Investigation into Pollution from On-Site Dry Sanitation Systems

Report to the
Water Research Commission

by

Simon Lorentz[1], Bruce Wickham[1] and David Still[2]
[1] Centre for Water Resources Research, University of KwaZulu-Natal
[2] Partners In Development, (Pty) Ltd

WRC Report No. 2115/1/15
ISBN 978-1-4312-0671-1

April 2015

Obtainable from
Water Research Commission
Private Bag X03
GEZINA, 0031

EXECUTIVE SUMMARY

The impact of onsite sanitation on water resources has been the subject of much study with regard to conventional septic tanks and soak-aways. However, research of impacts from rural and peri-urban communities using pit latrines, particularly in underdeveloped countries, has been unconvincing. With the increase in the extension of sanitation services provided by the South African Government anticipated to result in the establishment of some 6 million onsite dry sanitation systems, there is a need to assess the overall health and pollution impacts of these systems. The scale of application of these systems, in concert with highly variable climatic conditions and a range of geological formations and soilscapes, warrant a scientific assessment of the pollution potential of dry sanitation systems so that they can be properly sited, designed, installed, monitored and maintained.

The objectives of this study are therefore to:

- Develop an understanding of the conditions and processes that may lead to migration of pollutants from onsite dry sanitation systems so that guidelines to minimise the impact of onsite sanitation to the water resources in South Africa may be developed;
- Identify techniques, methods and models used in evaluating groundwater pollution from onsite sanitation; and to
- Derive the necessary knowledge for input to best practice guidelines for monitoring and minimising the impacts from onsite dry sanitation.

The study comprises a comprehensive overview of current research and systematic observation of selected sites, comprising a range of geologies and sanitation types in order to derive an understanding of the effluent migration sources, pathways and mechanisms to inform the development of best practice guidelines.

State-of-the-art

Many studies have been conducted on the widespread use of pit latrines. Regrettably, no consistent methodology has been used to monitor or report the extent of nutrient or pathogen movement. Very often, the studies comprise monitoring of local boreholes down gradient of informal or peri-urban developments. Several case studies report incidences of nutrient and pathogen contamination as a result of on-site sanitation contaminating water resources. Elevated concentrations of nutrients and pathogens have been observed between 20 and 90 m from latrines. Studies also claim that observations from boreholes some 900 m downstream of developments where pit latrines are used have shown increases in pathogen abundance. Only one study warns that the rapid lateral subsurface flow from extreme events may move nutrients and pathogens from pit latrines, but no observations are evident in the literature.

Methodology

Four sites on two geologies were established in this study. A transect of four VIP latrines were monitored on a hillslope and an associated background site was coupled with this transect. Three other sites were established to monitor individual pour flush latrines.

Observations comprised sampling of water from nearby streams, subsurface water from shallow piezometers and infiltrating soil water. The piezometers were established at selected intervals downslope of the latrines as well as at background stations upslope of the latrine. Infiltrated water was monitored through wetting front detectors. In addition geophysical and hydropedological surveys were conducted at each site in order to define the flow pathways and connectivity of the hillslopes. A nearby weather station was used to record meteorological data, while local rain gauges were established at the sites. Pit latrine contents were sampled on two occasions and analysed for nutrients and pathogens. Analyses on the water samples included stable isotopes of water to aid in the definition of connectivity of flow pathways, nitrate, ammonium, phosphate and a selection of cations and anions.

Findings

1. Taylors Halt:

In the streams, nitrate rarely exceeds 10 mg/l, with occasional values over 20 mg/l during extreme rainfall events. Near surface piezometers also exhibit low nutrient concentrations, again, except for at the toe of the hillslope after heavy rains, concentrations reached between 17 mg/l and 91 mg/l. *E. coli* counts ranged from 1-18600 MPN/100 ml in the piezometers. High values were again associated with toe slope stations after heavy rains.

2. Slangspruit:

Concentrations of nitrate nearest to the pour-flush ranged between 1 mg/l to 1656 mg/l, however it is unlikely that nitrate contamination will occur at distances further than 3 m, at this site, except during periods of high rainfall. However, faecal coliforms may exceed 26 m at all times.

3. Crèche:

Piezometers exhibit a rapid nitrate response in relation to rainfall. Nitrate concentrations were highest at 0.5 m from the leach pit (661 mg/l), which occurred after periods of high rainfall. Similarly, *E. coli* counts were higher at piezometers close to the leach pit, ranging from 86-7710 MPN/100 ml. The piezometers further from the sump seldom exceed 400 MPN/100 ml. Background piezometers, however, exhibited consistently high *E. coli* counts, ranging from 2092-2599 MPN/100 ml. This however may be due to the recent construction of an unimproved pit latrine located some 2.5 m away from these piezometers. At this site it is unlikely that contaminants will exceed 3 m, except in periods of significant rainfall, where contaminants are mobilised.

4. *Azalea:*

It is unlikely that nitrate and faecal coliform contamination will occur at distances further than 3 m, except during periods of high rainfall, where the nitrate my travel up to 17.5 m downslope of the leach pit. In the streams, nitrate does not exceed 12 mg/l. Piezometers adjacent to the stream on the low lying segment of the slope seldom record high values of nitrate and *E. coli* during the wet season.

Conclusions and Recommendations

In comparison to previous studies, nitrate movement does not appear to be as significant at the KwaZulu-Natal study sites compared to other studies. However they are consistent with each other in terms of greatest mobility during periods of high rainfall. The same can be said for the mobility of *E. coli*. However at the Slangspruit site, a distinct *E. coli* plume extended to 26 m, whereas the nitrate was only evident up to 3 m. At this site where the water table was consistently high (i.e. <1 m) it is suggested that in these circumstances, faecal coliform pose a risk of contaminating adjacent water resources.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

The increase in the extension of sanitation services provided by the South African Government will eventually result in the establishment of some 6 million onsite dry sanitation systems. However, there remain questions about the overall health and pollution impacts of these systems. The scale of application of these systems, in concert with highly variable climatic conditions and a range of geological formations and soilscapes, warrant a scientific assessment of the pollution potential of dry sanitation systems so that they can be properly sited, designed, installed, monitored and maintained.

The objectives of this study are therefore to:

- Develop an understanding of the conditions and processes that may lead to migration of pollutants from onsite dry sanitation systems. To develop guidelines to minimise the impact of onsite sanitation to the water resources in South Africa;
- Identify techniques, methods and models sued in evaluating groundwater pollution;
- Derive best practice guidelines for monitoring and minimising the impacts from onsite dry sanitation;
- Observe selected sites comprising a range of geologies and sanitation types in coastal and midland conditions to derive an understanding of the effluent migration and to provide test cases for the guidelines

2. STATE-OF-THE-ART REVIEW

2.1. On-site Dry Sanitation

On-site dry sanitation is an effective process for disposing human waste (faeces and urine) in-situ without relying on water to function; these systems are otherwise termed as Waterless toilets (Franceys et al., 1992). Typically these systems comprise a pit excavated in the ground, where the sides are lined from top to bottom, with a toilet pedestal on a concrete slab covering the hole. There are several examples of these waterless toilet systems; Figures 2.1, 2.2, and 2.3 (DWAF, 2002a) show examples on-site waterless toilet systems viz. Ventilated Improved Pit (VIP) toilet, Ventilated Improved Double Pit (VIDP) toilet and Composting/Urine Division (UD) toilet respectively, while Figure 2.4 shows the pour flush system.

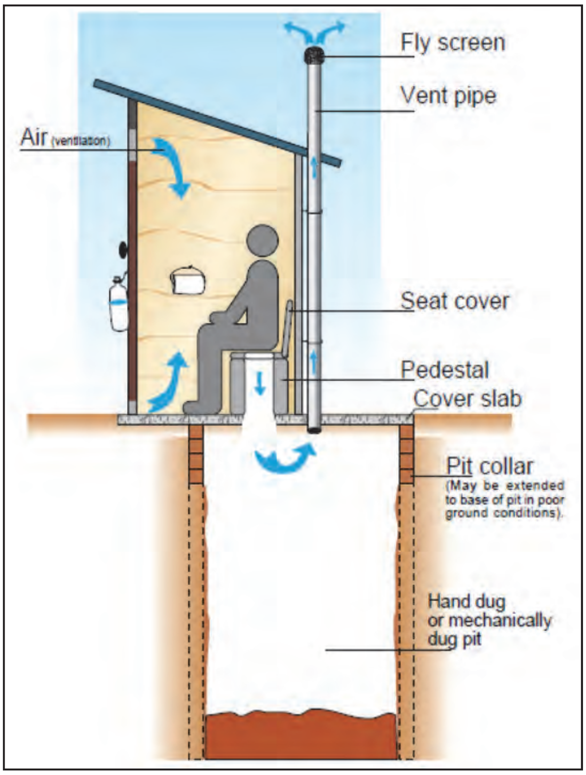


Figure 2.1 Typical structure for a VIP toilet system (DWAF, 2002a)

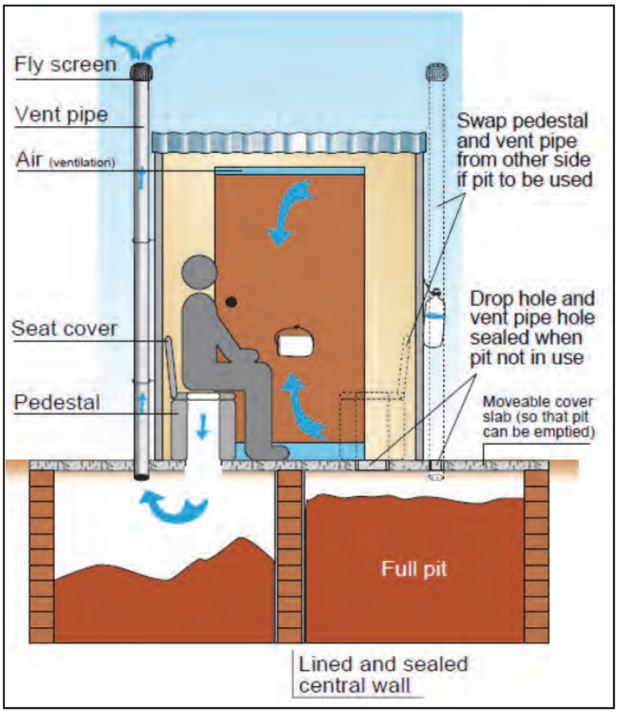


Figure 2.2 VIDP toilet system (DWAF, 2002a)

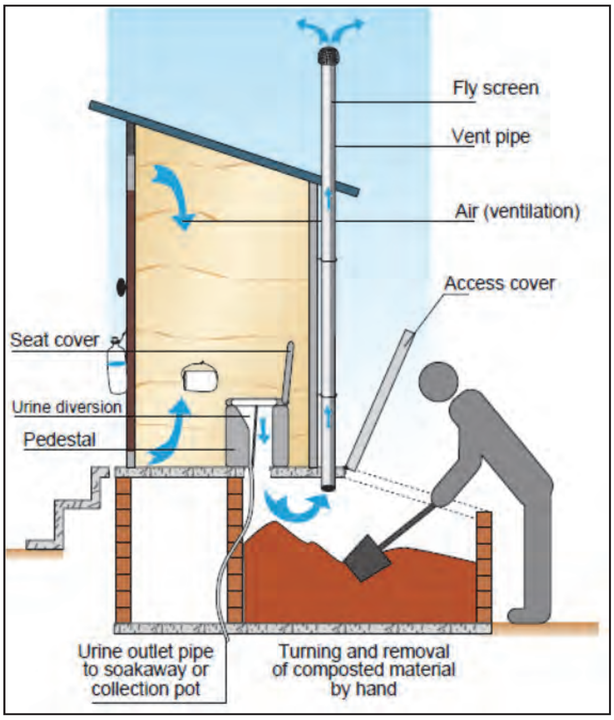


Figure 2.3 Composting/UD toilet system (DWAF, 2002a)

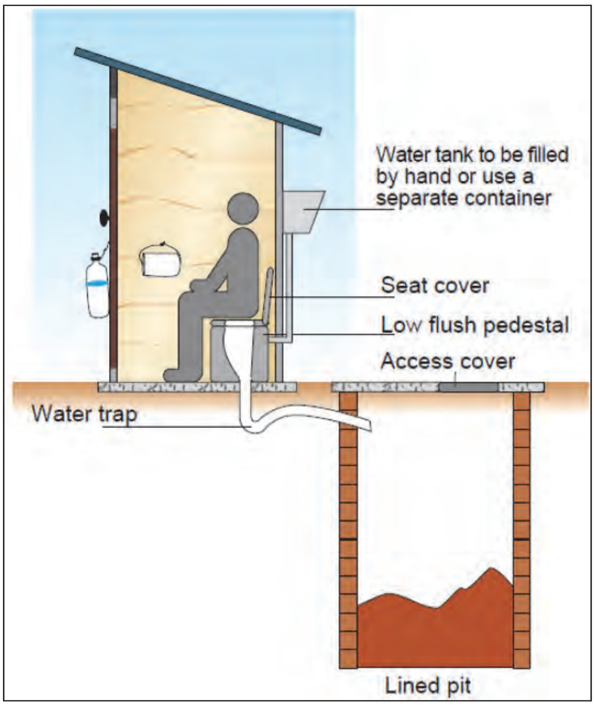


Figure 2.4 Pour-flush toilet system (DWAF, 2002a)

For a simplified summary, describing the principal behind the systems, the operational and installation requirements, and costs for each of the examples above, the reader is referred to the Sanitation Technology Options document produced by DWAF; i.e. DWAF (2002a).

One of the primary driving forces behind the development of Dry Sanitation Systems is water conservation. Given the fact that these sanitation systems do not require water to function (DWAF, 2002; Franceys et al., 1992), they represent a step towards achieving a balance between water conservancy and hygiene. This holds particular relevance to South Africa (SA), which is considered a water scarce nation; the Mean Annual Precipitation (MAP) is approximately half of the global MAP, the conversion of rainfall to run-off is low and the atmospheric evaporative demand ranges from 2 to 10 times as much as the rainfall (Schulze, 2011).

In 2007 the populace of SA was estimated at around 48.5 million and growing at an annual rate of 1.1% (Lehola, 2007). Of this, 71% live in formal dwellings of which only 88% have access to piped water (Lehola, 2007). In 2011, only 58.7% of SA households used flush toilet systems connected to a public municipal sewage network (Lehola, 2011). It is evident, therefore, that even if a situation existed where water was not limited, there would still be a vast number of people who would not be able to benefit or utilise water based sanitation systems that require piped municipal water supplies, and would thus still require other sanitation methods such VIP or VIDP systems.

One of the largest draw cards for VIP, VIDP or UD/compositing systems, is their relative ease of installation and maintenance, as well as low financial costs (Lehola, 2011; Ujang and Henze, 2006). Table 2.1 below (after DWAF, 2002a) provides an approximation of initial capital costs and operating expenses for VIP, VIDP and UD/composting onsite systems. These values will vary, depending upon the design characteristics of a system and the input from the household(s).

Table 2.1 Approximate expenses for 3 on-site dry sanitation systems (After DWAF, 2002)

Dry Sanitation System	Initial Capital costs	Operating Cost
VIP	R300-R600	R60/year
VIDP	R2500-R4500	R35-R135/ 2 years
UD/Composting	R3000-R4000	R35-500/year

2.2. Sources and Health Risk

Human excreta comprise numerous chemical (Table2.2) and pathogens (Table 2.3) species which pose a risk to human health and the natural environment. The chemical components that are the greatest concern are nitrate and phosphates. High levels of nitrate in drinking water (i.e. > 45 mg/l) are toxic to humans over a period of time. Methemaglobinemia commonly known as "blue baby syndrome" is a common result from infants consuming water with elevated levels of nitrate (Zeliger, 2011). Furthermore, Zeliger (2011) mention longer term consequences such as esophageal cancer from nitrate rich water. In addition to elevated levels of nitrate, high loads of phosphate into surface water bodies can trigger eutrophication which may impact on human health, social interaction, economic activities and the natural environment (Figure 2.5).

Table 2.2 Human waste composition (after Polprasert, 2007) * from Torondel, 2010

Compound	Faeces (% dry weight)	Urine (% weight)
Organic matter	88-97	65-85
Carbon (C)	44-55	11-17
Nitrogen (N)	5.0-7.0	15-19
Phosphorus (P_2O_5)	3.5-4.0	2.5-5.0
Potassium (K_2O)	1.0-2.5	3.0-4.5
Calcium (CaO)	4.5	4.5-6.0
Dry solids/person/day* (g)	30-70	50-70

Table 2.3 List of pathogenic pollutants found in human excreta (after Franceys et al. 1992)

Pathogen	Pathogen and illness	Present in (Faeces/Urine)
Bacteria		
Escherichia coli	diarrhoea	Both
Leptospira interrogans	leptospirosis	Urine
Salmonella typhi	typhoid	Both
Shigella spp	shigellosis	Faeces
Vibrio cholerae	cholera	Faeces
Viruses		
Poliovirus	poliomyelitis	Faeces
Rotaviruses	enteritis	Faeces
Protozoa: Amoeba or Cysts		
Entamoeba histolytica	amoebiasis	Faeces

Pathogen	Pathogen and illness	Present in (Faeces/Urine)
Giardia intestinalis	giardiasis	Faeces
Helminths – parasite eggs		
Ascaris lumbricoides	roundworm	Faeces
Fasciola hepatica	liver fluke	Faeces
Ancylostoma duodenale	hookworm	Faeces
Necator americanus	hookworm	Faeces
Schistosoma spp	schistosomiasis	Urine
Taenia spp	tapeworm	Faeces
Trichuris trichiura	whipworm	Faeces

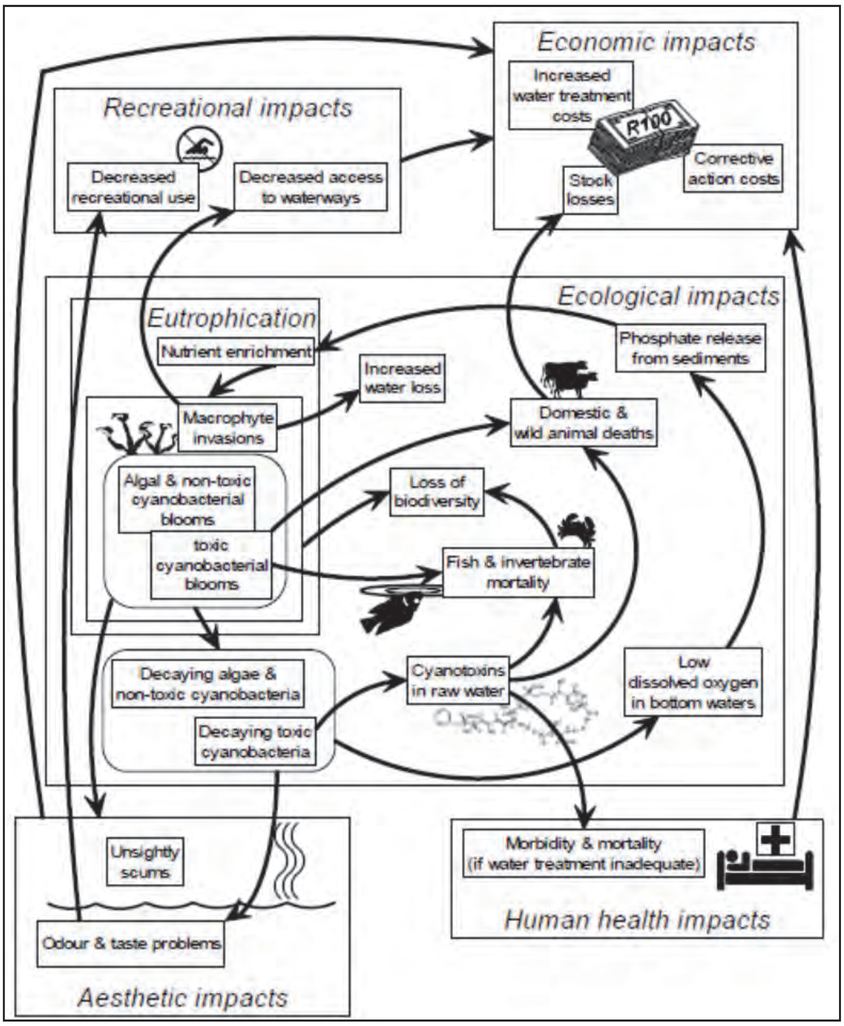


Figure 2.5 Potential impacts of eutrophication (from DWAF, 2002b)

2.3. Movement of Nutrients and Pathogens from On-Site Latrine

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 2.6). In this example, the leach pit is resting in 2.00 m or more of unsaturated sand or loam soil above the water table.

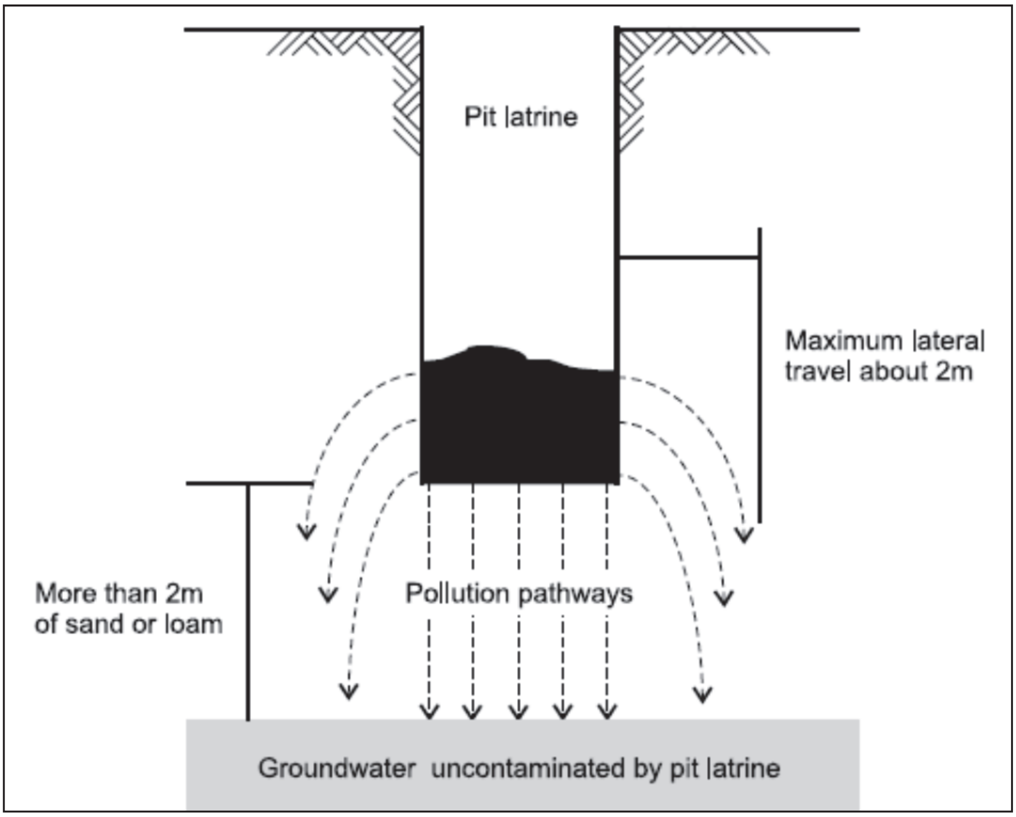


Figure 2.6 Pit latrine contaminant movement in the unsaturated zone (Harvey et al, 2002)

Once the contaminants from the on-site sanitation system reach the groundwater, they will travel in the direction of the groundwater flow, which may result in considerable lateral movement and reach drinking water abstraction points (Figure 2.7).

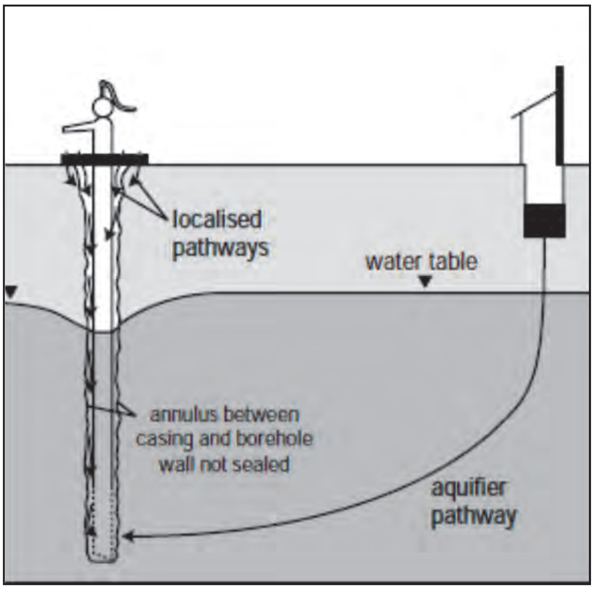


Figure 2.7 Aquifer and localised pathways of contaminant (from ARGOSS, 2001)

Under certain conditions, the vertical movement of the leachate from the on-site sanitation system may be inhibited, due to the presence of semi-pervious layers in the vadose zone (Figure 2.8). In these cases, temporary zones of saturation may form above these layers after prolonged periods of rainfall, and result in the rapid lateral movement of contaminants within the vadose zone, which can surface downslope (Figure 2.8).

Lastly, 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). The significance of preferential flow characteristics present in the vadose zone, means that there is less time that the contaminants remain in the unsaturated region of soil above the groundwater, and thus less impact from the natural attenuation processes acting upon the contaminants.

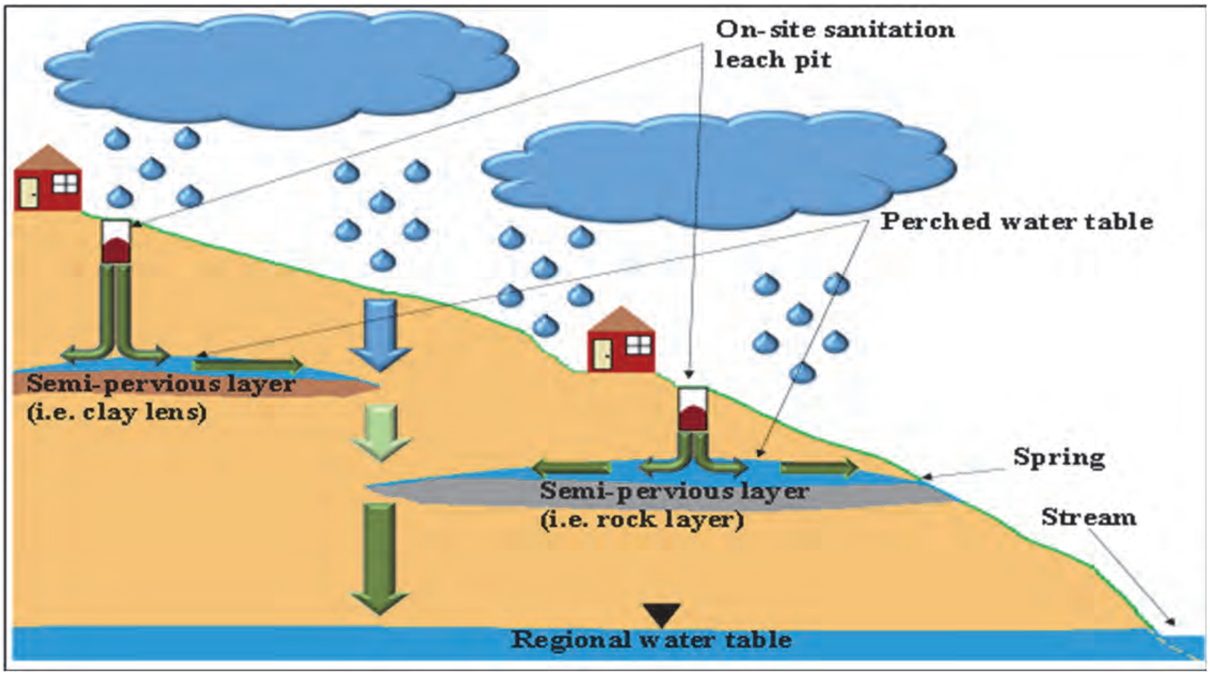


Figure 2.8 Semi-pervious layers leading to the formation of a perched water table and lateral spread of on-site sanitation contaminants

2.4. Factors Affecting the Fate of Nutrients and Pathogens

Considerable laboratory and field based research, from as early as the 1920's, but predominantly since the mid 1970's, has contributed to the understanding of the fate of pathogens and nutrients within and in seepage plumes emanating from on-site sanitation storage pits. This, together with a growing number of case studies has led to various international and South African guidelines. Despite this effort, however, there remain both reported uncertainties as well as knowledge gaps in likely mechanisms of movement, which have until recently, mostly been poorly defined.

The following section presents a summary of the predominant mechanisms determining the fate of pathogens and nutrients from on-site sanitation. The uncertainties and knowledge gaps are summarised in the next section before conclusions and recommendations are presented.

Numerous studies have listed mechanisms and conditions affecting the fate of nutrients and pathogens in soils and geological materials from onsite sanitation (Hall, 1990; Van Reyneveld and Fourie, 1997; Scandura and Sobsey, 1997; Cave and Kolsky, 1999; Engebretson and Tyler, 2001; ARGOSS, 2002; Cronin, et al., 2006; Zhang, 2008; Torondel, 2010). Many of these sources summarise key studies from the 1970's and 1980's and highlight the following dominant factors affecting migration of pathogens and nutrients from onsite sanitation sources.

- Latrine contents and environment,
- Pathogen type,

- Loading rate and extent of clogging,
- Soil pH, temperature, organic matter and adsorption capacity,
- Vadose zone characteristics and
- Groundwater aquifer characteristics.

These are discussed separately in the following sub-sections.

2.4.1. Latrine contents and environment

Clearly the source concentrations of nutrients and abundance of pathogens will influence their persistence in the soil and groundwater. However, pit latrine contents are highly variable due to diet, habits, surrounding soil type as well as pH, temperature and aerobic conditions in the pit (Torondel, 2010). Nitrogen (N) and Phosphorus (P) content alone can make up between 25% and 35% of total dry mass in a pit (Table 2.2), while pathogen abundance will depend on the health, hygiene and habits of the users.

Other site and usage conditions that affect the performance of a pit latrine are summarised in Table 2.4.

Table 2.4 Factors that may affect performance of a pit latrine (after Buckley et al., 2008)

Construction and location	Operation	Maintenance
- Construction of walls and base of the pit - Permeability of the walls and base of the pit - Construction of slab, collar and superstructure of the latrine - Height of water table (low/high) - Type of soil - Presence of bedrock or sandy aquifer - Proximity of other pits	- Age of the pit - Addition of other material (e.g. household waste) - Ingress of (non-urine) liquid via the top of the pit - Rate of filling / number of users	- Frequency/history of emptying - Amount of seed material left after emptying - Additives used to enhance digestion - Ownership: Communal or private

2.4.2. Pathogen type

Cell properties such as electrophoretic mobility, cell size and shape, hydrophobicity, charge density and extracellularpolymeric substance composition were shown to affect the transport behaviour of different *E. coli* isolates by Bolster, et al. (2009). Huysman and Verstraete, (1993), demonstrated that hydrophobic strains of bacteria were 2-3 times slower compared to hydrophilic strains. This resulted from an increased adhesion of the hydrophobic strains to the soil particle surfaces. Increasing the bulk density of the soil by some 8% resulted in a decrease in the bacteria migration of 30-60%. Likewise, adding 20% clay to a sandy soil decreased the bacteria migration by 40-80%; the reduction being more pronounced for the hydrophilic bacteria.

2.4.3. Loading rate and extent of clogging

Nutrients

The rate of nutrient migration in soil and groundwater is subject to advection, dispersion, adsorption, nitrification and denitrification processes, which are directly dependant on the mass loading rate.

Figures 2.9 and 2.10 describe the processes and pools of nitrogen and phosphate in the soil, which originated from the leachate of the on-site sanitation system.

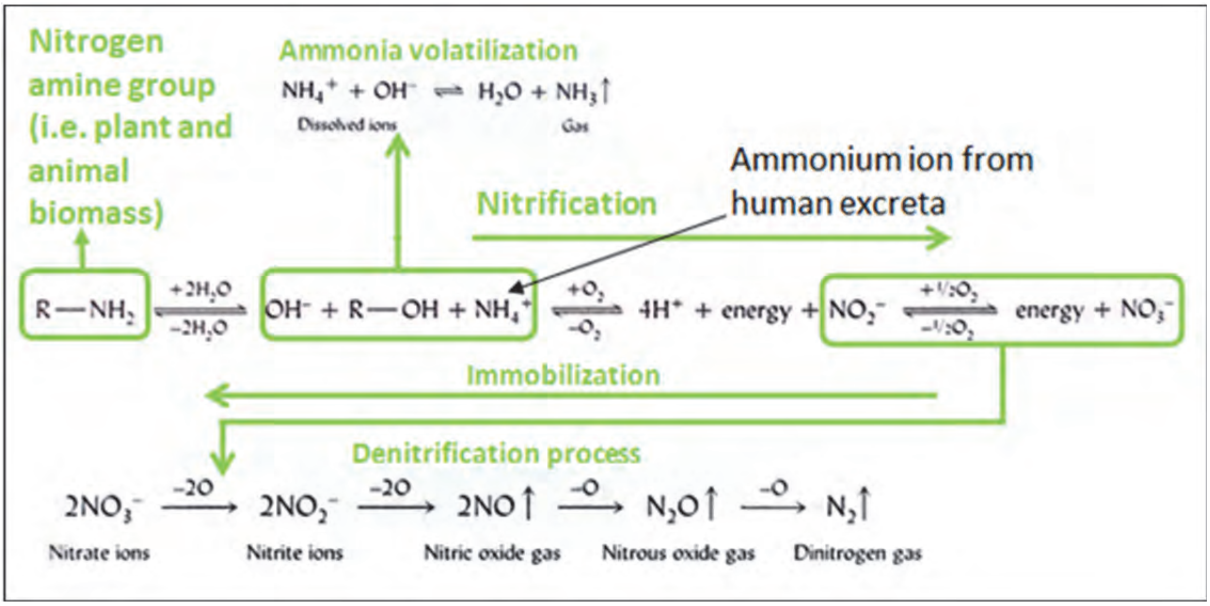


Figure 2.9 Nitrogen transformations in the soil (adapted from Brady and Weil, 2008)

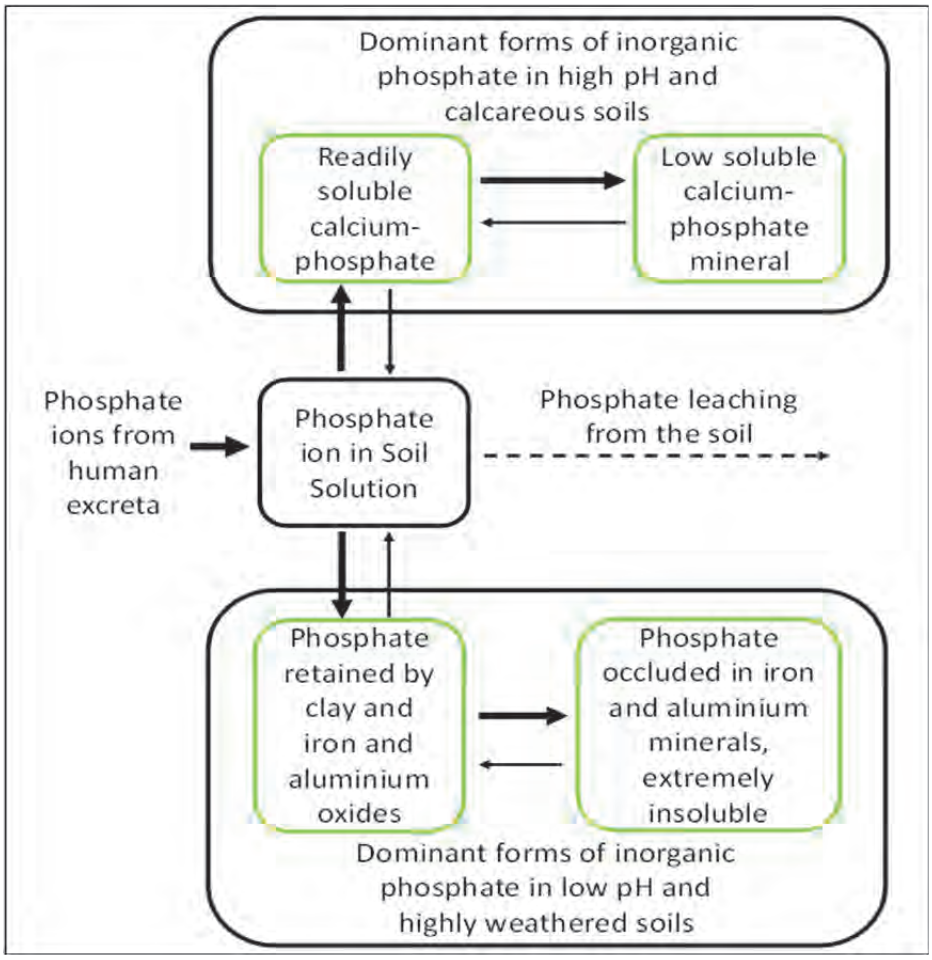


Figure 2.10 Phosphate transformations in the soil (adapted from Brady and Weil, 2008)

Pathogens

The survival of pathogens in saturated porous media has also been demonstrated to be dependent on loading rate (Green and Cliver, 1974), as shown in Figure 2.9. The die-off rate of pathogens from a low loading rate (5 cm/day) is more than double that resulting from a high loading rate (50 cm/day).

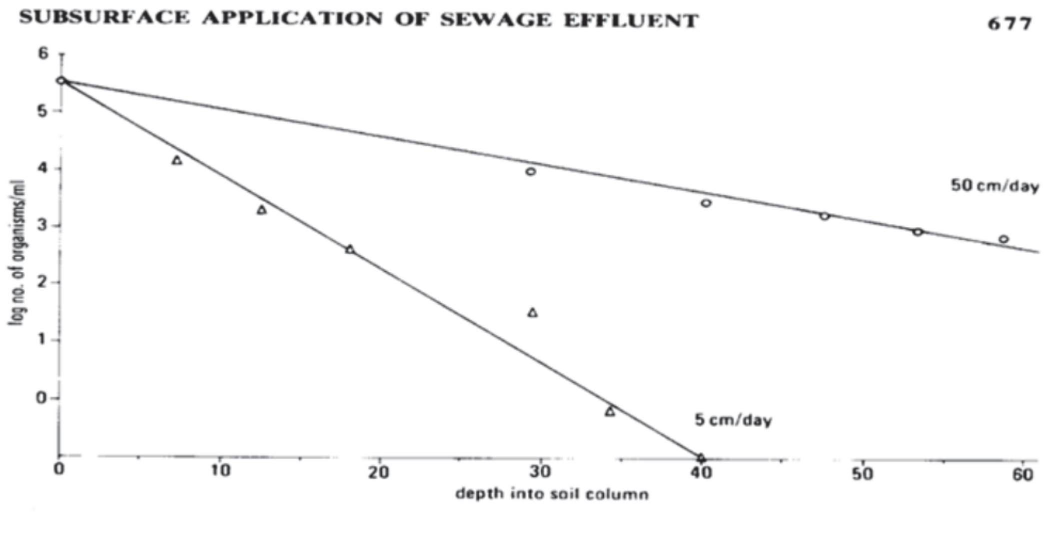


Figure 2.11 Effect of loading rate (cm/day) on pathogen reduction (after Green and Cliver, 1974)

Indeed, reducing the loading rate from an initial high rate (10 mm/day) to a low rate (3 mm/day) eliminates the population in different soils over 10 to 75 days, depending on the soil type (Bouma, 1975) as illustrated in Figure 2.10. Increasing the loading rate to 10 mm/day again, restores the previous population at the observation location within 10 days.

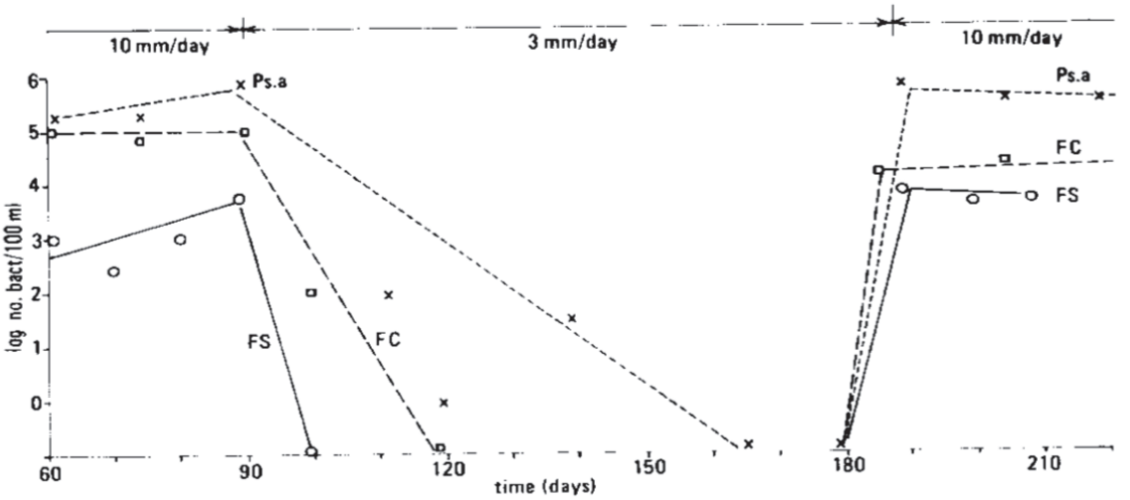


Figure 2.12 Change in pathogen migration and survival during a phased (high-low-high) loading rate (after Bouma, 1975)

Clogging of soil pores by bacteria is influenced by the content of organic matter in the soil, the degree of biofilm development and the electrostatic attraction between pathogen cells and soil particles (Stevick et al., 2004)

2.4.4. Soil conditions

Nutrients

Apart from the hydraulic characteristics of the soil, N migration is most sensitive to biological activity and organic carbon affecting oxidation and reduction, microbial activity and the distribution of clays and silts, (Rea and Upchurch, 1980).

Total reactive P and dissolved reactive P mobility is primarily dictated by the adsorption capacity of the soil. However, the transportability of colloid-associated P (particulate P) is only retarded in soils with high electrical conductivity (Zhang, 2008). Since pit latrine waste is a likely source for particulate P this mechanism of transport should not be overlooked.

Pathogens

The migration of pathogens in porous media is clearly affected by the size of pores through which they can move. Most viruses are likely to move easily through most soils and geological materials, except for those with pore sizes smaller than found in fine silts. Bacteria would move through materials with pore sizes ranging from sands and fissured rock to coarse silts (Figure 2.11).

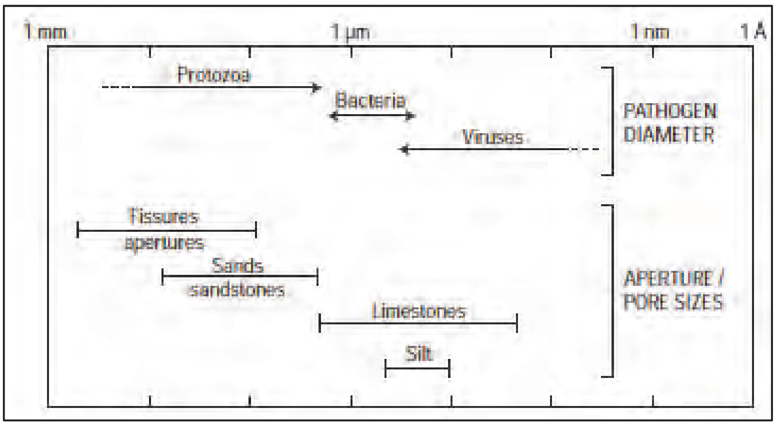


Figure 2.13 Comparison of pore sizes of various soils and rock types with typical pathogen diameters (after ARGOSS, 2002)

The rate of inactivation of pathogenic organisms is affected by factors such as soil water content, pH, temperature, organic matter, bacterial species, predation and antagonistic symbiosis between the microorganisms in the plume, (Stevik et al., 2004). The residence time of the pathogens in the porous media will clearly dictate the degree of influence of these factors. The residence time is determined by the hydraulic characteristics of the porous media and these are discussed separately below.

The rate of inactivation at any time, t (days) can be expressed as:

$$N = Noe\text{-}\lambda t$$

Where

N = pathogen population at time t,

No = pathogen population at time, 0 and

λ = decay loss rate (day-1).

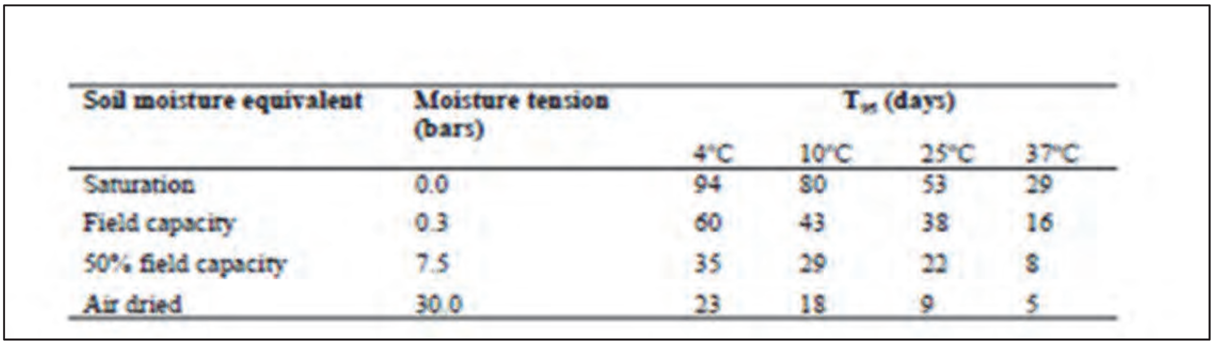
Values for λ have been measured at 1.14 day-1 for bacteria and 1.92 day-1 in saturated soils (Sinton, et al., 1997) and have been estimated to be larger for unsaturated soils (Pang, et al., 2006).

2.4.5. Vadose zone characteristics

Since the key factor in the removal of bacteria and viruses is a maximisation of the residence time between source and point of abstraction, the unsaturated (vadose) zone is seen as a first line of defence, since unsaturated hydraulic conductivities (and therefore flow velocities) are typically orders of magnitude lower than the saturated hydraulic conductivity (Cave and Kolsky, 1999).

The water content also affects survival as illustrated in Table 2.5. At 25oC, with a water content change from saturation to 50% of field capacity, the 95% population reduction time is halved, from 53 to 22 days.

Table 2.5 Average 95% population reduction times (T95) for faecal streptococcus at different water contents (After ARGOSS, 2002)



Soil moisture equivalent	Moisture tension (bars)	T_{95} (days)			
		4°C	10°C	25°C	37°C
Saturation	0.0	94	80	53	29
Field capacity	0.3	60	43	38	16
50% field capacity	7.5	35	29	22	8
Air dried	30.0	23	18	9	5

All studies highlight the value of a deep unsaturated zone to retard pathogen migration, but only a few hint at the very real danger of rapid response, lateral flows that often occur near surface (within the upper 2 3 m) during heavy rainfall events. In certain soilscapes, these events are likely to induce positive pressure, saturated discharge which has the potential to intersect onsite latrine pits and move both nutrients and pathogens rapidly downslope. Fourie and van Reyneveld, 1994, warn of macro pore flow and discharges in fissured rock above an aquifer, but provide no reference to observations of these mechanisms. In case studies, such phenomena are possibly reported as the movement of nutrients and pathogens in “shallow water tables” after heavy rains; as a macro pore phenomena or as preferential flow at soil and geological interfaces. Dzwairo et al., 2006, report 25 m of lateral movement of pathogens due to shallow water tables. Reneau et al., 1985, provide a summary of studies in which macro-pore flow through saturated, “strongly structured soils” resulted in pathogen movement over relatively long distances (24.4 m). In another study, Reneau et al., 1985, report horizontal movement of effluent above a fragipan, where faecal coliform concentration was not reduced significantly between 6 and 12 m from the source. Faulkner, et al., 2003, warn that extreme rainfall events and preferential flow should be carefully assessed as these conditions are likely to leach viruses. Tredoux et al., 2000, quoting a study of Lewis et al., 1978, indicate that the highest nitrate concentration from a leach study, was found in the layer directly above the consolidated rock, clearly the result of preferential, near surface discharge.

Despite these observations, guidelines continue to include the hydraulic conductivity and depth of the unsaturated zone and the travel time in an aquifer as the criteria for sighting onsite latrines or extraction wells. This requires scrutiny, since intermittent, but rapid saturated fluxes in the near surface have been observed in many geologies and soilscapes in South Africa (Lorentz et al., 2008; le Roux et al., 2010). These are induced either through macro-pore structures, interfaces between soil and bedrock or in soils where the horizontal hydraulic conductivity exceeds the vertical, such as in soils derived from sedimentary deposits. They are highly likely to intercept latrine storage pits and could impact either groundwater, through subsequent recharge, or local streams or wetlands at the base of hillslopes.

2.4.6. Saturated groundwater characteristics

Travel times of pathogens and nutrients in aquifers are controlled by the geological materials and topography. A recent study reported by Pujari et al., 2012, in India, clearly illustrates the differences between a significant onsite sanitation impact on groundwater quality in flood basalt geology near Indore and minimal impact in an alluvium near Kolkata. Both areas are subject to similar densities of onsite sanitation.

A number of guidelines provide lists or rules for interpreting the impact potential of different geological materials (Engebretson and Tyler, 2001; ARGOSS, 2002). These should be used together with a sound knowledge of the pit interception and recharge flowpaths and trigger mechanisms.

2.5. International Guidelines and Case studies

There are numerous drinking water quality guidelines which cover a wide range of chemical, physical and biological parameters. The most used and extensive are those developed by the World Health Organisation (WHO) and the United States Environmental Protection Agency (USEPA). The South African Nation Standards (SANS) sets identical drinking water limits. Table 2.6 lists the drinking water limits for nitrate, phosphate and faecal coliforms as described by WHO, USEAP and SANS.

Table 2.6 Maximum drinking water limits guidelines (after WHO, 2008; USEPA, 2009; SANS, 2011)

Contaminant	**WHO**	**USEPA**	**SANS**
Nitrate (as Nitrate)	50 mg/l	44 mg/l	49 mg/l
Phosphate (as orthophates)	-	-	-
Faecal coliforms (*E. coli*)	Not detectable	Not detectable	Not detectable

With regards to on-site sanitation systems there are several guidelines and studies that each produce a recommended safe lateral distances for installing an on-site sanitation system away from nearby drinking water point(s), which had been complied into Table 2.7. From these studies/guidelines, 15.00 m, 30.00 m and 50.00 m are the most commonly accepted safe lateral spacings for on-site sanitation systems. Furthermore, the guidelines suggest that 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.

Table 2.7 Recommended safe lateral spacing for on-site sanitation system

Suggested safe horizontal distance (m)	**Conditions**	**On-site sanitation contaminants**	**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	Chemical and microbial	McCarthy *et al*. (1994)

	downslope of a drinking water point		
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 5 m below the bottom of pit or soak-away	Chemical and microbial	CSIR (2005); Devilliers (1987)
15	If the highest water table level is between 1-5 m below ground	Chemical and microbial	CSIR (2005); Devilliers (1987)
30	If the highest water table level is less than 1 m	Chemical and microbial	CSIR (2005); Devilliers (1987)
No safe distance	Area comprises of coarse soil, fissured rock or limestone	Chemical and microbial	CSIR (2005)

Still and Nash, 2004, provide a summary of observations of bacterial transport through soils and rock formations. These studies, ranging from 1923 to 1979 include a number of instances where pathogens have been observed to travel 30 m in coarse grained aquifers. More recent observations (1995-2012) are presented in Table 2.8 where both pathogen and nitrate migration from pit latrines are assessed. Here nitrates have been observed to impact the basalt aquifer some 120 m distant from the residential source area. Pathogens have been observed in Kenya to have impacted the groundwater 60 m from the pit latrine source.

Table 2.8 Case studies of near surface water contamination

Sanitation system	Study area	Area (km^2)	Population	MAP (mm)	Soil	Geology	Water Sampling Point	Nitrate (mg/l)	Phosphate (mg/l)	Faecal coliforms (CFU/100 ml)	Distance from sample point to contaminant source (m)	Comment	Reference
Pit latrines	Bolama-Bijago´s Archipelago, Republic of Guinea-Bissau	102	6, 000	2500	Hydromorphic sandy-clay soils are acidic, with low organic matter contents	-	28 Hand dug shallow wells. Depth range 5-11 m	0.9-55.3	-	0-5, 000	few – 900	Greatest degree of well contamination occurred after periods of heavy rainfall	Bordalo and Savva-Bordalo (2007)
3 Pit latrines	Kamangira village, Zimbabwe	*0.02	100	-	Sandy, with high transmission of water	Faulted granitic rocks	3 Shallow wells	# 0-17.3	-	2-820	38-44	All shallow wells indicated faecal contamination.	Dzwario et al. (2006)
Pit latrines and septic tanks	Bonfi & Hafia-Mosqde districtcs, Conakry, Republic of Guinea	*2.17	850, 000	3000	Sand and highly permeable in Bonfi, rocky soil with low permeability in Hafia-Mosqde	-	46 Shallow wells in Bonfi (B) and 23 shallow wells in Hafia-Mosqde (HM)	50-229.3 (B); 31.4-197.4 (HM)	0.01-6.57 (B); 0.01-0.42 (HM)	# 50-183, 000 (B); 7, 000-163, 000 (HM)	*few – 500	High concentration of nitrate were recorded following the first rainfalls after a 6 month dry period..	Gelinas et al. (1996)
Pit latrines	Isale-Igbehin district, Abeokuta, Nigeria	-	-	1156	Mostly sandy, with some areas consisting of clay	-	12 Shallow wells	22.5-50.6	-	# 1400-3700	1.7-23.9	High nitrate and faecal coliforms levels were found in shallow wells as far a 17.5 m away from the latrines.	Adejuwon and Adeniyi (2011)

Pit latrines	Kampala, Uganda	*68.4	*323, 326	-	-	-	16 Springs from a shallow groundwater, during wet (W) and dry (D) season	19-106 (W); 33.2-221.3 (D)	-	#56-18, 262 (W); 31-1746 (D)	0.5-11	Describes low nitrate concentration in wet season due to the dilution effect.	Nsubaga et al. (2004)
Pit latrines	Langas, next to Eldoret town, Kenya	*5	*900, 000	-	-	-	31 Hand dug shallow wells	-	-	minimum of 1, 100	1-30	All but 1 of the shallow wells had faecal coliforms	Kimani-Murage and Ngindu (2007)
Septic tank	Karod, Bhopal city, India	-	1, 454, 830	1260	Alluvium	Deccan basalts, Bhander Sandstones and shales	10 Hand pumps and dug wells	1-48	-	0-180	*17-35	Highest contaminant concentrations during monsoon. Highest nitrate and faecal coliform values occurred at 18 m and 35 m away from septic tank.	Pujari et al., 2007
Septic tank	Kainchi, Bhopal city, India	-	1, 454, 830	1260	Alluvium	Deccan basalts, Bhander Sandstones and shales	8 Hand pumps and dug wells	10-141	-	8-360	*5-35	Highest contaminant concentrations during monsoon. Highest nitrate and faecal coliform values occurred at 10 m away from septic tank.	Pujari et al., 2007
Septic tank	Ahilya Nagar, Indore city, India	-	170	1050	Black cotton soil, 2-3 m thick	Hard basaltic rock, with fractures and vesicular units	9 open wells and hand pumps	3-114	-	20-1600	*20-150	Water table varies 5-20 m below surface. Highest contaminant concentrations during monsoon. Highest nitrate and faecal coliform values occurred at 100 m and 150 m away	Pujari et al., 2012

												from septic tank respectively.	
Septic tank	Chandan Nagar, Indore city, India	-	300	1050	Black cotton soil, 2-3 m thick	Hard basaltic rock, with fractures and vesicular units	6 open wells and hand pumps	2-158	-	2-600	*6-20	Water table varies 5-20 m below surface. Highest contaminant concentrations during monsoon. Highest nitrate and faecal coliform values occurred at 20 m and 6 m away from septic tank respectively.	Pujari et al., 2012

Table 2.9 Recent case studies on the fate of nutrient and pathogens from pit latrines

Location	Sanitation system	Pollutant	Concentration	Distance from source	Reference
Addis Ababa, Ethiopia	Pit Latrine	Nitrate	27.9 mg/l	<100 km	Abay, 2010
		E. coli	9 MPN/100 ml		
		Coliforms	46 MPN/100 ml		
Abeokuta, Nigeria	Pit Latrine	Nitrate	37.5 mg/l	23.9 m	Adejuwon and Adeniyi, 2011
		Total Coliform count	14 cfu/ml		
Kamangira village, Zimbabwe	Pit Latrine	Nitrate	1.4 mg/l	44 m	Dzwairo *et al.*, 2006
		Total Coliform count	708 cfu/100 ml		
Kwale, Kenya	Pit Latrine	Total Coliform count	950 cfu/100 ml	60 m	Tole, 1997
Sempra village, India	Pit Latrine	Nitrate	200 mg/l	30 m	Fourie and van Ryneveld, 1995
Kampala, Uganda	Pit latrine and animal husbandry	Nitrate	19.9 mg/l	<20 m	Nsubuga *et al.*, 2004
		Faecal coliforms	38 MPN/100 ml		
Epworth, Zimbabwe	Pit Latrine	Nitrate	30 mg/l	<1 km	Zingoni *et al.*, 2005
		Faecal coliforms	10,000 cfu/100 ml		
Kolkata, India	Pit Latrine	Nitrate	0.2 mg/l	120 m	Pujari *et al.*, 2012
		Faecal coliforms	2 mg/l		

2.6. Methods of Monitoring Nutrient and Pathogen Transport

One of the easiest methods to monitor the movement of nutrients and pathogens from and on-site sanitation system, is to install a series of piezometers down the hillslope in the direction of the groundwater movement, above and below where the sanitation system is installed. The piezometers should be installed to the depth of the water table, where water samples may be collected for chemical and biological analyses. In addition to piezometers upslope of the on-site system, rainfall samples should be collected as well as surface run-off and stream samples (where applicable), in order to draw a comparison between the groundwater samples downslope of the on-site sanitation system. Figure 2.14 describes the layout of instrumentation that may be used to collect rainfall (a), surface run-off and vertical infiltration (b), through-flow and groundwater (C) and stream samples (d).

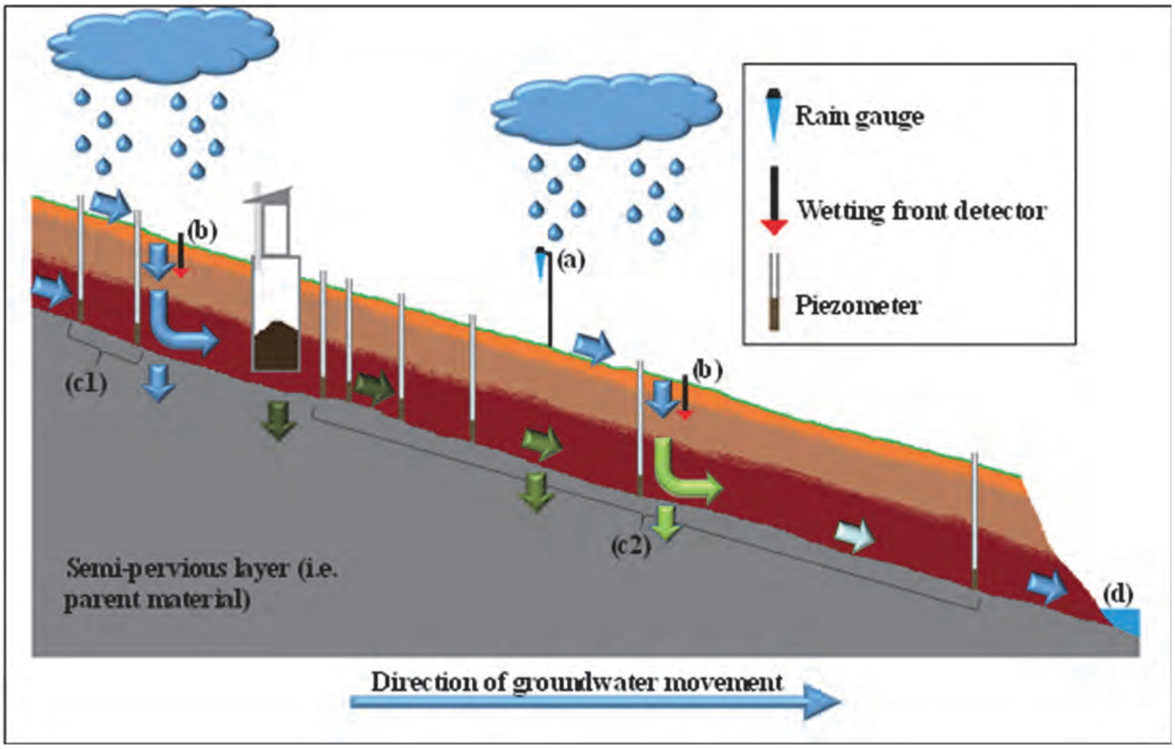


Figure 2.14 Generic layout of water sampling instrumentation for monitoring nutrient and pathogen transport

Water samples should be collected at regular intervals and analysed immediately after collection (especially for ammonium, nitrate and ORP), or stored in a fridge until they are analysed. Furthermore, the rain gauge, wetting front detectors and piezometers should be purged prior to sample collection, where a fresh sample can be collected.

2.7. Methods of Simulating Nutrient and Pathogen Transport

The HYDRUS simulation model has been used for unsaturated zone nutrient and pathogen transport assessment. The model can be configured for adsorption, phase change and uptake of nutrients as well as the attachment/detachment and decay mechanisms of pathogen movement (Šimůnek, et al., 2009). However, considerable care would have to be given to simulate the variability of preferential flow mechanisms and the conditions which trigger these. In a Monte Carlo simulation of pathogen transport, Faulkner et al., 2003, identify the unsaturated hydraulic conductivity characteristic as having the largest influence on the fate and transport of viruses in the unsaturated zone. Not surprisingly, they warn that extreme rainfall events and preferential flow will require attention if modelling predictions can be expected to be accurate.

3. EXPERIMENTAL SITES IN KWAZULU-NATAL

3.1. Site Description and Characterisation

A total of 4 study sites were established for the study. Three comprised of Pour-flush systems *viz*. Slangspruit, Creche and Azaela, where a transect covering a portion of a hillslope, was monitored. The remaining site comprised a transect down the length of a hillslope where VIP systems are present *viz*. Taylors Halt. Figure 3.1 is an aerial view of the study sites, showing their relative geographical position to one another. The general characteristics of each site are summarised in Table 3.1

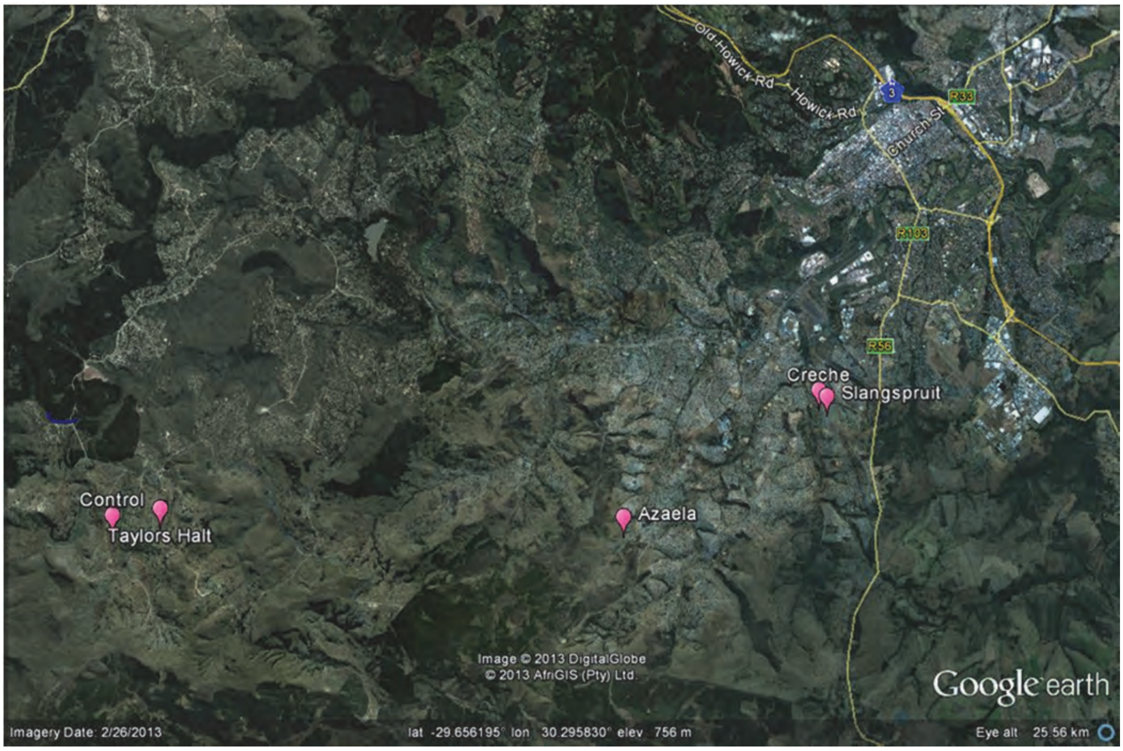


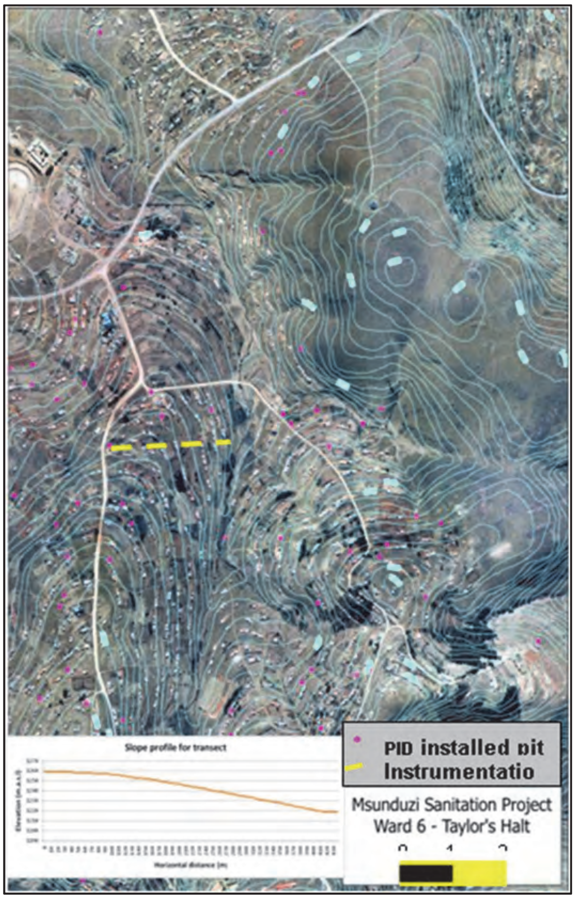
Figure 3.1 Position of experimental sites, south east of Pietermaritzburg

Table 3.1 General characteristics of study sites

Characteristic	**Taylors Halt & Control**	**Slangspruit & Creche**	**Azaela**	**Reference**
Age of on-site system	5 years	2 years	2 years	Home owner
Depth of pit	1.72 m	1.52 m	1.52 m	-
Underlying geology	Dolerite	PMB formation shale	Dolerite	Council for Geoscience, 1979
Natural veld types	Natal mist belt	Southern tall grassveld	Southern tall grassveld	Acocks, 1988
Altitude	1250 m.a.s.l	680 m.a.s.l	847 m.a.s.l	GPS
Mean annual precipitation	1000-1200 mm/y	1000-1200 mm/y	1000-1200 mm/y	Schulze, 1997
Maximum temperature range	26-28°C	26-28°C	26-28°C	Schulze, 1997
Minimum temperature range	4-6°C	4-6°C	4-6°C	Schulze, 1997

3.1.1. Taylors Halt

Figure 3.2 Location of the monitored transect at Taylor's Halt, south of Pietermaritzburg



During a site visit on 19 August 2011 the first site was identified at Taylors Halt, south of Pietermaritzburg (Figure 3.2). A hillslope transect has been selected for detailed instrumentation and observation. The line of the transect will be finalised on site to intersect as many pit latrines as possible. Instrumentation was placed in nests located various distances from selected latrines along the hillslope. The average slope of the transect is 1:10 with a total fall of 40 m. There are four latrines (VIP1-VIP4) along the general line of the transect. The slope is west-facing and a stream runs from south to north along the western toe of the hillslope. Figures 3.3 and 3.4 describe the instrumentation layout and soil profile at the Taylors Halt site.

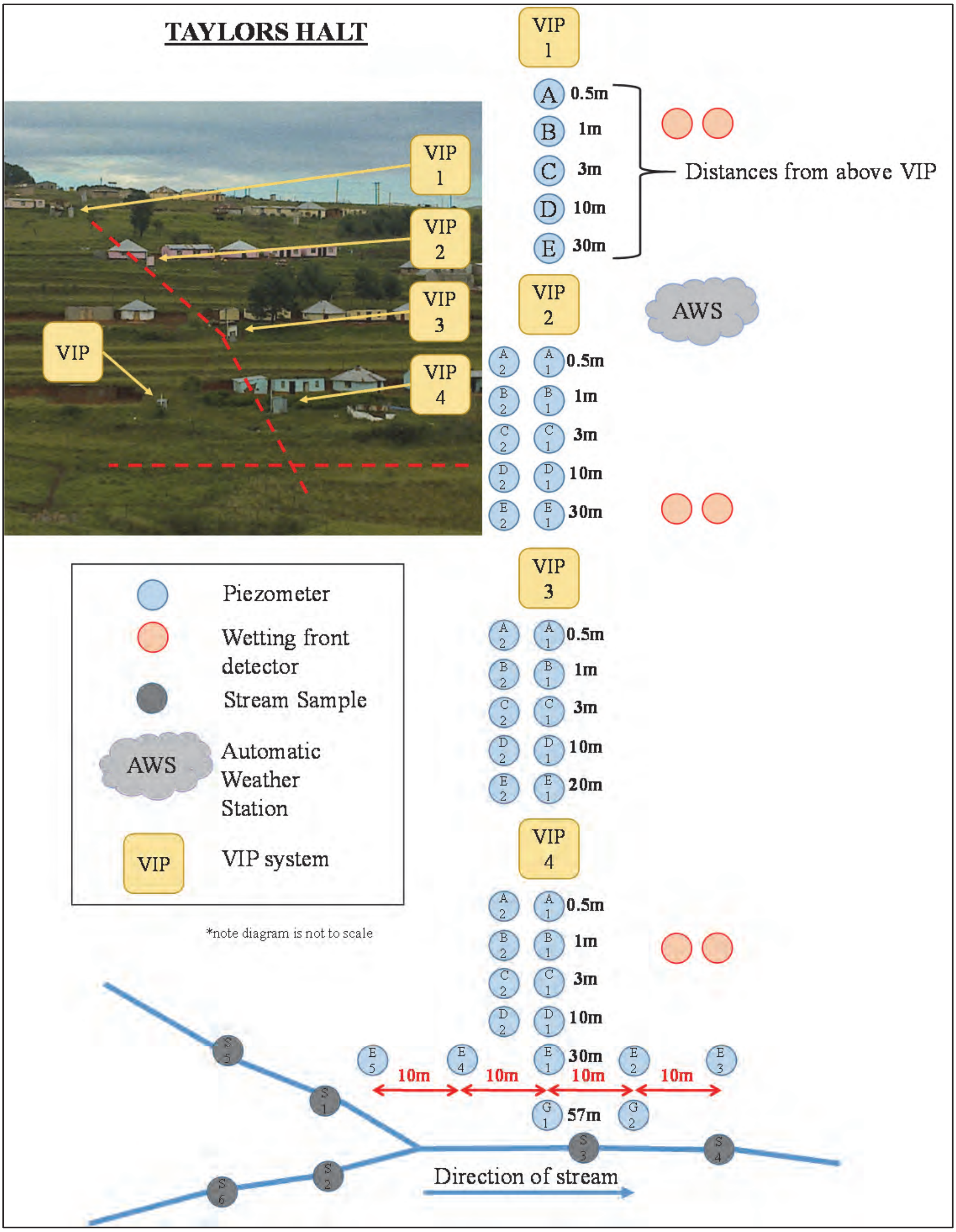


Figure 3.3 Layout of instrumentation at Taylors Halt study site

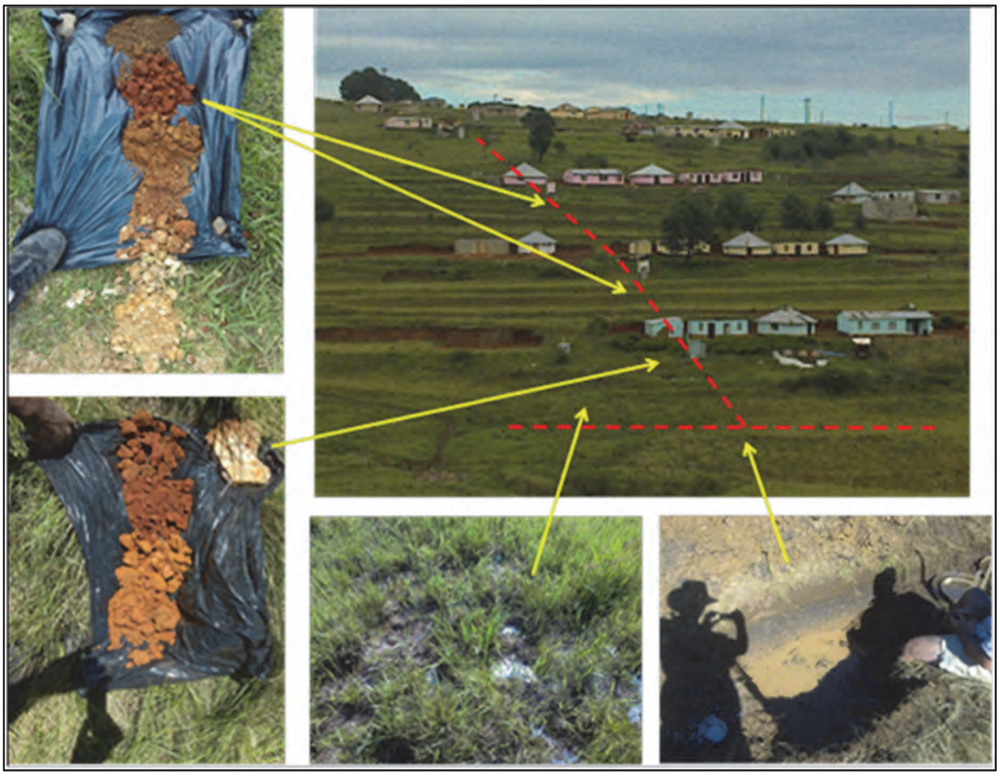


Figure 3.4 Indication of the soil profiles at the Taylors Halt hillslope transect

3.1.2. Slangspruit

The Slangspruit site comprised a rural community where an individual household used a pour-flush latrine. The site was marked by a steep slope and shallow near-surface water. Observation piezometers were installed in two transects downslope of the latrine since a plume was anticipated. Some 26 m downslope of the latrine a set of five observation piezometers were installed covering a cross-slope distance of some 20 m. Background observation piezometers was installed upslope of the latrine. Figures 3.5 and 3.6 describe the instrumentation layout and soil profile at the Slangspruit site.

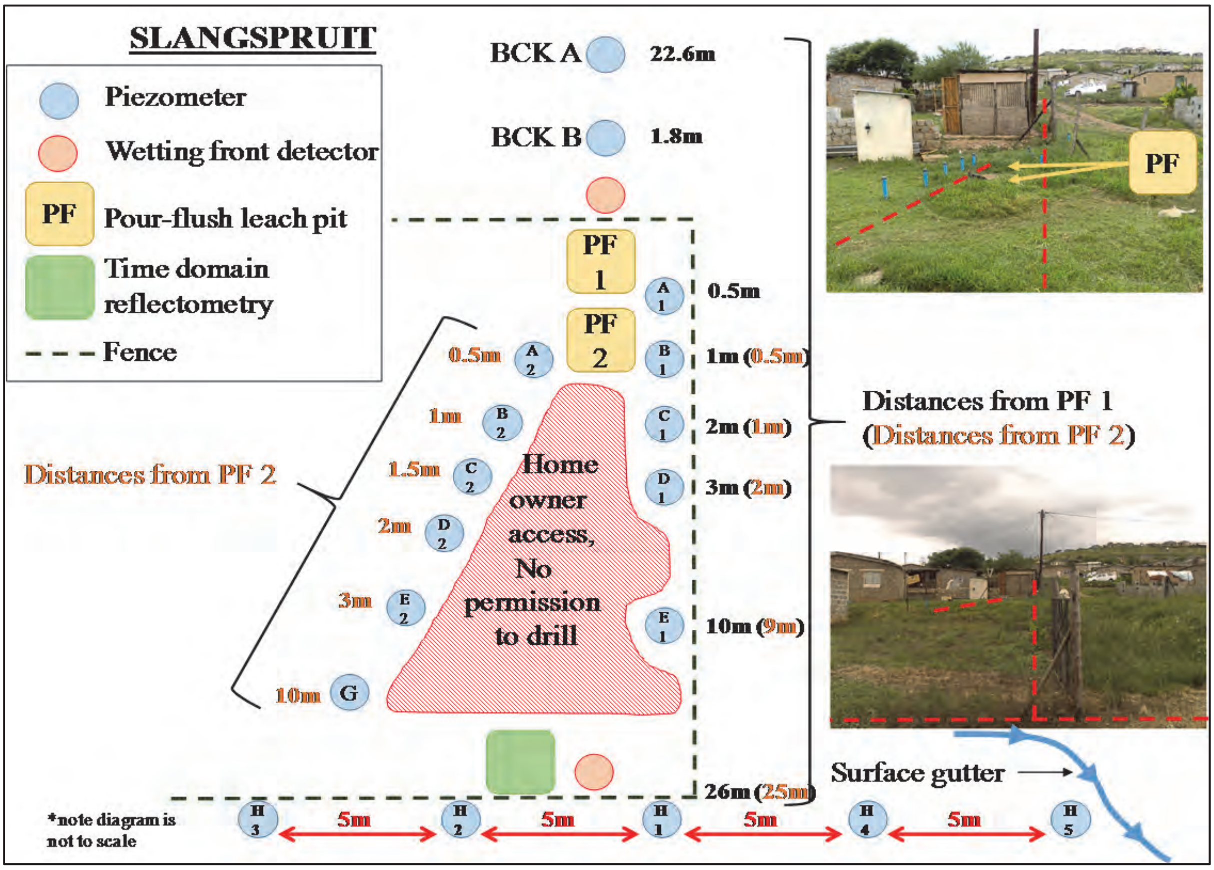


Figure 3.5 Layout of instrumentation at the Slangspruit study site

Figure 3.6 Indication of the soil profile at the Slangspruit site

3.1.3. Crèche

The Creche site comprised two pour-flush latrines servicing a busy Creche. Six observation piezometers were established downslope of the two pour flush latrines and a set of five piezometers were established 10 m downslope of the latrines, covering a cross-slope distance of 10 m. Two background piezometers were established upslope of the latrines. Figures 3.7 and 3.8 describe the instrumentation layout and soil profile at the Crèche site.

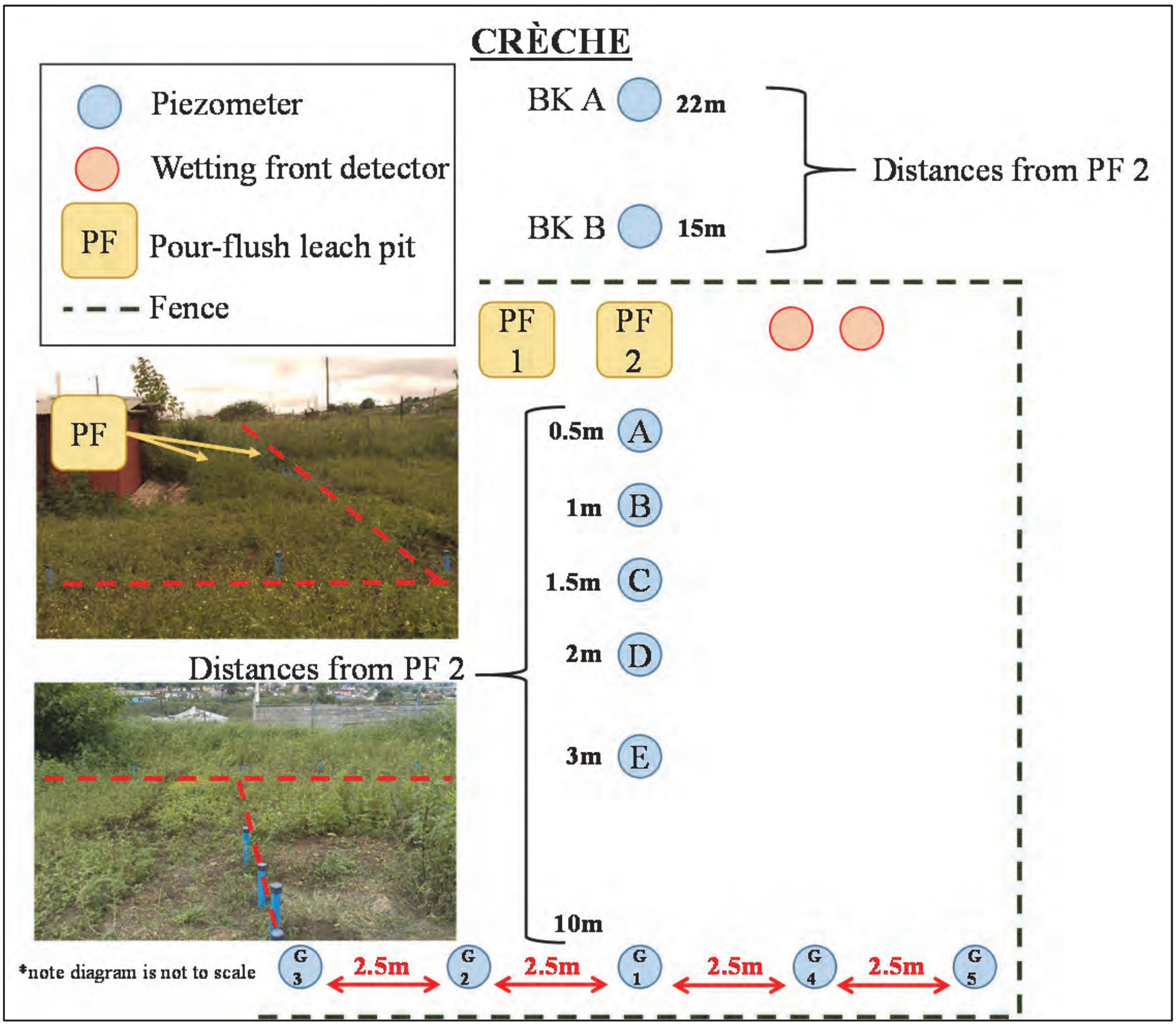


Figure 3.7 Layout of instrumentation at the Crèche study site

Figure 3.8 Indication of the soil profiles at the Crèche site

3.1.4.4 Azalea

The Azalea site comprised a family home pour-flush system near a stream. Five piezometers were established downslope of the latrine sump and 3 cross-slope piezometers were established some 17.5 m downslope of the latrine sump. Two background piezometers were established upslope of the sump. Figures 3.9 and 3.10 describe the instrumentation layout and soil profile at Azalea study site.

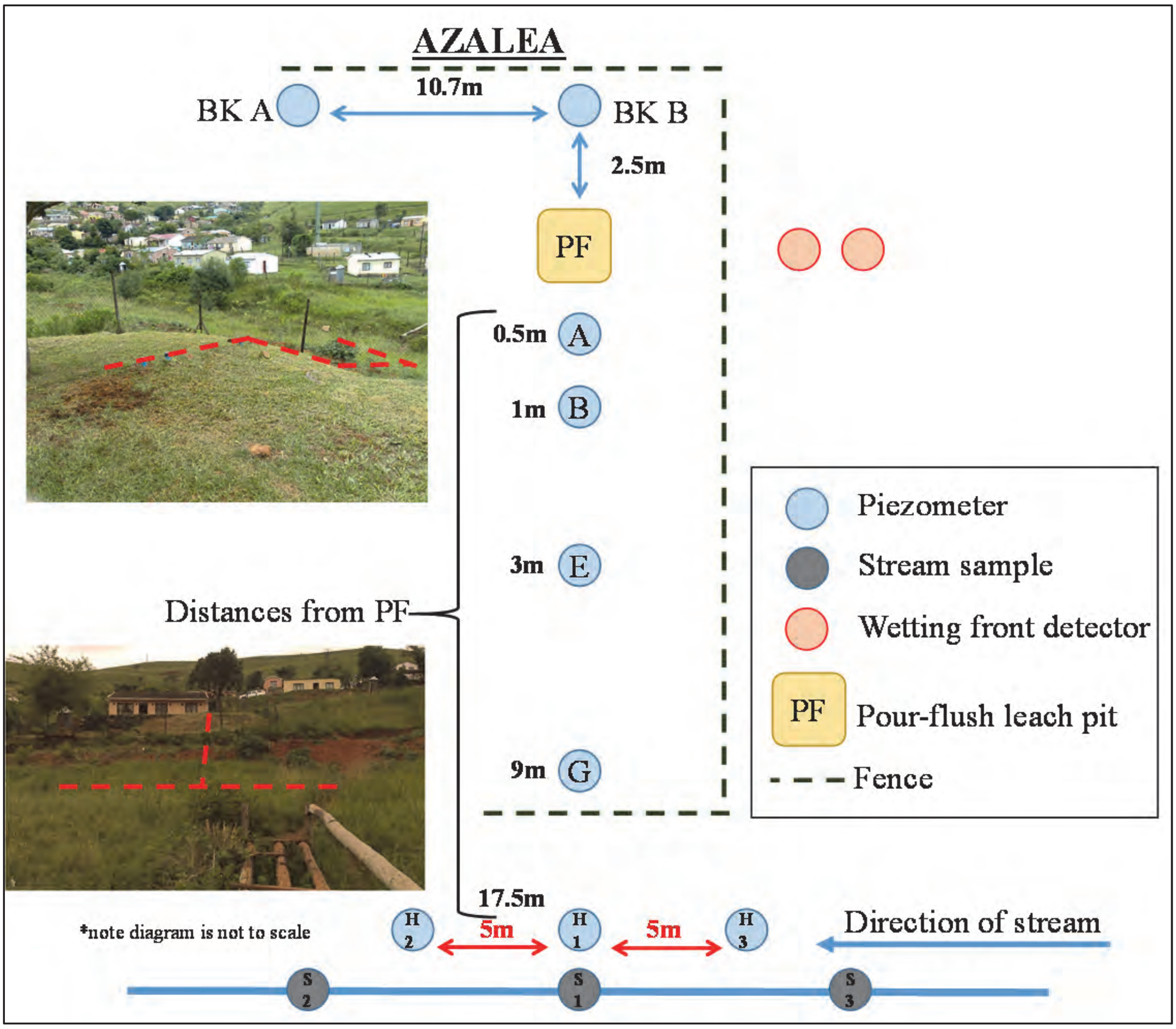


Figure 3.9 Layout of instrumentation at the Crèche study site

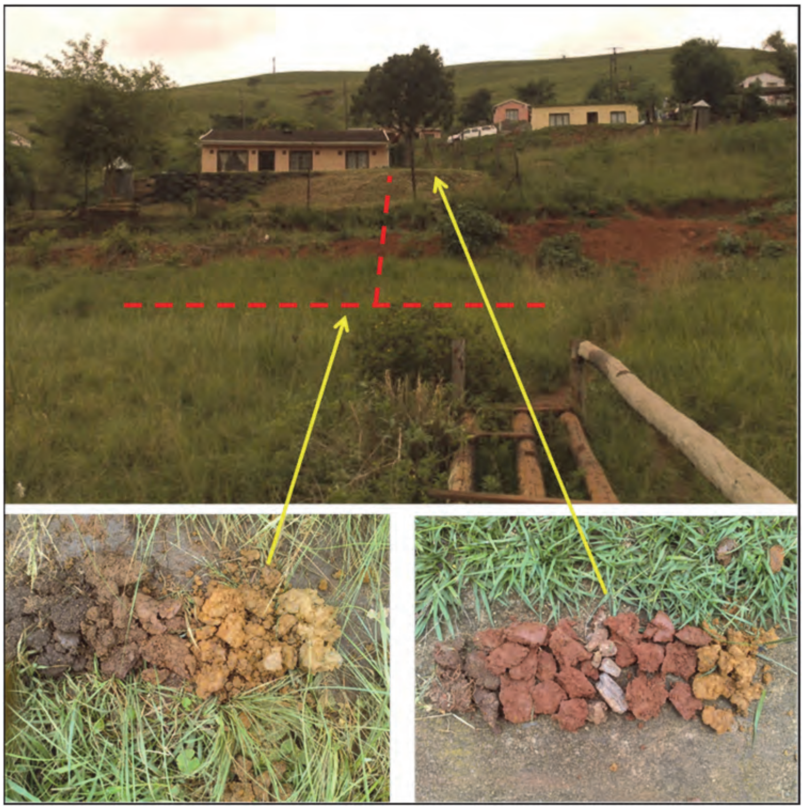


Figure 3.10 Location of piezometers and indication of soil profile at the Azalea site

4. ISOTOPE, NUTRIENT AND PATHOGEN OBSERVATIONS

For each water sample, stable isotopes of water (O^{18} and H^2), Nitrate, Ammonium, Phosphate, Sulphate, Chloride, Calcium, Magnesium, Sodium and Potassium were made at each study site.

4.1. Taylors Halt

The isotope data at the Taylors Halt site fell consistently along the meteoric water line (Figures 4.1 and 4.2). The rainfall isotope values vary widely. The small stream (S1 and S5) respond to the rainfall signature, while the larger main stream (S2, S3, S4 and S6) have isotope values similar to the near surface, piezometer isotopes. Hence it is apparent that the main stream is hydraulically linked to the hillslope water, whereas the small upland stream receives predominanlty event water.

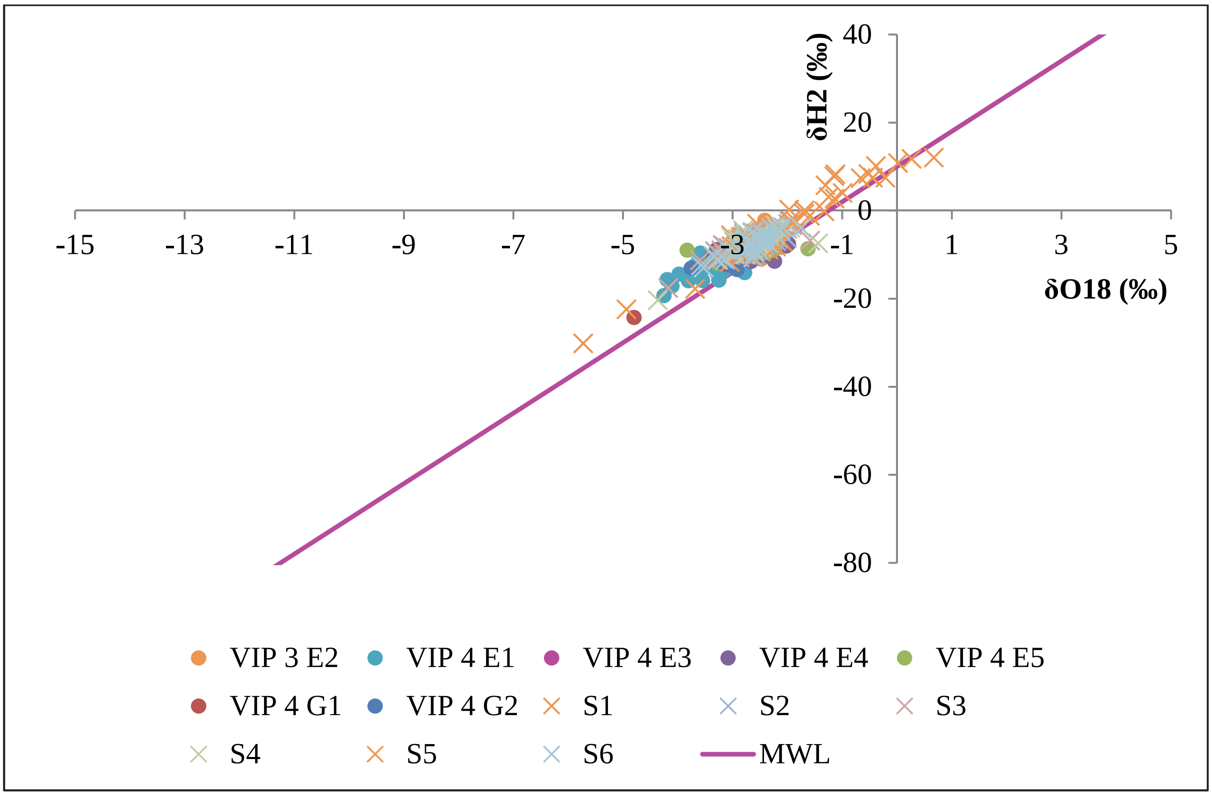


Figure 4.1 Isotope results for the piezometers and stream at Taylors Halt site

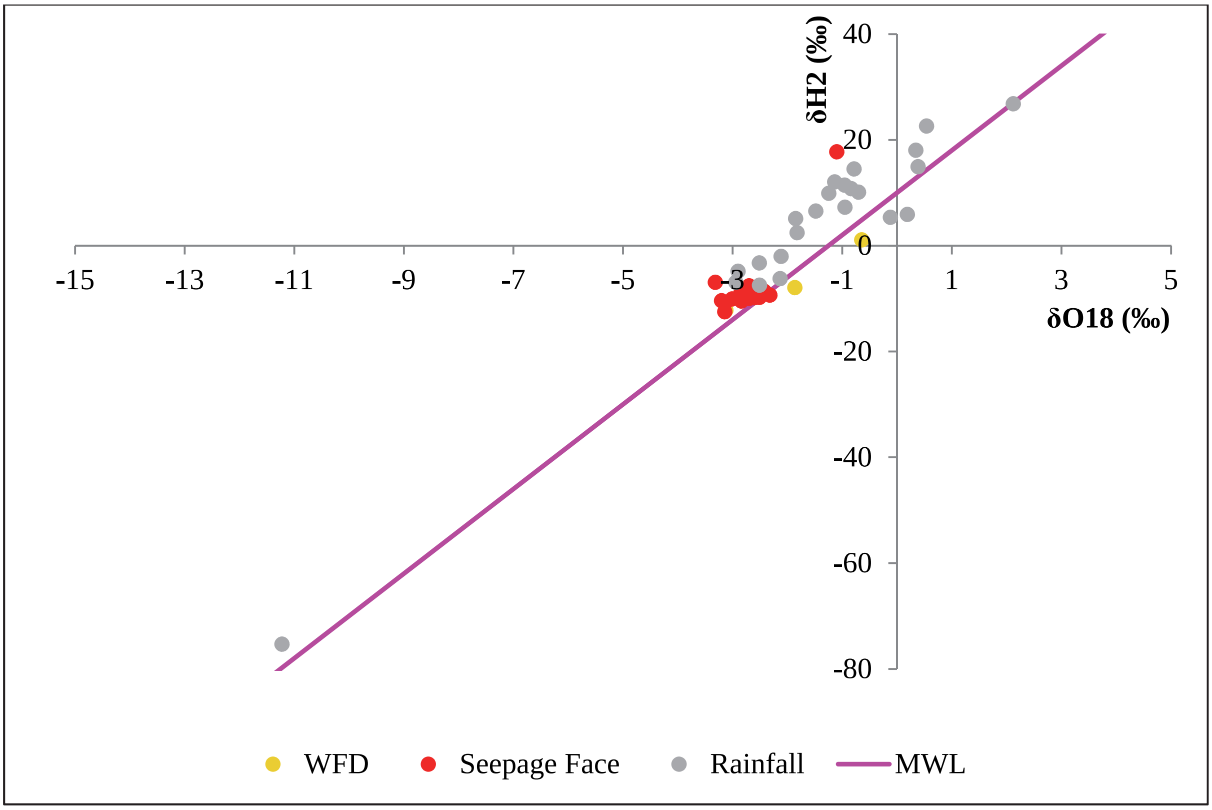


Figure 4.2 Isotope results for the WFD, seepage face and rainfall at Taylors Halt site

The Taylors Halt site consists of a hillslope transect of a series of VIP toilets on the slope (Figure 3.3). The soil varies in depth and characteristics throughout the hillslope. Near the top of the hillslope, the soil depth averages 1.8 m, whereas the middle of the slope consists of deep, well drained red appedal soil ranging from 3 m to >8 m, with no apparent signs of wetness (i.e. yellow/grey mottling). At the bottom of the slope the soil depth averages 2.5 m, where the upper 1.5 m of soil consists of well drained red appedal soil, with signs of wetness (i.e. yellow/grey mottling) at 1.5 m and more (Figure 3.4). Throughout the years only piezometers located at the bottom of the hillslope (horizontal transect piezometers E1-E5) had any water in them (VIP 3 E2 being the exception), particularly the ones sited within the seepage zone located on the left-hand side of the transect (E4 and E5).

With regard to the contaminants, it is not clear whether any pattern with distance from the VIP toilets exists, given that only the bottom horizontal transect has water. Piezometers VIP4 E1, VIP4 E5 and VIP4 G1 all exhibited intermittent high maximum nitrate values, above the 48 mg/l acceptable drinking water limit (Table 4.1). The same can be said for stream samples S1 and S5 (Table 4.1). In terms of phosphate, piezometers VIP4 E1, VIP4 E5, VIP4 G1 and VIP4 G2 also exhibited intermittent high maximum phosphate values (Table 4.1). Lastly, piezometers VIP3 E2 and VIP4 E1 showed high values for *E. coli* (Table 4.1), VIP4 E1 exhibited consistently high values.

Table 4.1 High maximum concentrations and source at Taylor's Halt site

Nitrate (as nitrate mg/l)	**Phosphate (as phosphate mg/l)**	***E. coli* (MPN/100 ml)**
VIP4 E1: 943.4	VIP4 E1: 206.2	VIP3 E2: 1159
VIP4 E5: 92.0	VIP4 E5: 3.7	VIP4 E1: 18600
VIP4 G1: 109.9	VIP4 G1: 12.9	S1: 6867
S1: 47.6	VIP4 G2: 4.5	S2: 3130
S5: 57.6	-	S3:1935
-	-	S5: 1124

The intermittently high contaminant concentrations at piezometers VIP4 E1, VIP4 E5, and VIP4 G1 indicate that there was possible leaching from the nearest VIP leach pit (i.e. VIP4). However given that these piezometers and the stream exhibited intermittently high values (sometimes only on one occasion) indicates that there is not a consistent plume of contaminants leaching from the leach pit. Instead, under the right circumstances (i.e. high rainfall, and presence of preferential flow *via* macropores in the subsurface), nitrate, phosphate and *E. coli* from the VIP systems may travel up to 30 m, 57 m or more.

Sulphate, ammonium, chloride and potassium revealed no noticeable pattern, as the concentration of the respective nutrients remained fairly similar through the different water sample points. The nitrate, phosphate and *E. coli* results of sampling for the Taylors Halt site, are shown in Figures 4.3 to 4.10. Plots are also included for the remainder of the species in the Appendices.

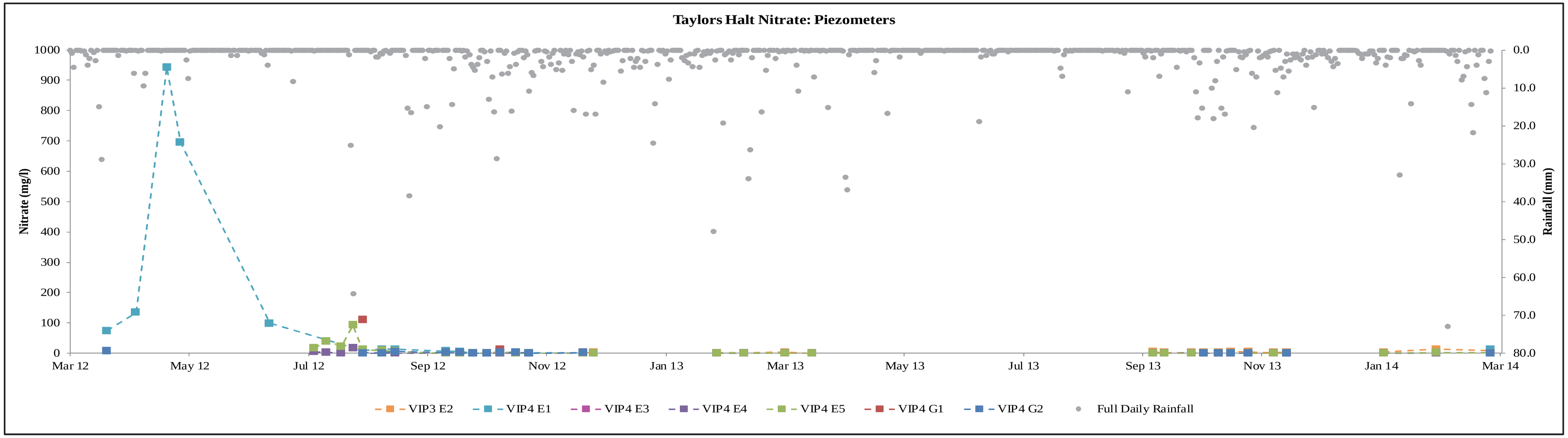


Figure 4.3 Nitrate results for the piezometers at Taylors Halt site

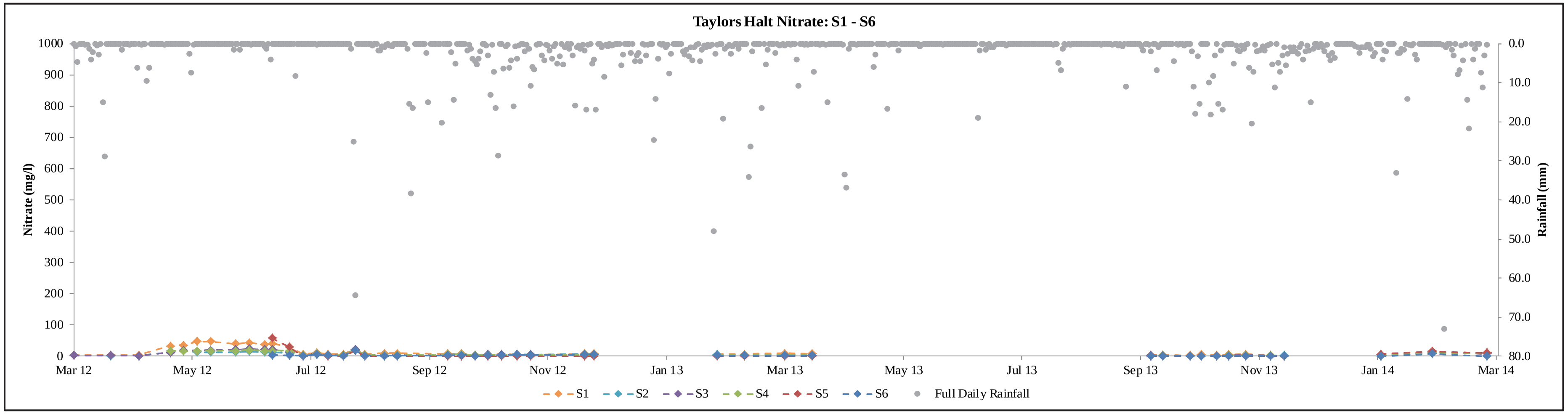


Figure 4.4 Nitrate results for the stream at Taylors Halt site

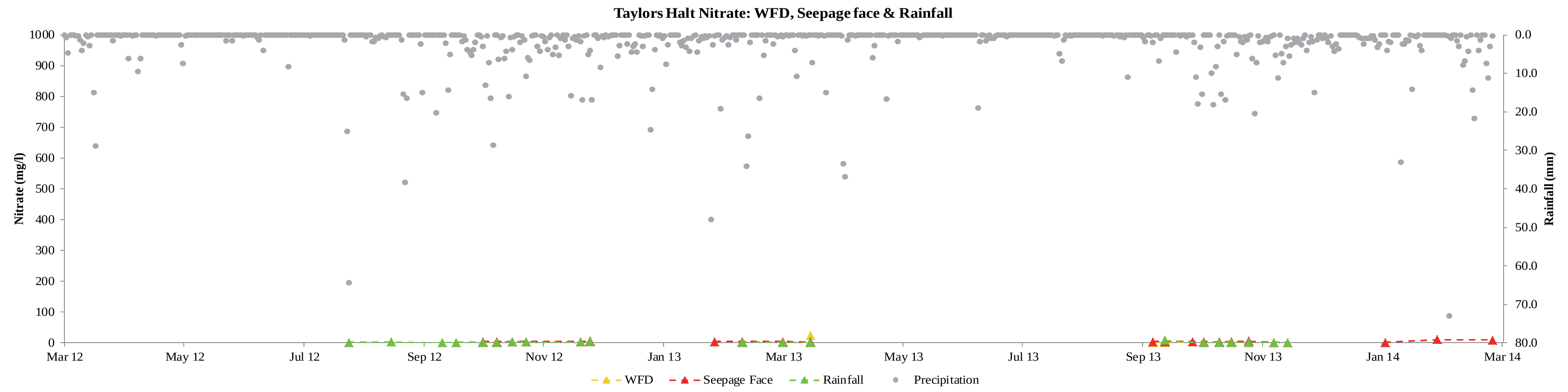


Figure 4.5 Nitrate results for the WFD, Seepage face and Rainfall at Taylors Halt site

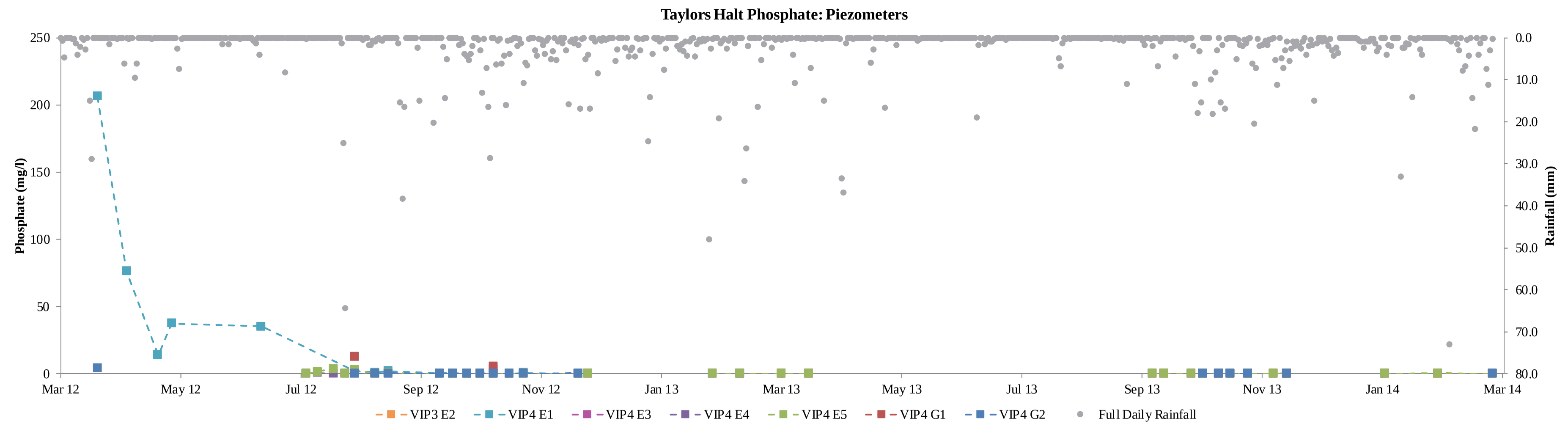


Figure 4.6 Phosphate results for the piezometers at Taylors Halt site

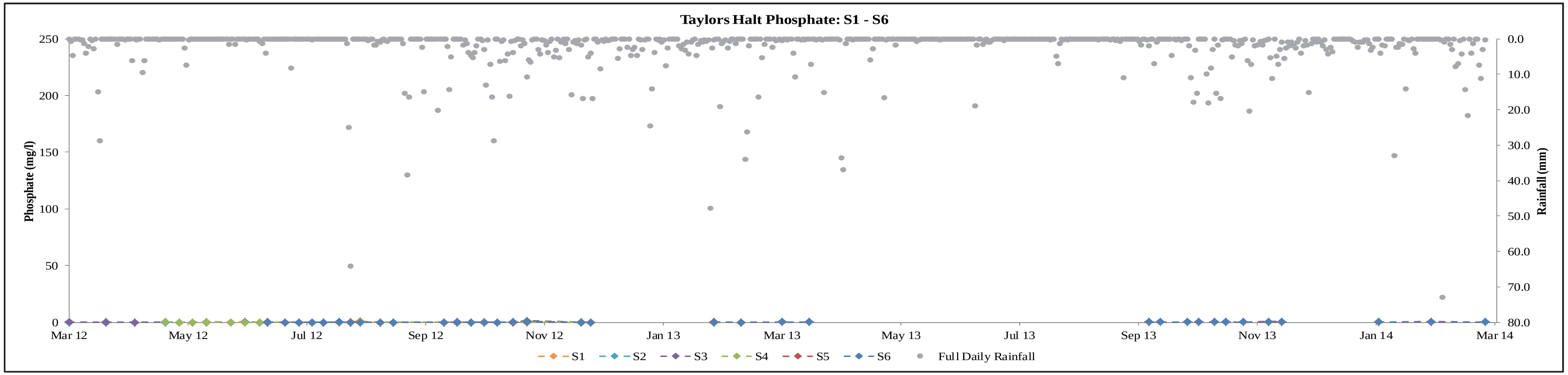


Figure 4.7 Phosphate results for the stream at Taylors Halt site

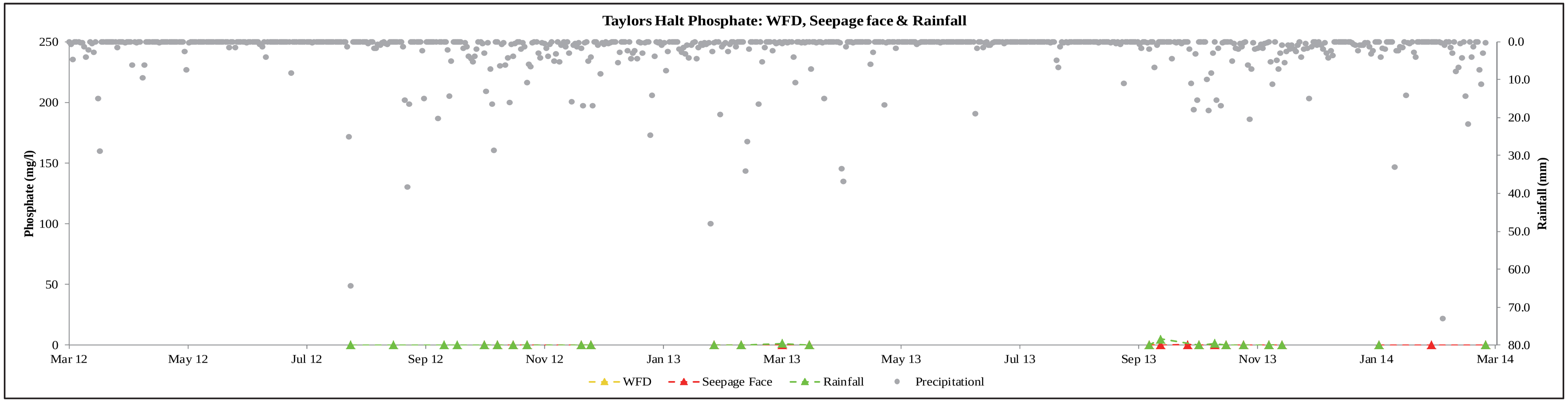


Figure 4.8 Phosphate results for the WFD, Seepage face and Rainfall at Taylors Halt site

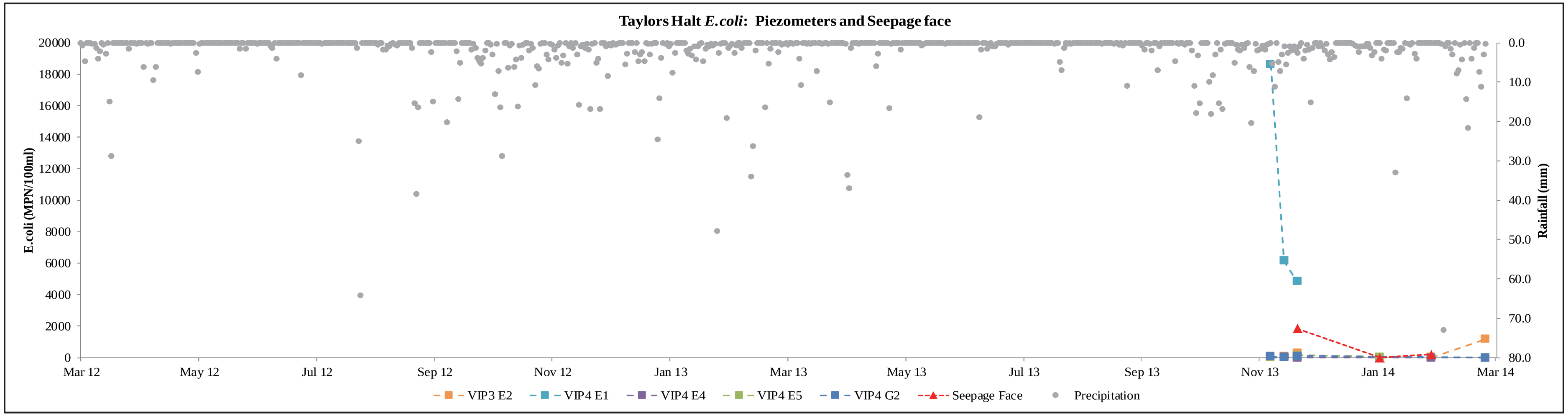


Figure 4.9 E. coli results for the Piezometers and Seepage face at Taylors Halt site

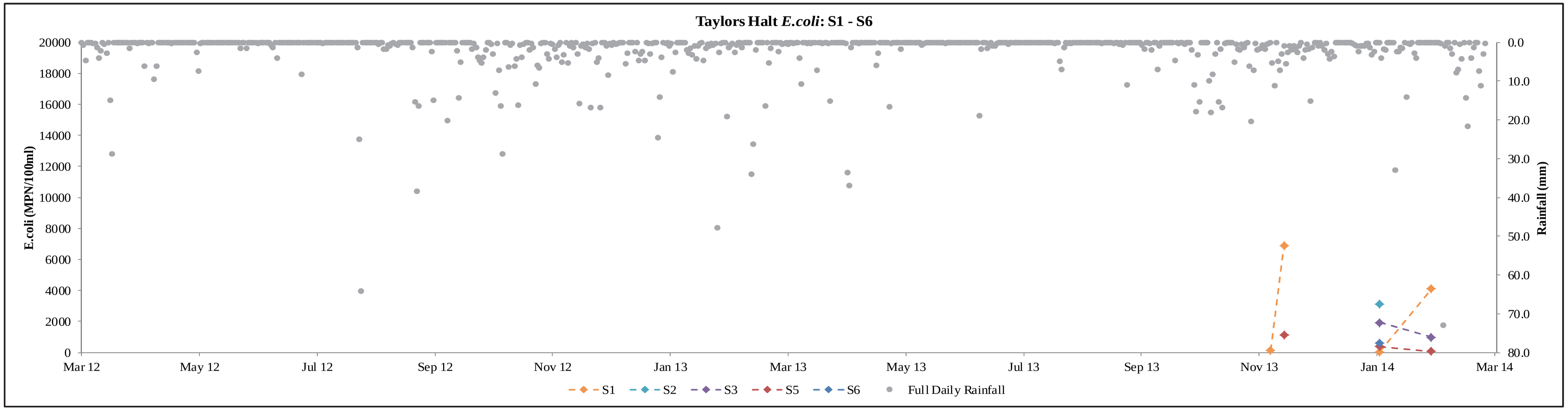


Figure 4.10 E. coli results for the stream at Taylors Halt site

4.2. Slangspruit

The isotope data at the Slangspruit site fell consistently along the meteoric water line (Figures 4.11 and 4.12). The rainfall isotope values vary widely. 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.

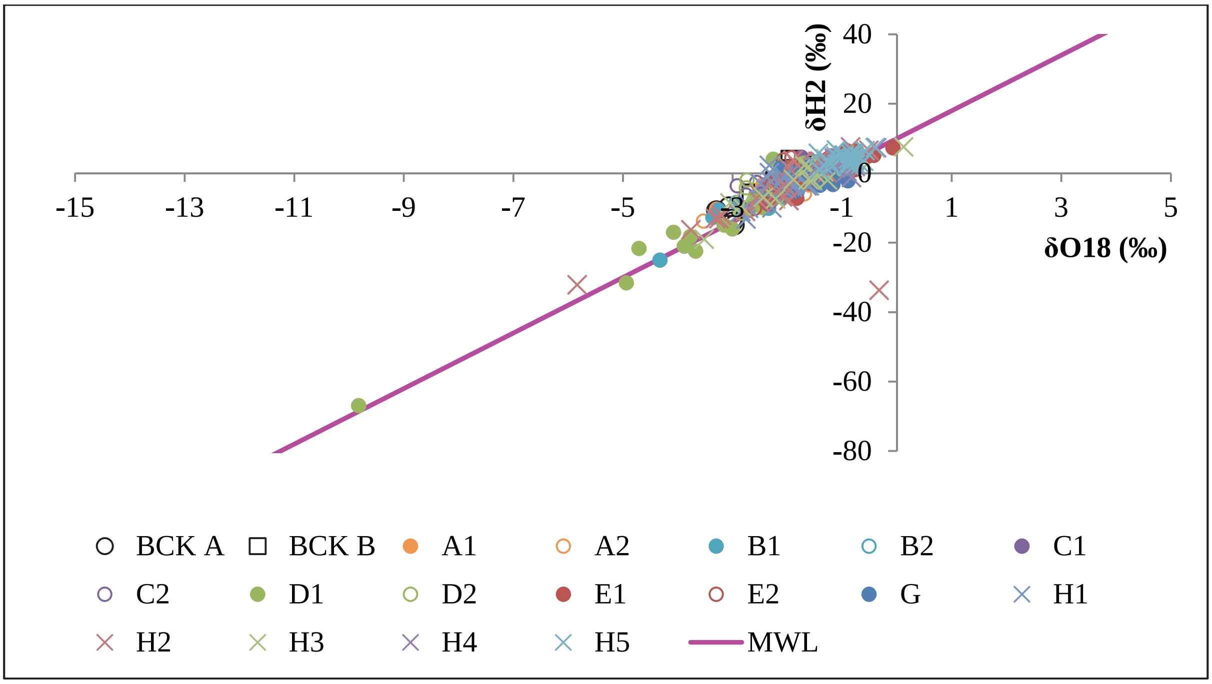


Figure 4.11 Isotope results for the piezometers at Slangspruit site

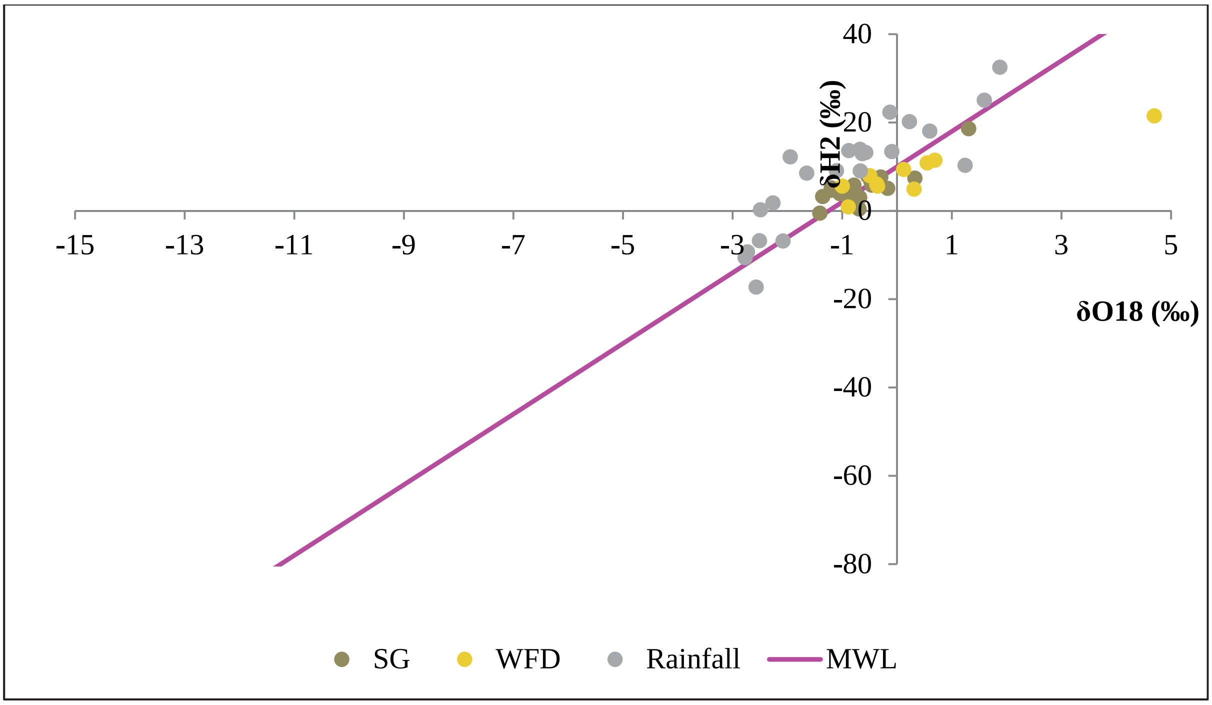


Figure 4.12 Isotope results for the Surface Gutter, WFD, and Rainfall at Slangspruit site

Unlike the Taylors Halt site, the soil profile at the Slangspruit site was considerably shallower, clayeyer and had a higher water table. The soil profile averages 1.5 m, with a distinct clay layer at 0.5 m. The water table remained near the surface, on average 0.4 m, which occasionally breached the soil surface shortly after high rainfall events. From the double ring infiltration measurements, the soil surface has a low infiltration rate of 0.46 cm/hr, and at 0.5 m no water infiltrated after 6 hours of measurements.

With regards to the contaminants, there are two distinct observations. Firstly, the highest concentrations were measured in the piezometers closest to the pour-flush leach pits (i.e. within 2 m), which generally decreased in value at greater distances from the leach pit (piezometers BCK A, H1-H5 being the exception). It was speculated that the elevated levels at BCK A, H1-H5 was due to their close proximity to chicken pens, the surface gutter used regularly to convey grey water and consistent defecation from domestic animals. Secondly, there was a distinct highly reducing zone 1 m from the leach pit. Here the ORP values were consistently negative and reached values up to -236 mV, and sulphate values had been considerably reduced (i.e. average 9.0 mg/l). At this point, nitrate values were considerably low (i.e. < 20.0 mg/l) and ammonium and phosphate values were at their highest (239.3 mg/l and 44.6 mg/l, respectively). The chloride, calcium, magnesium and sodium values were generally higher in the piezometers nearest to the leach pits, and decreased in concentration and greater distances from the leach pits. Table 4.3 shows the elevated levels of contaminants in selected piezometers.

Table 4.2 High maximum concentrations and source at Slangspruit site

Nitrate (as nitrate mg/l)	**Phosphate (as phosphate mg/l)**	***E. coli* (MPN/100 ml)**
A1: 1656.5	B1: 2.4	C1: 24192
A2: 773.9	B2: 7.3	D1: 7030
B1: 1502.0	C1: 44.6	E1: 24192
C2: 493.4	D1: 4.7	E2: 8164
D1: 165.7	-	-

It appears that the nutrients in the water samples originate from the leach pits. The clayey subsurface soils tend to act as an impervious layer, which favours a greater lateral movement of water compared to a vertical movement. This is confirmed considering that there is water throughout the year in all the piezometers except 1, and during the wet season, the water level remains close to the soil surface (approx. 0.4 m). The sharp drop in most nutrient concentrations within the first few meters from the leach pit, may be attributed to adsorption onto clay surfaces (cations, as well as phosphate). Prolonged reducing conditions may also result in partial inhibition of nitrification (i.e. high ammonium values) and gaseous losses of nitrogen, but the also the release of phosphate that were fix under previous aerobic conditions. The dilution effect is also likely to have some influence, but not as significant as the previous factors. The elevated nutrient concentrations in piezometer G may be because it is the deepest piezometer at the study site, and is intercepting a greater section of the contaminated plume. The nitrate, phosphate and *E. coli* results of sampling for the

Slangspruit site, are shown in Figures 4.13 to 4.17. Plots are also included for the remainder of the species in the Appendices.

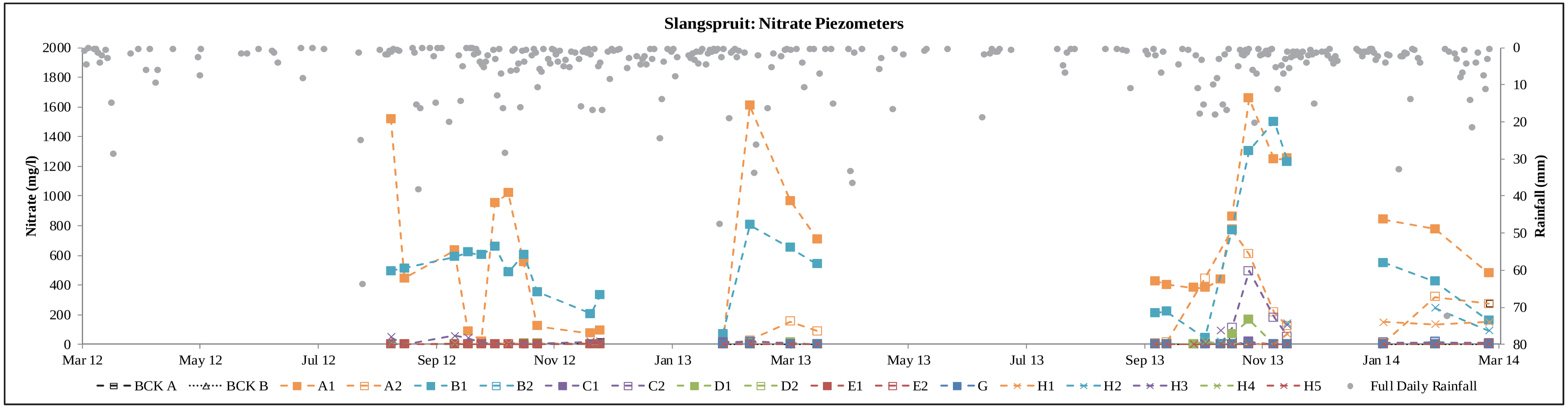


Figure 4.13 Nitrate results for the piezometers at Slangspruit site

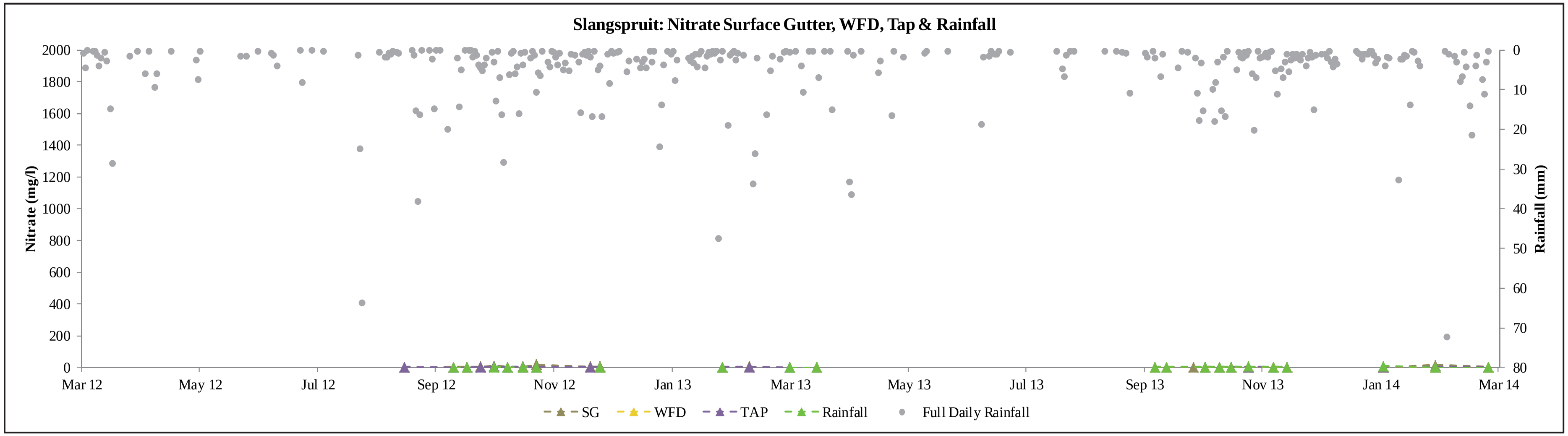


Figure 4.14 Nitrate results for the Surface Gutter, WFD, Tap and Rainfall at Slangspruit site

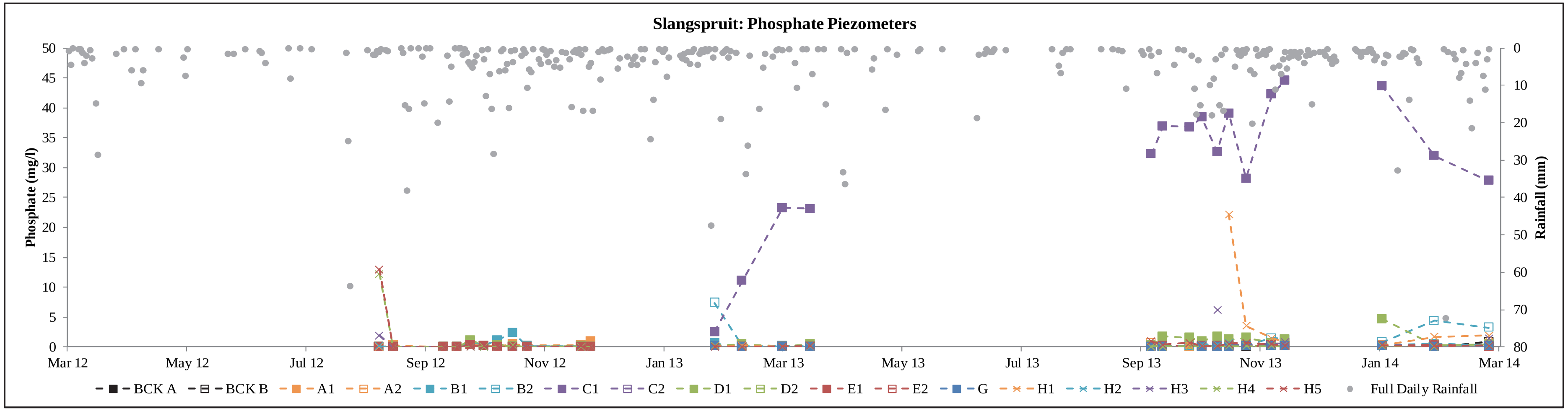


Figure 4.15 Phosphate results for the piezometers at Slangspruit site

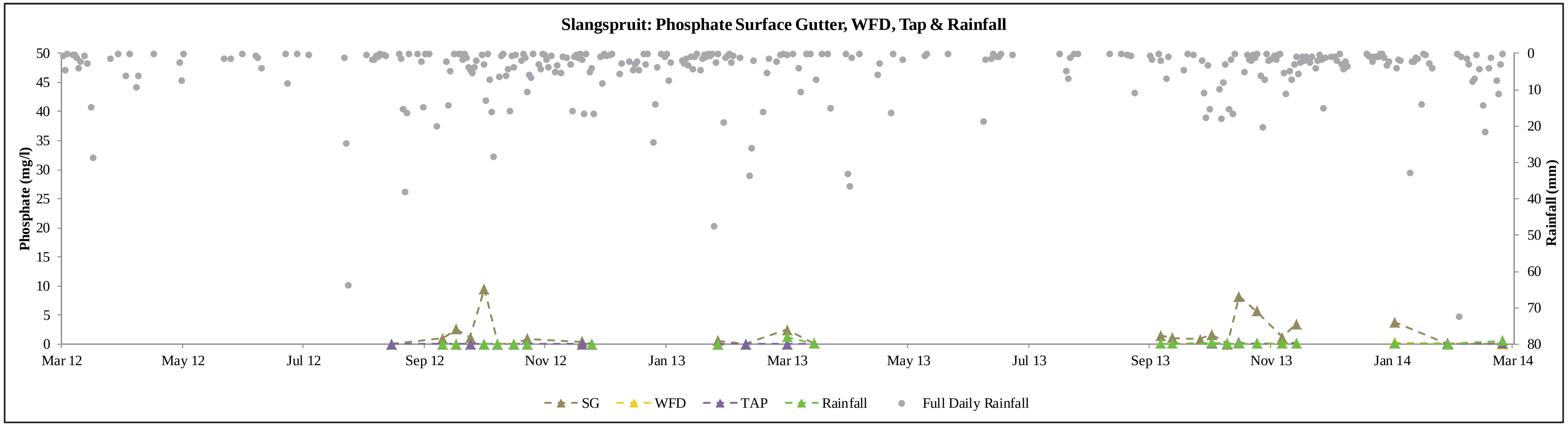


Figure 4.16 Phosphate results for the Surface Gutter, WFD, Tap and Rainfall at Slangspruit site

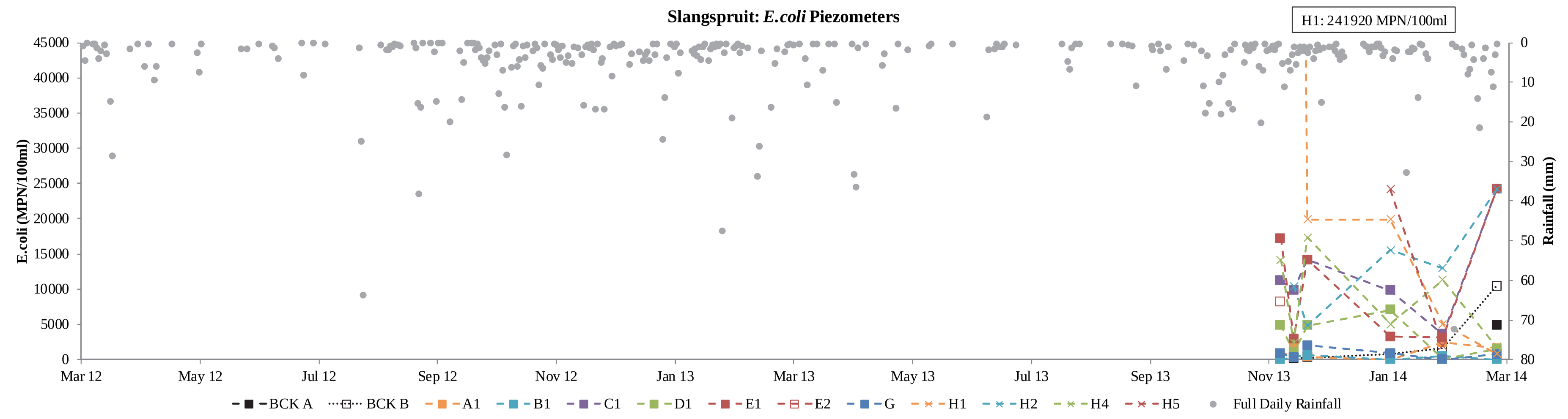


Figure 4.17 E. coli results at Slangspruit site

4.3. Crèche

The isotope data at the Crèche site fell consistently along the meteoric water line (Figures 4.18 and 4.19). The rainfall isotope values vary widely. 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.

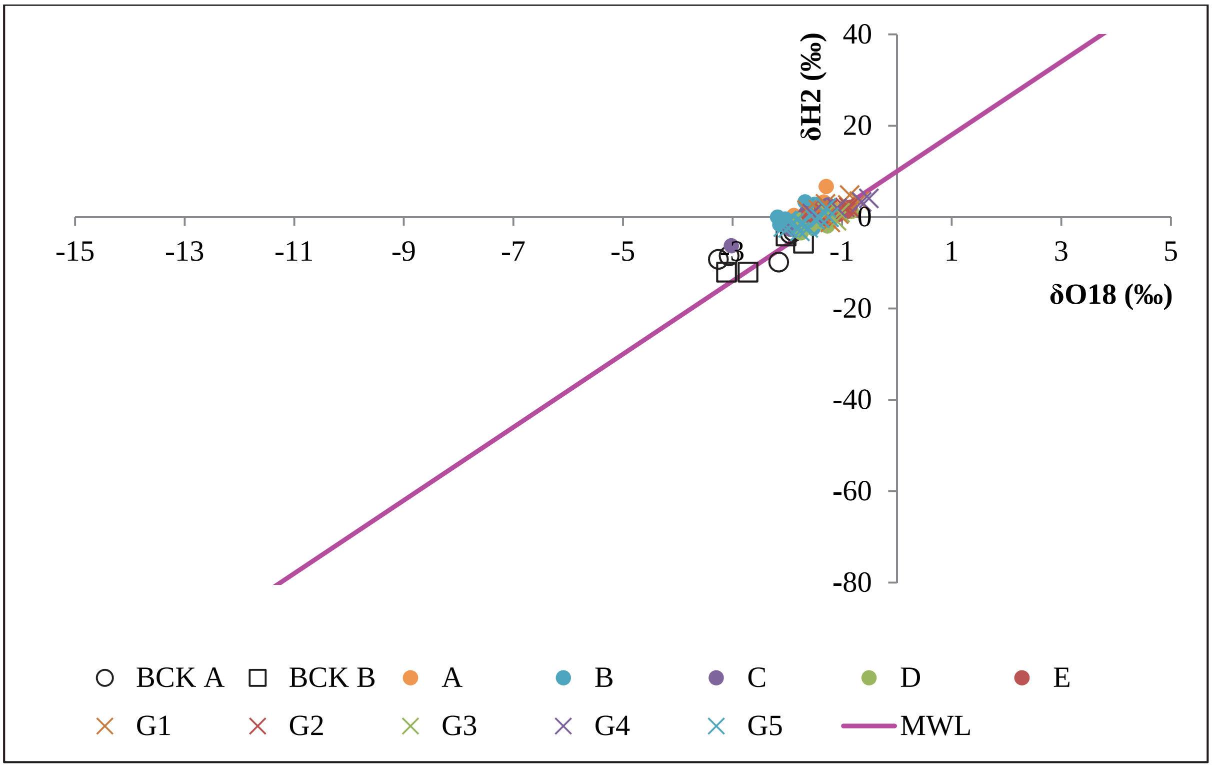


Figure 4.18 Isotope results for the piezometers at Crèche site

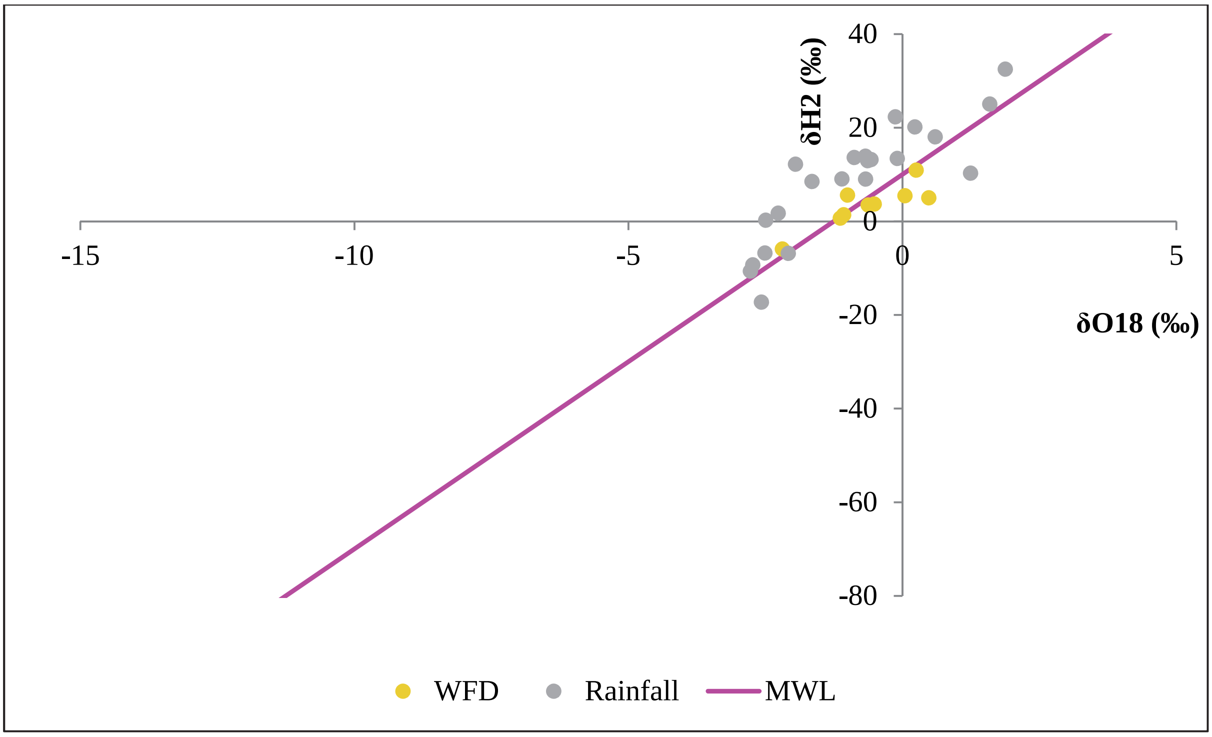


Figure 4.19 Isotope results for the WFD and Rainfall at Crèche site

The soil profile was similar to the Slangspruit site, in terms of it shallow depth (approx. 1.3 m), clayey properties and same parent material. From the double ring infiltration measurements, the soil surface has a low infiltration rate of 2.38 cm/hr, and 0.05 cm/hr at 0.45 m. Unlike the Slangspruit site, the water table was considerably lower (approx. 0.8 m and it never breached the soil surface), and was disturbed considerably near the bottom of the study transect. This indicates that while there may be similar near-surface water flow as the Slangspruit site, there is more vertical water movement than lateral. In the dry season, there is little water in the piezometers, where there was only water in piezometers A to E, G5 and rarely in G1 to G4 and background piezometers.

With regards to the contaminants, the plume behaviour at the Creche site appears to be similar to the Slangspruit site. High nitrate values are observed in piezometers A (0.5 m), and in G1-G4 when they exhibited a water sample. However unlike the Slangspruit site, the phosphate values were considerably low (i.e. all the piezometer showed values < 0.8 mg/l) at the Crèche, where piezometer A exhibited the highest value. Lastly, piezometers A, B and E exhibited high *E. coli* values. It was speculated that the intermittent elevated levels of *E. coli* in the background piezometers, was due to the nearby defecation from domestic animals and the unexpected installation of an unimproved pit latrine near background piezometer B. Table 4.4 shows the elevated levels of contaminants in selected piezometers. In general, the piezometers nearest to the pour-flush leach pit showed high nutrient concentrations, which decreased with distance from the leach pits.

Table 4.3 High maximum concentrations and source at Crèche site

Nitrate (as nitrate mg/l)	**Phosphate (as phosphate mg/l)**	***E. coli* (MPN/100 ml)**
A: 661.8	A: 0.7	A: 7701
G1: 62.8	B: 0.4	B: 992
G2: 47.0	-	E: 3106
G3: 70.2	-	
G4: 76.9	-	

Similar to Slangspruit, the nutrients do appear to originate from the leach pit, and the sharp drop in nutrient concentrations may be attributed to adsorption onto clay surfaces (cations, as well as phosphate); prolonged reducing conditions resulting in gaseous losses (nitrogen) and a dilution effect. The spike of Ca, Mg, Na and K nutrient concentrations in piezometer G5 may be due to the fact that it is the deepest piezometer at the study site, and is intersecting a greater portion of the contaminated plume. The nitrate, phosphate and *E. coli* results of sampling for the Crèche site, are shown in Figures 4.20 to 4.24. Plots are also included for the remainder of the species in the Appendices.

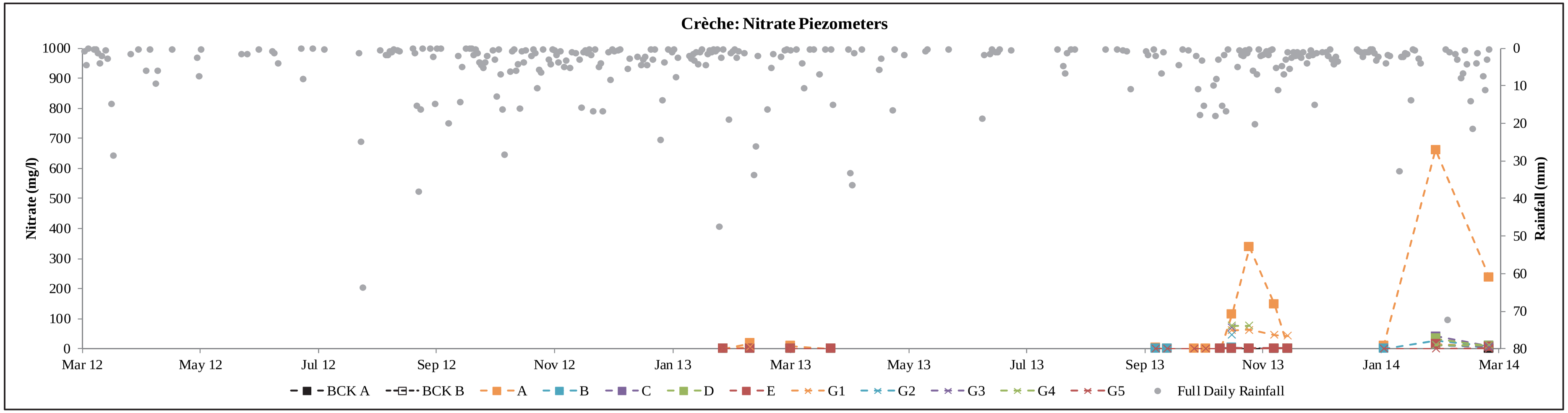


Figure 4.20 Nitrate results for the piezometers at Crèche site

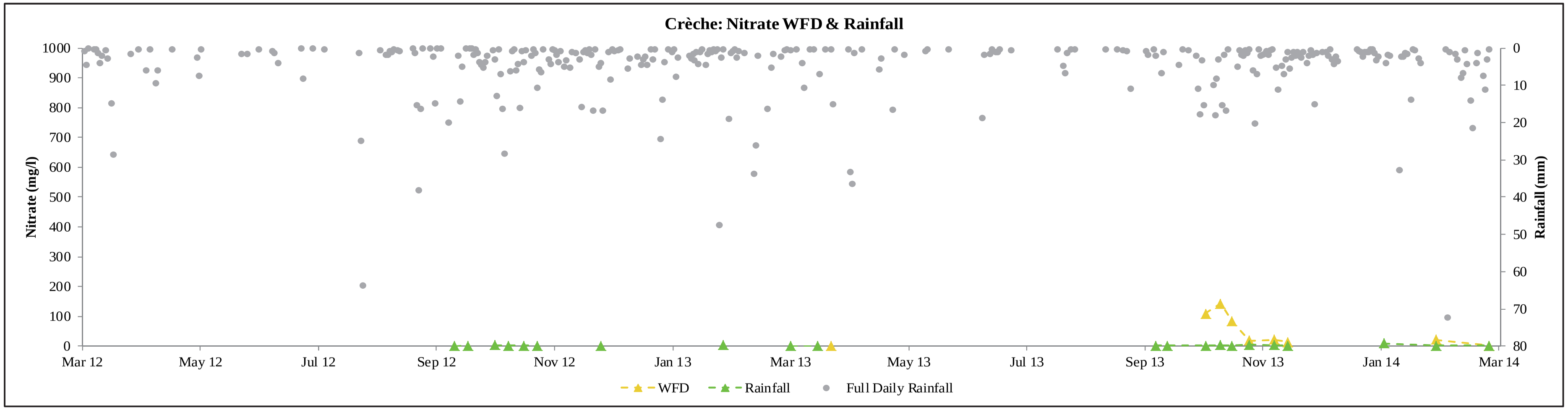


Figure 4.21 Nitrate results for the WFD and rainfall at Crèche site

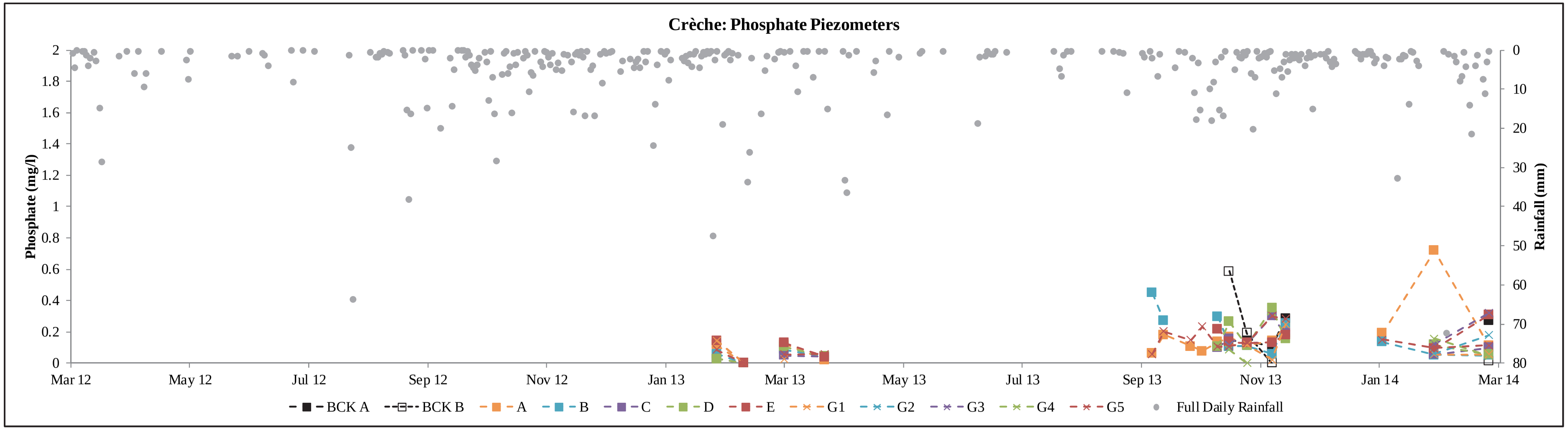


Figure 4.22 Phosphate results for the piezometers at Crèche site

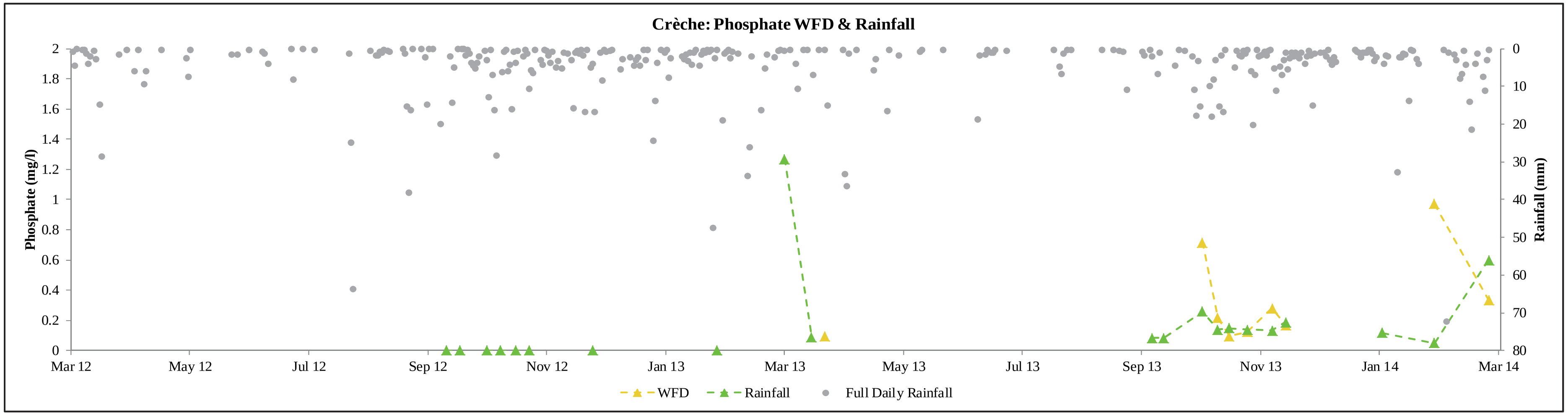


Figure 4.23 Phosphate results for the WFD and rainfall at Crèche site

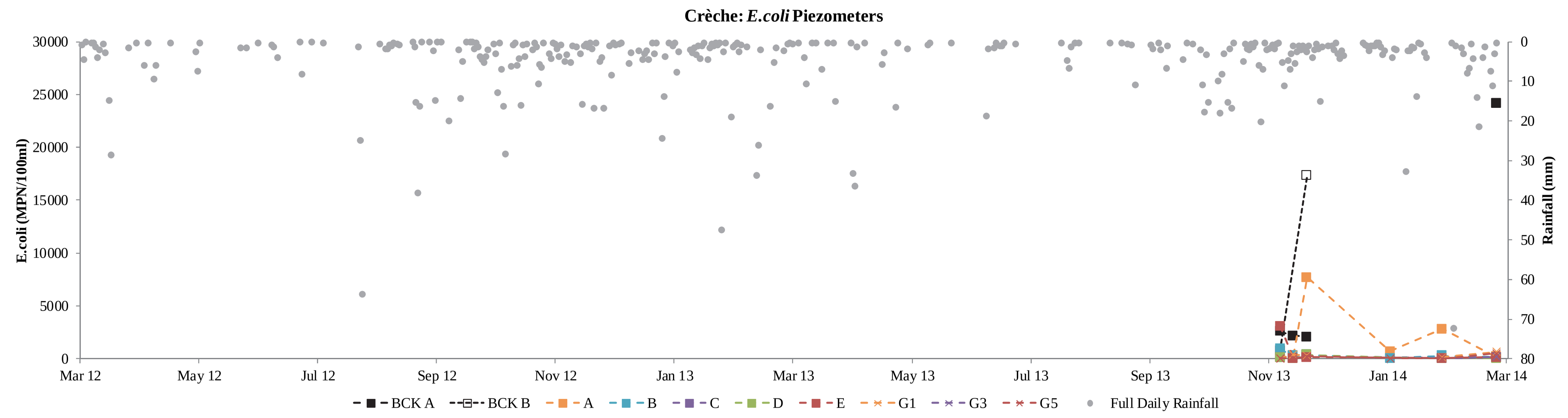


Figure 4.24 E. coli results at Crèche site

4.4. Azalea

The isotope data at the Azalea site fell consistently along the meteoric water line (Figures 4.25 and 4.26). The rainfall isotope values vary widely. The isotope values from the rainfall, wetting front detectors, piezometers and the stream, 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, and that the stream is hydraulically linked to the hillslope water.

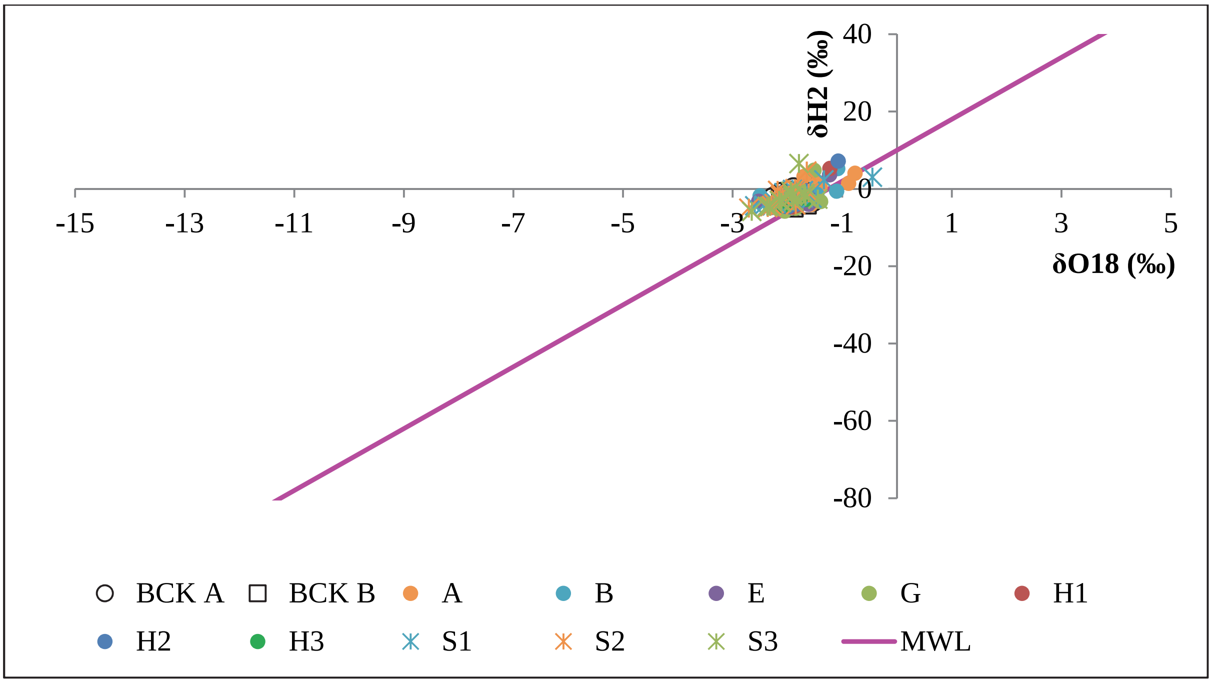


Figure 4.25 Isotope results for the piezometers and stream at Azalea site

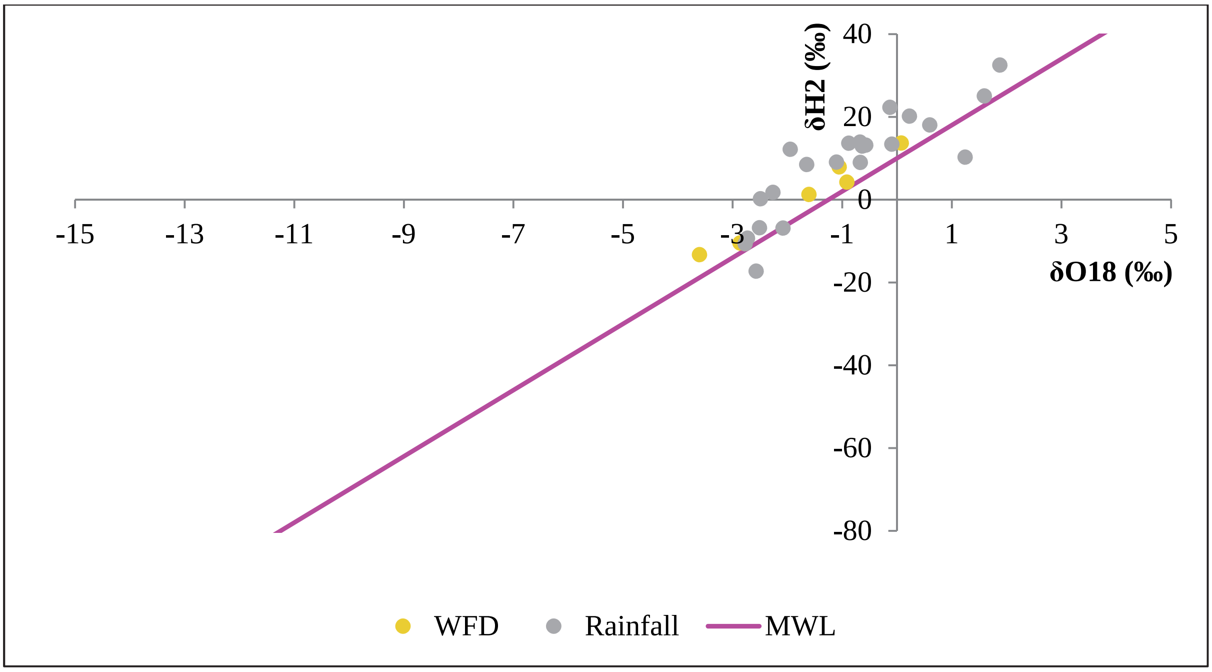


Figure 4.26 Isotope results for the WFD and Rainfall at Azalea site

The Azalea site layout, with a single house leach pit, is shown in Figure 3.9. At this steep site, adjacent to a stream, the soil profile was different to the previous sites, and more similar to the Taylor Halt site. From the double ring infiltration measurements, the soil surface has a infiltration rate of 1.65 cm/hr, 0.46 cm/hr 0.5 m and 0.41 cm/hr at 1.5 m. The decrease in the saturated hydraulic conductivity down the soil profile, is small compared the change at the previous 2 sites. This implies that while the vertical movement of infiltrating water will decrease when it reaches 0.5 m, it is not enough to cause significant lateral water movement at this depth. This is supported by investigating the soil profile at this site, as shown in the Figure 3.10. Here the first 5 m of soil consists of red apedal soil indicating a well-drained soil, and a yellow and grey mottled layer at more than 5 m, indicating periods of saturation. Furthermore, the water level in this soil profile fluctuates around 5.2 m, which supports this view. Thus this site is significantly different to the previous 2 study sites, where the pour-flush leach pit does not sit in the water table, but rather above it by at least 3.5 m of unsaturated well drained soil. Thus the movement the nutrients from the leach pit is likely to travel vertically through the 3.5 m of unsaturated soil, and only then possibly move laterally. By the time it reaches this zone however, the concentration of the nutrients will have been noticeably reduced due to adsorption on to the clay particles. However, there was still a distinct nutrient plume in the piezometers downslope of the pour-slush leach pit.

Unlike the previous two study sites that were "noisy" in their water analyses data, there was a clear impact from the pour-flush leach pit at the Azalea site. With regards to the contaminants, the piezometers located within 1 m exhibited a plume of consistently high nitrate, phosphate and *E. coli* concentrations, and intermittently high values at 3 m, 9 m and 17.5 m (Table 4.4). In general chloride, calcium, magnesium and sodium exhibited the same pattern as the contaminants. The nitrate, phosphate and *E. coli* results of sampling for the

Azalea site, are shown in Figures 4.27 to 4.34. Plots are also included for the remainder of the species in the Appendices.

Table 4.4 High maximum concentrations and source at Azalea site

Nitrate (as nitrate mg/l)	**Phosphate (as phosphate mg/l)**	***E. coli* (MPN/100 ml)**
A: 942.4	A: 0.5	A: 28510
B: 508.0	B: 0.4	B: 24192
E: 112.0	E: 0.4	E: 1095
G: 80.4	-	H1: 1034
H2: 85.2	-	-

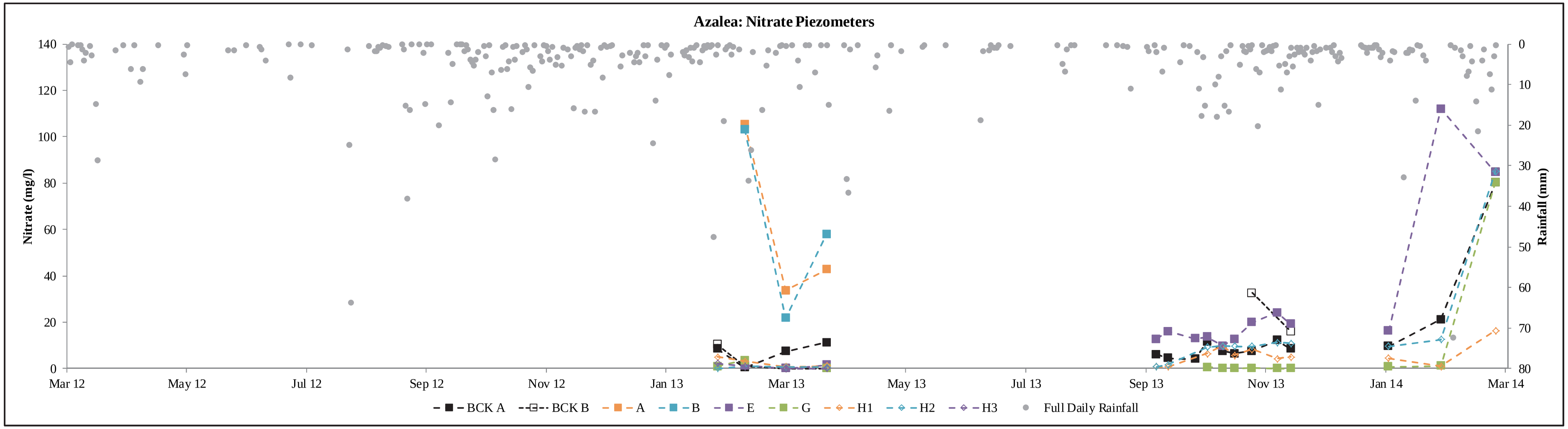


Figure 4.27 Nitrate results for the piezometers at Azalea site

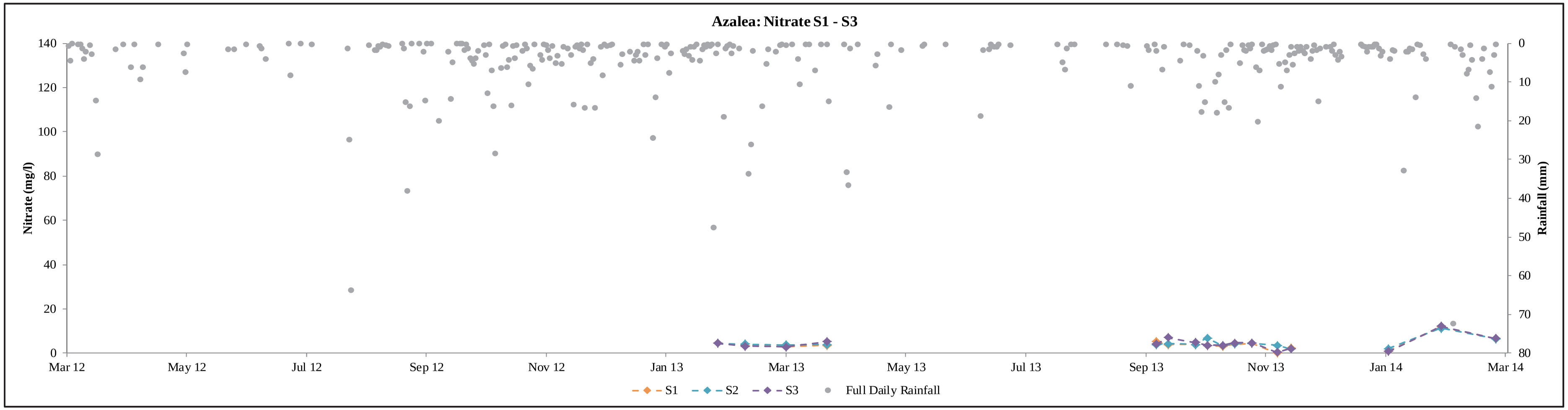


Figure 4.28 Nitrate results for the Stream at Azalea site

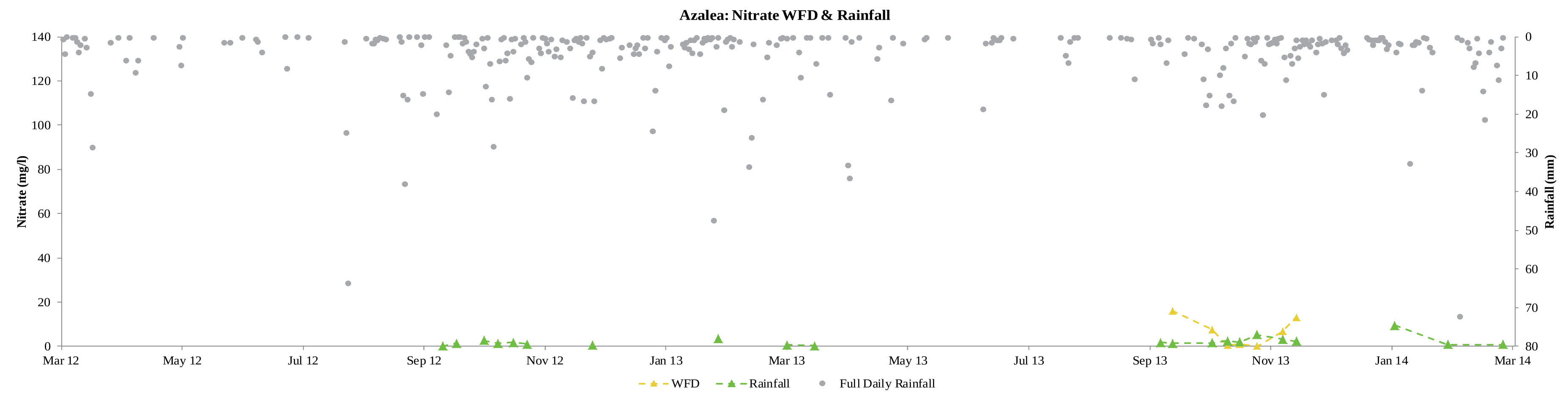


Figure 4.29 Nitrate results for WFD and Rainfall at Azalea site

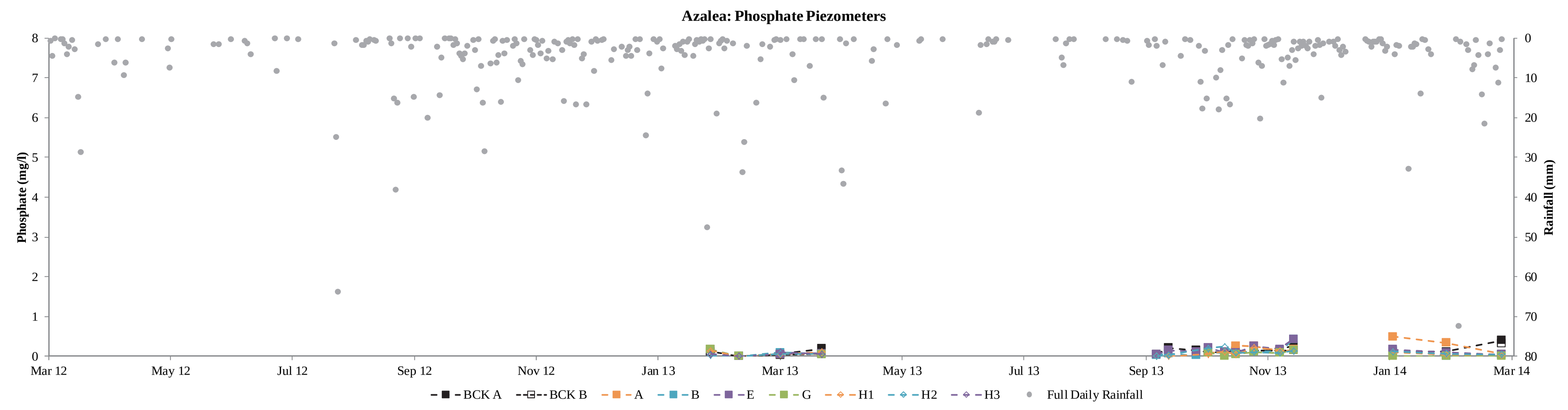


Figure 4.30 Phosphate results for the piezometers at Azalea site

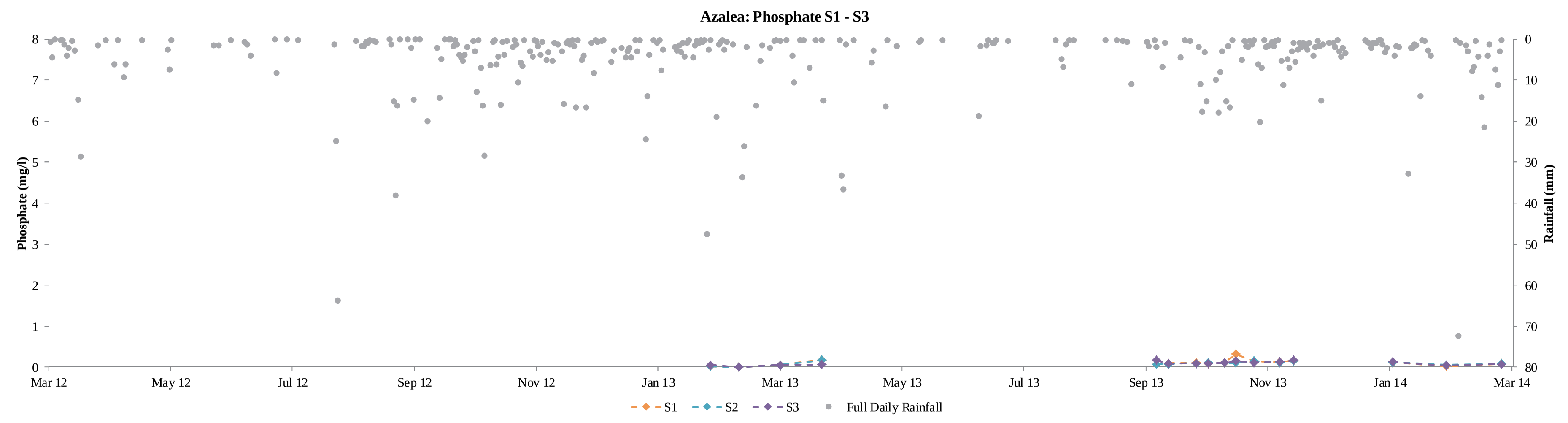


Figure 4.31 Phosphate results for the Stream at Azalea site

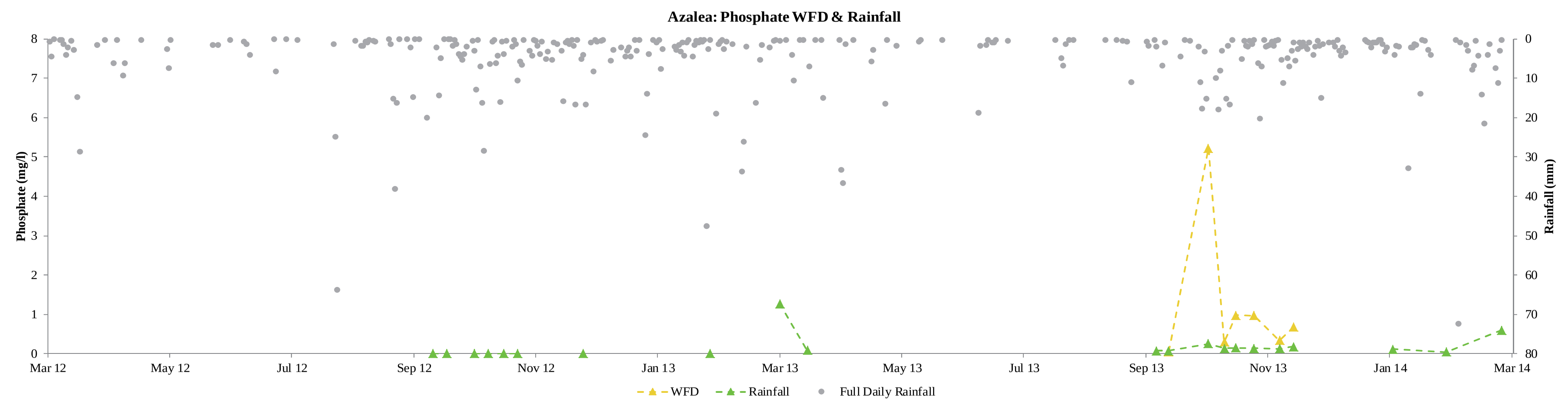


Figure 4.32 Phosphate results for WFD and Rainfall at Azalea site

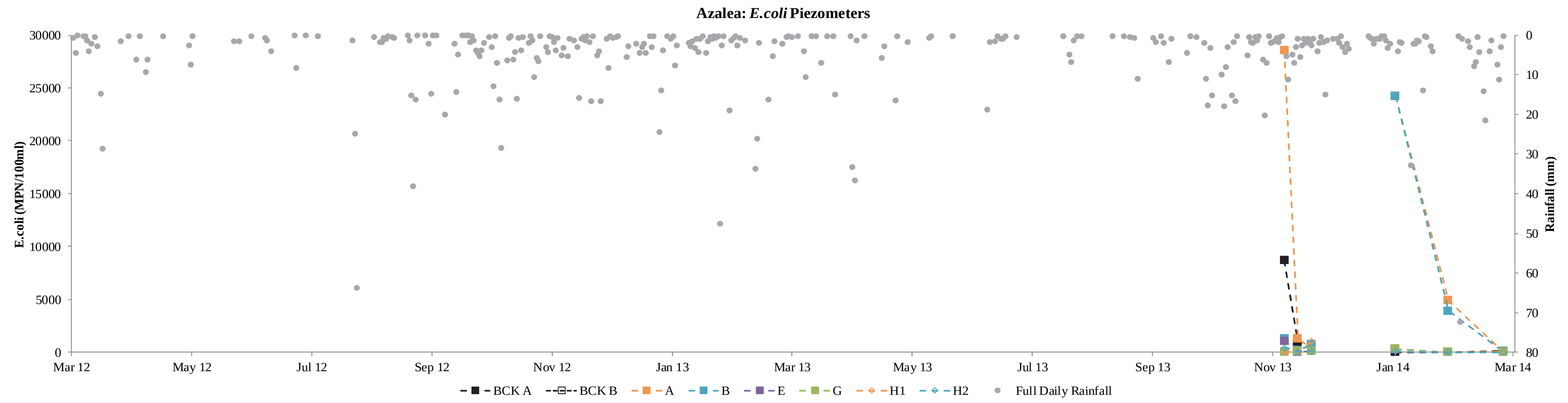


Figure 4.33 E. coli results for the piezometers at Azalea site

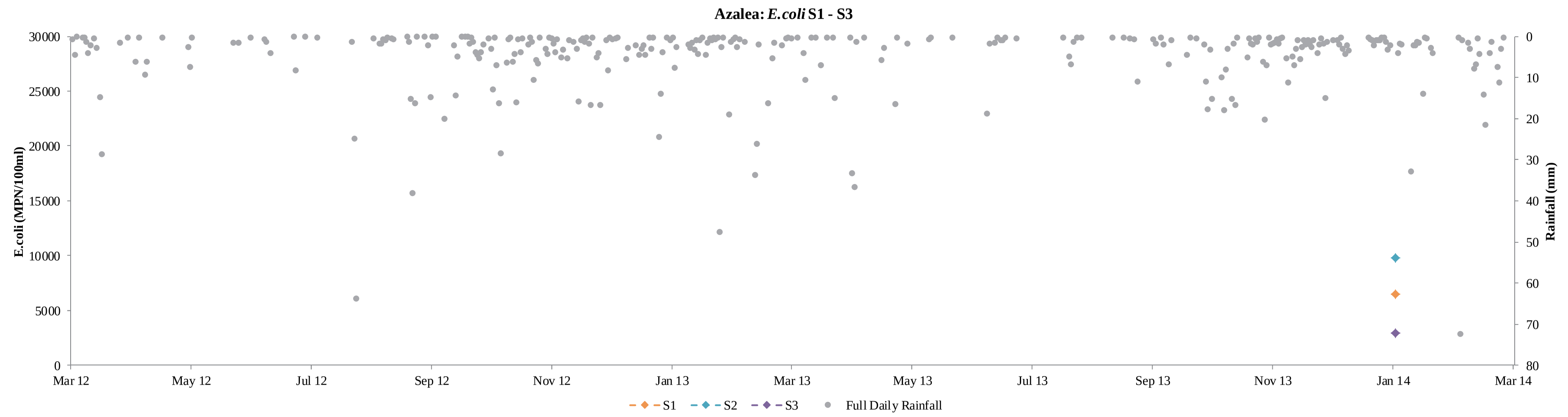


Figure 4.34 E. coli results for the Stream at Azalea site

5. LARGE SCALE LOADING

A river nutrient status, sampling campaign was conducted early May 2013. The results are reported in Figure 5.1. The objective was to relate any trends in the nutrient concentrations with associated land use, particularly adjacent on-site sanitation. Samples were taken from the uppermost reach of the stream of the Taylors Halt site (Figure 5.2), to its confluence with the Umsinduzi river. Various tributaries were also sampled.

While there is not a large variation in nitrate and phosphate concentrations, the headwaters of the Taylors Halt stream have very low nitrate and phosphate concentrations (station 21). The phosphate concentrations increase up to the confluence of the stream (station 11) with the main stem, where lower concentrations prevail (station 12). Further variations on the main stem appear to be influenced by incoming tributaries rather than adjacent land use.

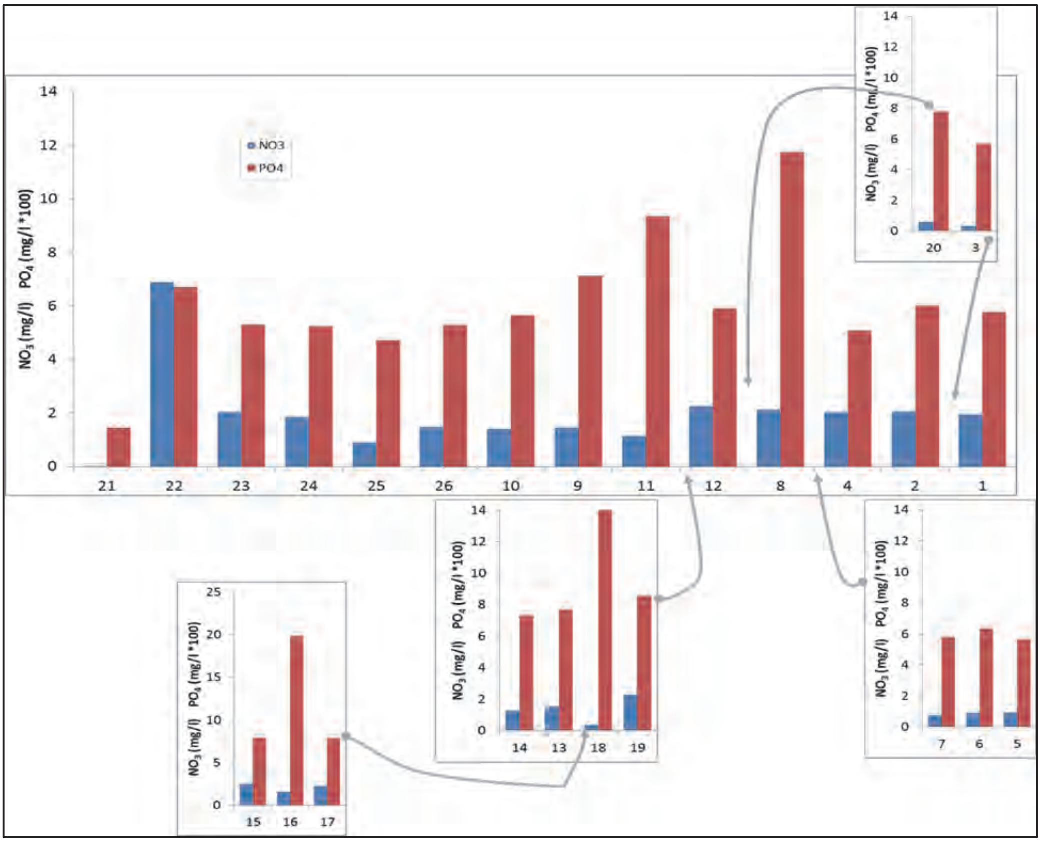


Figure 5.1 Surface water Nitrate and Phosphate concentrations from Taylors Halt stream to the Umsinduzi river

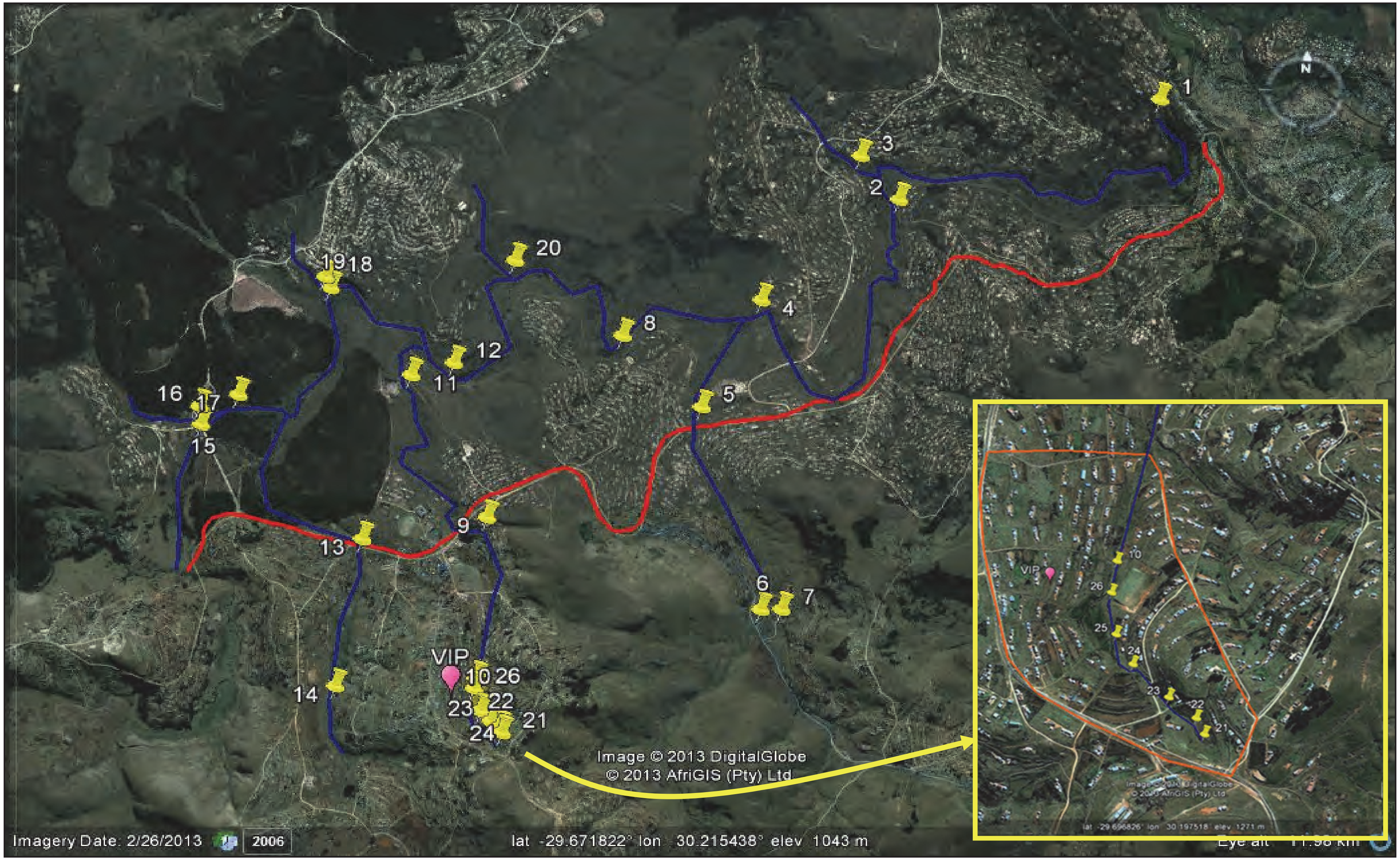


Figure 5.2 Map of sampling sites from the Taylors Halt area to the Umsinduzi river

6. IMPLICATIONS FOR GUIDELINE

Extensive auguring and topographical surveying with a differential GPS have been completed at each site. These data have been used in conjunction with the water and nutrient behaviour to develop site specific response sections (Figures 6.1 to 6.4). These can be used to identify critical features to avoid during siting of latrines.

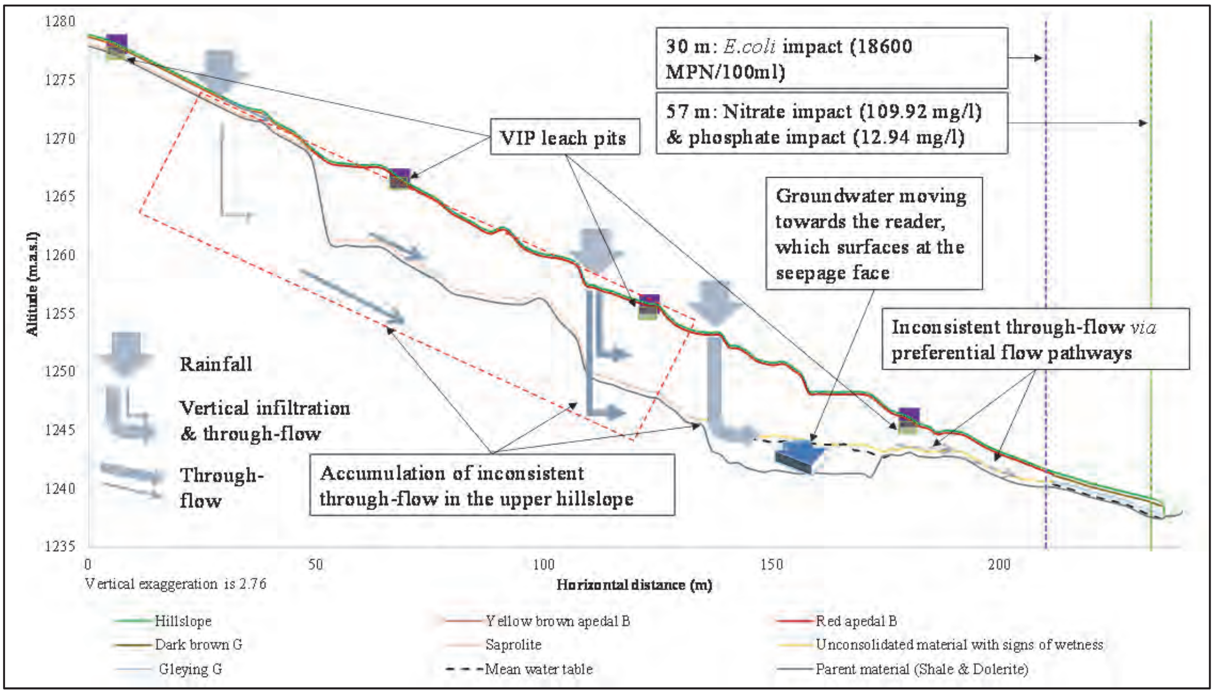


Figure 6.1 Cross-section of hillslope and contaminant migration at the Taylors Halt site

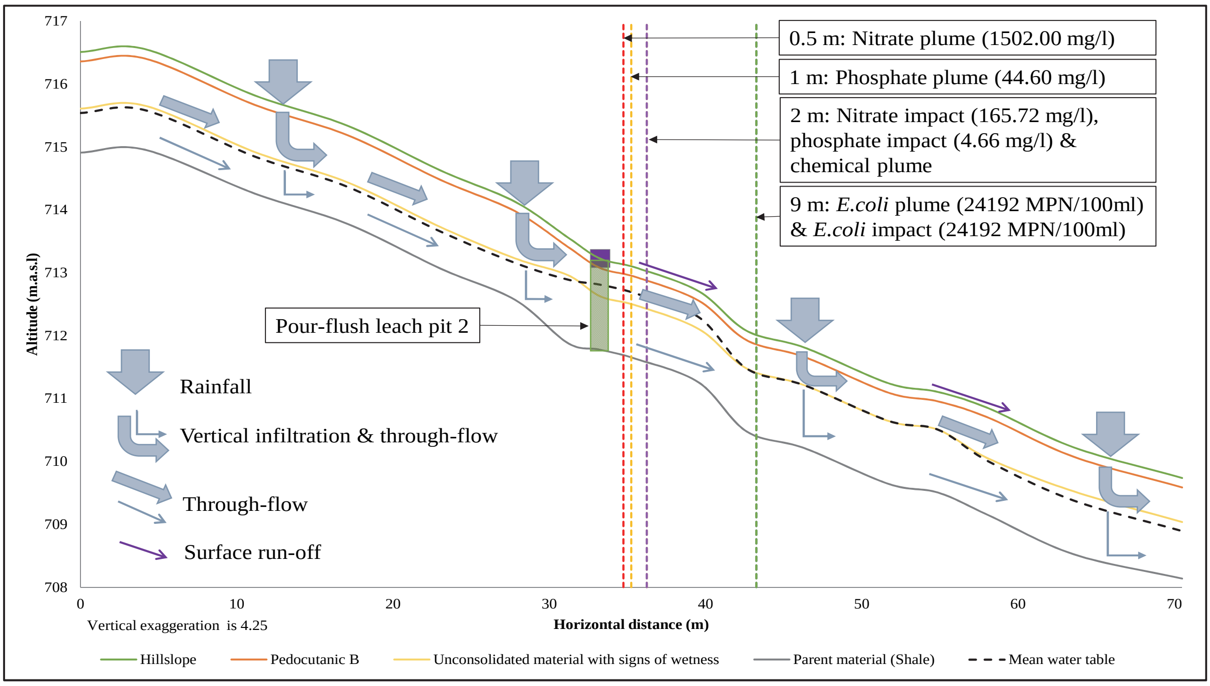


Figure 6.2 Cross-section of hillslope and contaminant migration at the Slangspruit site

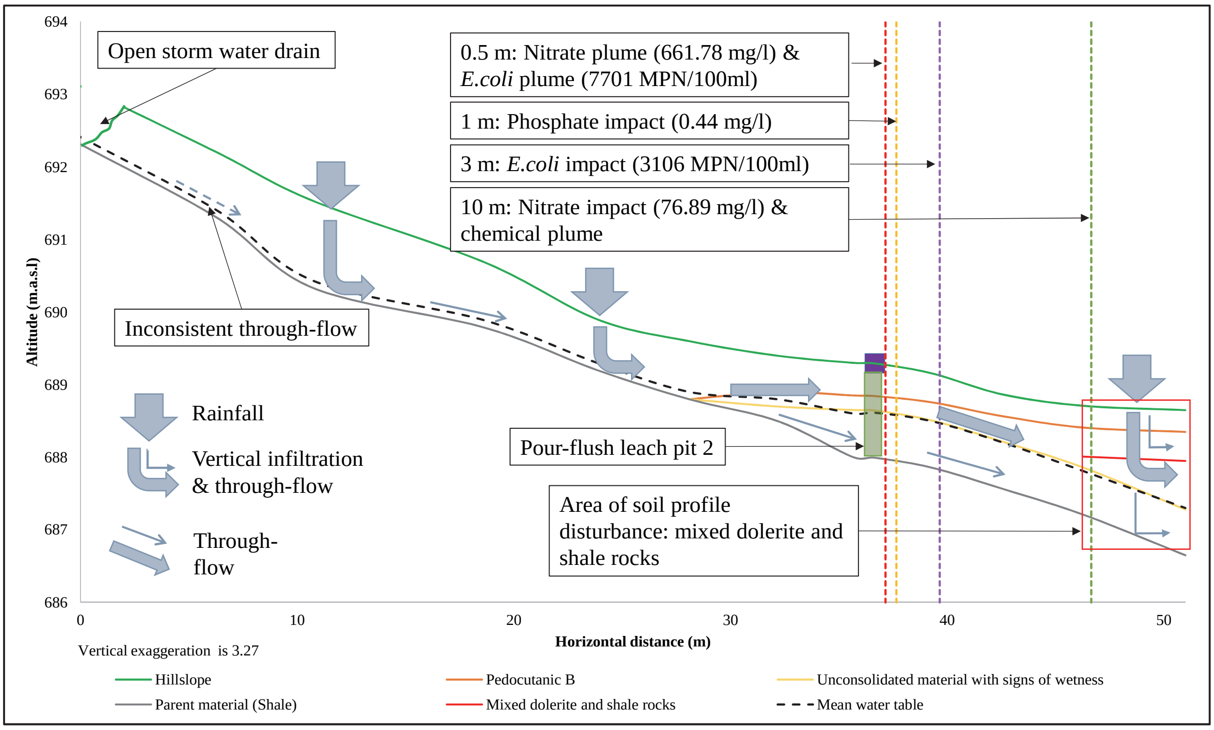


Figure 6.3 Cross-section of hillslope and contaminant migration at the Crèche site

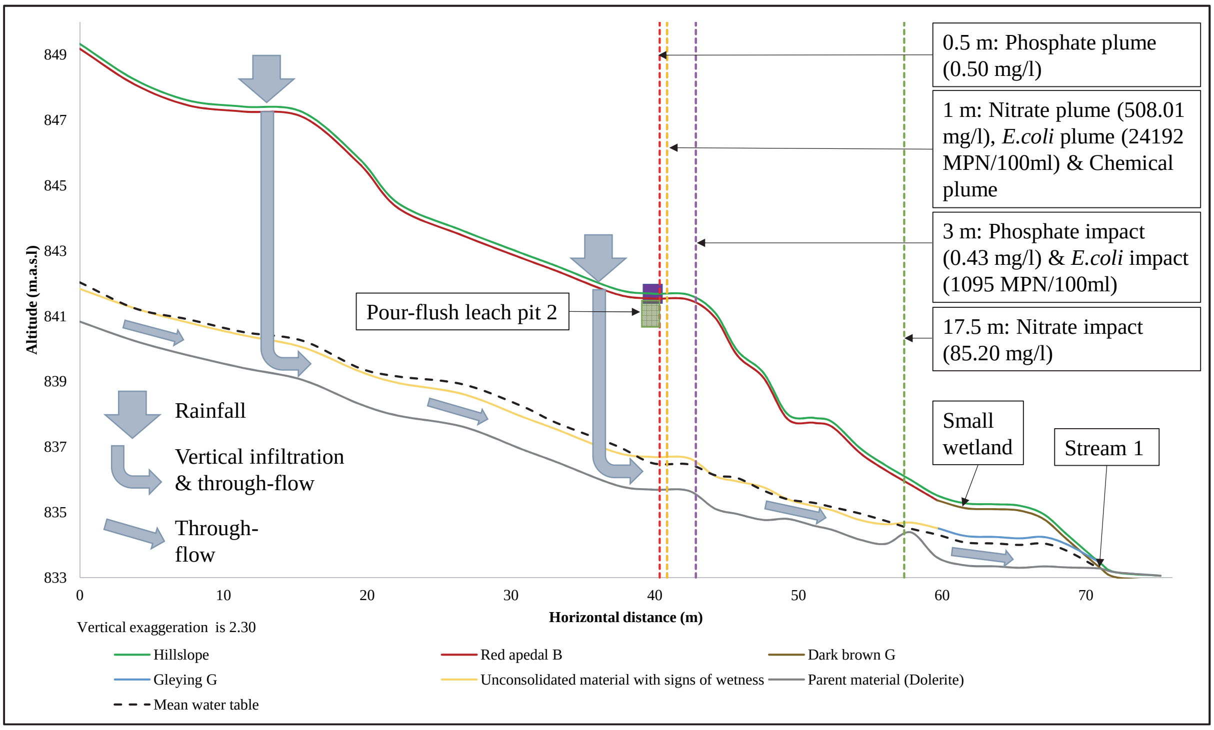


Figure 6.4 Cross-section of hillslope and contaminant migration at the Azalea site

7. CONCLUSIONS

7.1. Conclusions on Research Sites

In comparison to previous studies, nitrate movement does not appear to be as significant at the KwaZulu-Natal study sites compared to other studies. However they are consistent with each other in terms of greatest mobility during periods of high rainfall. The same can be said for the mobility of *E. coli*. However at the Slangspruit site, a distinct *E. coli* plume extended to 26 m, whereas the nitrate was only evident up to 3 m. At this site where the water table was consistently high (i.e. <1 m) it is suggested that in these circumstances, faecal coliform pose a risk of contaminating adjacent water resources.

7.1.1. Taylors Halt:

In the streams, nitrate rarely exceeds 10 mg/l. On one high rainfall event (46 mm), all the stream samples report a nitrate spike >20 mg/l. This may be due to the numerous animal excrete on the ground being transported with the surface run-off into the streams. However regarding the piezometers, they seldom exceed 10 mg/l, except on this rainfall event where piezometers VIP4 E4 and VIP4 E5 reached 17 mg/l and 91 mg/l respectively. Considering that the rainfall and wetting front detector values seldom exceed 5 mg/l, this support the possible “pulse’ of nitrate from the sub-surface into the streams during this particular rainfall event. Piezometers VIP4 E4 and VIP4 E5 are 32 m and 36 m down gradient from the nearest VIP respectively. In terms of faecal coliforms, *E. coli* counts ranged from 1-18600 MPN/100 ml. Piezometer VIP4 E1 (i.e. 30 m from VIP4) consistently shows high counts, ranging from 4838-18600 MPN/100 ml. Similarly S1 also indicates high *E. coli* counts, ranging from 30-6867 MPN/100 ml. This supports the idea of contaminants leaching from VIP4 and reaching the stream 60 m from the on-site system.

7.1.2. Slangspruit:

Piezometers A1 and B1 exhibit significantly high and erratic nitrate concentrations, particularly during high rainfall events. The values here range between 6-1656 mg/l and 42-1502 mg/l respectively. The remainder of the piezometers seldom exceed 15 mg/l. However there are spikes at A2, C2 and D1 during period’s high rainfall; 773 mg/l, 493 mg/l and 165 mg/l respectively. Similarly piezometer H1, H2 and H3 reveal spikes during periods of high rainfall; 69 mg/l, 141 mg/l and 128 mg/l respectively. In terms of faecal coliforms, piezometers C1, D1, E1, E2, H1, H2, H4 and H5 all exhibit high *E. coli* counts, seldom dropping below 1000 MPN/100 ml. The values range from 3590-24192 MPN/100 ml, 75-7030 MPN/100 ml, 2987-24192 MPN/100 ml, 81640 MPN/100 ml, 821- >241920 MPN/100 ml, 4838-24192 MPN/100 ml, 1780-17329 MPN/100 ml and 1961- >241920 MPN100 ml, respectively. However *E. coli* counts seldom exceed 700 CFU/100 ml at piezometers A1 and B1. In conclusion, it is unlikely that nitrate contamination will occur at distances further than 3 m, except during periods of high rainfall. However, faecal coliforms may exceed 26 m at all times.

7.1.3. Crèche:

Piezometers A and G1-G4 exhibit a rapid nitrate response in relation to rainfall. All the piezometers seldom exceed 18 mg/l, while piezometers G1-G4 seldom have any water. However following a period of rainfall with a significant event of 36 mm in 2 day, piezometers A and G1-G4 exhibited a spike in nitrate of 337 mg/l and 47-76 mg/l respectively. In terms of faecal coliforms, *E. coli* counts were on average higher at piezometers A and B, ranging from 86-7710 MPN/100 ml and 52-922 MPN100 ml respectively. The remaining piezometers seldom exceeding 400 MPN/100 ml, except in one case for piezometer E where counts spiked to 3106 MPN/100 ml. Background piezometers A and B however exhibited consistent high *E. coli* counts, ranging from 2092-224192 CFU/100 ml and 738-24192 CFU/100 ml respectively. This however may be due to the recent construction of an unimproved pit latrine >2.5 m away from these piezometers. At this site it is unlikely that contaminants will exceed 3 m, except in periods of significant rainfall, where contaminants are mobilised.

7.1.4. Azalea:

In the streams, nitrate does not exceed 13 mg/l. Piezometers A and B show significantly high nitrate concentration of 942 mg/l and 508 mg/l respectively. This is due to their close proximity to the leach pit; 0.5 m and 1 m, respectively. However the remainder of the piezometers seldom exceed 15 mg/l; rare occurrence of 32 mg/l at background B, possibly due to its close proximity to the leach pit (< 2.5 m). A similar pattern exists for the *E. coli* counts. Piezometers A and B both exhibit significantly higher counts than the remaining piezometers; 387 - > 28510 CFU/100 ml and 727 - > 24192 CFU/100 ml, respectively. The remaining piezometers seldom exceed 1000 CFU/100 ml. At this site it is unlikely that the contaminants from the leach pit of the pour-flush system exceed further than 3 m.

7.2. Summary of Uncertainties and Knowledge Gaps

Uncertainties and knowledge gaps are evident in the following:

- Understanding of the near surface interception of pit latrines by intermittent, saturated preferential flows induced by heavy rainfall events in specific soilscapes;
- Migration of pathogens and nutrients in the near surface and the accumulation of these in toe slopes, wetlands and riparian zones;
- The fate of pathogens in the unsaturated matrix in field situations;
- Using fixed distances of separation between groundwater extraction and on-site sanitation should be avoided unless the unsaturated zone and aquifer are uniform;
- The mechanisms and rates of pore clogging at the base of the latrines and the influence of this mechanism in promoting interception by subsurface discharge needs to be understood and quantified;

- "Many field studies indicate that lateral migration of microbial pollutants in the saturated zone is limited to the distance groundwater can travel in a period of not more than 15 days" (ARGOSS, 2002). However, extreme rainfall events, inducing near surface, saturated lateral discharge in soil horizons, can result in travel times from hillslope to stream of less than a day.

7.3. Towards a Guideline

Three key guidelines *viz.* Franceys *et al.*, 1992 (WHO); ARGOSS, 2001 and DWAF, 2003 were reviewed, while details in several other relevant documents and publications were assessed. All three guideline documents are relevant and useful for on-site sanitation development. The WHO guideline (i.e. Franceys *et al.*, 1992) is more comprehensive and in-depth than the other two, and provides a good general base for first time practitioners of on-site sanitation to work from. The AGROSS guideline might not cover as much as the WHO document, however it does provide a comprehensive section on different hydrogeological conditions and the associated implications on groundwater pollution. These need to be compared with expected South African conditions. It is also more focused on the correct installation and protection of groundwater abstraction systems from contamination, rather than the planning and design to minimise the pollution from on-site sanitation systems. The DWAF guideline was the briefest of the three and lacking in content and detail (such as advantages and disadvantages of various on-site systems or even design diagrams of the systems). However it did contain the South African context, it provided useful basic summaries or examples of different conditions/situations and the associated risks to groundwater contamination as well as the risk of surface water contamination, and it has a comprehensive section on assessing the risk of groundwater pollution from on-site sanitation, which is summaries in a easy to follow flow chart. Overall these three documents complement each other where one alone would not be sufficient to address on-site sanitation and potential water resource pollution. They are relatively easy to follow and understand, make use of diagrams and tables to assists in this, and are relevant to a large audience; policy makers, designers, researchers, planner, builders and the users.

In a South African context, there have been a number of recent key documents which have shed light on sanitation impact and highlight the need to address it; the White Paper on Water Supply and Sanitation Policy published in 1994, the National Sanitation White Paper published in 1996, the White Paper on Basic Household Sanitation published in 2001 and The Development of a Sanitation Policy and Practice in South Africa published in 2002. As a consequence, and with particular reference to on-site sanitation, several key documents have been developed, but particularly the Protocol to Manage the Potential of Groundwater Contamination from On-Site Sanitation.

The guideline document will be designed through selection of relevant features from the guidelines discussed in this document, consultation with practitioners and developed into an *aide memoir*. It is intended that the support system guide the user through a series of questions about the system type and loading, location, geology, hydropedology and climate. Where current knowledge is lacking, the guideline will recommend the measurement or survey required to assure impacts are minimised. The following four sections will form the basis of the guideline *aide memoire*:

- Type and loading of on-site sanitation system;
- Selection of site;
- Design of on-site sanitation system including site specific migration limiting features;
- Monitoring of on-site sanitation.

The Sustainable Sanitation Alliance, (SuSanA), Working Group 11 (Safer Siting of Sanitation Systems) has published a document describing eight criteria to take into account when siting sanitation systems. These include:

- Horizontal distance between drinking water source and latrine;
- Vertical distance between drinking water source and latrine;
- Aquifer type
- Groundwater flow direction
- Impermeable layers
- Slope and surface water drainage
- Volume of leaking water
- Superposition of multiple sources

Some of the Aquifer types listed and the associated risk levels include those illustrated in Figures 7.1a to d. Clearly, there is a need, particularly in sub-tropical environments, to include instance of near-surface lateral flow (Figure 7.1e), which may intercept pit latrine or soak pit effluent, as illustrated in this research.

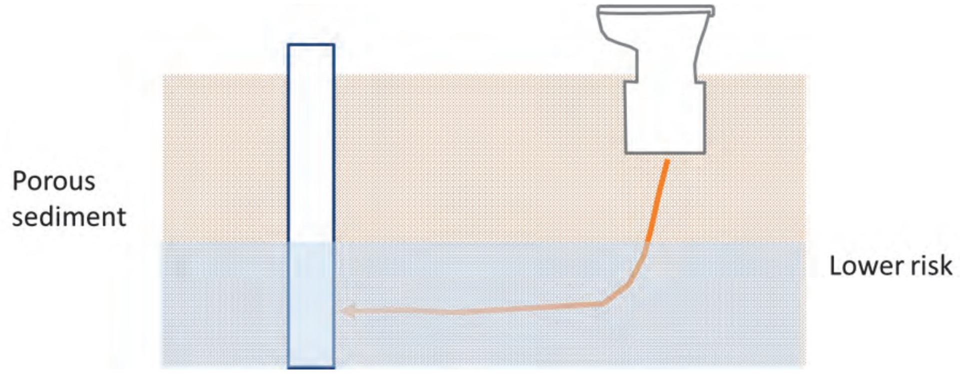


Figure 7.1a Pit latrine in porous sediment

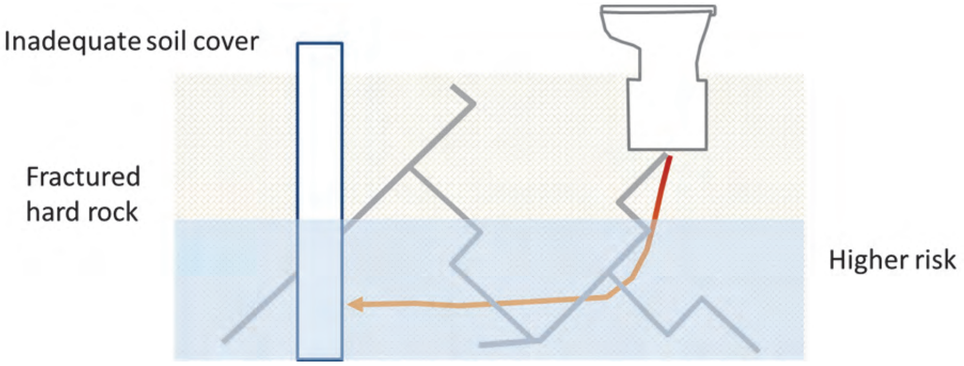


Figure 7.1b Pit latrine in fractured rock.

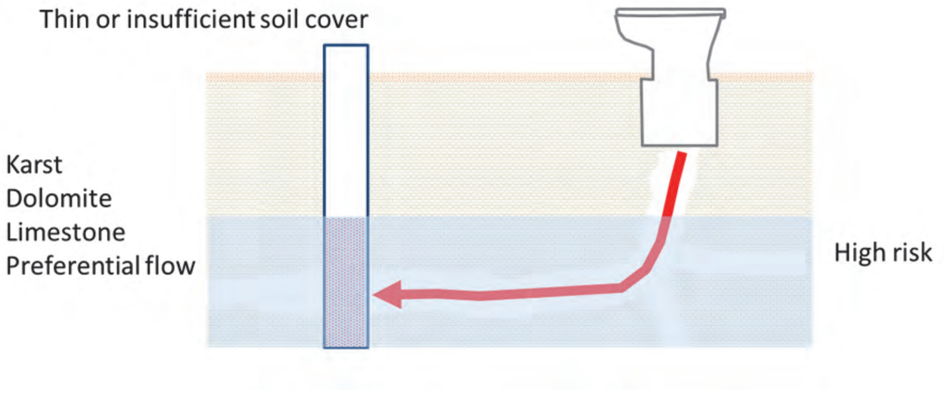


Figure 7.1c Pit latrine in dolomitic rock with thin cover.

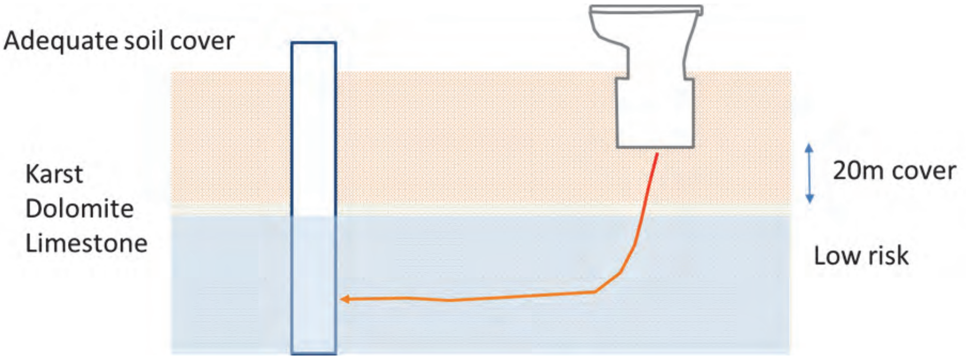


Figure 7.1d Pit latrine in karst rock with adequate cover.

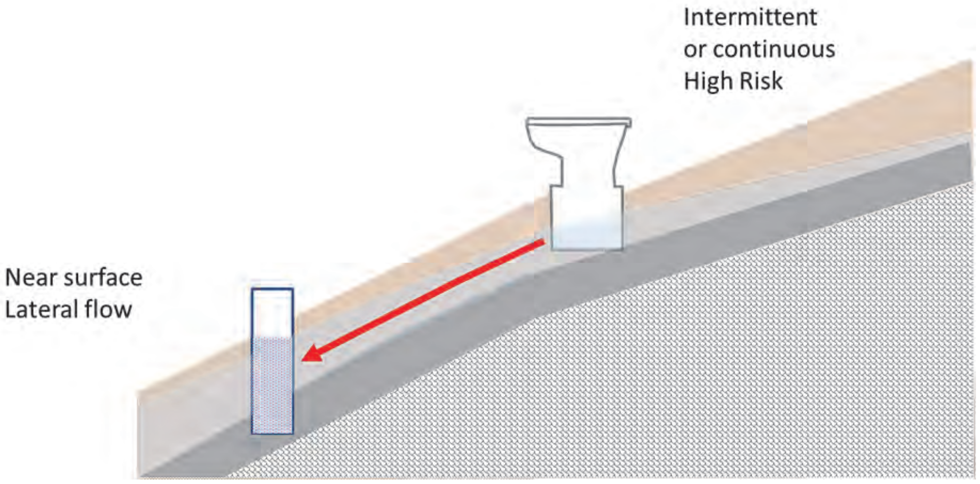


Figure 7.1e Pit latrine in near-surface, lateral flow regime.

8. REFERENCES

Abay, G. K. 2010. The Impact of Low Cost Sanitation on Groundwater Contamination in the City of Addis Ababa. Unpublished PhD Thesis, Environmental Science, University of South Africa.

Abu-ashour, J., Joy, D. M., Lee, H., Whiteley, H. R and Zelin, S. 1994. Transport of microorganisms through soil. *Water, Air and Soil Pollution* 75:141-158.

Acocks, J. P. H. 1988. *Veld Types of South Africa*. Botanical Research Institute, Pretoria, RSA.

Adejuwon, J. O and Adeniyi, D. O. 2011. Pollution effect of pit latrines on shallow wells at Isale-Igbehin community, Abeokuta, Nigeria. *Journal of Geology and Mining*

Amadi, A. N., Dan-Hassan, M. A., Okoye, N. O., Ejiofor, I. C and Aminu, T. 2013. Studies on Pollution Hazards of Shallow Hand-Dug Wells in Erena and Environs, North-Central Nigeria. *Environment and Natural Resources Research* 3(2): 69-77.

Amato, M and Ritchie, J. T. 1995. Small Spatial Scale Soil Water Content Measurement with Time-Domain Reflectometry. *Soil Science Society of American Journal* 59(2):325-329

ARGOSS 2001. Guidelines for assessing the risk to groundwater from on-site sanitation. *British Geological Survey Commissioned Report*, CR/01/142. 97pp

ARGOSS 2002. *Assessing Risk to Groundwater from On-site Sanitation: Scientific Review and Case Studies*. British Geological Survey report No. CR/02/079N, British Geological Survey, Keyworth, United Kingdom.

Ashbolt, N. J. 2004. Microbial contamination of drinking water and disease outcomes in developing regions. *Toxicology* 198:229-238. *Research* 3(8):p211-218.

Ashley, K., Mavinic, D and Koch, F. 2009. *International Conference on Nutrient Recovery from Wastewater Streams*. IWA Publishing, London, UK.

Barrel, R. A. E and Rowland, M. G. M. 1979. The relationship between rainfall and well water pollution in a West African (Gambian) village. *The journal of Hygiene* 83(1):143-150.

Baas-Becking, L. G. M., Kaplan, I. R and Moore, D. 1960. Limits of the natural environment in terms of pH and oxidation-reduction potentials. *The Journal of Geology* 68:243-285.

Banerjee G. 2011. Underground pollution travel from leach pits of on-site sanitation facilities: a case study. *Clean Technol. Environ. Policy* 13(3):489-497.

Bester, J. W and Austin, L. M. 2000. *DESIGN, CONSTRUCTION, OPERATION AND MAINTENANCE OF VENTILATED IMPROVED PIT TOILETS IN SOUTH AFRICA*. Report No. 709/1/00, Water Research Commission, Pretoria, RSA

Bouma, J. 1975. Unsaturated flow phenomena during subsurface disposal of septic tank effluent. J. Am. Environ. Eng. Div. Am. Soc. Civil Eng. Vol. 101. no. EE6, Proc. Pap. 11783. p. 967-983.

Bordalo, A. A and Savva-Bordalo, J. 2007. The quest for safe drinking water: An example from Guinea-Bissau (West Africa). *Water Research* 41:2978-2986.

Bouwer, H. 1978. *Groundwater Hydrology (McGraw-Hill Series in Water Resources and Environmental Engineering*. McGraw-Hill, New York, USA.

Brady, N, C and Weil, R, R. 2008. *The Nature and Properties of Soils 14th Ed*. Pearson Prentice Hall, New Jersey, USA.

Buchan, G. D and Flury, M. 2004. Pathogen Transport by Water. In: ed. Steward, B. A and Howell, T. A. *Encyclopedia of Water Science*. Marcel Dekker Inc, New York, USA.

Caldwell, E. L. and Parr, L. W. 1937. Ground Water Pollution and the Bored Hole Latrine. *The Journal of Infectious Diseases* 61 (2):148-183

Carodona, M. 1998. Nutrient and Pathogen Contributions to Surface and Subsurface Waters From On-site Wastewater Systems – A Review. [Internet]. North Carolina State University Cooperative Extension Service, Raleigh, USA. Available from: http://www.deh.enr.state.nc.us/osww_new/new1/images/NutrientandPathogenTransport.pdf. Accessed: 21 September 2012.

Cave, B and Kolsky, P. 1999. *Groundwater, latrines and health*. Report No. 163.Water and Environmental Health at London and Loughborough, UK.

Cogger, B.L., C.G. Carlile. 1984. Field Performance of conventional and alternative septic systems in wet soils. *Journal of Environmental Quality* 13 (1) 137-142.

Council for Geoscience. 1979. 1:50 000 Geological maps: 2930 CA Merrivale and 2930 CB Pietermaritzburg. Council for Geoscience, Pietermaritzburg, RSA.

Crane, S. R and Moore, J. A. 1984. Bacterial pollution of groundwater: A review. *Water, Air and Soil Pollution* 22:67-83.

CSIR. 2005. Sanitation. In: ed. CSIR, *Guidelines for human settlement planning and design Vol 2*, Ch 10. Council for Scientific and Industrial Research (CSIR), Pretoria, RSA.

DeLaune, R. D and Reddy, K. R. 2005. Redox Potential. In ed: Hillel, D. *Encyclopedia of Soils in the Environment*, 366-371. Academic Press, Waltham, USA.

Department of Water Affairs (DWA). 2012. Sanitation Services – Quality of Sanitation in South Africa: Report on the Status of Sanitation Services in South Africa, March 2012. [Internet]. DWA, Pretoria, Available from: http://www.info.gov.za/view/DownloadFileAction?id=178724. Accessed on 23 February 2013

Devilliers, D. C. 1987. Evaluation of sites for on-site sanitation systems. *Trans. S. A. Inst. Civ. Eng*. 29(8):313-315.

Dillon, P. 1997. *International Hydrological Programme: Groundwater pollution by sanitation on tropical islands*. Report No. SC-97/WS/8. UNESCO, Paris, France.

DOH. 2012. Annual Performance Plan 2012/13-2014/15. [Internet]. Department of Health, Pretoria, South Africa. Available from: http://www.doh.gov.za/docs/stratdocs/2012/app2012.pdf. [Accessed on 14 July 2013].

DWAF, 2012. Sanitation Services – Quality of Sanitation in South Africa: Report on the Status of sanitation services in South Africa. [Internet]. Department of Water and Forestry, Pretoria, South Africa. Available from: http://www.info.gov.za/view/DownloadFileAction?id=178724. [Accessed on 19 February 2013].

DWAF. 2003. Strategic Framework for Water Services: Water is life, Sanitation is Dignity. [Internet]. Department of Water and Forestry, Pretoria, South Africa. Available from: http://www.dwaf.gov.za/Documents/Policies/Strategic%20Framework%20approved.pdf. [Accessed on 19 February 2013].

DWAF. 2002. [Internet]. National Eutrophication Monitoring Programme: Implementation manual final draft. Department of Water and Forestry, Pretoria, South Africa, Available from: http://www.dwa.gov.za/iwqs/eutrophication/NEMP/EutrophicationMonitoringProgramme.pdf. Accessed: 17 January 2012.

Dyer, B.R and Bhaskaran, T.R. 1945. Investigations of groundwater pollution, part II: Soil characteristics in West Bengal, India, at the site of groundwater pollution investigations. *Indian Journal of Medical Research* 33:17-22.

Dzwairo, B., Hoko, Z., Love, D and Guzha, E. 2006. Assessment of the impacts of pit latrines on groundwater quality in rural areas: A case study from Marondera district, Zimbabwe. *Physics and Chemistry of the Earth* 31:779-788

Engebretson, A.C., and E.J. Tyler. 2001. Using soil surveys to predict the type of onsite wastewater treatment system. p 116-124. In K. Mancel (ed.) Proc. Int. Symp. on Individual and Small Community Sewage Systems. 9th, Fort Worth, TX. 11-14 Mar. 2001. ASAE, St. Joseph, MI.

Esrey ,S. A., Potash, J. B., Roberts, L and Shiff, C. 1991. Effects of improved water supply and sanitation on ascariasis, diarrhoea, dracunculiasis, hookworm infection, schistosomiasis, and trachoma. 69 (5): 609-621. World Health Organisation. Geneva, USA

Fiedler, S., Vepraskas, M. J and Richardson, J. L. 2007. Soil redox potential: importance, field measurements and observations. *Advances in Agronomy* 94:1-54.

Faulknera, B. R., Lyonb, W. G., Khanc, F. A and Chattopadhyayd S. 2003. Modeling leaching of viruses by the Monte Carlo method. *Water Research* 37(19): 4719-4729

Fourie, A. B and van Ryneveld, M. B. 1995. The fate in the sub-surface of contaminants associated with on-site sanitation: A Review. *Water SA* 21(2):p101-111.

Franceys, R., Pickford, J and Reed, R. 1992. *A Guide to the Development of on-site Sanitation*. World Health Organisation, Geneva, USA.

Gelinas, Y., Randall, H., Robidoux, L and Schmit, JP. 1996. Well water survey in two districts of Conakry (Republic of Guinea), and comparison with the piped city water. *Water Resources* 30(9):2017-2026.

Green, K. M., and D. O. Cliver. 1974. Removal of virus from septic tank effluent. p. 137-144. In Proc. Symp. Home Sewage Disposal. Pub. 175. Am. Soc. Agric. Eng., St. Joseph, Mich. 242 p.

Godfrey, S., Timo, F and Smith, M. 2005. Relationship between rainfall and microbiological contamination of shallow groundwater in Northern Mozambique. *WaterSA* 31(4):609-614.

Gosselin, D. C., Headrick, J., Tremblay, R., Chen, X and Summerside, S. 1997. Domestic Well Water Quality in Rural Nebraska: Focus on Nitrate-Nitrogen, Pesticides, and Coliform Bacteria. *Groundwater Monitoring & Remediation* 17(2):77-87

Harvey, P., Baghri, S and Reed, B. 2002. *Emergency Sanitation: Assessment and Programme Design*. WEDC, Leicestershire, UK.

Herselman, JE and Moodley, P. 2009. *Guidelines for the Utilisation and Disposal of Wastewater Sludge Volume 4: Requirements for the beneficial use of sludge at high loading rates*. WRC Report No. TT 350/09, Water Research Commission, Pretoria, South Africa.

Howard, G., Pedley, S., Barrett, M., Nalubega, M and Johal, K. 2003. Risk factors contributing to microbiological contamination of shallow groundwater in Kampala, Uganda. *Water Research* 37:3421-3429.

Illing, C and Lagardien, A. 2008. Job creation opportunities for the operation and maintenance of basic sanitation service provision to informal settlements. WISA paper No. 078. South Africa.

Jack, G., Sefe, F., Carling, M., Hammar, M and Letsamao, P. 1999. Tentative nitrogen budget for pit latrines – eastern Botswana. *Environmental Geology* 38(3):199-203.

Jury, W. A and Horton, R. 2004. *Soil Physics 6th Ed*. John Wiley and Sons, Hoboken, USA.

Kalbermatten, J.K., D.S. Julius and C.G. Gunnerson. 1980. *Appropriate Technology ^or Water Supply and Sanitation: Tze.hnic.al and economic optioni.* Report of Transportation, Water, and Telecommunication Department, The World Bank, Washington.

Kimani-Murage, E. W and Ngindu, A. M. 2007. Quality of Water the Slum Dwellers Use: The Case of a Kenyan Slum. *Journal of Urban Health: Bulletin of the New York Academy of Medicine* 84(6):829-838.

Kirchmann, H and Pettersson, S. 1995. Human Urine – Chemical composition and fertilizer use efficiency. *Fertilizer Research* 40:149-154.

Kropf, F. W., Healy, K. A and Laak, R. 1974. *Soil clogging in subsurface absorption systems for liquid domestic wastes*. University of Connecticut, school of engineering, civil engineering department, Connecticut, USA.

Lal, R and Shukla, M. K. 2004. *Principals of Soil Physics*. Marcel Dekker, New York, USA.

Lehohla, P. 2011. *GHS series Volume III: Water and Sanitation 2002-2011, In-depth Analysis of the General Household Survey Data*. Report No. 03-18-02, Statistics South Africa, Pretoria, South Africa.

Lewis, W. J., Foster, S. S. D and Drasar, B. S. 1982. *The Risk of Groundwater Pollution by On-Site Sanitation in Developing Countries: A Literature Review*, IRCWD Report No 01/82, International Reference Centre for Wastes Disposal (IRCWD), Duebendorf, Switzerland.

Looney, B, B and Falta, R, W. 2000. *Vadose Zone: Science and Technology Solutions Vol 1*. Battelle Memorial Institute, Columbus, USA.

Mackay, D. M., Roberts, P. V and Cherry, J. A. 1985. Transport of organic contaminants in groundwater. *Environ. Sci. Technol.*19(5)384-392.

McCarthy, T. S., Ellery, W. N and Gieske, A. 1994. Possible groundwater pollution by sewage effluent at camps in the Okavango delta: suggestions for its prevention. *Botswana Notes and Records* 26:129-138.

Miyazaki, T. 2006. *Water Flow in Soils 2nd Ed*. CRC Press Taylor and Francis Group, USA.

Municipal Systems Act. 2000. RSA Government Gazette No. 32 of 2000: 20 November 2000, No. 21776. Cape Town, RSA

Nsubuga, F. B., Kansiime, F and Okot-Okumu, J. 2004. Pollution of protected springs in relation to high and low density settlements in Kampala—Uganda. *Physics and Chemistry of the Earth* 29:p1153-1159.

Nyenje, P. M., Foppen., J. W., Kulabako, R., Muwanga, A and Uhlenbrook, S. 2013. Nutrient pollution in shallow aquifers underlying pit latrines and domestic solid waste dumps in urban slums. *Journal of Environmental Management* 122:15-24.

Polprasert, C. 2007. *Organic Waste Recycling: Technology and Management 3rd Ed.* IWA Publishing, London, UK.

Phuc, P. D., Konradsen, F., Phuong, P. T., Cam, P. D and Dalsgaard, A. 2006. Practice of using human excreta as fertilizer, and implications for health in Nghean Province, Vietnam. *The Southeast Asian Journal of Tropical Medicine and Public Health* 37(1):222-229.

Pujari, P. R., Padmakar, C., Labhasetwar, P. K., Mahore, P and Ganguly, A. K. 2012. Assessment of the impact of on-site sanitation systems on groundwater pollution in two diverse geological settings – a case study from India. *Environmental Monitoring and Assessment* 184(1):p251-263.

Pujari, P. R., Nanoti, M., Nitnaware, V. C., Khare, L. A., Thacker, N. P and Kelkar, P. S. 2007. Effect of on-site sanitation on groundwater contamination in basaltic environment – A case study from India. *Environ Monit Assess* 134:271-278.

Rea, R.A and Upchurch, S.B. 1980. Influence of regolith properties on migration of septic tank effluent. *Groundwater* 18:118-125

Reneau, R.B. Jr., C. Hagedorn, and M.J. Degen. 1989. Fate and transport of biological and inorganic contaminants from on-site disposal of domestic wastewater. *Journal of Environmental Quality* 18:135-144.

Robertson, W.D., J.A. Cherry, and E.A. Sudicky. 1991. Ground-water contamination from two small septic systems on sand aquifers. *Ground Water* 29 (1) 82-92.

Röhrs, LH, Fourie, AB and Blight, GE. 1998. Effects of sewage sludge and refuse composition on the rate of degradation and leachate quality of co-disposed waste in a water-deficient environment. Water SA 24(2):137-146.

Romero, J. C. 1970. The movement of bacteria and viruses through porous media. *Groundwater* 8(2):37-48

Still DA, Nash SR. 2002. Groundwater contamination due to pit latrines located in a sandy aquifer: a case study from Maputaland [Internet] In: Water Institute of Southern Africa Biennial Conference. Durban, South Africa: Water Institute of Southern Africa, 1-6. Available from: http://www.sswm.info/sites/default/files/reference_attachments/STILL%20and%20NASH%202002%20Groundwater%20contamination%20due%20to%20pit%20latrines%20located%20in%20a%20sandy%20aquifer.pdf [Accessed on 1 May 2014].

SANS. 2011. *South African National Standard: Drinking Water Part 1: Microbial, physical, aesthetic and chemical determinands*. SABS Standards Division, Pretoria, South Africa

Schouw, N. L., Danteravanich, S., Mosbaek, H and Tjell, J. C. 2002. Composition of human excreta – a case study from Southern Thailand. *The Science of the Total Environment* 286:155-166

Schulze, R. E. 1997. *South African Atlas of Agrohydrology and Climatology*. Water Research Commission, Pretoria, Report TT82/96.

Schüring, J., Schulz, H. D., Fischer, W. R, Böttcher, J and Duijnisveld, W. H. M. 1999. Redox: *Fundamentals, Processes and Applications*. Springer-Verlag, New York, USA.

Stevik, T.K., K. Aa, G. Ausland, and J.F. Hanssen. 2004. Retention and Removal of Pathogenic Bacteria in Wastewater Percolating through Porous Media: A Review. *Water Research* 38:1355-67.

Sinton, L. W., R. K. Finlay, L. Pang, and D. M. Scott (1997). Transport of bacteria and bacteriophages in irrigated effluent into and through an alluvial gravel aquifer. *Water, Air, and Soil Pollution* 98(1-2): 17-42

Šimůnek, J., M. Šejna, H. Saito, M. Sakai, and M. Th. van Genuchten, The HYDRUS-1D Software Package for Simulating the Movement of Water, Heat, and Multiple Solutes in Variably Saturated Media, Version 4.08, HYDRUS Software Series 3, Department of Environmental Sciences, University of California Riverside, Riverside, California, USA, pp. 330, 2008.

SuSanA, 2015. How to keep your groundwater drinkable: Safer siting of sanitation systems. Safer siting of sanitation systems: Working Group 11. January 2015.

Tandia, A. A., Diop, E. S and Gaye C. B. 1999. Nitrate groundwater pollution in suburban areas: example of groundwater from Yeumbeul, Senegal. *Journal of African Earth Sciences* 29(4):809-822.

Taylor, R., Cronin, A., Pedley, S., Barker, J and Atkinson, T. 2004. The implications of groundwater velocity variations on microbial transport and wellhead protection – review of field evidence. *FEMS Microbiology Ecology* 49:17-26

The Sphere Project. 2011. Minimum standards in water supply, sanitation and hygiene promotion. [Internet].In: Humanitarian Charter and Minimum Standards in Humanitarian Response, Geneva, The Sphere Project. Available from: http://www.ifrc.org/PageFiles/95530/The-Sphere-Project-Handbook-20111.pdf [Accessed 30 April 2014].

Terry, S., Howard, J ., McGee, S and Furness, H. 1993. Waterborne sewerage reticulation problems within dense formal settlements – Implications for water quality management and selection of the most appropriate sanitation system. *First South African Water and Waste Conference*., Johannesburg.

Tole, M. P. 1997. Pollution of Groundwater in the Coastal Kwale District, Kenya. In ed: Rosbjerg, D., Boutayeb, N. E., Gustard, A., Kundzewicz, W and Rasmussen, P. F. *Sustainability of Water Resources under Increasing Uncertainty*, 287-297. International Association of Hydrological Sciences, Oxfordshire, UK.

Topp, G. C and Davis, J. L. Measurement of Soil Water Content using Time-domain Reflectrometry (TDR): A Field Evaluation. *Soil Science Society of American Journal* 49(1):19-24.

Pang, L. Nokes, C. Simunek, J., Hector, R. Kikkert, H., 2006. Modeling the impact of clustered septic tanks systems on groundwater quality. *Vadose Zone Journal* 5:599-609.

USEPA. 2009. National primary water drinking regulations. United States Environmental Protection Agency, Washington DC. USA. Available from: http://www.epa.gov/ogwdw/consumer/pdf/mcl.pdf. [Accessed: 14 April 2012].

USDIWPRS (U.S Department of the Interior Water and Power resources Services). 1981. *Ground Water Manual: A water resources technical publication*. John Wiley & Sons. New York, USA.

UNAIDS. 2008. Global Report 2008: Annex HIV and AIDS estimates and data, 2007 and 2001. [Internet]. UNAIDS. New York, Unites States of America. Available from: http://data.unaids.org/pub/GlobalReport/2008/jc1510_2008_global_report_pp211_234_en.pdf. [Accessed: 14 July 2013].

UN-Water. 2012. Drinking Water, Sanitation & Hygiene. [Internet]. Un-Water, New York, Unites States of America. Available from: [http://www.unwater.org/statistics_san.html]. [Accessed: 12 May 2013].

UNICEF and WHO. 2012. Progress on Drinking Water and Sanitation: 2012 update. [Internet]. UNICEF and World Health Organisation, New York, USA. Available from: http://www.unicef.org/media/files/JMPreport2012.pdf. [Accessed: 12 May 2013].

Van der Laan, M., Stirzaker, R. J., Annandale, J. G., Bristow, K. L and Du Preez, C. C. 2010. Monitoring and modelling draining and resident soil water nitrate concentrations to estimate leaching losses. *Agricultural Water Management* 97(11):1779-1786

Van Ryneveld, M .B and Fourie, A. B. 1997. A strategy for evaluating the environmental impact of on-site sanitation systems. *WaterSA* 23(4): 279-291.

Wagner, E. G and Lanoix, J. N. 1958. *Disposal for rural areas and small communities.* World Health Organisation, Geneva, Switzerland

Walker, W. G., Bouma, J., Keeney, D. R and Magdoff, F. R. 1973. Nitrogen transformation during subsurface disposal of septic tank effluent in sands: I. Soil transformations. *Journal of Environmental Quality* 2: 475-480.

WaterAid. 2011. Technology Notes. [Internet]. WaterAid. Available from: http://www.wateraid.org/documents/plugin_documents/technology_notes_2011.pdf [Accessed: 30 May 2014].

Water Services Act. 1997. RSA Government Gazette No. 108 of 1997: 19 December 1997, No. 18522. Cape Town, RSA.

Weiskel, P.K., B.L. Howes. 1992. Differential transport of sewage-derived nitrogen and phosphorus through a coastal watershed. Environmental Science and Technology 26: 352-360.

Wilhelm, S.R., Schiff, S. L and Robertson. W. D. 1994. Chemical fate and transport in a domestic septic system: unsaturated and saturated zone geochemistry. *Environmental Toxicology and Chemistry* 13(2): 193-203.

WHO. 2008. *Guidelines for drinking-water quality: 3rd Ed incorporating the 1st and 2nd addenda, Vol1 Recommendations.* World Health Organisation. Geneva, USA.

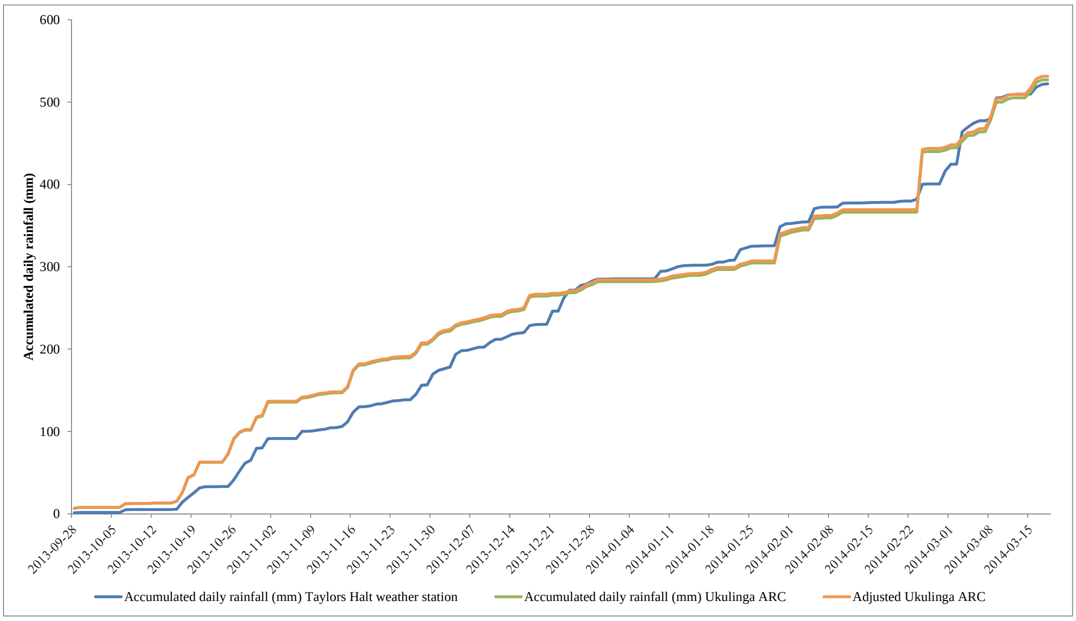
WHO 2002. Emerging and epidemic-prone diseases. In: Global Defence Against the Infectious Disease Threat. World Health Organization, Geneva (Chapter 4).

Xu, Y and Braune, E. 1995. *A Guideline for Groundwater Protection for the Community Water Supply and Sanitation Programme*. DWAF, Pretoria, South Africa.

Zhang, M. K. 2008. Effects of soil properties on phosphorus subsurface migration in sandy soils. *Pedosphere.* 18(5): 599-610

Zingoni, E., Love, D., Magadza, C., Moyce, W and Musiwa, K. 2005. Effects of a semi-formal urban settlement on groundwater quality Epworth (Zimbabwe): Case study and groundwater quality zoning. *Physics and Chemistry of the Earth* 30:p680-688

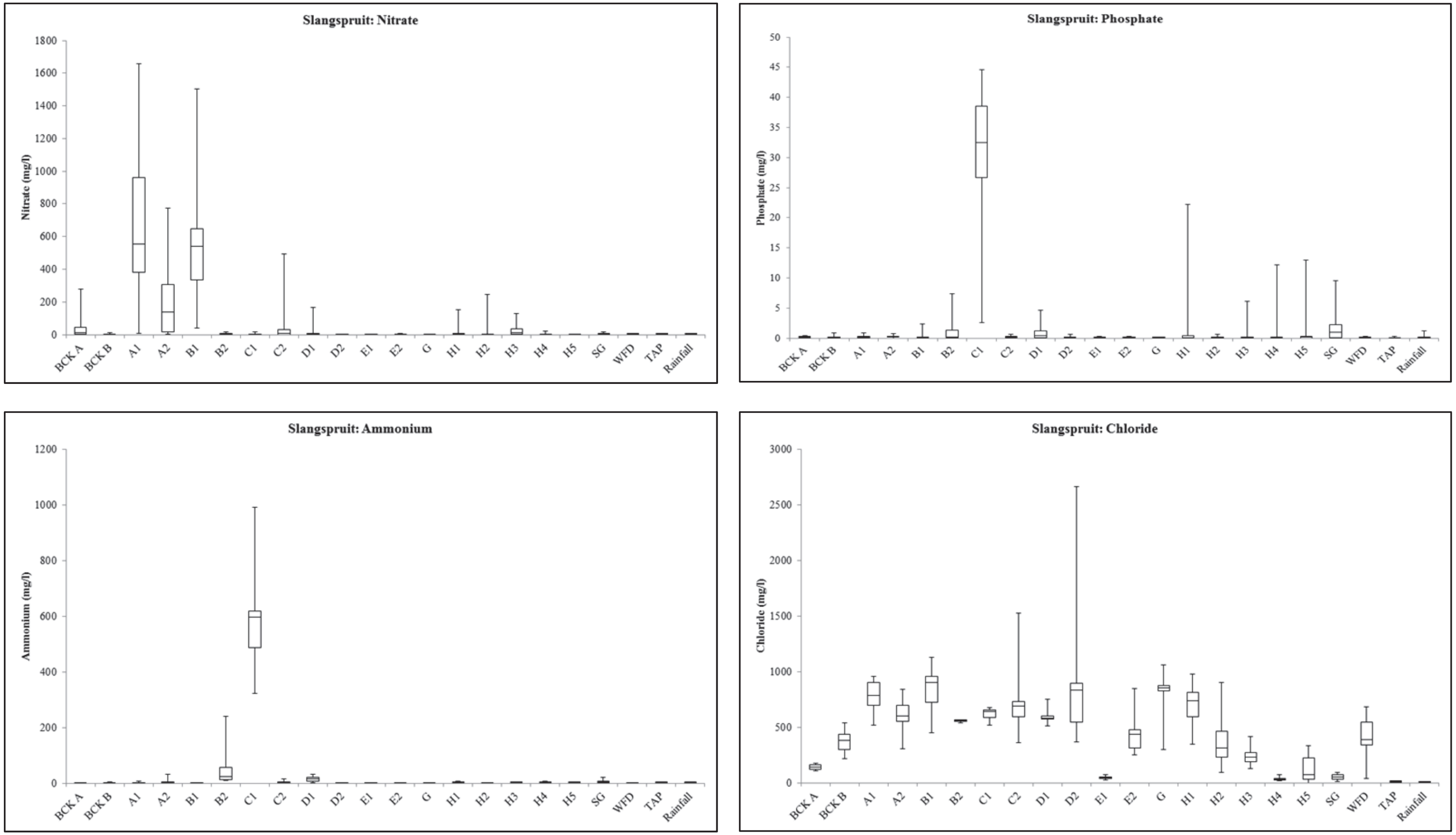
APPENDICES



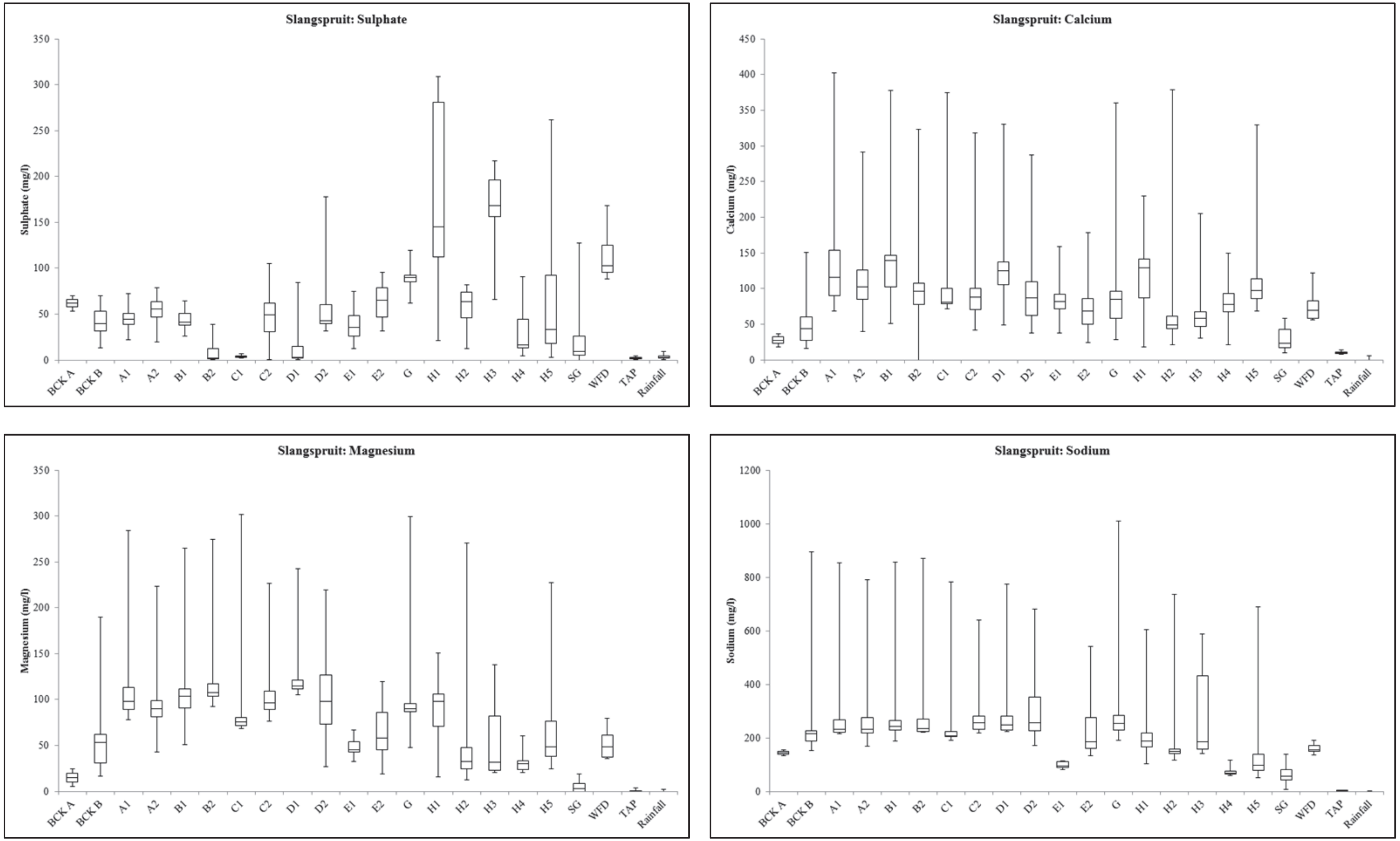
Appendix 1: Accumulated daily rainfall for Taylors Halt and U2E002, Cedara stations.

Slangspruit		**Crèche**		**Azalea**		**Taylors Halt**		**Taylors Halt Control**	
Piezo	Depth of Piezo (m.b.s)	Piezo	Depth of Piezo (m.b.s)	Piezo	Depth of Piezo (m.b.s)	Piezo	Depth of Piezo (m.b.s)	Piezo	Depth of Piezo (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		

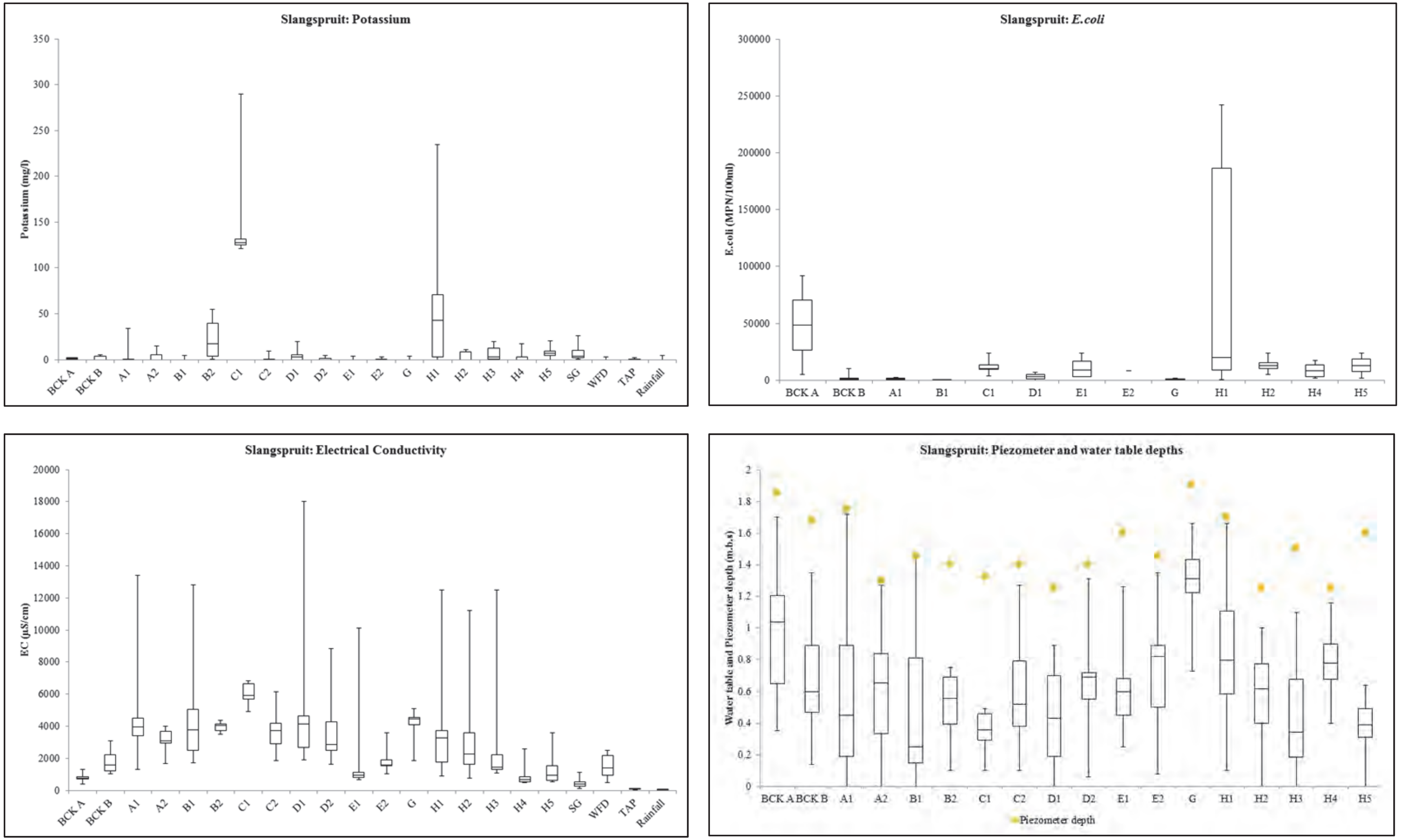
Appendix 2: Depth of piezometers for the 5 study sites



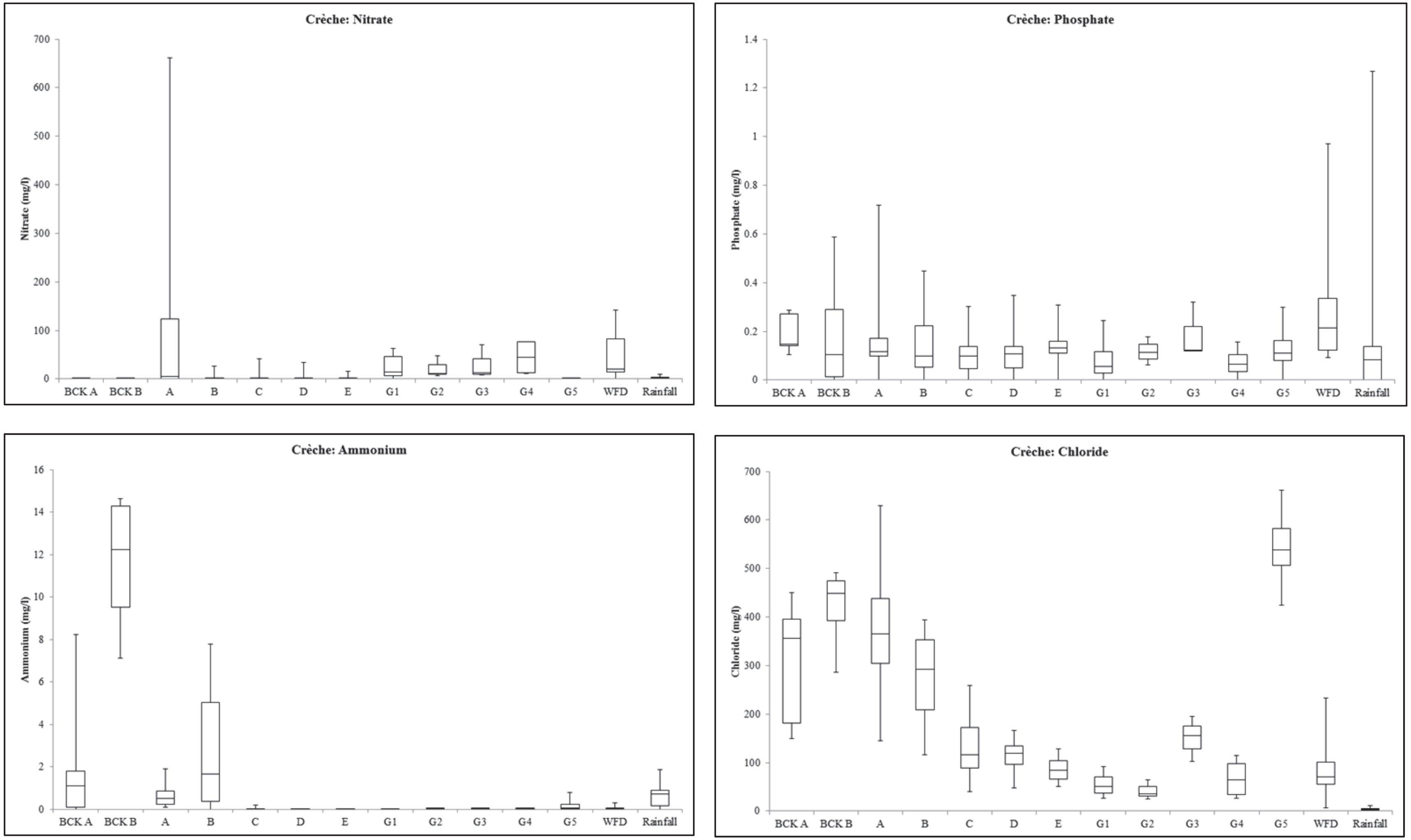
Appendix 3: Statistics of the Nitrate, Ammonium, Phosphate and Chloride samples at Slangspruit.



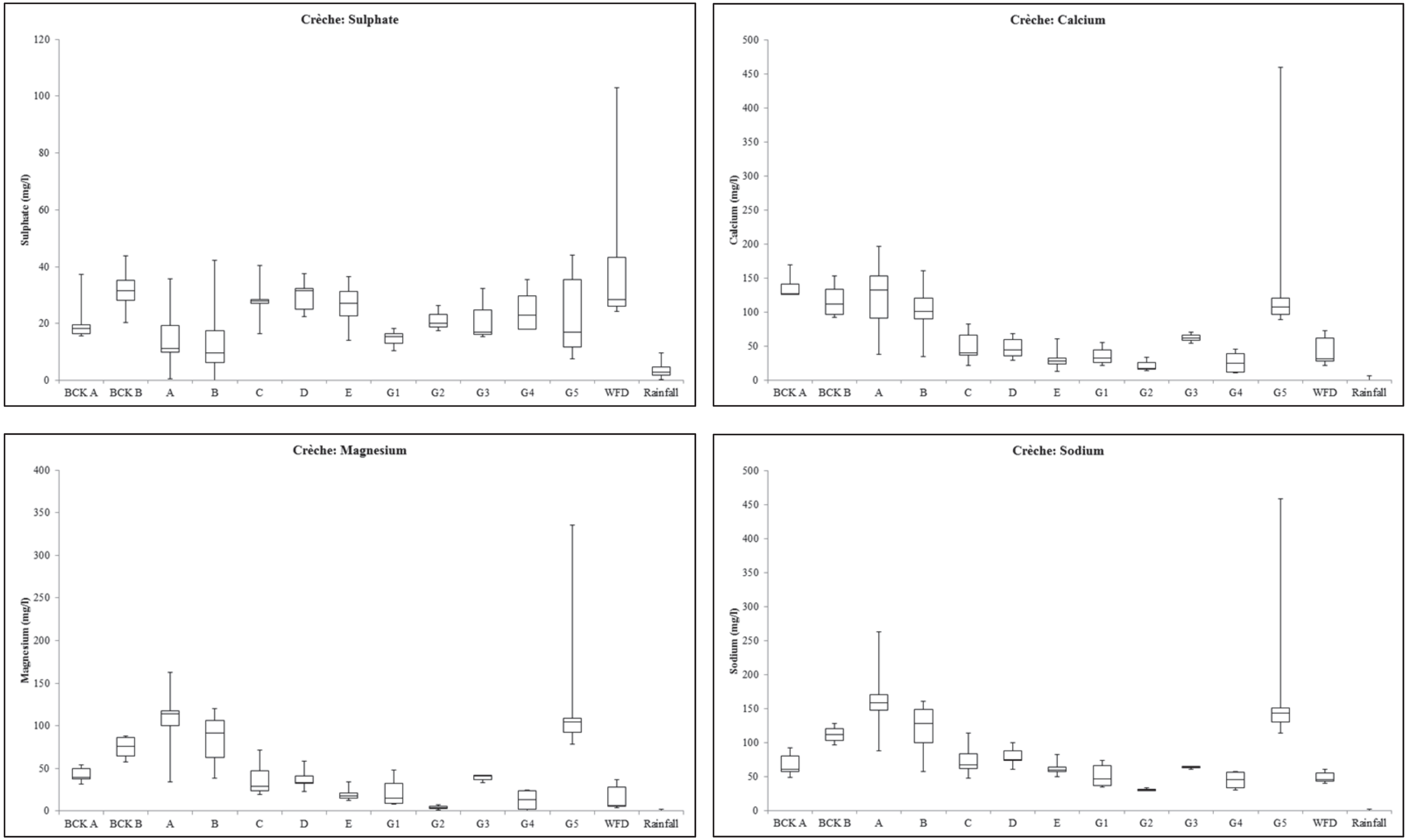
Appendix 4: Statistics of the Sulphate, Magnesium, Calcium and Sodium samples at Slangspruit.



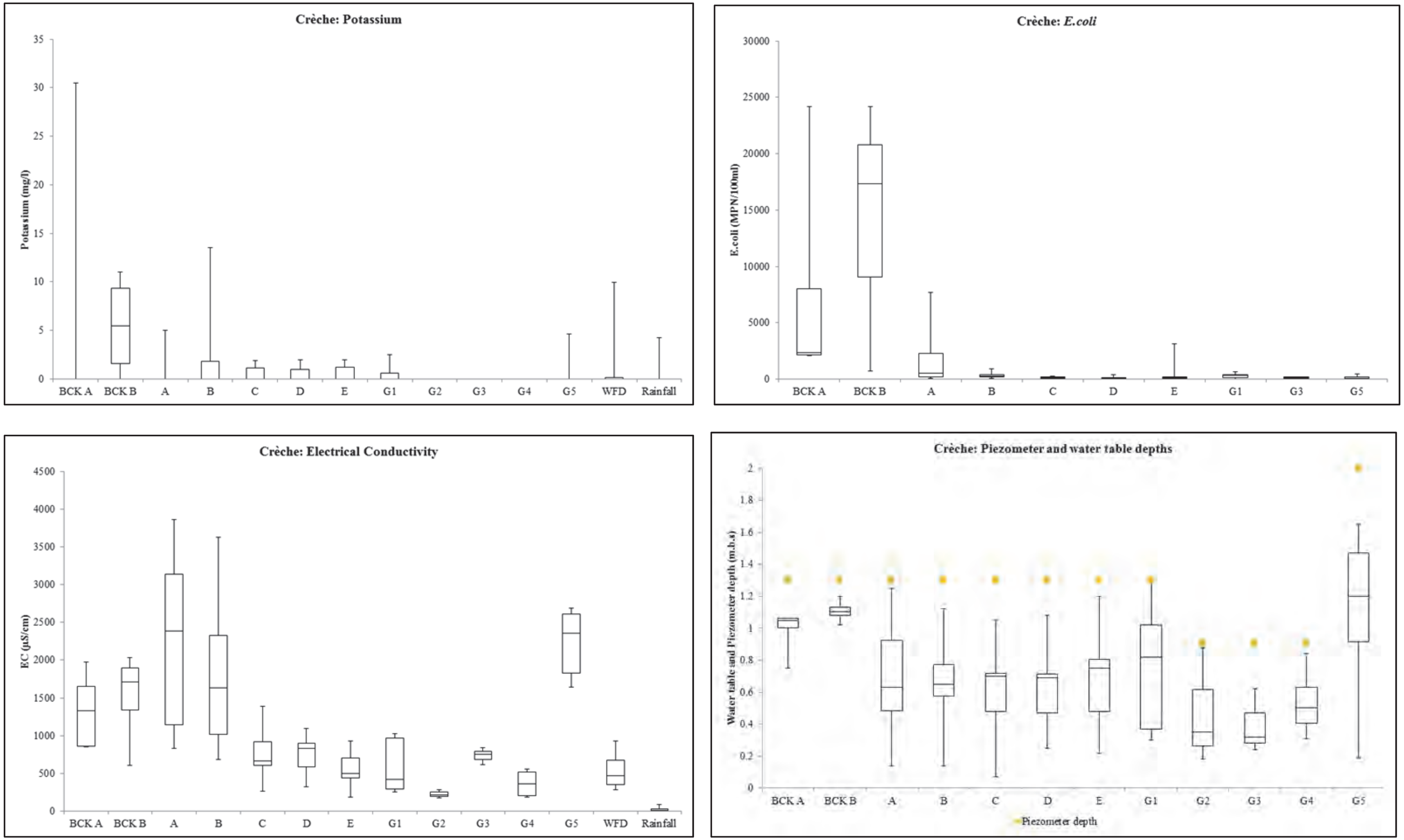
Appendix 5: Statistics of the Potassium, EC, *E coli* samples and water table depths at Slangspruit.



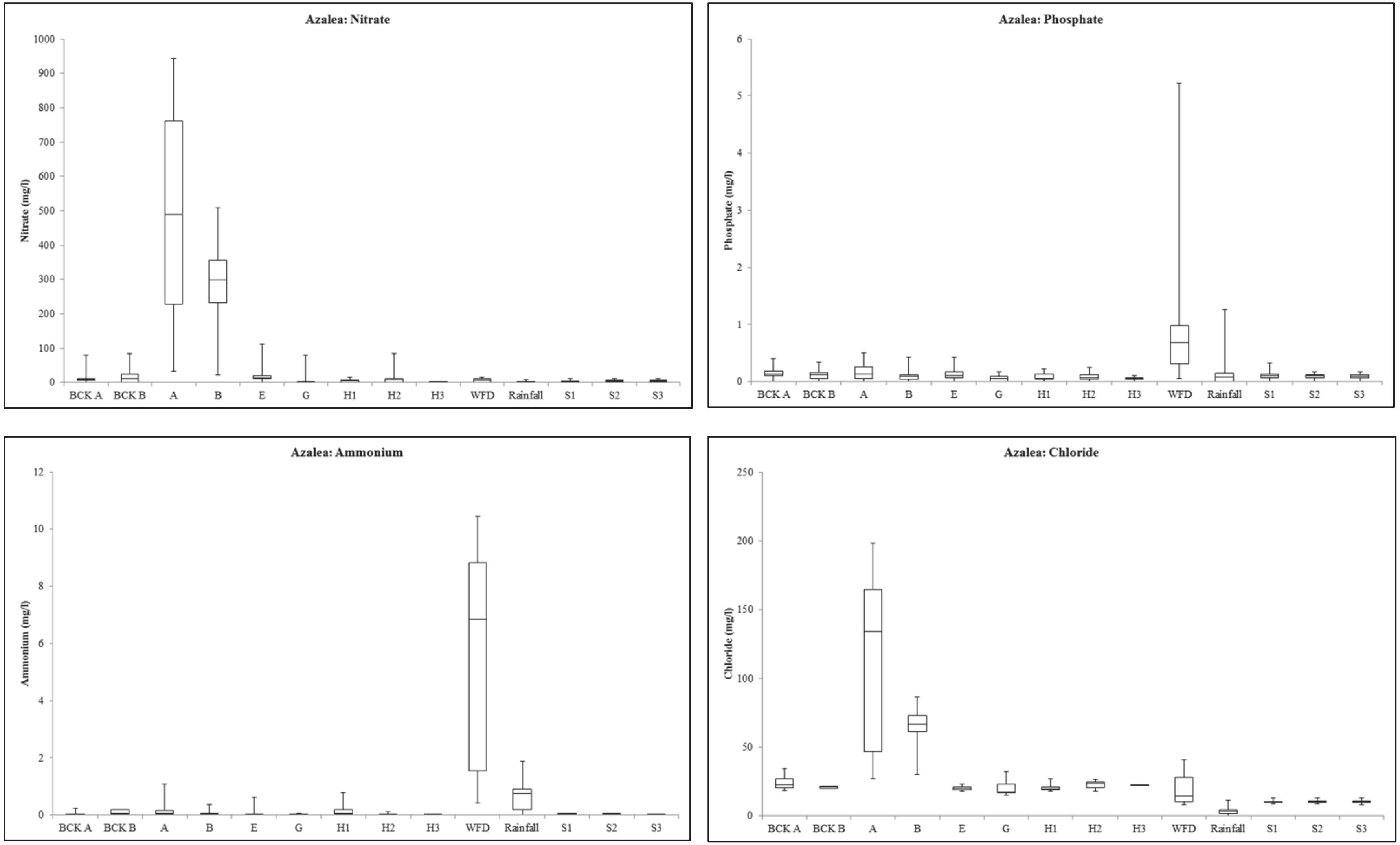
Appendix 6: Statistics of the Nitrate, Ammonium, Phosphate and Chloride samples at Creche.



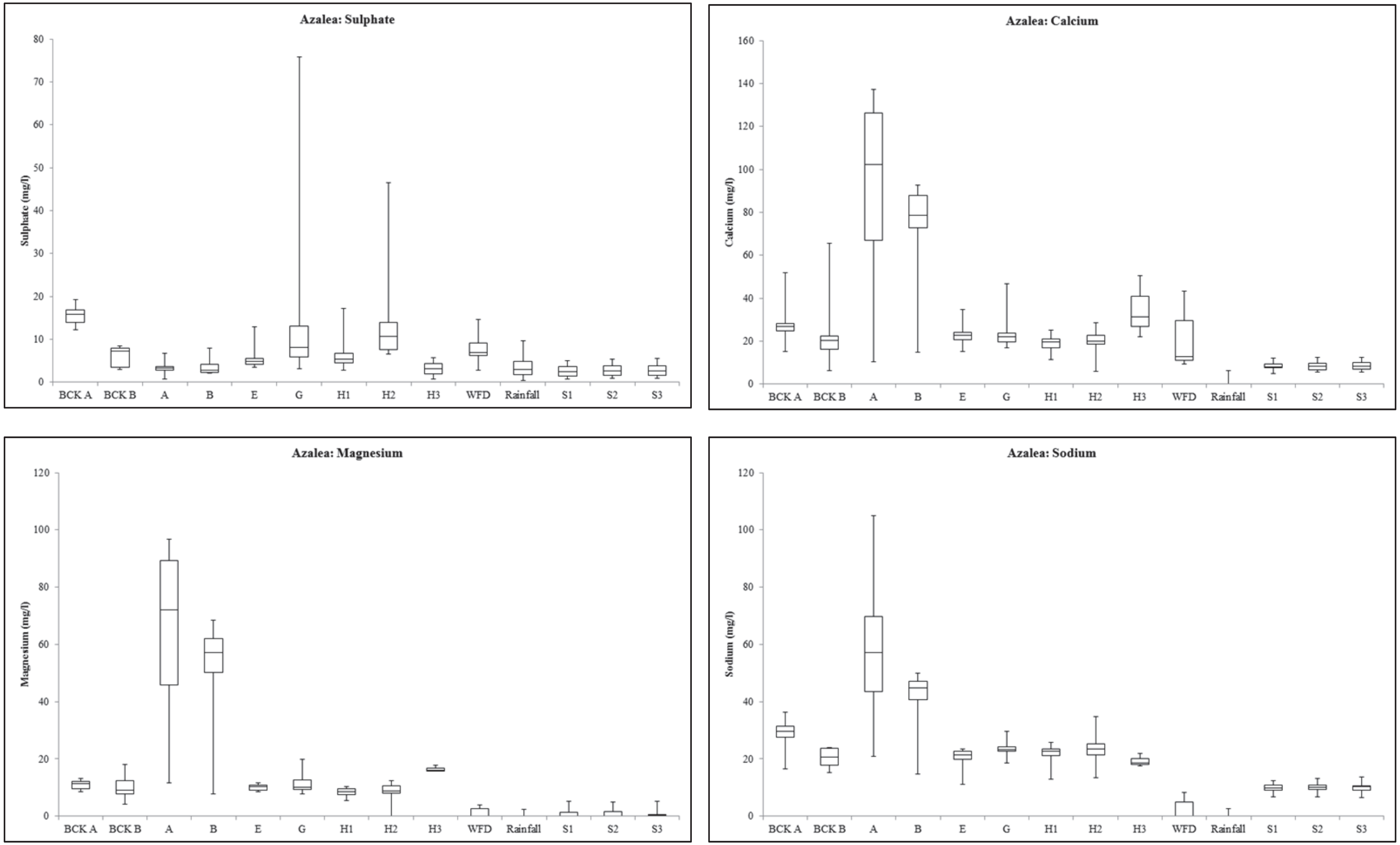
Appendix 7: Statistics of the Sulphate, Magnesium, Calcium and Sodium samples at Creche.



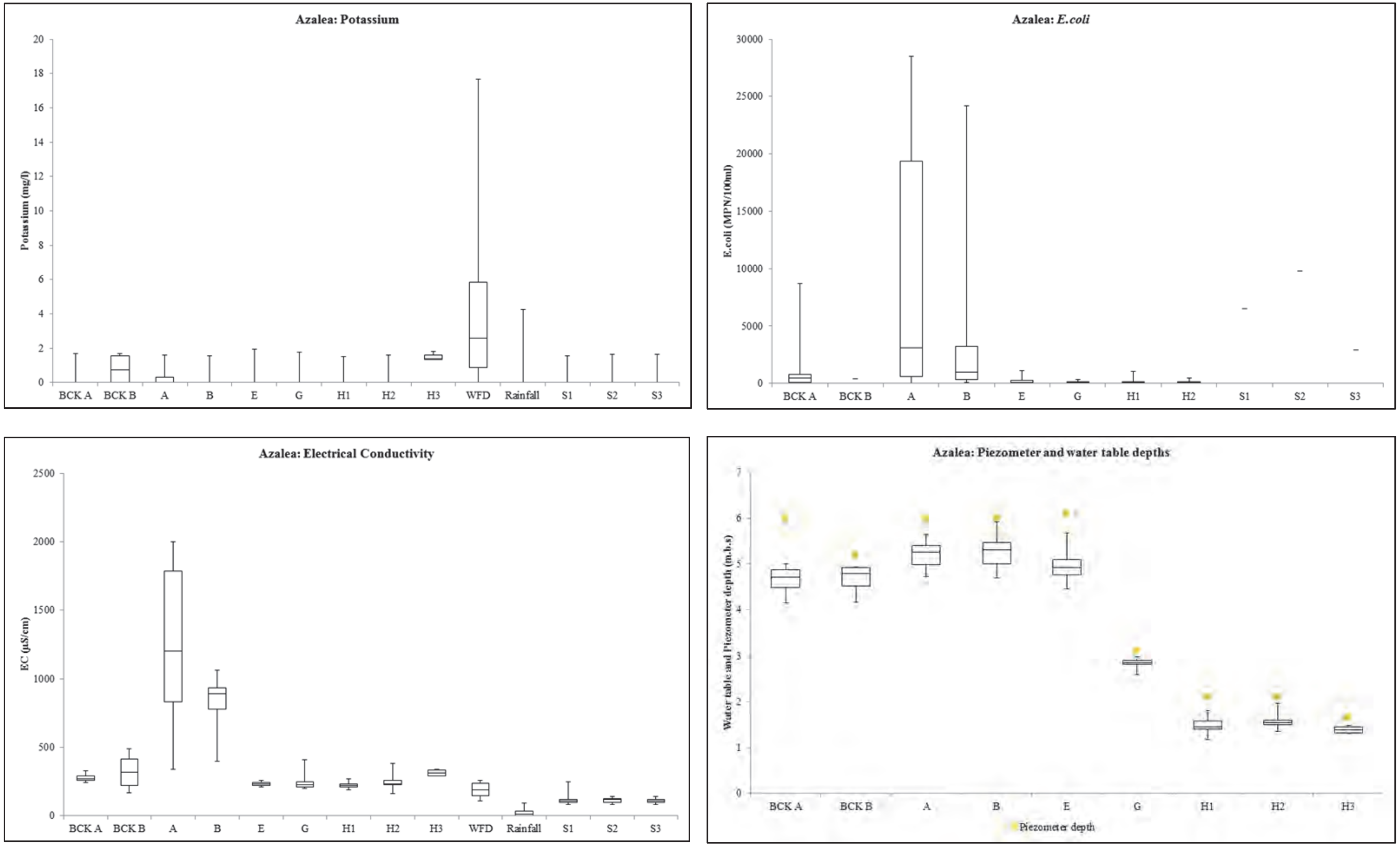
Appendix 8: Statistics of the Potassium, EC, *E coli* samples and water table depths at Creche.



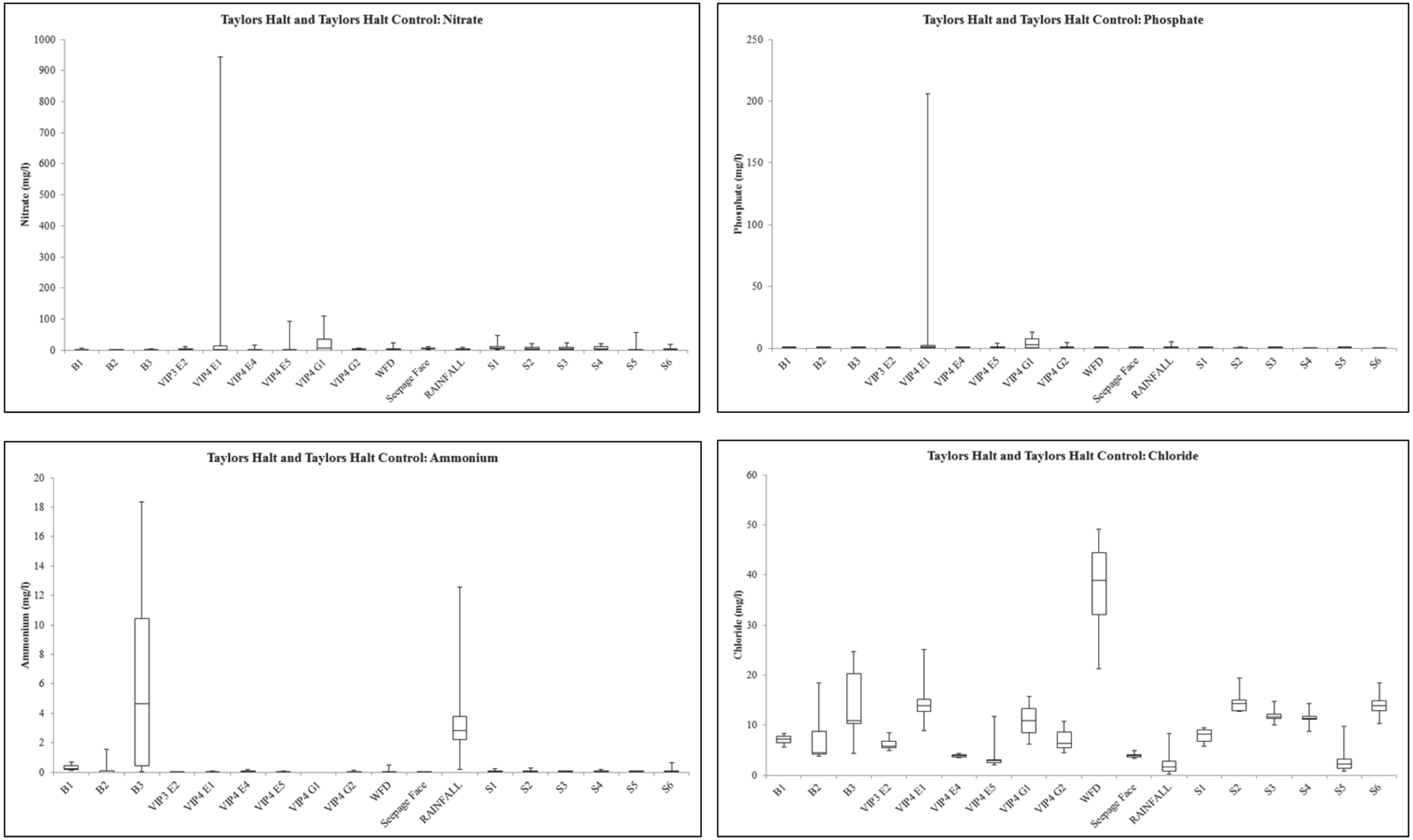
Appendix 9: Statistics of the Nitrate, Ammonium, Phosphate and Chloride samples at Azalea.



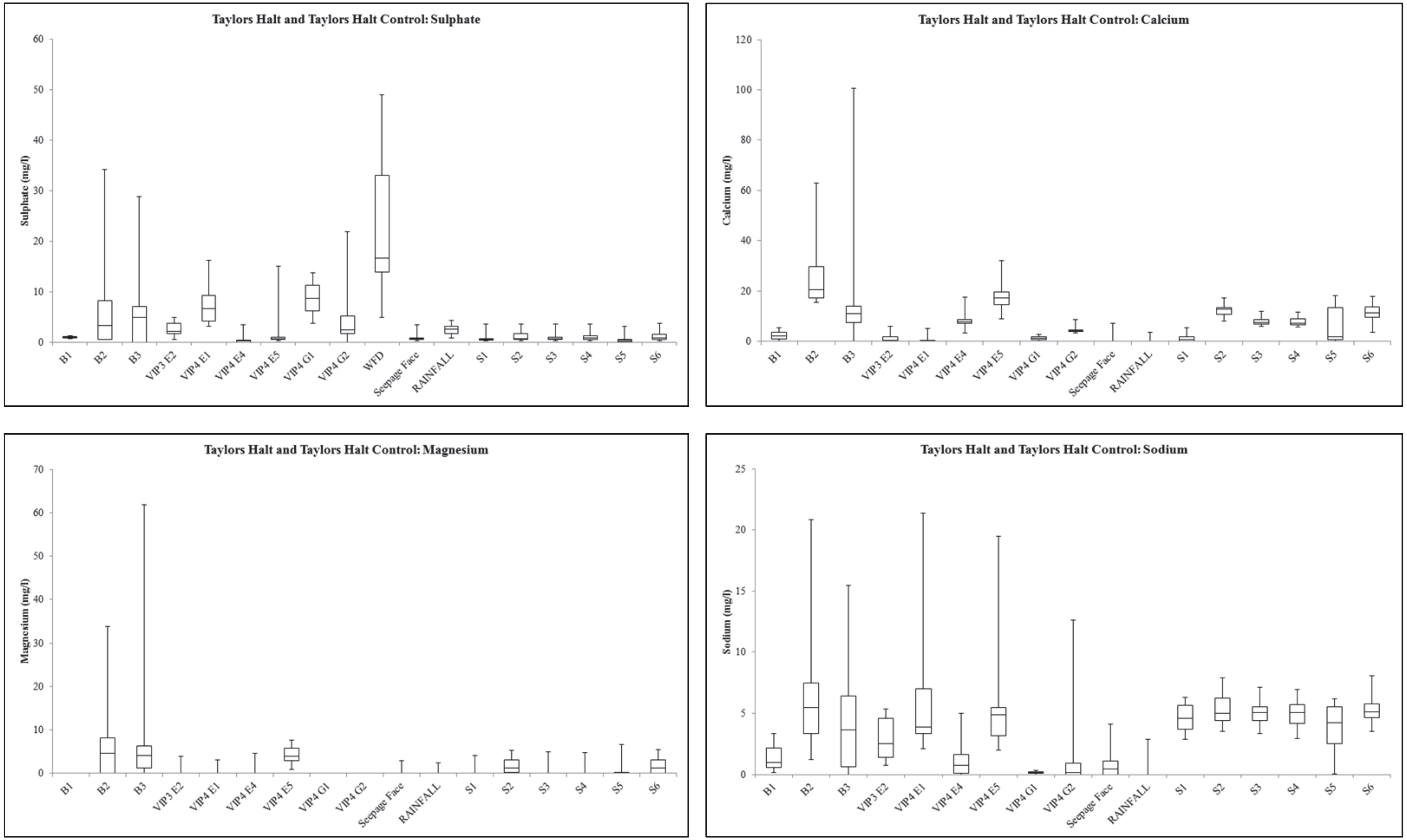
Appendix 10: Statistics of the Sulphate, Magnesium, Calcium and Sodium samples at Azalea.



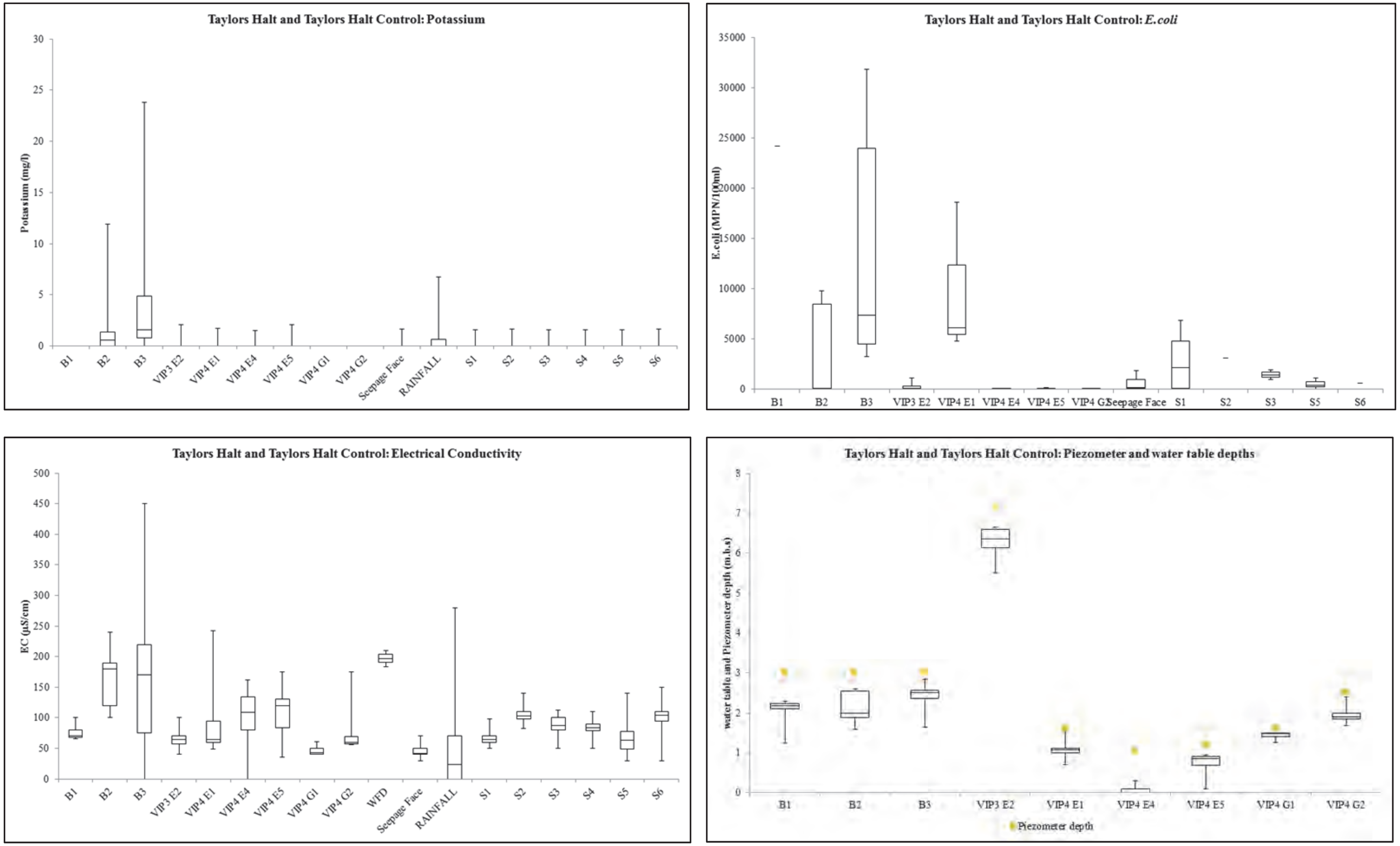
Appendix 11: Statistics of the Potassium, EC, *E coli* samples and water table depths at Azalea.



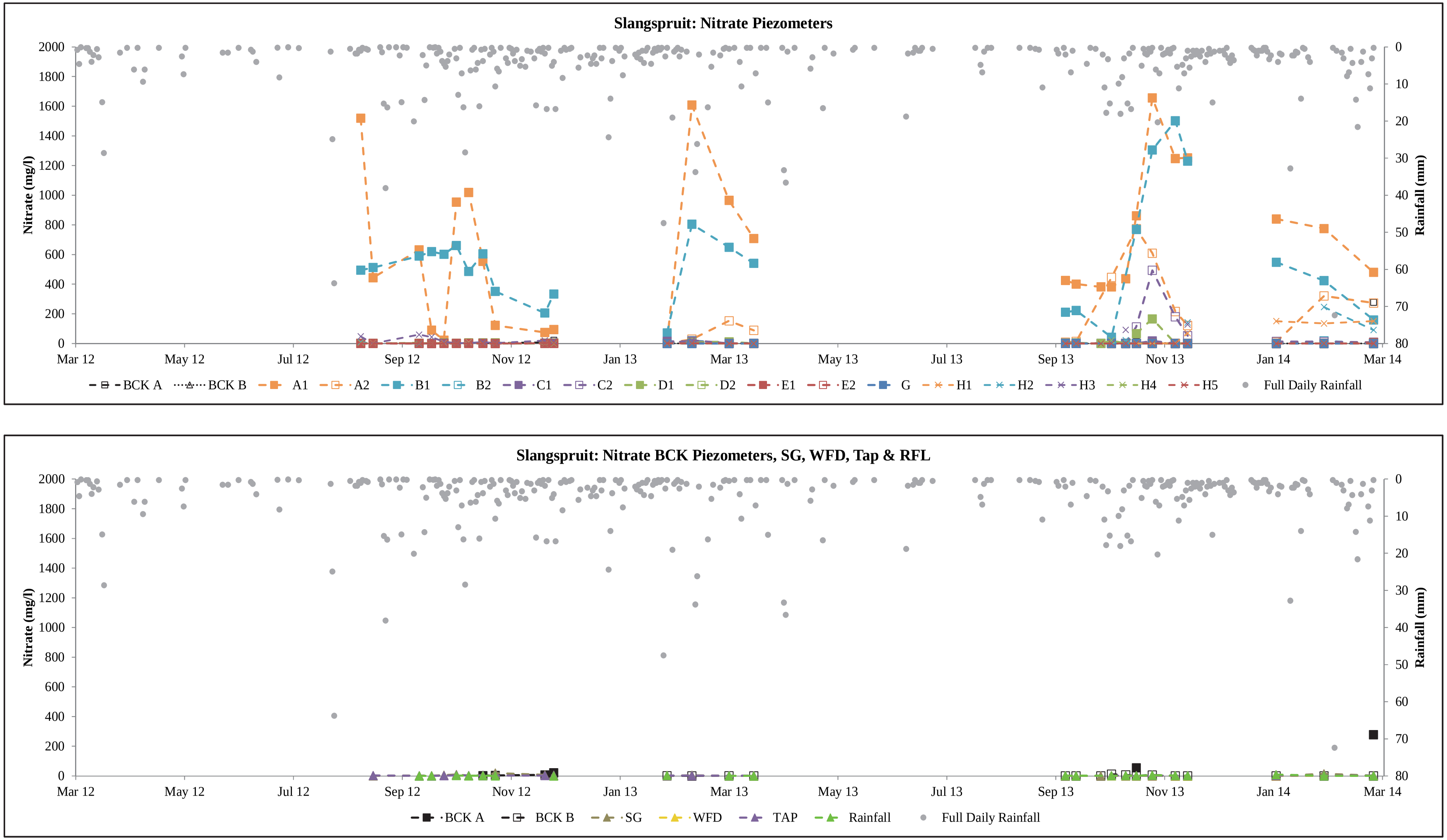
Appendix 12: Statistics of the Nitrate, Ammonium, Phosphate and Chloride samples at Taylors Halt Control.



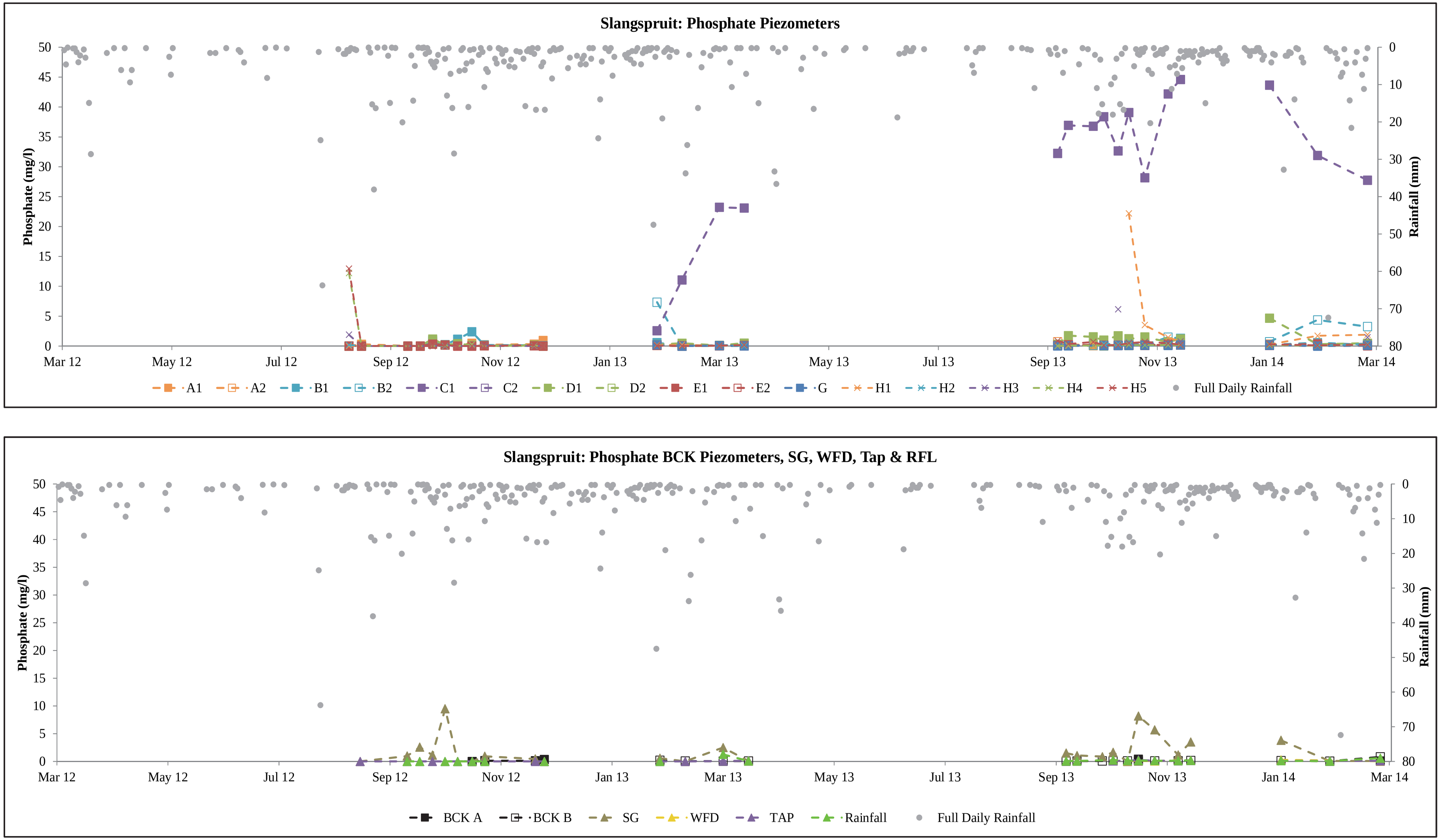
Appendix 13: Statistics of the Sulphate, Magnesium, Calcium and Sodium samples at Taylors Halt Control.



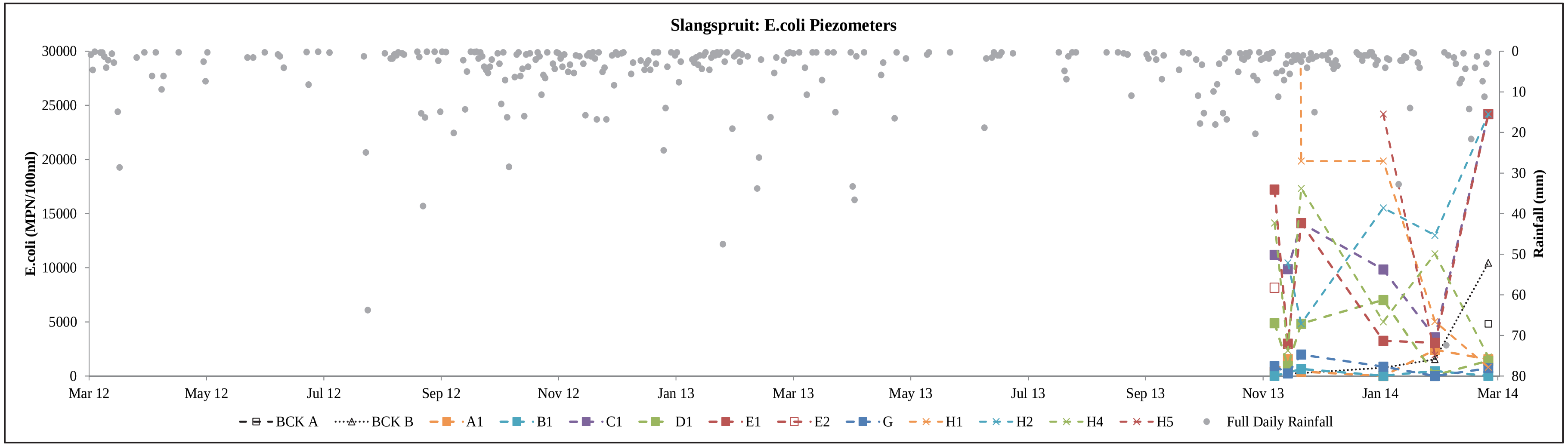
Appendix 14: Statistics of the Potassium, EC, *E coli* samples and water table depths at Taylors Halt and Taylors Halt Control.



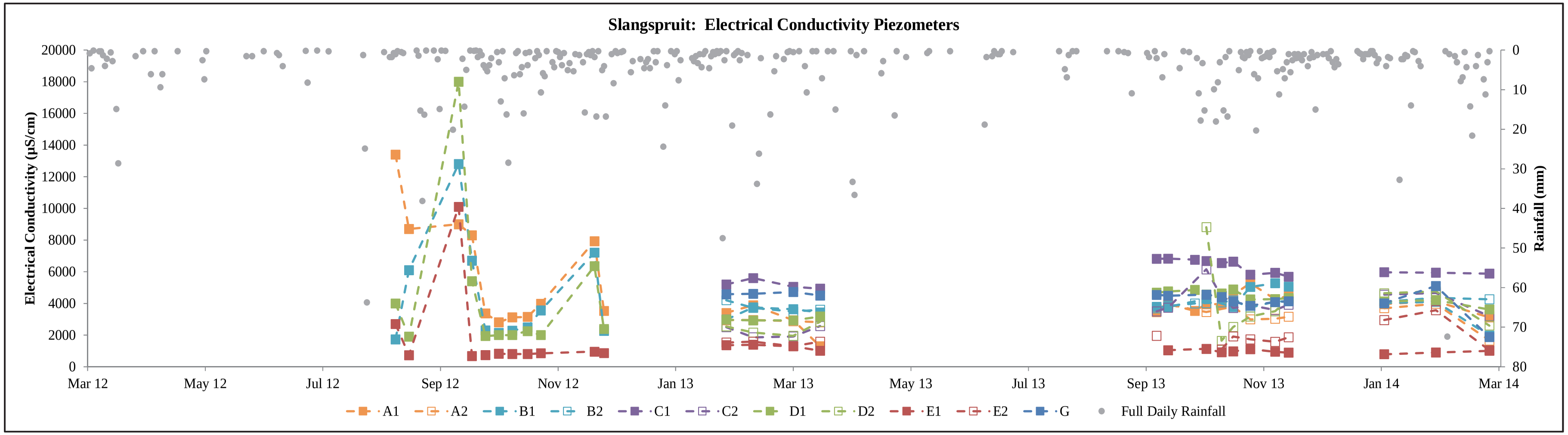
Appendix 15: Nitrate time series at Slangspruit.

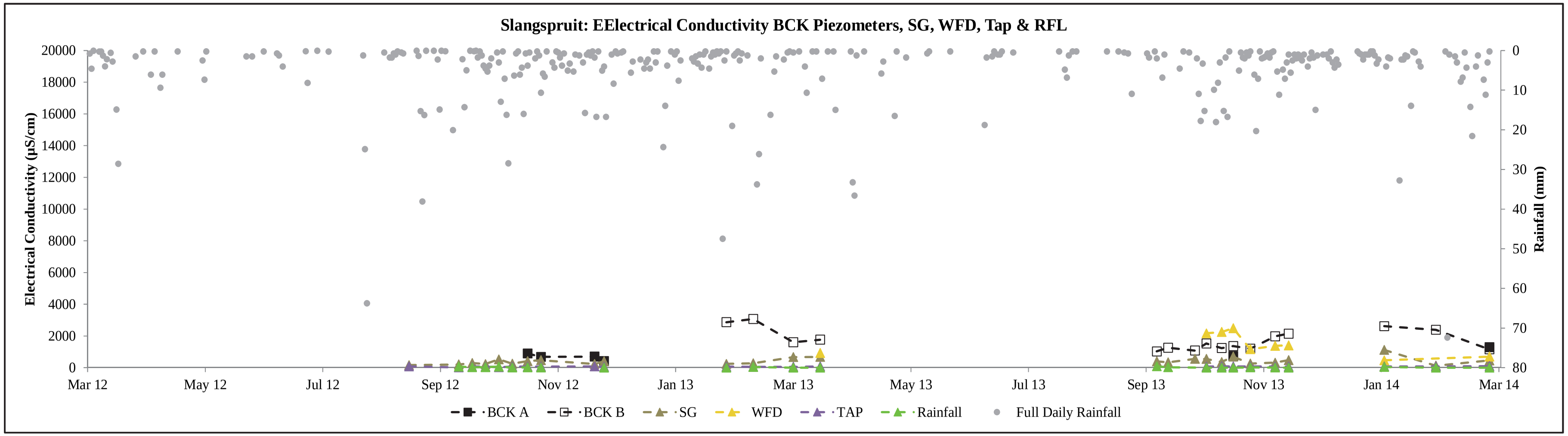


Appendix 16: Phosphate time series at Slangspruit.

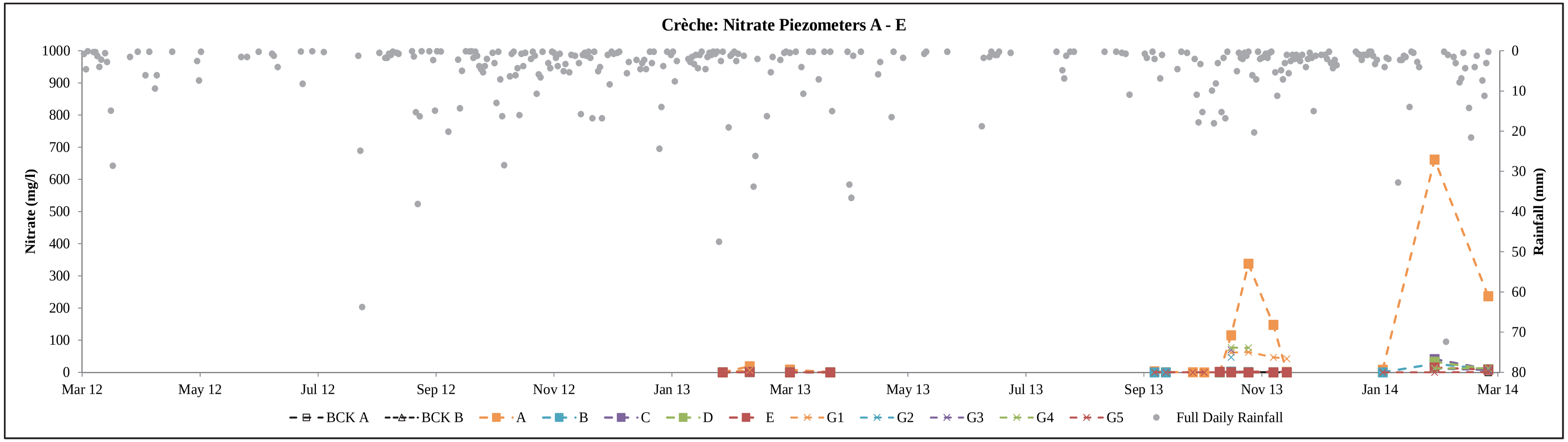


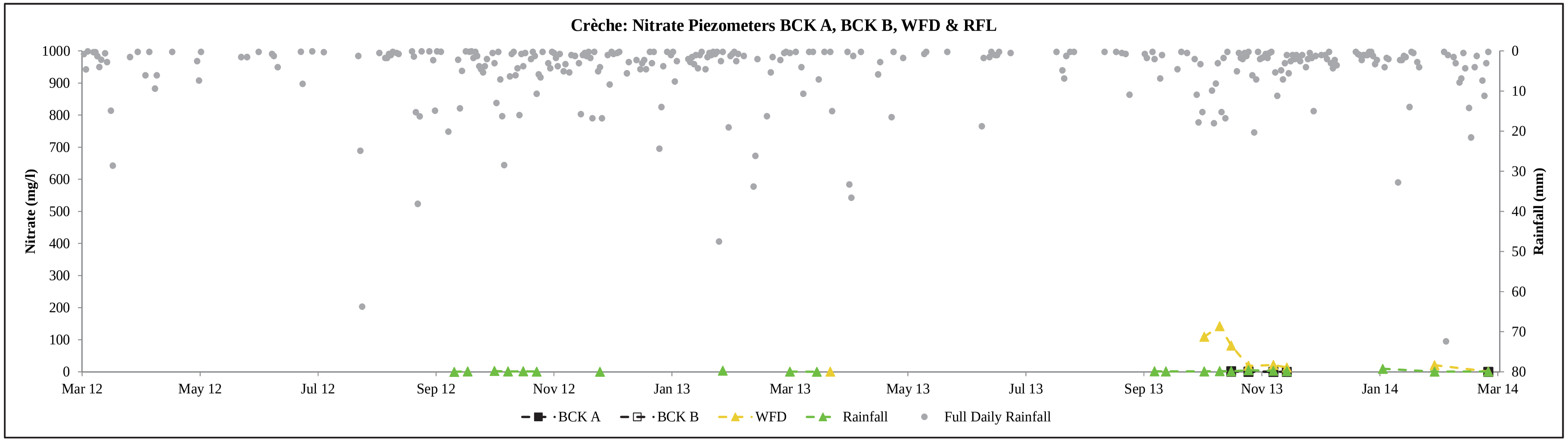
Appendix 17: *E. coli* time series at Slangspruit.



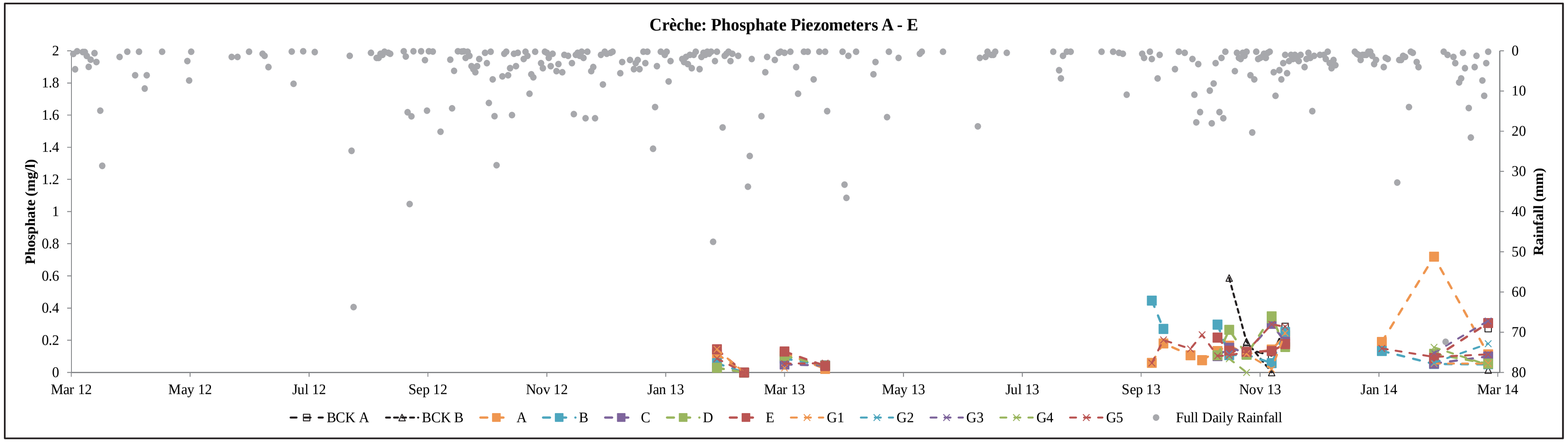


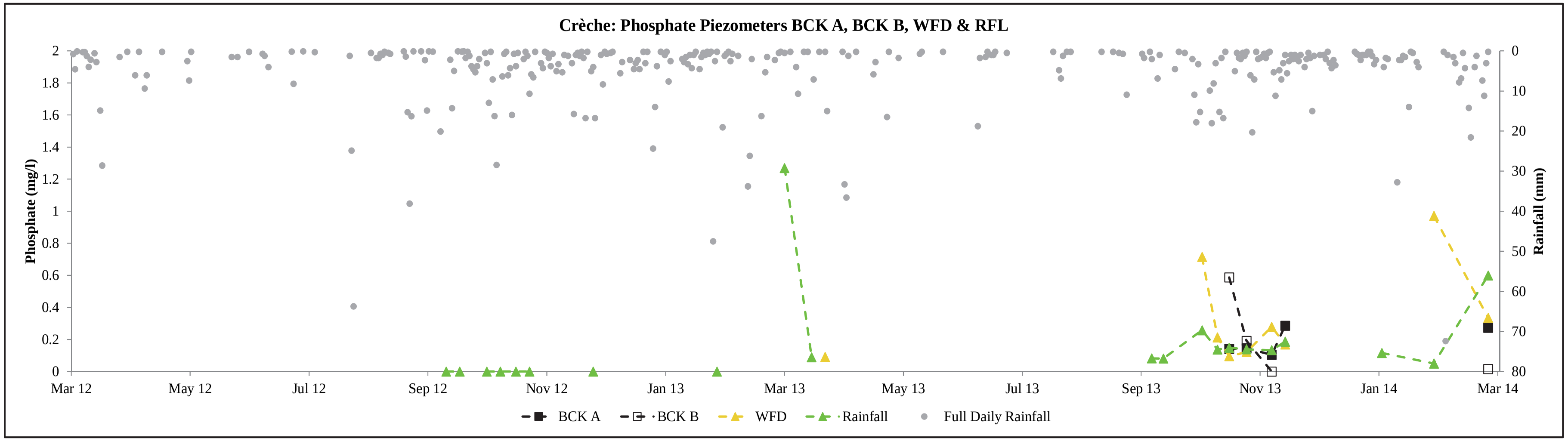
Appendix 18: EC time series at Slangspruit.



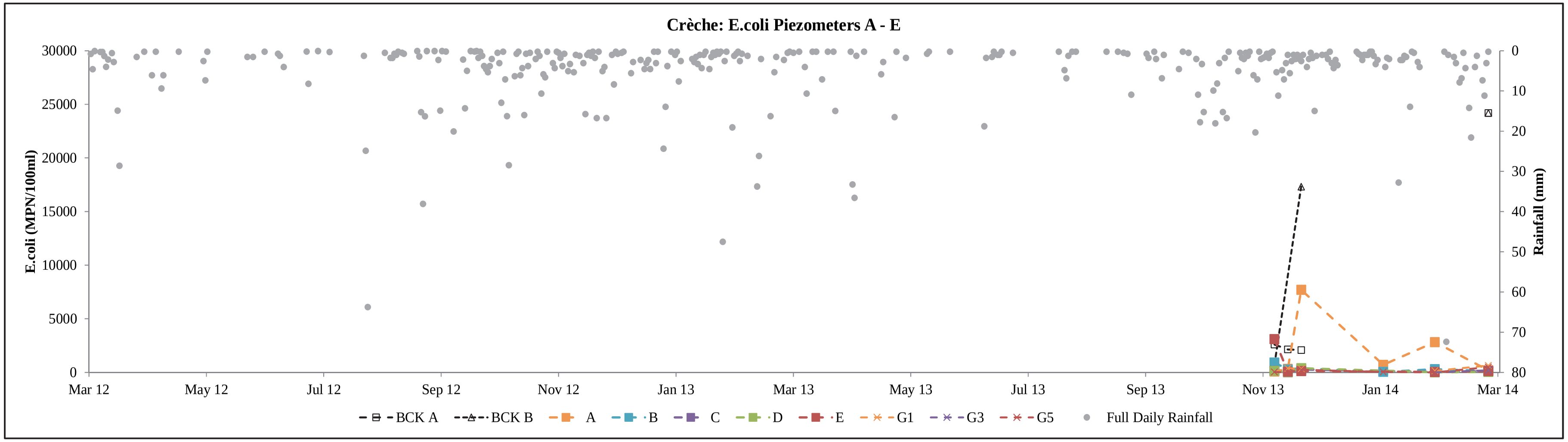


Appendix 19: Nitrate time series at Creche.

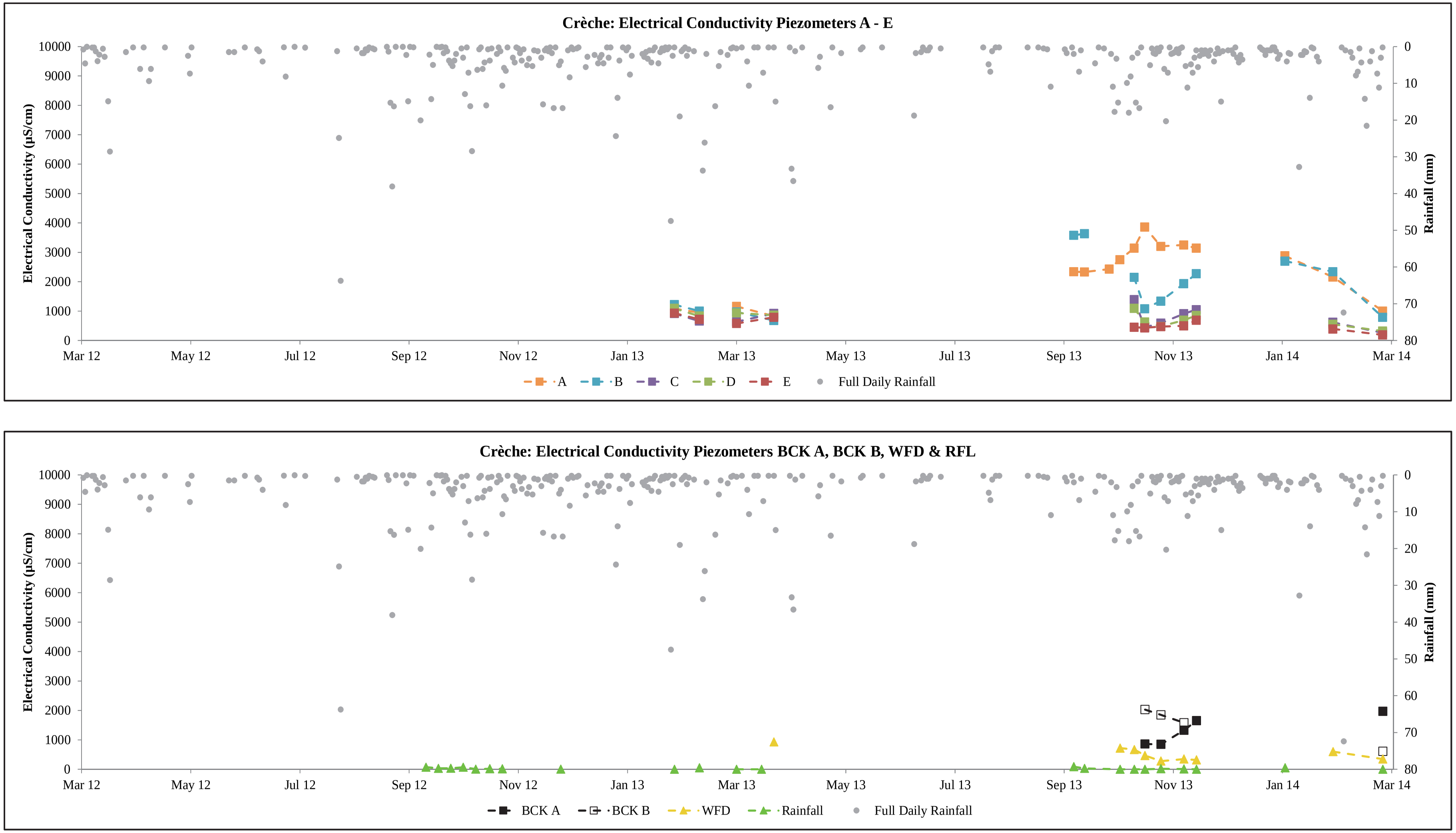




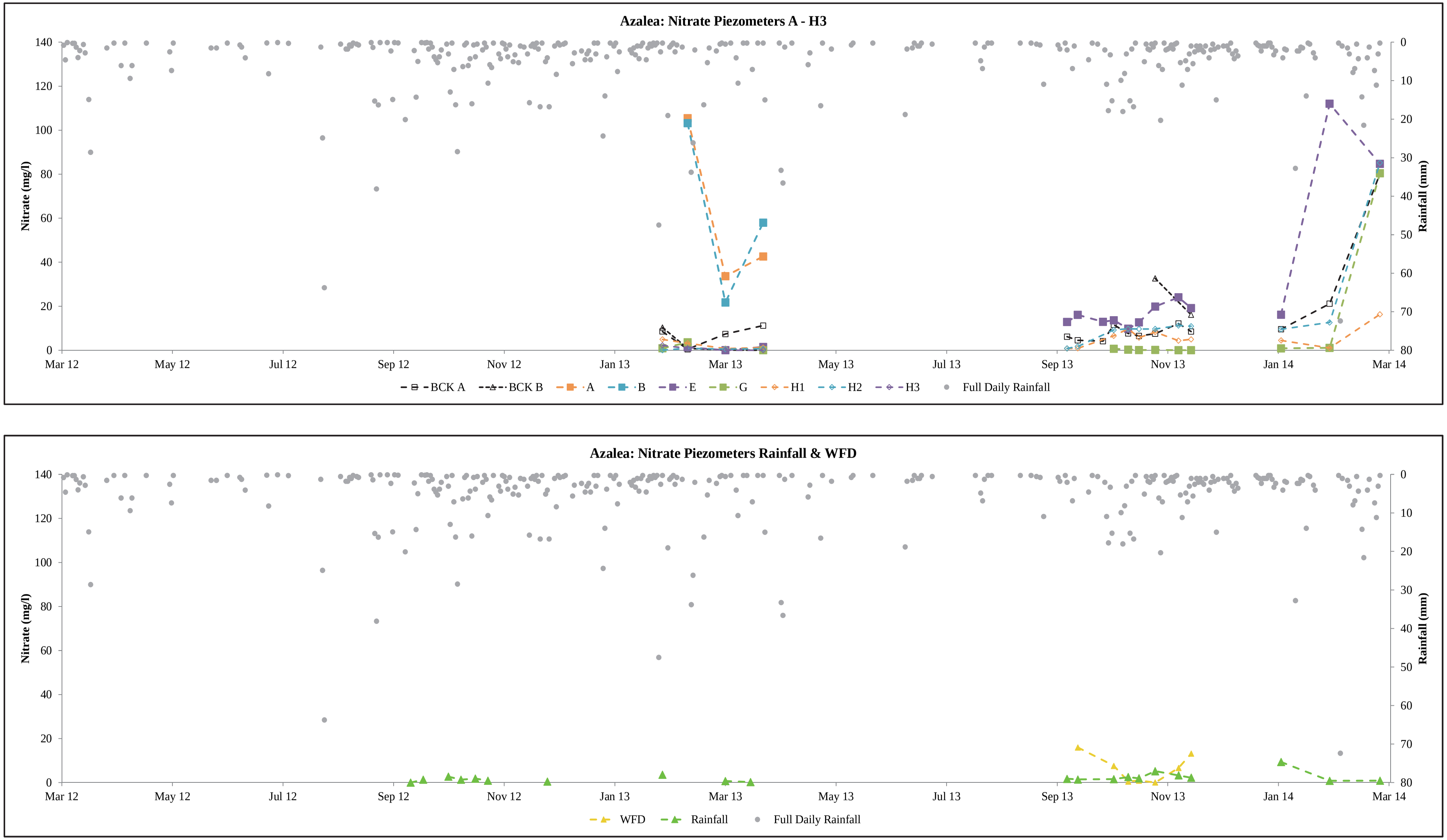
Appendix 20: Phosphate time series at Creche.



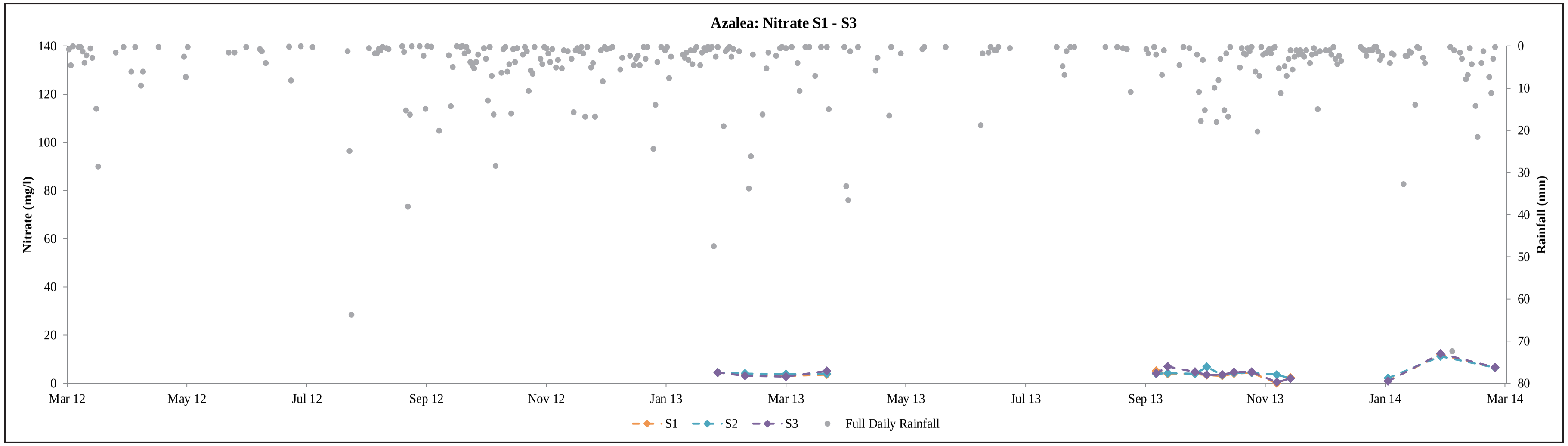
Appendix 21: *E. coli* time series at Creche.

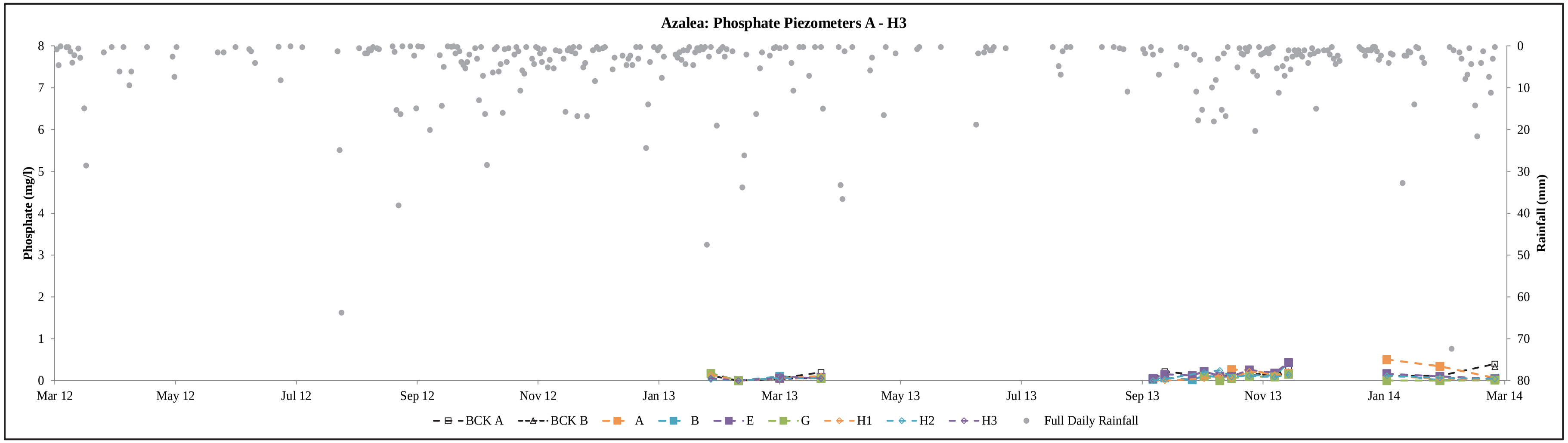


Appendix 22: EC time series at Creche.

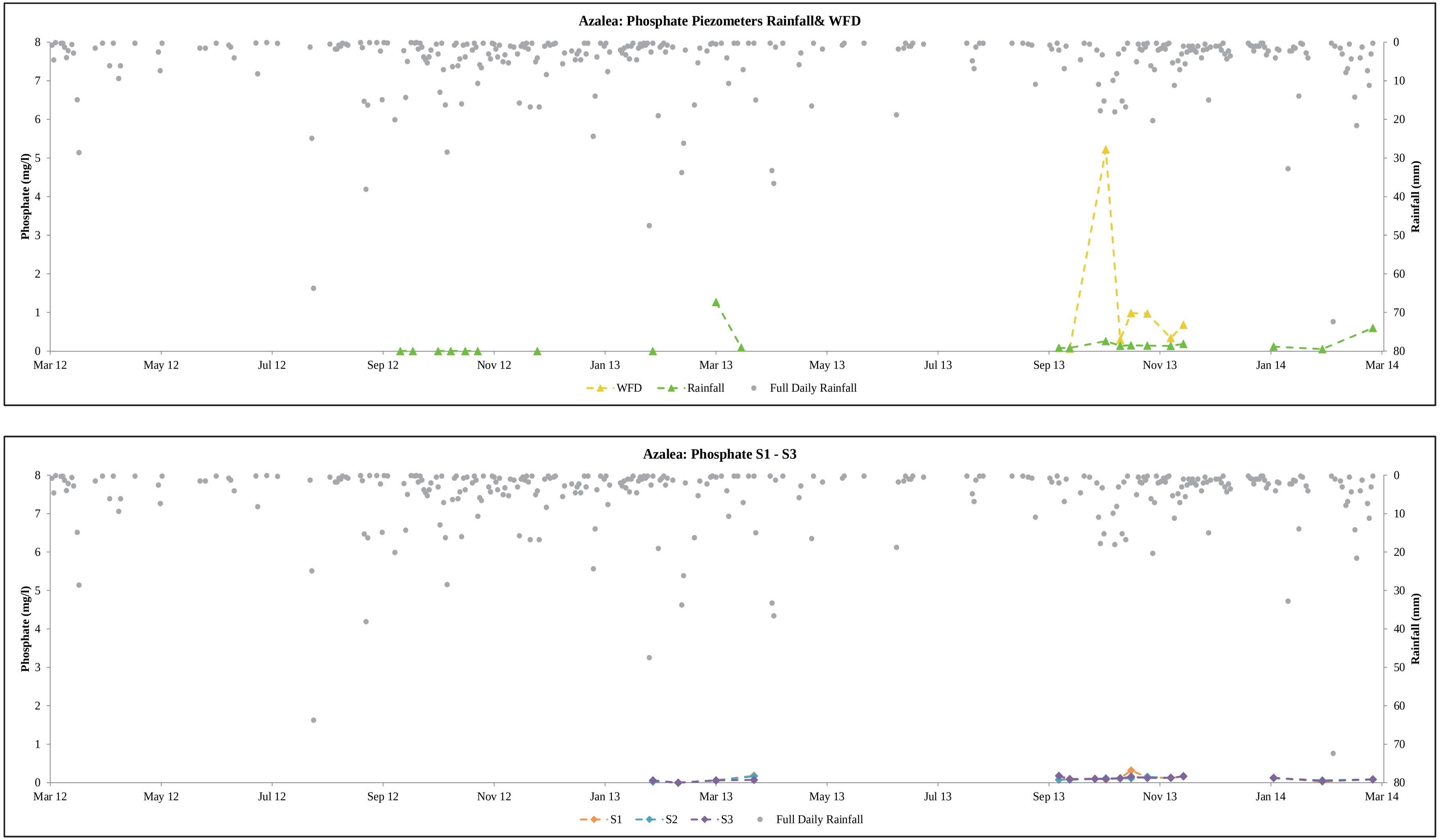


Appendix 23: Nitrate time series at Azalea.

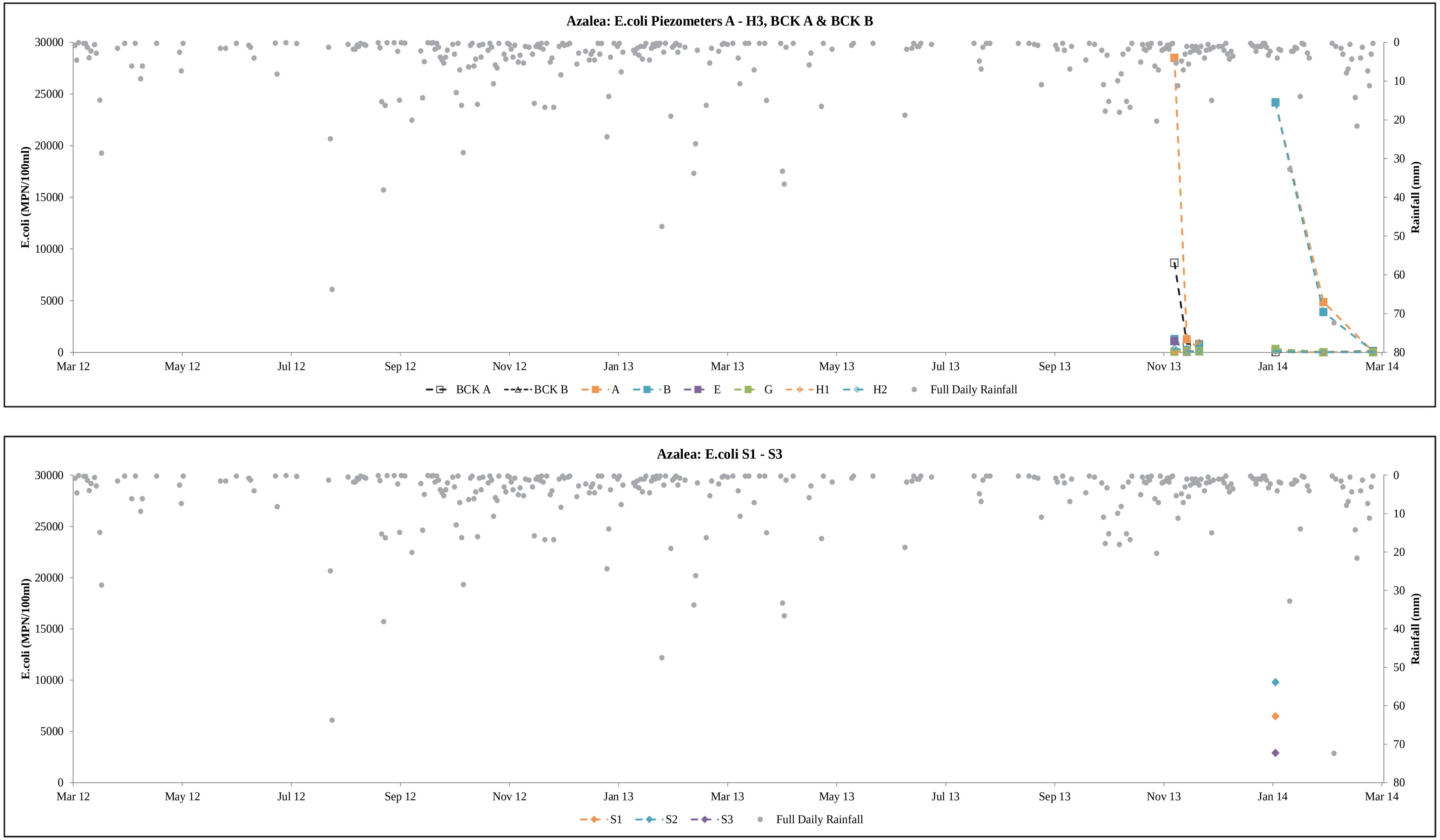




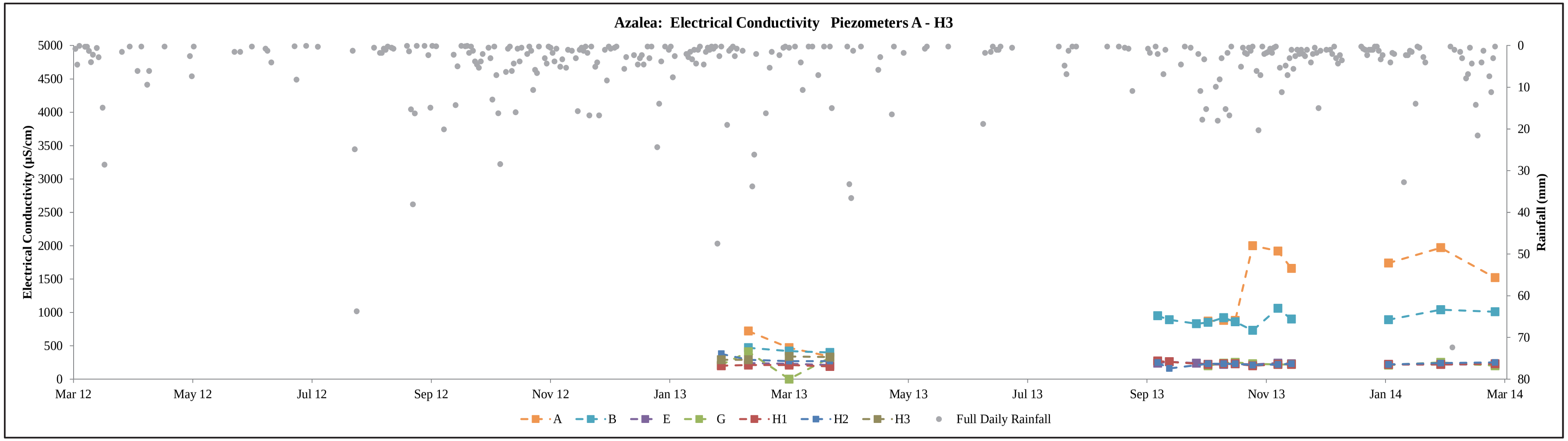
Appendix 24: Phosphate time series at Azalea.

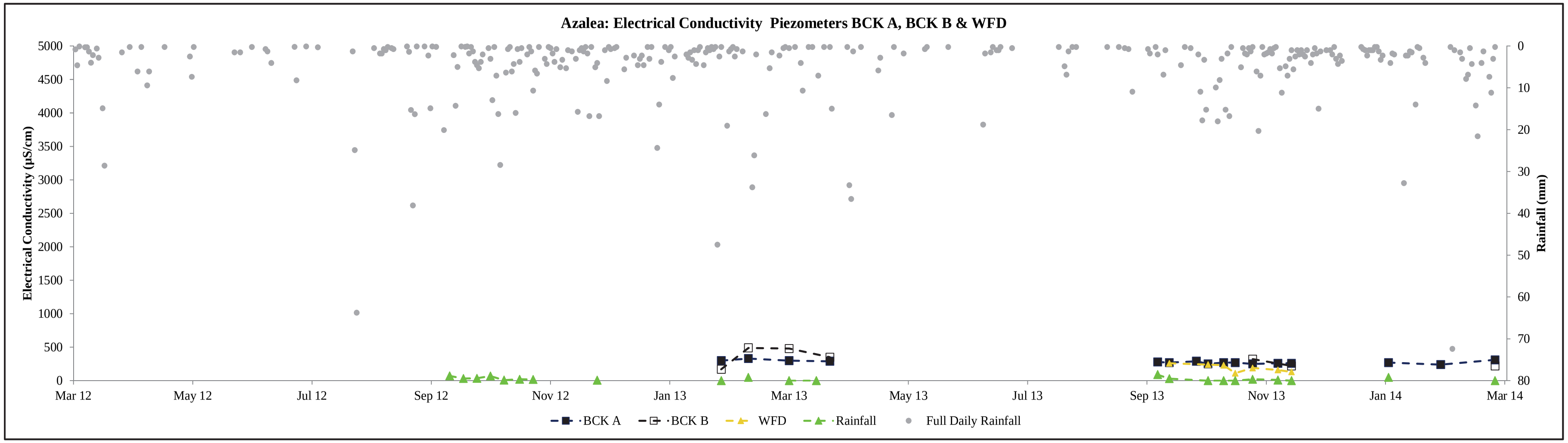


Appendix 25: Phosphate time series at Azalea (2)

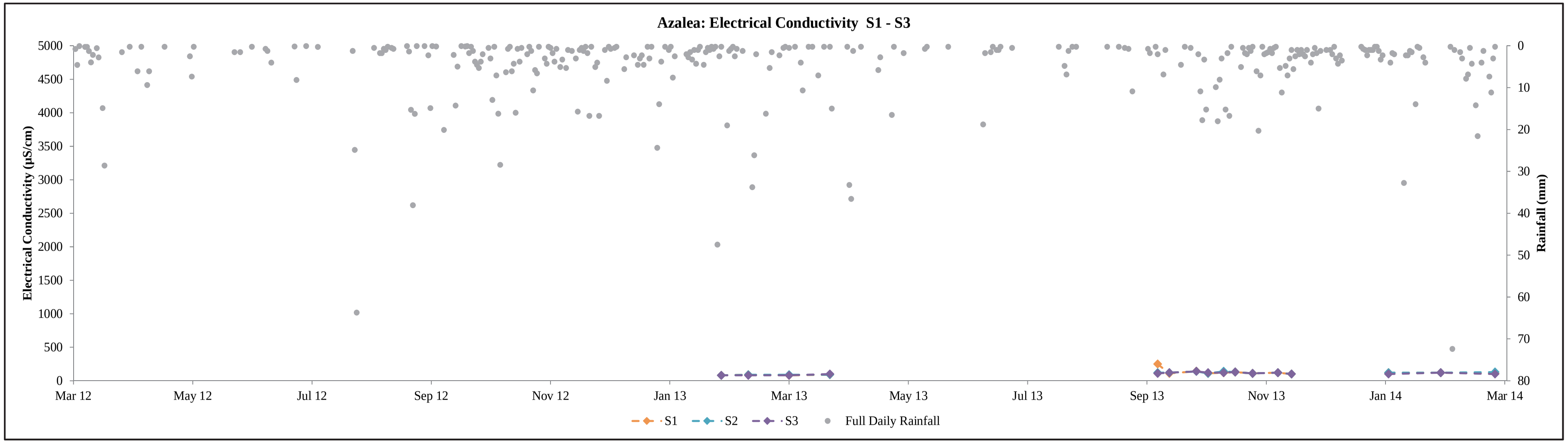


Appendix 26: *E. coli* time series at Azalea

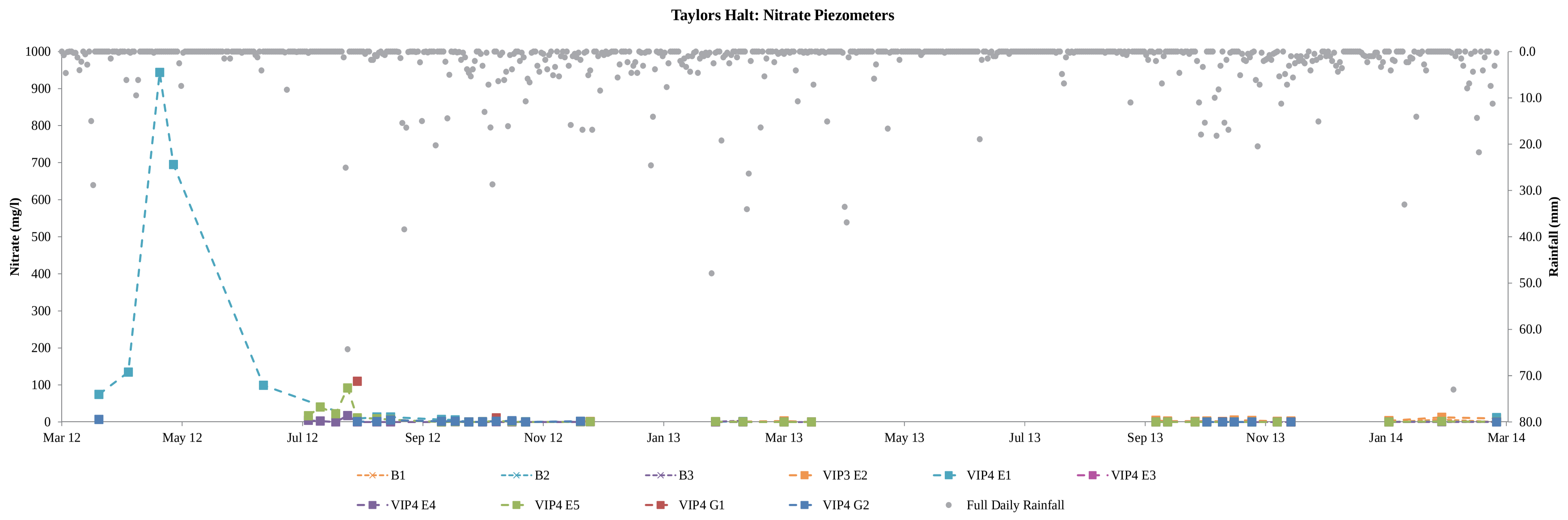

Azalea: Electrical Conductivity Piezometers A - H3

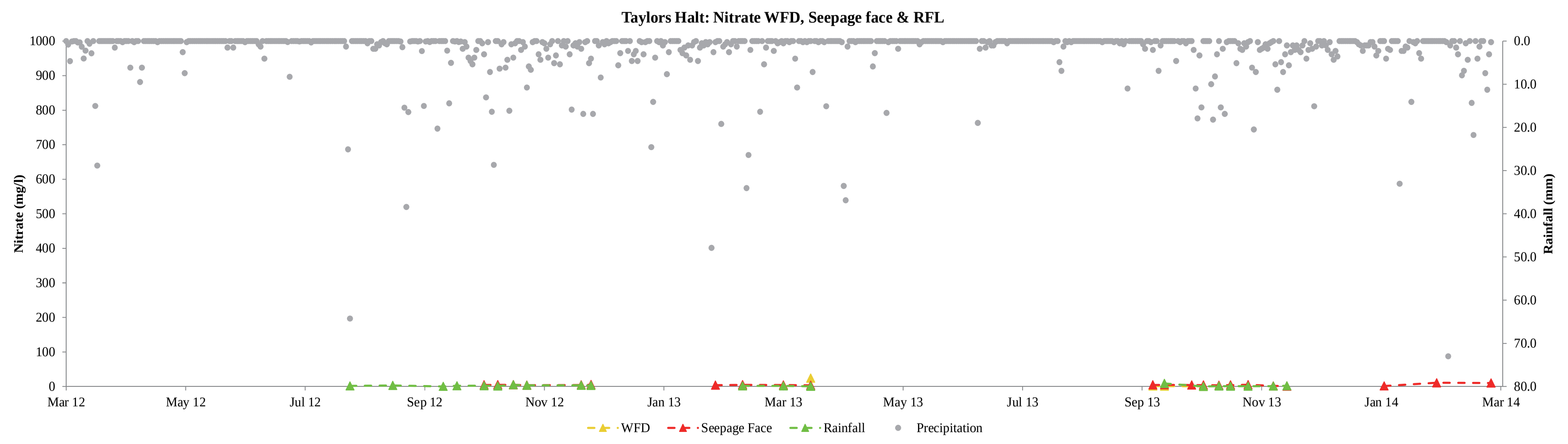

Azalea: Electrical Conductivity Piezometers BCK A, BCK B & WFD

Appendix 27: EC time series at Azalea

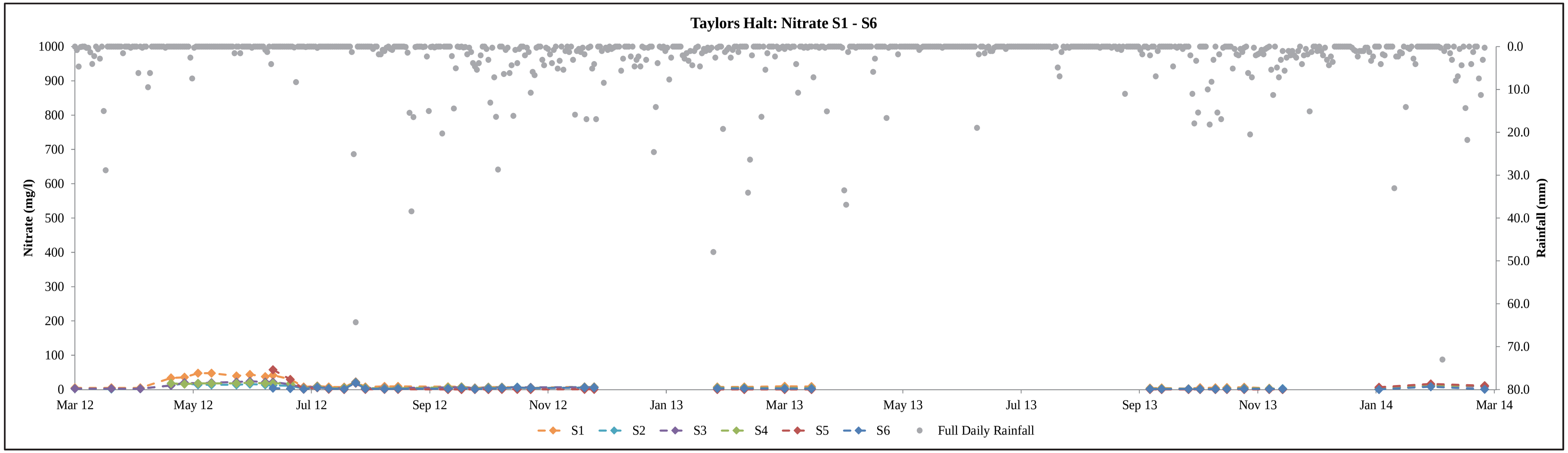


Appendix 28: EC time series at Azalea (2)

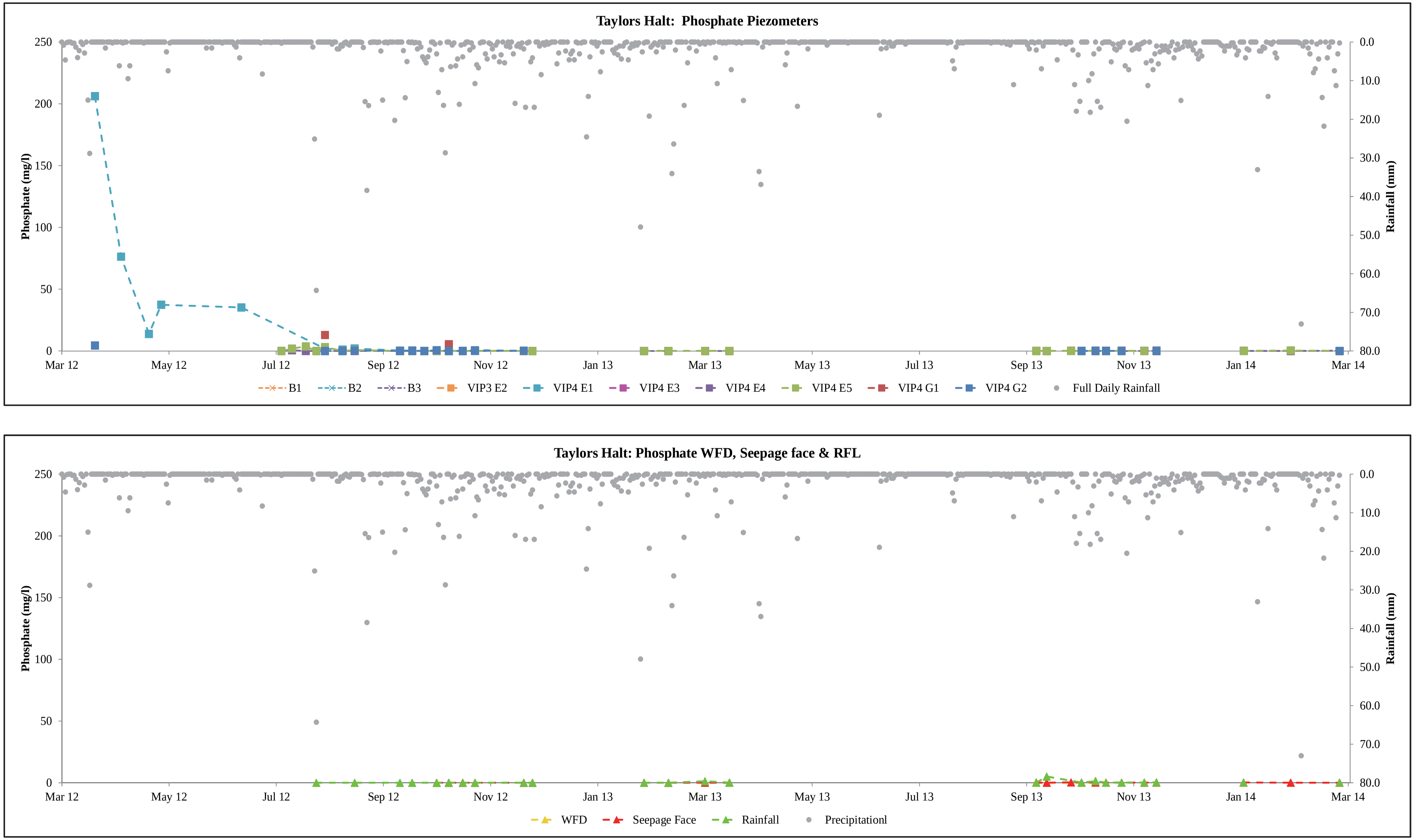




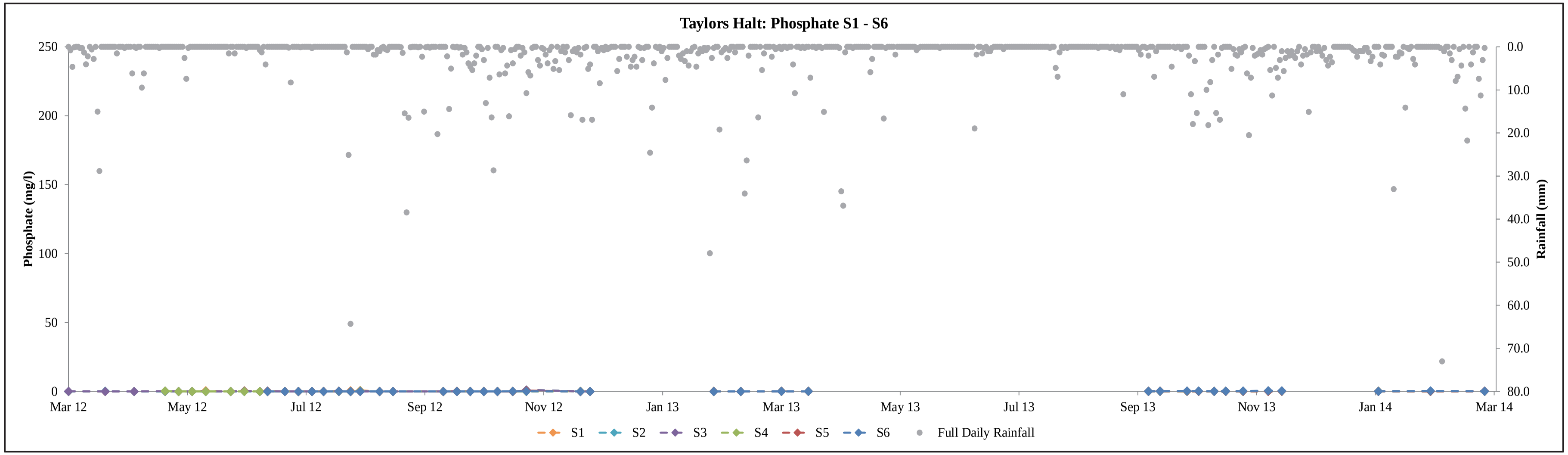
Appendix 29: Nitrate time series at Taylors Halt.



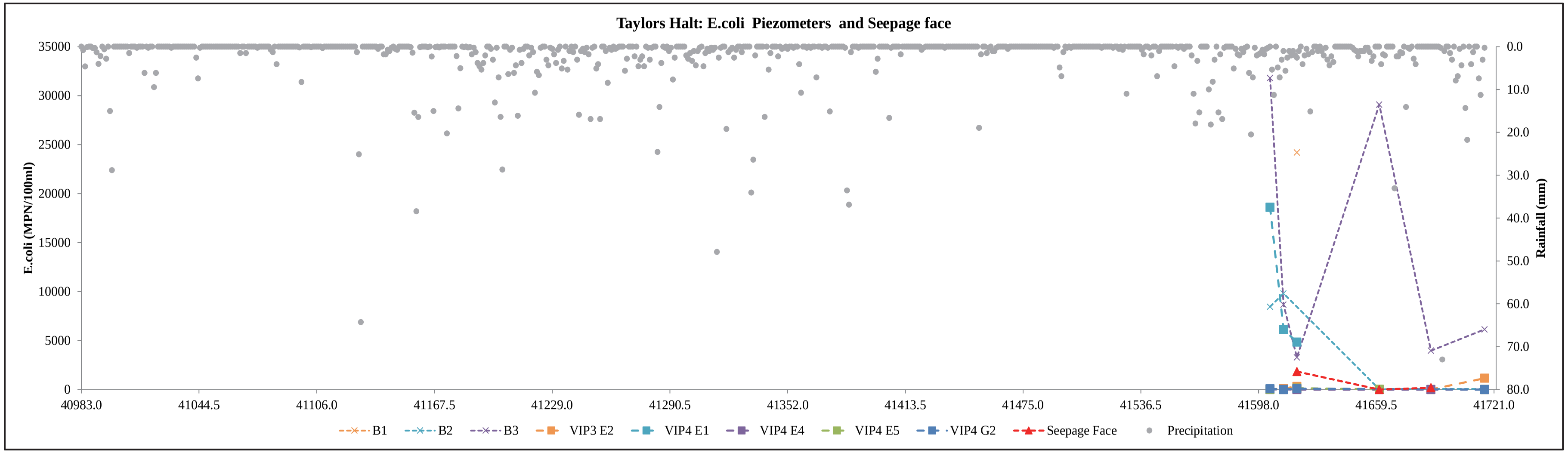
Appendix 30: Nitrate time series at Taylor’s Halt (2).

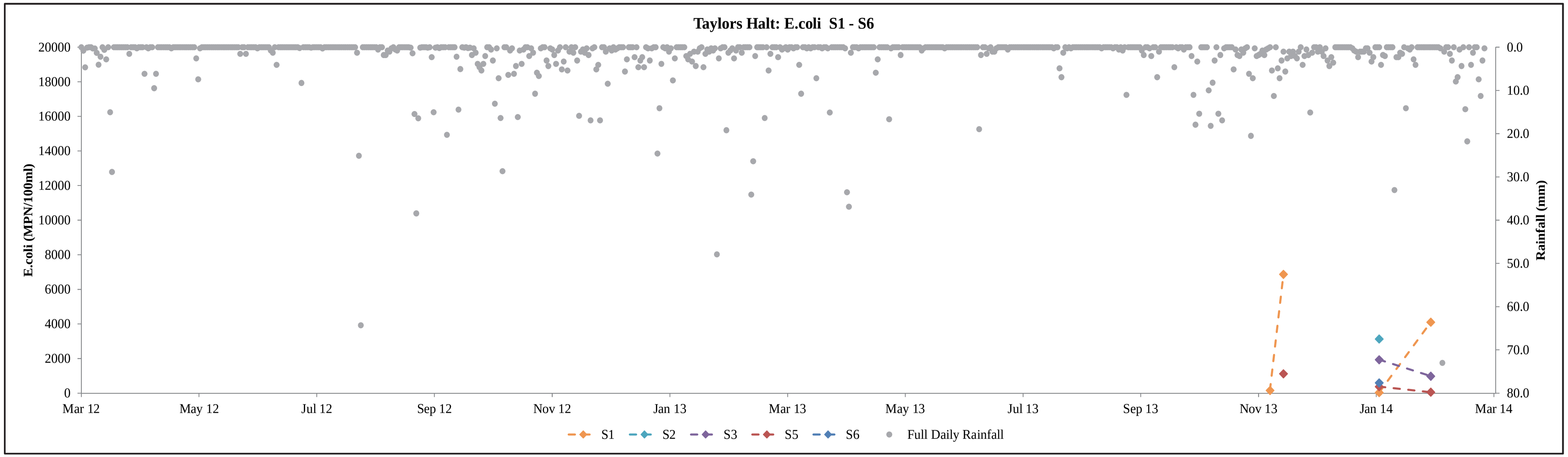


Appendix 31: Phosphate time series at Taylors Halt.

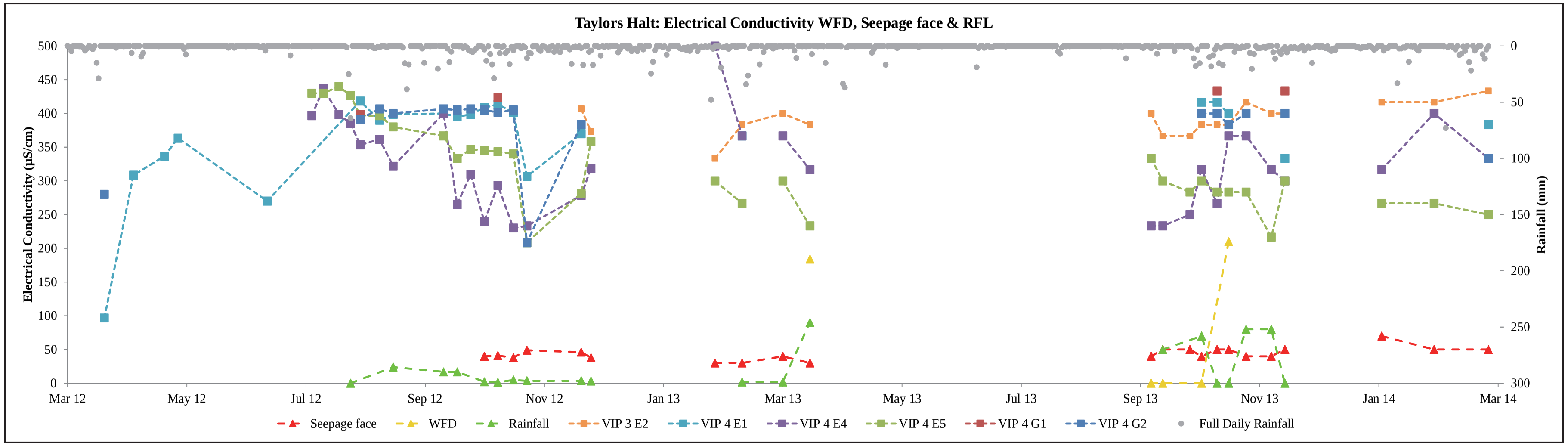


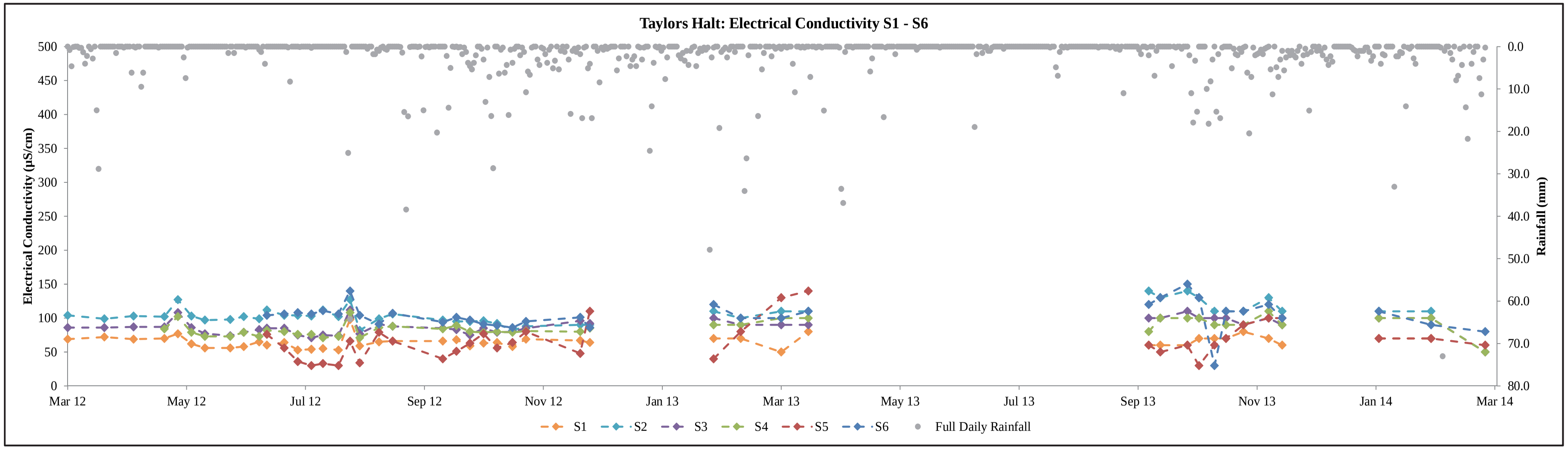
Appendix 32: Phosphate time series at Taylors Halt (2).



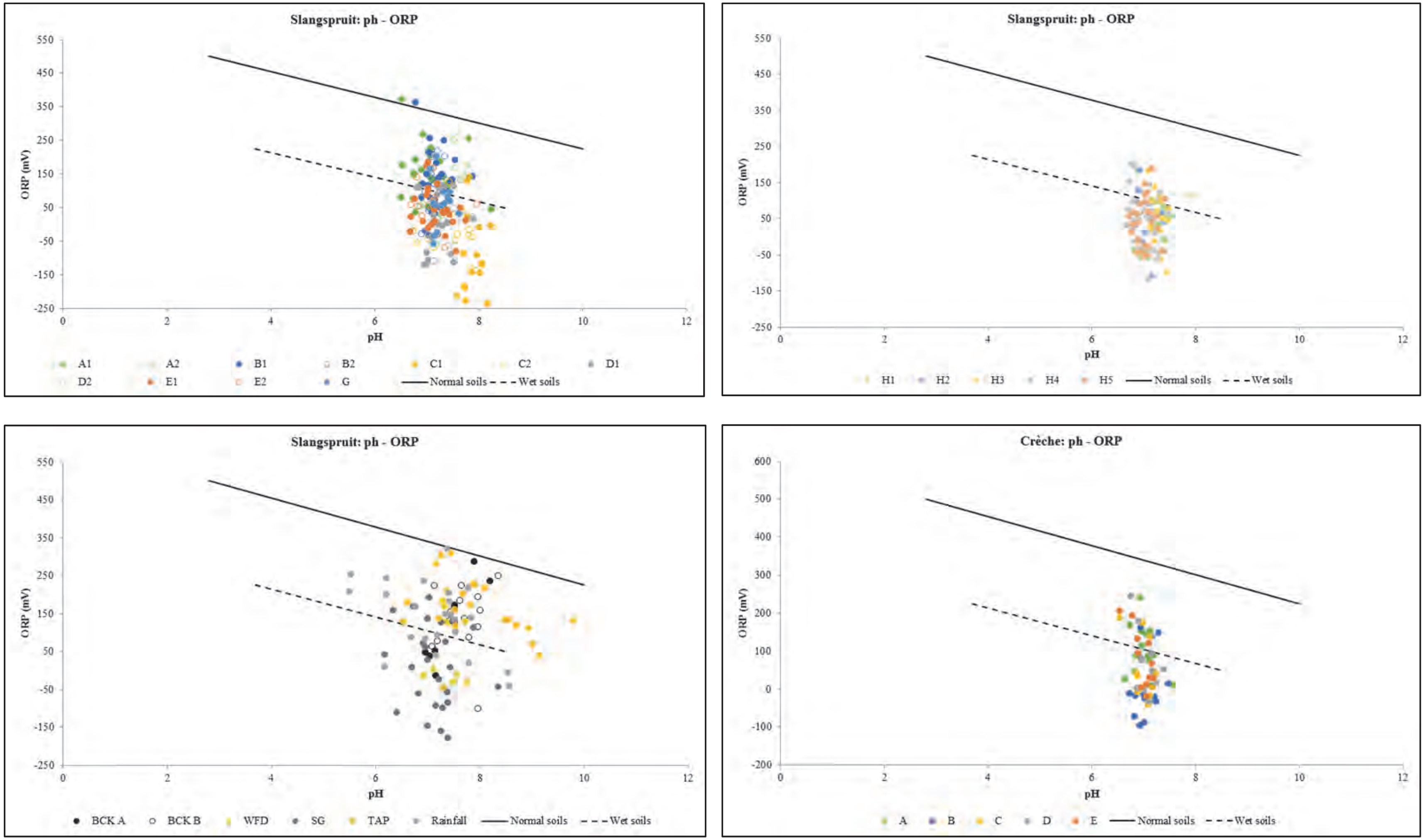


Appendix 33: *E. coli* time series at Taylors Halt.

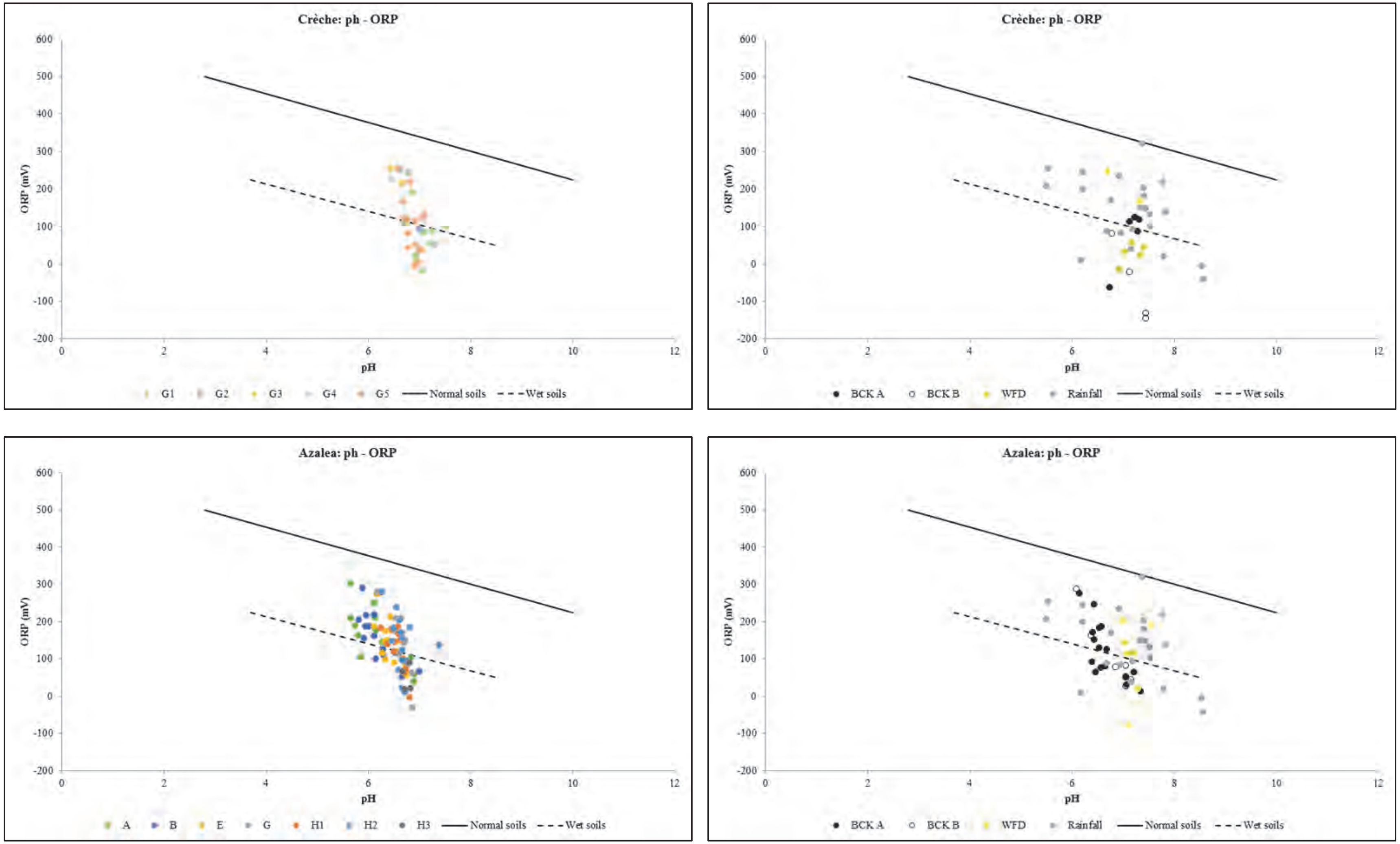




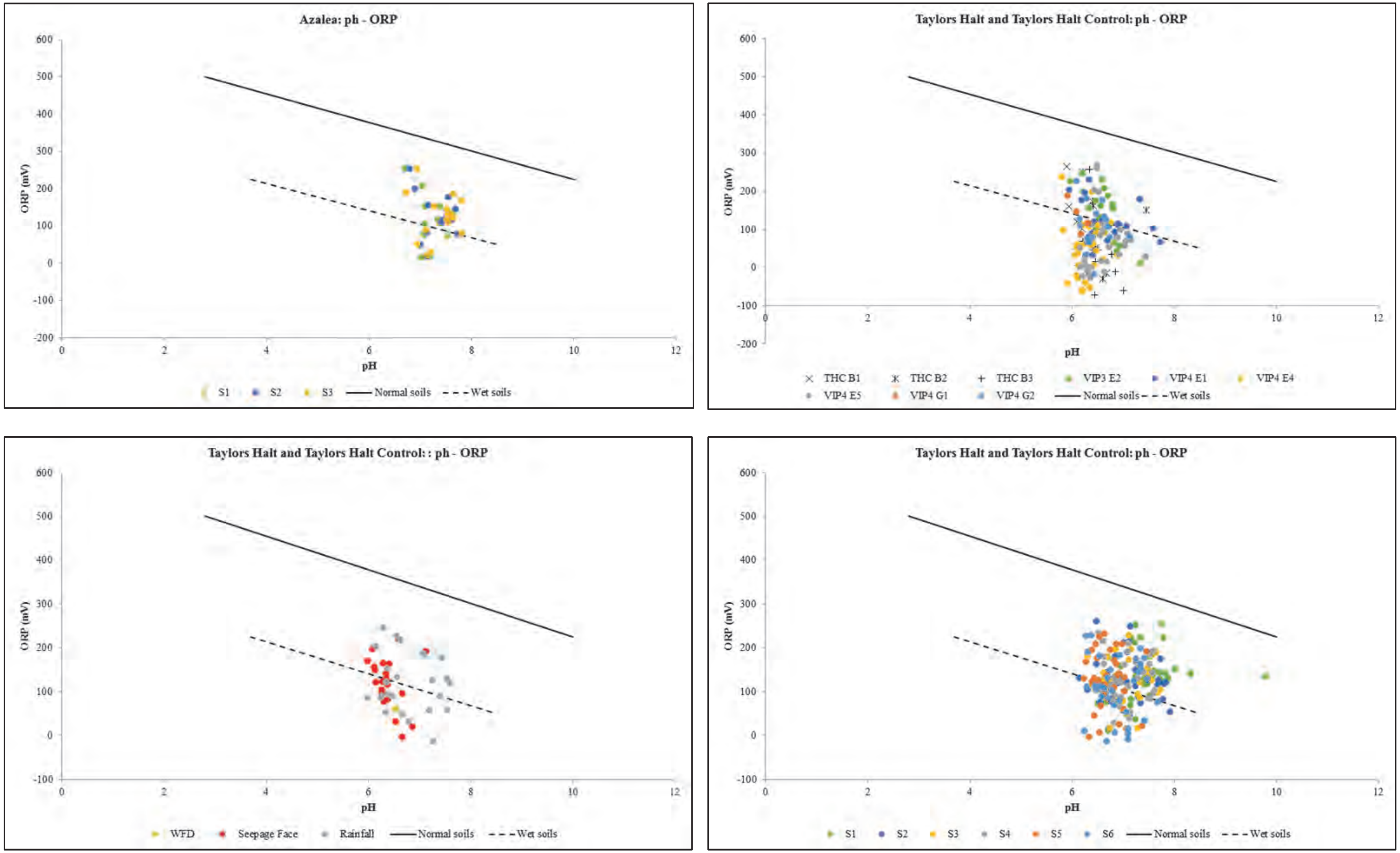
Appendix 34: EC time series at Taylors Halt.



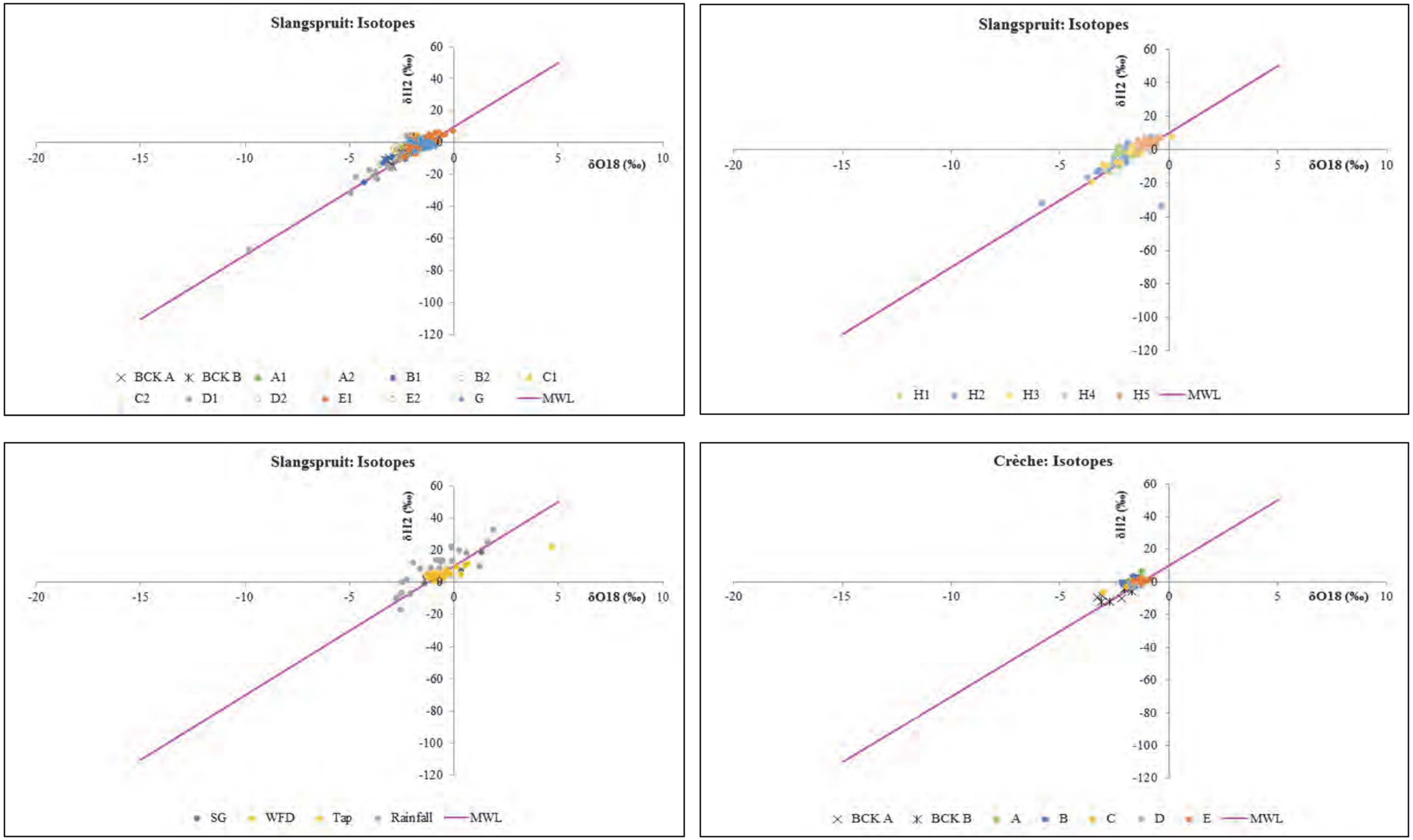
Appendix 35: pH-ORP relationships at Slangspruit.



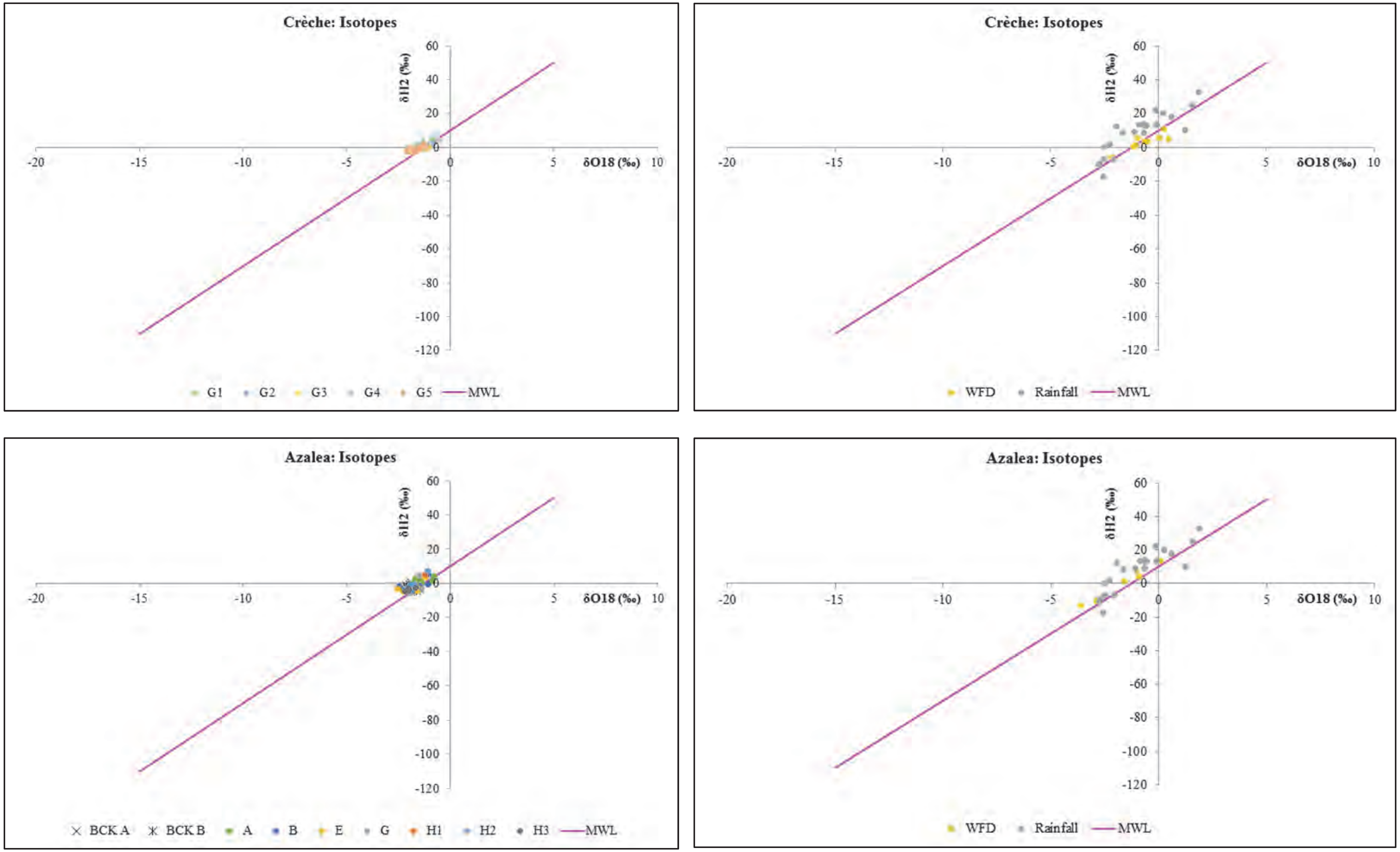
Appendix 36: pH-ORP relationships at Azalea



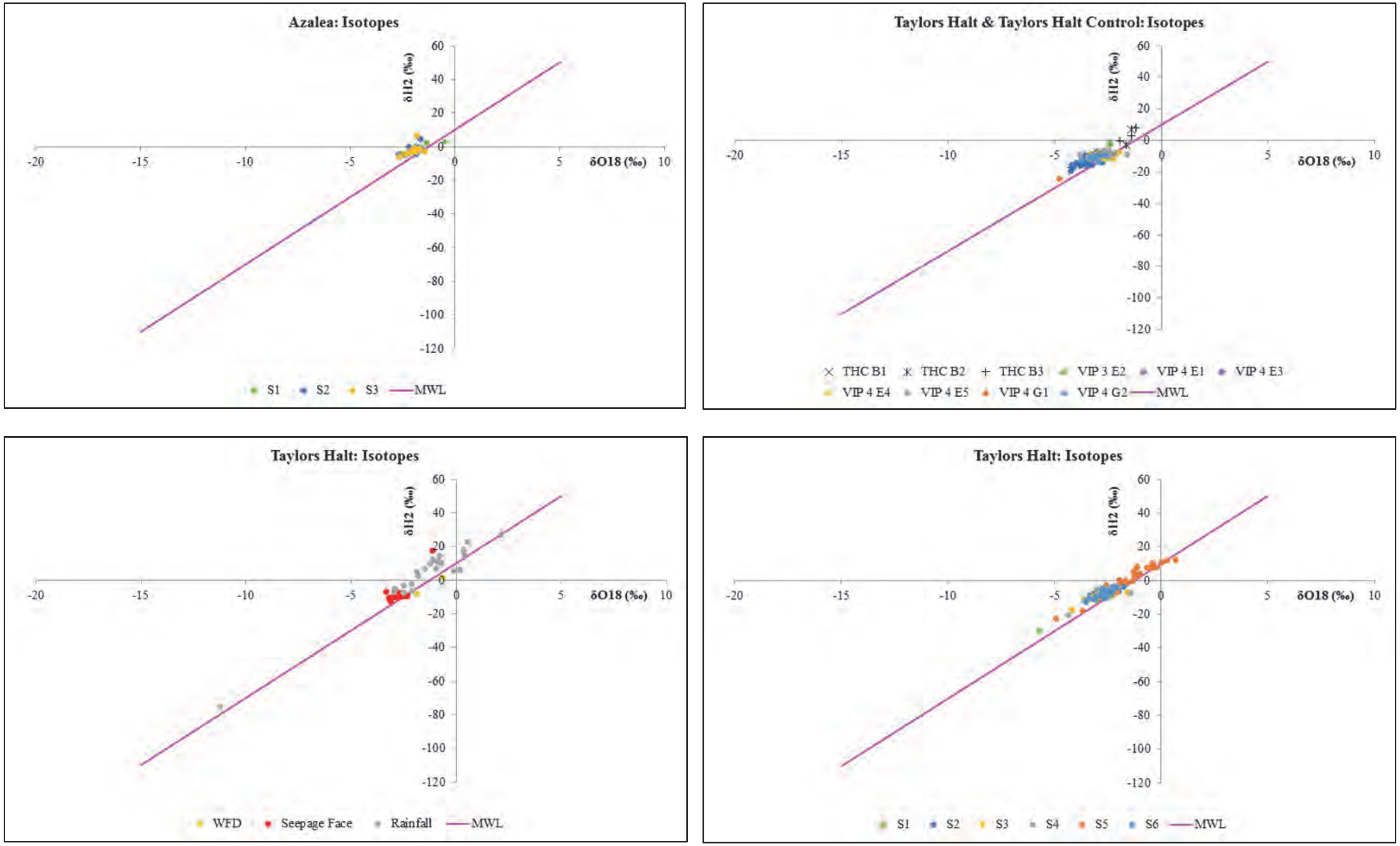
Appendix 37: pH-ORP relationships at Taylors Halt and Taylors Halt Control.



Appendix 38: Stable isotope relationships at Slangspruit and Creche.



Appendix 39: Stable isotope relationships at Creche and Azalea.



Appendix 40: Stable isotope relationships at Azalea and Taylors Halt.