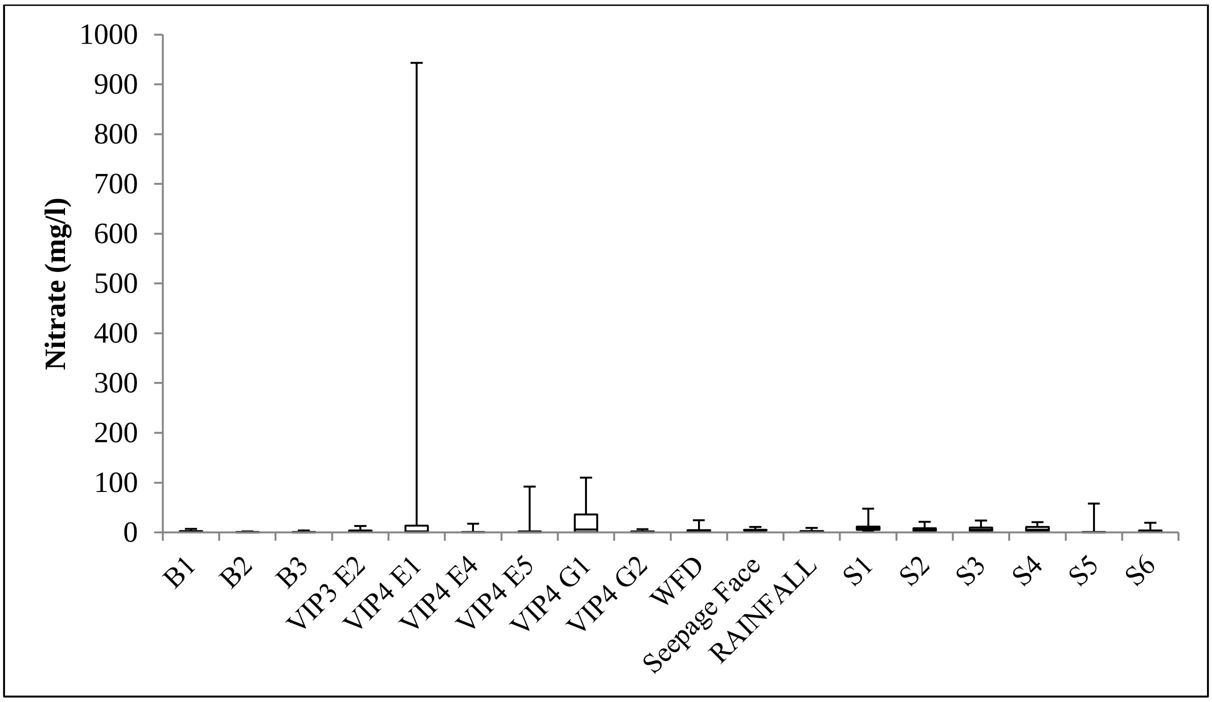

Figure 5.45 Nitrate values for the Taylors Halt and Taylors Halt Control sites

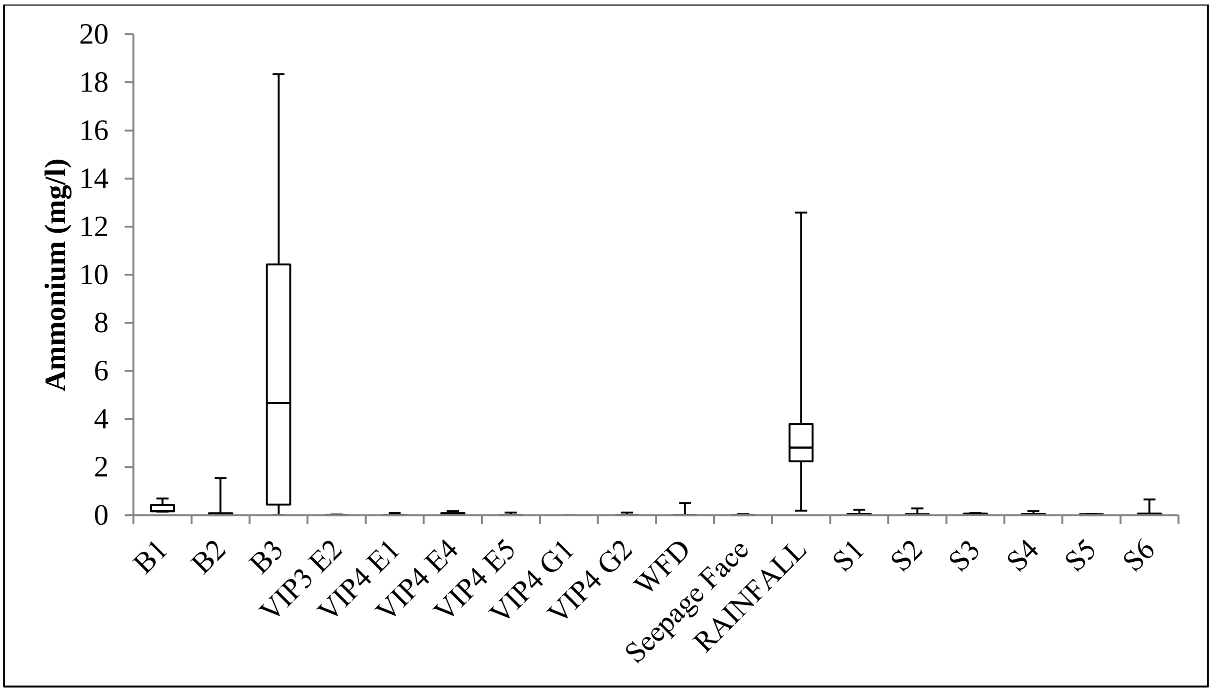

Figure 5.46 Ammonium values for the Taylors Halt and Taylors Halt Control sites

At the Taylors Halt and Taylors Halt Control sites, piezometers B1, B2, VIP4 E1, VIP4 E4, VIP4 E5, VIP4 G1 and VIP4 G2 exhibited maximum phosphate values above the 0.30 mg/l limit for eutrophication (Figure 5.47). However none of the piezometers exhibited relatively high phosphate values, compared to the previous study sites (i.e. seldom were the values > 1.00 mg/l (Figure 5.47). Piezometers VIP4 E1 and VIP4 G1 exhibited intermittent high phosphate values after several high rainfall events. Bearing in mind the wetting front detectors exhibited low phosphate values, suggested that there were intermittent phosphate contributions to the near surface hillslope through-flow from the VIP systems (Figure 5.47). This intermittent phosphate impact extended to piezometers VIP4 E1 and VIP4 G1 (Figure 5.47), however it was not clear if the phosphate reached the stream.

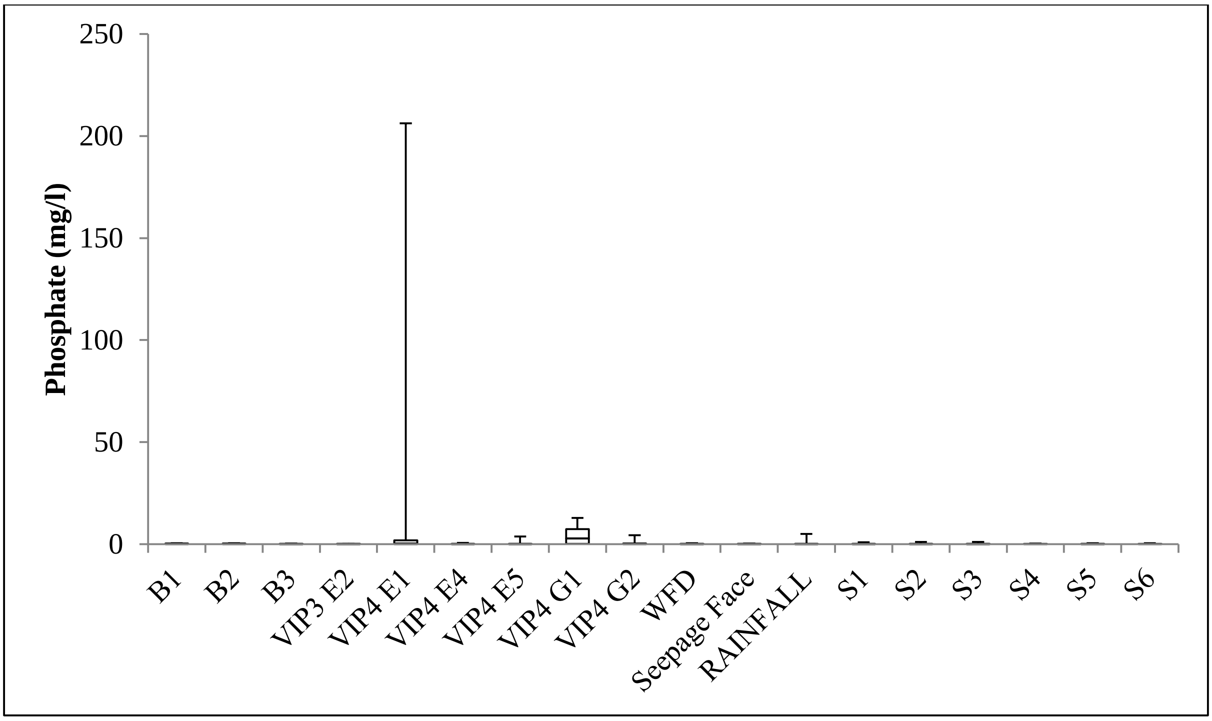

Figure 5.47 Phosphate values for the Taylors Halt and Taylors Halt Control sites

At the Taylors Halt and Taylors Halt Control sites, all the piezometers exhibited maximum *E.coli* values above the 0 bacteria/100 ml limit (Figure 5.48). Piezometers B1, B2, B3 and VIP4 E1 exhibited high maximum *E.coli* values (Figure 5.48). The consistently high values at VIP4 E1 (i.e. 75 % of the values were > 5484.50 MPN/100ml) indicated that the VIP systems were impacting the near surface hillslope through-flow at this point, after high rainfall events (Figure 5.48). The seepage face and stream sample 1 exhibited high values, and was attributed to the intermittent defecation of animals at these locations (Appendix 33). The high values at piezometers B1, B2 and B3 was attributed to the close proximity of an unimproved pit latrine and the ingress of the surface run-off suspending animal excreta material. By comparison to the background values (i.e. B1, B2 and B3), there was no clear *E.coli* impact from the pour-flush system in the near surface hillslope through-flow (Figure 5.48). However piezometer VIP4 E1 exhibited consistently higher values compared to the piezometers downslope, which indicated an *E.coli* impact from the VIP systems upslope, in the near surface hillslope through-flow (Figure 5.48).

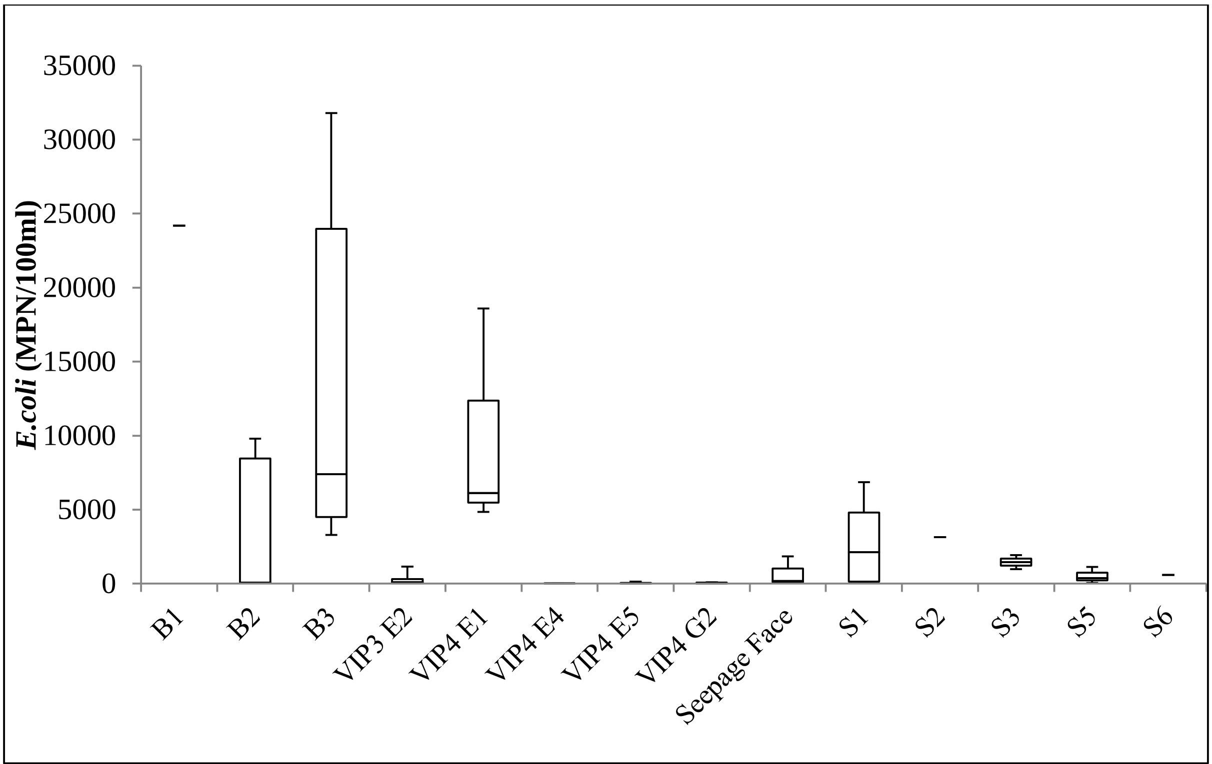

Figure 5.48 *E.coli* values for the Taylors Halt and Taylors Halt Control sites

Unlike the previous sites, the EC, SO_4^{2-}, Cl^-, Ca^{2+}, Mg^{2+} and Na^+ analyses of the water samples at the Taylors Halt and Taylors Halt Control sites revealed no clear pattern of a chemical plume from the VIP systems in the near surface hillslope through-flow (Figure 5.49). The background piezometers at the Taylors Halt Control site were noisier than the piezometers at Taylors Halt site (Figure 5.49). The general pattern of the SO_4^{2-}, Cl^-, Ca^{2+}, Mg^{2+} and Na^+ analyses are summarized in the EC values (Figure 5.49). Only VIP4 E1 exhibited higher values than the background piezometers, which indicated an intermittent impact from the VIP systems up to this point on the hillslope (Figure 5.49).

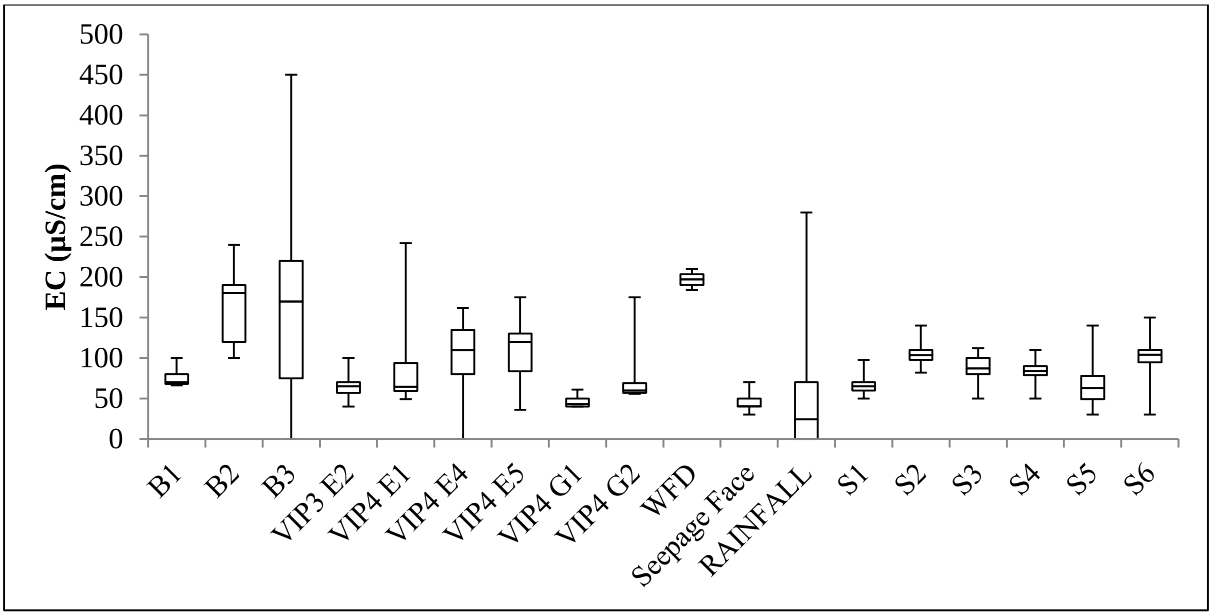

Figure 5.49 Electrical conductivity for the Taylors Halt and Taylors Halt Control sites

5.3. Contaminants and Rainfall Time Series

All of the sites exhibited changes in the nitrate, phosphate and *E.coli* contaminants in the near surface hillslope through-flow, as a response to changes in the rainfall. In some cases, there was a significant increase after a high rainfall event(s). On the other hand there was a substantial decrease, or no apparent change after a high rainfall event(s).

Using the Slangspruit site as an example, piezometers A1, A2, B1 and C2 all indicated a significant change in the nitrate values after a high rainfall event(s) (Figure 5.50). In some cases the rainfall event(s) initiated an increase in the nitrate values (i.e. red circles in Figure 5.50) or a decrease (i.e. blue circles in Figure 5.50). Similar observations were observed at the other study sites. At the start of the wet season (i.e. 25/09/2013 – 13/12/2013) the onset of the rainfall initiated a flushing-out effect of the nitrate which built up during the dry season (Figure 5.50). However, throughout the wet season after frequent rainfall events (i.e. 22/01/2014 – 18/03/2014), a large portion of the nitrate had already been flushed out and the rainfall had a diluting effect on the nitrate in the near surface hillslope through-flow (Figure 5.50). The same pattern was exhibited at the Crèche site but not at the Azalea or Taylors Halt sites. At the Azalea and Taylors Halt sites, the soil profiles were significantly deeper, compared to the Slangspruit and Crèche sites. Thus the infiltrating water from the rainfall had a greater distance to travel before it reach the water table, which resulted in a delayed effect from the rainfall acting upon the nitrate in the hillslope through-flow. At the Azalea and Taylors Halt sites the highest nitrate values occurred near the end of the wet season (i.e. March).

Unlike nitrate, the phosphate exhibited a less eccentric change in the values in the near surface hillslope through-flow after a high rainfall event(s) (Figure 5.51). This was expected given that phosphate typically is rapidly fixed within a soil. Using the Slangspruit site as an example, the phosphate values exhibited a changed after a high rainfall event(s) (Figure 5.51). Again the red and blue circles in Figure 5.51 indicated an increase or decrease in the phosphate values in the near surface hillslope through-flow, after rainfall event(s). With the progression of the wet season, the soil became saturated and highly anaerobic in some areas (i.e. piezometer C1). Thus the accumulated phosphate in the soil at these points, was released into the soil solution and increased the concentration of phosphate in the through-flow. However near the end of the wet season the phosphate values started to decrease, either due to a dilution effect or diminishing reserves of phosphate in the soil. The other sites exhibited relatively consistent and stable values of phosphate in the near surface hillslope through-flow. At these sites, there were no areas of consistent, highly anaerobic conditions, and the fixed phosphate in the soil was less susceptible to being released into the soil water. This was more evident at the Azalea and Taylors Halt sites where the soil profiles were deeper, and there was more soil between the leach pit and the water table to adsorb and fix the phosphate.

The *E.coli* data only spanned a portion of one wet season and provided a limited view of the rainfall impact (Figure 5.52). Nevertheless the *E.coli* values at all the sites indicated an erratic change after a high rainfall event(s) (Figure 5.52). Using the Slangspruit site as an example, the rainfall had no clear or consistent impact on the *E.coli* values in the near surface hillslope through-flow (Figure 5.52). There were flushing out and diluting effects on the *E.coli* at all the sites, but they were not consistent in relation to the rainfall. Considering that there are several other factors which influence the survival of bacteria in the subsurface (i.e. section 3.3) as well as the dynamic nature of bio-mats surrounding the soil particles, it is likely that these factors played a larger role in determining the mobility and concentration of *E.coli* in the near surface hillslope through-flow, than the prevailing rainfall conditions, at the study sites.

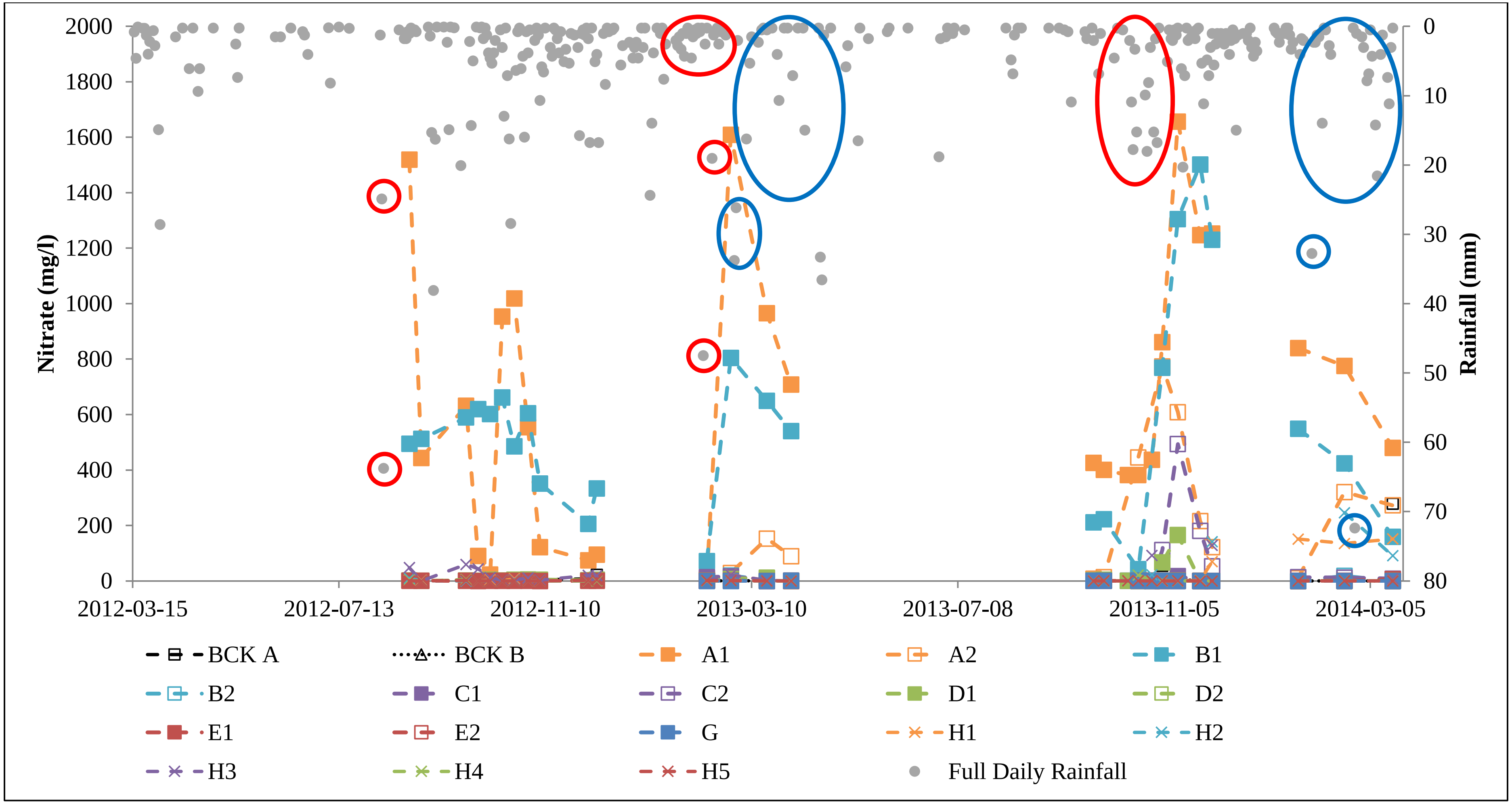

Figure 5.50 Nitrate and rainfall time series for the Slangspruit site

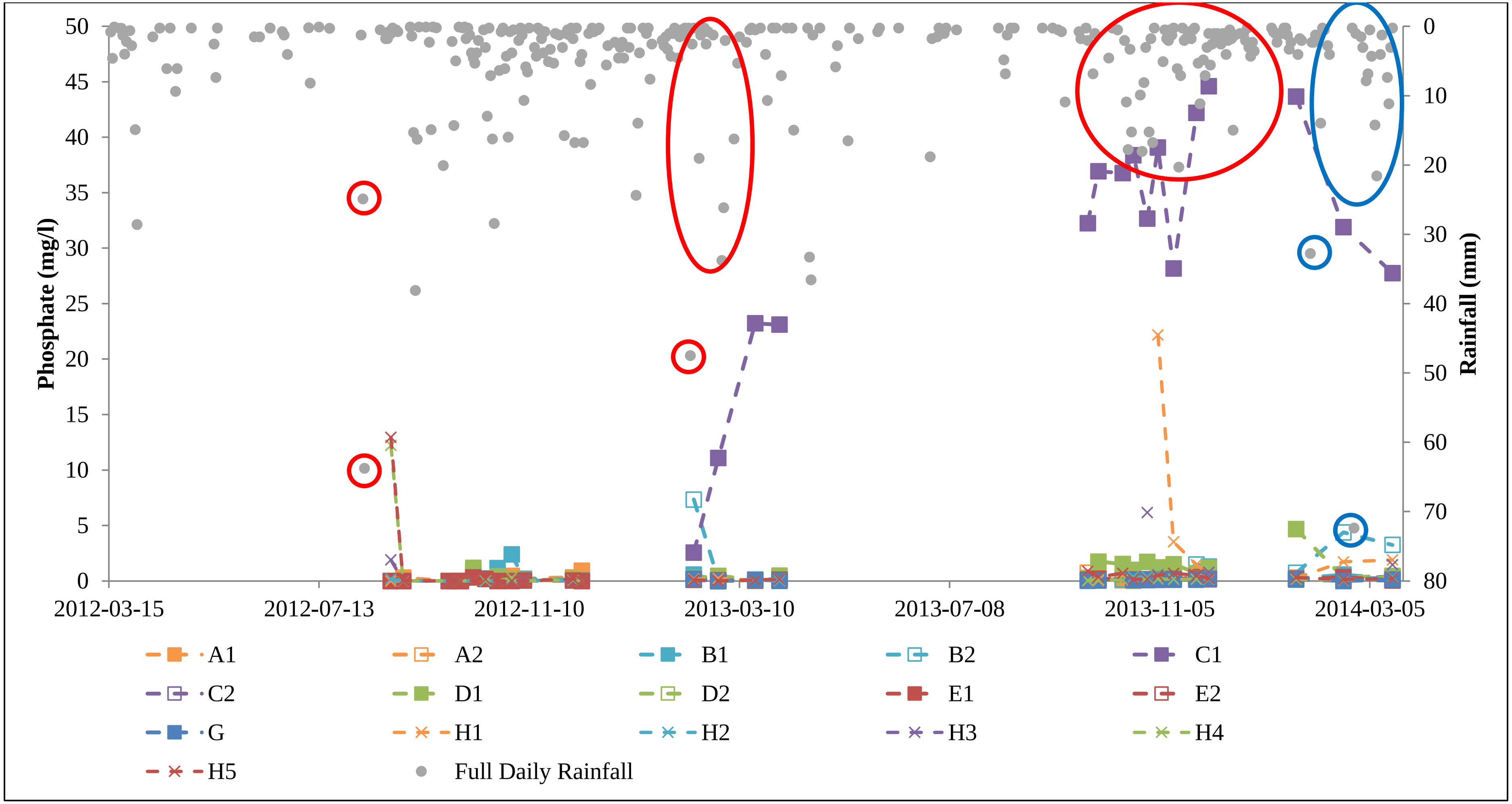

Figure 5.51 Phosphate and rainfall time series for the Slangspruit site

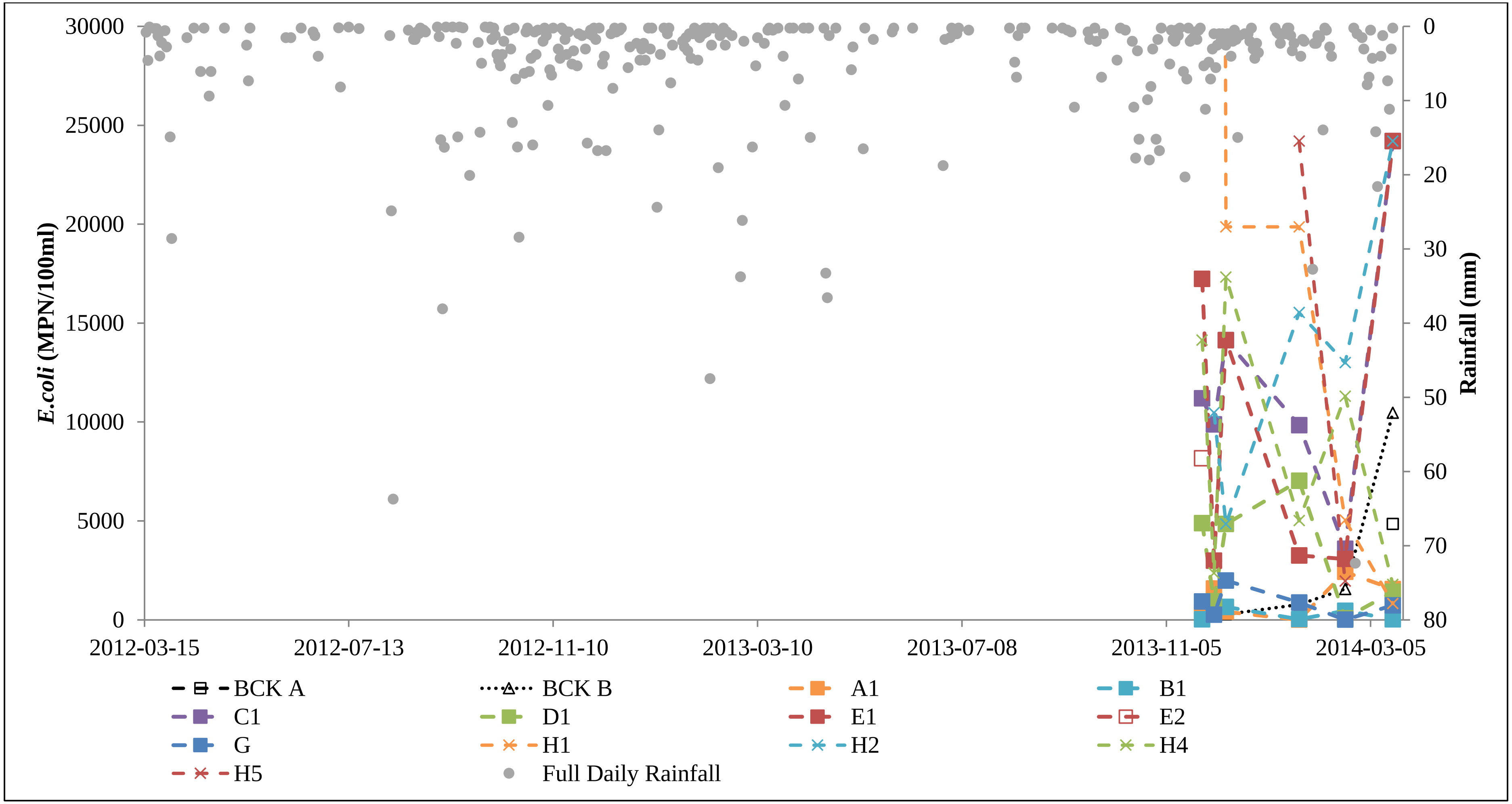

Figure 5.52 *E.coli* and rainfall time series for the Slangspruit site

6. DISCUSSION

The data from the study sites described the soil profile characteristics, which was used to infer the hillslope water movement at each site. The water analyses results provided information on the lateral spread of contaminants and the chemical plume from the on-site sanitation systems, in the near surface hillslope through-flow. The pH and ORP analyses also provided fundamental information on the aerobic or anaerobic status in the subsurface, which directly affected the nitrate and phosphate contaminants in the near surface through-flow. Lastly, the water analyses were measured before, during and after rainfall events of varying magnitudes, which provided information on the impact rainfall has on the on-site sanitation contaminants. All this data and information was used to describe the lateral movement of on-site sanitation contaminants, in the near surface hillslope through-flow. A set of diagrams were produced that summarised the information from the study, to answer the research question. The findings from each site were compared to each other and the case studies in the literature, and the significant differences were explained.

6.1. Slangspruit

At the Slangspruit site, the infiltrating water from the rainfall moved slowly through the clayey soil profile and was significantly retarded at the prominent clayey layer (i.e. 0.50 m). At this point the water movement shifted from a primarily vertical direction to a horizontal one, and resulted in lateral through-flow. A portion of the water infiltrated through or around the clay layer (i.e. TDR values at 1.30 m indicated near saturated conditions which exhibited minor changes after high rainfall events) and became the lateral through-flow along the semi-pervious parent material. During prolonged periods of high rainfall, the shallow soil profile quickly became saturated and the water table surfaced, especially near the pour-flush leach pit and surface gutter.

The near surface hillslope through-flow intersected the leach pits from the pour-flush system, and there was a clear nitrate, phosphate and *E.coli* impact on the water (Figure 6.1). A clear chemical plume extended up to 2.00 m downslope from the pour-flush leach pit 2. There was a consistent nitrate plume which reached a maximum value of 1502.00 mg/l, at 0.50 m downslope of leach pit 2. The nitrate impacted up to 2.00 m from the pour-flush leach pit 2, where the maximum value reached was 165.72 mg/l. There was a consistent phosphate plume which reached a maximum value of 44.60 mg/l, at 0.50 m downslope of leach pit 2. There was no clear phosphate impact beyond 2.00 m from the pour-flush leach pit 2, where the maximum value reached was 165.72 mg/l. A consistent *E.coli* plume was present up to 9.00 m from the pour-flush leach pit, where the maximum value reached was 24192 MPN/100ml. Elevated levels of nitrate, phosphate and *E.coli* were measured in the near surface hillslope through-flow at 25.00 m downslope of leach pit 2. However it was not clear whether it was the pour-flush leach pit that was the sole cause of the impact, or the regular defecation of animal excreta on the soil surface at this distance. Nevertheless, the relatively low nitrate and phosphate values in the near surface hillslope through-flow between 2.00 m and 25.00 m from leach pit 2, indicated that the elevated values at 25.00 m were primarily from the animal excreta on the soil surface and not the pour-flush leach pit.

The aerobic or anaerobic status in the near surface hillslope through-flow had a significant impact on the nitrate and phosphate contaminants. The soil water within 0.50 m around the leach pits, experienced minor anaerobic conditions and permitted nitrification to occur, and also the typical rapid fixing of phosphate in the soil. However between 0.50 m and 2.00 m from the leach pits, the soil water was more anaerobic and inhibited the nitrification of the ammonium from the leach pits: this was indicated by the relatively high ammonium values and considerably low sulphate values in the soil water at this distance. Furthermore the iron, in the iron-phosphate compounds in the soil, was reduced which facilitated the release of phosphate into the surrounding soil water.

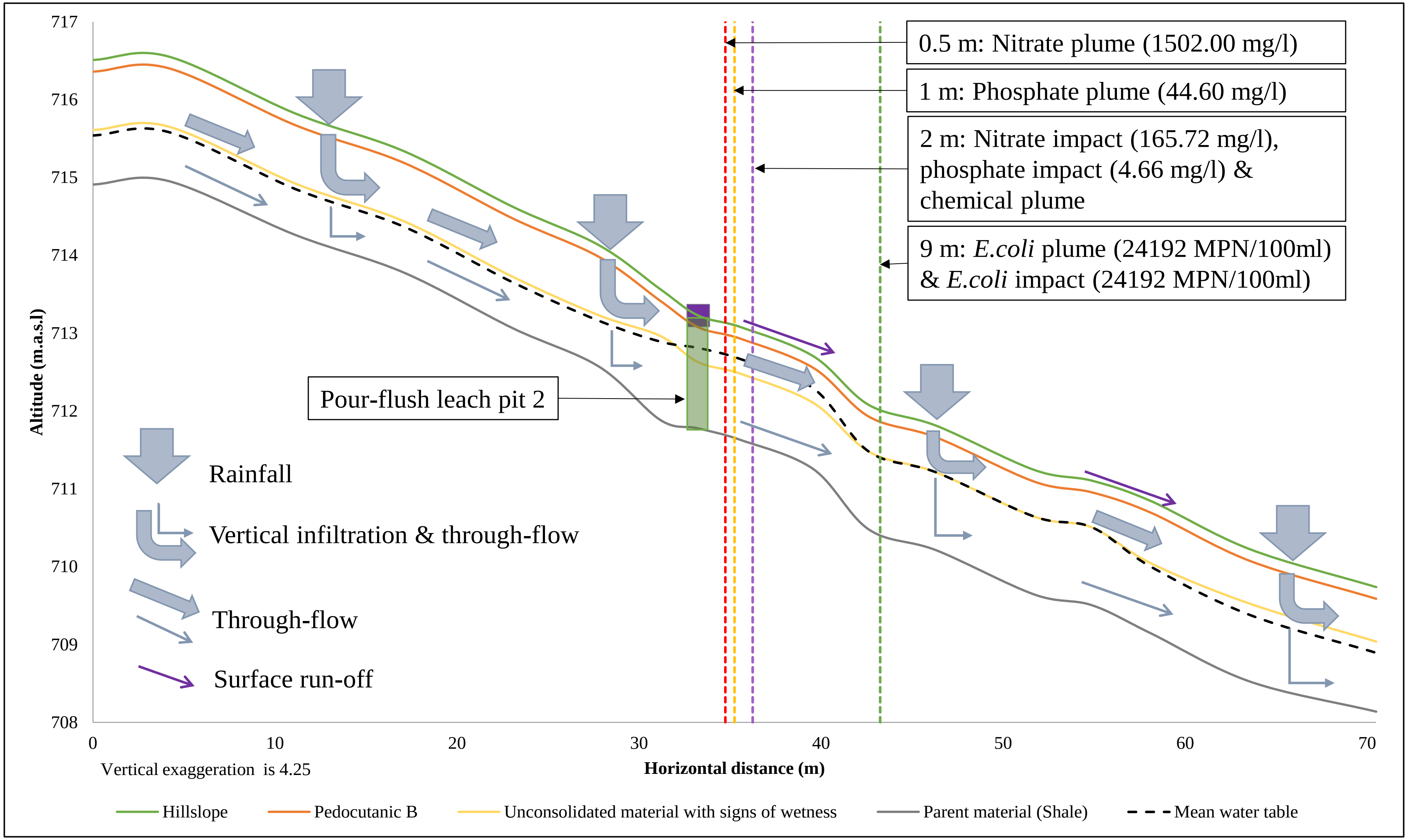

Figure 6.1 Near surface hillslope water movement and lateral spread of contaminants for the Slangspruite site

6.2. Crèche

At the Crèche site, downslope of the pour-flush leach pits, the infiltrating water from the rainfall moved relatively quickly in the first 0.45 m of soil, where it reached a clayey-rocky layer. At this point the water movement shifted from a primarily vertical direction to a horizontal one, and resulted in lateral through-flow. However the soil was disturbed around piezometers G1 –G5, which caused the hillslope lateral through-flow to infiltrate deeper towards the original depth of the parent material. Only after frequent periods of high rainfall did the soil around piezometers G1 – G4 become saturated and experienced intermittent hillslope through-flow. The soil profile upslope of the pour-flush leach pits seldom exhibited a water table depth above the parent material. This was due to the large open storm water drain located upslope of the pour flush system. The storm water drain ran across the hillslope which intersected the through-flow and prevented a large portion of it from reaching the pour-flush leach pits. Unlike the Slangspruit site, the water table never breached the soil surface, due to the marginally higher K_{sat} properties of the soil, and the considerably lower water table in the upper hillslope.

The near surface hillslope through-flow intersected the leach pits from the pour-flush system, and there was a clear nitrate, phosphate and *E.coli* impact on the water (Figure 6.2). A clear chemical plume extended up to 10.00 m downslope from pour-flush leach pit 2. There was a consistent nitrate plume which reached a maximum value of 661.78 mg/l, at 0.50 m downslope of leach pit 2. The nitrate impacted up to 10.00 m (or more) from pour-flush leach pit 2, where the maximum value reached was 76.89 mg/l. There was no consistent phosphate plume downslope of leach pit 2, however there was a phosphate impact at 1.00 m from leach pit 2, where the maximum value reached was 0.44 mg/l. A consistent *E.coli* plume was present up to 0.50 m from pour-flush leach pit 2, where the maximum value reached was 7701 MPN/100ml. The *E.coli* impacted up to 3.00 m from pour-flush leach pit 2 where the maximum value reached was 3106 MPN/100ml.

Similar to the Slangspruit site, the aerobic or anaerobic status in the near surface hillslope through-flow had an impact on the nitrate contaminant, but was not as pronounced. The phosphate values remained relatively unchanged, where there was no clear impact on the phosphate contaminants as a result of a changing aerobic or anaerobic status. At 1.00 m downslope from leach pit 2, the conditions were anaerobic, which inhibited the nitrification of the ammonium ions, but it was not as severe compared to the Slangspruit site at 1.00 m.

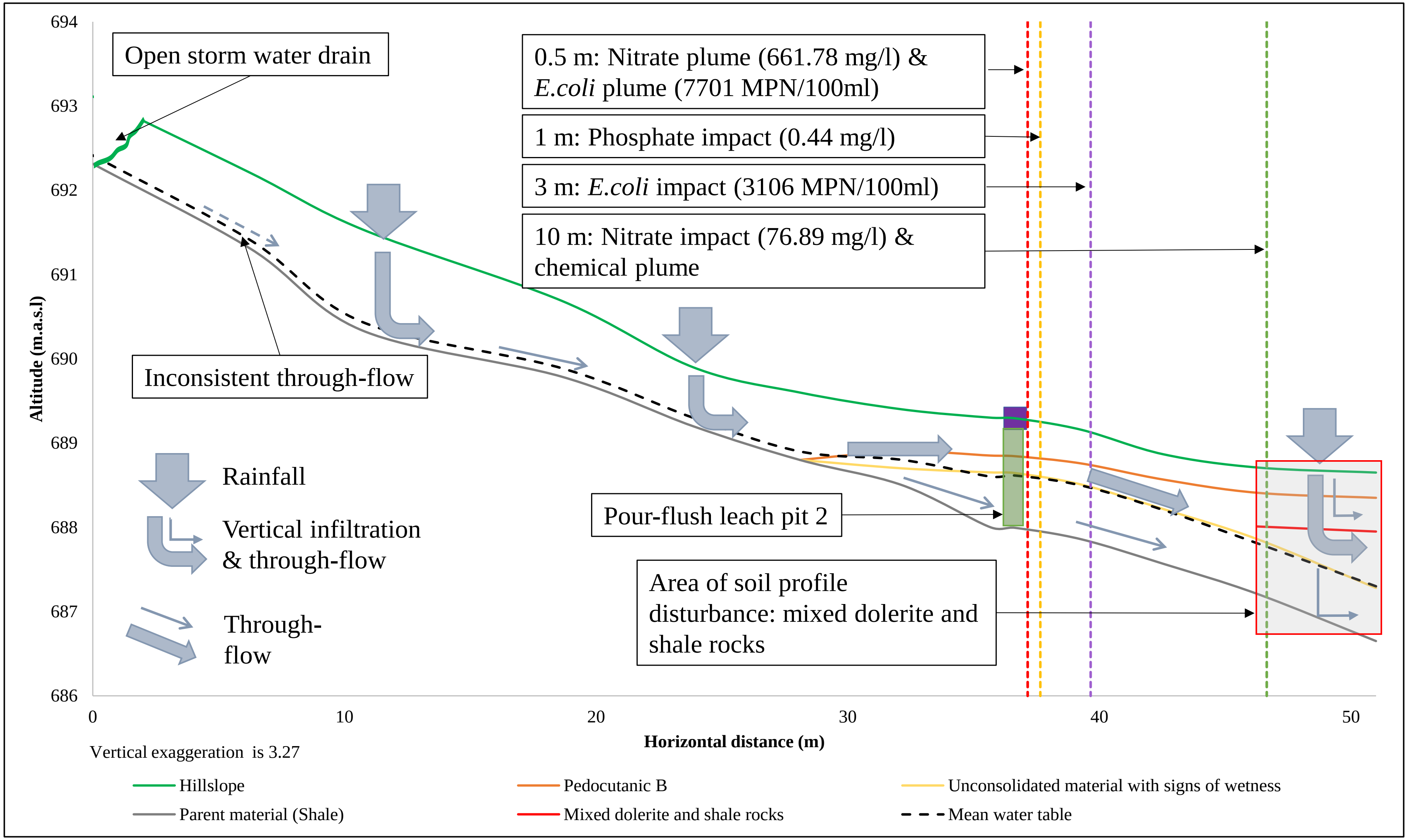

Figure 6.2 Near surface hillslope water movement and lateral spread of contaminants for the Crèche site

6.3. Azalea

At the Azalea site, the soil profile was well drained (as indicated by the red colour in the subsoil), and the infiltrating water from the rainfall moved at a faster rate in the soil profile compared to the Slangspruit and Crèche sites (i.e. higher K_{sat} values). However the soil profile was considerably deeper than the previous sites and the infiltrating water had to travel further to reach the water table. At the semi-permeable parent material, the vertical infiltrating water was retarded, where it accumulated and shifted from a primarily vertical direction to a horizontal one, and resulted in the lateral through-flow downslope. Unlike the slangspruit site, the water table never breached the soil surface, due to the higher K_{sat} properties of the soil, and the considerably deeper soil profile.

Unlike the Slangspruit and Crèche sites, the water table never intersected the leach pits of the pour-flush system, yet there was still a clear nitrate, phosphate and *E.coli* impact on the near surface hillslope through-flow (Figure 6.3), due to the pit leachate moving down towards the water table. A clear chemical plume extended up to 1.00 m downslope from pour-flush leach pit 2. There was a consistent nitrate plume which reached a maximum value of 508.01 mg/l, at 1.00 m downslope of leach pit 2. The nitrate impacted up to 17.50 m (or more) from pour-flush leach pit 2, where the maximum value reached was 85.20 mg/l. There was a consistent phosphate plume which reached a maximum value of 0.50 mg/l, at 0.50 m downslope of leach pit 2. There was no clear phosphate impact beyond 3.00 m from pour-flush leach pit 2, where the maximum value reached was 0.43 mg/l. A consistent *E.coli* plume was present up to 1.00 m from pour-flush leach pit 2, where the maximum value reached was 24192 MPN/100ml. The *E.coli* impacted up to 3.00 m from pour-flush leach pit 2 where the maximum value reached was 1095 MPN/100ml.

The aerobic or anaerobic status in the near surface hillslope through-flow had an impact on the nitrate contaminant, but was not as pronounced as the Slangspruit and Crèche sites. At the Azalea site, the near surface hillslope through-flow was considerably less anaerobic than at the Slangspruit site, which permitted nitrification to occur, and the typical rapid fixing of phosphate in the soil. Unlike the previous sites, there was approximately 4.50 m of unsaturated soil between the bottom of the pour-flush leach pit and the water table. Thus the resident time of the contaminants in the unsaturated soil was greater compared to the Slangspruit and Crèche sites, which resulted in a greater impact from the various attenuation processes that acted upon the contaminants.

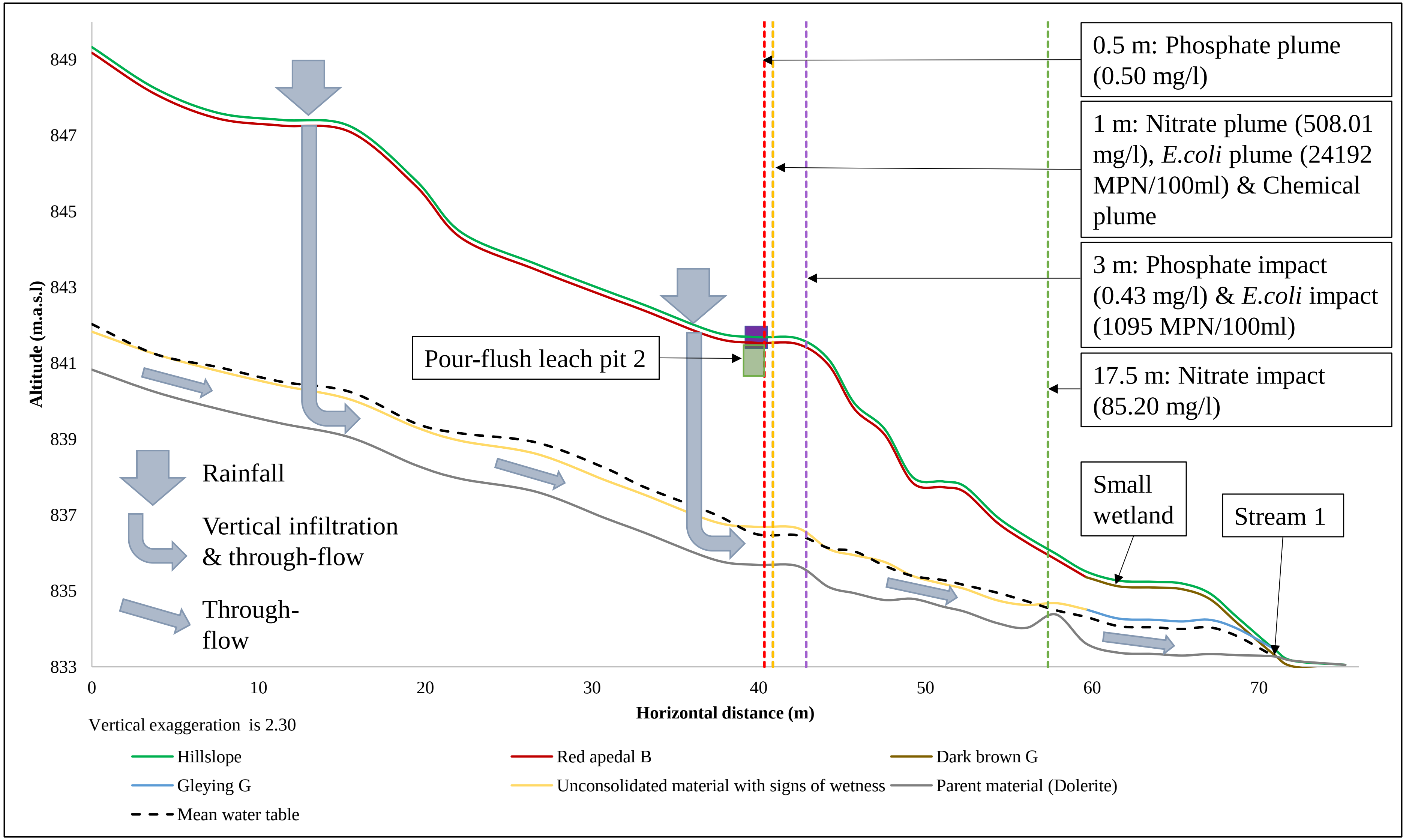

Figure 6.3 Near surface hillslope water movement and lateral spread of contaminants for the Azalea site

6.4. Taylors Halt and Taylors Halt Control

At the Taylors Halt site, the soil profile was well drained and the infiltrating water from the rainfall moved at a faster rate in the soil profile compared to the Slangspruit and Crèche sites. However the soil profile was considerably deeper than all the previous sites and had to travel further to reach the water table. Furthermore, the study transect at the Taylors Halt site occupied an entire hillslope, unlike all the previous sites which were located near the toe of their respective hillslopes. Thus the Slangspruit, Creche and Azalea sites represented the accumulation of the upslope hillslope through-flow, while the Taylors Halt site represented the entire hillslope through-flow, and only exhibited the accumulation of the entire hillslope through-flow at the bottom. The accumulated hillslope through-flow at the toe, travelled along the parent material across the hillslope and breached the surface at the seepage face further down the hillslope. Furthermore, there were large animal burrows and joints or cracks in the dolerite rock at the toe of the hillslope which acted as preferential flow pathways for inconsistent near surface hillslope through-flow, after periods of rainfall (Appendix 34).

Similar to the Azalea site, the water table never intersected the pit of the VIP systems, yet there was a clear nitrate, phosphate and *E.coli* impact on the near surface hillslope through-flow (Figure 6.4), due to the pit leachate moving down towards the water table. There was no clear chemical plume from the VIP system on the hillslope. Furthermore, there were no clear and consistent nitrate, phosphate and *E.coli* plumes from the VIP systems. However the nitrate and phosphate intermittently impacted the near surface hillslope through flow at 57.00 m downslope of the nearest VIP leach pit. Similarly the *E.coli* intermittently impacted at 30.00 m downslope of the nearest VIP leach pit. The maximum values for the nitrate, phosphate and *E.coli* at these distances were 109.92 mg/l, 12.94 mg/l and 18600 MPN/100 ml respectively. The presence of the large animal burrows and joints or cracks in the dolerite rock at the toe of the hillslope along with the intermittent high nitrate, phosphate and *E.coli* values, indicated that the contaminants from the VIP 4 leach pit travelled rapidly in the near surface *via* preferential flow paths, after periods of high rainfall. Similar to the Azalea site, there was a deep region of unsaturated soil between the bottom of the VIP leach pit and the water table. Compared to the previous sites, this resulted in a greater resident time of the contaminants in this zone and thus a greater impact from the various attenuation processes acting upon the contaminants. Furthermore, the hillslope through-flow did not experience highly reducing conditions as in the case at Slangspruit (i.e. relatively high ORP and sulphate values), which allowed for sufficient nitrification and rapid fixation of phosphate in the soil.

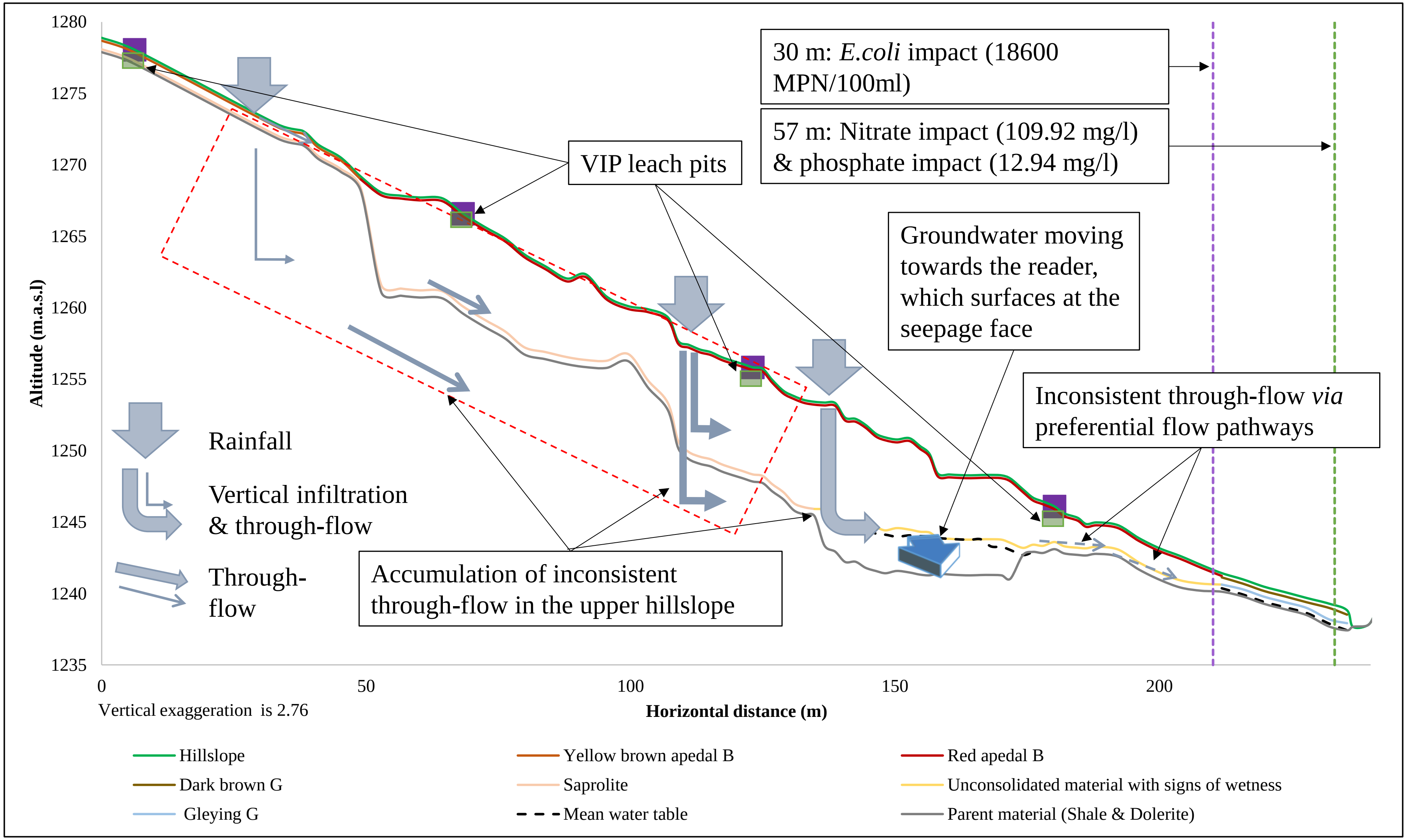

Figure 6.4 Near surface hillslope water movement and lateral spread of contaminants for the Taylors Halt site

6.5. Comparison of Results

The Slangspruit site exhibited consistently higher nitrate, phosphate and *E.coli* values in the near surface hillslope through-flow, compared to the other study sites. There were several reasons for this. Firstly the soil profile and water table were considerably deeper at the Azalea and Taylors Halt sites. Thus the resident time of the contaminants in the region of unsaturated soil between the leach pits and the water table, was longer at these sites. This resulted in a greater effect from the natural attenuation processes in the subsurface, which acted upon the contaminants. On the other hand, the water table at the Slangspruit and Crèche sites, consistently intersected the pour-flush leach pits, which provided little opportunity for the natural attenuation processes to act upon the contaminants in the unsaturated zone. This was more pronounced at the Slangspruit site, where the water table was consistently high around the leach pits and intersected a larger surface area of the leach pit, compared to the leach pits at the Crèche site.

Furthermore, by comparing the results of the contaminants at the similar study sites *viz*. Azalea and Taylors Halt sites, one can compare the different impacts from the on-site sanitation systems (i.e. Pour-flush and VIP). The pour-flush system at the Azalea site exhibited consistently high nitrate, phosphate and *E.coli* values in the first 3.00 m of soil downslope of the leach pits. However the VIP system at the toe of the hillslope (i.e. VIP 4) did not reveal consistently high values near the leach pit, but only showed intermittently high contaminant values, at 57.00 m downslope of the system (due to the preferential flow paths). In both these settings, there existed a region of unsaturated soil between the leach pit and the water table, however given that the pour-flush system uses water to function, this leach pit will receive more water. Thus the soil water content in the soil below the pour-flush leach pit will increase and lead to a faster movement of contaminants through the soil profile (i.e. *via* the infiltrating water) as it shifts closer towards saturated flow water conditions. Thus the Azalea site exhibited consistently high nitrate, phosphate and *E.coli* values. In addition, the VIP system has a ventilation pipe directly connected to its leach pit, which can release as much as 70 % of the total nitrogen introduced to the leach pit, as nitrogen gas to the atmosphere, *via* the denitrification process. Thus the Taylors Halt site exhibited consistently lower nitrate values compared to the other sites.

The results from this study indicated a similarity to the findings from the case studies and examples discussed in the literature review. At the Slangspruit and Crèche sites, there was a clear link between the ammonium and nitrate values in the near surface through-flow, nearest to the leach pits. This inverse relationship between the ammonium and nitrate values, was dependent upon prevailing aerobic or anaerobic conditions in the soil. Similarly high phosphate values were measured at the Slangspruit site, in areas of highly reduced conditions in the near surface through-flow, due to the reduction of iron in the iron-phosphate compounds in the soil.

The impact of rainfall on the spread and concentration of the contaminants was unclear in some instances, however there was one general pattern which emerged from the data. The high rainfall events which occur at the end of the dry season (i.e. August – October) caused a noticeable increase in the contaminants in the near surface through-flow. During the transition period towards the start of the wet season, the first set of high rainfall events had a flushing out effect on the contaminants that accumulated during the dry season. However, the high rainfall events which occur in the middle and end of the wet season (i.e. January – March) had a diluting effect on the contaminants in the near surface through-flow. Barrell and Rowland (1979) and Nsubuga *et al*. (2004) reported similar findings in their studies. Furthermore, the differences in the soil texture and thus K_{fs} values between the study sites, contributed to the variances of the effects that rainfall had on the movement and concentration of the contaminants in the subsurface.

In addition, the effect from the preferential flow paths at the bottom of the Taylors Halt site indicated just how far and rapid the contaminants from an on-site sanitation system may move in the near surface, under the right conditions. Similar findings of far and rapid movement of on-site sanitation contaminants *via* preferential flow paths were reported in Skilton and Wheeler (1988), Champ and Schroeter (1988) and Pujari *et al* 2012.

Furthermore, the differences in the depth of the water table relative to the leach pit of the on-site sanitation system, had a marked impact on the concentration of the contaminants in the near surface hillslope through-flow. At the study sites where the leach pits were installed several meters above the level of the water table, these exhibited lower concentrations of the contaminants in the near surface through-flow. A similar result was observed in Tandia *et al*. (1999), Dzwario e*t al*. (2006) and Banerjee (2011).

The faecal coliform results in the case studies presented in the literature review, showed little deviation of the contaminant, where only Tandai *et al.* (1999), Pujari *et al*. (2012) and Dzwario *et al*. (2006) exhibited noticeable changes in the faecal coliform values. On the other hand, the *E.coli* values at the study sites revealed significant fluctuations, (e.g. 6 - 241920 MPN/100ml and 4 – 28510 MPN/100 ml at the Slangspruit and Azalea sites respectively). These distinct changes in the *E.coli* values were due to changes in the biomat in the soil surrounding the leach pits, and other factors which influence the die-off of the bacteria (i.e. nutrient availability, temperature, moisture and pH).

Lastly the clayey nature of the soil at the study sites had an important impact on the spread and concentration of the contaminants in the near surface hillslope through-flow. At the Slangspruit, Crèche and Azalea sites, the contaminant concentrations decreased significantly (i.e. 70 % to 98 % reductions) within the first few meters downslope of the leach pits. This was due to the slow water movement through the clayey soil profile, which resulted in a longer resident time in the soil near the leach pits and promoted the natural attenuation processes acting upon the contaminants. Banerjee (2011) and Crane and Moore (1984) observed sharp decreases in the contaminants within the groundwater, in clayey soils. In contrast, the case studies from the literature review which exhibited sandy soils, indicated considerably lower contaminant concentration values, but at a more consistent concentration over a longer distance in the groundwater, downslope of an on-site sanitation system.

As to the recommended safe distances for on-site sanitation systems, the 15.00 m minimum safe distance guideline was sufficient to avoid all of the contaminant plumes in the near surface through flow, at all the study sites. However, in the infrequent situations where the nitrate, phosphate and *E.coli* contaminants exceeded 15.00 m (i.e. Taylors Halt), there were preferential flow path characteristics, and a greater lateral distance should be used, as indicated by several on-site sanitation guidelines and studies.

7. CONCLUSION AND RECOMMENDATIONS

The results of the study provided useful information which answered the research question as such: To what extent do on-site sanitation systems contaminants travel in the vadose zone, in the presence of a near surface semi-pervious layer, in a rural and peri-urban housing environment.

(a) There was a consistently high nitrate plume (i.e. > 48.00 mg/l) 0.50 m to 1.00 m downslope from an on-site sanitation system in the near surface hillslope through-flow. However high nitrate values (i.e. > 48.00 mg/l) may be found 57.00 m downslope of an on-site sanitation system in the near surface hillslope through-flow, under preferential flow characteristics and prolonged high rainfall conditions.

(b) There was a consistently high phosphate plume (i.e. > 0.13 mg/l) 0.50 m to 1.00 m downslope from an on-site sanitation system in the near surface hillslope through-flow. However high phosphate values (i.e. > 48 mg/l) may be found 57.00 m downslope of an on-site sanitation system in the near surface hillslope through-flow, under preferential flow characteristics and prolonged high rainfall conditions.

(c) There was a consistently high *E.coli* plume (i.e. > 0.00 MPN/100ml) 0.50 m to 9.00 m downslope from an on-site sanitation system in the near surface hillslope through-flow. However high *E.coli* values (i.e. > 0.0 MPN/100ml) may be found 30.00 m downslope of an on-site sanitation system in the near surface hillslope through-flow, under preferential flow characteristics and prolonged high rainfall conditions.

Based on the results of the study, the 15.00 m lateral spacing guideline for on-site sanitation was acceptable, in the clayey soil conditions that were present at the study sites. However it is recommended that the lateral distance be increased to at least 60 m in situations where preferential flow pathways are present. Furthermore, the formation of a highly reduced zone in the near surface through-flow had a positive impact for the nitrate (i.e. it was reduced to nitrogen gas), however it lead to the release of phosphate ions into the soil water, which were rapidly fixed in more aerobic environments downslope. Thus the presence of a highly anaerobic environment located a few meters downslope of the leach pit from an on-site sanitation system, would be beneficial to the prevention of nitrate reaching a nearby water resource. Furthermore, in situations where there is a semi-pervious layer (i.e. clay lenses or rock strata) near the soil surface, and the water table is shallow, the leach pit should be raised out of the ground and a soil mound be installed around the section of the leach pit above the ground. This will assist to prevent the near surface through-flow from directly intersecting the leach pit, while maximising the resident time of the contaminants in the unsaturated soil, and thus the attenuation processes acting upon them. Additionally, a clay envelope should be installed around the leach pit, in sandy soils environments, to limit the concentration of the contaminants to a few meters around the leach pit. Lastly if there is a drinking water supply (i.e. stream, shallow well or spring) located near an on-site sanitation system, the water should not be used following the on-set of high rainfall at the beginning of the wet season. Instead the water should only be used in the middle and late end of the wet season.

The results of this study have described the lateral spread of on-site sanitation contaminants in the near surface, and as a result, the importance of the processes occurring within the vadose zone. The concentration and spread of the contaminants are largely determined by the conditions of the soil between the leach pit and the water table, and it is unfortunate that much of the existing literature has focused the contamination of deep groundwater resources, and the processes occurring within. Thus the results of this study have aided in improving the understanding of the possible contamination of precious water resources from on-site sanitation systems. Furthermore the information describing the lateral spread of contaminants will be used in the development of better guidelines for the siting of on-site sanitation systems, which will lead to the improvement of the health and wellbeing for many, especially for those in peri-urban and rural areas in developing nations.

Lastly there are several areas for interesting future research on this study that can improve the understanding of the impact of on-site sanitation systems on water resources, which can incorporate the following:

(a) Measure the dissolved organic carbon and dissolved oxygen values, which can describe the microbiological activity in the soil water near the leach pit,
(b) Drill boreholes at the study site(s) to collect deeper groundwater samples, and compare to the near surface groundwater samples, to differentiate the level of contamination between the two pools of water resources,
(c) Collect more K_{sat} values at deeper soil depths, in order to gain more representative values, and a better description of the water movement through the soil profile. In addition, measure the unsaturated soil hydraulic conductivity at different tensions

using a Tension Disk Infiltrometer, which would be useful in a modelling exercise of the contaminant movement in the near surface,

(d) Install more TDR apparatus and Water Marks at the different study sites, to gain a better understanding of the water movement in the subsoil and the potential impact from rainfall,

(e) Incorporate the results from the study into a computer model (i.e. HYDRUS 2D/3D), which can potentially be used to ascertain the suitability of an unstudied site for on-site sanitation systems, in terms of potential water quality issues, and

(f) Identify more suitable study sites where that have minimal less soil disturbance, vandalism and background interference on the chemical and microbiological water analyses.

Incorporation of these recommendations may shed light on some of the aspects identified. However it is evident that the generic safe distance for on-site sanitation systems may not be adequate where preferential flow paths exist in the subsurface, where rainfall is erratic, where the soil profile is shallow and near surface impervious layer are present and/or where contaminant loads are high. It is hoped that this research will contribute to the safe siting of on-site sanitation systems, thereby improving the environmental and human health in rural and peri-urban areas in South Africa.

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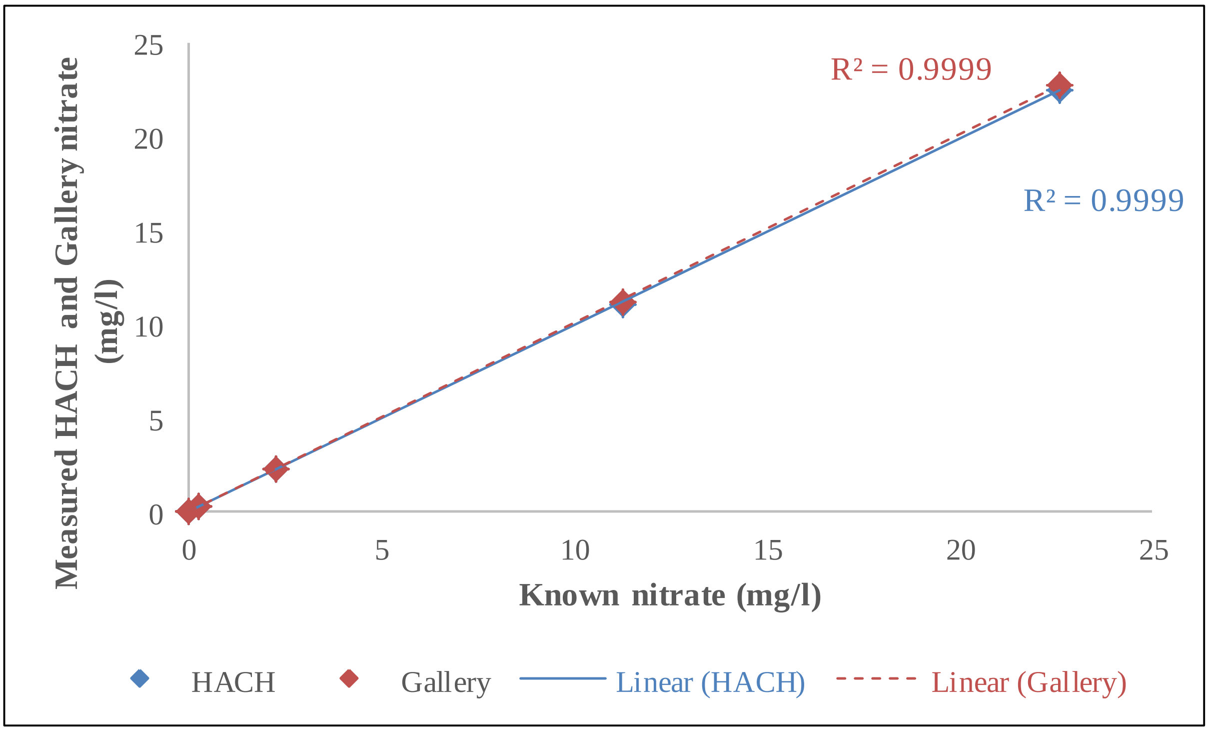
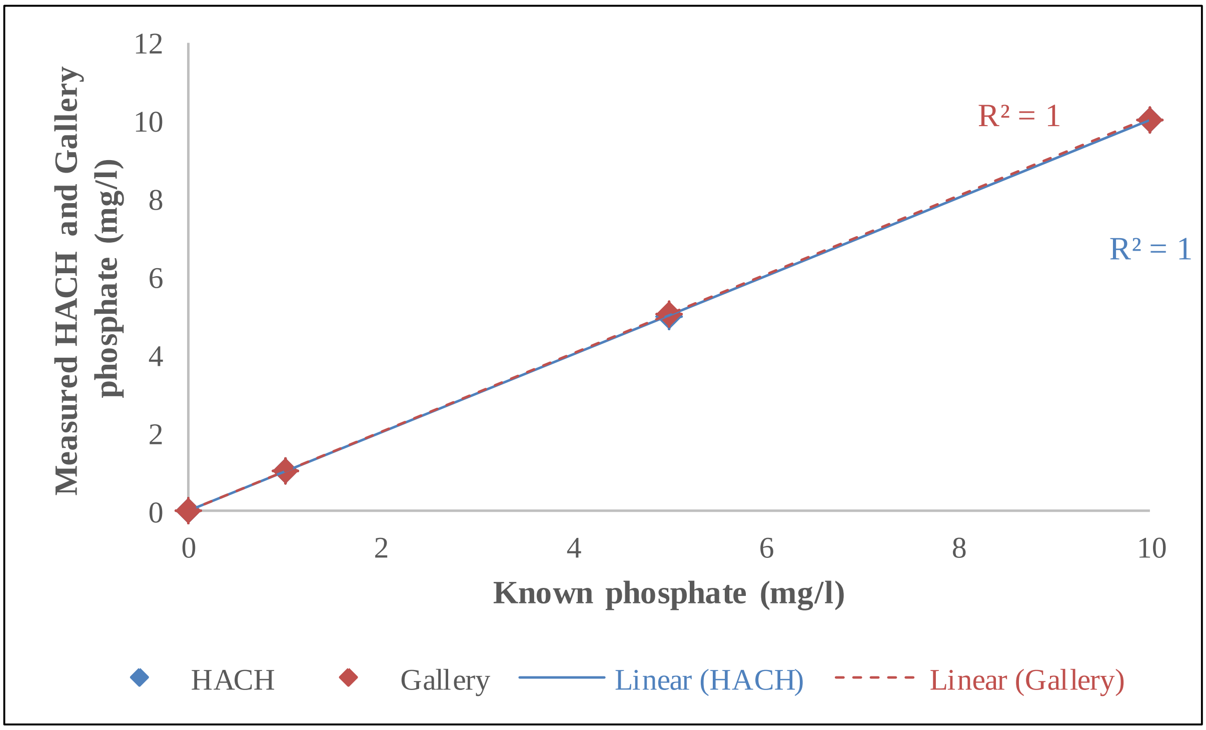
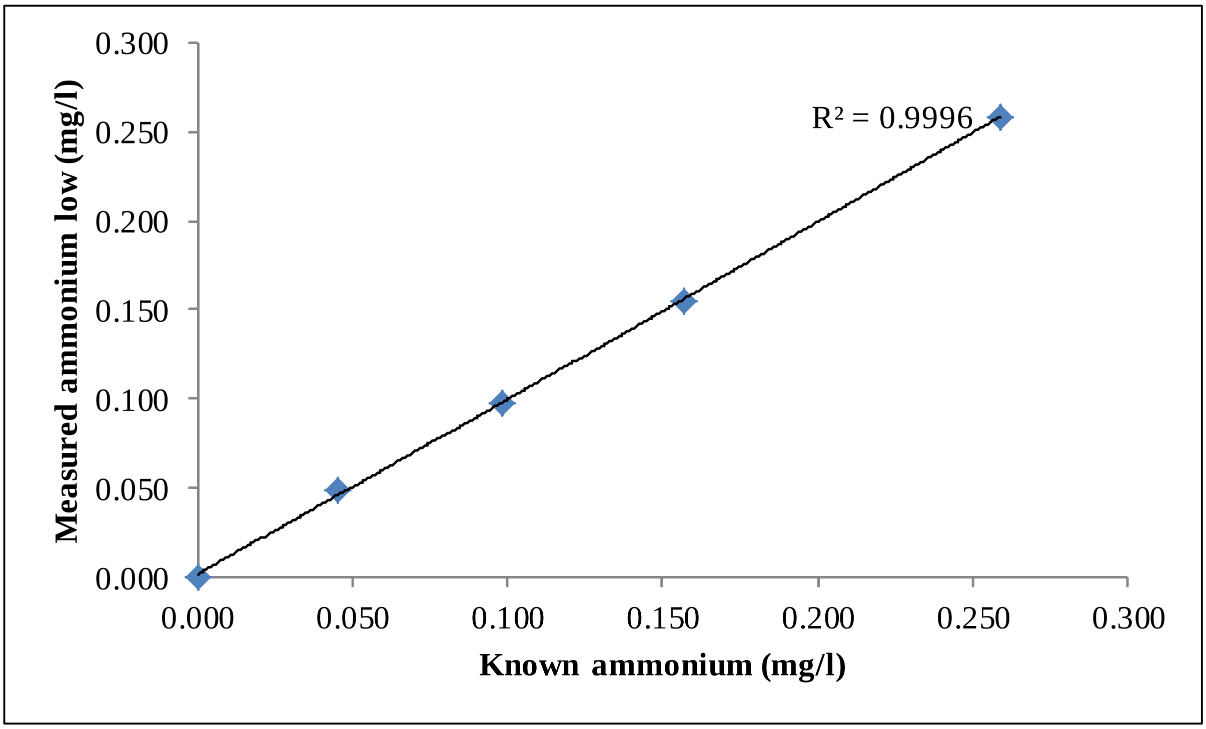
9. APPENDICES



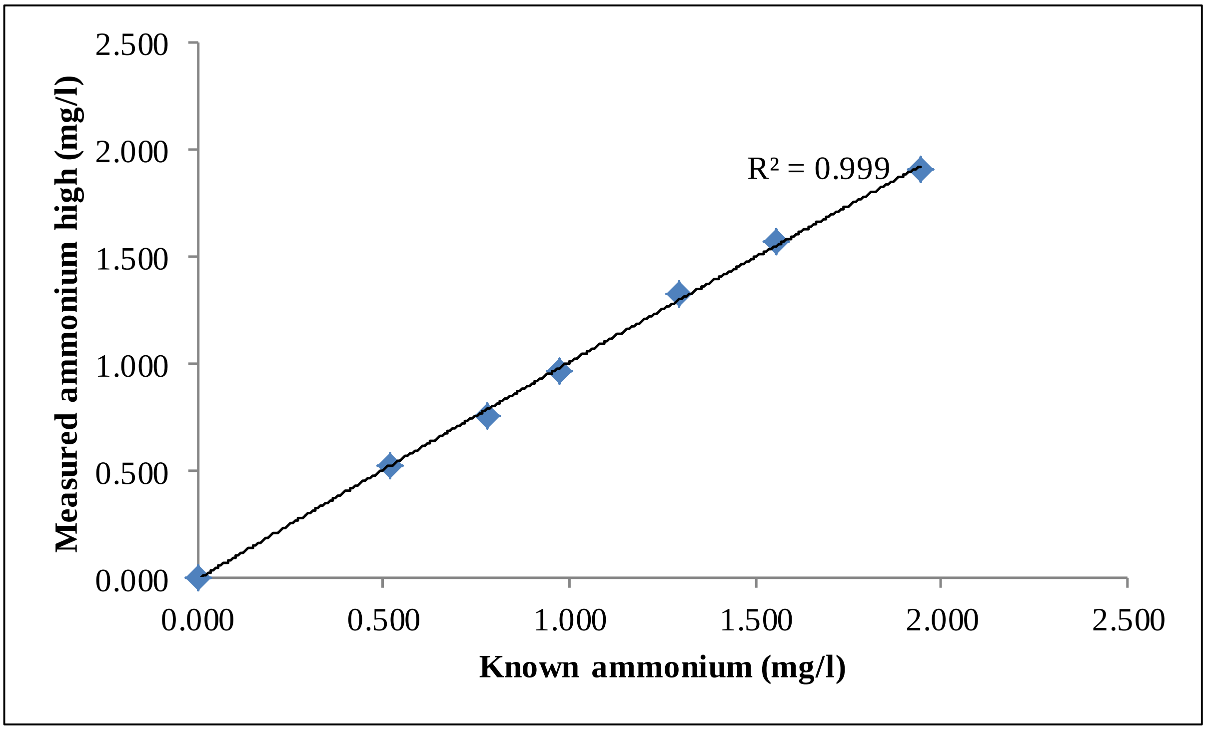
Appendix 1: HACH and Gallery comparison for nitrate calibration



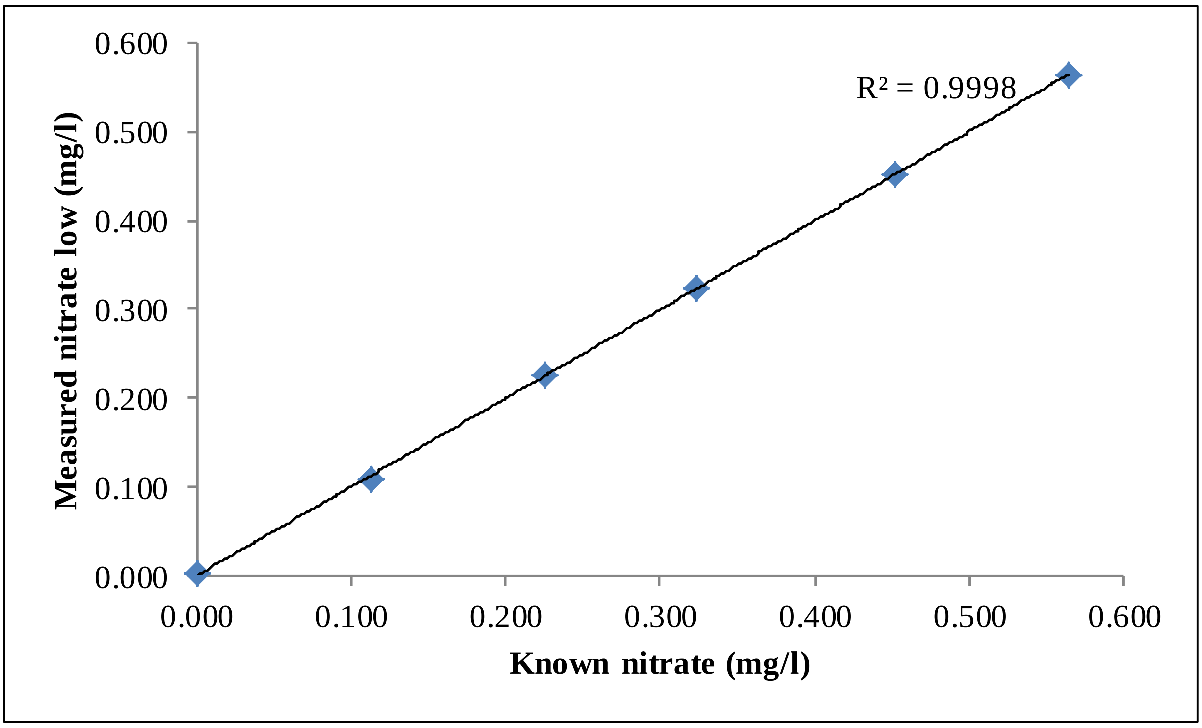
Appendix 2: HACH and Gallery comparison for phosphate calibration



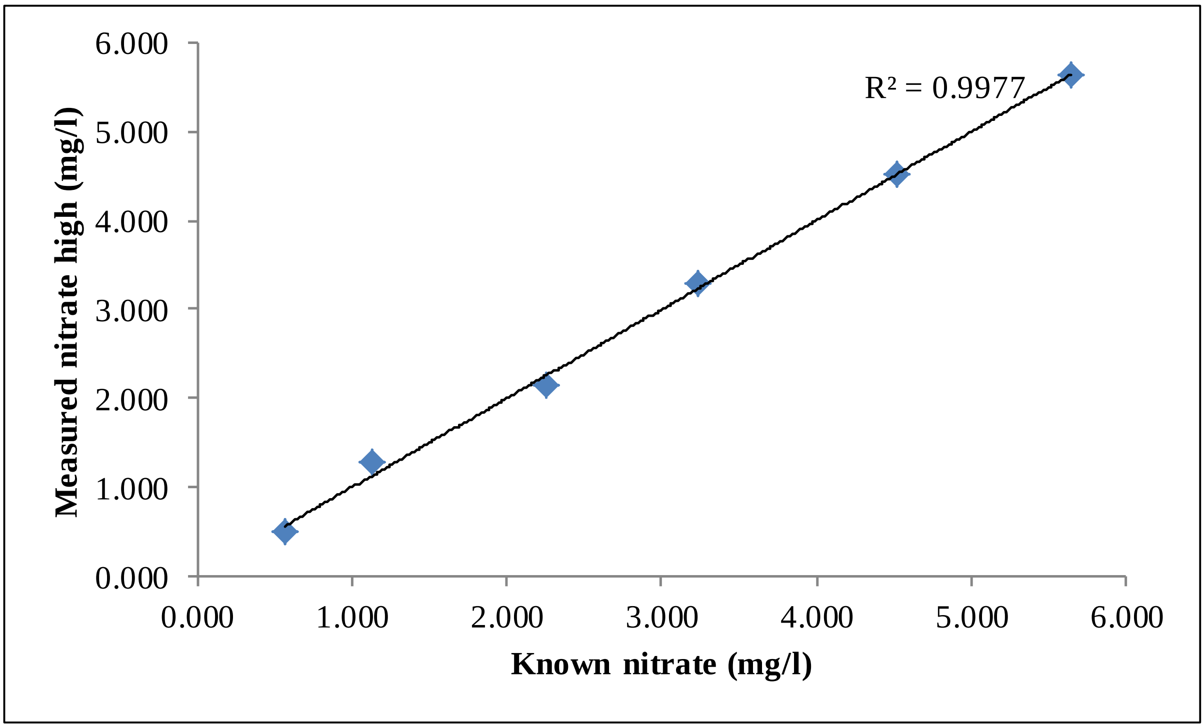
Appendix 3: Ammonium low calibration for Gallery analyser



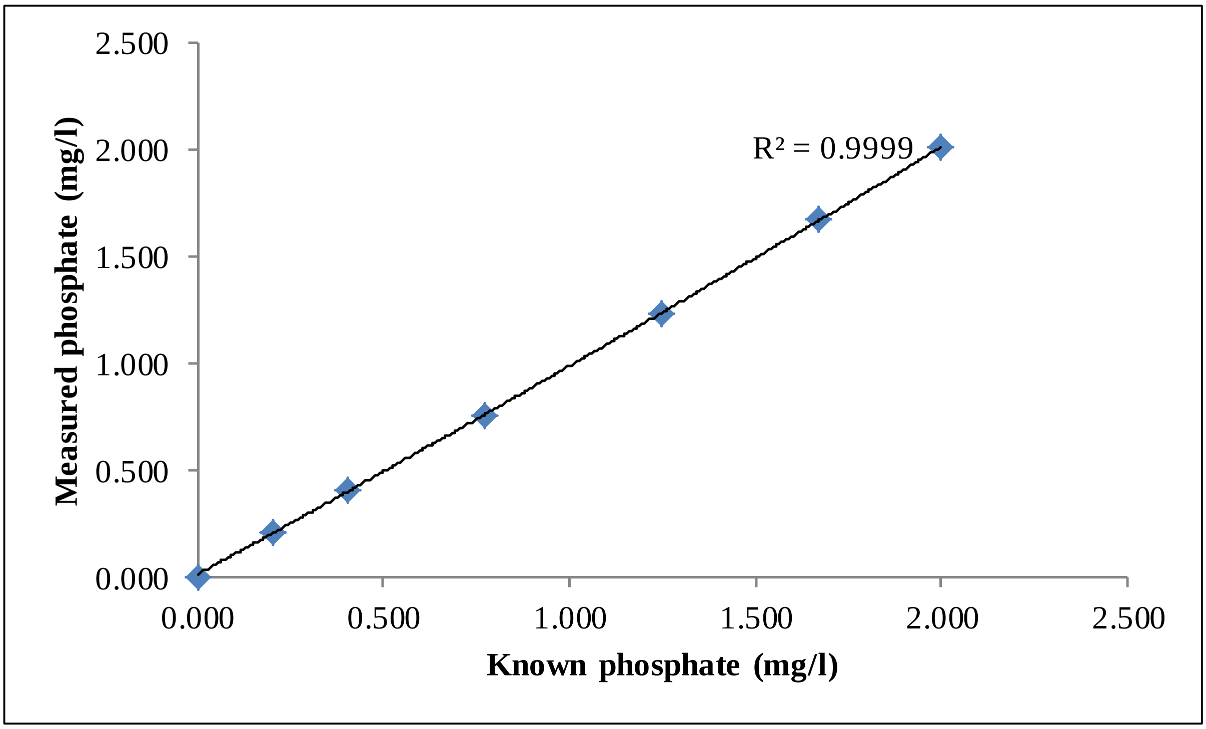
Appendix 4: Ammonium high calibration for Gallery analyser



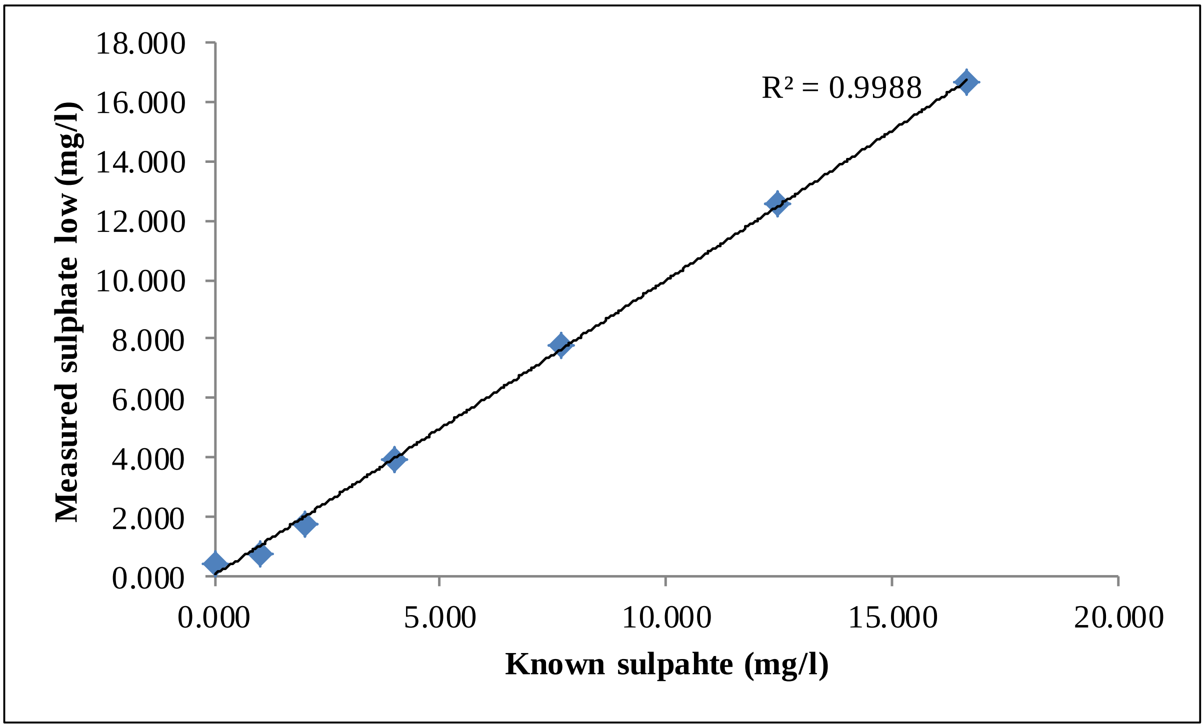
Appendix 5: Nitrate low calibration for Gallery analyser



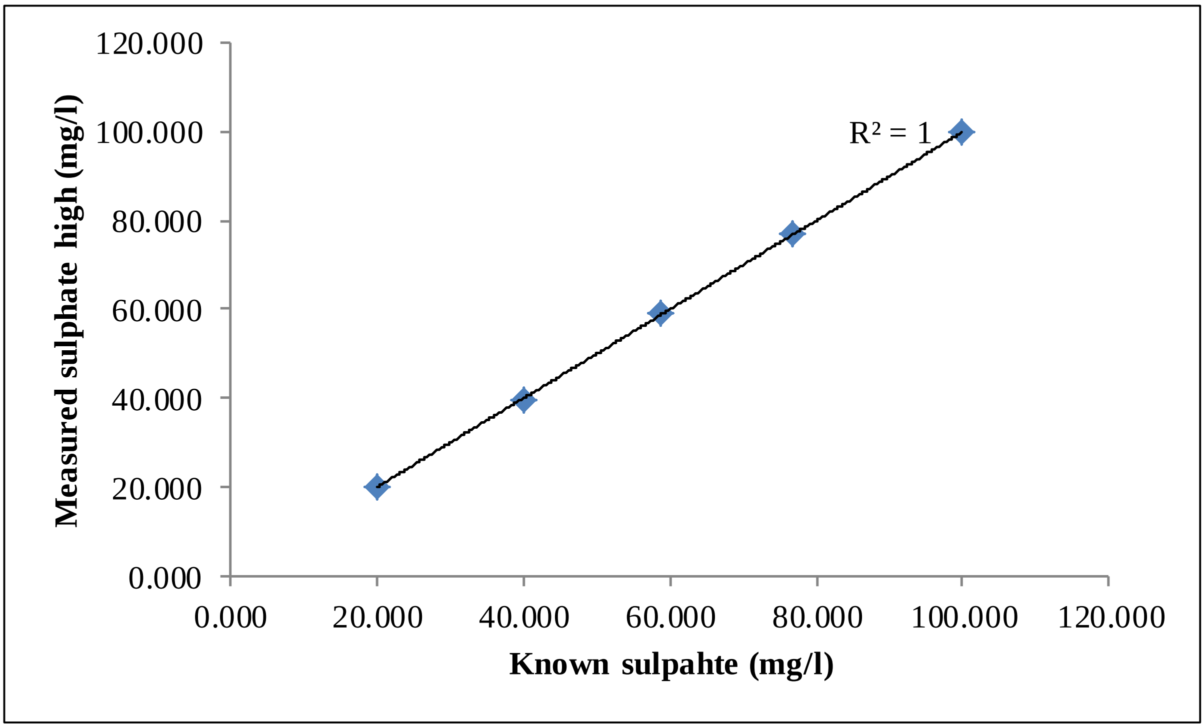
Appendix 6: Nitrate high calibration for Gallery analyser



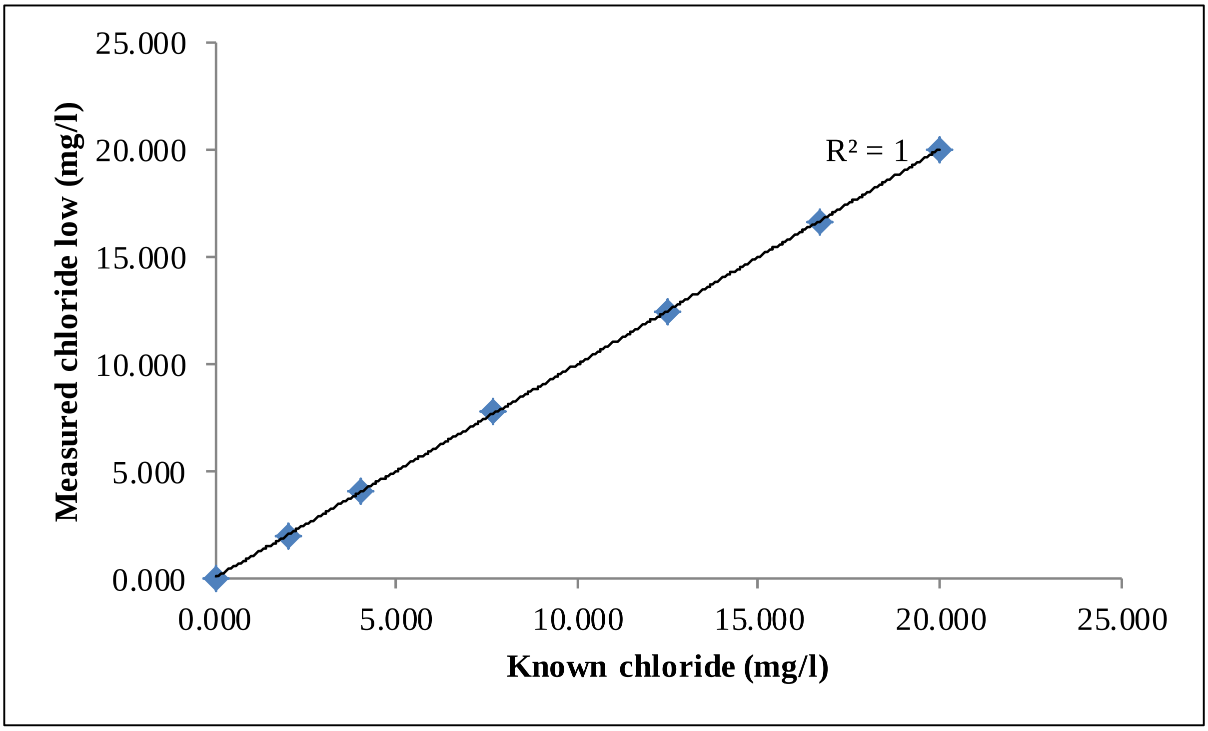
Appendix 7: Phosphate calibration for Gallery analyser



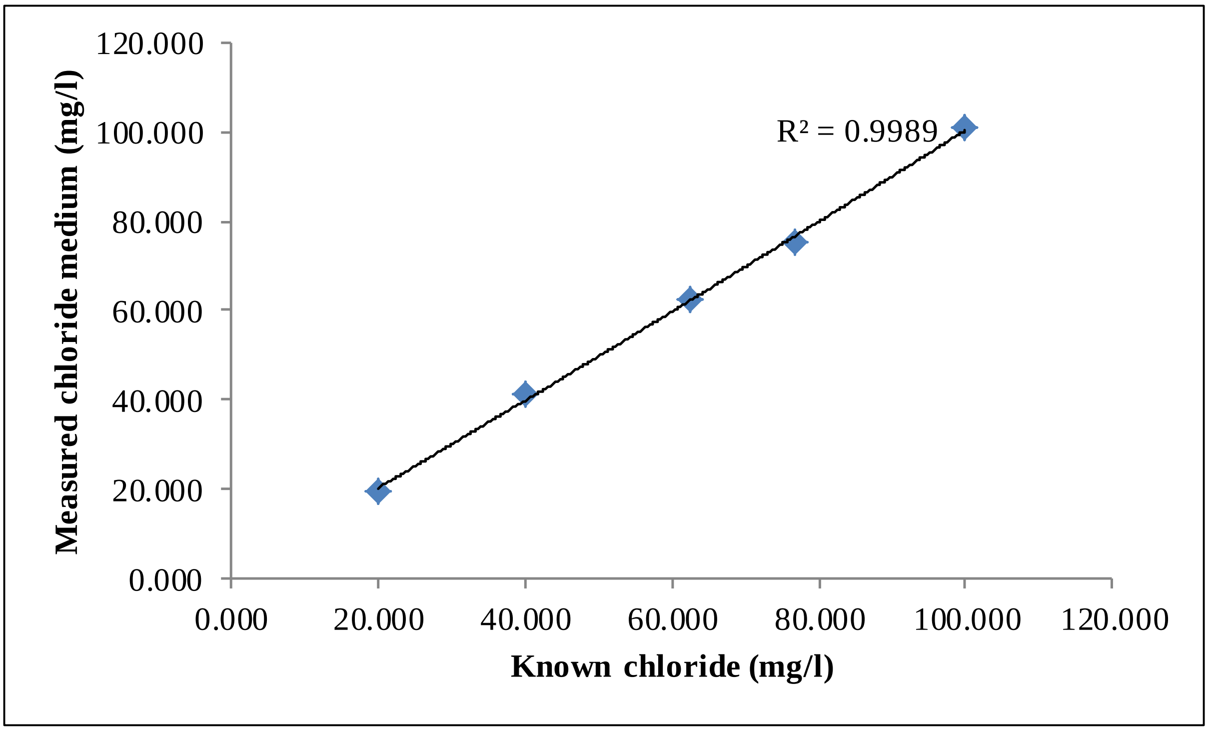
Appendix 8: Sulphate low calibration for Gallery analyser



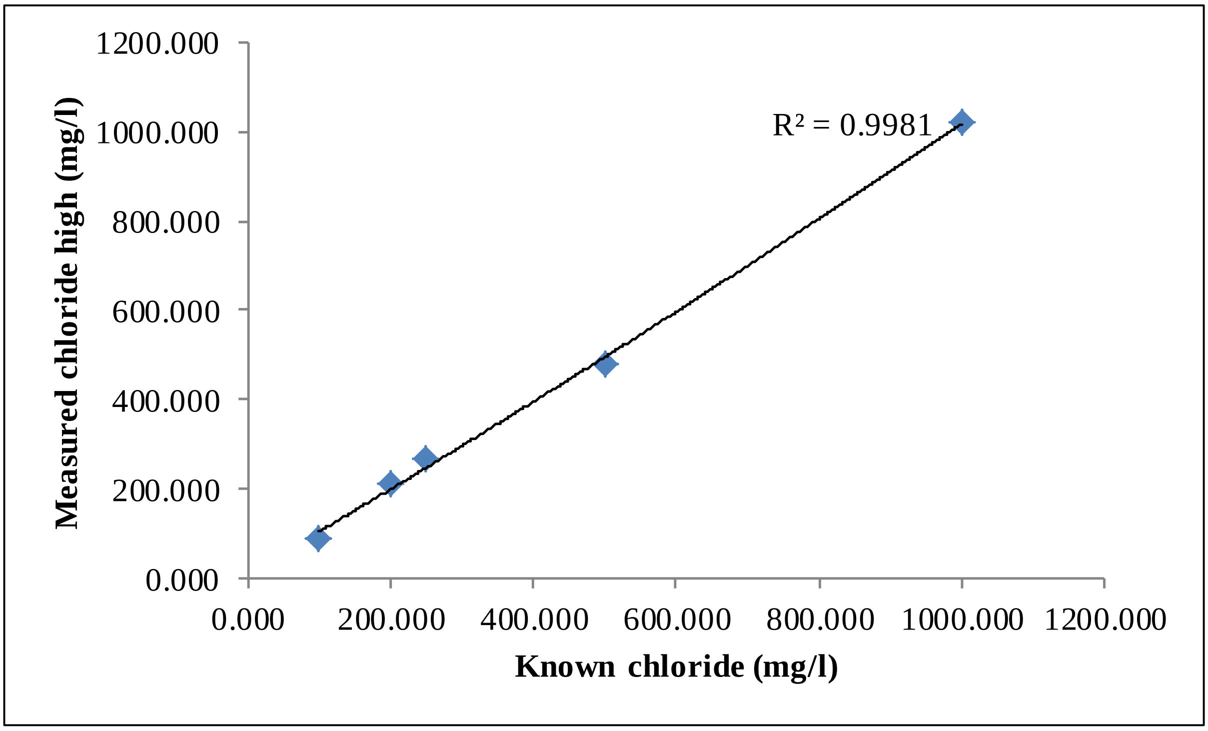
Appendix 9: Sulphate high calibration for Gallery analyser



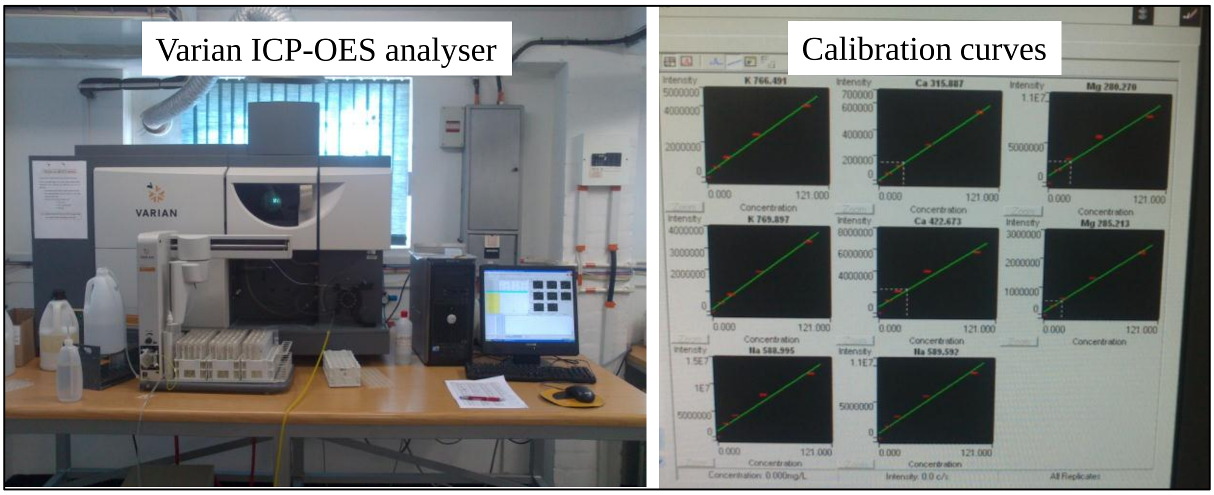
Appendix 10: Chloride low calibration for Gallery analyser



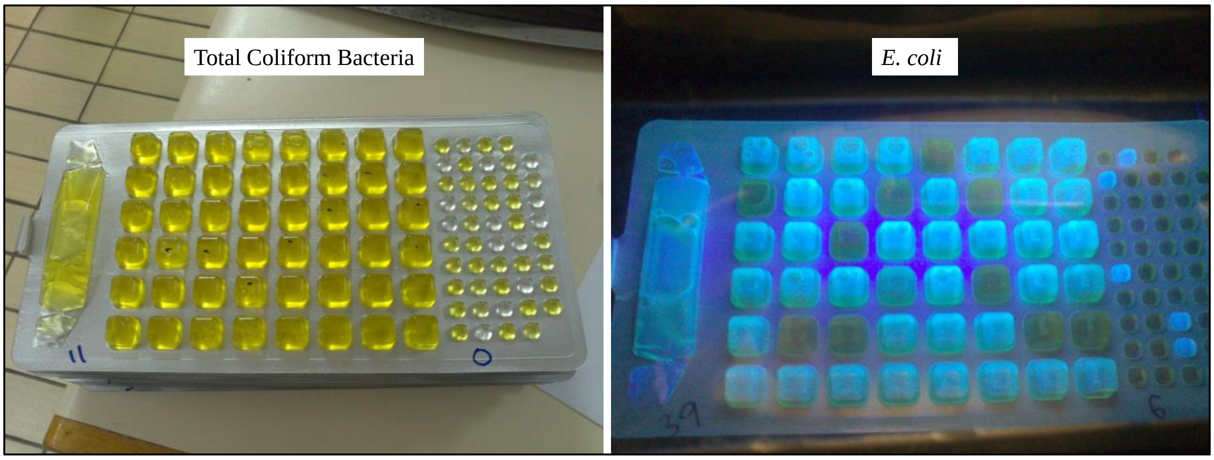
Appendix 11: Chloride medium calibration for Gallery analyser



Appendix 12: Chloride high calibration for Gallery analyser



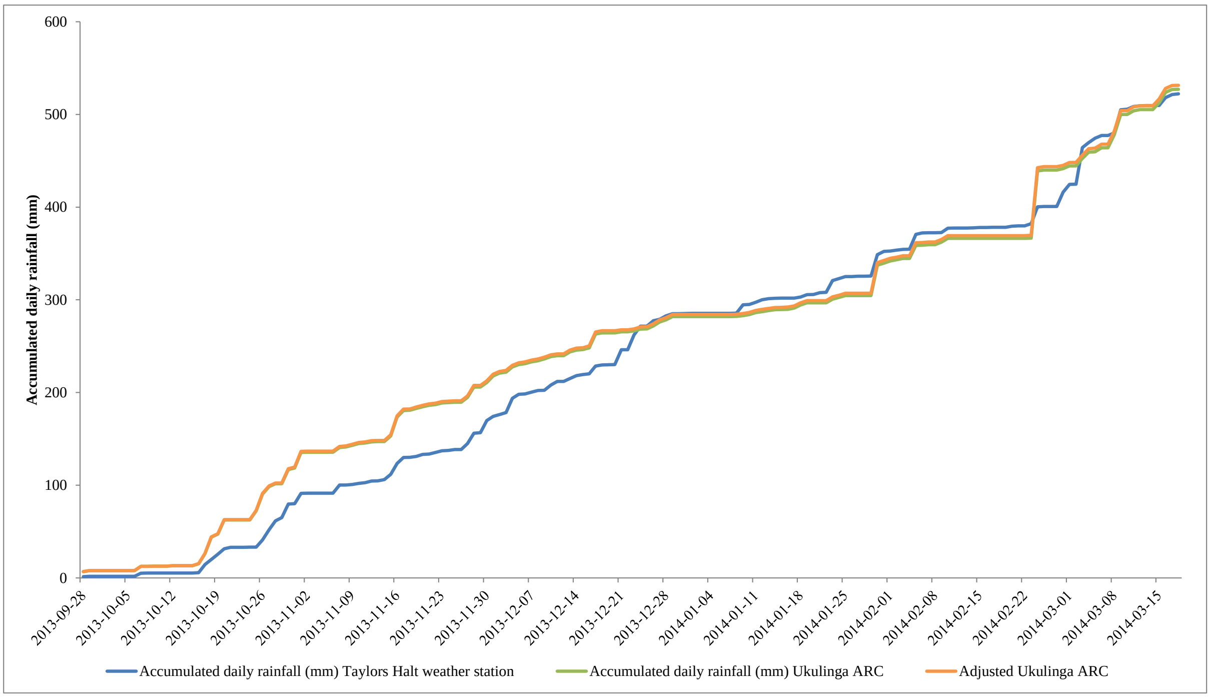
Appendix 13: Varian ICP-OES analyser and screen shot of calibration curve for selected 8 wavelengths



Appendix 14: Colilert ™ method for total coliform bacteria and *E. coli*

Number of tips	Known volume per tip (ml)	Equivalent depth per tip (mm)
0	0	0
1	5.2	0.24
2	3.3	0.15
3	5.1	0.24
4	3.4	0.16
5	5	0.23
6	3.5	0.16
7	5	0.23
8	3	0.14
9	5.3	0.25
10	3	0.14
11	6	0.28
12	2.5	0.12
Average		0.20

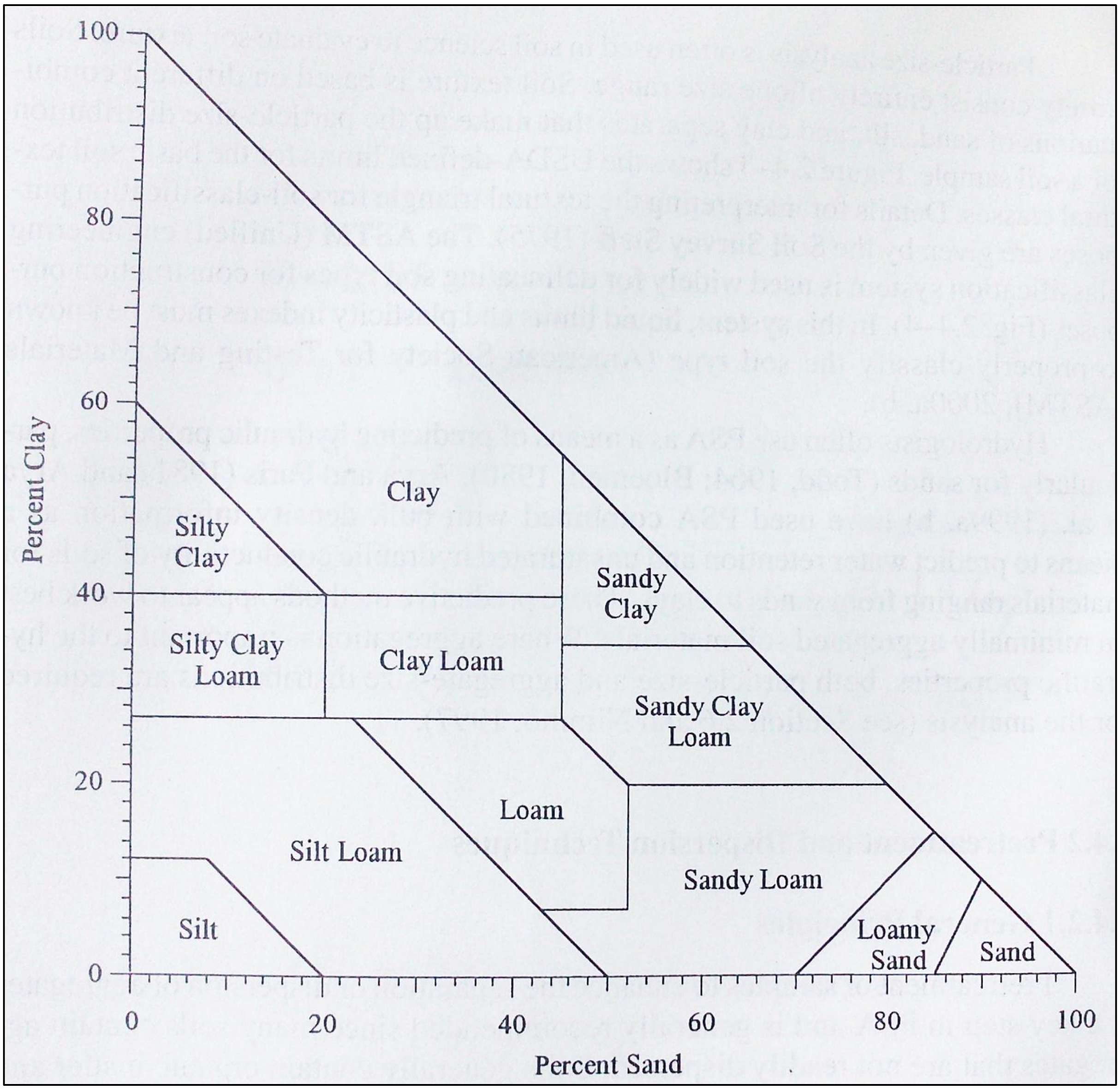
Appendix 15: Calibration of tipping bucket rain gauge



Appendix 16: Accumulated daily rainfall for Talyors Halt and U2E002 Cedara weather stations

Temperature (ºC)	**Settling time for sand and silt particles**	
	0.05 mm (seconds)	0.002 mm (hh:mm)
16	49	08:35
17	48	08:21
18	47	08:09
19	46	07:58
20	45	07:46
21	44	07:35
22	43	07:24
23	42	07:16
24	41	07:03
25	40	06:54
26	39	06:45
27	38	06:36
28	37	06:27

Appendix 17: Settling times for sand and silt particles



Appendix 18: USDA soil texture triangle (from Dane and Topp, 2002)

Appendix 19: Double ring infiltrometer at 2 different depths

Inner ring diameter (cm)	9.8000
a-Inner ring IR (cm)	4.9000
Inner ring cross sectional area (cm^2)	75.4296
Inner ring height (cm)	18.0000
d-Depth into soil (cm)	3.0000
H-Depth of water ponding (cm)	15.0000
α*	0.0400
C_1	0.9927
C_2	0.5781
q_s-Quasi steady fall rate in resivor (cm/s)	0.0010
K_{fs} (cm/s)	0.0001
K_{fs} (cm/h)	0.4585

$K_{fs} = q_s/[(H/(C_1 d + C_2 a)) + (1/(\alpha^*(C_1 d + C_2 a))) + 1]$

$K_{fs} = 0.001/[(15/(0.9927 \times 3 + 0.5781 \times 4.9)) + (1/(0.04(0.9927 \times 3 + 0.5781 \times 4.9))) + 1]$

$K_{fs} = 0.4585$ cm/hr.

Appendix 20: Example calculation of K_{fs} from double ring infiltrometer

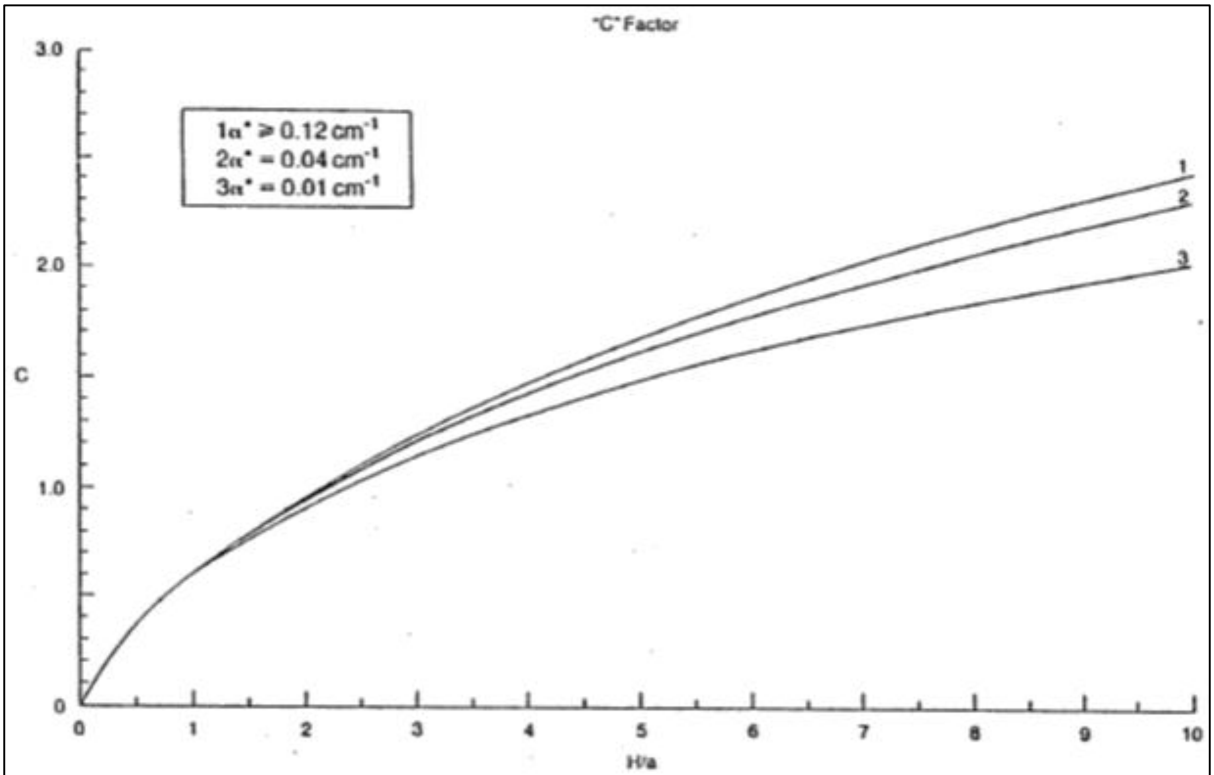
Resivoir ID (cm)	4.6
Guelph permeameter resivoir radius (cm)	2.3
A = cross sectional area of the Guelph permeameter (cm^2)	16.62
Height of air entry pipe inlet (cm)	2
Auger hole depth (cm)	130
a = the radius of the well (cm)	4.25
d-Depth of guelph permeameter (cm)	125
H = steady depth of water in the well (i.e. set by the height of the air tube) (cm)	7
α*	0.04
R = steady state rate of fall of water in the Guelph permeameter reservoir ($cm.s^{-1}$)	0.00347
C = dimensionless shape factor	0.865
K_{fs}-Single head (cm/s)	0.00003
K_{fs}-Single head (cm/h)	0.12336

$$K_{fs} = CAR/[2\pi H^2 + C\pi a^2 + (2\pi H/\alpha^*)]$$

$$K_{fs} = 0.865 \times 16.62 \times 0.00347/[2\pi 7^2 + 0.865\pi 4.25^2 + (2\pi 7/0.04)]$$

$$K_{fs} = 0.123 \text{ cm/hr}$$

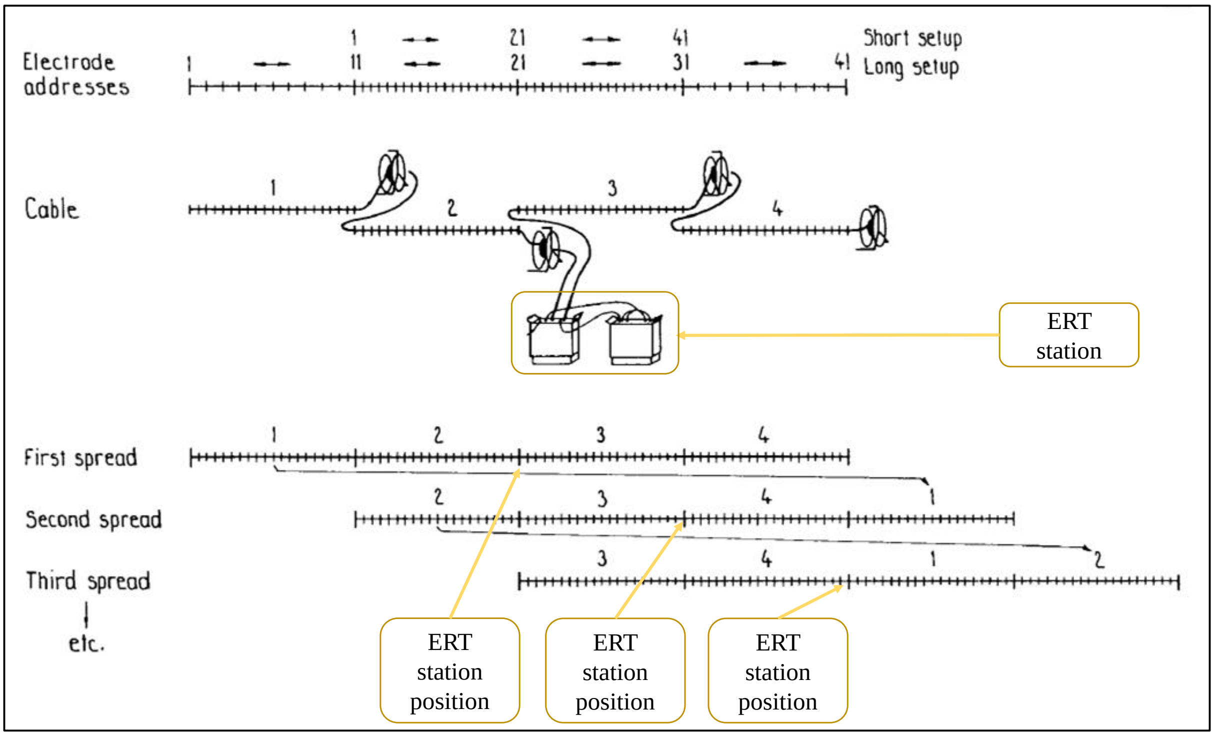
Appendix 21: Example calculation of K_{fs} from Guelph permeameter



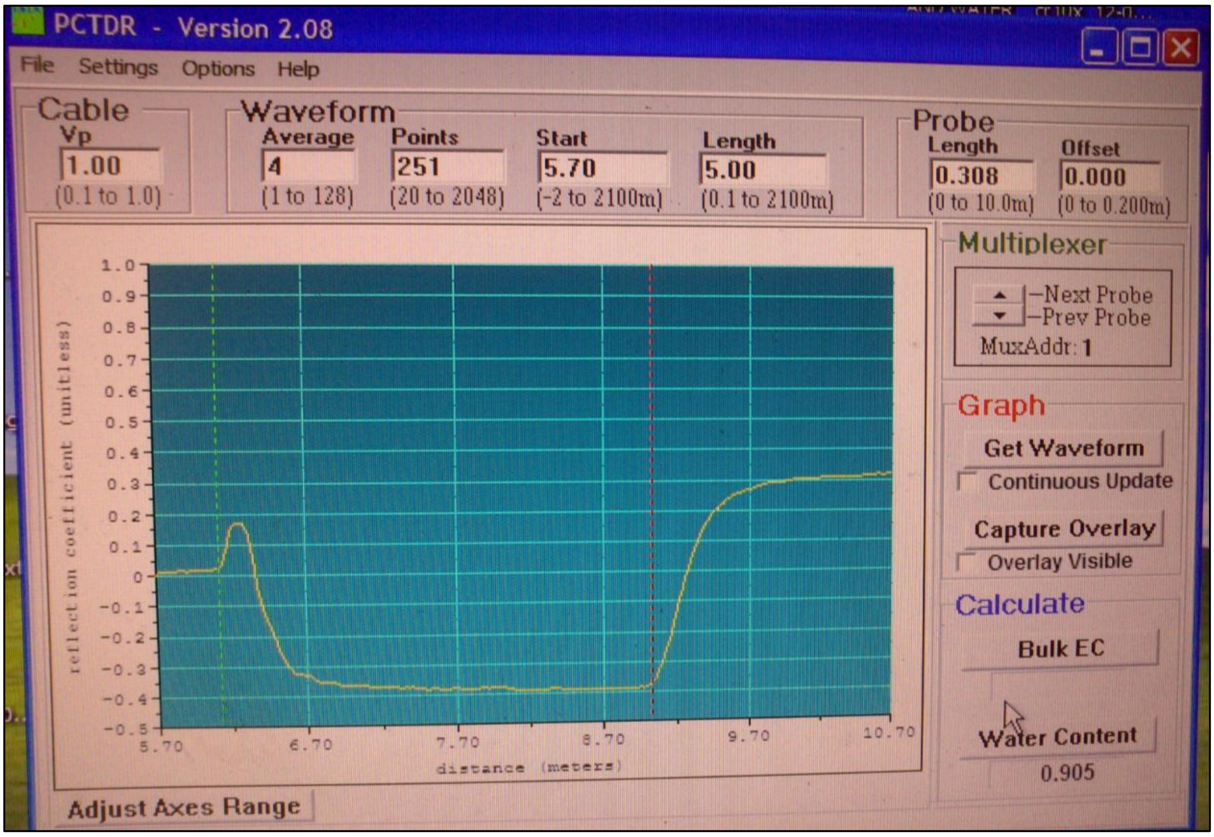
Appendix 22: Determination of C factor for the Guelph Permeameter

Soil Texture / Structure Category	α* (cm · -1)
compacted, structureless, clayey materials such as landfill caps and liners, lacustrine or marine sediments, etc.	0.01
soils that are both fine textured (clays) and unstructured.	0.04
most structured soils from clays through loams; including unstructured medium to fine sands. (the first choice for most soils)	0.12
coarse and gravelly sands; may include some highly structured soils with large cracks (vertisols) and macropores.	0.36

Appendix 23: Determination of soil macroscopic capillary length parameter



Appendix 24: Layout of ERT apparatus for Schlumberger short and long protocols, and a roll-along procedure (from ABEM, 2009



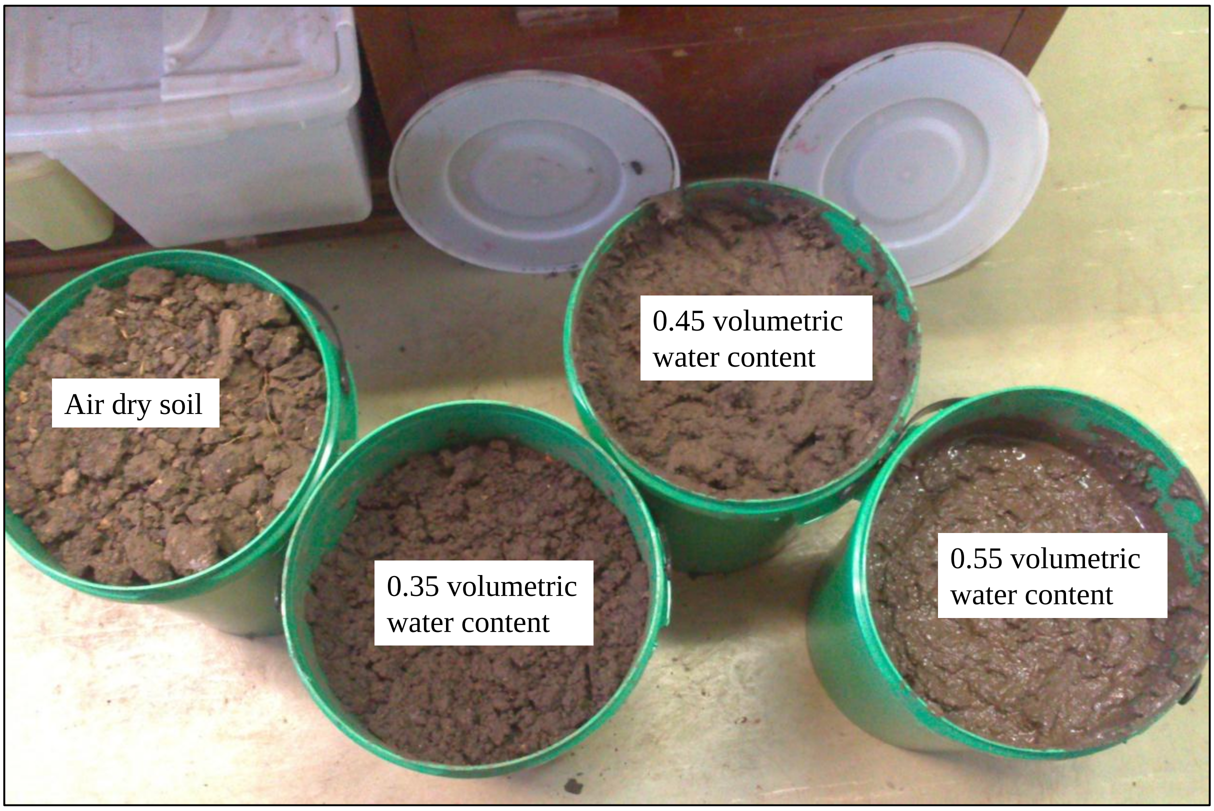
Appendix 25: PCTDR interface with relevant parameters for TDR probe 1

Probe	Probe rod length-L (m)	Temperature of water (°C)	Dielectric permittivity of water @ 22°C	Apparent length-La (m)	Cable propagation velocity-Vp (m.s^{-1})	Waveform average	Waveform points	Waveform start (m)	Waveform length (m)	PCTDR volumetric water content-Θ_V	Start index	Start distance (m)	End index	End distance (m)	Probe off-set
1	0.308	22.0	79.630	2.748	1.0	4.0	251.0	5.7	5.0	0.905	20.900	0.418	167.185	3.344	0.177
1	0.308	22.0	79.630	2.748	1.0	4.0	251.0	5.7	5.0	0.905	20.768	0.415	167.211	3.344	0.180
1	0.308	22.0	79.630	2.748	1.0	4.0	251.0	5.7	5.0	0.905	20.741	0.415	167.248	3.345	0.182
Average	0.308	22.0	79.630	2.748	1.0	4.0	251.0	5.7	5.0	0.905	20.803	0.416	167.214	3.344	0.180
2	0.302	22.0	79.630	2.695	1.0	4.0	251.0	5.7	5.0	0.913	21.829	0.437	166.306	3.326	0.195
2	0.302	22.0	79.630	2.695	1.0	4.0	251.0	5.7	5.0	0.913	21.759	0.435	166.235	3.325	0.195
2	0.302	22.0	79.630	2.695	1.0	4.0	251.0	5.7	5.0	0.913	21.739	0.435	166.502	3.330	0.200
Average	0.302	22.0	79.630	2.695	1.0	4.0	251.0	5.7	5.0	0.913	21.776	0.436	166.348	3.327	0.197
3	0.304	22.0	79.630	2.713	1.0	4.0	251.0	5.7	5.0	0.900	20.423	0.408	164.502	3.290	0.169
3	0.304	22.0	79.630	2.713	1.0	4.0	251.0	5.7	5.0	0.900	20.166	0.403	163.502	3.270	0.154
3	0.304	22.0	79.630	2.713	1.0	4.0	251.0	5.7	5.0	0.900	20.445	0.409	163.847	3.277	0.155
Average	0.304	22.0	79.630	2.713	1.0	4.0	251.0	5.7	5.0	0.900	20.345	0.407	163.951	3.279	0.159
4	0.309	22.0	79.630	2.757	1.0	4.0	251.0	5.7	5.0	0.894	21.450	0.429	166.849	3.337	0.151
4	0.309	22.0	79.630	2.757	1.0	4.0	251.0	5.7	5.0	0.894	21.504	0.430	166.743	3.335	0.147
4	0.309	22.0	79.630	2.757	1.0	4.0	251.0	5.7	5.0	0.894	21.503	0.430	166.758	3.335	0.148
Average	0.309	22.0	79.630	2.757	1.0	4.0	251.0	5.7	5.0	0.894	21.485	0.430	166.783	3.336	0.149
5	0.304	22.0	79.630	2.713	1.0	4.0	251.0	5.7	5.0	0.908	23.078	0.462	167.530	3.351	0.176
5	0.304	22.0	79.630	2.713	1.0	4.0	251.0	5.7	5.0	0.908	22.972	0.459	167.848	3.357	0.185
5	0.304	22.0	79.630	2.713	1.0	4.0	251.0	5.7	5.0	0.908	23.258	0.465	168.107	3.362	0.184
Average	0.304	22.0	79.630	2.713	1.0	4.0	251.0	5.7	5.0	0.908	23.102	0.462	167.828	3.357	0.182
6	0.301	22.0	79.630	2.686	1.0	4.0	251.0	5.7	5.0	0.913	22.229	0.445	166.261	3.325	0.195
6	0.301	22.0	79.630	2.686	1.0	4.0	251.0	5.7	5.0	0.913	22.157	0.443	166.345	3.327	0.198
6	0.301	22.0	79.630	2.686	1.0	4.0	251.0	5.7	5.0	0.913	22.504	0.450	166.637	3.333	0.197
Average	0.301	22.0	79.630	2.686	1.0	4.0	251.0	5.7	5.0	0.913	22.297	0.446	166.414	3.328	0.196
7	0.307	22.0	79.630	2.740	1.0	4.0	251.0	5.7	5.0	0.901	24.017	0.480	169.410	3.388	0.168
7	0.307	22.0	79.630	2.740	1.0	4.0	251.0	5.7	5.0	0.901	23.425	0.468	169.029	3.381	0.173
7	0.307	22.0	79.630	2.740	1.0	4.0	251.0	5.7	5.0	0.901	23.887	0.478	169.514	3.390	0.173
Average	0.307	22.0	79.630	2.740	1.0	4.0	251.0	5.7	5.0	0.901	23.776	0.476	169.318	3.386	0.171
8	0.308	22.0	79.630	2.748	1.0	4.0	251.0	5.7	5.0	0.904	9.468	0.189	167.859	3.357	0.419
8	0.308	22.0	79.630	2.748	1.0	4.0	251.0	5.7	5.0	0.904	9.488	0.190	167.984	3.360	0.421
8	0.308	22.0	79.630	2.748	1.0	4.0	251.0	5.7	5.0	0.904	9.499	0.190	167.775	3.355	0.417
Average	0.308	22.0	79.630	2.748	1.0	4.0	251.0	5.7	5.0	0.904	9.485	0.190	167.873	3.357	0.419

Appendix 26: Parameters used to calculate the TDR probe off-sets

Dielectric Permittivity value for a range of temperatures	
Temperature (°C)	**Dielectric Permittivity**
15	82.23
15.5	82.04
16	81.85
16.5	81.67
17	81.48
17.5	81.29
18	81.1
18.5	80.92
19	80.73
19.5	80.55
20	80.36
20.5	80.18
21	79.99
21.5	79.81
22	79.63
22.5	79.44
23	79.26
23.5	79.08
24	78.9
24.5	78.72
25	78.54
25.5	78.36
26	78.18
26.5	78
27	77.82
27.5	77.65
28	77.47
28.5	77.29
29	77.112
29.5	76.94
30	76.76

Appendix 27: Dielectric Permittivity value for a range of temperatures



Appendix 28: Four 20 litre buckets with a known volumteric water contents

TDR probe repetition	TDR volumetric water content ($cm^3.cm^{-3}$)	Known volumetric water content ($cm^3.cm^{-3}$)
1	0.29	0.35
2	0.29	
3	0.31	
Average	0.30	
1	0.41	0.45
2	0.45	
3	0.44	
Average	0.43	
1	0.55	0.55
2	0.54	
3	0.54	
Average	0.54	

Appendix 29: Calibration results of TDR

Appendix 30: Surfacing of water table at the Slangspruit site after prolonged rainfall conditions

Appendix 31: Disturbed soil profile at the Crèche site

Appendix 32: Domestic animals and animal waste surrounding piezometers at Slangspruit

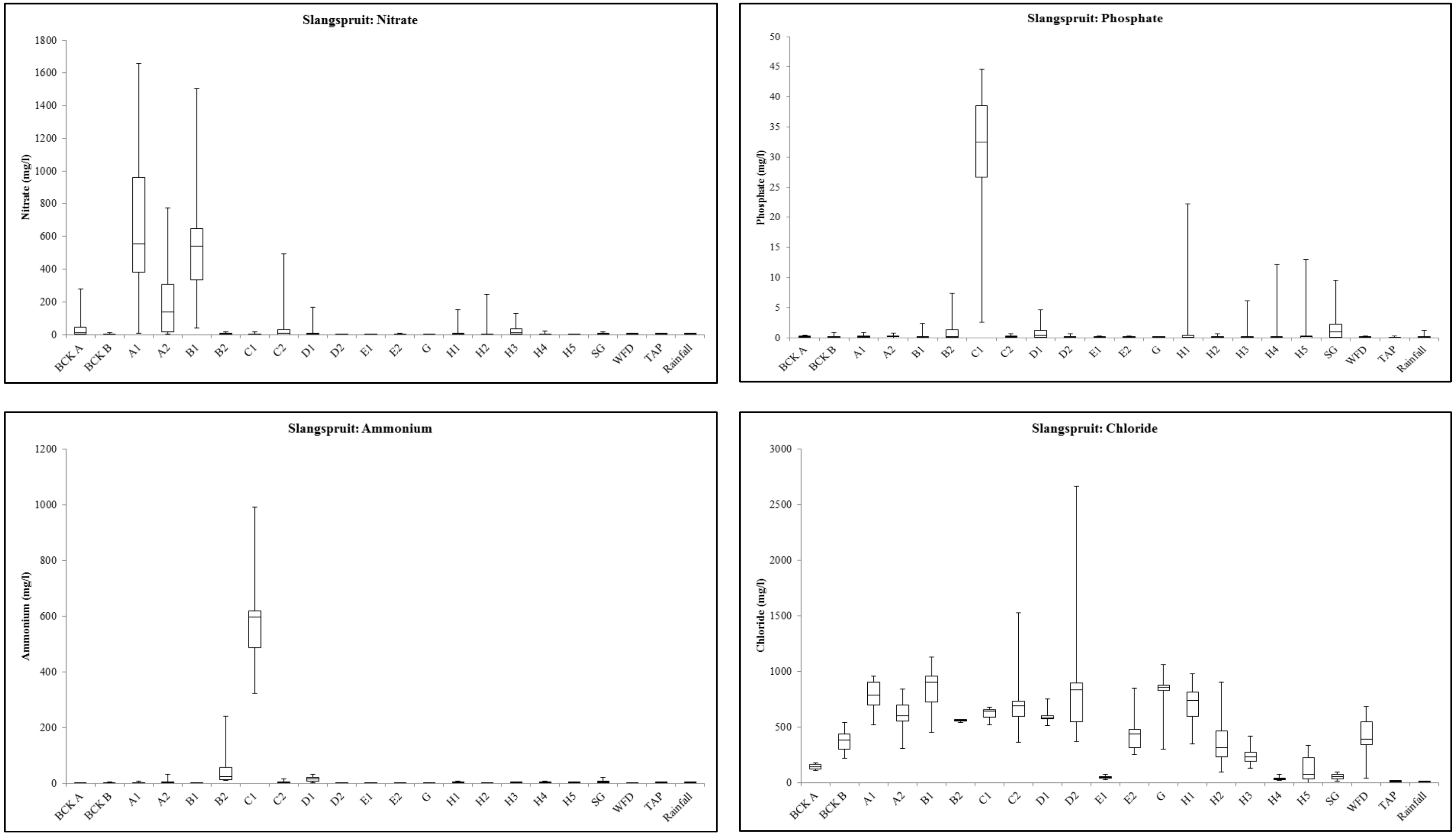
Appendix 33: Cattle grazing and defecating near seepage face at the Taylors Halt site

Appendix 34: Preferential flow paths via large animal burrows and joints or cracks in the parent material at the Taylors Halt site

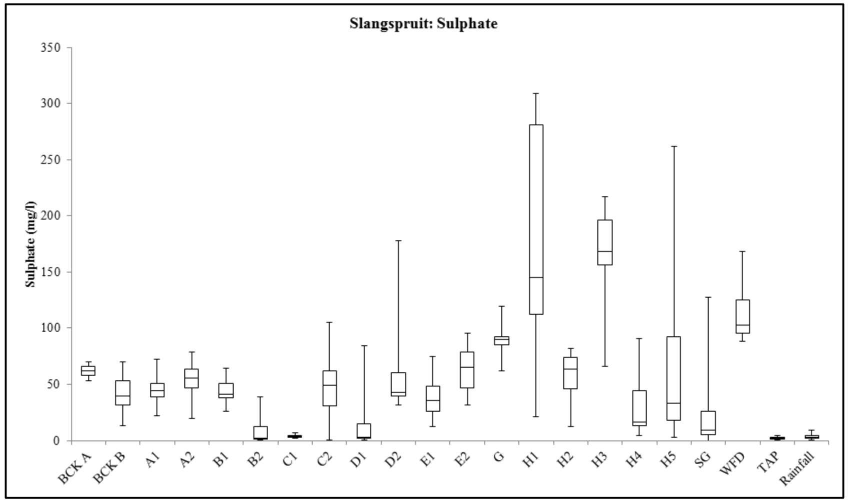
Slangspruit		**Crèche**		**Azalea**		**Taylors Halt**		**Taylors Halt Control**	
Piezometer	Depth of Piezometer (m.b.s)	Piezometer	Depth of Piezometer (m.b.s)	Piezometer	Depth of Piezometer (m.b.s)	Piezometer	Depth of Piezometer (m.b.s)	Piezometer	Depth of Piezometer (m.b.s)
A1	1.75	A	1.3	A	6	VIP1 A	1.8	A	1.7
A2	1.3	B	1.3	B	6	VIP1 B	1.5	B1	3
B1	1.45	C	1.3	E	6.1	VIP1 C	1.5	B2	3
B2	1.4	D	1.3	G	3.1	VIP1 D	1.25	B3	3
C1	1.32	E	1.3	H1	2.1	VIP1 E	1		
C2	1.4	G1	1.3	H2	2.1	VIP2 A1	2		
D1	1.25	G2	0.9	H3	1.65	VIP2 A2	6.6		
D2	1.4	G3	0.9	Background A	6	VIP2 B1	3		

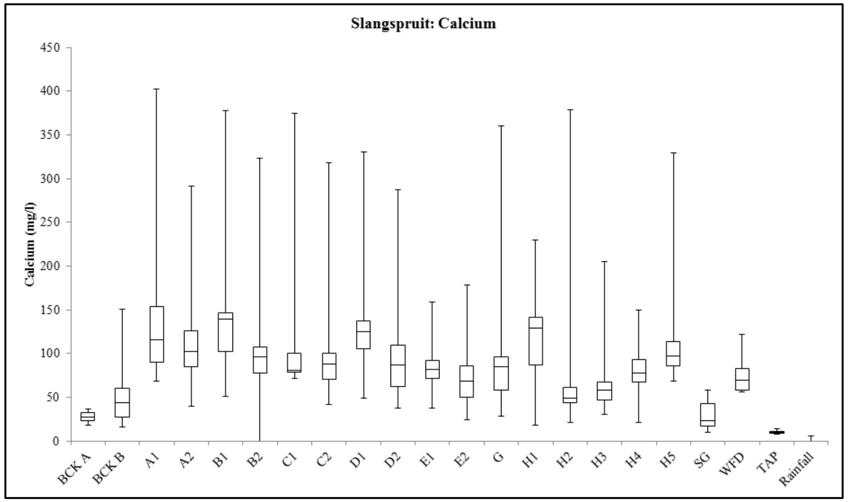
E1	1.6	G4	0.9	Background B	5.2	VIP2 B2	6.4
E2	1.45	G5	2			VIP2 C1	3
G	1.9	Background A	1.3			VIP2 C2	6.2
H1	1.7	Background B	1.3			VIP2 D1	3
H2	1.25					VIP2 D2	6
H3	1.5					VIP2 E1	2.8
H4	1.25					VIP2 E2	3.35
H5	1.6					VIP3 A1	2
Background A	1.85					VIP3 A2	7.1
Background B	1.68					VIP3 B1	3
						VIP3 B2	7.8
						VIP3 C1	3
						VIP3 C2	7.5
						VIP3 D1	3
						VIP3 D2	7.6
						VIP3 E1	3
						VIP3 E2	7.1
						VIP4 A1	2
						VIP4 A2	3
						VIP4 B1	3
						VIP4 B2	3
						VIP4 C1	2.4
						VIP4 C2	2.6
						VIP4 D1	2.2
						VIP4 D2	2.2
						VIP4 E1	1.6
						VIP4 E2	0.8
						VIP4 E3	2.1
						VIP4 E4	1
						VIP4 E5	1.2
						VIP4 G1	1.6
						VIP4 G2	2.5

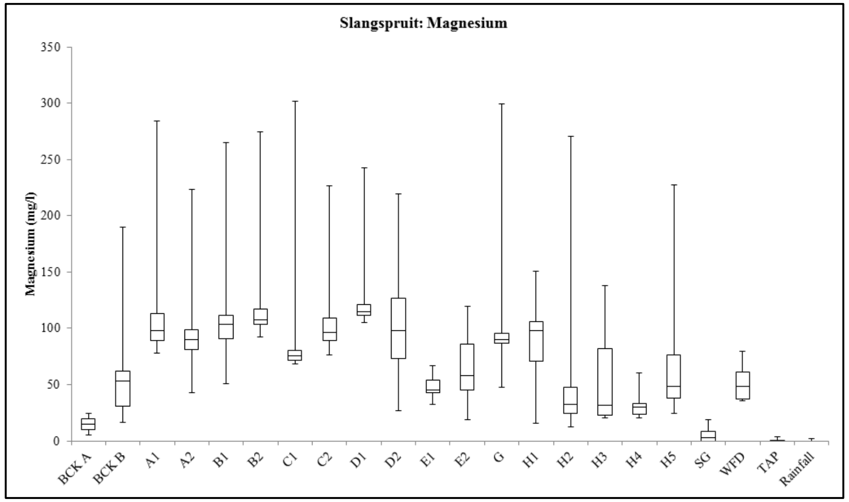
Appendix 35: Depth of piezometers for the 5 study sites

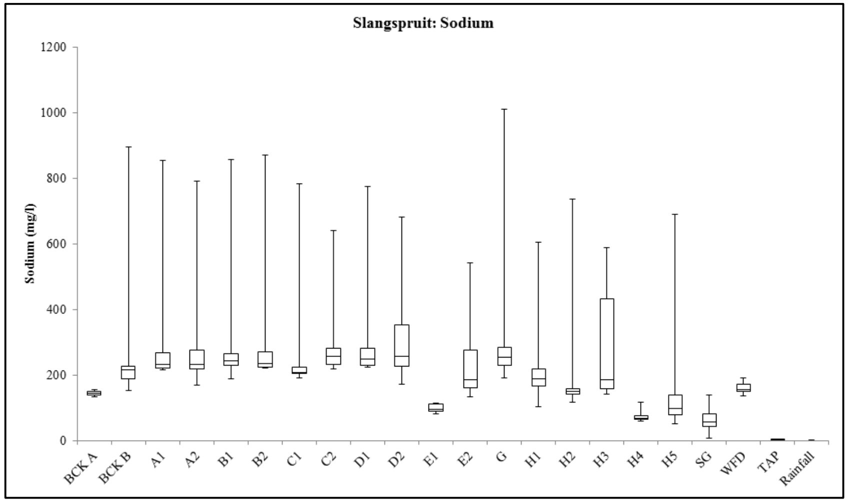


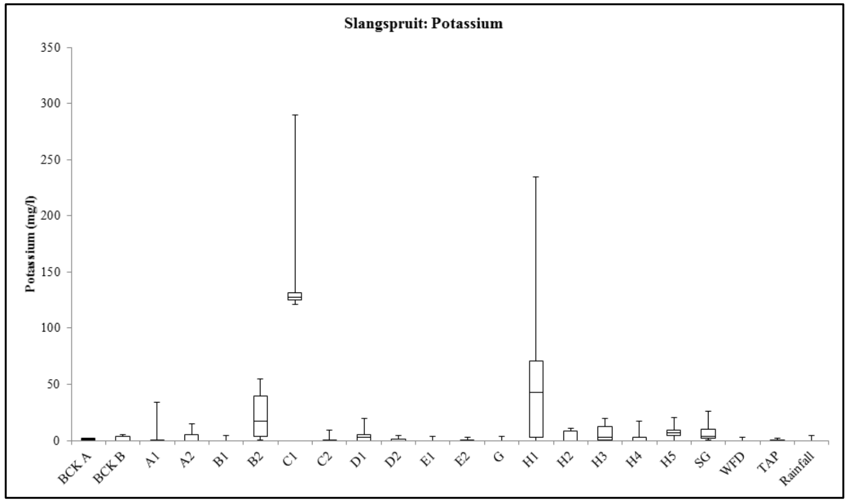
Slangspruit: Nitrate
Nitrate (mg/l)
Slangspruit: Phosphate
Phosphate (mg/l)
Slangspruit: Ammonium
Ammonium (mg/l)
Slangspruit: Chloride
Chloride (mg/l)
BCK A
BCK B
A1
A2
B1
B2
C1
C2
D1
D2
E1
E2
G
H1
H2
H3
H4
H5
SG
WFD
TAP
Rainfall

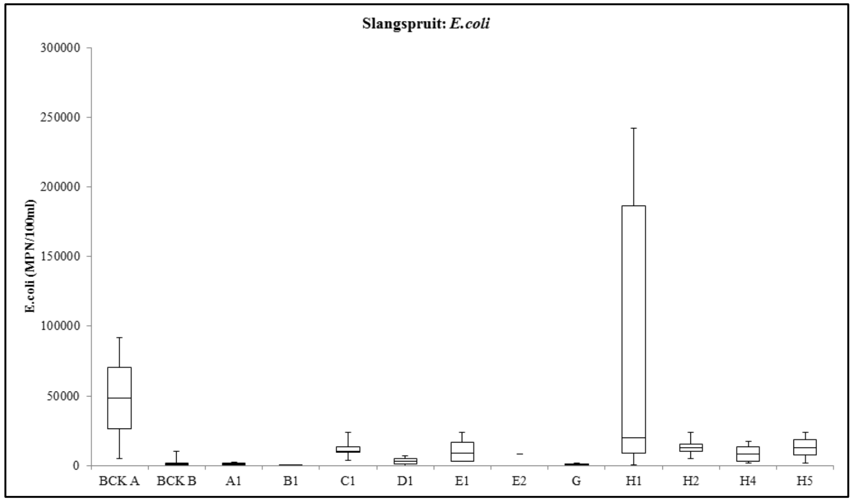

Slangspruit: Sulphate
Sulphate (mg/l)
0
50
100
150
200
250
300
350
BCK A
BCK B
A1
A2
B1
B2
C1
C2
D1
D2
E1
E2
G
H1
H2
H3
H4
H5
SG
WFD
TAP
Rainfall

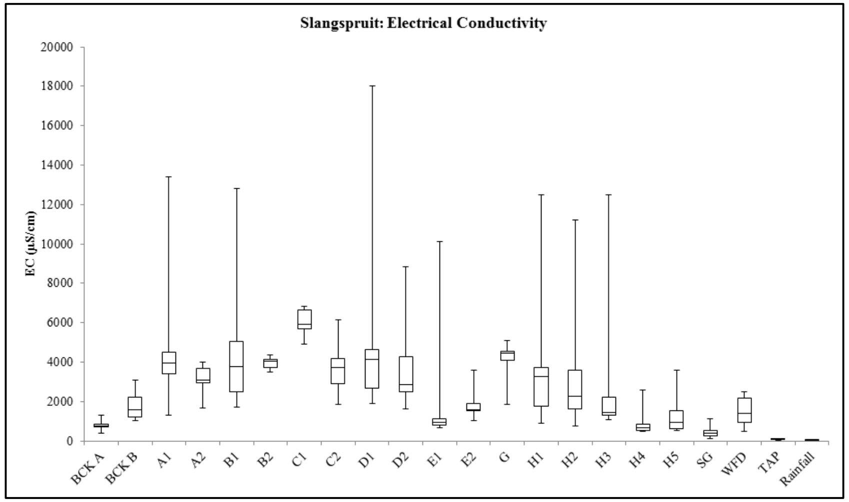

Slangspruit: Calcium
Calcium (mg/l)
0
50
100
150
200
250
300
350
400
450
BCK A
BCK B
A1
A2
B1
B2
C1
C2
D1
D2
E1
E2
G
H1
H2
H3
H4
H5
SG
WFD
TAP
Rainfall

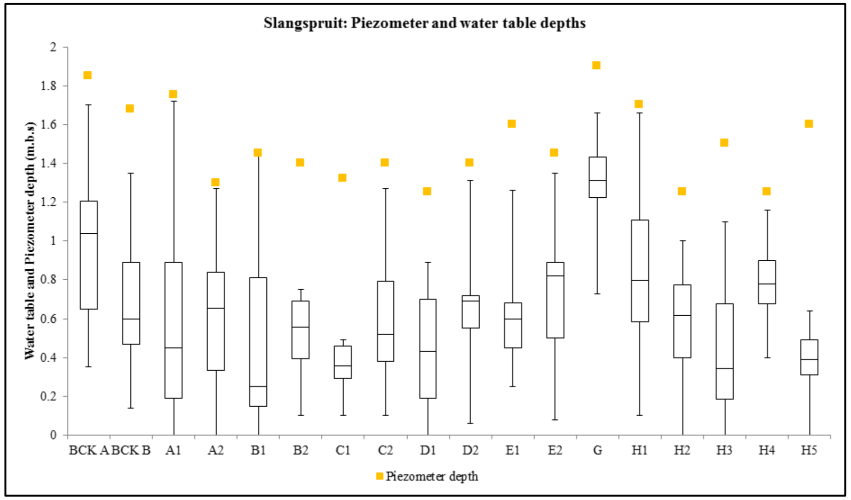

Slangspruit: Magnesium
Magnesium (mg/l)
0
50
100
150
200
250
300
350
BCK A
BCK B
A1
A2
B1
B2
C1
C2
D1
D2
E1
E2
G
H1
H2
H3
H4
H5
SG
WFD
TAP
Rainfall

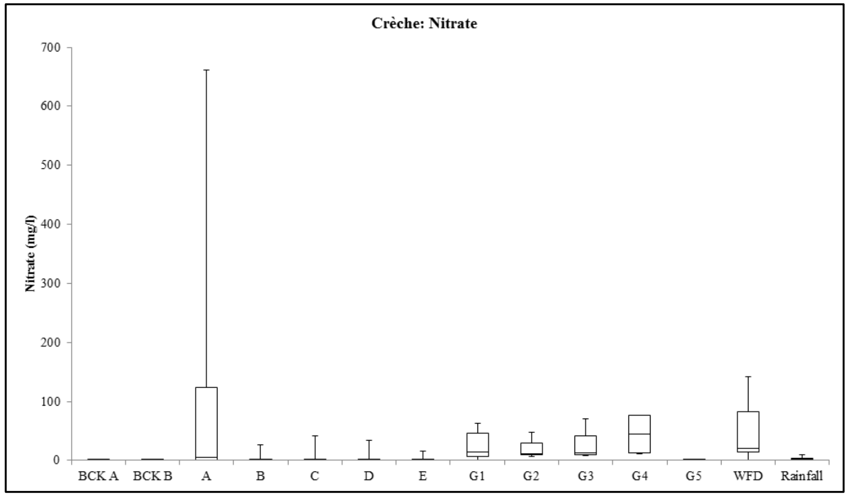

Slangspruit: Sodium
Sodium (mg/l)
0
200
400
600
800
1000
1200
BCK A
BCK B
A1
A2
B1
B2
C1
C2
D1
D2
E1
E2
G
H1
H2
H3
H4
H5
SG
WFD
TAP
Rainfall

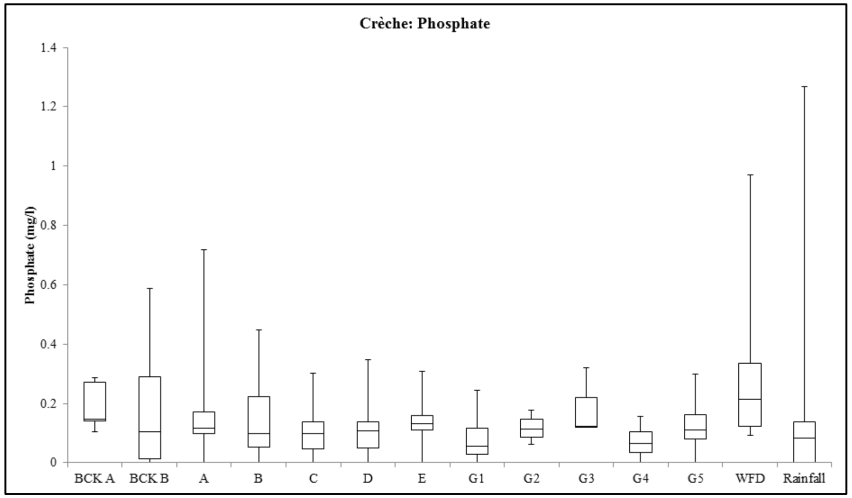

Slangspruit: Potassium
Potassium (mg/l)
350
300
250
200
150
100
50
0
BCK A
BCK B
A1
A2
B1
B2
C1
C2
D1
D2
E1
E2
G
H1
H2
H3
H4
H5
SG
WFD
TAP
Rainfall

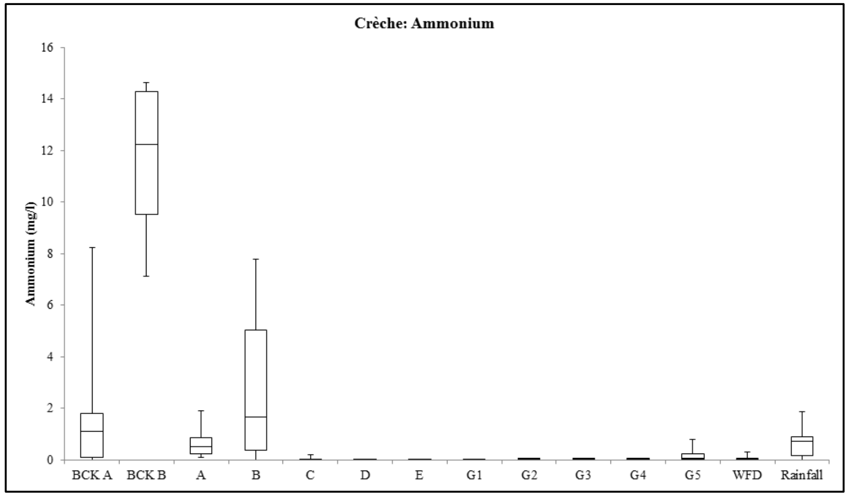

Slangspruit: E.coli
E.coli (MPN/100ml)
300000
250000
200000
150000
100000
50000
0
BCK A
BCK B
A1
B1
C1
D1
E1
E2
G
H1
H2
H4
H5

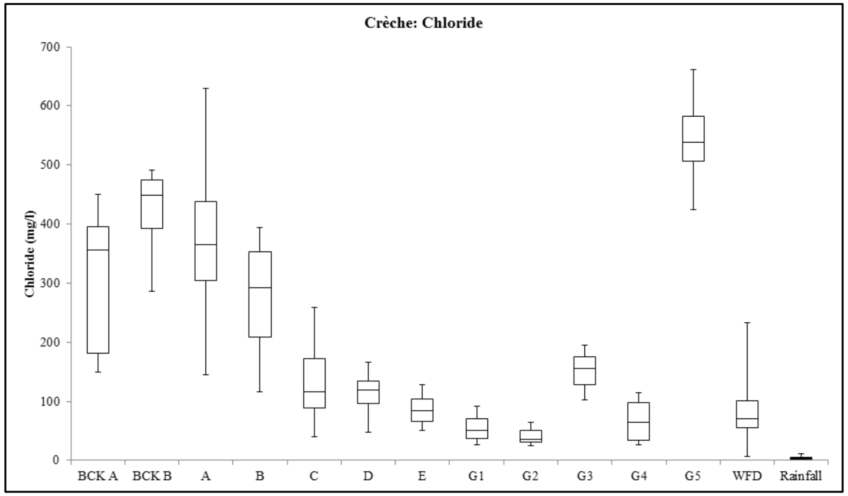

Slangspruit: Electrical Conductivity
EC (µS/cm)
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
BCK A
BCK B
A1
A2
B1
B2
C1
C2
D1
D2
E1
E2
G
H1
H2
H3
H4
H5
SG
WFD
TAP
Rainfall

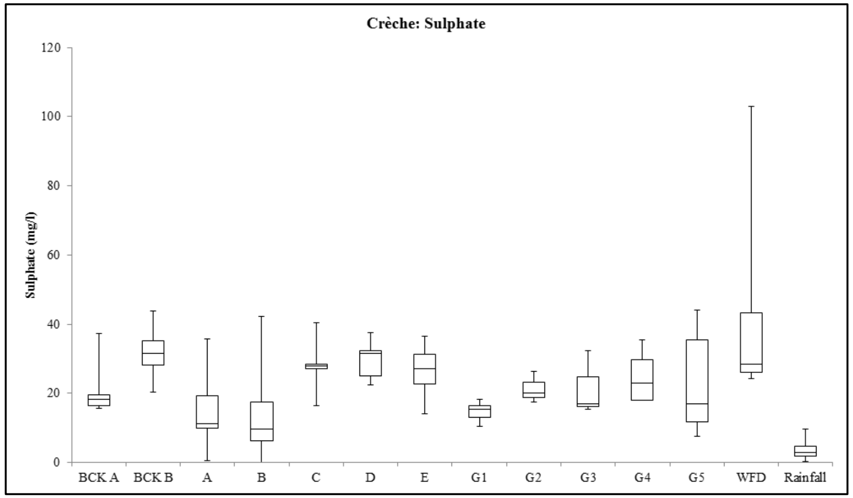

Slangspruit: Piezometer and water table depths
Water table and Piezometer depth (m.b.s)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
BCK A
BCK B
A1
A2
B1
B2
C1
C2
D1
D2
E1
E2
G
H1
H2
H3
H4
H5
Piezometer depth

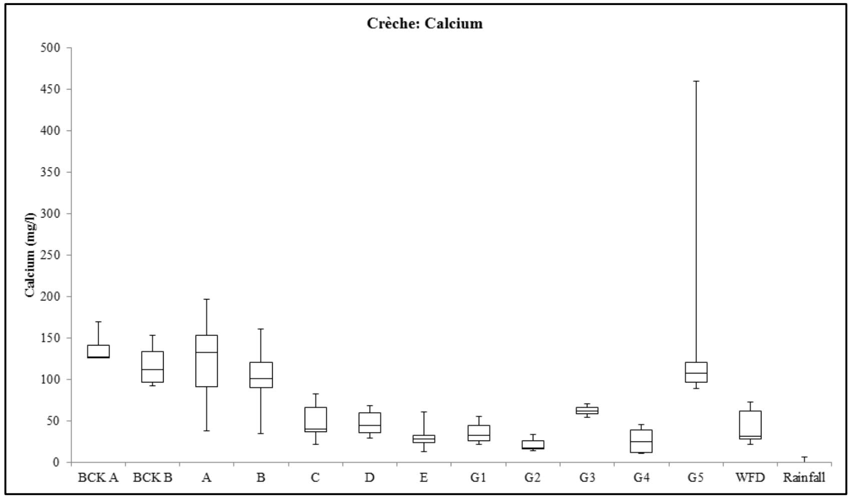

Crèche: Nitrate
Nitrate (mg/l)
700
600
500
400
300
200
100
0
BCK A
BCK B
A
B
C
D
E
G1
G2
G3
G4
G5
WFD
Rainfall

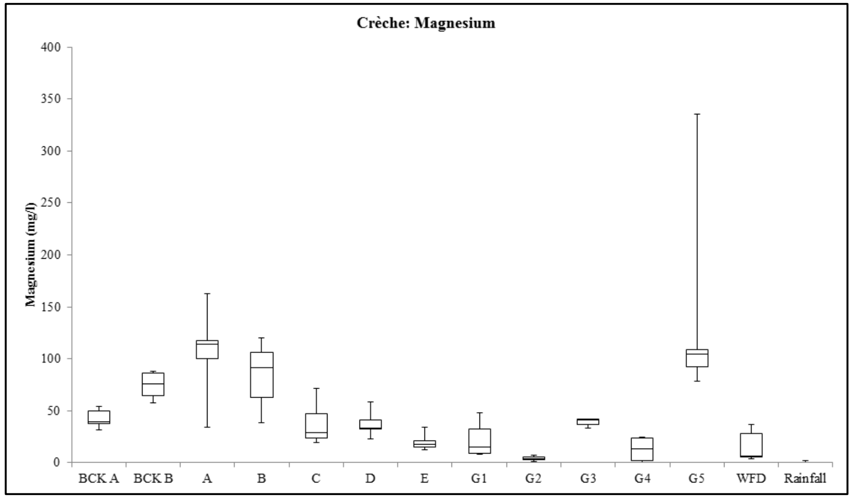

Crèche: Phosphate
Phosphate (mg/l)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
BCK A
BCK B
A
B
C
D
E
G1
G2
G3
G4
G5
WFD
Rainfall

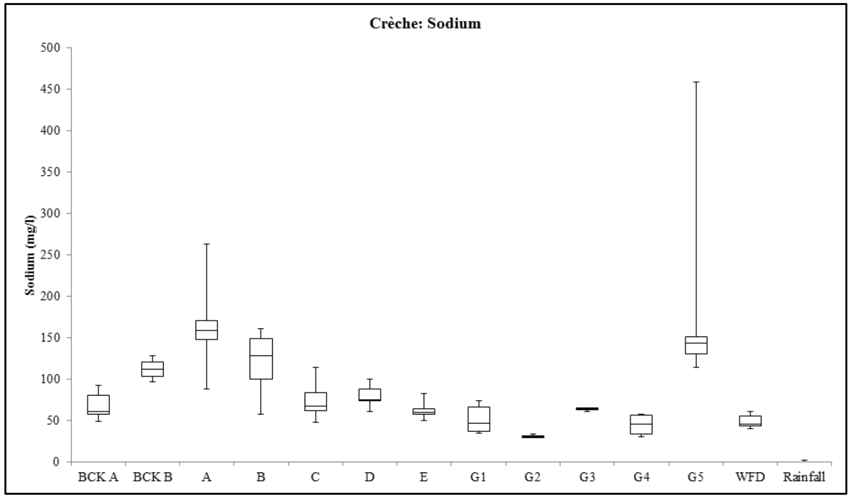

Crèche: Ammonium
Ammonium (mg/l)
16
14
12
10
8
6
4
2
0
BCK A
BCK B
A
B
C
D
E
G1
G2
G3
G4
G5
WFD
Rainfall

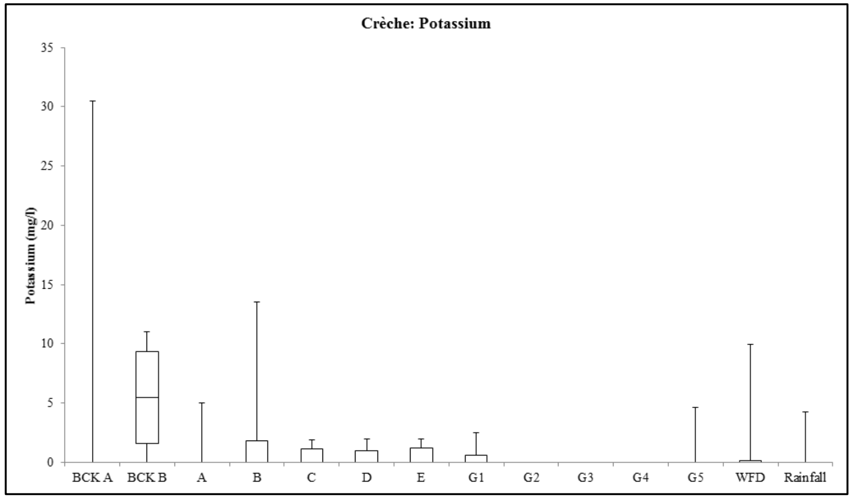

Crèche: Chloride
Chloride (mg/l)
700
600
500
400
300
200
100
0
BCK A
BCK B
A
B
C
D
E
G1
G2
G3
G4
G5
WFD
Rainfall

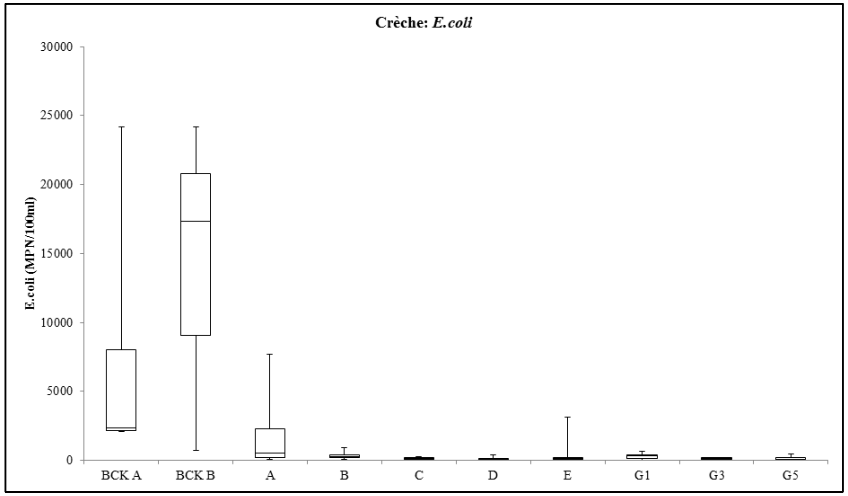

Crèche: Sulphate
Sulphate (mg/l)
120
100
80
60
40
20
0
BCK A
BCK B
A
B
C
D
E
G1
G2
G3
G4
G5
WFD
Rainfall

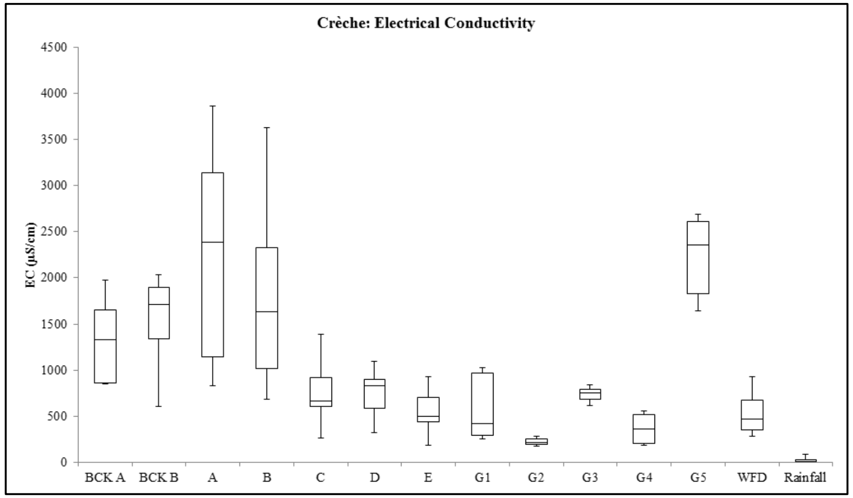

Crèche: Calcium
Calcium (mg/l)
500
450
400
350
300
250
200
150
100
50
0
BCK A
BCK B
A
B
C
D
E
G1
G2
G3
G4
G5
WFD
Rainfall

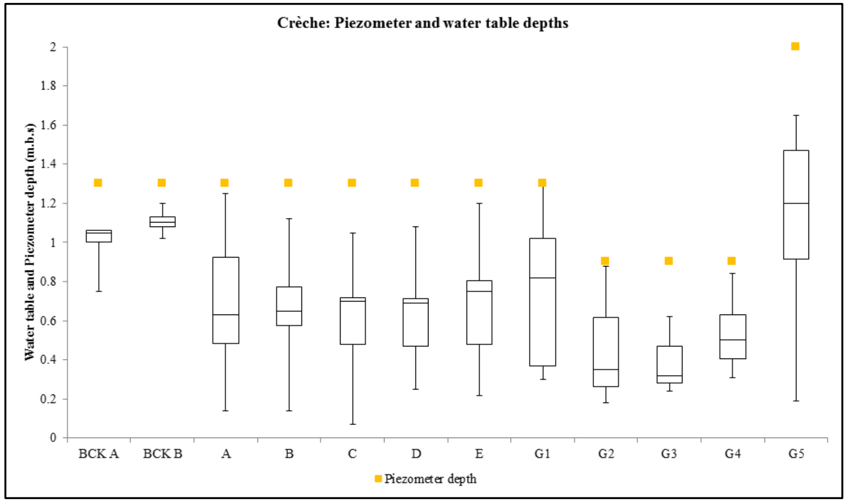

Crèche: Magnesium
Magnesium (mg/l)
400
350
300
250
200
150
100
50
0
BCK A
BCK B
A
B
C
D
E
G1
G2
G3
G4
G5
WFD
Rainfall

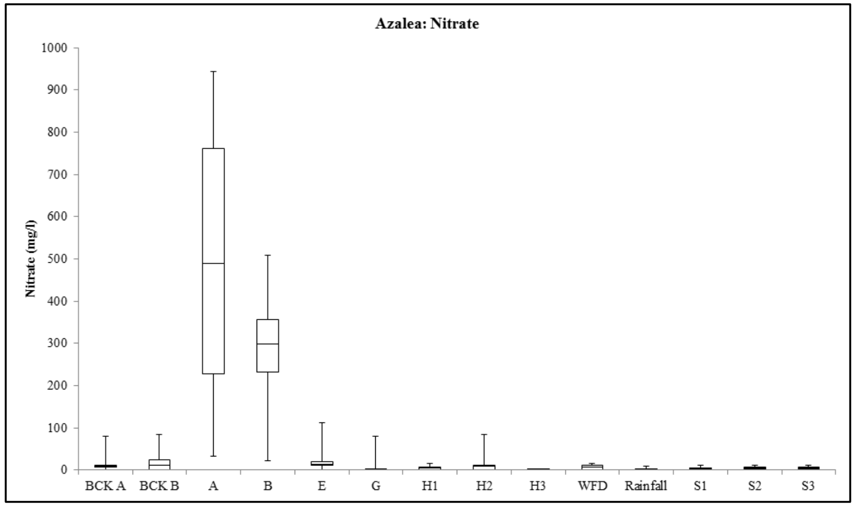

Crèche: Sodium
Sodium (mg/l)
500
450
400
350
300
250
200
150
100
50
0
BCK A
BCK B
A
B
C
D
E
G1
G2
G3
G4
G5
WFD
Rainfall

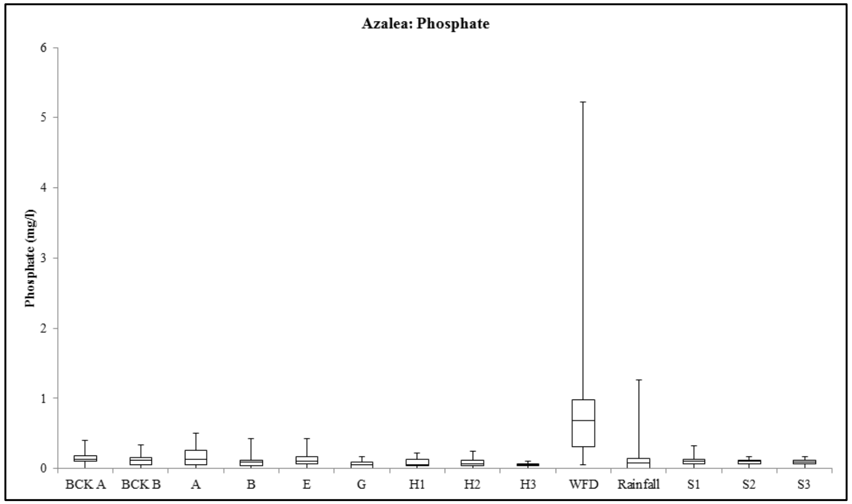

Crèche: Potassium
Potassium (mg/l)
BCK A
BCK B
A
B
C
D
E
G1
G2
G3
G4
G5
WFD
Rainfall

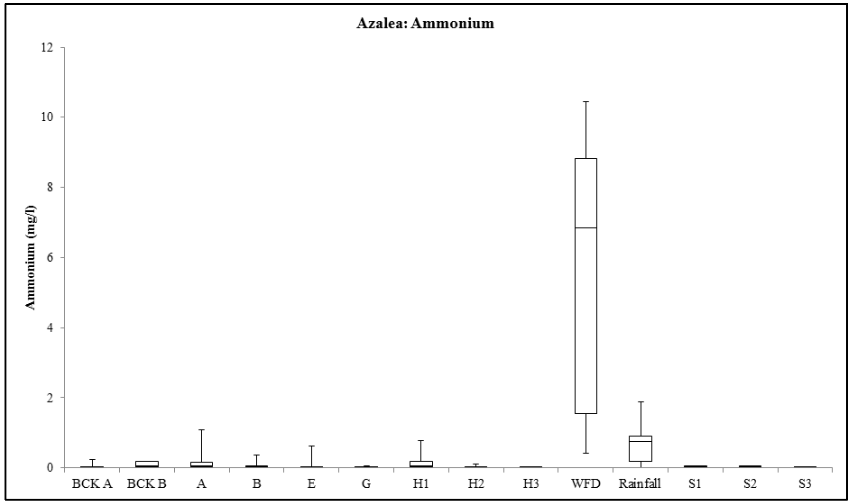

Crèche: E.coli
E.coli (MPN/100ml)
BCK A
BCK B
A
B
C
D
E
G1
G3
G5

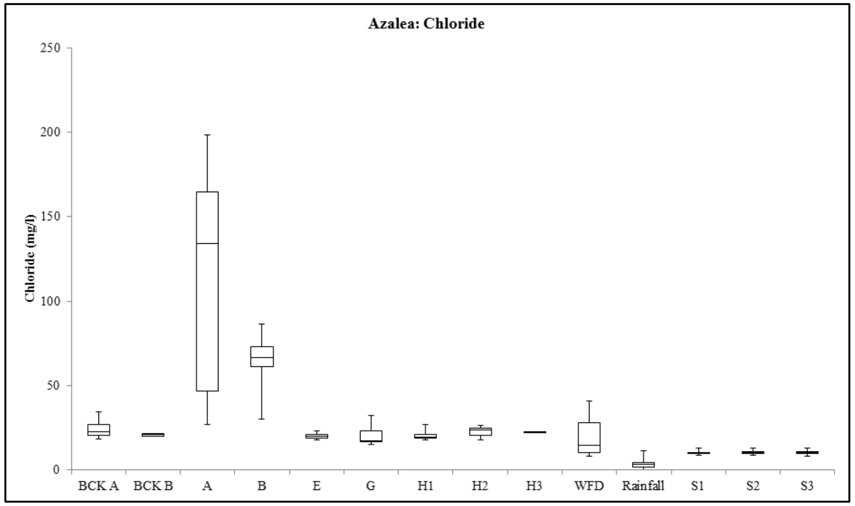

Crèche: Electrical Conductivity
EC (µS/cm)
BCK A
BCK B
A
B
C
D
E
G1
G2
G3
G4
G5
WFD
Rainfall

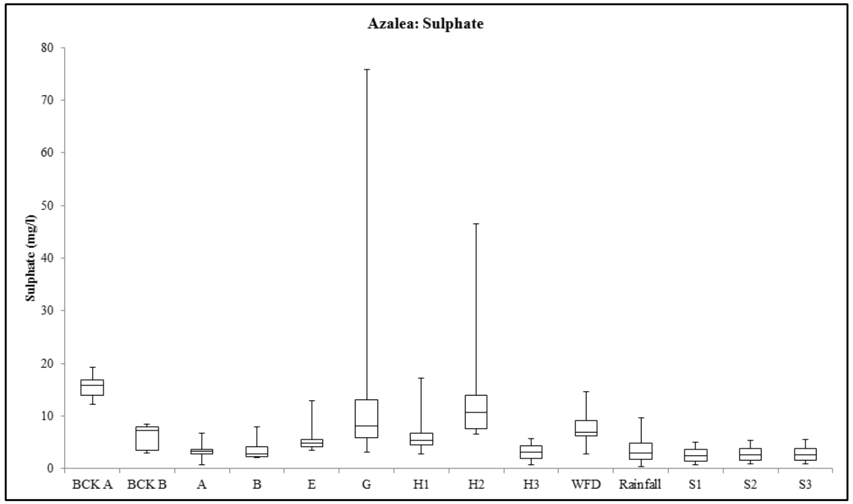

Crèche: Piezometer and water table depths
Water table and Piezometer depth (m.b.s)
BCK A
BCK B
A
B
C
D
E
G1
G2
G3
G4
G5
Piezometer depth


Azalea: Nitrate
Nitrate (mg/l)
1000
900
800
700
600
500
400
300
200
100
0
BCK A
BCK B
A
B
E
G
H1
H2
H3
WFD
Rainfall
S1
S2
S3

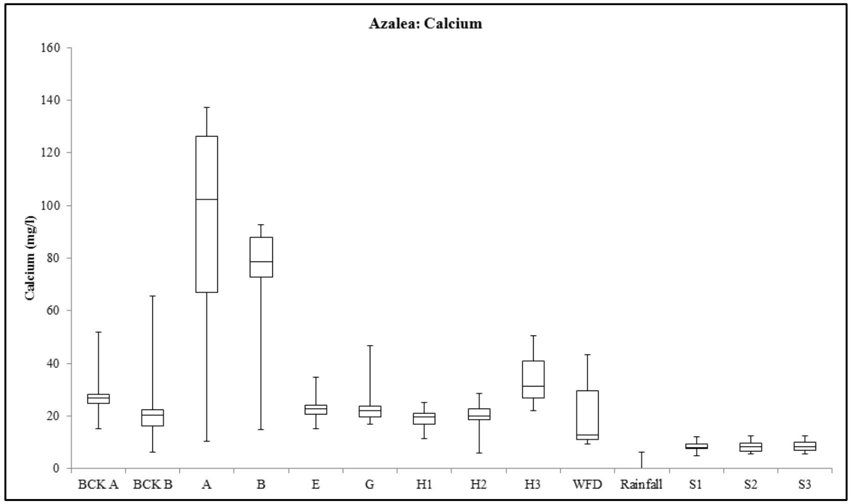

Azalea: Phosphate
Phosphate (mg/l)
6
5
4
3
2
1
0
BCK A
BCK B
A
B
E
G
H1
H2
H3
WFD
Rainfall
S1
S2
S3


Azalea: Ammonium
Ammonium (mg/l)
12
10
8
6
4
2
0
BCK A
BCK B
A
B
E
G
H1
H2
H3
WFD
Rainfall
S1
S2
S3

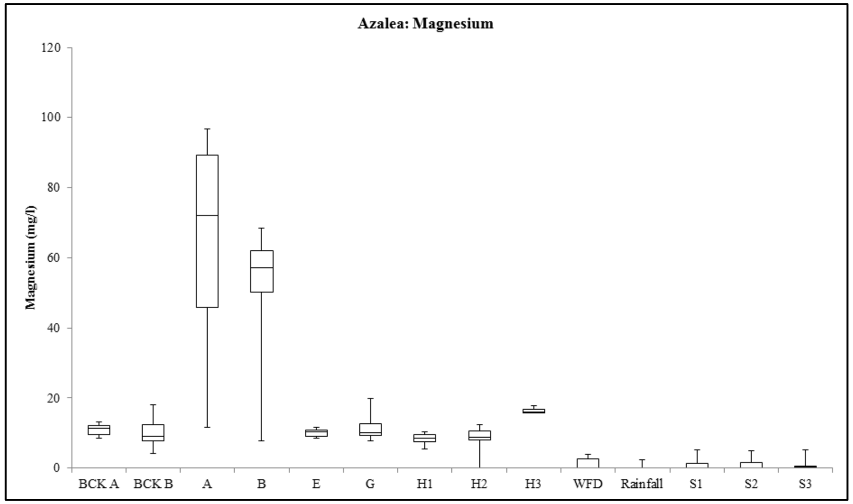

Azalea: Chloride
Chloride (mg/l)
250
200
150
100
50
0
BCK A
BCK B
A
B
E
G
H1
H2
H3
WFD
Rainfall
S1
S2
S3



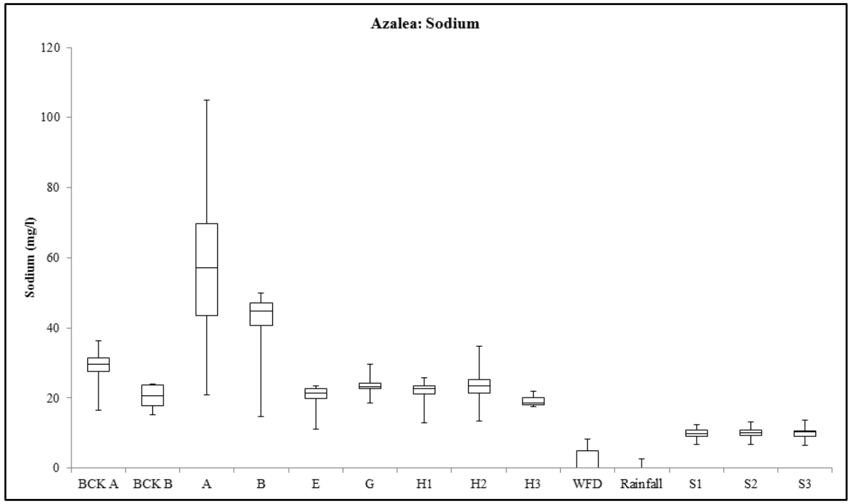
Azalea: Sulphate
Sulphate (mg/l)
80
70
60
50
40
30
20
10
0
BCK A
BCK B
A
B
E
G
H1
H2
H3
WFD
Rainfall
S1
S2
S3



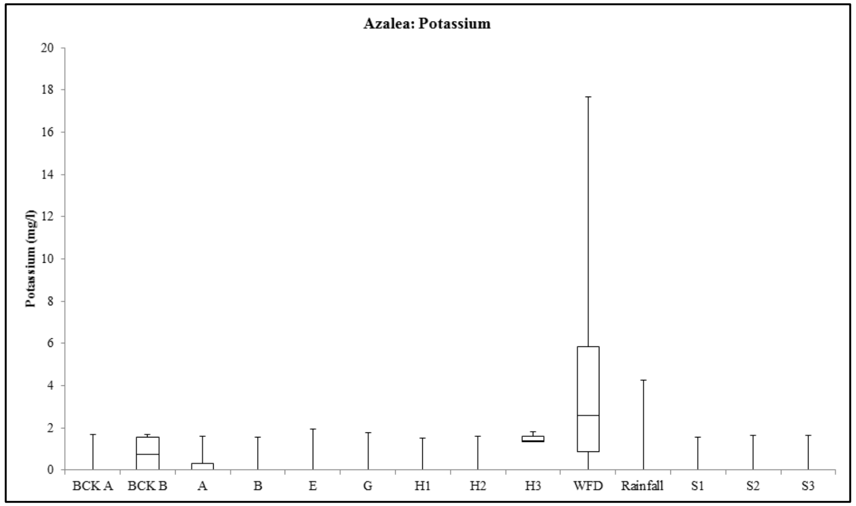
Azalea: Calcium
Calcium (mg/l)
160
140
120
100
80
60
40
20
0
BCK A
BCK B
A
B
E
G
H1
H2
H3
WFD
Rainfall
S1
S2
S3

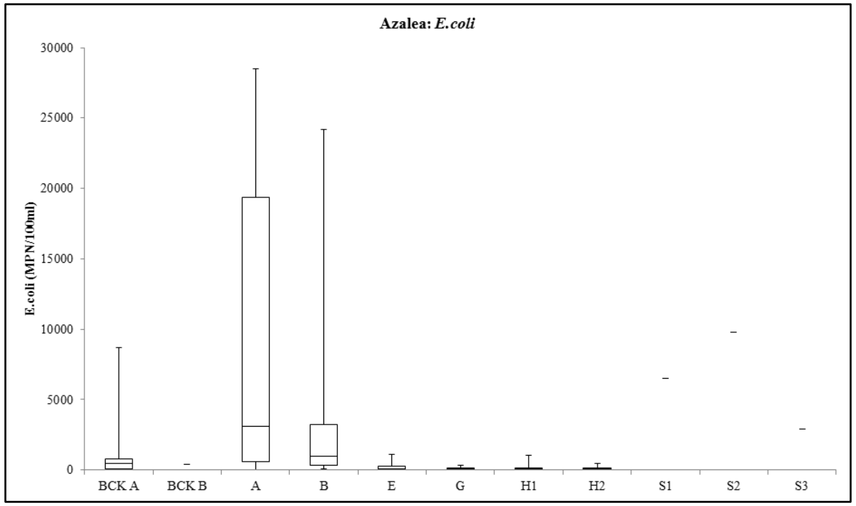


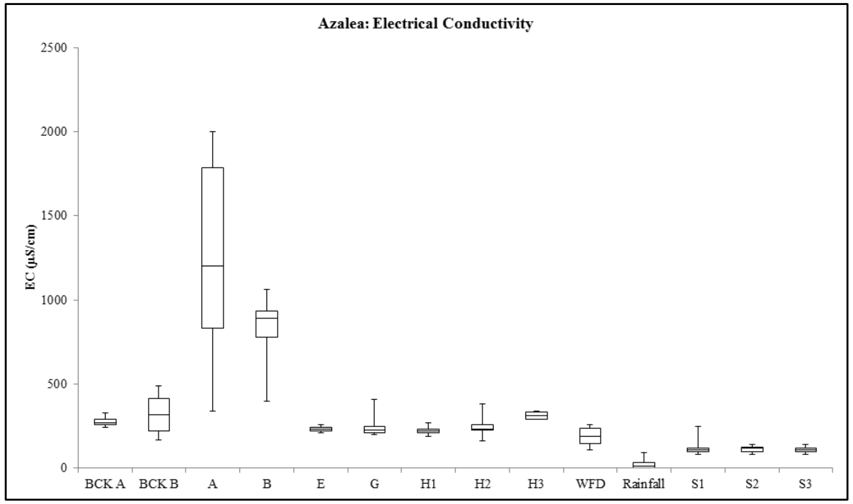
Azalea: Magnesium
Magnesium (mg/l)
120
100
80
60
40
20
0
BCK A
BCK B
A
B
E
G
H1
H2
H3
WFD
Rainfall
S1
S2
S3

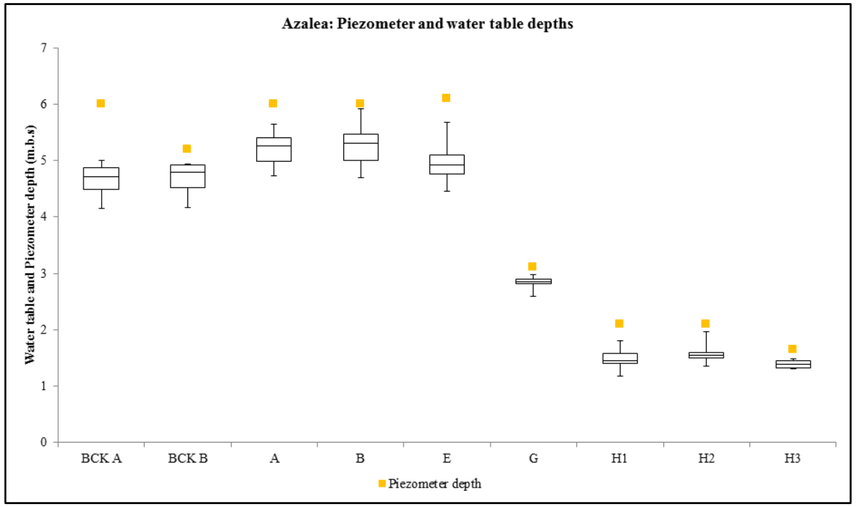


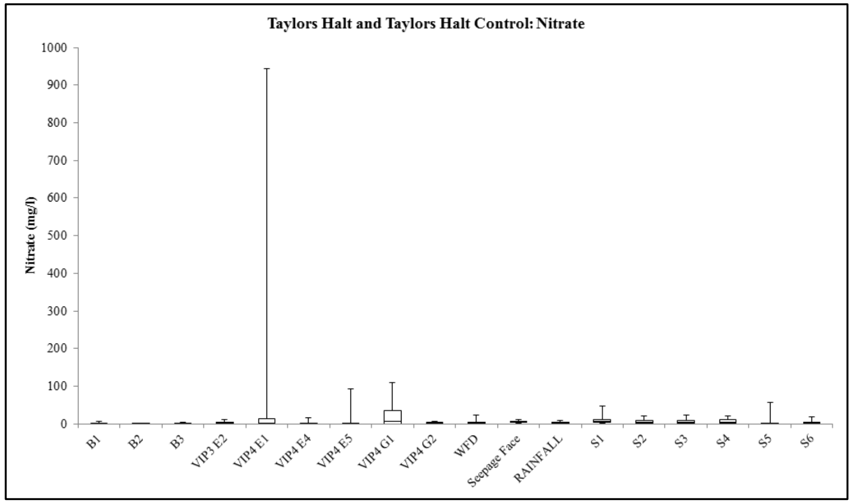
Azalea: Sodium
Sodium (mg/l)
120
100
80
60
40
20
0
BCK A
BCK B
A
B
E
G
H1
H2
H3
WFD
Rainfall
S1
S2
S3

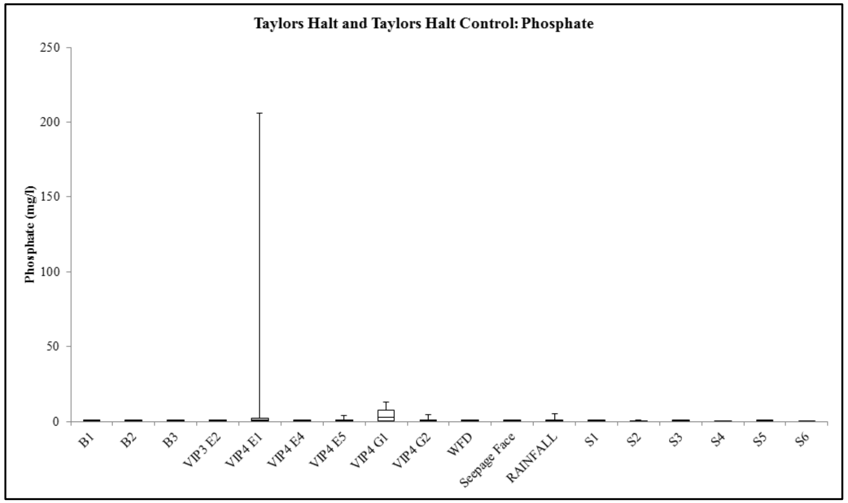

Azalea: Potassium
Potassium (mg/l)
0
2
4
6
8
10
12
14
16
18
20
BCK A
BCK B
A
B
E
G
H1
H2
H3
WFD
Rainfall
S1
S2
S3

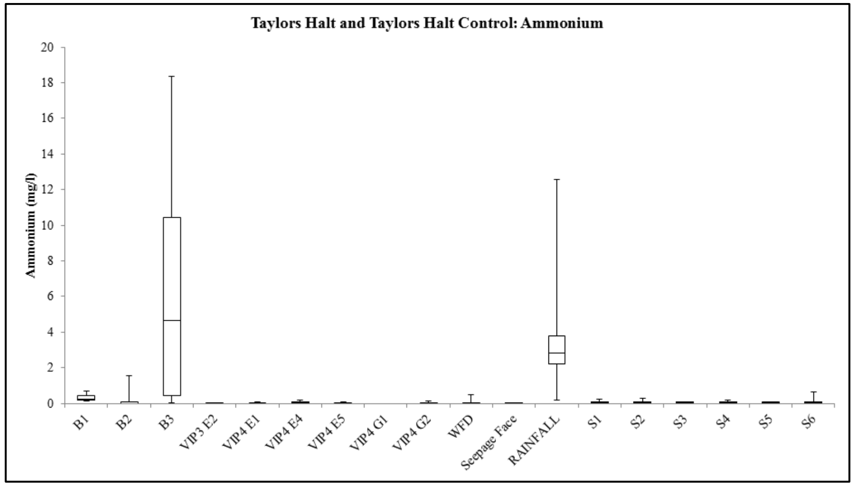

Azalea: E.coli
E.coli (MPN/100ml)
0
5000
10000
15000
20000
25000
30000
BCK A
BCK B
A
B
E
G
H1
H2
S1
S2
S3

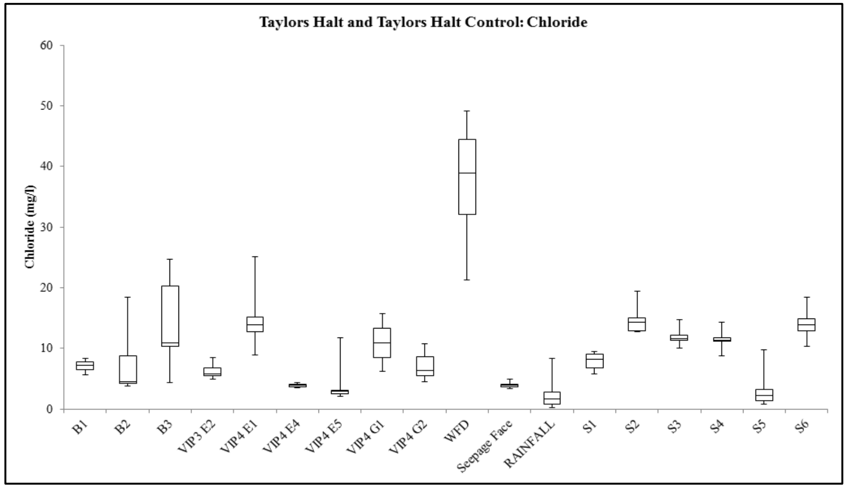

Azalea: Electrical Conductivity
EC (µS/cm)
0
500
1000
1500
2000
2500
BCK A
BCK B
A
B
E
G
H1
H2
H3
WFD
Rainfall
S1
S2
S3

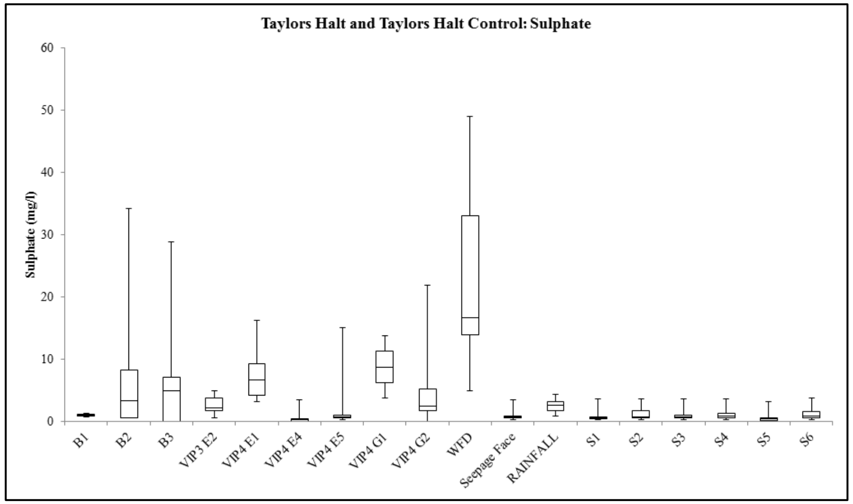

Azalea: Piezometer and water table depths
Water table and Piezometer depth (m.b.s)
0
1
2
3
4
5
6
7
BCK A
BCK B
A
B
E
G
H1
H2
H3
Piezometer depth

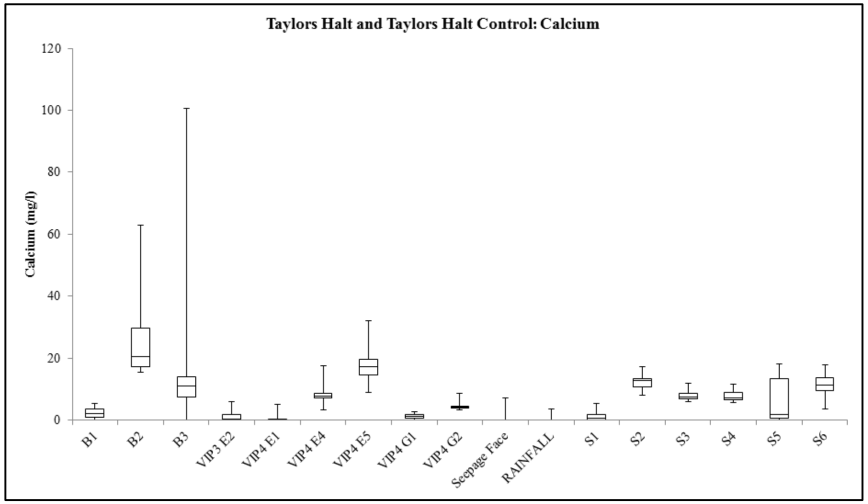

Taylors Halt and Taylors Halt Control: Nitrate
Nitrate (mg/l)
0
100
200
300
400
500
600
700
800
900
1000
B1
B2
B3
VIP3 E2
VIP4 E1
VIP4 E4
VIP4 E5
VIP4 G1
VIP4 G2
WFD
Seepage Face
RAINFALL
S1
S2
S3
S4
S5
S6

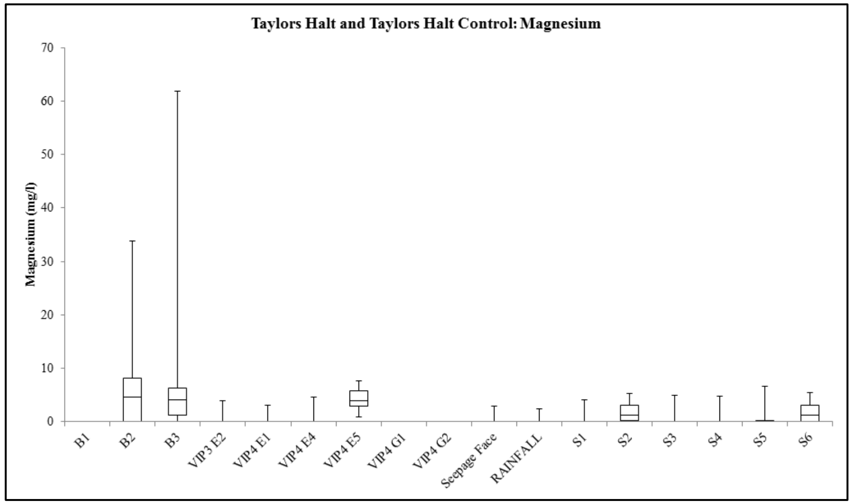

Taylors Halt and Taylors Halt Control: Phosphate
Phosphate (mg/l)
0
50
100
150
200
250
B1
B2
B3
VIP3 E2
VIP4 E1
VIP4 E4
VIP4 E5
VIP4 G1
VIP4 G2
WFD
Seepage Face
RAINFALL
S1
S2
S3
S4
S5
S6

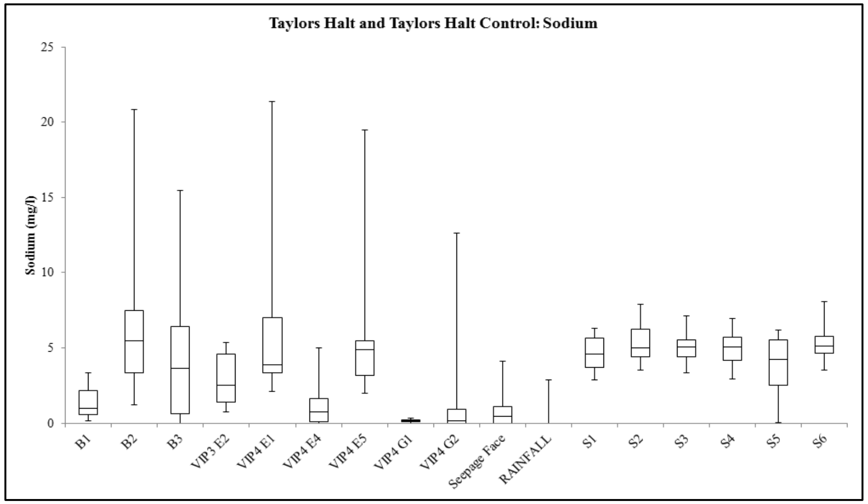

Taylors Halt and Taylors Halt Control: Ammonium
Ammonium (mg/l)
0
2
4
6
8
10
12
14
16
18
20
B1
B2
B3
VIP3 E2
VIP4 E1
VIP4 E4
VIP4 E5
VIP4 G1
VIP4 G2
WFD
Seepage Face
RAINFALL
S1
S2
S3
S4
S5
S6

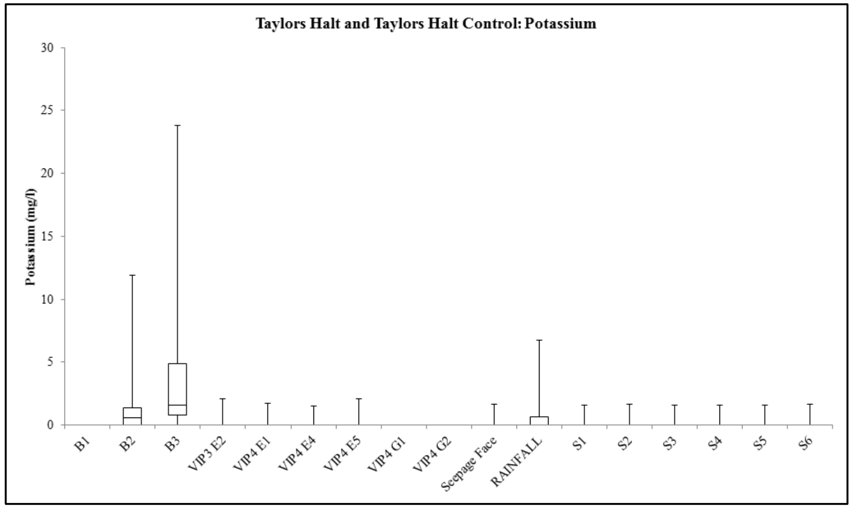

Taylors Halt and Taylors Halt Control: Chloride
Chloride (mg/l)
0
10
20
30
40
50
60
B1
B2
B3
VIP3 E2
VIP4 E1
VIP4 E4
VIP4 E5
VIP4 G1
VIP4 G2
WFD
Seepage Face
RAINFALL
S1
S2
S3
S4
S5
S6

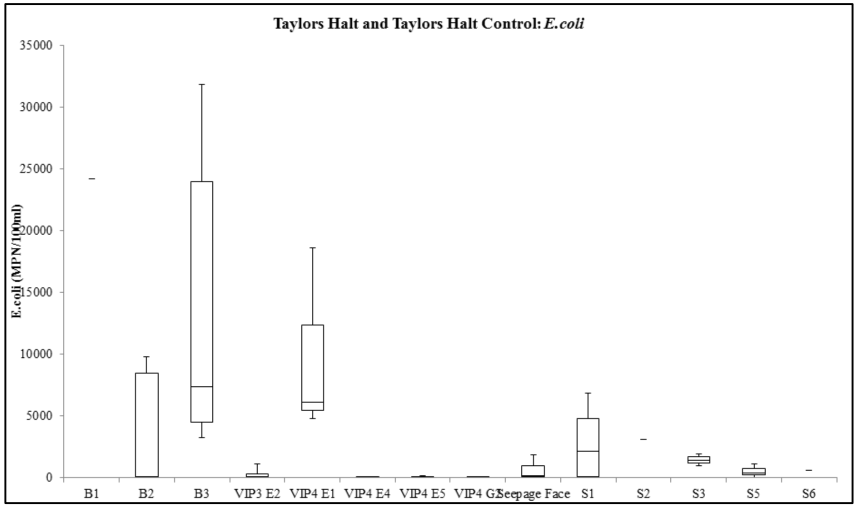

Taylors Halt and Taylors Halt Control: Sulphate
Sulphate (mg/l)
0
10
20
30
40
50
60
B1
B2
B3
VIP3 E2
VIP4 E1
VIP4 E4
VIP4 E5
VIP4 G1
VIP4 G2
WFD
Seepage Face
RAINFALL
S1
S2
S3
S4
S5
S6

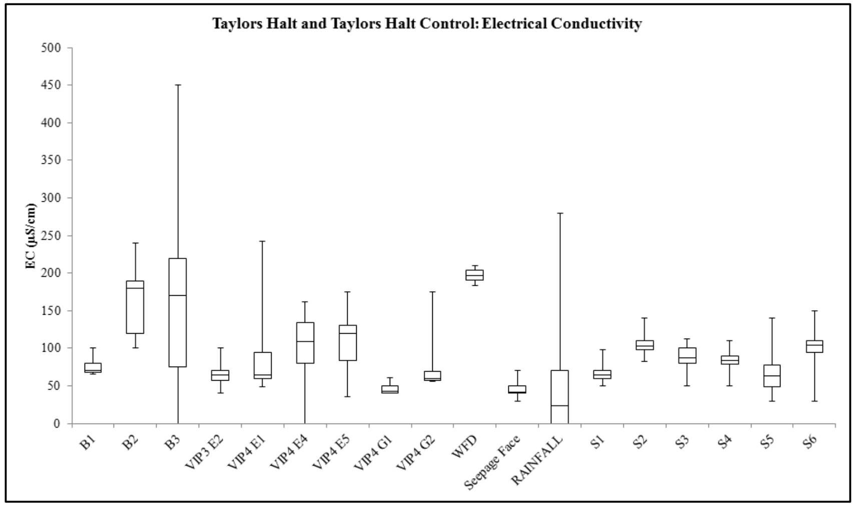

Taylors Halt and Taylors Halt Control: Calcium
Calcium (mg/l)
0
20
40
60
80
100
120
B1
B2
B3
VIP3 E2
VIP4 E1
VIP4 E4
VIP4 E5
VIP4 G1
VIP4 G2
Seepage Face
RAINFALL
S1
S2
S3
S4
S5
S6

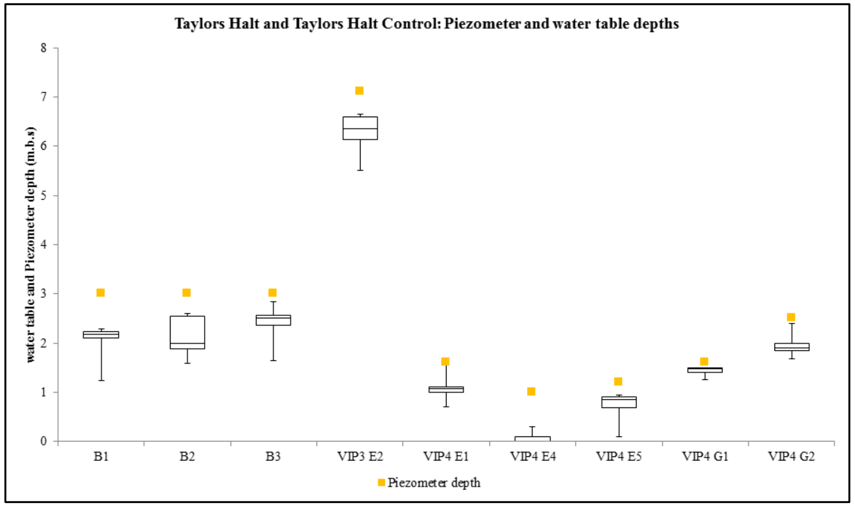

Taylors Halt and Taylors Halt Control: Magnesium
Magnesium (mg/l)
0
10
20
30
40
50
60
70
B1
B2
B3
VIP3 E2
VIP4 E1
VIP4 E4
VIP4 E5
VIP4 G1
VIP4 G2
Seepage Face
RAINFALL
S1
S2
S3
S4
S5
S6


Taylors Halt and Taylors Halt Control: Sodium
Sodium (mg/l)
0
5
10
15
20
25
B1
B2
B3
VIP3 E2
VIP4 E1
VIP4 E4
VIP4 E5
VIP4 G1
VIP4 G2
Seepage Face
RAINFALL
S1
S2
S3
S4
S5
S6









Appendix 36: Box and Whisker plots of the water analyses and water table depths at all the study sites

Slangspruit

pH

	BCK A	BCK B	A1	A2	B1	B2	C1	C2	D1	D2	E1	E2	G	H1	H2	H3	H4	H5	SG	WFD	TAP	Rainfall
Mean	7.42	7.65	7.07	7.34	7.19	7.16	7.90	7.54	7.21	7.39	7.19	7.14	7.27	7.21	7.11	7.29	7.02	7.03	7.11	7.36	7.91	7.13
STD.dev	0.43	0.34	0.38	0.28	0.23	0.13	0.18	0.42	0.22	0.32	0.28	0.30	0.16	0.25	0.18	0.12	0.22	0.17	0.45	0.22	0.81	0.79

ORP (mV)

	BCK A	BCK B	A1	A2	B1	B2	C1	C2	D1	D2	E1	E2	G	H1	H2	H3	H4	H5	SG	WFD	TAP	Rainfall
Mean	115.43	136.06	153.19	105.21	131.20	101.00	-92.86	-29.47	23.74	7.46	43.24	53.69	60.20	49.08	51.35	50.78	47.00	39.56	-2.12	74.67	152.13	137.22
STD.dev	105.69	80.31	72.26	83.00	86.97	84.09	114.50	62.35	89.98	57.12	60.15	58.23	65.88	69.40	63.08	65.25	79.38	64.02	120.36	82.27	89.77	91.40

EC (µS/cm)

	BCK A	BCK B	A1	A2	B1	B2	C1	C2	D1	D2	E1	E2	G	H1	H2	H3	H4	H5	SG	WFD	TAP	Rainfall
Mean	785.57	1770.00	4718.30	3210.71	4177.60	3970.00	6017.50	3608.67	4200.00	3494.62	1390.84	1820.00	4236.67	3740.50	3475.00	3329.44	808.78	1234.22	414.08	1441.11	70.78	23.27
STD.dev	246.61	647.51	2519.36	589.17	2266.06	250.45	618.06	1086.84	2959.30	1812.40	1819.44	681.83	703.81	3262.18	2956.23	3790.55	488.10	745.21	211.16	676.39	16.75	26.64

Nitrate (mg/l)

	BCK A	BCK B	A1	A2	B1	B2	C1	C2	D1	D2	E1	E2	G	H1	H2	H3	H4	H5	SG	WFD	TAP	Rainfall

Mean	61.23	1.73	664.78	218.74	557.50	3.59	3.17	59.70	10.81	0.43	0.29	0.62	0.05	22.98	25.81	26.31	1.40	0.45	3.25	0.76	2.22	2.09
STD.dev	98.60	3.30	481.23	234.38	356.43	5.96	6.12	126.05	32.81	0.59	0.29	1.68	0.08	48.59	61.60	34.71	4.02	0.79	4.74	0.71	1.01	2.02

Phosphate (mg/l)

	BCK A	BCK B	A1	A2	B1	B2	C1	C2	D1	D2	E1	E2	G	H1	H2	H3	H4	H5	SG	WFD	TAP	Rainfall
Mean	0.18	0.14	0.19	0.26	0.30	1.25	30.89	0.21	0.73	0.16	0.10	0.11	0.09	1.35	0.12	0.60	0.55	0.68	1.78	0.13	0.06	0.16
STD.dev	0.14	0.18	0.20	0.21	0.51	1.99	11.21	0.17	0.96	0.16	0.10	0.08	0.06	4.43	0.18	1.45	2.29	2.42	2.47	0.07	0.08	0.28

Ammonium (mg/l)

	BCK A	BCK B	A1	A2	B1	B2	C1	C2	D1	D2	E1	E2	G	H1	H2	H3	H4	H5	SG	WFD	TAP	Rainfall
Mean	0.12	0.35	0.92	5.84	0.41	55.71	582.12	4.16	15.21	0.26	0.16	0.06	0.08	3.08	0.20	2.03	1.32	0.93	5.09	0.03	0.83	0.75
STD.dev	0.02	0.99	1.81	8.96	0.80	71.64	183.45	4.40	8.25	0.12	0.16	0.08	0.07	2.38	0.21	1.75	1.51	0.44	5.41	0.03	0.20	0.56

Chloride (mg/l)

	BCK A	BCK B	A1	A2	B1	B2	C1	C2	D1	D2	E1	E2	G	H1	H2	H3	H4	H5	SG	WFD	TAP	Rainfall
Mean	142.09	369.99	786.22	609.91	854.56	555.94	617.79	695.37	592.09	899.14	48.13	450.65	834.90	699.48	388.19	245.72	36.22	118.82	52.49	404.06	8.30	3.43
STD.dev	36.01	89.57	129.23	132.06	188.80	9.57	47.88	265.42	56.55	609.55	13.97	183.73	173.62	208.22	259.82	95.97	16.03	117.54	26.13	185.92	1.15	2.93

Sulpahte (mg/l)

	BCK A	BCK B	A1	A2	B1	B2	C1	C2	D1	D2	E1	E2	G	H1	H2	H3	H4	H5	SG	WFD	TAP	Rainfall
Mean	61.84	42.04	44.97	53.97	44.45	8.98	3.94	46.11	15.49	59.90	37.92	64.09	89.48	184.12	55.87	160.69	32.17	77.40	22.14	117.89	2.12	3.47
STD.dev	8.39	17.20	11.57	16.13	10.09	12.60	1.37	29.06	24.73	39.06	16.76	18.82	12.48	100.97	24.85	51.81	28.54	84.64	31.95	29.07	1.06	2.56

Calcium (mg/l)

	BCK A	BCK B	A1	A2	B1	B2	C1	C2	D1	D2	E1	E2	G	H1	H2	H3	H4	H5	SG	WFD	TAP	Rainfall
Mean	27.52	54.03	137.88	114.42	139.98	99.85	114.32	100.14	129.21	99.56	84.30	72.15	98.40	120.10	94.61	77.59	82.59	114.25	30.71	74.95	10.40	1.16
STD.dev	9.49	36.59	79.86	57.83	78.51	70.50	76.68	63.34	61.11	62.14	27.35	38.41	77.06	53.61	106.95	58.37	31.43	61.84	16.79	20.89	2.04	2.22

Magnesium (mg/l)

	BCK A	BCK B	A1	A2	B1	B2	C1	C2	D1	D2	E1	E2	G	H1	H2	H3	H4	H5	SG	WFD	TAP	Rainfall
Mean	14.81	67.72	132.34	112.85	131.40	137.94	118.35	109.98	134.97	104.06	48.01	65.19	128.66	91.82	80.27	56.90	31.47	81.64	5.26	50.96	0.87	0.34
STD.dev	9.62	54.01	75.37	58.75	72.84	64.89	88.79	38.18	44.29	48.67	9.07	31.46	82.75	33.26	94.10	44.77	9.92	71.62	5.64	15.04	1.51	0.79

Sodium (mg/l)

	BCK A	BCK B	A1	A2	B1	B2	C1	C2	D1	D2	E1	E2	G	H1	H2	H3	H4	H5	SG	WFD	TAP	Rainfall
Mean	143.41	311.52	337.92	335.06	357.34	346.90	307.52	322.97	338.76	338.60	98.41	254.21	388.50	241.23	256.77	293.61	72.78	194.45	63.44	159.14	1.15	0.45

STD.dev	10.65	238.27	214.62	211.37	229.08	228.13	205.27	149.26	194.64	177.86	11.94	143.21	281.59	145.29	221.19	182.65	13.27	208.91	32.55	16.84	1.48	0.87

Potassium (mg/l)

	BCK A	BCK B	A1	A2	B1	B2	C1	C2	D1	D2	E1	E2	G	H1	H2	H3	H4	H5	SG	WFD	TAP	Rainfall
Mean	0.99	1.55	5.98	3.31	0.96	21.11	157.44	1.83	4.52	1.08	0.67	0.71	0.81	55.09	3.47	6.79	2.45	7.65	7.13	0.35	0.52	0.45
STD.dev	0.99	2.10	11.88	5.30	1.76	18.78	62.05	3.43	5.43	1.88	1.23	1.24	1.56	65.80	4.26	7.67	4.67	5.07	7.39	0.91	0.90	1.17

E.Coli (MPN/100ml)

	BCK A	BCK B	A1	B1	C1	D1	E1	E2	G	H1	H2	H4	H5
Mean	48459.00	2654.80	1058.67	249.00	12137.83	3195.83	10812.67	8164.00	794.67	88237.83	13604.00	8653.33	13076.50
STD.dev	43621.00	3932.85	850.61	244.02	6240.53	2525.80	8260.84	0.00	627.74	108896.15	6370.28	5951.14	11115.50

Appendix 37: Mean and standard deviation of the water analyses results at the Slangspruit site

Crèche

pH

	BCK A	BCK B	A	B	C	D	E	G1	G2	G3	G4	G5	WFD	Rainfall
Mean	7.15	7.21	7.03	7.07	7.02	7.05	6.98	7.08	6.77	6.62	6.82	6.88	7.12	7.13
STD.dev	0.21	0.28	0.21	0.20	0.20	0.18	0.19	0.22	0.17	0.13	0.31	0.15	0.22	0.79

ORP (mV)

	BCK A	BCK B	A	B	C	D	E	G1	G2	G3	G4	G5	WFD	Rainfall

Mean	75.20	-55.50	81.69	7.93	53.18	67.45	77.64	84.33	185.00	192.00	156.75	92.31	80.85	137.22
STD.dev	70.27	92.01	75.34	81.56	73.90	78.17	72.62	80.03	67.66	60.60	80.21	74.26	80.07	91.40

EC (µS/cm)

	BCK A	BCK B	A	B	C	D	E	G1	G2	G3	G4	G5	WFD	Rainfall
Mean	1332.00	1517.50	2281.25	1834.29	764.55	757.27	558.18	568.89	226.67	736.67	367.50	2251.88	521.11	23.27
STD.dev	438.93	547.88	954.95	949.91	297.49	235.68	199.81	313.74	41.10	90.31	168.58	392.13	209.47	26.64

Nitrate (mg/l)

	BCK A	BCK B	A	B	C	D	E	G1	G2	G3	G4	G5	WFD	Rainfall
Mean	0.62	0.17	96.32	2.90	4.92	4.05	2.38	26.83	21.89	29.94	44.48	0.67	45.69	2.09
STD.dev	0.83	0.21	175.91	7.10	11.77	9.60	4.63	24.76	17.92	28.55	32.21	0.95	49.06	2.02

Phosphate (mg/l)

	BCK A	BCK B	A	B	C	D	E	G1	G2	G3	G4	G5	WFD	Rainfall
Mean	0.19	0.20	0.16	0.14	0.10	0.12	0.14	0.09	0.12	0.19	0.07	0.13	0.33	0.16
STD.dev	0.07	0.24	0.16	0.12	0.08	0.10	0.08	0.07	0.05	0.09	0.06	0.08	0.29	0.28

Ammonium (mg/l)

	BCK A	BCK B	A	B	C	D	E	G1	G2	G3	G4	G5	WFD	Rainfall
Mean	2.25	11.56	0.61	2.82	0.05	0.02	0.01	0.02	0.03	0.02	0.02	0.17	0.06	0.75
STD.dev	3.07	3.05	0.46	2.82	0.07	0.02	0.02	0.02	0.01	0.01	0.02	0.22	0.10	0.56

Chloride (mg/l)

	BCK A	BCK B	A	B	C	D	E	G1	G2	G3	G4	G5	WFD	Rainfall
Mean	306.56	418.51	375.22	277.42	131.57	116.87	86.17	54.69	41.71	150.46	67.70	539.86	89.65	3.43

STD.dev	119.53	80.06	128.23	91.74	68.59	34.54	27.08	22.81	16.59	38.14	36.60	67.03	62.71	2.93

Sulphate (mg/l)

	BCK A	BCK B	A	B	C	D	E	G1	G2	G3	G4	G5	WFD	Rainfall
Mean	21.47	31.82	15.16	13.04	28.56	29.57	26.86	14.77	21.31	21.57	24.77	22.85	40.47	3.47
STD.dev	8.06	8.35	10.06	10.92	7.26	4.69	6.73	2.44	3.75	7.71	7.37	12.63	24.07	2.56

Calcium (mg/l)

	BCK A	BCK B	A	B	C	D	E	G1	G2	G3	G4	G5	WFD	Rainfall
Mean	137.72	117.49	123.49	102.58	48.71	47.96	31.40	35.68	22.04	62.55	26.54	136.80	42.46	1.16
STD.dev	17.07	24.53	46.26	37.21	19.15	13.79	12.63	11.79	8.63	6.42	14.94	90.35	19.57	2.22

Magnesium (mg/l)

	BCK A	BCK B	A	B	C	D	E	G1	G2	G3	G4	G5	WFD	Rainfall
Mean	42.51	74.43	108.78	84.62	36.75	36.63	19.97	21.43	4.14	38.56	12.85	135.18	15.08	0.34
STD.dev	8.24	12.57	26.09	27.81	17.10	10.40	7.12	14.43	2.19	3.55	11.35	81.00	12.62	0.79

Sodium (mg/l)

	BCK A	BCK B	A	B	C	D	E	G1	G2	G3	G4	G5	WFD	Rainfall
Mean	67.85	112.00	163.89	121.72	74.43	78.26	62.77	51.46	30.83	63.81	44.56	185.97	48.89	0.45
STD.dev	15.84	12.29	36.20	31.62	19.13	12.25	9.53	15.29	1.81	1.78	12.20	104.81	7.04	0.87

Potassium (mg/l)

	BCK A	BCK B	A	B	C	D	E	G1	G2	G3	G4	G5	WFD	Rainfall
Mean	6.09	5.51	0.79	2.58	0.53	0.51	0.54	0.60	0.00	0.00	0.00	0.83	1.32	0.45
STD.dev	12.18	4.56	1.63	4.70	0.82	0.79	0.83	1.04	0.00	0.00	0.00	1.67	3.27	1.17

E.Coli (MPN/100ml)

	BCK A	BCK B	A	B	C	D	E	G1	G3	G5
Mean	7756.25	14086.33	1973.00	342.83	124.80	119.80	691.80	307.60	102.50	137.33
STD.dev	9491.24	9845.77	2726.02	281.37	83.29	141.06	1207.51	212.72	94.50	177.88

Appendix 38: Mean and standard deviation of the water analyses results at the Crèche site

Azalea

pH

	BCK A	BCK B	A	B	E	G	H1	H2	H3	WFD	Rainfall	S1	S2	S3
Mean	6.67	6.81	6.18	6.24	6.43	6.64	6.57	6.67	6.76	7.19	7.13	7.27	7.34	7.38
STD.dev	0.32	0.38	0.45	0.34	0.17	0.18	0.16	0.23	0.07	0.18	0.79	0.26	0.28	0.32

ORP (mV)

	BCK A	BCK B	A	B	E	G	H1	H2	H3	WFD	Rainfall	S1	S2	S3
Mean	119.94	103.29	161.17	150.00	143.20	143.08	133.87	139.67	47.50	99.57	137.22	116.69	118.19	121.81
STD.dev	73.78	85.13	73.81	64.47	54.06	77.27	63.77	72.49	30.12	92.38	91.40	62.38	60.01	59.03

EC (µS/cm)

	BCK A	BCK B	A	B	E	G	H1	H2	H3	WFD	Rainfall	S1	S2	S3
Mean	277.50	321.43	1247.50	814.67	229.33	246.67	222.00	245.33	312.50	188.57	23.27	117.63	113.06	108.13
STD.dev	23.58	118.25	587.82	208.87	12.36	58.36	20.40	46.31	22.78	53.30	26.64	38.07	17.84	17.40

Nitrate (mg/l)

	BCK A	BCK B	A	B	E	G	H1	H2	H3	WFD	Rainfall	S1	S2	S3

Mean	12.96	20.67	481.92	278.79	23.78	7.34	4.88	11.50	0.79	6.40	2.09	4.02	4.55	4.38
STD.dev	17.92	28.28	325.89	133.65	30.41	22.06	4.09	20.23	0.92	5.91	2.02	2.48	2.09	2.66

Phosphate (mg/l)

	BCK A	BCK B	A	B	E	G	H1	H2	H3	WFD	Rainfall	S1	S2	S3
Mean	0.15	0.12	0.17	0.10	0.14	0.06	0.08	0.09	0.05	1.22	0.16	0.11	0.10	0.10
STD.dev	0.09	0.10	0.14	0.10	0.10	0.06	0.06	0.07	0.04	1.66	0.28	0.07	0.05	0.05

Ammonium (mg/l)

	BCK A	BCK B	A	B	E	G	H1	H2	H3	WFD	Rainfall	S1	S2	S3
Mean	0.03	0.09	0.19	0.06	0.06	0.02	0.14	0.02	0.01	5.50	0.75	0.02	0.02	0.02
STD.dev	0.06	0.08	0.31	0.09	0.16	0.02	0.20	0.03	0.01	3.89	0.56	0.01	0.01	0.01

Chloride (mg/l)

	BCK A	BCK B	A	B	E	G	H1	H2	H3	WFD	Rainfall	S1	S2	S3
Mean	23.94	20.74	111.48	64.96	20.10	20.69	20.55	22.87	22.13	20.16	3.43	10.07	10.28	10.24
STD.dev	4.29	0.72	63.83	15.97	1.52	5.89	2.72	2.58	0.18	11.52	2.93	1.04	0.98	1.01

Sulphate (mg/l)

	BCK A	BCK B	A	B	E	G	H1	H2	H3	WFD	Rainfall	S1	S2	S3
Mean	15.50	6.01	3.16	3.53	5.32	18.51	6.80	13.10	3.16	7.89	3.47	2.64	2.73	2.77
STD.dev	2.22	2.31	1.50	1.70	2.24	22.60	4.42	10.16	2.50	3.46	2.56	1.44	1.46	1.48

Calcium (mg/l)

	BCK A	BCK B	A	B	E	G	H1	H2	H3	WFD	Rainfall	S1	S2	S3
Mean	27.28	25.01	89.15	70.47	22.81	23.55	18.86	19.66	34.64	20.94	1.16	8.42	8.55	8.57
STD.dev	7.87	19.00	43.81	25.50	4.05	7.68	3.42	5.73	11.86	12.30	2.22	1.81	2.09	1.95

Magnesium (mg/l)

	BCK A	BCK B	A	B	E	G	H1	H2	H3	WFD	Rainfall	S1	S2	S3
Mean	11.04	10.22	63.47	50.64	10.09	11.72	8.44	8.49	16.42	1.33	0.34	1.10	1.16	1.05
STD.dev	1.45	4.37	30.32	18.97	1.01	3.63	1.47	3.39	1.06	1.63	0.79	1.84	1.81	1.85

Sodium (mg/l)

	BCK A	BCK B	A	B	E	G	H1	H2	H3	WFD	Rainfall	S1	S2	S3
Mean	28.64	20.36	56.65	40.21	20.06	23.48	21.46	23.11	19.38	2.57	0.45	9.78	9.94	9.92
STD.dev	5.47	3.54	24.44	11.10	3.85	2.65	3.62	5.01	1.88	3.23	0.87	1.71	1.75	1.91

Potassium (mg/l)

	BCK A	BCK B	A	B	E	G	H1	H2	H3	WFD	Rainfall	S1	S2	S3
Mean	0.33	0.79	0.34	0.28	0.28	0.29	0.26	0.27	1.50	4.81	0.45	0.27	0.28	0.28
STD.dev	0.66	0.79	0.59	0.56	0.58	0.61	0.50	0.52	0.21	5.74	1.17	0.54	0.57	0.56

E.Coli (MPN/100ml)

	BCK A	BCK B	A	B	E	G	H1	H2	S1	S2	S3
Mean	1739.00	389.00	9881.33	5075.50	262.33	114.50	222.50	128.67	6488.00	9804.00	2909.00
STD.dev	3115.09	0.00	11816.78	8642.68	384.60	105.20	365.15	144.27	0.00	0.00	0.00

Appendix 39: Mean and standard deviation of the water analyses results at the Azalea site

Taylors Halt and Taylors Halt Control

pH

	B1	B2	B3	VIP3 E2	VIP4 E1	VIP4 E4	VIP4 E5	VIP4 G1	VIP4 G2	WFD	Seepage Face	RAINFALL	S1	S2	S3	S4	S5	S6
Mean	6.04	6.56	6.51	6.61	6.73	6.30	6.61	6.13	6.46	7.09	6.40	6.76	7.34	7.03	6.98	6.97	6.72	6.89
STD.dev	0.11	0.34	0.26	0.31	0.43	0.24	0.32	0.15	0.25	0.55	0.26	0.50	0.57	0.46	0.39	0.37	0.29	0.40

ORP (mV)

	B1	B2	B3	VIP3 E2	VIP4 E1	VIP4 E4	VIP4 E5	VIP4 G1	VIP4 G2	WFD	Seepage Face	RAINFALL	S1	S2	S3	S4	S5	S6
Mean	140.60	101.67	40.09	145.44	117.78	48.25	66.25	133.00	102.50	88.50	120.00	115.76	129.75	124.20	122.02	125.21	123.97	108.03
STD.dev	70.77	86.59	85.31	66.30	46.74	72.12	75.73	37.52	55.28	29.50	55.44	63.81	52.83	49.93	47.16	46.59	64.61	66.37

EC (µS/cm)

	B1	B2	B3	VIP3 E2	VIP4 E1	VIP4 E4	VIP4 E5	VIP4 G1	VIP4 G2	WFD	Seepage Face	RAINFALL	S1	S2	S3	S4	S5	S6
Mean	76.80	162.22	174.55	65.11	82.05	103.66	107.06	46.75	72.78	197.00	43.73	48.80	65.20	106.14	87.91	85.50	65.86	103.80
STD.dev	12.56	47.56	129.08	13.75	42.37	39.09	37.42	8.58	31.07	13.00	8.84	65.04	8.56	13.62	11.62	11.79	26.53	19.65

Nitrate (mg/l)

	B1	B2	B3	VIP3 E2	VIP4 E1	VIP4 E4	VIP4 E5	VIP4 G1	VIP4 G2	WFD	Seepage Face	RAINFALL	S1	S2	S3	S4	S5	S6

	B1	B2	B3	VIP3 E2	VIP4 E1	VIP4 E4	VIP4 E5	VIP4 G1	VIP4 G2	WFD	Seepage Face	RAINFALL	S1	S2	S3	S4	S5	S6
Mean	2.56	0.55	0.57	3.43	87.57	0.89	6.63	30.46	1.62	6.26	4.62	2.00	13.84	6.56	7.79	7.64	4.28	3.28
STD.dev	2.43	0.63	1.16	3.02	231.36	3.11	17.46	46.09	1.83	9.13	2.14	1.88	13.76	4.97	6.82	6.25	11.14	3.26

Phosphate (mg/l)

	B1	B2	B3	VIP3 E2	VIP4 E1	VIP4 E4	VIP4 E5	VIP4 G1	VIP4 G2	WFD	Seepage Face	RAINFALL	S1	S2	S3	S4	S5	S6
Mean	0.21	0.13	0.09	0.07	16.38	0.08	0.37	4.65	0.37	0.14	0.10	0.37	0.13	0.08	0.09	0.05	0.07	0.09
STD.dev	0.19	0.13	0.10	0.05	44.23	0.13	0.87	5.27	1.00	0.17	0.10	1.02	0.20	0.17	0.17	0.07	0.10	0.13

Ammonium (mg/l)

	B1	B2	B3	VIP3 E2	VIP4 E1	VIP4 E4	VIP4 E5	VIP4 G1	VIP4 G2	WFD	Seepage Face	RAINFALL	S1	S2	S3	S4	S5	S6
Mean	0.34	0.24	6.31	0.00	0.02	0.06	0.01	0.00	0.02	0.10	0.01	3.69	0.04	0.05	0.04	0.04	0.02	0.09
STD.dev	0.25	0.54	6.17	0.01	0.03	0.05	0.03	0.00	0.04	0.20	0.01	3.24	0.06	0.07	0.02	0.04	0.01	0.16

Chloride (mg/l)

	B1	B2	B3	VIP3 E2	VIP4 E1	VIP4 E4	VIP4 E5	VIP4 G1	VIP4 G2	WFD	Seepage Face	RAINFALL	S1	S2	S3	S4	S5	S6
Mean	7.09	7.53	13.88	6.26	14.92	3.90	3.45	10.93	7.08	37.17	3.90	2.53	7.91	14.55	11.69	11.36	3.53	13.94
STD.dev	1.12	5.05	6.34	1.10	4.98	0.26	2.33	4.79	2.24	9.78	0.37	2.45	1.14	1.78	1.14	1.26	3.11	1.81

Sulphate (mg/l)

	B1	B2	B3	VIP3 E2	VIP4 E1	VIP4 E4	VIP4 E5	VIP4 G1	VIP4 G2	WFD	Seepage Face	RAINFALL	S1	S2	S3	S4	S5	S6
Mean	1.02	7.96	7.07	2.55	7.71	0.69	2.03	8.72	5.44	23.50	1.03	2.63	1.05	1.30	1.14	1.21	0.75	1.29

STD.dev	0.21	11.28	8.53	1.31	4.42	1.12	3.71	5.02	6.98	15.64	1.00	1.05	1.10	1.10	1.02	1.01	1.04	1.07

Calcium (mg/l)

	B1	B2	B3	VIP3 E2	VIP4 E1	VIP4 E4	VIP4 E5	VIP4 G1	VIP4 G2	Seepage Face	RAINFALL	S1	S2	S3	S4	S5	S6
Mean	2.47	27.18	20.53	1.33	0.79	8.59	17.76	1.35	4.75	0.75	0.28	1.44	12.25	8.03	7.89	6.50	11.41
STD.dev	2.20	15.10	27.86	1.82	1.77	3.16	5.37	1.35	1.79	2.01	0.97	1.81	2.42	1.60	1.69	6.85	3.48

Magnesium (mg/l)

	B1	B2	B3	VIP3 E2	VIP4 E1	VIP4 E4	VIP4 E5	VIP4 G1	VIP4 G2	Seepage Face	RAINFALL	S1	S2	S3	S4	S5	S6
Mean	0.00	7.55	9.64	0.77	0.45	0.82	4.13	0.00	0.00	0.56	0.51	0.81	1.88	0.95	0.93	0.98	1.78
STD.dev	0.00	10.57	17.74	1.54	1.10	1.65	1.92	0.00	0.00	1.13	0.94	1.56	1.94	1.91	1.86	2.10	2.06

Sodium (mg/l)

	B1	B2	B3	VIP3 E2	VIP4 E1	VIP4 E4	VIP4 E5	VIP4 G1	VIP4 G2	Seepage Face	RAINFALL	S1	S2	S3	S4	S5	S6
Mean	1.50	6.83	4.55	2.99	6.87	1.36	5.24	0.16	2.35	1.02	0.37	4.68	5.39	5.09	4.93	3.81	5.33
STD.dev	1.36	5.69	4.52	1.72	6.18	1.66	4.04	0.16	4.62	1.45	0.87	1.14	1.38	1.06	1.17	2.09	1.15

Potassium (mg/l)

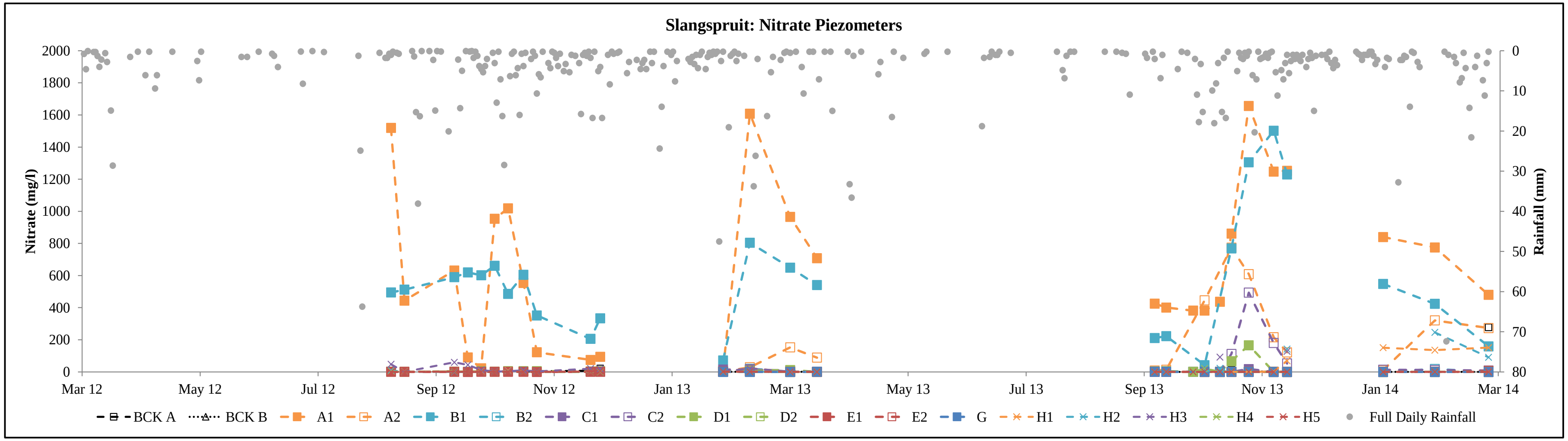
	B1	B2	B3	VIP3 E2	VIP4 E1	VIP4 E4	VIP4 E5	VIP4 G1	VIP4 G2	Seepage Face	RAINFALL	S1	S2	S3	S4	S5	S6
Mean	0.00	1.99	4.25	0.36	0.25	0.25	0.36	0.00	0.00	0.27	1.01	0.28	0.29	0.27	0.27	0.28	0.28

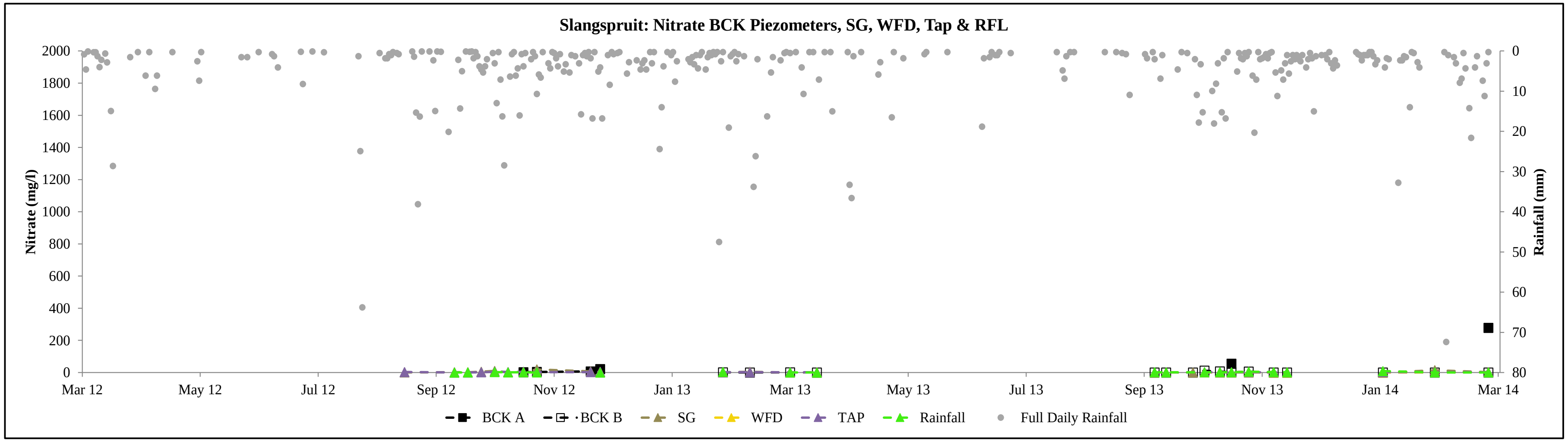
STD.dev	0.00	3.79	6.83	0.73	0.61	0.51	0.72	0.00	0.00	0.55	1.98	0.55	0.57	0.55	0.55	0.56	0.57

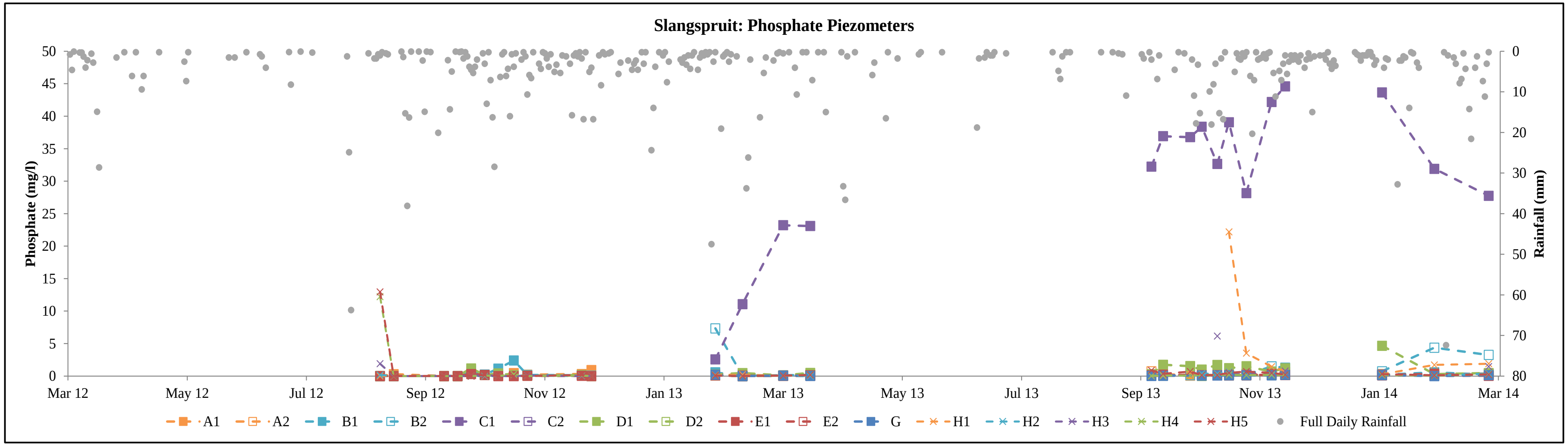
E.Coli (MPN/100ml)

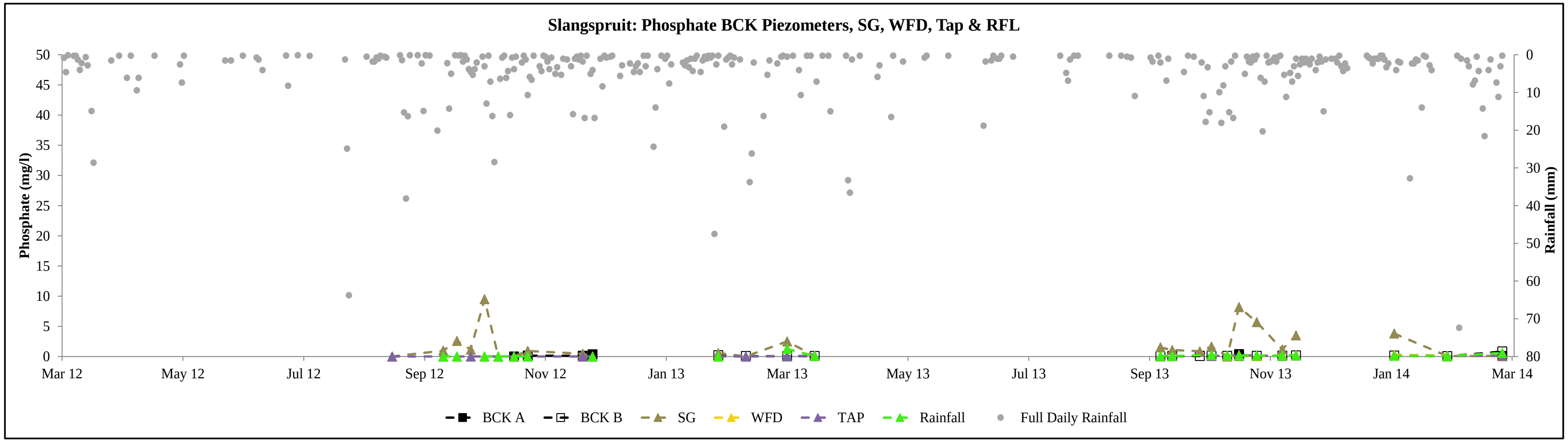
	B1	B2	B3	VIP3 E2	VIP4 E1	VIP4 E4	VIP4 E5	VIP4 G2	Seepage Face	S1	S2	S3	S5	S6
Mean	24192.00	3679.60	13822.83	319.60	9856.33	3.50	49.75	44.75	676.67	2790.25	3130.00	1457.50	520.00	594.00
STD.dev	0.00	4468.37	11903.99	433.46	6205.20	3.04	57.08	39.69	827.51	2867.87	0.00	477.50	446.87	0.00

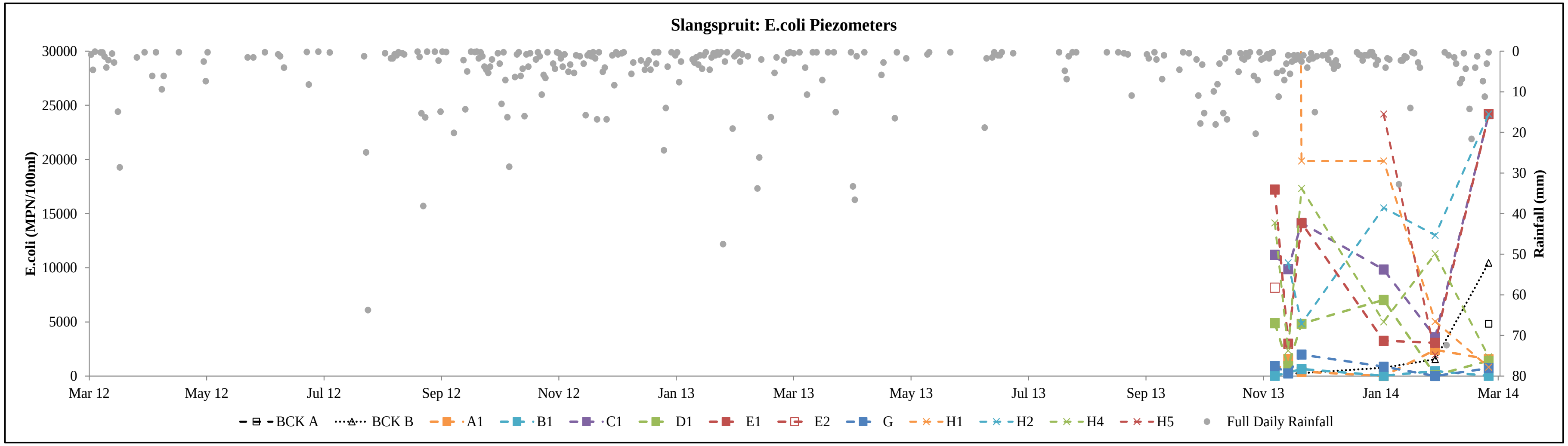
Appendix 40: Mean and standard deviation of the water analyses results at the Taylors Halt and Taylors Halt Control sites

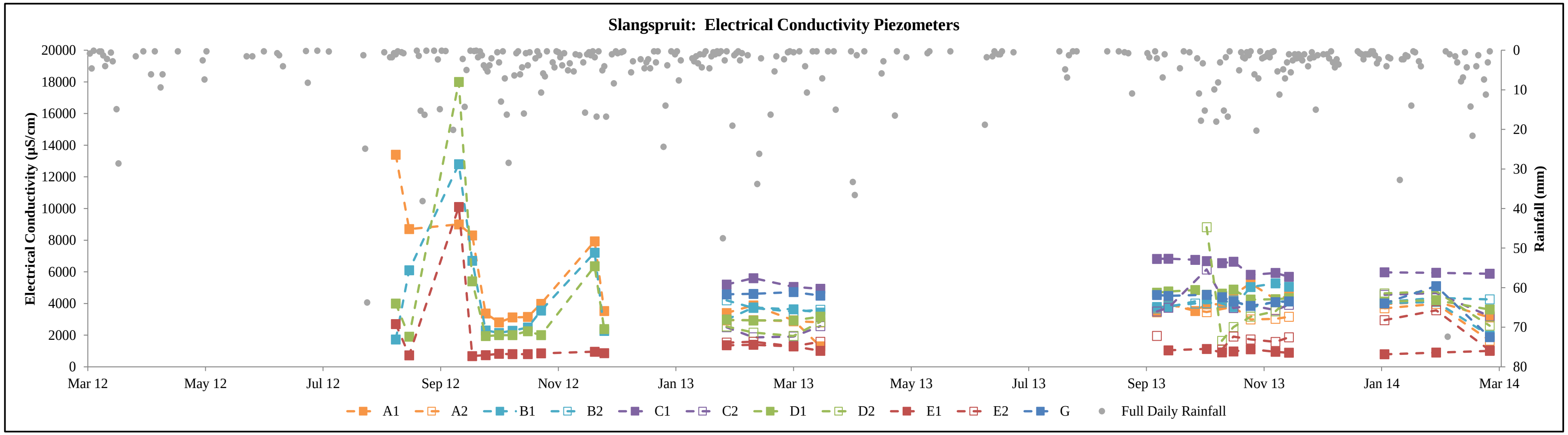


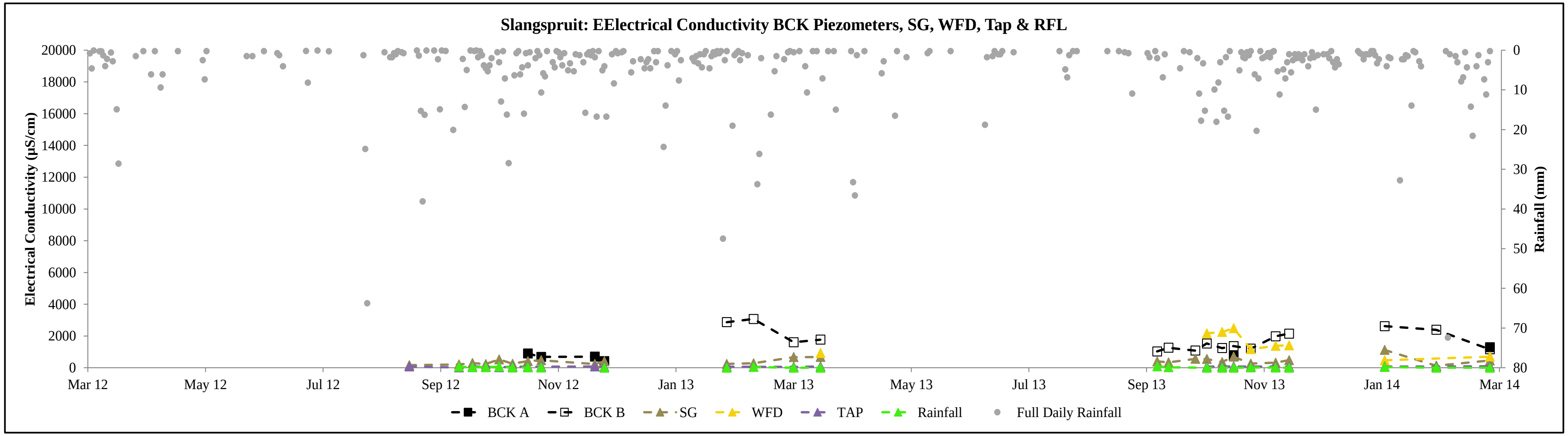

Slangspruit: Nitrate BCK Piezometers, SG, WFD, Tap & RFL
Nitrate (mg/l)
Rainfall (mm)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
10
20
30
40
50
60
70
80
Mar 12
May 12
Jul 12
Sep 12
Nov 12
Jan 13
Mar 13
May 13
Jul 13
Sep 13
Nov 13
Jan 14
Mar 14
BCK A
BCK B
SG
WFD
TAP
Rainfall
Full Daily Rainfall

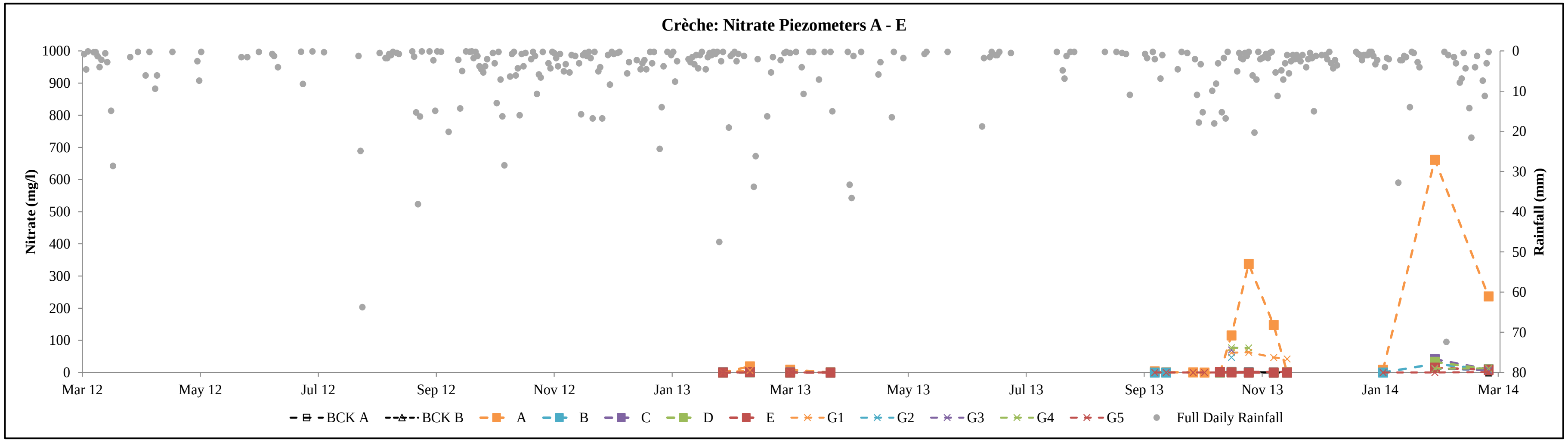

Slangspruit: Phosphate Piezometers
Phosphate (mg/l)
Rainfall (mm)
50
45
40
35
30
25
20
15
10
5
0
10
20
30
40
50
60
70
80
Mar 12
May 12
Jul 12
Sep 12
Nov 12
Jan 13
Mar 13
May 13
Jul 13
Sep 13
Nov 13
Jan 14
Mar 14
A1
A2
B1
B2
C1
C2
D1
D2
E1
E2
G
H1
H2
H3
H4
H5
Full Daily Rainfall


Slangspruit: Phosphate BCK Piezometers, SG, WFD, Tap & RFL
Phosphate (mg/l)
Rainfall (mm)
0
5
10
15
20
25
30
35
40
45
50
0
10
20
30
40
50
60
70
80
Mar 12
May 12
Jul 12
Sep 12
Nov 12
Jan 13
Mar 13
May 13
Jul 13
Sep 13
Nov 13
Jan 14
Mar 14
BCK A
BCK B
SG
WFD
TAP
Rainfall
Full Daily Rainfall

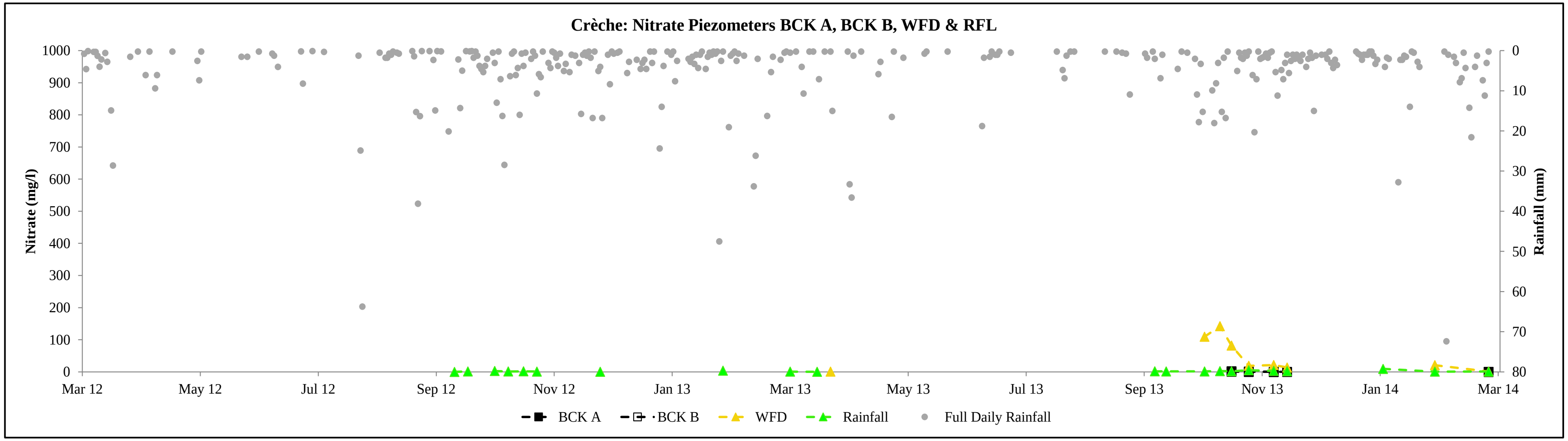

Slangspruit: E.coli Piezometers
E.coli (MPN/100ml)
Rainfall (mm)
0
5000
10000
15000
20000
25000
30000
0
10
20
30
40
50
60
70
80
Mar 12
May 12
Jul 12
Sep 12
Nov 12
Jan 13
Mar 13
May 13
Jul 13
Sep 13
Nov 13
Jan 14
Mar 14
BCK A
BCK B
A1
B1
C1
D1
E1
E2
G
H1
H2
H4
H5
Full Daily Rainfall


Slangspruit: Electrical Conductivity Piezometers
Electrical Conductivity (µS/cm)
Rainfall (mm)
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
0
10
20
30
40
50
60
70
80
Mar 12
May 12
Jul 12
Sep 12
Nov 12
Jan 13
Mar 13
May 13
Jul 13
Sep 13
Nov 13
Jan 14
Mar 14
A1
A2
B1
B2
C1
C2
D1
D2
E1
E2
G
Full Daily Rainfall

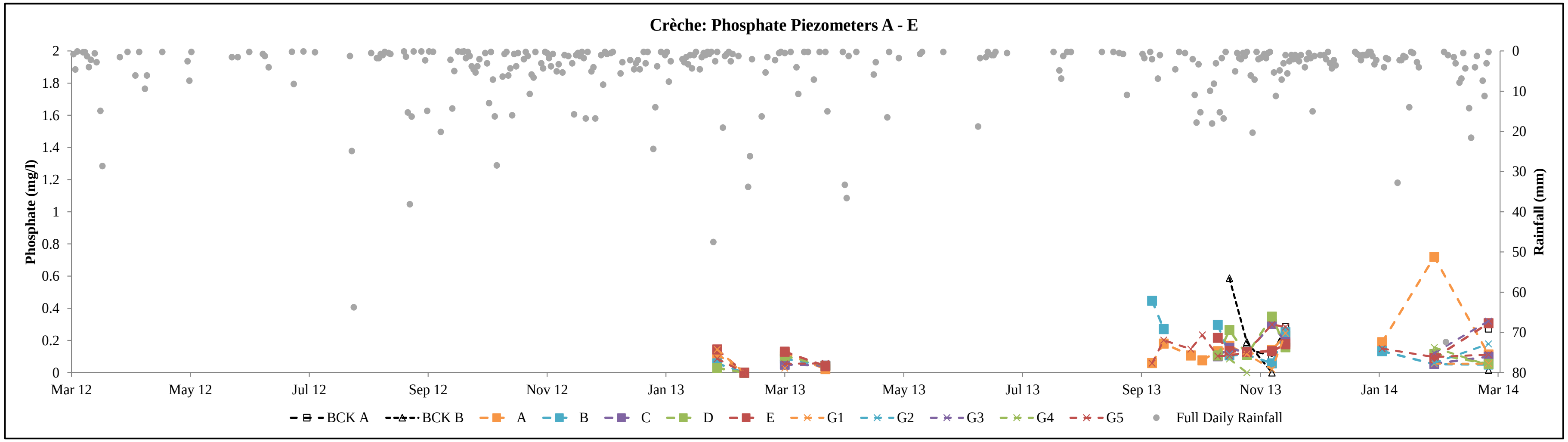

Slangspruit: EElectrical Conductivity BCK Piezometers, SG, WFD, Tap & RFL
Electrical Conductivity (µS/cm)
Rainfall (mm)
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
0
10
20
30
40
50
60
70
80
Mar 12
May 12
Jul 12
Sep 12
Nov 12
Jan 13
Mar 13
May 13
Jul 13
Sep 13
Nov 13
Jan 14
Mar 14
BCK A
BCK B
SG
WFD
TAP
Rainfall
Full Daily Rainfall

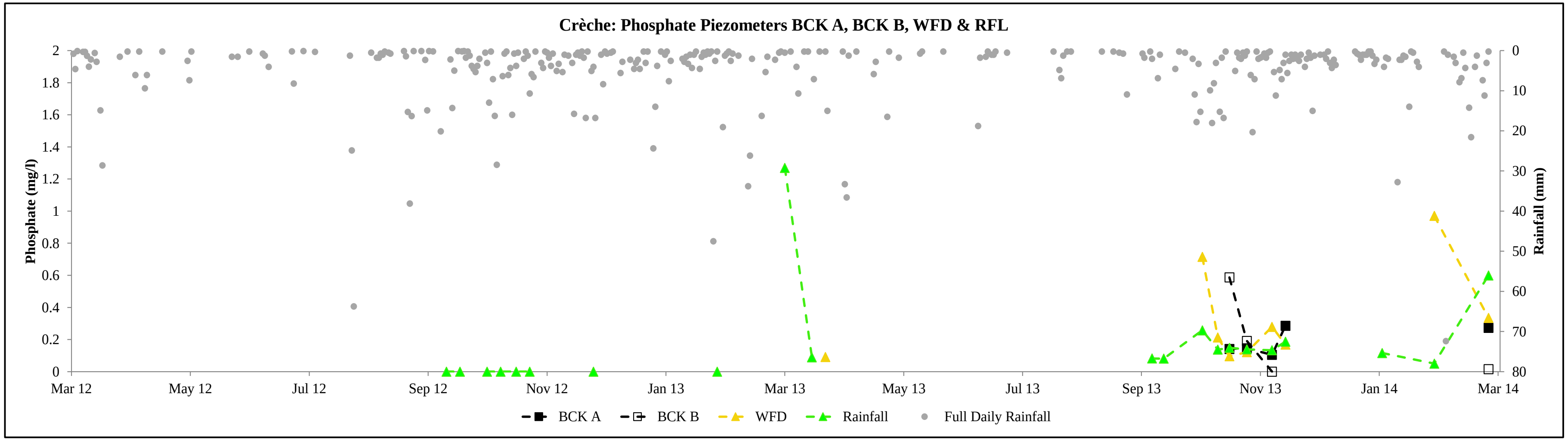


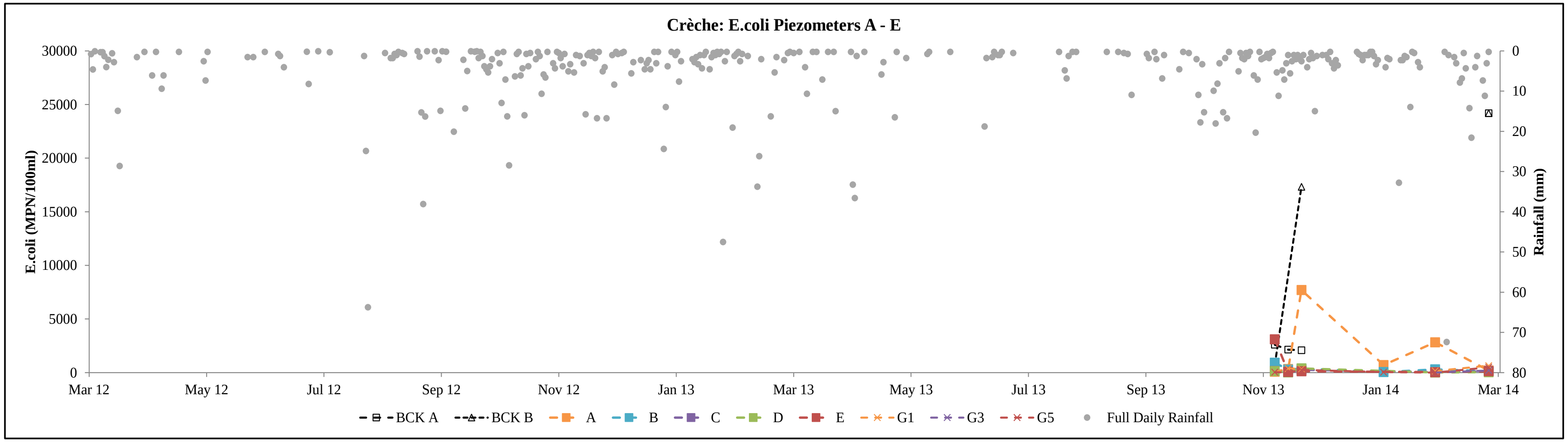
Crèche: Nitrate Piezometers A - E
Nitrate (mg/l)
Rainfall (mm)
1000
900
800
700
600
500
400
300
200
100
0
0
10
20
30
40
50
60
70
80
Mar 12
May 12
Jul 12
Sep 12
Nov 12
Jan 13
Mar 13
May 13
Jul 13
Sep 13
Nov 13
Jan 14
Mar 14
BCK A
BCK B
A
B
C
D
E
G1
G2
G3
G4
G5
Full Daily Rainfall

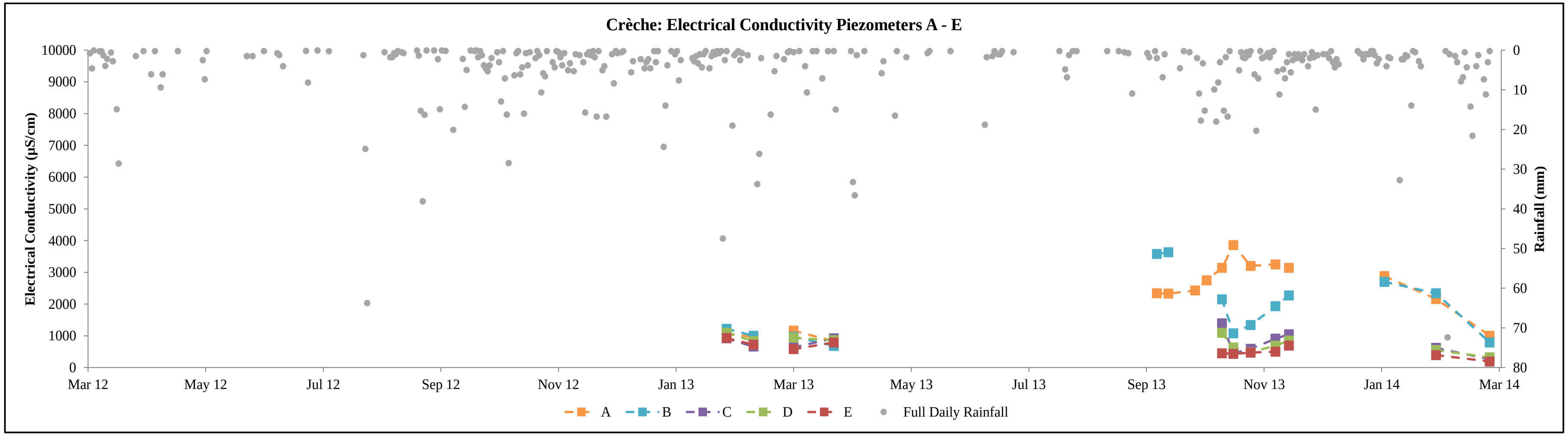


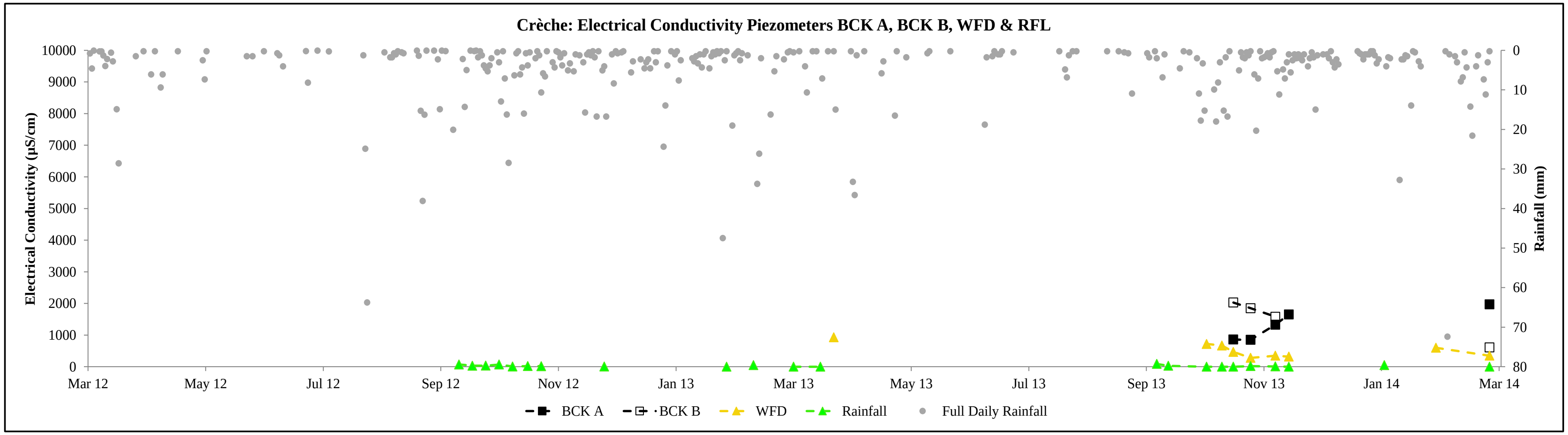
Crèche: Nitrate Piezometers BCK A, BCK B, WFD & RFL
Nitrate (mg/l)
Rainfall (mm)
1000
900
800
700
600
500
400
300
200
100
0
0
10
20
30
40
50
60
70
80
Mar 12
May 12
Jul 12
Sep 12
Nov 12
Jan 13
Mar 13
May 13
Jul 13
Sep 13
Nov 13
Jan 14
Mar 14
BCK A
BCK B
WFD
Rainfall
Full Daily Rainfall

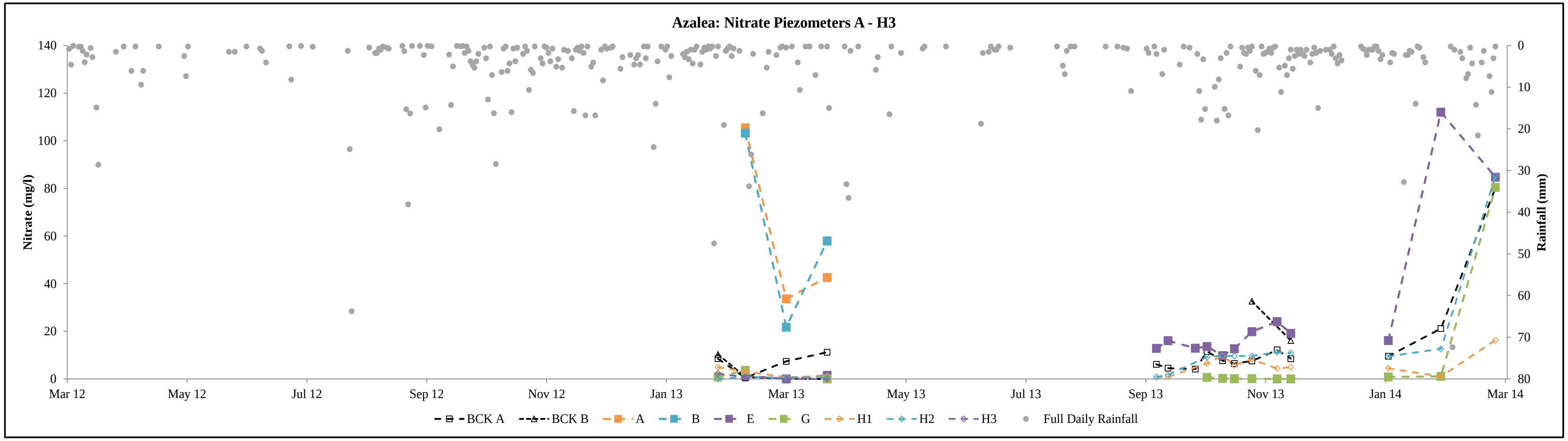

Crèche: Phosphate Piezometers A - E
Phosphate (mg/l)
Rainfall (mm)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
10
20
30
40
50
60
70
80
Mar 12
May 12
Jul 12
Sep 12
Nov 12
Jan 13
Mar 13
May 13
Jul 13
Sep 13
Nov 13
Jan 14
Mar 14
BCK A
BCK B
A
B
C
D
E
G1
G2
G3
G4
G5
Full Daily Rainfall

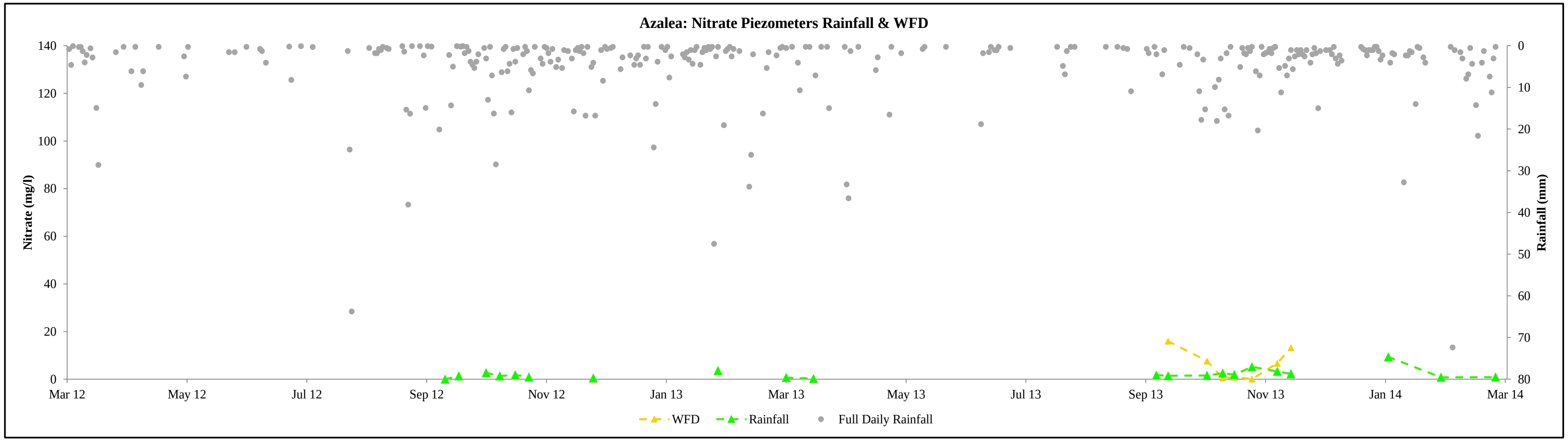

Crèche: Phosphate Piezometers BCK A, BCK B, WFD & RFL
Phosphate (mg/l)
Rainfall (mm)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
10
20
30
40
50
60
70
80
Mar 12
May 12
Jul 12
Sep 12
Nov 12
Jan 13
Mar 13
May 13
Jul 13
Sep 13
Nov 13
Jan 14
Mar 14
BCK A
BCK B
WFD
Rainfall
Full Daily Rainfall


Crèche: E.coli Piezometers A - E
E.coli (MPN/100ml)
Rainfall (mm)
30000
25000
20000
15000
10000
5000
0
0
10
20
30
40
50
60
70
80
Mar 12
May 12
Jul 12
Sep 12
Nov 12
Jan 13
Mar 13
May 13
Jul 13
Sep 13
Nov 13
Jan 14
Mar 14
BCK A
BCK B
A
B
C
D
E
G1
G3
G5
Full Daily Rainfall

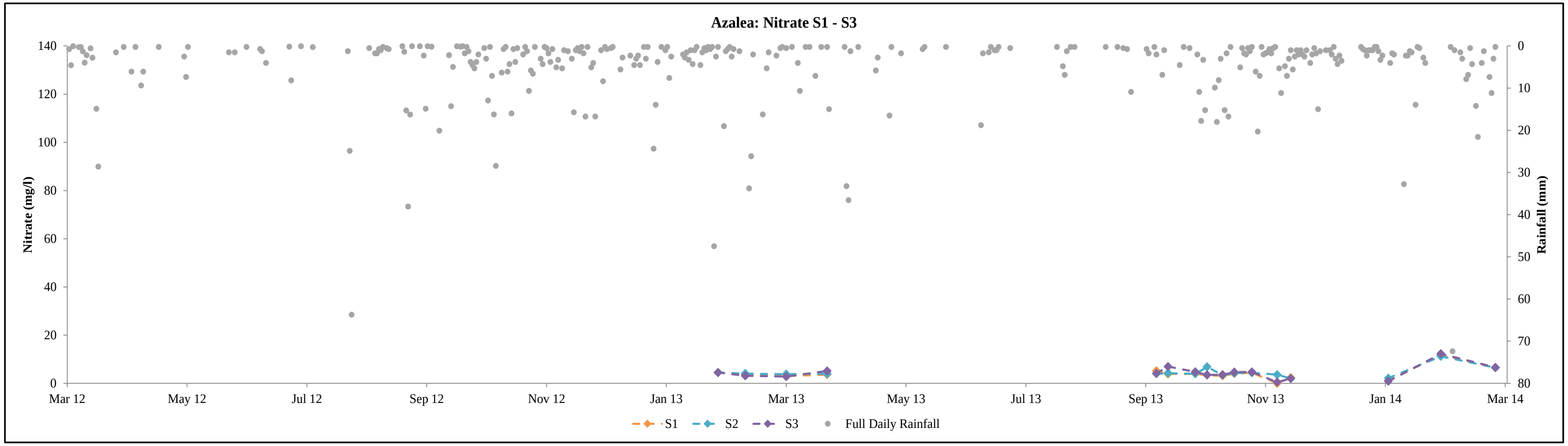

Crèche: Electrical Conductivity Piezometers A - E
Electrical Conductivity (µS/cm)
Rainfall (mm)
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
10
20
30
40
50
60
70
80
Mar 12
May 12
Jul 12
Sep 12
Nov 12
Jan 13
Mar 13
May 13
Jul 13
Sep 13
Nov 13
Jan 14
Mar 14
A
B
C
D
E
Full Daily Rainfall


Crèche: Electrical Conductivity Piezometers BCK A, BCK B, WFD & RFL
Electrical Conductivity (µS/cm)
Rainfall (mm)
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
10
20
30
40
50
60
70
80
Mar 12
May 12
Jul 12
Sep 12
Nov 12
Jan 13
Mar 13
May 13
Jul 13
Sep 13
Nov 13
Jan 14
Mar 14
BCK A
BCK B
WFD
Rainfall
Full Daily Rainfall

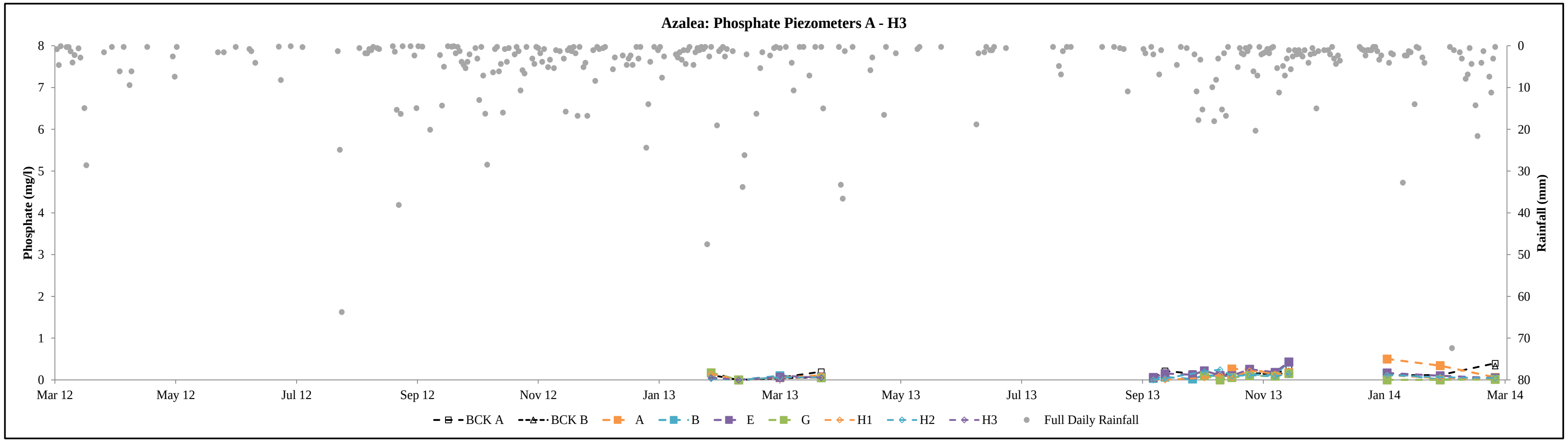

Azalea: Nitrate Piezometers A - H3
Nitrate (mg/l)
Rainfall (mm)
140
120
100
80
60
40
20
0
0
10
20
30
40
50
60
70
80
Mar 12
May 12
Jul 12
Sep 12
Nov 12
Jan 13
Mar 13
May 13
Jul 13
Sep 13
Nov 13
Jan 14
Mar 14
BCK A
BCK B
A
B
E
G
H1
H2
H3
Full Daily Rainfall

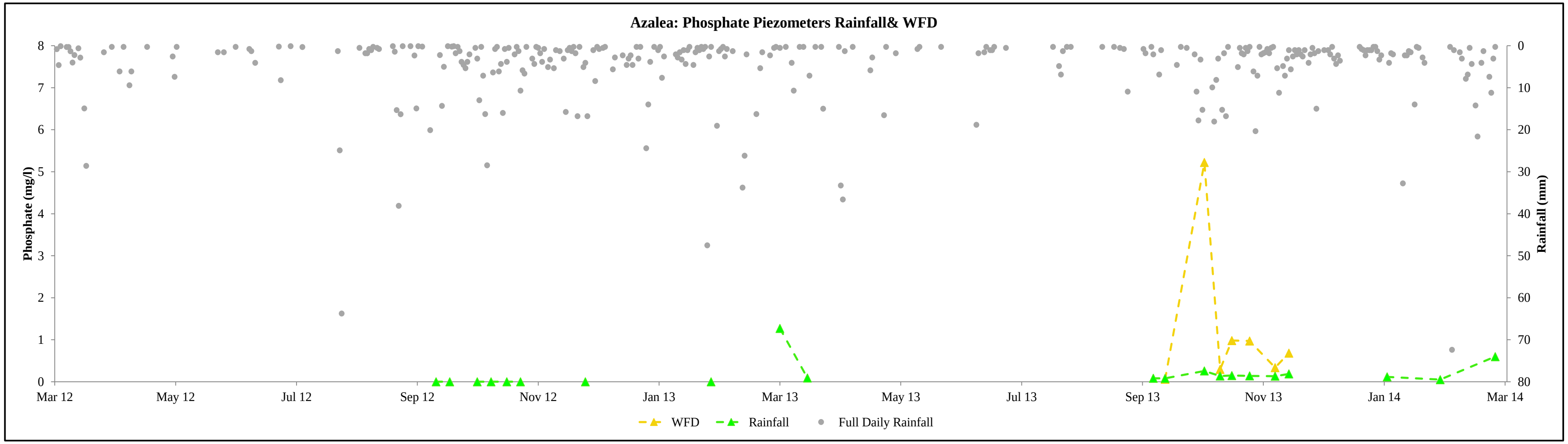


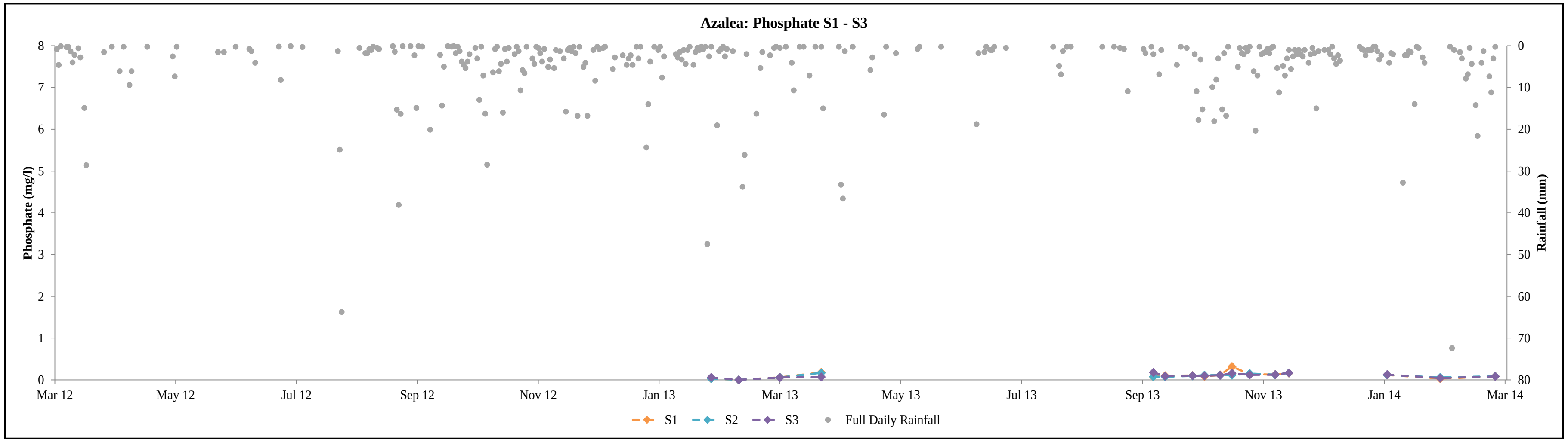
Azalea: Nitrate Piezometers Rainfall & WFD
Nitrate (mg/l)
Rainfall (mm)
140
120
100
80
60
40
20
0
0
10
20
30
40
50
60
70
80
Mar 12
May 12
Jul 12
Sep 12
Nov 12
Jan 13
Mar 13
May 13
Jul 13
Sep 13
Nov 13
Jan 14
Mar 14
WFD
Rainfall
Full Daily Rainfall

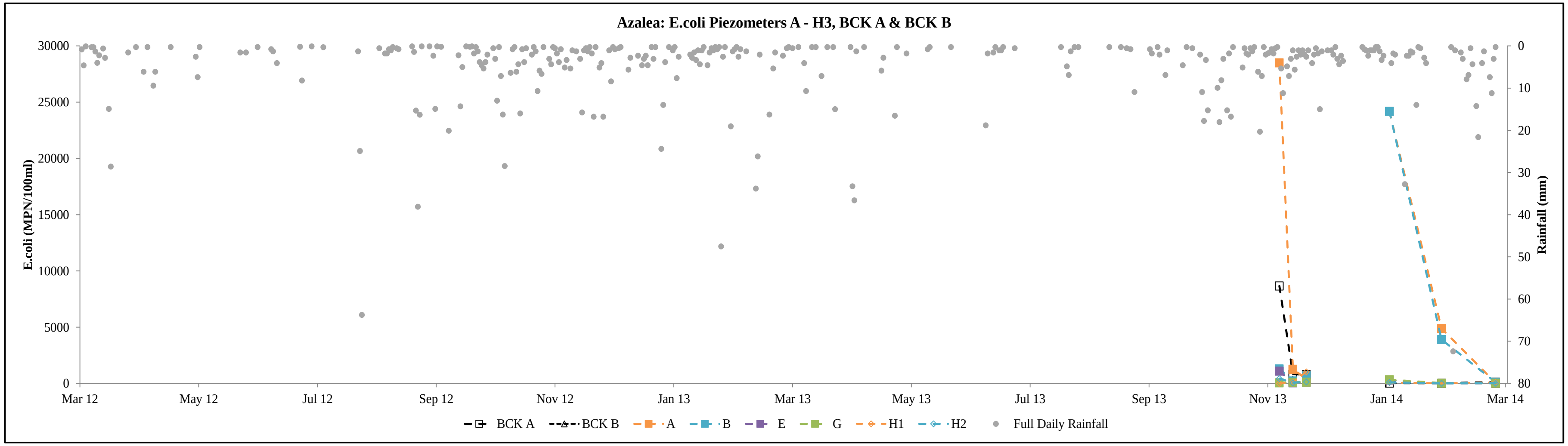


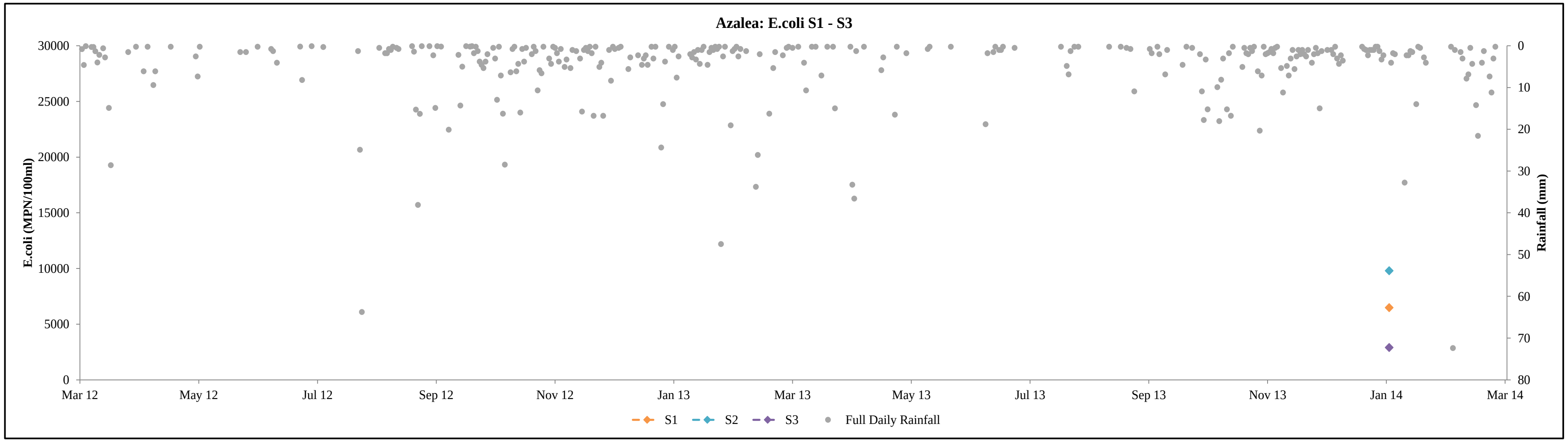
Azalea: Nitrate S1 - S3
Nitrate (mg/l)
Rainfall (mm)
140
120
100
80
60
40
20
0
0
10
20
30
40
50
60
70
80
Mar 12
May 12
Jul 12
Sep 12
Nov 12
Jan 13
Mar 13
May 13
Jul 13
Sep 13
Nov 13
Jan 14
Mar 14
S1
S2
S3
Full Daily Rainfall

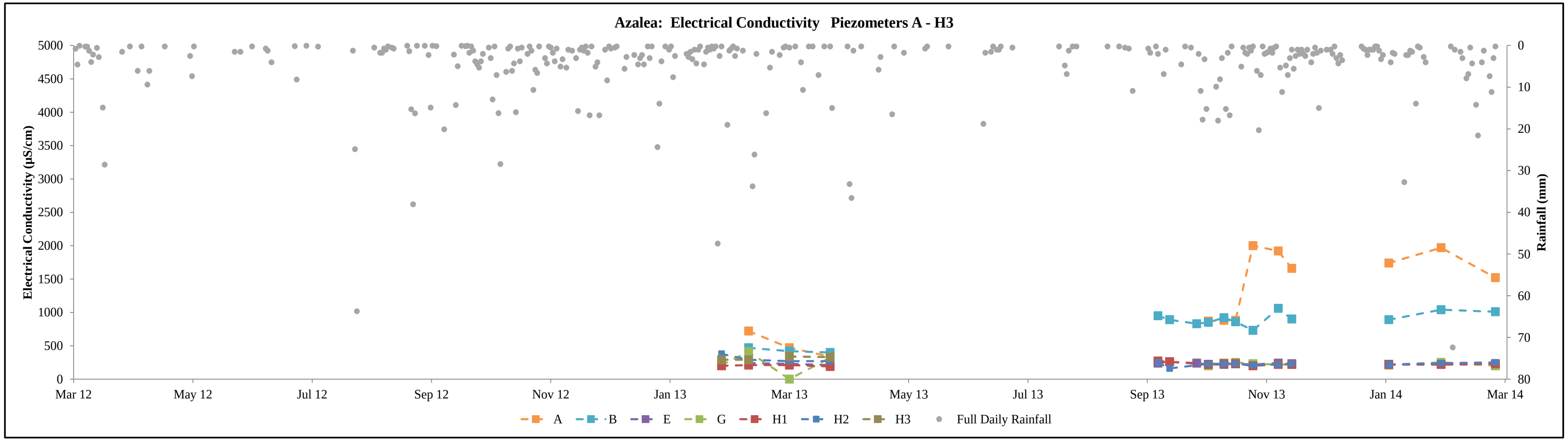

Azalea: Phosphate Piezometers A - H3
Phosphate (mg/l)
Rainfall (mm)
Mar 12
May 12
Jul 12
Sep 12
Nov 12
Jan 13
Mar 13
May 13
Jul 13
Sep 13
Nov 13
Jan 14
Mar 14
BCK A
BCK B
A
B
E
G
H1
H2
H3
Full Daily Rainfall

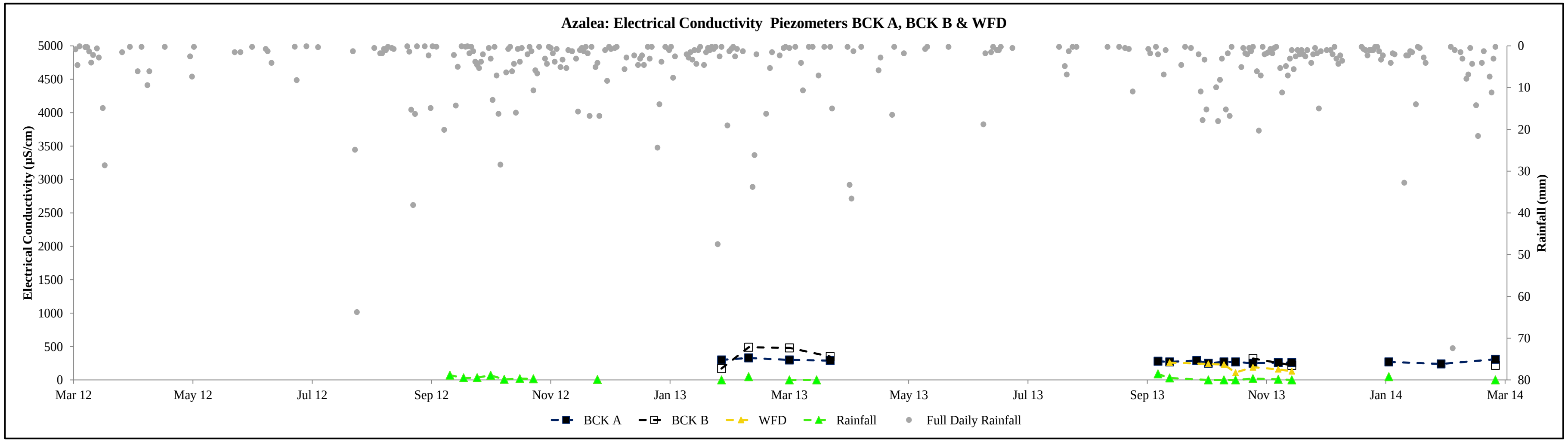

Azalea: Phosphate Piezometers Rainfall& WFD
Phosphate (mg/l)
Rainfall (mm)
Mar 12
May 12
Jul 12
Sep 12
Nov 12
Jan 13
Mar 13
May 13
Jul 13
Sep 13
Nov 13
Jan 14
Mar 14
WFD
Rainfall
Full Daily Rainfall

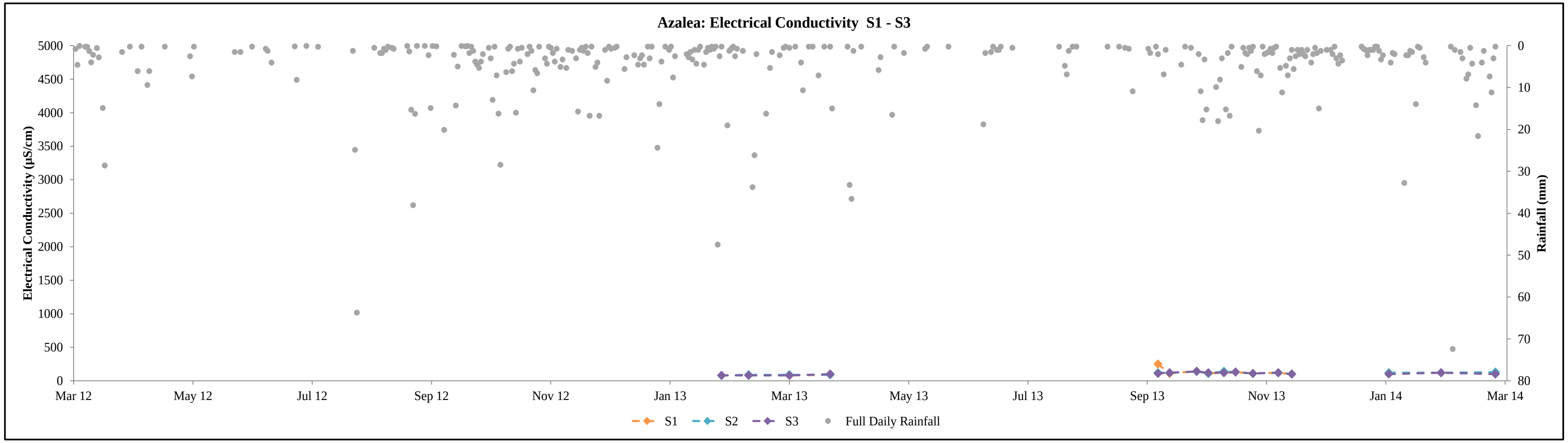

Azalea: Phosphate S1 - S3
Phosphate (mg/l)
Rainfall (mm)
Mar 12
May 12
Jul 12
Sep 12
Nov 12
Jan 13
Mar 13
May 13
Jul 13
Sep 13
Nov 13
Jan 14
Mar 14
S1
S2
S3
Full Daily Rainfall

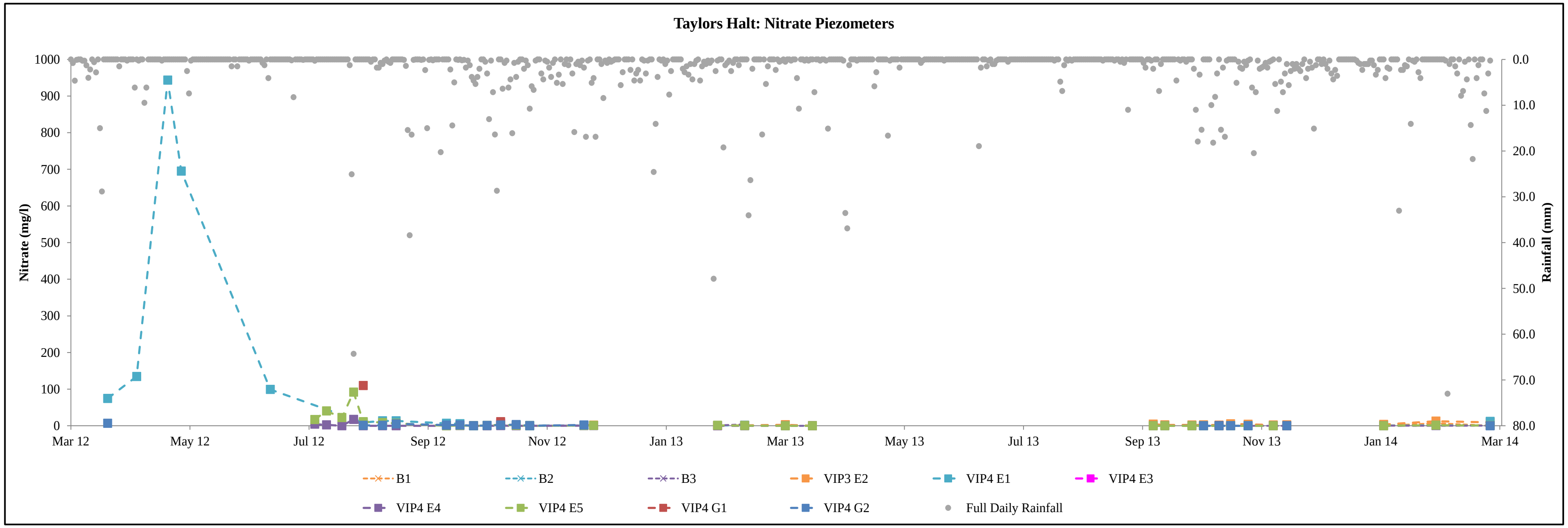

Azalea: E.coli Piezometers A - H3, BCK A & BCK B
E.coli (MPN/100ml)
Rainfall (mm)
Mar 12
May 12
Jul 12
Sep 12
Nov 12
Jan 13
Mar 13
May 13
Jul 13
Sep 13
Nov 13
Jan 14
Mar 14
BCK A
BCK B
A
B
E
G
H1
H2
Full Daily Rainfall

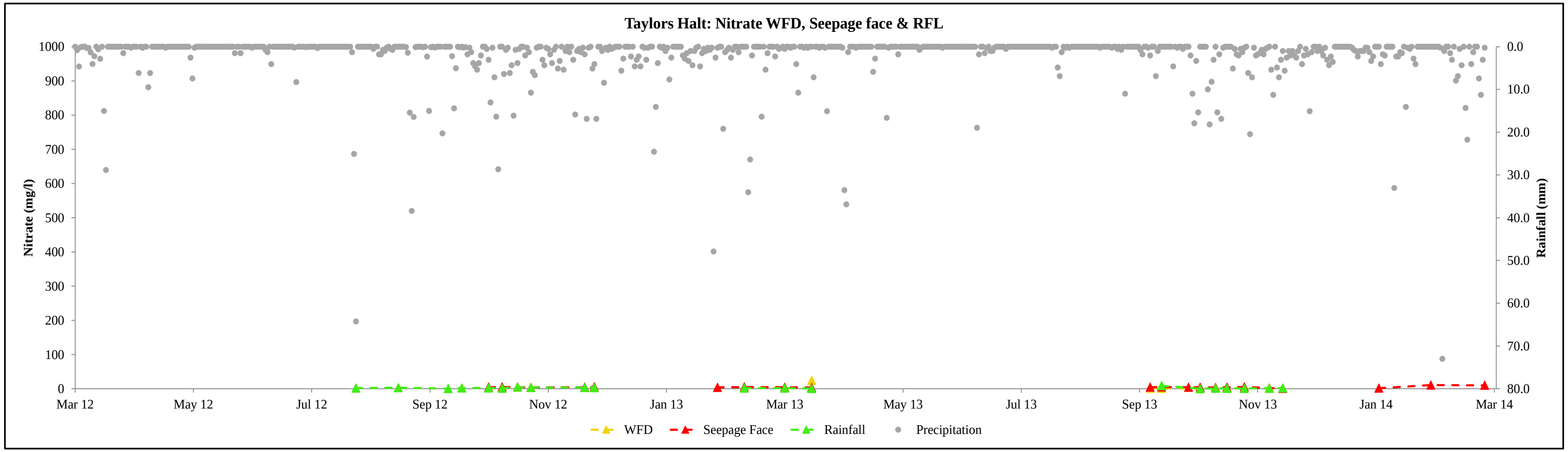

Azalea: E.coli S1 - S3
E.coli (MPN/100ml)
Rainfall (mm)
30000
25000
20000
15000
10000
5000
0
0
10
20
30
40
50
60
70
80
Mar 12
May 12
Jul 12
Sep 12
Nov 12
Jan 13
Mar 13
May 13
Jul 13
Sep 13
Nov 13
Jan 14
Mar 14
S1
S2
S3
Full Daily Rainfall

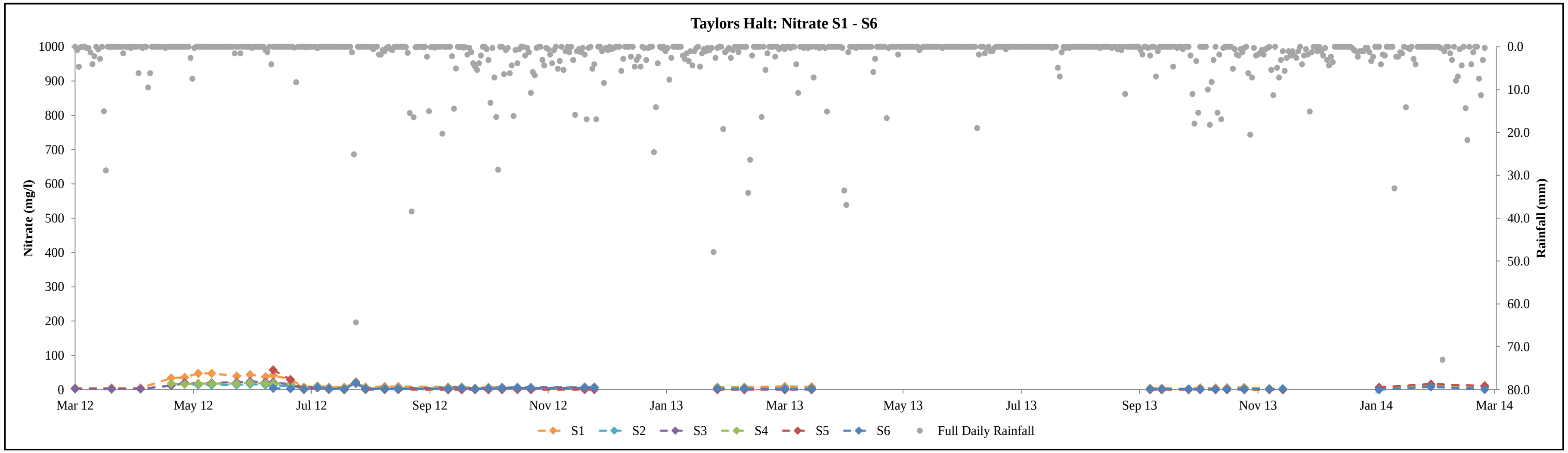

Azalea: Electrical Conductivity Piezometers A - H3
Electrical Conductivity (µS/cm)
Rainfall (mm)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
10
20
30
40
50
60
70
80
Mar 12
May 12
Jul 12
Sep 12
Nov 12
Jan 13
Mar 13
May 13
Jul 13
Sep 13
Nov 13
Jan 14
Mar 14
A
B
E
G
H1
H2
H3
Full Daily Rainfall

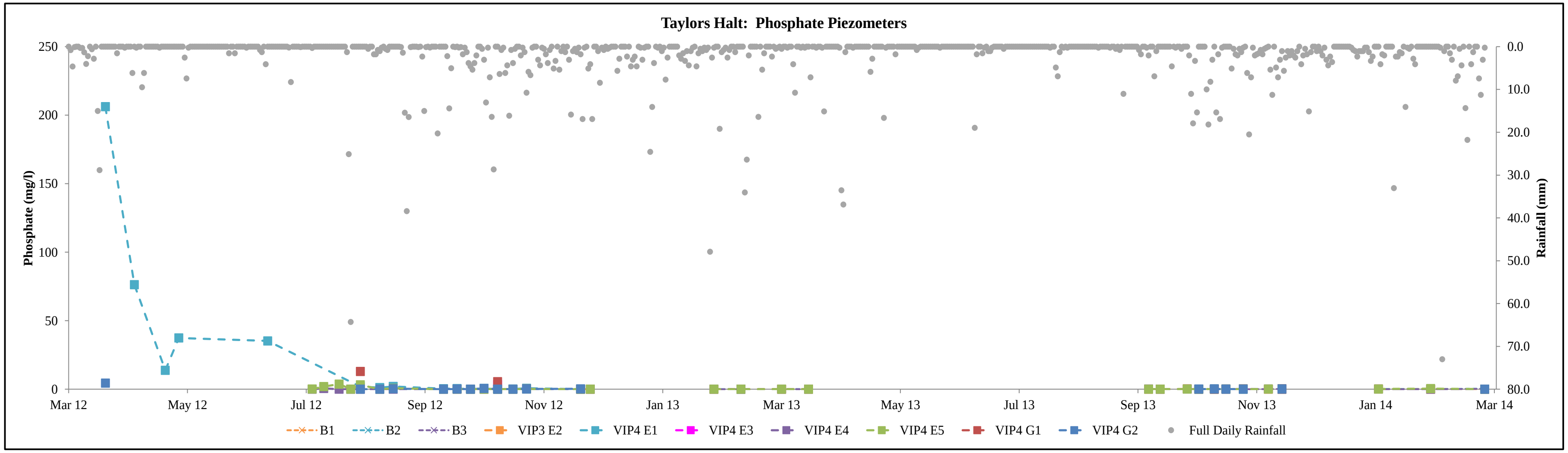

Azalea: Electrical Conductivity Piezometers BCK A, BCK B & WFD
Electrical Conductivity (µS/cm)
Rainfall (mm)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
10
20
30
40
50
60
70
80
Mar 12
May 12
Jul 12
Sep 12
Nov 12
Jan 13
Mar 13
May 13
Jul 13
Sep 13
Nov 13
Jan 14
Mar 14
BCK A
BCK B
WFD
Rainfall
Full Daily Rainfall

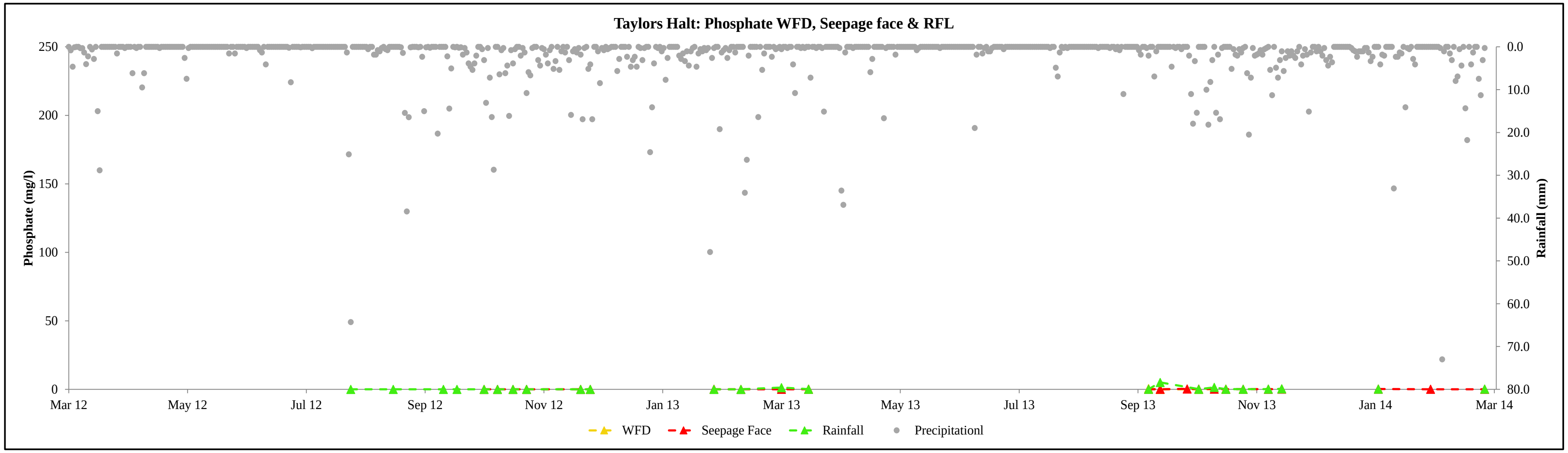

Azalea: Electrical Conductivity S1 - S3
Electrical Conductivity (µS/cm)
Rainfall (mm)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
10
20
30
40
50
60
70
80
Mar 12
May 12
Jul 12
Sep 12
Nov 12
Jan 13
Mar 13
May 13
Jul 13
Sep 13
Nov 13
Jan 14
Mar 14
S1
S2
S3
Full Daily Rainfall

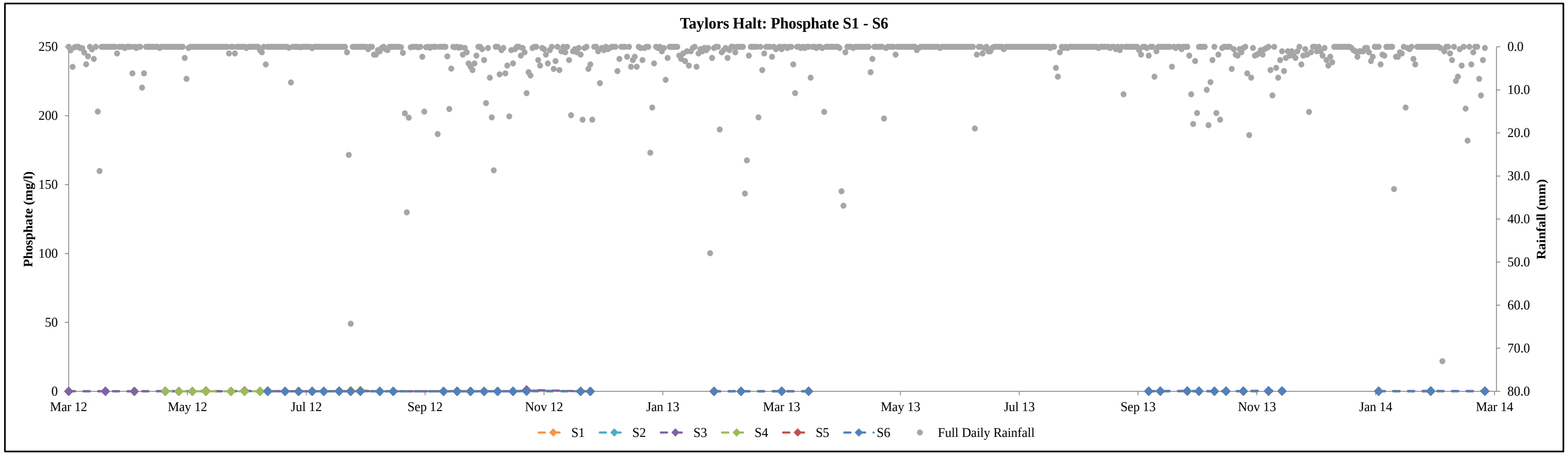

Taylors Halt: Nitrate Piezometers
Nitrate (mg/l)
Rainfall (mm)
1000
900
800
700
600
500
400
300
200
100
0
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
Mar 12
May 12
Jul 12
Sep 12
Nov 12
Jan 13
Mar 13
May 13
Jul 13
Sep 13
Nov 13
Jan 14
Mar 14
B1
B2
B3
VIP3 E2
VIP4 E1
VIP4 E3
VIP4 E4
VIP4 E5
VIP4 G1
VIP4 G2
Full Daily Rainfall

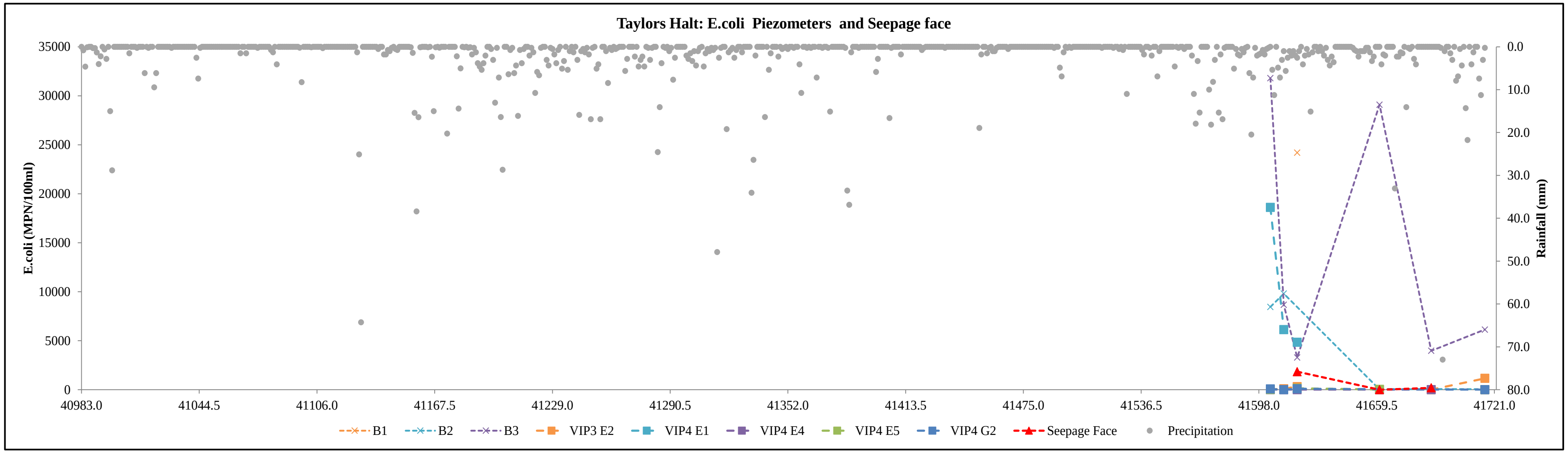

Taylors Halt: Nitrate WFD, Seepage face & RFL
Nitrate (mg/l)
Rainfall (mm)
1000
900
800
700
600
500
400
300
200
100
0
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
Mar 12
May 12
Jul 12
Sep 12
Nov 12
Jan 13
Mar 13
May 13
Jul 13
Sep 13
Nov 13
Jan 14
Mar 14
WFD
Seepage Face
Rainfall
Precipitation

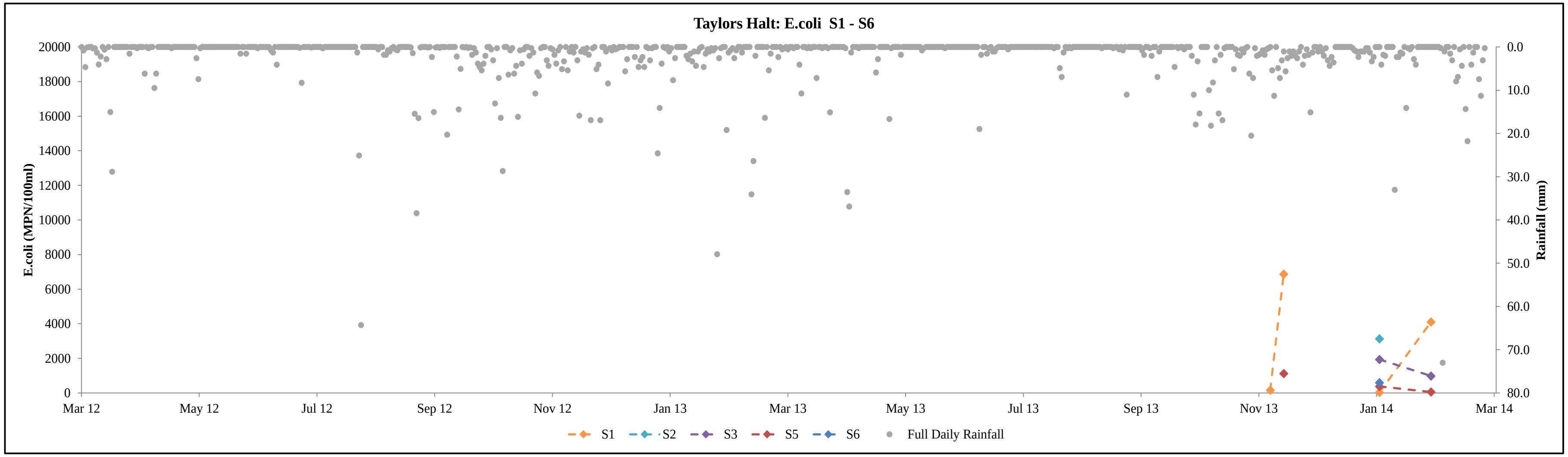

Taylors Halt: Nitrate S1 - S6
Nitrate (mg/l)
Rainfall (mm)
1000
900
800
700
600
500
400
300
200
100
0
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
Mar 12
May 12
Jul 12
Sep 12
Nov 12
Jan 13
Mar 13
May 13
Jul 13
Sep 13
Nov 13
Jan 14
Mar 14
S1
S2
S3
S4
S5
S6
Full Daily Rainfall

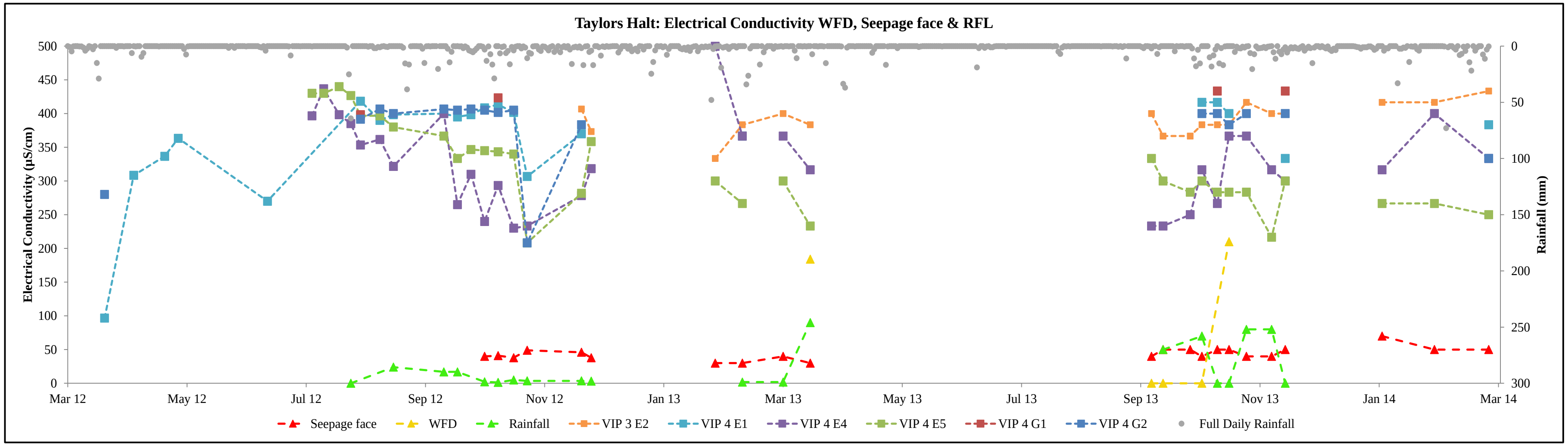

Taylors Halt: Phosphate Piezometers
Phosphate (mg/l)
Rainfall (mm)
250
200
150
100
50
0
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
Mar 12
May 12
Jul 12
Sep 12
Nov 12
Jan 13
Mar 13
May 13
Jul 13
Sep 13
Nov 13
Jan 14
Mar 14
B1
B2
B3
VIP3 E2
VIP4 E1
VIP4 E3
VIP4 E4
VIP4 E5
VIP4 G1
VIP4 G2
Full Daily Rainfall

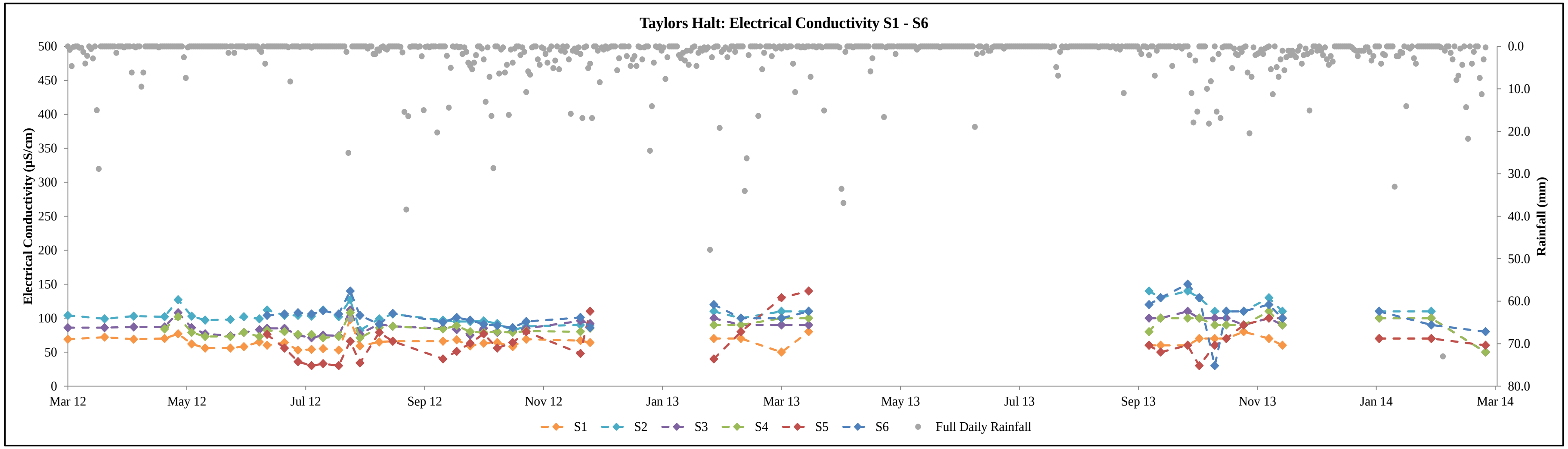

Taylors Halt: Phosphate WFD, Seepage face & RFL
Phosphate (mg/l)
Rainfall (mm)
250
200
150
100
50
0
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
Mar 12
May 12
Jul 12
Sep 12
Nov 12
Jan 13
Mar 13
May 13
Jul 13
Sep 13
Nov 13
Jan 14
Mar 14
WFD
Seepage Face
Rainfall
Precipitationl


Taylors Halt: Phosphate S1 - S6
Phosphate (mg/l)
Rainfall (mm)
250
200
150
100
50
0
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
Mar 12
May 12
Jul 12
Sep 12
Nov 12
Jan 13
Mar 13
May 13
Jul 13
Sep 13
Nov 13
Jan 14
Mar 14
S1
S2
S3
S4
S5
S6
Full Daily Rainfall

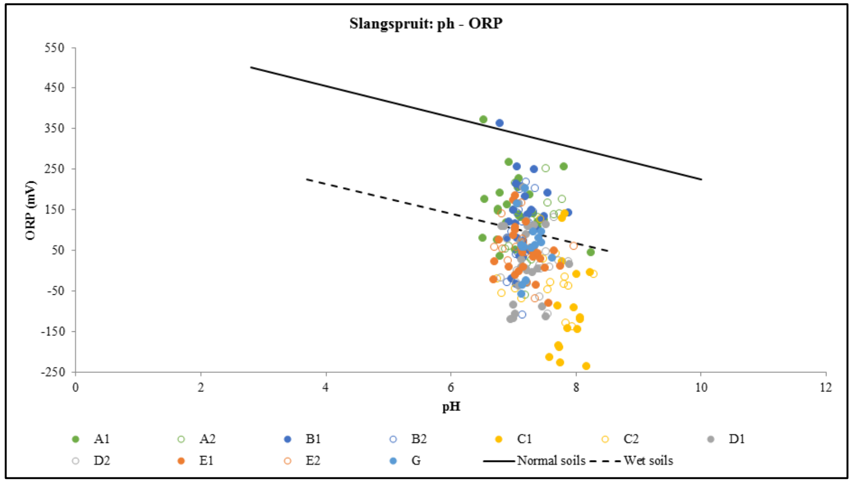

Taylors Halt: E.coli Piezometers and Seepage face
E.coli (MPN/100ml)
Rainfall (mm)
35000
30000
25000
20000
15000
10000
5000
0
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
40983.0
41044.5
41106.0
41167.5
41229.0
41290.5
41352.0
41413.5
41475.0
41536.5
41598.0
41659.5
41721.0
B1
B2
B3
VIP3 E2
VIP4 E1
VIP4 E4
VIP4 E5
VIP4 G2
Seepage Face
Precipitation

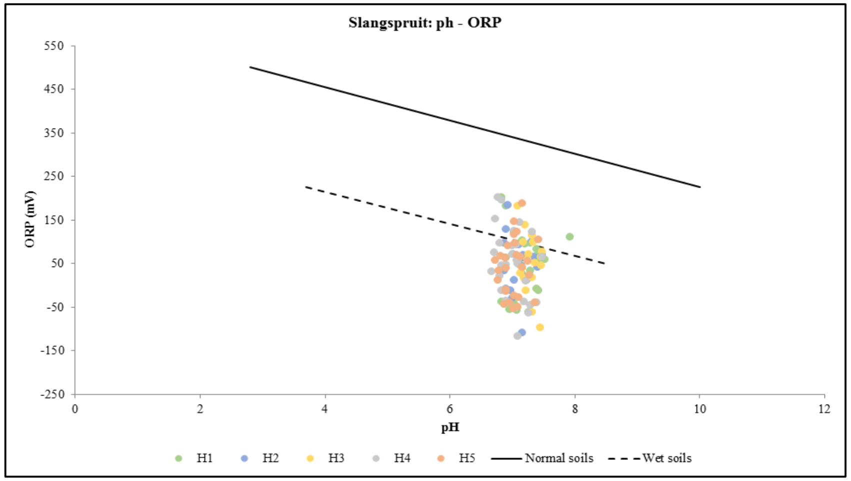

Taylors Halt: E.coli S1 - S6
E.coli (MPN/100ml)
Rainfall (mm)
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
Mar 12
May 12
Jul 12
Sep 12
Nov 12
Jan 13
Mar 13
May 13
Jul 13
Sep 13
Nov 13
Jan 14
Mar 14
S1
S2
S3
S5
S6
Full Daily Rainfall

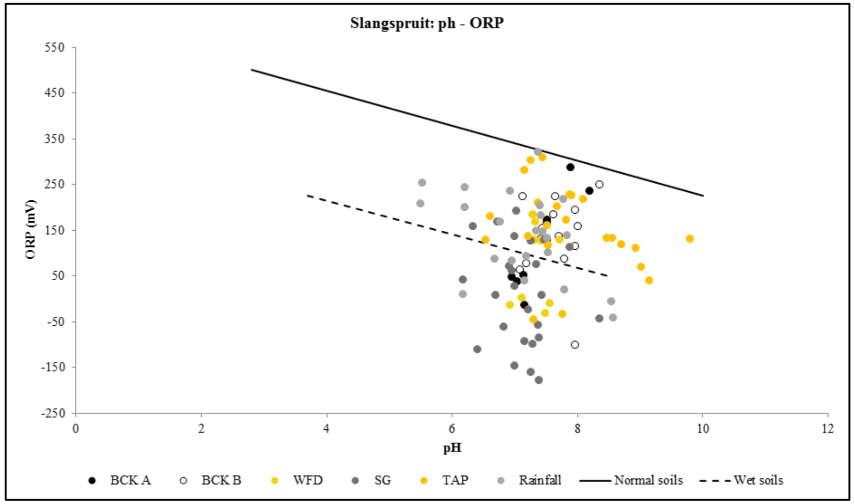


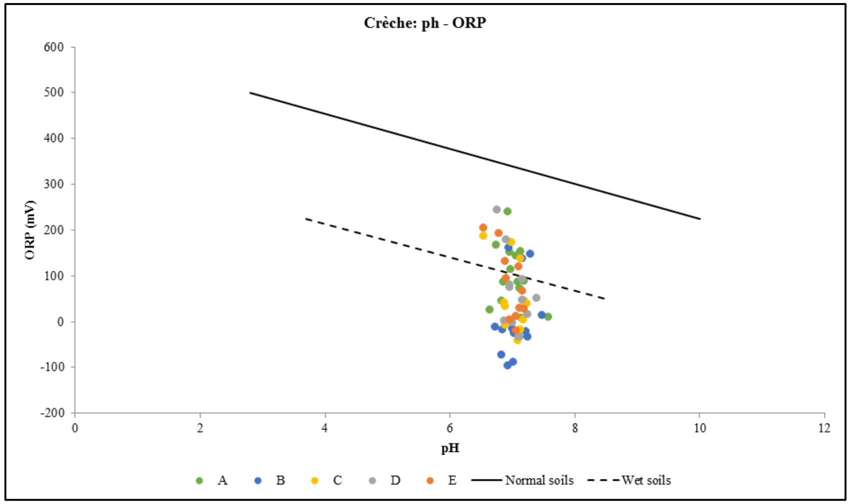


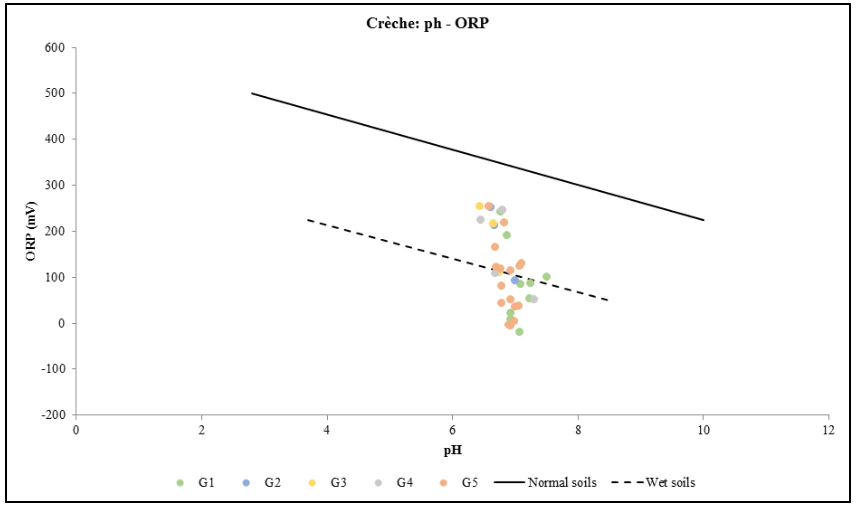
Appendix 41: Rainfall time series at all the study sites


Slangspruit: ph - ORP
ORP (mV)
pH
A1
A2
B1
B2
C1
C2
D1
D2
E1
E2
G
Normal soils
Wet soils

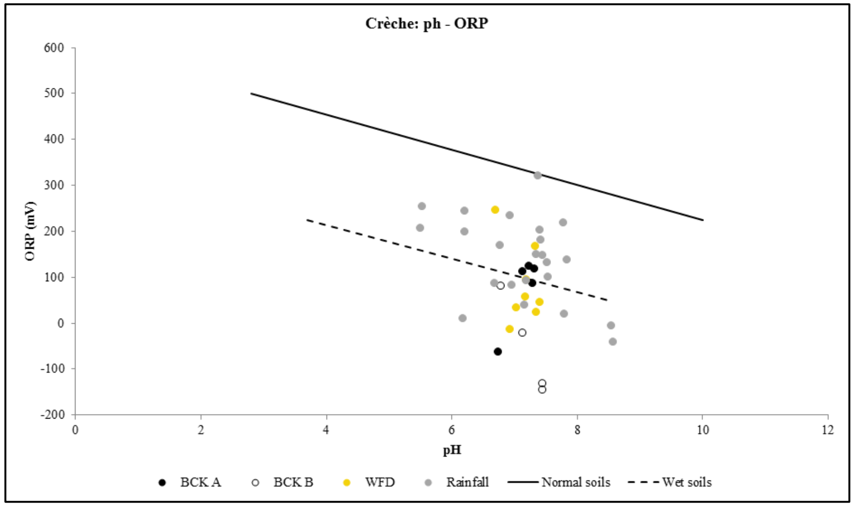

Slangspruit: ph - ORP
ORP (mV)
pH
H1
H2
H3
H4
H5
Normal soils
Wet soils


Slangspruit: ph - ORP
ORP (mV)
pH
BCK A
BCK B
WFD
SG
TAP
Rainfall
Normal soils
Wet soils

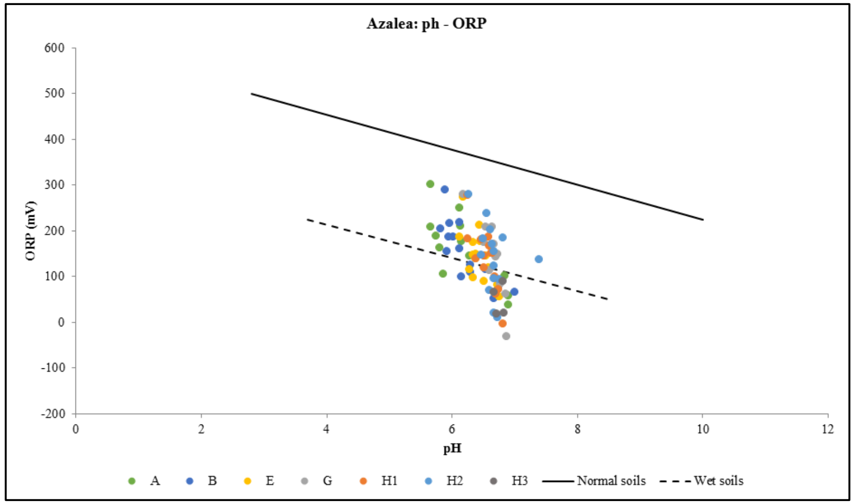

Crèche: ph - ORP
ORP (mV)
pH
A
B
C
D
E
Normal soils
Wet soils



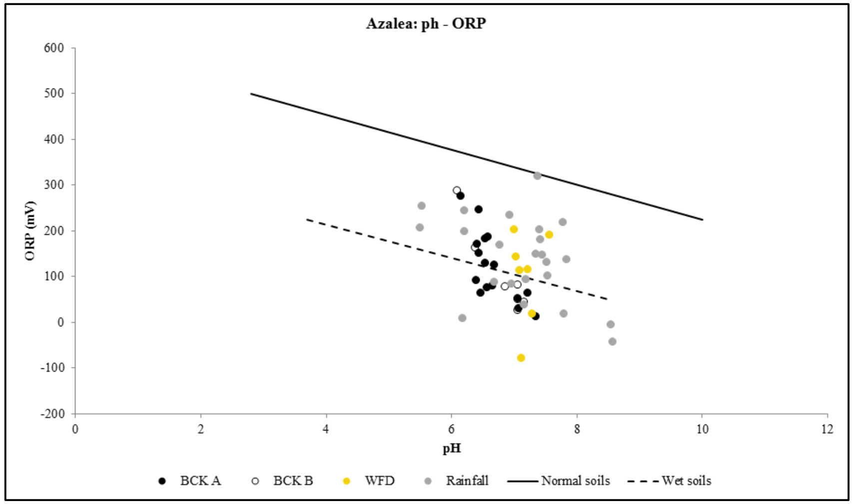
Crèche: ph - ORP
ORP (mV)
pH
G1
G2
G3
G4
G5
Normal soils
Wet soils



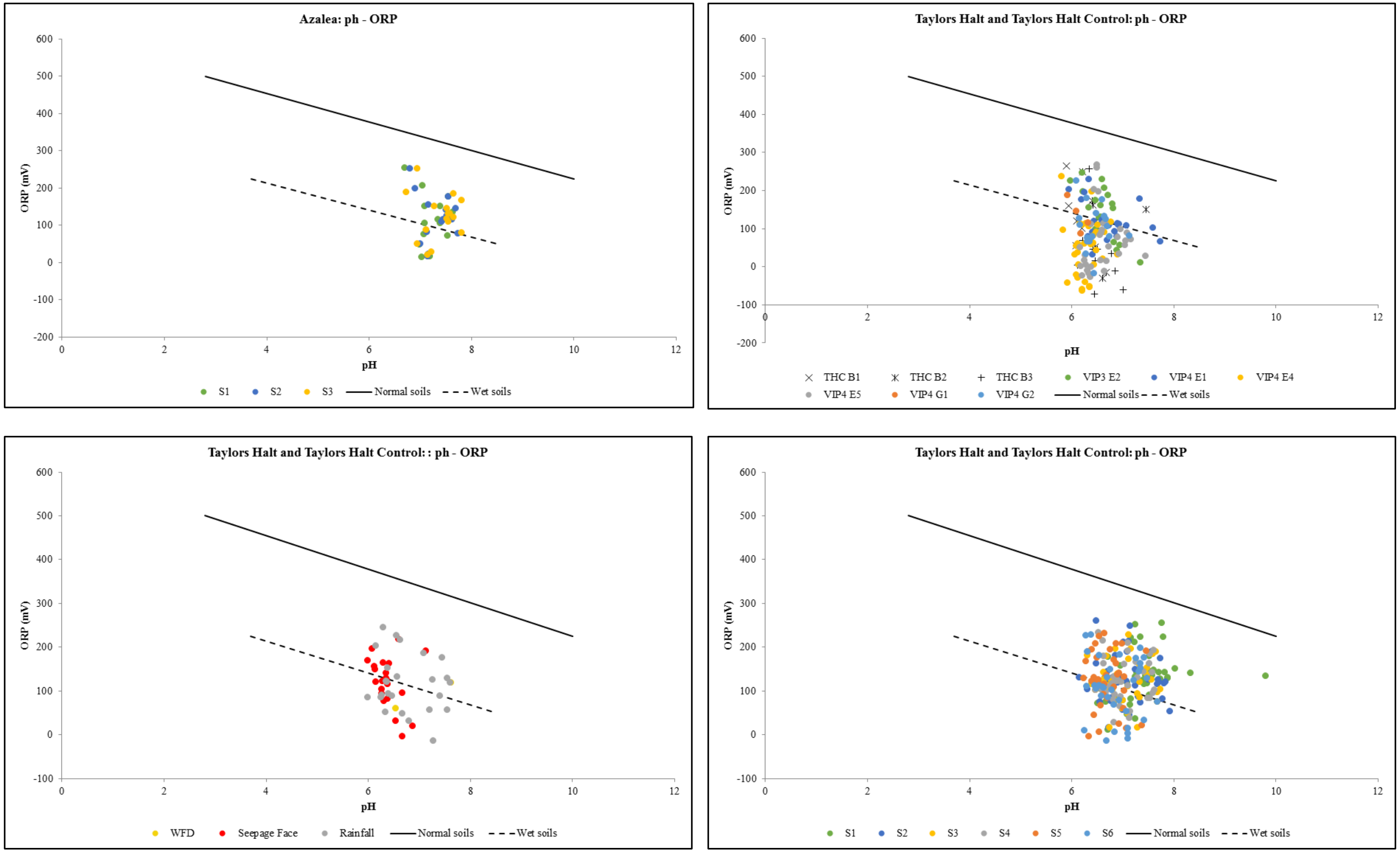
Crèche: ph - ORP
ORP (mV)
pH
BCK A
BCK B
WFD
Rainfall
Normal soils
Wet soils



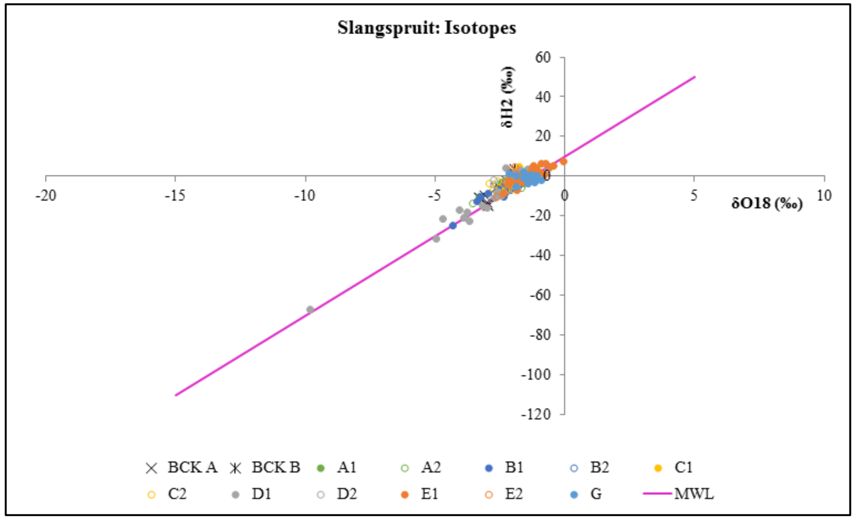
Azalea: ph - ORP
ORP (mV)
pH
A
B
E
G
H1
H2
H3
Normal soils
Wet soils

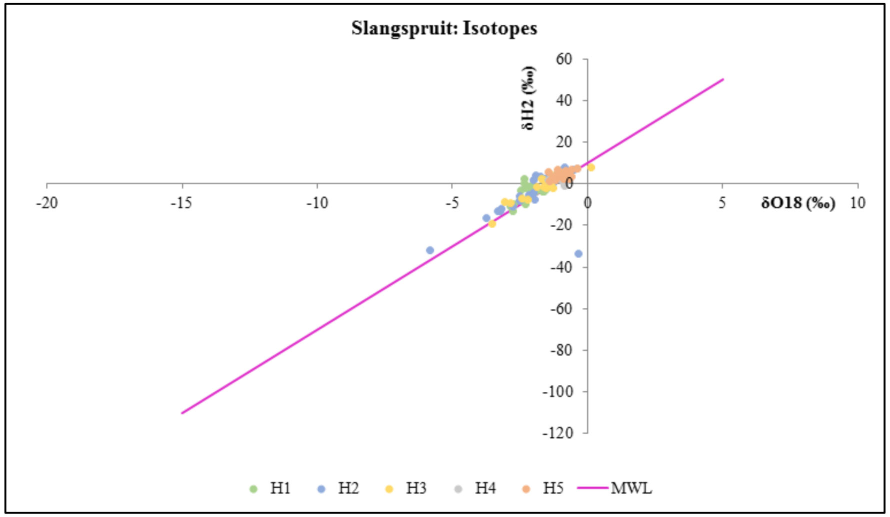


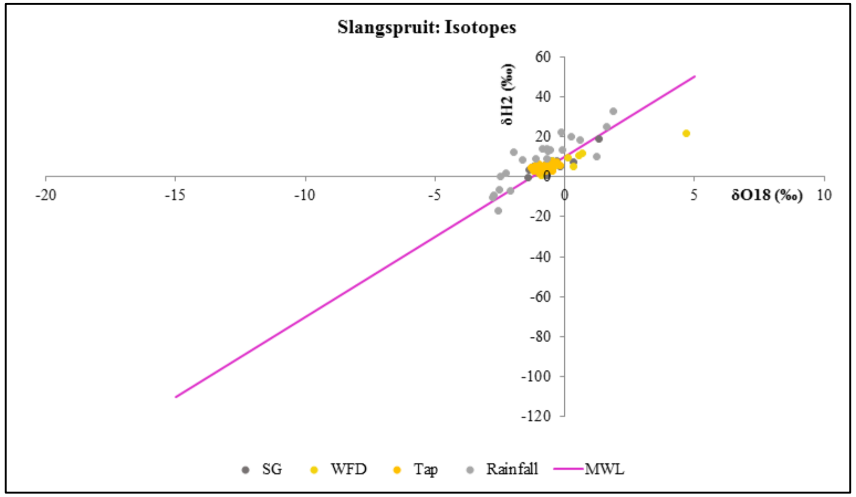
Azalea: ph - ORP
ORP (mV)
pH
BCK A
BCK B
WFD
Rainfall
Normal soils
Wet soils

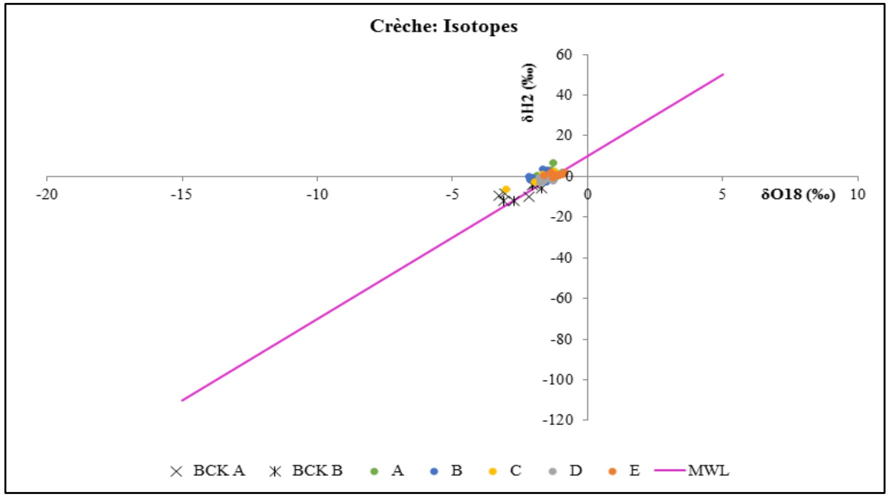


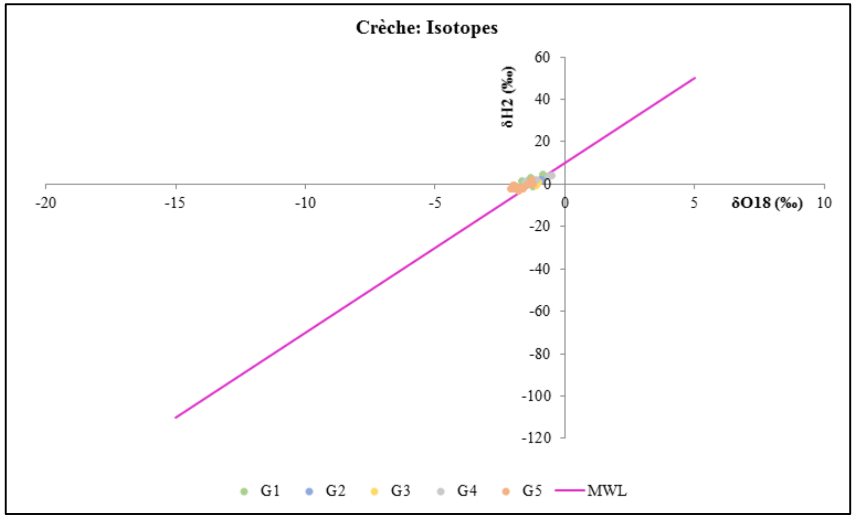
Appendix 42: pH-ORP values for the water analyses at all the study sites

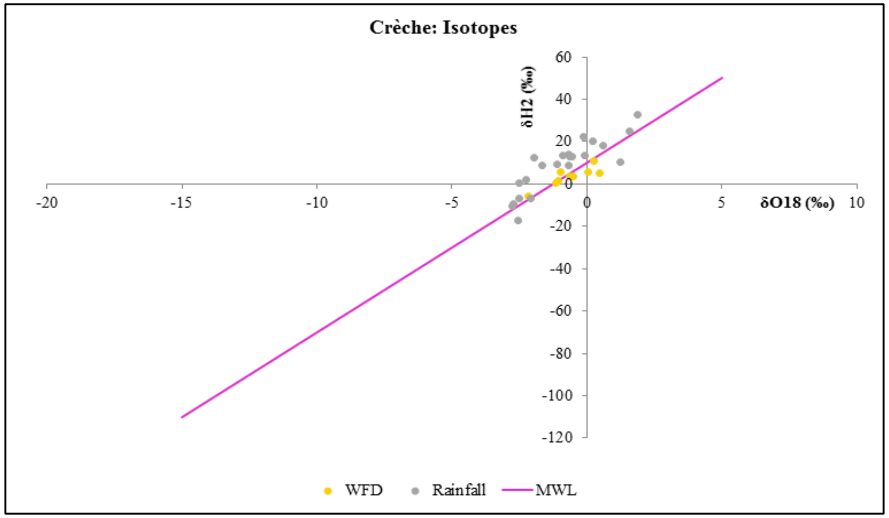

Slangspruit: Isotopes
δH2 (‰)
δO18 (‰)
60
40
20
0
-20
-40
-60
-80
-100
-120
-20
-15
-10
-5
0
5
10
BCK A
BCK B
A1
A2
B1
B2
C1
C2
D1
D2
E1
E2
G
MWL

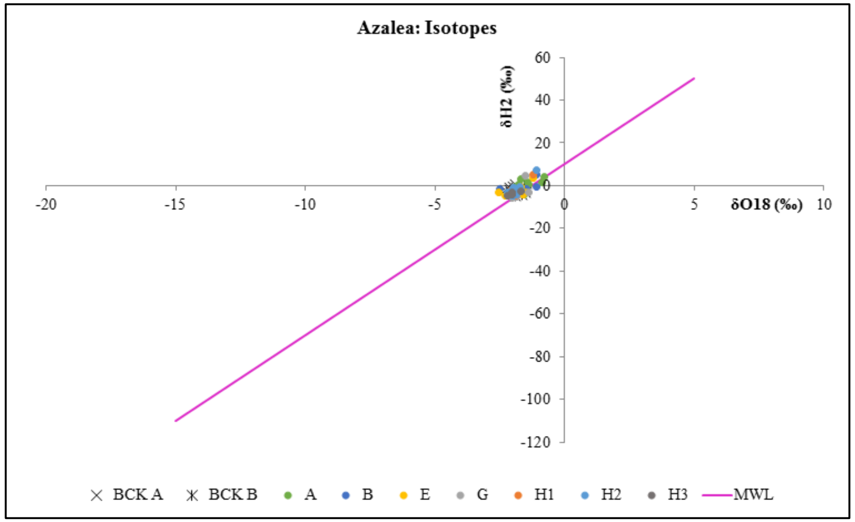

Slangspruit: Isotopes
δH2 (‰)
δO18 (‰)
60
40
20
0
-20
-40
-60
-80
-100
-120
-20
-15
-10
-5
0
5
10
H1
H2
H3
H4
H5
MWL

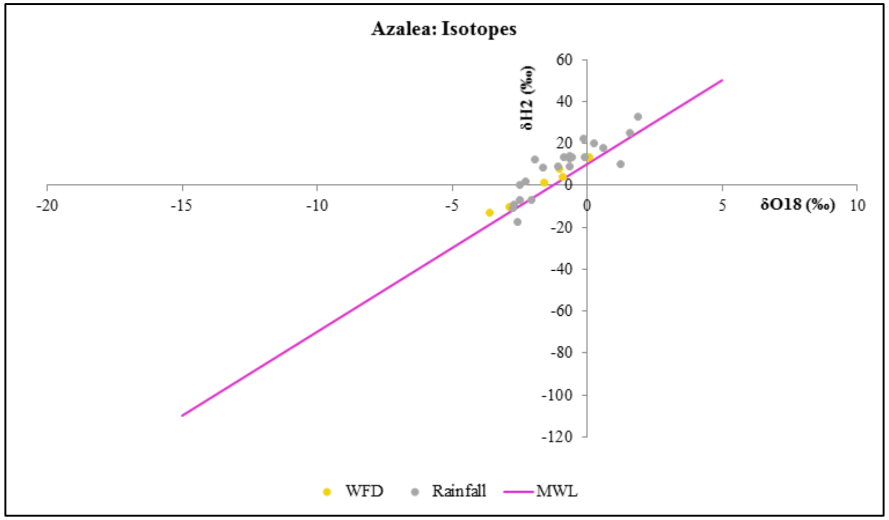

Slangspruit: Isotopes
δH2 (‰)
δO18 (‰)
60
40
20
0
-20
-40
-60
-80
-100
-120
-20
-15
-10
-5
0
5
10
SG
WFD
Tap
Rainfall
MWL

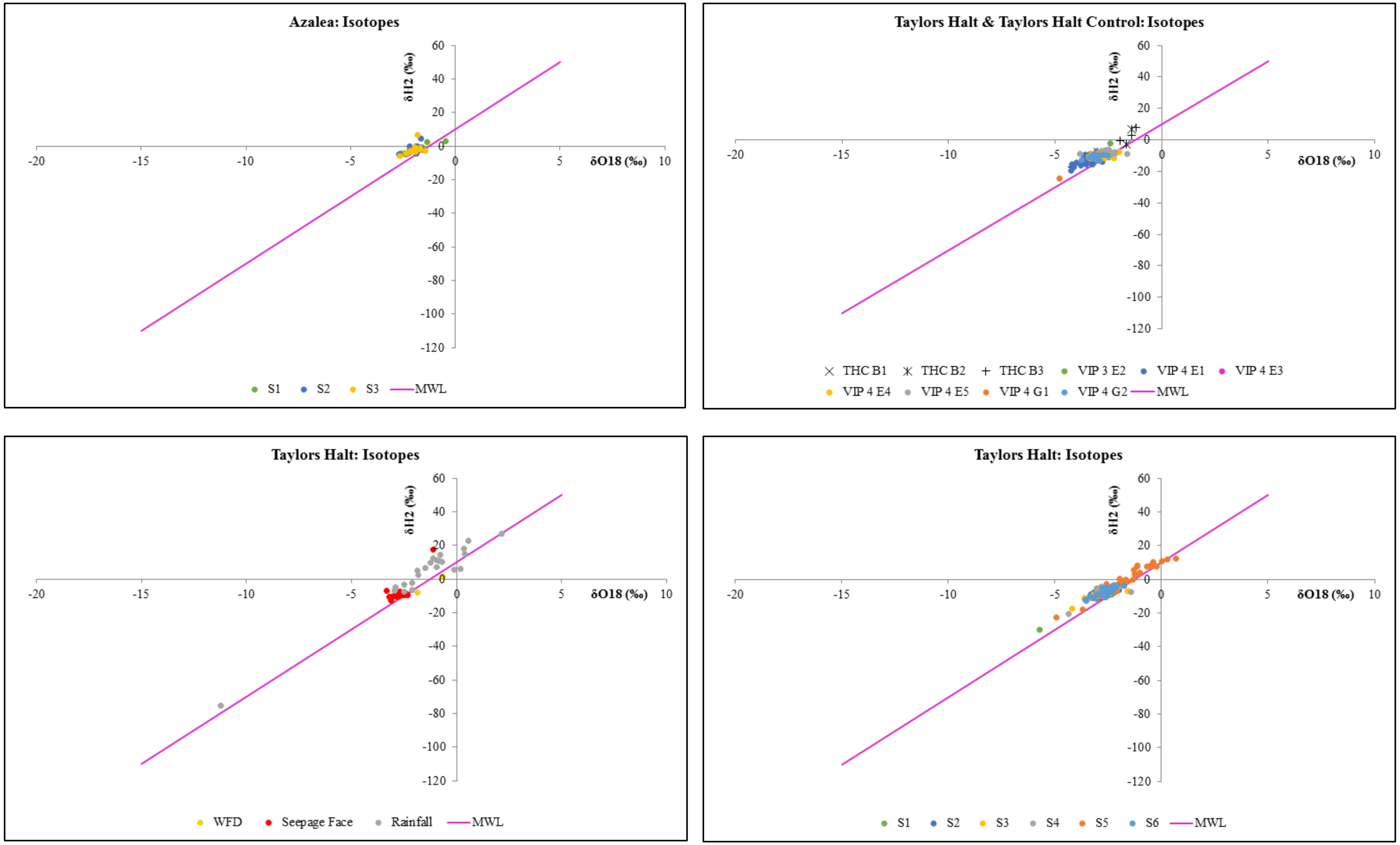

Crèche: Isotopes
δH2 (‰)
δO18 (‰)
60
40
20
0
-20
-40
-60
-80
-100
-120
-20
-15
-10
-5
0
5
10
BCK A
BCK B
A
B
C
D
E
MWL


Crèche: Isotopes
δH2 (‰)
δO18 (‰)
G1
G2
G3
G4
G5
MWL


Crèche: Isotopes
δH2 (‰)
δO18 (‰)
WFD
Rainfall
MWL


Azalea: Isotopes
δH2 (‰)
δO18 (‰)
BCK A
BCK B
A
B
E
G
H1
H2
H3
MWL


Azalea: Isotopes
δH2 (‰)
δO18 (‰)
WFD
Rainfall
MWL



Appendix 43: Isotope analyses data for all the study sites

Double ring infiltrometer

Soil Surface #1

	Time (s)	Interval (s)	Depth interval (cm)	Volume (cm^3)	Infiltration rate (cm^3/s)
1	655	655	1	75.43	0.115
2	1460	805	1	75.43	0.094
3	2395	935	1	75.43	0.081
4	3340	945	1	75.43	0.080
5	4130	790	1	75.43	0.095
6	5075	945	1	75.43	0.080
7	6132	1057	1	75.43	0.071
8	7070	938	1	75.43	0.080
9	8087	1017	1	75.43	0.074
10	9065	978	1	75.43	0.077
11	10056	991	1	75.43	0.076
12	11036	980	1	75.43	0.077
13	12051	1015	1	75.43	0.074
Inner ring diameter (cm)	9.8000			Average	0.076
a-Inner ring IR (cm)	4.9000				
Inner ring cross sectional area (cm^2)	75.4296				
Inner ring height (cm)	18.0000				

d-Depth into soil (cm)	3.0000
H-Depth of water ponding (cm)	15.0000
α*	0.0400
C_1	0.9927
C_2	0.5781
q_s-Quasi steady fall rate in resivor (cm/s)	0.0010
K_{fs} (cm/s)	0.0001
K_{fs} (cm/h)	0.4585

Double ring infiltrometer

Soil Surface #2

	Time (ss)	Interval (s)	Depth interval (cm)	Volume (cm^3)	Infiltration rate (cm^3/s)
1	589	589	1	75.43	0.128
2	1422	833	1	75.43	0.091
3	2378	956	1	75.43	0.079
4	2989	611	1	75.43	0.123
5	4002	1013	1	75.43	0.074
6	5103	1101	1	75.43	0.069
7	6199	1096	1	75.43	0.069
8	6829	630	1	75.43	0.120

9	7809	980	1	75.43	0.077
10	8811	1002	1	75.43	0.075
11	9836	1025	1	75.43	0.074
12	10845	1009	1	75.43	0.075
13	11867	1022	1	75.43	0.074
Inner ring diameter (cm)	9.8000			Average	0.075
a-Inner ring IR (cm)	4.9000				
Inner ring cross sectional area (cm^2)	75.4296				
Inner ring height (cm)	18.0000				
d-Depth into soil (cm)	3.0000				
H-Depth of water ponding (cm)	15.0000				
α^*	0.0400				
C_1	0.9927				
C_2	0.5781				
q_s-Quasi steady fall rate in resivor (cm/s)	0.0010				
K_{fs} (cm/s)	0.0001				
K_{fs} (cm/h)	0.4533				
Average Ksat (cm/h) at soil surface					0.45590815 5

Appendix 44: K_{sat} data at soil surface for Slangspruit

Double ring infiltrometer

50 cm below the soil surface #1

No water movement in 5 hours

Double ring infiltrometer

50 cm below the soil surface #2

water moved 1.2 cm in 5 hours

Average Ksat (cm/h) at 0.5 m 0.24

Appendix 45: K_{sat} data at 0.5 m for Slangspruit

Guelph permeameter

Height 1: 130 cm below soil surface

Water resivor depths (cm)	Time (seconds)	Interval (seconds)	Depth interval (cm)	Volume (cm^3)	Infiltration rate (cm^3/s)
1	443	443	1	16.619	0.038
2	820	377	1	16.619	0.044
3	1108	288	1	16.619	0.058
4	1422	314	1	16.619	0.053
5	1734	312	1	16.619	0.053
6	1984	250	1	16.619	0.066
7	2272	288	1	16.619	0.058

8	2582	310	1	16.619	0.054
9	2886	304	1	16.619	0.055
10	3197	311	1	16.619	0.053
11	3481	284	1	16.619	0.059
12	3753	272	1	16.619	0.061
13	4067	314	1	16.619	0.053
14	4336	269	1	16.619	0.062
15	4643	307	1	16.619	0.054
Resivoir ID (cm)	4.6			Average	0.058
Guelph permeameter resivoir radius (cm)	2.3				
A = cross sectional area of the Guelph permeameter (cm^2)	16.62				
Height of air entry pipe inlet (cm)	2				
Auger hole depth (cm)	130				
a = the radius of the well (cm)	4.25				
d-Depth of guelph permeameter (cm)	125				
H = steady depth of water in the well (i.e. set by the height of the air tube) (cm)	7				
α*	0.04				
R = steady state rate of fall of water in the Guelph permeameter reservoir ($cm.s^{-1}$)	0.00347				
C = dimensionless shape factor	0.865				
K_{fs}-Single head (cm/s)	0.00003				

K_{fs}-Single head (cm/h) 0.12336

Guelph permeameter

Height 2: 130 cm below soil surface

Water resivor depths (cm)	Time (seconds)	Interval (seconds)	Depth interval (cm)	Volume (cm^3)	Infiltration rate (cm^3/s)
1	5001	358	1	16.619	0.046
2	5938	937	1	16.619	0.018
3	6252	314	1	16.619	0.053
4	6540	288	1	16.619	0.058
5	7035	495	1	16.619	0.034
6	7588	553	1	16.619	0.030
7	8070	482	1	16.619	0.034
8	8555	485	1	16.619	0.034
9	8920	365	1	16.619	0.046
10	9281	361	1	16.619	0.046
11	9644	363	1	16.619	0.046
12	10012	368	1	16.619	0.045
13	10383	371	1	16.619	0.045
14	10683	300	1	16.619	0.055
15	11044	361	1	16.619	0.046

Resivoir ID (cm)	4.6	Average	0.047
Guelph permeameter resivoir radius (cm)	2.3		
A = cross sectional area of the Guelph permeameter (cm^2)	16.62		
Height of air entry pipe inlet (cm)	2		
Auger hole depth (cm)	130		
a = the radius of the well (cm)	4.25		
d-Depth of guelph permeameter (cm)	120		
H = steady depth of water in the well (i.e. set by the height of the air tube) (cm)	12		
α*	0.04		
R = steady state rate of fall of water in the Guelph permeameter reservoir ($cm.s^{-1}$)	0.00285		
C = dimensionless shape factor	1.161		
K_{fs}-Single head (cm/s)	0.00002		
K_{fs}-Single head (cm/h)	0.06940		
Average Ksat (cm/h) at 1.3 m	0.096379832		

Appendix 46: K_{sat} data at 1.3 m for Slangspruit

Double ring infiltrometer

Soil Surface #1

	Time (seconds)	Interval (seconds)	Depth interval (cm)	Volume (cm^3)	Infiltration rate (cm^3/s)
1	85	85	2	150.86	1.77

2	171	86	2	150.86	1.75
3	280	109	2	150.86	1.38
4	476	196	2	150.86	0.77
5	642	166	2	150.86	0.91
6	860	218	2	150.86	0.69
7	1080	220	2	150.86	0.69
8	1342	262	2	150.86	0.58
9	1600	258	2	150.86	0.58
10	1861	261	2	150.86	0.58
11	2185	324	2	150.86	0.47
12	2507	322	2	150.86	0.47
13	2826	319	2	150.86	0.47
14	3153	327	2	150.86	0.46
15	3482	329	2	150.86	0.46
16	3818	336	2	150.86	0.45
17	4203	385	2	150.86	0.39
18	4578	375	2	150.86	0.40
19	4960	382	2	150.86	0.39
20	5350	390	2	150.86	0.39
21	5720	370	2	150.86	0.41

22	6093	373	2	150.86	0.40
23	6467	374	2	150.86	0.40
24	6845	378	2	150.86	0.40
25	7225	380	2	150.86	0.40
Inner ring diameter (cm)	9.8			Average	0.402
a-Inner ring IR (cm)	4.9000				
Inner ring cross sectional area (cm^2)	75.4296				
Inner ring height (cm)	18.0000				
d-Depth into soil (cm)	3.0000				
H-Depth of water ponding (cm)	15.0000				
α^*	0.0400				
C_1	0.9927				
C_2	0.5781				
q_s-Quasi steady fall rate in resivor (cm/s)	0.0053				
K_{fs} (cm/s)	0.0007				
K_{fs} (cm/h)	2.4356				

Double ring infiltrometer

Soil Surface #2

	Time (seconds)	Interval (seconds)	Depth interval (cm)	Volume (cm^3)	Infiltration rate (cm^3/s)
1	67	67	2	150.86	2.25

2	145	78	2	150.86	1.93
3	298	153	2	150.86	0.99
4	455	157	2	150.86	0.96
5	621	166	2	150.86	0.91
6	798	177	2	150.86	0.85
7	1132	334	2	150.86	0.45
8	1398	266	2	150.86	0.57
9	1578	180	2	150.86	0.84
10	1889	311	2	150.86	0.49
11	2172	283	2	150.86	0.53
12	2516	344	2	150.86	0.44
13	2836	320	2	150.86	0.47
14	3102	266	2	150.86	0.57
15	3515	413	2	150.86	0.37
16	3827	312	2	150.86	0.48
17	4208	381	2	150.86	0.40
18	4596	388	2	150.86	0.39
19	4971	375	2	150.86	0.40
20	5361	390	2	150.86	0.39
21	5750	389	2	150.86	0.39

22	6149	399	2	150.86	0.38
23	6532	383	2	150.86	0.39
24	6925	393	2	150.86	0.38
25	7321	396	2	150.86	0.38
Inner ring diameter (cm)	9.8			Average	0.385

a-Inner ring IR (cm)	4.9000	
Inner ring cross sectional area (cm^2)	75.4296	
Inner ring height (cm)	18.0000	
d-Depth into soil (cm)	3.0000	
H-Depth of water ponding (cm)	15.0000	
α*		0.0400
C_1	0.9927	
C_2	0.5781	
q_s-Quasi steady fall rate in resivor (cm/s)		0.0051
K_{fs} (cm/s)		0.0006
K_{fs} (cm/h)		2.3303
Average Ksat (cm/h) at soil surface	2.382931128	

Appendix 47: K_{sat} data at soil surface for Crèche

Double ring infiltrometer

45 cm below the soil surface #1

	Time (seconds)	Interval (seconds)	Depth interval (cm)	Volume (cm^3)	Infiltration rate (cm^3/s)
1	1193	1193	1	75.43	0.063
2	10343	9150	1	75.43	0.008
3	20238	9895	1	75.43	0.008
Inner ring diameter (cm)	9.8			Average	0.008
a-Inner ring IR (cm)	4.9000				
Inner ring cross sectional area (cm^2)	75.4296				
Inner ring height (cm)	18.0000				
d-Depth into soil (cm)	3.0000				
H-Depth of water ponding (cm)	15.0000				
α*	0.0400				
C_1	0.9927				
C_2	0.5781				
q_s-Quasi steady fall rate in resivor (cm/s)	0.0001				
K_{fs} (cm/s)	0.0000				
K_{fs} (cm/h)	0.0480				

Double ring infiltrometer

35 cm below the soil surface #2

	Time (seconds)		Interval (seconds)	Depth interval (cm)	Volume (cm^3)	Infiltration rate (cm^3/s)
1	472		472	1	75.43	0.160
2	1329		1329	1	75.43	0.057
3	11263		9934	1	75.43	0.008
4	20256		8993	1	75.43	0.008
Inner ring diameter (cm)	9.8				Average	0.008
a-Inner ring IR (cm)	4.9000					
Inner ring cross sectional area (cm^2)	75.4296					
Inner ring height (cm)	18.0000					
d-Depth into soil (cm)	3.0000					
H-Depth of water ponding (cm)	15.0000					
α*		0.0400				
C_1	0.9927					
C_2	0.5781					
q_s-Quasi steady fall rate in resivor (cm/s)		0.0001				
K_{fs} (cm/s)		0.0000				
K_{fs} (cm/h)		0.0484				
Average Ksat (cm/h) at 0.35 m	0.048199357					

Appendix 48: K_{sat} data at 0.45 m for Crèche

Guelph permeameter

Height 1: 100 cm below soil surface

	Time (seconds)	Interval (seconds)	Depth interval (cm)	Volume (cm^3)	Infiltration rate (cm^3/s)
1	652	652	1	16.62	0.03
2	1045	393	1	16.62	0.04
3	1542	497	1	16.62	0.03
4	2015	473	1	16.62	0.04
5	2505	490	1	16.62	0.03
6	2968	463	1	16.62	0.04
7	3527	559	1	16.62	0.03
8	4010	483	1	16.62	0.03
9	4530	520	1	16.62	0.03
10	4985	455	1	16.62	0.04
11	5394	409	1	16.62	0.04
12	5785	391	1	16.62	0.04
13	6303	518	1	16.62	0.03
14	6707	404	1	16.62	0.04

15	7072	365	1	16.62	0.05
16	7487	415	1	16.62	0.04
17	7850	363	1	16.62	0.05
Resivoir ID (cm)	4.6			Average	0.041
Guelph permeameter resivoir radius (cm)	2.3				
A = cross sectional area of the Guelph permeameter (cm^2)	16.62				
Height of air entry pipe inlet (cm)	2				
Auger hole depth (cm)	100				
a = the radius of the well (cm)	4.25				
d-Depth of guelph permeameter (cm)	95				
H = steady depth of water in the well (i.e. set by the height of the air tube) (cm)	7				
α*	0.04				
R = steady state rate of fall of water in the Guelph permeameter reservoir ($cm.s^{-1}$)	0.00246				
C = dimensionless shape factor	0.865				
K_{fs}-Single head (cm/s)	0.00002				
K_{fs}-Single head (cm/h)	0.08749				
Guelph permeameter					

Height 2: 100 cm below soil surface

	Time (seconds)	Interval (seconds)	Depth interval (cm)	Volume (cm^3)	Infiltration rate (cm^3/s)

1	7980	130	1	16.62	0.13
2	8400	420	1	16.62	0.04
3	8760	360	1	16.62	0.05
4	9000	240	1	16.62	0.07
5	9300	300	1	16.62	0.06
6	9540	240	1	16.62	0.07
7	10380	840	1	16.62	0.02
8	10860	480	1	16.62	0.03
9	11100	240	1	16.62	0.07
10	11220	120	1	16.62	0.14
11	11400	180	1	16.62	0.09
12	11700	300	1	16.62	0.06
13	11940	240	1	16.62	0.07
14	12240	300	1	16.62	0.06
15	12600	360	1	16.62	0.05
16	13140	540	1	16.62	0.03
17	13380	240	1	16.62	0.07
18	13645	265	1	16.62	0.06
19	13871	226	1	16.62	0.07
20	14074	203	1	16.62	0.08

21	14309	235	1	16.62	0.07
22	14518	209	1	16.62	0.08
23	14765	247	1	16.62	0.07
24	14978	213	1	16.62	0.08
Resivoir ID (cm)	4.6			Average	0.075
Guelph permeameter resivoir radius (cm)	2.3				
A = cross sectional area of the Guelph permeameter (cm^2)	16.62				
Height of air entry pipe inlet (cm)	2				
Auger hole depth (cm)	100				
a = the radius of the well (cm)	4.25				
d-Depth of guelph permeameter (cm)	90				
H = steady depth of water in the well (i.e. set by the height of the air tube) (cm)	12				
α*	0.04				
R = steady state rate of fall of water in the Guelph permeameter reservoir ($cm.s^{-1}$)	0.00454				
C = dimensionless shape factor	1.161				
K_{fs}-Single head (cm/s)	0.00003				
K_{fs}-Single head (cm/h)	0.11043				
Average Ksat (cm/h) at 1m	0.098961621				

Appendix 49: K_{sat} data at 1 m for Crèche

Double ring infiltrometer

Soil Surface #1

	Time (seconds)	Interval (seconds)	Depth interval (cm)	Volume (cm^3)	Infiltration rate (cm^3/s)
1	246	246	2	150.86	0.61
2	543	297	2	150.86	0.51
3	912	369	2	150.86	0.41
4	1374	462	2	150.86	0.33
5	1794	420	2	150.86	0.36
6	2229	435	2	150.86	0.35
7	2663	434	2	150.86	0.35
8	3146	483	2	150.86	0.31
9	3656	510	2	150.86	0.30
10	4186	530	2	150.86	0.28
11	4670	484	2	150.86	0.31
12	5214	544	2	150.86	0.28
13	5750	536	2	150.86	0.28
14	6340	590	2	150.86	0.26
15	6961	621	2	150.86	0.24
16	7503	542	2	150.86	0.28
17	8043	540	2	150.86	0.28

18	8605	562	2	150.86	0.27
19	9175	570	2	150.86	0.26
20	9751	576	2	150.86	0.26
Inner ring diameter (cm)	9.8			Average	0.271
a-Inner ring IR (cm)	4.9000				
Inner ring cross sectional area (cm^2)	75.4296				
Inner ring height (cm)	18.0000				
d-Depth into soil (cm)	3.0000				
H-Depth of water ponding (cm)	15.0000				
α*	0.0400				
C_1	0.9927				
C_2	0.5781				
q_s-Quasi steady fall rate in resivor (cm/s)	0.0036				
K_{fs} (cm/s)	0.0005				
K_{fs} (cm/h)	1.6378				

Double ring infiltrometer

Soil Surface #2

	Time (seconds)	Interval (seconds)	Depth interval (cm)	Volume (cm^3)	Infiltration rate (cm^3/s)
1	312	312	2	150.86	0.48
2	462	150	2	150.86	1.01
3	889	427	2	150.86	0.35
4	1279	390	2	150.86	0.39
5	1599	320	2	150.86	0.47
6	2172	573	2	150.86	0.26
7	2624	452	2	150.86	0.33
8	3132	508	2	150.86	0.30
9	3602	470	2	150.86	0.32
10	4098	496	2	150.86	0.30
11	4642	544	2	150.86	0.28
12	5178	536	2	150.86	0.28
13	5702	524	2	150.86	0.29
14	6368	666	2	150.86	0.23
15	6929	561	2	150.86	0.27
16	7483	554	2	150.86	0.27
17	8014	531	2	150.86	0.28
18	8557	543	2	150.86	0.28
19	9104	547	2	150.86	0.28

	20		9677	573	2	150.86	0.26
Inner ring diameter (cm)		9.8			Average		0.275
a-Inner ring IR (cm)		4.9000					
Inner ring cross sectional area (cm^2)		75.4296					
Inner ring height (cm)		18.0000					
d-Depth into soil (cm)		3.0000					
H-Depth of water ponding (cm)		15.0000					
α*			0.0400				
C_1		0.9927					
C_2		0.5781					
q_s-Quasi steady fall rate in resivor (cm/s)			0.0036				
K_{fs} (cm/s)			0.0005				
K_{fs} (cm/h)			1.6628				
Average Ksat (cm/h) at soil surface	1.65028111						

Appendix 50: K_{sat} data at soil surface for Azalea

Double ring infiltrometer

50 cm below the soil surface #1

	Time (seconds)	Interval (seconds)	Depth interval (cm)	Volume (cm^3)	Infiltration rate (cm^3/s)

1	242	242	1	75.43	0.311692726
2	496	254	1	75.43	0.296967085
3	848	352	1	75.43	0.214288749
4	1334	486	1	75.43	0.15520502
5	1874	540	1	75.43	0.139684518
6	2490	616	1	75.43	0.122450714
7	3481	991	1	75.43	0.076114672
8	4531	1050	1	75.43	0.071837752
9	5857	1326	1	75.43	0.056885098
10	7350	1493	1	75.43	0.050522197
11	8829	1479	1	75.43	0.051000432
12	9831	1002	1	75.43	0.075279081
13	10701	870	1	75.43	0.086700735
14	11531	830	1	75.43	0.090879084
15	12349	818	1	75.43	0.092212273
16	13196	847	1	75.43	0.089055064
17	14008	812	1	75.43	0.092893645
18	15214	1206	1	75.43	0.062545306
19	16800	1586	1	75.43	0.047559672
20	17952	1152	1	75.43	0.065477118

Inner ring diameter (cm)	9.8	Average	0.072
a-Inner ring IR (cm)	4.9000		
Inner ring cross sectional area (cm^2)	75.4296		
Inner ring height (cm)	18.0000		
d-Depth into soil (cm)	3.0000		
H-Depth of water ponding (cm)	15.0000		
α*	0.0400		
C_1	0.9927		
C_2	0.5781		
q_s-Quasi steady fall rate in resivor (cm/s)	0.0009		
K_{fs} (cm/s)	0.0001		
K_{fs} (cm/h)	0.4329		

Double ring infiltrometer

50 cm below the soil surface #2

	Time (seconds)	Interval (seconds)	Depth interval (cm)	Volume (cm^3)	Infiltration rate (cm^3/s)
1	347	347	1	75.43	0.217376483
2	603	256	1	75.43	0.29464703
3	934	331	1	75.43	0.227884108
4	1403	469	1	75.43	0.160830788
5	1953	550	1	75.43	0.137144799

6	2612	659	1	75.43	0.114460758
7	3602	990	1	75.43	0.076191555
8	4696	1094	1	75.43	0.068948482
9	5978	1282	1	75.43	0.058837472
10	7238	1260	1	75.43	0.059864793
11	8425	1187	1	75.43	0.063546453
12	9417	992	1	75.43	0.076037943
13	10363	946	1	75.43	0.079735348
14	11332	969	1	75.43	0.077842765
15	12306	974	1	75.43	0.077443162
16	13245	939	1	75.43	0.080329755
17	14201	956	1	75.43	0.078901297
				Average	0.079

Inner ring diameter (cm)	9.8
a-Inner ring IR (cm)	4.9000
Inner ring cross sectional area (cm^2)	75.4296
Inner ring height (cm)	18.0000
d-Depth into soil (cm)	3.0000
H-Depth of water ponding (cm)	15.0000
α^*	0.0400
C_1	0.9927

C_2	0.5781
q_s-Quasi steady fall rate in resivor (cm/s)	0.0010
K_{fs} (cm/s)	0.0001
K_{fs} (cm/h)	0.4773
Average Ksat (cm/h) at soil surface	0.455114261

Appendix 51: K_{sat} data at 0.5 m for Azalea

Guelph permeameter

Height 1: 150 cm below soil surface

	Time (seconds)	Interval (seconds)	Depth interval (cm)	Volume (cm^3)	Infiltration rate (cm^3/s)
1	1824	1824	1	16.62	0.01
2	1847	23	1	16.62	0.72
3	1867	20	1	16.62	0.83
4	1888	21	1	16.62	0.79
5	1904	16	1	16.62	1.04
6	1930	26	1	16.62	0.64
7	1948	18	1	16.62	0.92
8	1969	21	1	16.62	0.79
9	1993	24	1	16.62	0.69

10	2015	22	1	16.62	0.76
11	2296	281	1	16.62	0.06
12	2450	154	1	16.62	0.11
13	2776	326	1	16.62	0.05
14	3331	555	1	16.62	0.03
15	4015	684	1	16.62	0.02
16	4745	730	1	16.62	0.02
17	5390	645	1	16.62	0.03
18	5910	520	1	16.62	0.03
19	6849	939	1	16.62	0.02
20	9107	2258	1	16.62	0.01
21	9415	308	1	16.62	0.05
22	9540	125	1	16.62	0.13
23	9685	145	1	16.62	0.11
24	9820	135	1	16.62	0.12
25	9946	126	1	16.62	0.13
26	10073	127	1	16.62	0.13
27	10203	130	1	16.62	0.13
28	10332	129	1	16.62	0.13
29	10455	123	1	16.62	0.14

30	10594	139	1	16.62	0.12
31	10722	128	1	16.62	0.13
32	10800	78	1	16.62	0.21
33	10851	51	1	16.62	0.33
34	10937	86	1	16.62	0.19
35	11006	69	1	16.62	0.24
36	11083	77	1	16.62	0.22
37	11168	85	1	16.62	0.20
38	11249	81	1	16.62	0.21
39	11323	74	1	16.62	0.22
40	11404	81	1	16.62	0.21
41	11476	72	1	16.62	0.23
Resivoir ID (cm)	4.6			Average	0.21
Guelph permeameter resivoir radius (cm)	2.3				
A = cross sectional area of the Guelph permeameter (cm^2)	16.62				
Height of air entry pipe inlet (cm)	2				
Auger hole depth (cm)	150				
a = the radius of the well (cm)	4.25				
d-Depth of guelph permeameter (cm)	145				
H = steady depth of water in the well (i.e. set by the height of the air tube) (cm)	7				

α*	0.04
R = steady state rate of fall of water in the Guelph permeameter reservoir ($cm.s^{-1}$)	0.01277
C = dimensionless shape factor	0.865
K_{fs}-Single head (cm/s)	0.00013
K_{fs}-Single head (cm/h)	0.45386

Guelph permeameter

Height 2: 150 cm below soil surface

	Time (seconds)	Interval (seconds)	Depth interval (cm)	Volume (cm^3)	Infiltration rate (cm^3/s)
1	12388	77	1	16.62	0.22
2	12480	92	1	16.62	0.18
3	12548	68	1	16.62	0.24
4	12616	68	1	16.62	0.24
5	12683	67	1	16.62	0.25
6	12773	90	1	16.62	0.18
7	12863	90	1	16.62	0.18
8	12925	62	1	16.62	0.27
9	13017	92	1	16.62	0.18
10	13080	63	1	16.62	0.26
11	13172	92	1	16.62	0.18

12	13241	69	1	16.62	0.24
13	13315	74	1	16.62	0.22
14	13377	62	1	16.62	0.27
15	13449	72	1	16.62	0.23
16	13517	68	1	16.62	0.24
17	13593	76	1	16.62	0.22
18	13654	61	1	16.62	0.27
Resivoir ID (cm)	4.6			Average	0.25
Guelph permeameter resivoir radius (cm)	2.3				
A = cross sectional area of the Guelph permeameter (cm^2)	16.62				
Height of air entry pipe inlet (cm)	2				
Auger hole depth (cm)	150				
a = the radius of the well (cm)	4.25				
d-Depth of guelph permeameter (cm)	140				
H = steady depth of water in the well (i.e. set by the height of the air tube) (cm)	12				
α*	0.04				
R = steady state rate of fall of water in the Guelph permeameter reservoir ($cm.s^{-1}$)	0.01486				
C = dimensionless shape factor	1.161				
K_{fs}-Single head (cm/s)	0.00010				
K_{fs}-Single head (cm/h)	0.36119				

Average Ksat (cm/h) at soil surface	0.407524276

Appendix 52: K_{sat} data at 1.5 m for Azalea

Double ring infiltrometer

At VIP 2, Soil Surface #1

	Time (seconds)	Interval (seconds)	Depth interval (cm)	Volume (cm^3)	Infiltration rate (cm^3/s)
1	68.64	68.64	1	75.43	1.10
2	506.13	437.49	1	75.43	0.17
3	1221.64	715.50	1	75.43	0.11
4	1681.25	459.62	1	75.43	0.16
5	3232.09	1550.83	1	75.43	0.05
6	3999.32	767.23	1	75.43	0.10
7	4768.70	769.38	1	75.43	0.10
8	5224.29	455.60	1	75.43	0.17
9	6073.63	849.34	1	75.43	0.09
10	6675.06	601.43	1	75.43	0.13
11	7158.81	483.76	1	75.43	0.16
12	7606.06	447.25	1	75.43	0.17
13	8306.05	699.99	1	75.43	0.11
14	8773.72	467.66	1	75.43	0.16

Inner ring diameterfor red ring (cm)	9.8	Average	0.144
a-Inner ring IR (cm)	4.9000		
Inner ring cross sectional area (cm^2)	75.4296		
Inner ring height (cm)	18.0000		
d-Depth into soil (cm)	3.0000		
H-Depth of water ponding (cm)	15.0000		
α^*	0.0400		
C_1	0.9927		
C_2	0.5781		
q_s-Quasi steady fall rate in resivor (cm/s)	0.0019		
K_{fs} (cm/s)	0.0002		
K_{fs} (cm/h)	0.8706		

Double ring infiltrometer

At VIP 4, Soil Surface #2

	Time (seconds)	Interval (seconds)	Depth interval (cm)	Volume (cm^3)	Infiltration rate (cm^3/s)
1	628	628	2	150.86	0.24
2	1752	1124	2	150.86	0.13
3	2789	1037	2	150.86	0.15
4	4303	1514	2	150.86	0.10

	5	5703	1400	2	150.86	0.11
	6	7034	1331	2	150.86	0.11
	7	8389	1355	2	150.86	0.11
	8	9723	1334	2	150.86	0.11
	9	11043	1320	2	150.86	0.11
Inner ring diameter (cm)	9.8			Average		0.112

a-Inner ring IR (cm)	4.9000	
Inner ring cross sectional area (cm^2)	75.4296	
Inner ring height (cm)	18.0000	
d-Depth into soil (cm)	3.0000	
H-Depth of water ponding (cm)	15.0000	
α^*		0.0400
C_1	0.9927	
C_2	0.5781	
q_s-Quasi steady fall rate in resivor (cm/s)		0.0015
K_{fs} (cm/s)		0.0002
K_{fs} (cm/h)		0.6778

Double ring infiltrometer

Near stream, Soil Surface #3

	Time (seconds)	Interval (seconds)	Depth interval (cm)	Volume (cm^3)	Infiltration rate (cm^3/s)
1	489	489	2	150.86	0.31
2	1146	657	2	150.86	0.23
3	2043	897	2	150.86	0.17
4	3031	988	2	150.86	0.15
5	4117	1086	2	150.86	0.14
6	5226	1109	2	150.86	0.14
7	6347	1121	2	150.86	0.13
8	7436	1089	2	150.86	0.14
9	8565	1129	2	150.86	0.13
				Average	0.136

Inner ring diameter (cm)	9.8	
a-Inner ring IR (cm)	4.9000	
Inner ring cross sectional area (cm^2)	75.4296	
Inner ring height (cm)	18.0000	
d-Depth into soil (cm)	3.0000	
H-Depth of water ponding (cm)	15.0000	
α*		0.0400
C_1	0.9927	
C_2	0.5781	
q_s-Quasi steady fall rate in resivor (cm/s)		0.0018

K_{fs} (cm/s)	0.0002
K_{fs} (cm/h)	0.8253

Appendix 53: K_{sat} data at soil surface for Taylors Halt

Double ring infiltrometer

At VIP 2, 50 cm below the soil surface #1

	Time (seconds)	Interval (seconds)	Depth interval (cm)	Volume (cm^3)	Infiltration rate (cm^3/s)
1	114.40	114.40	1	75.43	0.66
2	525.84	411.43	1	75.43	0.18
3	978.41	452.58	1	75.43	0.17
4	1430.99	452.58	1	75.43	0.17
5	1996.71	565.72	1	75.43	0.13
6	2449.29	452.58	1	75.43	0.17
7	2901.87	452.58	1	75.43	0.17
8	3354.45	452.58	1	75.43	0.17
Inner ring diameter (cm)	9.8			Average	0.167
a-Inner ring IR (cm)	4.9000				
Inner ring cross sectional area (cm^2)	75.4296				
Inner ring height (cm)	18.0000				
d-Depth into soil (cm)	3.0000				

H-Depth of water ponding (cm)	15.0000
α*	0.0400
C_1	0.9927
C_2	0.5781
q_s-Quasi steady fall rate in resivor (cm/s)	0.0022
K_{fs} (cm/s)	0.0003
K_{fs} (cm/h)	1.0090

Double ring infiltrometer

At VIP 4, 50 cm below the soil surface #2

	Time (seconds)	Interval (seconds)	Depth interval (cm)	Volume (cm^3)	Infiltration rate (cm^3/s)
1	765	765	1	75.43	0.098600836
2	1692	927	1	75.43	0.081369622
3	2526	834	1	75.43	0.090443213
4	3027	501	1	75.43	0.150558163
5	3581	554	1	75.43	0.136154584
6	4114	533	1	75.43	0.141519024
7	4711	597	1	75.43	0.126347805
8	5250	539	1	75.43	0.139943673
Inner ring diameter (cm)	9.8			Average	0.121

a-Inner ring IR (cm)	4.9000	
Inner ring cross sectional area (cm^2)	75.4296	
Inner ring height (cm)	18.0000	
d-Depth into soil (cm)	3.0000	
H-Depth of water ponding (cm)	15.0000	
α^*		0.0400
C_1	0.9927	
C_2	0.5781	
q_s-Quasi steady fall rate in resivor (cm/s)		0.0016
K_{fs} (cm/s)		0.0002
K_{fs} (cm/h)		0.7302

Double ring infiltrometer

Near stream, 50 cm below the soil surface #3

		Time (seconds)	Interval (seconds)	Depth interval (cm)	Volume (cm^3)	Infiltration rate (cm^3/s)
	1	1395	1395	1	75.43	0.054071426
	2	4029	2634	1	75.43	0.028636917
	3	8188	4159	1	75.43	0.018136485
	4	12609	4421	1	75.43	0.017061669
Inner ring diameter (cm)		9.8			Average	0.018

a-Inner ring IR (cm)	4.9000	
Inner ring cross sectional area (cm^2)	75.4296	
Inner ring height (cm)	18.0000	
d-Depth into soil (cm)	3.0000	
H-Depth of water ponding (cm)	15.0000	
α*		0.0400
C_1	0.9927	
C_2	0.5781	
q_s-Quasi steady fall rate in resivor (cm/s)		0.0002
K_{fs} (cm/s)		0.0000
K_{fs} (cm/h)		0.1065

Appendix 54: K_{sat} data at 0.5 m for Taylors Halt

Guelph permeameter

At VIP 2 Height 1: 150 cm below soil surface

	Time (seconds)	Interval (seconds)	Depth interval (cm)	Volume (cm^3)	Infiltration rate (cm^3/s)
1	58	58	1	16.62	0.29
2	70	12	1	16.62	1.38
3	109	39	1	16.62	0.43

4	145	36	1	16.62	0.46
5	171	26	1	16.62	0.64
6	201	30	1	16.62	0.55
7	238	37	1	16.62	0.45
8	268	30	1	16.62	0.55
9	303	35	1	16.62	0.47
10	338	35	1	16.62	0.47
11	369	31	1	16.62	0.54
12	400	31	1	16.62	0.54
13	434	34	1	16.62	0.49
14	469	35	1	16.62	0.47
15	500	31	1	16.62	0.54
16	538	38	1	16.62	0.44
17	572	34	1	16.62	0.49
18	605	33	1	16.62	0.50
Resivoir ID (cm)	4.6			Average	0.49
Guelph permeameter resivoir radius (cm)	2.3				
A = cross sectional area of the Guelph permeameter (cm^2)	16.62				
Height of air entry pipe inlet (cm)	2				
Auger hole depth (cm)	150				

a = the radius of the well (cm)	4.25
d-Depth of guelph permeameter (cm)	145
H = steady depth of water in the well (i.e. set by the height of the air tube) (cm)	7
α*	0.04
R = steady state rate of fall of water in the Guelph permeameter reservoir (cm.s^{-1})	0.02937
C = dimensionless shape factor	0.865
K_{fs}-Single head (cm/s)	0.00029
K_{fs}-Single head (cm/h)	1.04377

Guelph permeameter

At VIP 4 Height 1: 150 cm below soil surface

	Time (seconds)	Interval (seconds)	Depth interval (cm)	Volume (cm^3)	Infiltration rate (cm^3/s)
1	8	8	1	16.62	2.08
2	17	9	1	16.62	1.85
3	26	9	1	16.62	1.85
4	34	8	1	16.62	2.08
5	43	9	1	16.62	1.85
6	53	10	1	16.62	1.66
7	65	12	1	16.62	1.38
8	79	14	1	16.62	1.19

9	96	17	1	16.62	0.98
10	115	19	1	16.62	0.87
11	135	20	1	16.62	0.83
12	157	22	1	16.62	0.76
13	171	14	1	16.62	1.19
14	206	35	1	16.62	0.47
15	253	47	1	16.62	0.35
16	313	60	1	16.62	0.28
17	364	51	1	16.62	0.33
18	413	49	1	16.62	0.34
19	488	75	1	16.62	0.22
20	569	81	1	16.62	0.21
21	637	68	1	16.62	0.24
22	731	94	1	16.62	0.18
23	832	101	1	16.62	0.16
24	922	90	1	16.62	0.18
25	962	40	1	16.62	0.42
Resivoir ID (cm)	4.6			Average	0.24
Guelph permeameter resivoir radius (cm)	2.3				
A = cross sectional area of the Guelph permeameter (cm^2)	16.62				

Height of air entry pipe inlet (cm)	2
Auger hole depth (cm)	150
a = the radius of the well (cm)	4.25
d-Depth of guelph permeameter (cm)	145
H = steady depth of water in the well (i.e. set by the height of the air tube) (cm)	7
α*	0.04
R = steady state rate of fall of water in the Guelph permeameter reservoir ($cm.s^{-1}$)	0.01427
C = dimensionless shape factor	0.865
K_{fs}-Single head (cm/s)	0.00014
K_{fs}-Single head (cm/h)	0.50715

Appendix 55: K_{sat} data at 1.5 m for Taylors Halt