Carroll, Steven and Goonetilleke, Ashantha (2005)
Assessment of high density of onsite wastewater treatment systems on a shallow groundwater coastal aquifer using PCA.
Environmetrics 16(3): 257-274

ASSESSMENT OF HIGH DENSITY OF ONSITE WASTEWATER TREATMENT SYSTEMS ON A SHALLOW GROUNDWATER COASTAL AQUIFER USING PCA

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Summary

Onsite wastewater treatment systems are common throughout the world including Australia, with approximately 17% of the Australian population relying on these systems to treat and ultimately dispose of wastewater. Systems which are properly sited, designed and managed are an effective way of providing the necessary treatment of wastewater. However, numerous incidence of onsite system failure is common, and this is further compounded in areas where high densities of systems are established. The density of systems is not appropriately assessed in the siting and design stage. Various factors, such as site and soil characteristics and climate can influence the treatment efficiency, and this is more critical in high density areas. Principal component analysis was used for assessing chemical and microbiological data from shallow groundwater below a high density of onsite treatment systems. The results of this study confirmed that high system densities can significantly impact on shallow groundwater systems. Additionally, changes in spatial and climatic conditions, as well as the type of onsite system can also influence the quality of groundwater.

Keywords: Onsite systems, high density, groundwater, Principal Component Analysis

1. Introduction

Approximately 17% of the Australian population is reliant on the onsite treatment of wastewater and land disposal of effluent (O'keefe 2001). Due to its simplicity and low cost, septic tank-soil absorption systems (septic systems) remain by far the most common. This is despite the fact that aerobic wastewater treatment systems (aerobic systems) are becoming more prevalent with time. The satisfactory treatment of wastewater, for septic systems in particular, is reliant on location specific factors such as, suitable soil and site conditions, climate and topography (Dawes and Goonetilleke 2003, Khalil et al. 2003, Siegrist 2000). Numerous incidences of poor treatment performance of onsite systems, in particular septic systems, are quite common (USEPA 2002). This is further compounded by the existence of large densities of such systems in many urban fringe areas. This situation is particularly prevalent in the Southeast region of Queensland State, Australia, which is the most rapidly urbanising area in the country. In the absence of appropriate management strategies to assess and control the impacts of increased densities of onsite wastewater treatment systems (OWTS) in the region, the resulting environmental and public health risks associated with the poor system performance increases substantially.

The density of OWTS is not appropriately assessed in the siting and design stage of these systems. Regulatory authorities have their own requirements in regard to the specific lot size required for the use of OWTS, but this can differ substantially from one jurisdiction to another. Most authorities either specify a required minimum lot size, or determine this through the use of setback distances. This is to ensure that adequate dilution and attenuation of chemical and microbiological pollutants is achieved within the required distance (Perkins 1984). However, this approach does not take into consideration the varying capacities of different soil types for effluent renovation or the cumulative impact of large numbers of OWTS in a locality.

The presence of OWTS densities as low as 15 systems/km^2 has been suggested as having undesirable impacts on groundwater and the surrounding environment (Perkins 1984, Yates 1985). Numerous research studies (for example Hoxely and Dudding 1994, Perkins 1984, Whitehead and Geary 2000, Lipp et al 2001) provide evidence that high densities of OWTS are capable of contaminating groundwater. However these studies have generally only investigated the quality of groundwater in the vicinity of high densities of OWTS. The impact of variations in soil characteristics climatic conditions and system type on groundwater quality in relation to high densities of OWTS have not been investigated in-depth.

This paper presents the outcomes of a research investigation into the impact of high density of OWTS on shallow groundwater quality. Data obtained from groundwater monitoring wells were analysed using Principal Component Analysis (PCA). Analysis of the data using PCA allowed an in-depth investigation into the influence of spatial changes in contamination, climatic conditions and treatment system type (for example clusters of septic and aerobic systems) on the quality of groundwater.

2. Materials and Methods

2.1 Study Area

The study area for this investigation was the Jacobs Well community. Jacobs Well is a small coastal community located in the northern outskirts of Gold Coast region, Queensland State, Australia, as depicted in Figure 1. The entire community is dependent on onsite wastewater treatment systems, with septic systems being by far the most evident. However, aerobic systems are also utilised, and two clusters in the community which rely on aerobic systems were identified, as shown in Figure 1. This reliance on onsite systems is a major concern in regards to groundwater quality. The average residential block size in this area is approximately 400m^2, and with a total of 445 systems within the community, the current density of OWTS in Jacobs Well is very high, with 290 onsite systems/km^2. The overall performance of these systems is highly variable, with some systems having been in place for 30 years or more and with limited maintenance being undertaken. The Jacobs Well area is currently undergoing extensive new housing developments, which will substantially add to the severity of the detrimental impacts.

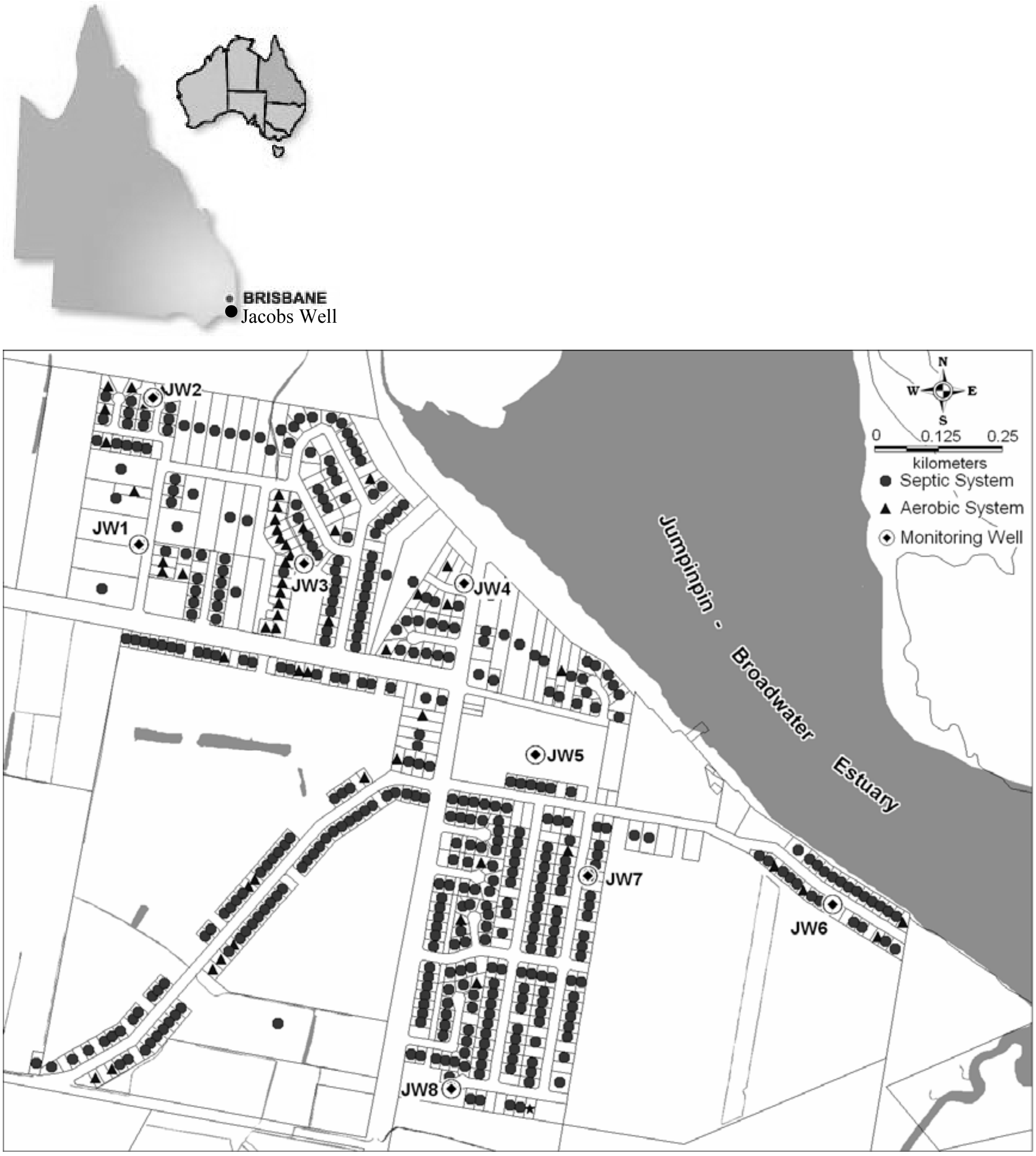

Figure 1: Jacobs Well study area in Southeast Queensland, Australia.

Due to the subtropical climate in the study region, rainfall has a significant impact on the recharging of the shallow aquifers in the area. The annual average rainfall at Jacobs Well is approximately 1500mm/year. Due to the permeable soil conditions, approximately 50% of the rainfall provides recharge to the shallow aquifers. The main concern in this regard is the potential contamination of the shallow groundwater. This can be on average between 0.1 to 1m below the surface, depending on the prevailing climatic conditions. Typically, the unsaturated soil between the subsurface disposal trenches and the underlying groundwater is expected to provide sufficient treatment of the effluent prior to entering the groundwater system, as depicted in Figure 2. However, as the water table below Jacobs Well generally less than 1m from the surface, during extended wet periods some of the trenches may be submerged, allowing little if any treatment of discharged effluent prior to entry into the groundwater system. The groundwater primarily discharges into the adjacent *Jumpinpin-Broadwater* estuary which is frequented by large numbers of visitors for recreational fishing and boating activities. Additionally, most homeowners have installed spear pumps to allow access to the groundwater for irrigation purposes. Due to the large number of onsite wastewater treatment systems and the shallow groundwater level in Jacobs Well, it can be surmised that the effluent disposed to the soil is a potential groundwater recharge source. A large groundwater mound is evident beneath the community, and has a major influence on the direction of groundwater flow. The ability of the shallow aquifer to remove pollutants and provide suitable quality groundwater under these conditions is questionable. The community uses the shallow groundwater as an irrigation source for gardens and parks. Consequently, the risk of contamination due to chemical and microbiological pollutants is an important issue.

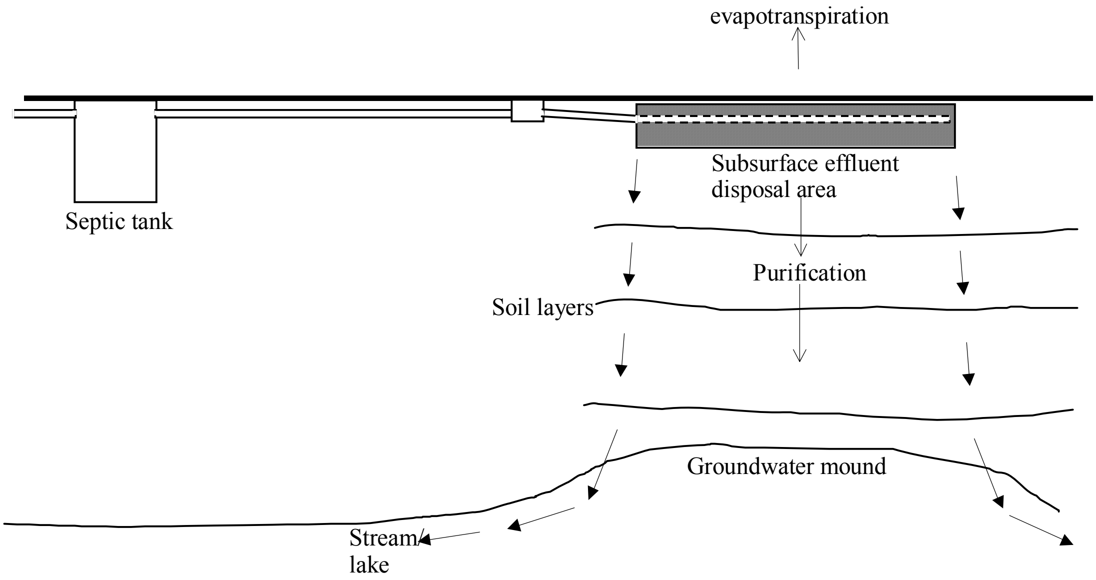

Figure 2: Major components and pathways in subsurface disposal of effluent

2.2 Hydrogeology

According to the Australian Soil Classification (Isbell 1996), the major soil conditions in the area consist of two main groups. Salic Hydrosols or permanently saturated soils which are equivalent to Ultisols or Inceptisols (NRCS 1999) account for most of the soil directly within Jacobs Well. The Hydrosol soil contains 80% sand and 5% clay with the remainder consisting of mostly organic material. The average size of the sand particles in the hydrosolic soil conditions is approximately 300μm in diameter, typical of very fine sand. The soil graduates into Bleached-Orthic Tenosols which is similar to Inceptisols or Entisols (NRCS 1999) further inland. The area is a flat coastal plain, with an average ground elevation ranging from 2-3m at its highest point. The geology beneath Jacobs Well consists of Cainozoic (Holocene) dune sand underlain by layers of 'coffee rock' or indurated sand rock 3-6m below the surface, with a sandy clay horizon from 10-30m. This creates two shallow aquifers with substantially different characteristics. A shallow perched aquifer lies on top of the sand rock layer, providing an average water table depth of approximately 0.5m below the surface. A semi-confined shallow aquifer is located beneath the 'coffee' rock, which in turn is confined at the bottom by the sandy clay stratum. Although retaining a fairly low permeability, it is predicted that the sand rock has numerous cracks and fissures which would allow flow from the unconfined aquifer to penetrate into the semi-confined main aquifer. Though both aquifers are primarily recharged by rainfall, due to the large number of onsite wastewater treatment systems, an appreciable percolation of wastewater into the shallow aquifers can be expected to occur.

2.3 Monitoring Wells

In order to assess the quality of groundwater in the shallow aquifer and the extent of contamination from the large number of onsite systems, seven monitoring wells (JW1-4 and JW6-8) were installed throughout the Jacobs Well area. Figure 1 shows the location of these wells. The locations of these monitoring wells were selected firstly to provide adequate representation of the groundwater conditions throughout the area. Secondly, wells JW2 and JW3 were located within the identified clusters of aerobic systems. This allowed the comparison of impacts between septic systems and aerobic systems on the groundwater conditions. Monitoring wells were installed by augering to a depth of approximately 3-5m, depending on the underlying hydrogeological features of the area. 50mm diameter PVC pipes, with a 1.5m well screened were installed, with 2-3mm pea gravel used as a filter pack around the screen. Monitoring well JW5 was a pre-installed bore in the local Community Centre grounds and penetrates to a depth of 12m into the semi-confined aquifer. This was used for sampling of groundwater from the deeper semi-confined aquifer to assess the potential seepage of pollutants through the 'coffee' rock layer.

2.4 Sampling

Groundwater samples were collected from each monitoring well on a fortnightly basis over a three month period. This sampling period was selected, to collect samples during the drier winter period and following into the spring wet season. Each groundwater well was purged to remove at least three well volumes and to allow stabilisation of fresh groundwater prior to sampling. Samples for chemical analysis were stored in sterilised PVC sample bottles. Samples for microbiological analysis were collected in sterilised glass bottles. All samples were stored and transported in crushed ice until analysis could be undertaken and were analysed within 24 hours after sampling.

Collected water samples were tested for several physical and chemical parameters including pH, Electrical Conductivity (EC), Chlorides (Cl^-), Nitrate + Nitrite (NO_X^--N = NO_3^--N + NO_2^--N), Organic nitrogen + Ammonia (TKN), Total Nitrogen (TN), Phosphate (PO_4^{3+} -P) and Total Phosphorus (TP). pH and EC were determined using a combined pH/EC meter. NO_x^--N, TKN, TN, PO_4^{3-} and TP were determined according to the methods outlined in APHA (1999) and measured using colourmetric analysis using a HACH DR4000/U spectrophotometer. Samples were also analysed for several bacterial indicators including Heterotrophic Plate Counts (HPC), Total coliforms (TC) and Total faecal coliforms (FC). Heterotrophic bacteria (total bacteria) were enumerated in duplicate by membrane filtration (47mmΦ 0.45um cellulose filters), using M-Heterotrophic Plate Count medium (Millipore Corporation, Bedford, Massachusetts) with appropriate dilutions aiming to achieve 20-200 colonies per filter. Similarly, coliforms were enumerated in duplicate by membrane filtration (47mmΦ 0.45um cellulose filters), using M-Endo broth (Millipore Corporation, Bedford, Massachusetts). Dark colonies forming on the M-

Endo were taken to be coliforms whilst colonies with a golden sheen were considered as faecal coliforms. Field blanks consisting of sterilised distilled water were collected in the same manner as bacteria samples. All blanks returned negative counts for HPC, TC and FC.

2.5 Principal Component Analysis

To assess the groundwater sample data, Principal Component Analysis (PCA) was undertaken to: (1) identify correlations among variables; (2) to determine which wells had higher levels of contaminants; (3) to assess the seasonal impact of groundwater quality resulting from possible aquifer recharge with sewage effluent and (4) to compare the difference in groundwater quality near clusters of septic and aerobic systems. All raw data analysed by PCA was firstly log transformed to remove large data variations. The data was subsequently mean-centered and auto-scaled prior to conducting the PCA. Generally, in analysing environmental data, the distribution of parameter standard deviations can be significantly different. As an example, variations between EC values can be between 0.001 and 50 mS/cm. In order to overcome these large variations in environmental data, decomposition of the correlation matrix is generally used so that each variable is normalized to unit variance and therefore contributes equally to the overall principal component analysis (Farnham et al 2003). Therefore, the decomposition of the correlation matrix was used for PCA of the pre-treated data.

Initially, PCA was used to provide a general analysis of the entire data matrix. The initial data matrix analysed consisted of 64 observations of 12 variables. However, from the results of the preliminary analysis, it was decide to investigate smaller subsets of the original data matrix. Firstly, the matrix was separated into two subsets (32x12 matrix) to analyse the data corresponding to both the wet (sampling periods 23 June to 21 July and 19 August) and dry (sampling periods 4 August and 1 September to 23 September) periods of the sampling episodes. Secondly, because initial results also indicated that some differences in the analysed variables between areas subject to clusters of aerobic and septic systems may be significant in relation to the quality of groundwater. Subsequently, the initial data set was also separated into two subsets to analyse differences in groundwater quality in the vicinity of septic systems (48x12 matrix) and aerobic systems (16x12 matrix).

3. Results and Discussion

3.1 Shallow Groundwater General Trends

Table 1 gives the averaged results and range of the groundwater samples analysed over the four month sampling period from each of the monitoring wells. Clearly, the main chemical pollutant evident in the shallow groundwater is inorganic nitrogen NO_X^--N (NO_3^- + NO_2^-), with all wells having average NO_X^--N concentrations in excess of the stipulated water quality criteria of 10mg-N/L (NH&MRC 1996). The NO_X^--N component is also the dominant form of the nitrogen species, indicating that the groundwater is generally aerobic, providing exceptional nitrification, but little denitrification. This would be expected in shallow groundwater in sandy alluvial soils where the fluctuating water table will provide suitable means for aerobic conditions to exist. The highest levels of NO_X^--N were observed at well JW3, which had consistent NO_X^--N levels higher than 10mg-N/L over the entire sampling period. JW3 is located in a cluster of aerobic systems incorporating surface irrigation, as shown in Figure 1. Comparatively, lower average NO_X^--N levels, although still exceeding the water quality criteria, were found only where septic systems were present.

Table 1: Analysed variables used in assessment of groundwater

Sample ID		WTd	pH	EC	Cl^-	NO_X^--N	TKN	TN	PO_4^{3-} -P	TP	HPC	TC	FC
		m		µS/cm	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	cfu/100mL	cfu/100mL	cfu/100mL
JW1	Average	0.85	6.01	235.16	67.42	44.95	21.51	64.69	2.05	3.73	3983	80	25
	Max	1.16	6.92	592.00	227.75	143.10	41.75	171.85	6.37	8.15	12000	300	100
	Min	0.42	5.17	104.90	24.25	9.04	2.21	13.11	0.38	1.43	25	10	10
JW2	Average	0.62	5.95	178.87	45.01	43.26	14.70	56.35	2.20	3.90	441000	1346	40
	Max	0.81	6.59	214.30	102.50	130.50	30.00	160.50	6.85	9.56	1000000	7000	100
	Min	0.38	5.29	137.70	18.21	4.22	2.44	10.80	0.40	2.15	98000	100	10
JW3	Average	0.26	5.96	822.74	245.87	113.12	22.50	128.84	1.09	5.81	55375	4520	81
	Max	0.49	6.33	1218.00	578.25	223.94	64.50	248.65	1.89	14.06	85000	12000	400
	Min	0.01	5.35	138.70	86.50	34.47	3.71	58.22	0.35	0.47	26000	100	10
JW4	Average	1.39	5.55	378.22	133.09	38.80	21.96	54.60	1.54	5.18	56875	760	88
	Max	1.60	6.01	1046.00	624.00	97.88	41.50	127.38	4.59	7.82	100000	2600	220
	Min	1.23	4.97	148.40	47.25	3.63	1.95	13.65	0.45	1.92	10000	80	10
JW5	Average	2.41	5.41	207.43	54.73	14.74	15.77	29.48	1.40	5.26	82375	2325	81
	Max	2.97	6.19	350.00	85.25	32.66	29.50	57.06	4.83	9.99	260000	15000	180
	Min	2.20	4.79	160.39	32.75	1.84	1.54	14.93	0.45	2.04	2000	20	10
JW6	Average	1.73	6.74	422.28	17.69	15.48	13.16	27.43	1.26	5.24	90588	9729	104
	Max	1.85	7.35	485.00	40.00	28.09	30.00	55.09	3.27	12.98	400000	42000	600
	Min	1.59	6.17	388.00	7.50	6.29	1.31	13.14	0.08	1.47	1700	900	8
JW7	Average	1.40	3.90	143.61	43.13	47.27	21.99	65.82	2.88	7.67	154305	2735	24
	Max	1.62	4.03	205.90	77.25	87.80	45.50	117.55	5.31	13.69	500000	10000	100
	Min	1.21	3.63	120.00	26.00	7.35	2.51	33.65	1.23	2.67	940	10	10
JW8	Average	1.54	5.08	235.80	26.36	36.04	16.88	51.47	2.23	3.59	78338	1524	78
	Max	1.79	5.30	285.00	76.00	72.75	33.50	97.95	7.18	7.44	250000	10000	320
	Min	1.24	4.79	94.90	6.00	7.32	3.71	15.91	0.14	1.99	3500	20	10

The concentration of pollutants was also observed to vary considerably with recharge of the aquifer following significant rainfall. Figure 3 shows plots of rainfall versus chemical pollutants (Cl^-, NO_X^--N, TKN, TN, PO_4^{3-}-P and TP) for each of the monitoring wells. From Figure 3 it can be observed that during periods of little sustained rainfall or periods of dry weather, the chemical concentration of NO_X^--N and PO_4^{3-}-P is reduced, with TKN and TP increasing significantly. Comparatively, the more soluble pollutants NO_X^--N and PO_4^{3-}-P are more dominant in wet periods. In relation to the nitrogen species, the expected aerobic conditions of the groundwater would be more prevalent during wet weather as fresh water resulting from rainfall percolates through the sandy soil matrix, allowing suitable conditions for nitrification and subsequently increasing the levels of NO_X^--N. During drier weather however, the dissolved oxygen is reduced through the process of nitrification of organic nitrogen into NO_X^--N, which subsequently allows an increase in the TKN concentrations to occur due to reduced nitrification reactions. Similarly, PO_4^{3-}-P concentrations represent the dominant form of phosphorus in the groundwater during wet periods. As the water table drops, the phosphate reacts with other available ions such as aluminium (Al) and iron (Fe) in acidic conditions and calcium (Ca) in calcareous conditions (Gold and Sims 2000). This subsequently reduces the level of phosphate available as most of the TP species is provided for in the form of precipitated and adsorbed phosphorus. A relationship is also observed between the nitrogen and phosphorus species and the Cl^- ion concentrations. Cl^- is a widely recognised tracer of effluent movement through the soil, primarily due to its limited soil absorption ability and does not undergo biochemical transformations. As the chloride ion concentration changes in the same manner as the other contaminants during dry and wet periods, obviously the majority of the chemical pollutants are sourced from the high density of onsite systems in the area. The liner relationship between Cl^- and NO_X^--N can provide an indication as to the source of NO_X^--N. Ratios of between 1:1 to 8:1 NO_X^--N:Cl^- suggested that the NO_X^--N is primarily from a faecal source, in this case onsite systems. (Lawrence 2001). Ratios greater than 8:1 are primarily sourced from other sources such as inorganic agricultural fertilisers. Figure 4 provides a plot of Cl^- verses NO_X^--N for JW1, JW4, JW6, JW7 and JW8 located in the middle of the community. Most of the samples collected are closely correlated to the 1:1 Cl^-:NO_X^- ratio, indicating that most of the NO_X^--N is from a faecal source, in this case the onsite systems.

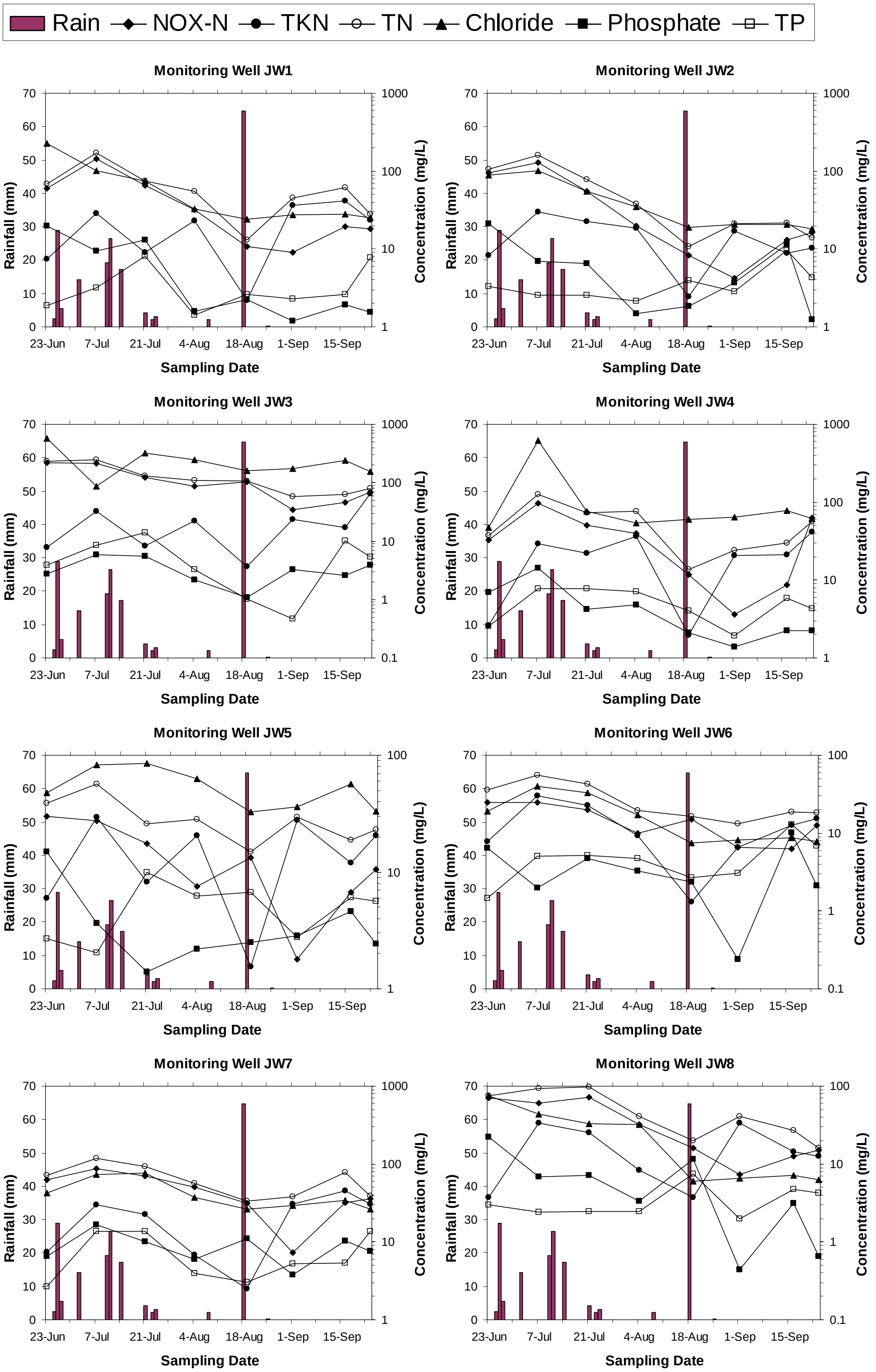

Figure 3: Plots of Rainfall vs Chemical concentrations

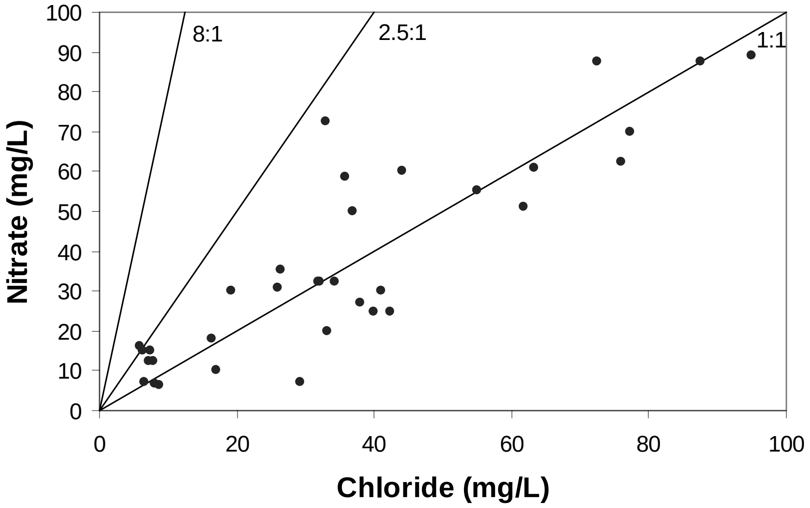

Figure 4: Correlation between Chloride and Nitrate at selected wells.

From Table 1, substantial faecal contamination of groundwater is also evident with most wells having average faecal coliform concentrations of ≥25 cfu/100mL, exceeding the required NH&MRC (1996) and ANZECC (2000) guidelines of no faecal bacteria for drinking water, although below the 150 faecal coliforms/100mL recreational water quality guidelines (ANZECC 2000). Several wells have however had counts much higher than this on several occasions as shown in Table 1. The concentration of bacteria in the groundwater samples was influenced by rainfall, with counts increasing as recharge of the aquifer occurs with rainfall. This phenomenon is to be expected as the sandy soil acts as a filtration device, filtering out most bacteria in the discharged effluent when adequate unsaturated sand is present. As the water table rises due to aquifer recharge, the sand becomes saturated, thereby allowing bacteria to freely move through the soil matrix deeper into the aquifer, consequently increasing the concentrations. However, during drier periods, as the only recharge source to the aquifer is from onsite wastewater treatment systems, FC levels will increase as continued application of effluent occurs with more predominant flow of effluent through the larger soils pores.

3.2 Principal Component Analysis (PCA)

PCA undertaken on the obtained data showed that 66.5% of the data variance extracted was contained within the first two principal components. A subsequent scree test indicated that the third principal component, contributing 11.8% towards the data variance, was not significant and therefore only the first two PCs were included. The main correlations between the respective variables determined by PCA are given in Table 2, with Figure 5 providing a biplots for PC1 vs PC2 from the PCA undertaken. From the PCA results of the chemical and microbiological analysis undertaken it is evident that the pollution of the shallow aquifer is predominantly due to effluent from OWTS. Most of the parameters which contaminate the aquifer are common to sewage effluent and are closely correlated together, thereby confirming that they originate from the same source. The close relationship between Cl^- and NO_X^--N (Figure 4) confirms this further. All species of nitrogen (NO_X^--N, TKN and TN), PO_4^{3-} and FC are also highly correlated with the chloride ion.

In relation to the nitrogen species, a clear correlation between TN and NO_X^--N exists, with both having high negative scores on PC1. This signifies that the majority of TN in the groundwater is primarily in NO_X^--N form. In comparison, most of the sampling episodes undertaken during the dry periods also have negative scores on PC1 as highlighted in Figure 6. TKN (Ammonia and organic nitrogen) scored low on both PC1 and PC2, indicating that the levels of TKN in the groundwater are less of a concern. This is due to the obvious nitrification of TKN into nitrate, particularly during wet periods. TKN levels are higher in wells that have a lower pH and EC, in particular JW7, which has an average pH of 3.90. Phosphate and Total phosphorous levels are highest in wells JW4 and JW7, with highest levels observed during drier periods. Both of these sites have low pH. pH has a significant influence on the reactivity of phosphate, with lower pH increasing the level of reactive phosphate. Similarly, as the pH of the other wells increase, the level of reactivity is reduced. There is some correlation of TP with the depth to the water table, suggesting that as the water table lowers, the phosphate reacts with other chemical ions such as Al, Fe and Ca in the groundwater, allowing precipitates to form or are absorbed to the soil or organic particles. These precipitated forms of phosphorus subsequently make up the majority of the TP species.

Table 2: Correlation Matrix of variables analysed with PCA. Higher correlations between variables shown in bold.

	WTd	pH	EC	Cl^-	NO_x^-	TKN	TN	PO_4^{3-}-P	TP	HPC	TC	FC
WTd	1.000											
pH	-0.199	1.000										
EC	-0.392	**0.520**	1.000									
Cl^-	-0.490	0.021	**0.464**	1.000								
NO_x^-	-0.477	-0.146	0.259	**0.633**	1.000							
TKN	0.000	-0.177	-0.020	0.189	0.113	1.000						
TN	-0.461	-0.191	0.230	**0.701**	**0.855**	**0.451**	1.000					
PO_4^{3-}-P	-0.079	-0.242	-0.046	0.307	**0.472**	-0.031	**0.430**	1.000				
TP	-0.042	-0.244	-0.111	0.005	0.036	0.105	-0.027	**0.235**	1.000			
HPC	-0.130	0.069	-0.210	0.046	0.122	**0.239**	0.128	0.017	0.124	1.000		
TC	-0.136	**0.271**	**0.298**	0.074	0.047	-0.003	-0.003	-0.091	0.043	0.089	1.000	
FC	-0.172	0.129	0.068	0.193	0.236	-0.146	**0.225**	**0.275**	0.036	-0.125	0.084	1.000

From the PCA, the correlations between the HPC, TC and FC highlight similar issues as noted above. Namely, as the water table is lowered, the presence of bacteria is significantly reduced. The sandy alluvial soils essentially act as a large sand filter, removing bacteria and other suspended matter. However, after significant rainfall and aquifer recharge, the water table will increase allowing bacteria to move more freely through the substratum. However, the relationship between HPC counts and TC and FC counts is negative. As the native bacteria population increases with recharge, then Total Coliform and subsequently faecal coliform levels are reduced due to competition for necessary resources. In contrast, as the water table level drops and the groundwater is recharged via effluent, the native bacteria are reduced allowing an increase in the TC and FC numbers, although only small in comparison to the total number of HPC. Significantly, monitoring wells that exhibited higher pH and EC values, typically as a result of changes in the groundwater conditions due to effluent recharge, also have higher TC and FC counts. In comparison, higher HPC counts are obvious at monitoring wells which exhibit lower pH and EC. This suggest that wells with high HPC counts and low pH and EC levels are not as affected by the effluent contaminants as other locations.

Wells JW5 and JW6 had the highest FC counts out of all the wells. This indicates that the semi-confined aquifer (investigated using JW5) beneath the coffee rock is being contaminated by effluent, particularly faecal coliforms. The earlier prediction that cracking and fissures in the coffee rock layer would allow transport of bacteria and chemical pollutants through into the underlying groundwater was confirmed. Similar results from a study undertaken by Powell et al (2003) on the impact of sewage contamination on two sandstone aquifers in the United Kingdom found that cracks and fissures provided exceptional transport pathways for micro-organisms originating from effluent. However, the results for well JW5 showed relatively reduced contamination from NO_X^--N but increased contamination from phosphorus is taking place in the deeper, semi-confined aquifer. As phosphorus undergoes various chemical reactions with soil particles and other ions, it would be expected that over time, the level of TP would increase.

3.3 PCA of Climate and Seasonal Patterns

The PCA biplot and scores plot of all of the analysed variables, shown in Figure 5 and Figure 6 respectively, highlight that two significant clusters are present relating to the water table depth (WTd) and therefore rainfall. This indicates that there are various reactions occurring during both the dry and wet periods as previously postulated. Consequently, a further principal component analysis was undertaken to investigate the correlations and patterns between the sampling results during dry and wet periods.

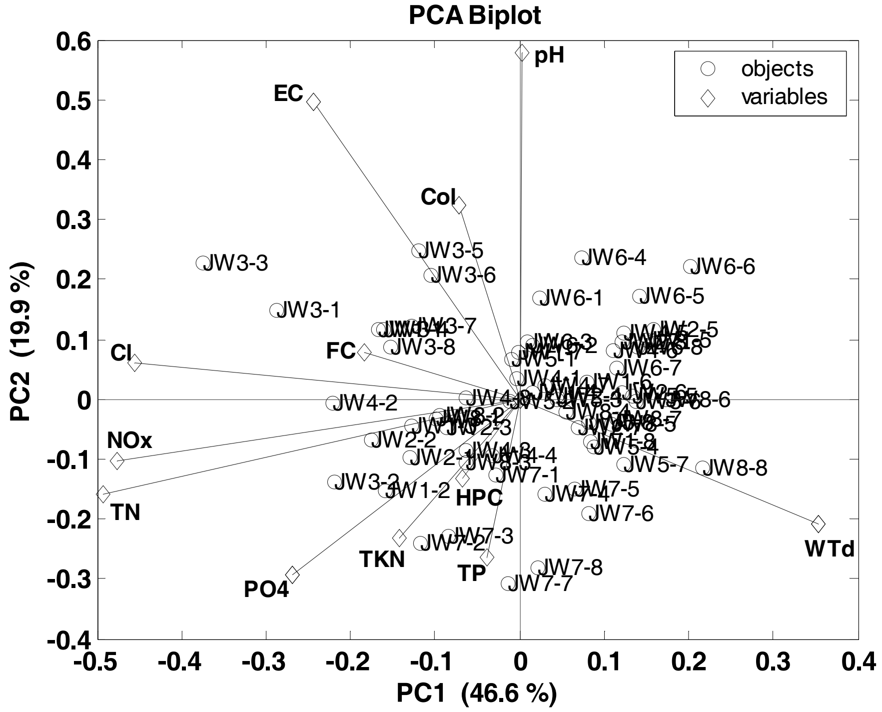

Figure 5: Biplot of PCA on groundwater data

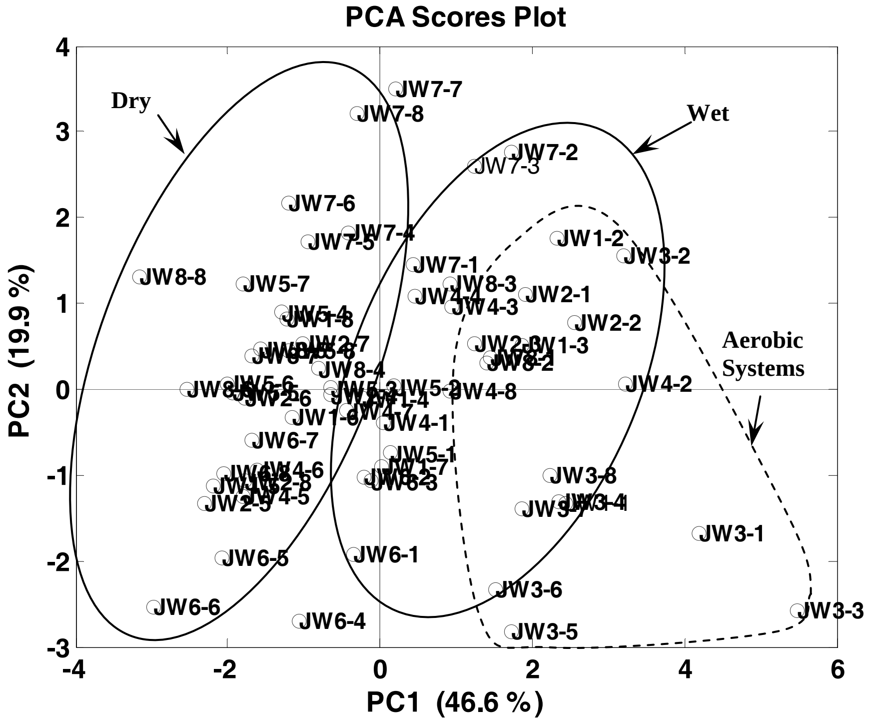

Figure 6: Scores Plot of PCA on groundwater data

The analytical results obtained during periods with high rainfall indicated that 65.4% of the total variance was incorporated in the first two PCs. A subsequent scree test of the analysed eigenvalues indicated that only the first two PCs were significant, and therefore these were used for the PCA. The analysis conducted on the samples from drier periods showed that 55.9% of the total data variance was retained in the first two PCs. Figures 7(a) and 7(b) provide the PCA biplots obtained through the PCA for the wet and dry periods respectively. From the results of the analysis undertaken, significant differences between the wet and dry periods can be observed. The most noticeable of these is the relationship between the HPC and FC bacteria. Some correlation is observed between HPC and FC variables in wells sampled in wetter periods with both having positive scores on PC1, indicating that both HPC and FC levels are increased following rainfall. However, during dry periods, FC is shown to remain positive on PC1 where HPC has a negative score, indicating that no correlation between HPC and FC is evident. This indicates the same response as highlighted by the previous PCA that during wet periods, the indigenous bacteria have favourable conditions to multiply, and therefore compete with the FC bacteria to reduce their numbers. However, in dry periods, the indigenous bacteria numbers decrease due to filtering and adsorption processes as the water table recedes, thereby allowing a slight increase in the level of FC.

Similar correlations exist between the nitrogen and phosphorus species from both the wet and dry periods for all wells, except for TN. TN was observed to be more closely correlated with the NO_X^--N form under wet conditions, whereas during drier periods, TKN dominates the nitrogen species. Again, this correlates well with the earlier prediction in relation to nitrification and rainfall. Similarly for phosphorus, phosphate is observed to be the more dominant form during wet weather suggesting that most of the phosphorus during these periods is in the more reactive form, than during drier periods. However, similar correlations between PO_4^{3-}-P and TP are evident at both times.

The major difference highlighted between both PCA undertaken is the respective clusters formed from the sampling episodes. Clusters formed from the data analysis during the wet period, as shown in Figure 7a, are mostly in relation to the sampling time, rather than the individual wells. This suggests that most of the wells retain similar variations in the parameters due to the recharge of the aquifer by rainfall. On the other hand, the wells sampled during drier periods cluster according to the individual well locations, indicating that during dry weather, the groundwater is definitely influenced by effluent recharge.

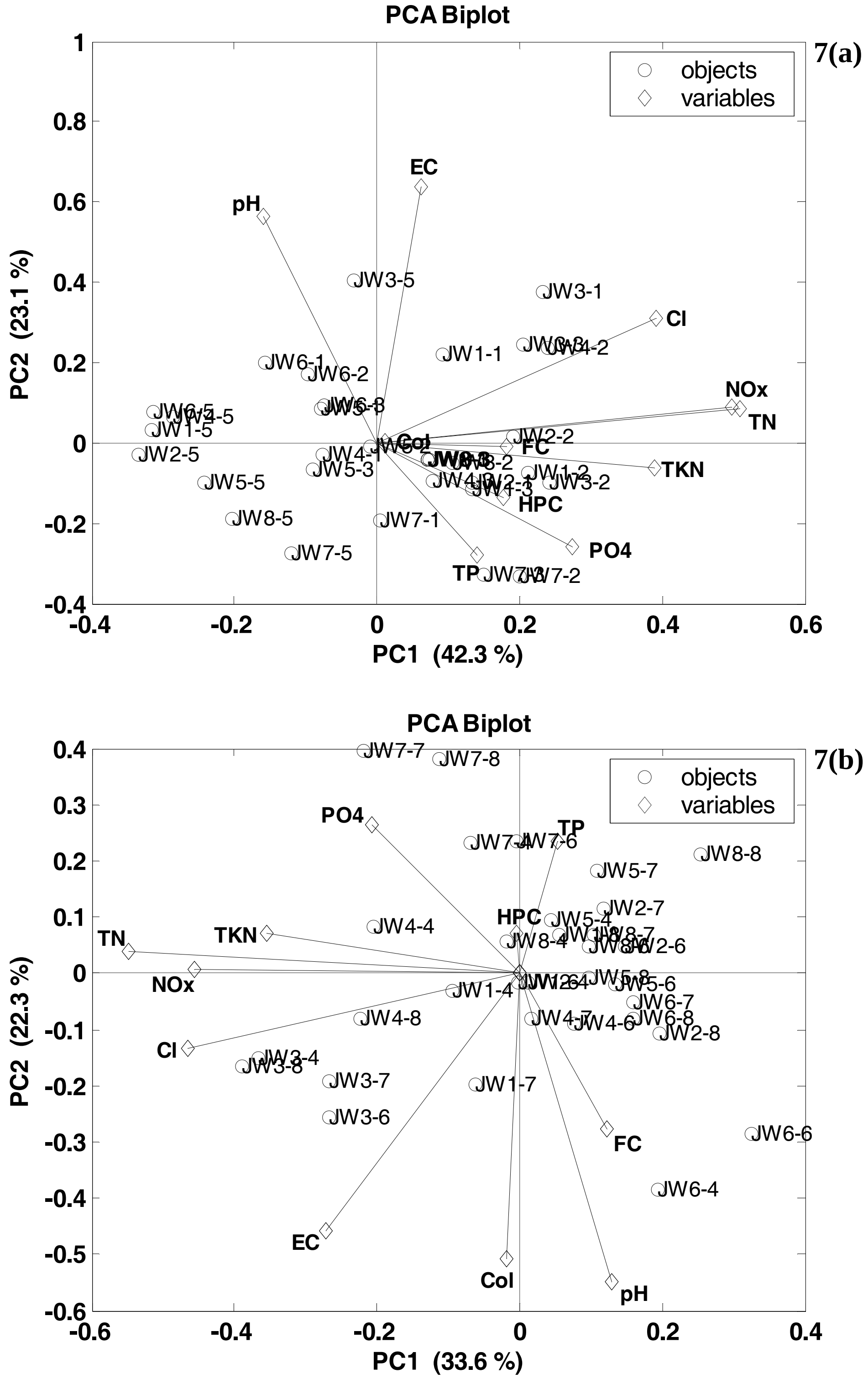

Figure 7: Biplots of PCA analysis of groundwater data during (a) wet periods and (b) dry periods

3.4 PCA of Variations of System Type

The results of the initial PCA analysis also indicated that differences exist between system types, as depicted in Figure 6. Comparison of groundwater quality between clusters of septic and aerobic systems was undertaken to determine if any major impact was evident in proximity to each of these system types. The initial dataset was subdivided between monitoring wells located near septic system clusters (JW1, JW4, JW6-8) and wells near aerobic system clusters (JW2, JW3). JW5 was excluded, as although it provided an overall indication of groundwater quality within the semi-confined aquifer, it is not located in proximity to either system type cluster. PCA on the dataset representing septic systems provided 57.8% variance in the first two PCs. The PCA for aerobic systems provided 60.6% of the data variance in the first two PCs, and were considered to be adequate. Figure 8a and 8b provides the PCA biplots for the septic system and aerobic system clusters respectively.

The most notable difference between the outcomes of the two analyses relates to the nitrogen component. TN is closely correlated with NO_X^--N for the septic systems, although some correlation with TKN is evident. This is typical as the nitrogen emitted from septic systems is generally in the form of NH_4^+, with subsequent nitrification to NO_X^- -N if the groundwater is aerobic. This has been discussed previously. In contrast, for aerobic systems TN is very closely correlated with the NO_X^- -N species, with less correlation with TKN. The reason for this is due to the treatment process that sewage undergoes in aerobic systems. Due to the aerobic conditions in a typical system, the organic and ammonia nitrogen species are generally already in the form of nitrates, unless a specific nitrogen reduction treatment forms part of the onsite treatment system. TP and PO_4^{3-}-P have similar correlations for both system types, although PO_4^{3-}-P is more correlated with the NO_X^- -N for septic systems.

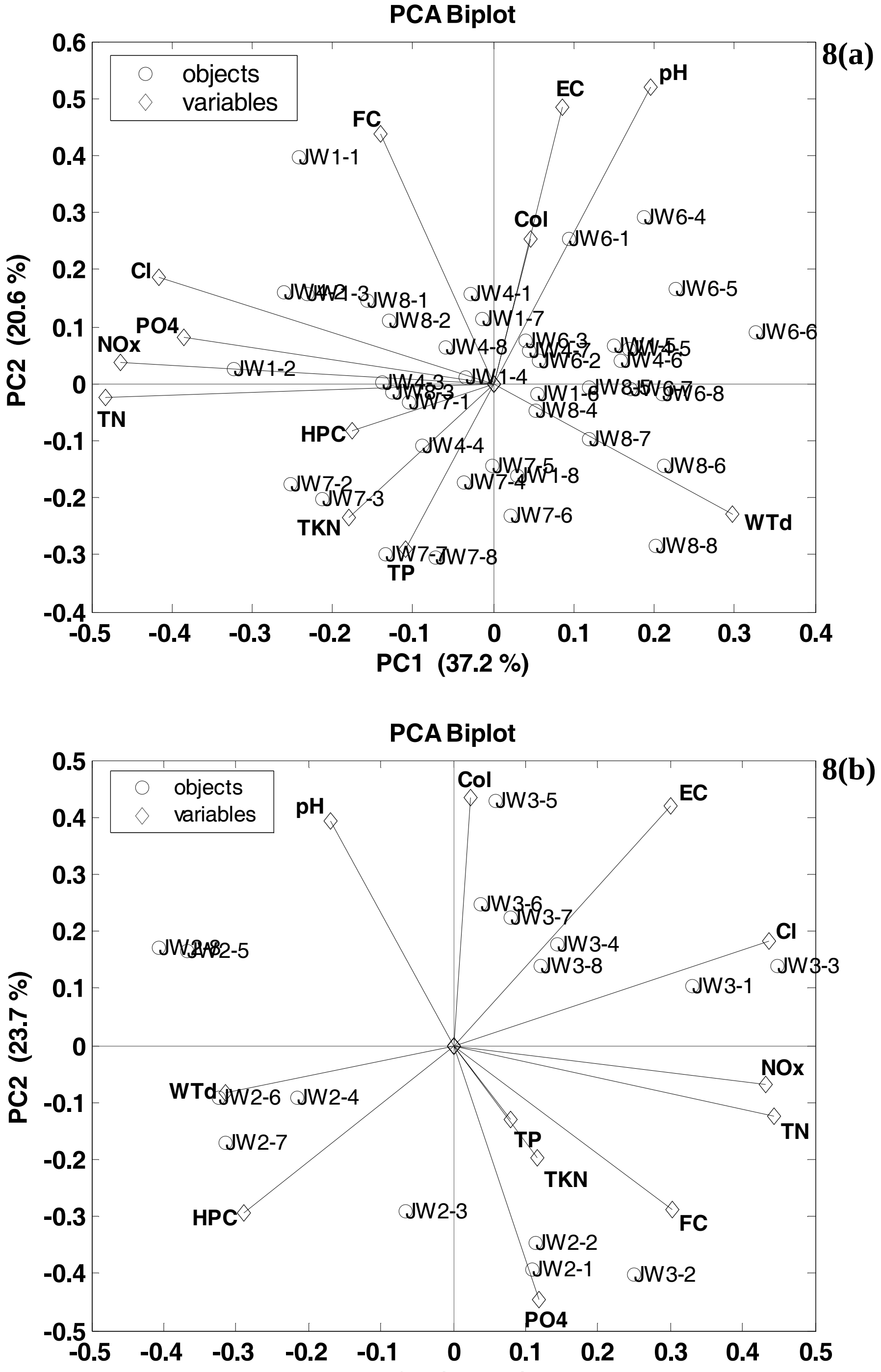

Figure 8: Biplots of PCA analysis of groundwater data for (a) septic systems and (b) aerobic systems

The only noticeable cluster formed through the PCA of septic systems is that related to sites with a lower pH, with JW7 being the most noticeable. All other sites are evenly distributed across PC1. This is related mostly to rainfall events, and changes in WTd. The PCA from the aerobic systems produced significant clusters, although again, these are related generally to rainfall and changes in WTd. However, as most of the effluent discharged from aerobic systems is used for surface irrigation, this can be an important issue. From the biplot in Figure 6, three major clusters are obvious. In general these can also be subdivided according to the respective monitoring well locations, ie JW2 or JW3. Two of these clusters fall positive on PC1, directly opposite the WTd variable. As such, these are distinguished by the wet periods. This is significant as most of the contaminants observed with higher concentrations relevant to effluent contamination also fall positive on PC1. Therefore, this suggests that most of the contamination of the groundwater around clusters of aerobic systems occurs during rainfall events.

4. Conclusion

The results of the groundwater investigation indicates that substantial pollution of the both the shallow aquifer and the semi-confined aquifer is taking place. Therefore, any reliance on the groundwater as a water resource needs to be carefully considered. Due to significant levels of faecal coliforms evident in all monitoring wells, substantial public health concerns are obvious, making the shallow groundwater unfit for human consumption without prior treatment. Similarly, the very high level of nitrogen and phosphorus contained in the shallow groundwater is cause for concern, and pose a substantial environmental risk to the nearby estuary and local watercourses.

The results of the principal component analysis highlight some important issues in relation to high densities of OWTS. Firstly, as most of the pollutants which are common to the effluent discharged are highly correlated suggest that they are sourced from the large numbers of OWTS in the area. Rainfall plays a significant role in determining the fate and transport of most pollutants. In particular, with additional recharge of the aquifer during rainfall events, increases in contaminant levels were observed. Conversely, during dry weather, bacteria levels decrease due to filtration/adsorption of bacteria by the sand particles. Septic systems provide most of the contamination to the shallow aquifer, due to the continual discharge of effluent into the subsurface environment. Aerobic systems contribute pollutants mostly during wet weather periods.

Although this study highlights that high densities of OWTS lead to significant contamination of shallow groundwater, it is evident that certain factors play important roles which can either decrease or increase the extent of contamination. These include site related factors such as soil and topography, climatic conditions and the type of onsite systems used.

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