CONGRESS HANDBOOK

CHENGDU 2013

35TH IAHR WORLD CONGRESS

September 8-13, 2013 | Chengdu, China

The wise find pleasure in water:
meandering through water science and engineering

www.iahr2013.org iahr2013@vip.163.com

Ministry of Water Resources of People's Republic of China

International Association for Hydro-Environment Engineering and Research

Proceedings of 2013 IAHR World Congress

Exploring Changes in Nitrate Contamination in the Coastal and Hautere Zone Aquifers, Wellington, New Zealand

Deepthi Jayatha Dias-Wanigasekera
University of Southern Queensland

Associate Professor Gregory De Costa
Dept. of Civil Engineering, Unitec Institute of Technology, New Zealand, rdecosta@unitec.ac.nz

Associate Professor John Worden
University of Southern Queensland Australia

Dr. Beatrice Dias-Wanigasekera

ABSTRACT: Fifteen years of groundwater quality monitoring in the Kapiti Coast by the local authority in Wellington, New Zealand, has identified an area of elevated nitrate concentrations in the Te Horo area, with some monitoring bores testing for concentrations above 5 mg/L. However, recent analysis seems to indicate that contaminant levels have decreased from what was previously recorded, although still remaining elevated. The purpose of this study is to investigate if changes in nitrate concentrations over time were significant, and, if so, determine which factors have contributed to these changes. Initial temporal trend analysis indicated that nitrate concentrations since 1993 have decreased in the majority of monitoring bores. Tobit regression analysis was subsequently undertaken using several land use, land cover, soil type, climate and chemical explanatory variables. Results indicated that beef cattle farming, fruit growing, settlements and lifestyle blocks were associated with increased nitrate concentrations. Groundwaters higher in dissolved oxygen which underlie fine sandy loam soils (which are highly permeable soils) were also identified as been susceptible to higher nitrate concentrations.It was ultimately determined that the temporal decrease in concentrations is best explained by improved land use practices as physical characteristics and land cover overlying groundwater had not changed substantially and thereby explaining the decreasing trend in nitrate concentrations.

KEY WORDS; Ground water, nitrate contamination

1 INTRODUCTION

The Resource Management Act (RMA) 1991 is the principal legislation governing the allocation and use of New Zealand's natural resources. Under the provisions of the RMA, regional councils are responsible for the management of groundwater resources. In Wellington, a baseline groundwater quality monitoring network in the regions of Hutt Valley and Kapiti Coast was first set up in 1993 by the Greater Wellington Regional Council (GWRC) (Hughes 1995). Since then, the network has expanded significantly and quarterly monitoring of what is now known as the Groundwater State of the Environment (GWSoE) Network is conducted in order to establish current and long term trends in water quality.Continued State of The Environment (SoE) monitoring and has resulted in the identification of the Coastal and Hautere groundwater zones of the Kapiti Coast district in Wellington as areas of persistent nitrate contamination (Hughes 1995, 1996, 1997; Jones & Baker 2005). Sampling from a number of wells showed elevated NO_3-N (future reference to "nitrate" concentrations in this report will be in terms of NO_3-N in mgL^{-1}) levels close to or exceeding the Maximum Acceptable Value (MAV) for drinking water of $11.3mgL^{-1}$. The MAV is a standard of drinking water outlined in the Drinking Water Standards for New Zealand (Ministry of Health 2008). Brydon Hughes (1996) investigated the potential reasons behind high nitrate levels in the Kapiti Coast based on the annual baseline groundwater monitoring results. This also coincided with the adoption of drinking water standards by New Zealand authorities. Excess nitrate levels were linked to land use variables such as agricultural effluent disposal, fertilizer application and septic tank effluent discharge based on the spatial distribution of the sample wells. Wider literature suggests that nitrate concentrations are also controlled by aquifer processes as well as external factors such as recharge, land use change, climate and aquifer lithology (Overgaard 1984; Spalding & Exner 1993; Trojan et al. 2003). For this reason, a comprehensive analysis of temporal nitrate concentration has to include a consideration of some of these variables. Identify reasons behind the changes in nitrate concentrations over time. This will require, analyses of catchment changes (such as land use change, changes in rainfall, climate etc.). The aim of this investigation is to explain changes in long term temporal trends in ground water nitrate levels in the Kapiti coast from 1993 to December 2009 in terms of land use changes and aquifer properties.

2 STUDY AREA

2.1 Groundwater Zones

Located on the South-Western coast of the North Island, New Zealand, the Kapiti Coast groundwater reserve has been classed into six different groundwater zones based on similar hydrogeological characteristics. These are the Raumati Paekakariki Zone, Waikanae Zone, Coastal Zone, Hautere Zone, Otaki Zone and Waitohu Zone.

Figure 1 Diagram of Wellington, New Zealand. The Kapiti Coast (GoogleTM 2012)

The area is a plain of river gravels and undulating sand dunes along the coast, bounded on the East by the foothills of the Tararua Ranges. This study focuses on a roughly 60km^2 zone which comprises of the Hautere and Coastal groundwater zones.

2.2 Hautere Groundwater Zone

This groundwater zone covers an area of approximately 25km^2 and underlies what is presently known as the Hautere Plain. It is composed of fluvial outwash fans deposited during the last glacial (Otira glaciation) period. The plain forms a high terrace along the Otaki River which defines the Northern border of this zone. To the West, The alluvial fans are truncated by a sea cliff. This marks the marine transgression event which took place 6,000 years before present (BP) during the Aranuian interglaciation when sea level rose above the present day level (Hydrological Services Group 1994). This sea cliff signifies the Western limit of the groundwater zone. The Eastern and Southern borders are formed by the foothills of the Tararua Ranges. The Hautere zone is conceptualized as consisting of three aquifers (Kampman & Caldwell 1985). This distinction was largely based on water quality results. Similar water levels in all three aquifers indicate that there is vertical leakage between the layers.

2.3 Coastal Groundwater Zone

This is an area of roughly $33km^2$ bounded by a high terrace running along the Otaki River to the North and Peka Peka and Hadfield Roads in the South (refer to figure 2). The Eastern boundary is roughly defined by the 6,000 BP sea cliff. Kampman and Caldwell (1985) identified four aquifers at various depths.

2.4 Geology

The geology of the Kapiti coast is characterized by alternating layers of strata deposited during glacial and interglacial cycles, particularly in the last 250,000 years (Tidswell 2009).

2.5 Glacial deposits

The expansion of ice caps during glacial periods resulted in lowered sea levels. The present day coastline along the Kapiti coast would have been approximately 10 kilometers offshore during these periods. Steeper flow gradients of rivers sourced from the Tararua Ranges meant that rivers had more down cutting erosional power. Freeze thaw processes and accelerated erosion of the Ranges would have also added to increased amounts of sediment and rock being transported by rivers.The Hautere Groundwater Zone is comprised of outwash fan material deposited during the Otiran glaciation interspersed with silt and silt and clay layers. The lower confined, water bearing layers of the Coastal zone are also comprised of gravel material deposited during the Otiran glaciation. These deeper gravel deposits are said to be a continuation of the outwash deposits forming the Hautere Groundwater Zone.

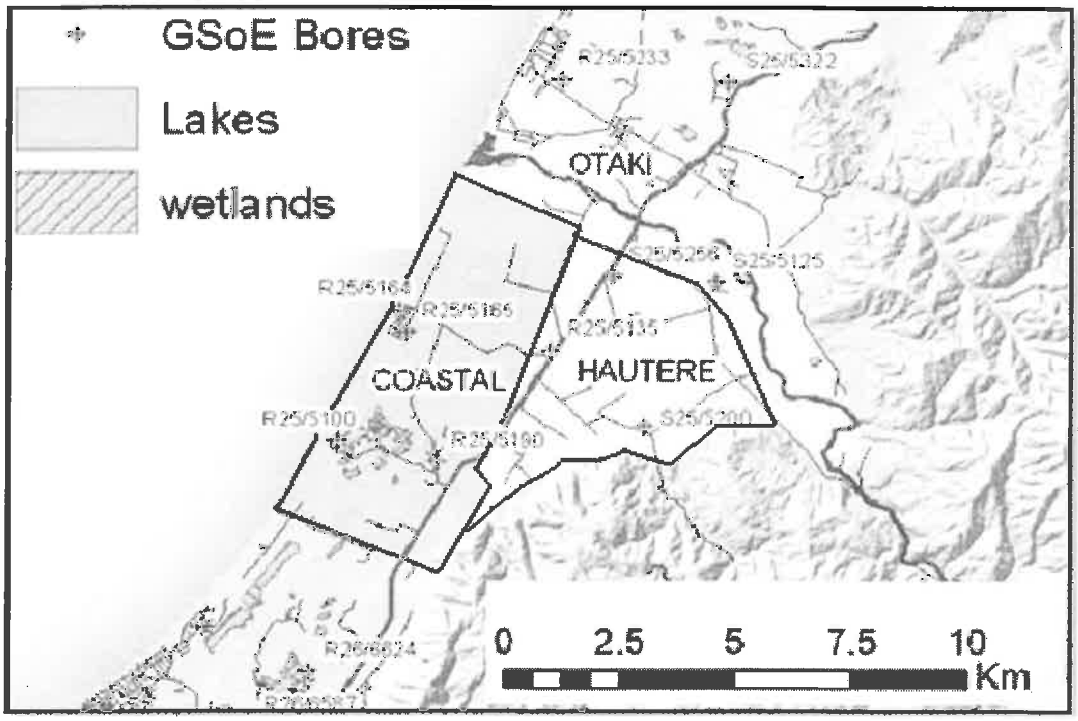

Figure 2 Showing the study site by aquifer zone. The Hautere and Coastal Zones

2.6 Postglacial and Interglacial Deposits

During warmer interglacial cycles, increased vegetation cover at higher altitudes and milder climatic conditions resulted in less erosion of the ranges. Significant volumes of water were released from ice caps due to warmer global temperatures, causing sea level rise. Coasts gradually migrated inland, which also decreased river flow gradients. This enabled a period where rivers could entrench into glacial period deposits which were poorly sorted and poorly rounded. This material was reworked during fluvial transport and re-deposited as gravel, sand, and silt further downstream within the confines of the river channels. The reworked deposits were usually better sorted and contained less silt and clay in the matrix.The rise in sea level also resulted in transgression deposits of fluvial gravel, sand, silt and clay along the coast. These transgression deposits are overlaid by marine and estuarine sand, as well as lagoon clay and peat. The upper 40 meters of the Coastal Groundwater Zone is comprised of postglacial and interglacial sand, silt, and swamp material.

2.7 Hydrogeology

Piezometric surveying was conducted in 1993 and contours of groundwater head were plotted. The pressure head decreases in an east to west direction, showing that groundwater flows from the Tararua ranges towards the coast. A gradual widening in contour lines towards the west showed a decline in hydraulic gradient. This represents a decrease in the rate of flow towards the coast (Allen 2010; Cussins 1994; Tidswell 2009). Hydraulic conductivity is thought to decrease towards the coast. Cussins (1994) estimated representative hydraulic conductivities of 10 m/day for the Hautere zone unconfined aquifer and 5 m/day for the Coastal unconfined aquifer. Previous investigations have found that seepage velocity in the Coastal, unconfined aquifer is as low as 0.1m/day (Allen 2010; Cussins 1994) whereas seepage velocities in the Hautere unconfined aquifer was estimated to be around 1m/day (Cussins 1994). Calculated seepage velocities for confined aquifers in the Coastal zone are similar to those in Hautere zone, reflecting the connectivity between aquifers at depth. The observed springs and seepage channels along the 6000 BP sea cliff are due to the sharp change in aquifer hydraulic conductivities at the boundary between the two unconfined aquifers (Cussins 1994).

Trasmissivities are locally variable, but generally low (30 – 150 m^2/day). However, average transmissivities were similar for all aquifers within the Hautere zone (Cussins 1994; Kampman & Caldwell 1985). Transmissivities for the unconfined sandy aquifer in the Coastal zone were about 15 – 100 m^2/day. Deeper Coastal zone aquifers show similar transmissivities as the Hautere zone water bearing layers. The Wellington Regional Council calculated representative values for transmissivity and storage coefficients for the different aquifers within the study site (Hydrological Services Group 1994). The table below summarizes their findings.

Table 1 Representative transmissivities and storage coefficients of aquifers within the Hautere and Coastal groundwater zones

Aquifer Depth (m)	Transmissivity (m^2/day)	Storage Coefficient
10-30 (Hautere)	124	5×10^{-4}
40-70 (Hautere)	54	3×10^{-4}
90-150 (Hautere)	68	1×10^{-4}
5-30 (Coastal)	10	0.3
35-56 (Coastal)	120	5×10^{-4}
65-110 (Coastal)	170	3×10^{-4}
164-172 (Coastal)	150	1×10^{-4}

The calculated storage coefficient for the Hautere surface aquifer is more reflective of a confined aquifer. Pump tests undertaken by Cussins (1994) yielded similar results. This indicates that the surface aquifer shows a degree of confinement, most likely due to the presence of discontinuous silt lenses throughout this layer which act as localized aquitards. However, due to the rapid response of groundwater levels to rainfall events, the aquifer is considered to be largely unconfined (Cussins 1994).The aquifers are primarily recharged by rainfall infiltration (Cussins 1994). Previous studies indicate that the volume of rainfall increases from a West to East gradient. This is primarily due to orographic lift. Higher volumes of rainfall at the foot of the Tararua ranges (at the eastern boundary of the study site) is thought to be a source of recharge for both the unconfined aquifer and the deeper confined aquifers in the Hautere zone(Tidswell 2009). Nine springs roughly located along the 6000 BP sea cliff discharge water from the Hautere to the Coastal zone. This may also provide and intermittent source of groundwater recharge to the Coastal unconfined aquifer (Cussins 1994). The amount of recharge has not yet been quantified.

3. METHODOLOGY

3.1 Regression Analysis

Tobit regression analysis was conducted on available land surface data, climate data and chemical data variables in order to determine if they significantly influenced observed nitrate concentrations. Several studies have incorporated Tobit regression models in order to predict or investigate contaminant concentrations with respect to chosen explanatory variables (Barringer et al. 1990; Gardner & Vogel 2005; Liu et al. 1997; Stackelberg et al. 2012; Tesoriero & Voss 1997). The advantage of Tobit regression over ordinary least squares regression is its ability to incorporate values below a reporting limit in the dependent variable (Helsel 2011) and produce unbiased multivariate regression models.
The Tobit regression model is expressed in terms of the latent dependent variable:

$$y_i^* = \alpha + \bar{\beta}\bar{x}_i + \varepsilon_i$$

where, in the context of this study, y_i^* is the latent variable, α is a constant, β is a vector of parameter slope estimates, x_i represents the explanatory variables, and ε_i are normally and independently distributed residual errors with mean zero and variance σ^2.
Observed nitrate concentrations can be described in terms of the latent variable if concentrations are above the detection limit, *c*. Alternatively, if nitrate concentrations are below the detection limit (0.01mg/L), then the latent variable becomes *c*:

$$y_i = y_i^* \quad if\, N_i > c$$
$$y_i = c \; otherwise$$

Assuming the errors are independent and homoscedastic, the vector parameters in the linear equation can be estimated using Maximum Likelihood Estimation (MLE) (Gardner & Vogel 2005; Helsel 2011; Liu et al. 1997). Statistical software (Minitab 2010) was used to perform interval censored likelihood estimation on selected explanatory variables.

4 DATA SOURCES

The dependent variable in this study was nitrate concentration values (mg/L) measured as part of the GWRC quarterly monitoring network. Dissolved oxygen and TDS data was also obtained from the groundwater quality sampling results. Explanatory variables were land use, land cover, soil type, rainfall, temperature, dissolved oxygen and TDS. The choice of explanatory variable was dictated by studies found in previous literature as well as the availability of data.Land use data was originally sourced by the AsureQuality's Agribase™ (AsureQuality 2008) database. GWRC could only provide 2008 data for this study. Agribase collates voluntary rural land use data and stores this information in a high quality GIS database. Land use data was provided as a GIS shapefile. Land cover data was extracted from New Zealand's Ministry for the Environment (MFE) (Ministry for the Environment 2009), who survey land cover as part of their Land Use Carbon Analysis System (LUCAS). Land cover was available for 1990, 2008 and 2012 and was provided in shapefile format.

Soil type data for the study site was extracted from the "Soil Map of Otaki District" GIS shapefile published by Landcare Research NZ (Landcare Research NZ Ltd 2005). The data represents information obtained from a national soil survey undertaken by the Soil Bureau prior to 1992. Due to the high variability of soil classifications across the study site, soil types were reclassified into their broader soil types. That is, high order soil type classification polygon parcels were merged to represent their lower order general soil type using ArcGIS software. This was decided with the intent of making regression results easier to interpret by having fewer variables. Main types of different land use, land cover, soil type, climatic factors and chemical influences in a step wise regression processes. Variables were added step by step and excluded from the model if they did not make a significant improvement to the model equation. Partial likelihood tests were conducted in order to determine this significant improvement (or lack of). The partial likelihood statistic is defined as:

$$G_{partial}^2 = [-2L(\beta_{without})] - [-2L(\beta_{with})]$$

where $L(\beta_{without})$ was the model log likelihood of the regression equation without the variable of interest and $L(\beta_{with})$ was the model log likelihood of the regression equation with the variable of interest. The resulting partial likelihood statistic was compared to a chi squared table of critical values with degrees of freedom 1 (as only one variable was being added with every step). If the p-value was less than or equal to 0.05, the variable was seen to provide a significant improvement to the model fit, and left in the regression equation (Helsel 2011).

After the best model for each group was determined, the regression models were tested against the null model (all β's = 0) in order to determine if having a regression model provided a better explanation of the data than having no model at all. The overall log likelihood test was used to determine the test statistic with a p-value of 0.05.

Table 2 Number and types of variables tested within each regression group.

Land Use Variables (Ha)	Land Cover Variables (Ha)	Soil Type Variables (%)	Chemical Variables (mg/L)	Climate Variables
Beef Cattle Farming	High Producing Grasslands	Peat	Dissolved Oxygen	Rainfall (mm)
Dairy Cattle Farming	Low Producing Grasslands	Sand	TDS	Mean Air Temperature (°C)
Settlement	Vegetated Wetlands	Peaty Loam		
Lifestyle Block	Township	Silt Loam		
Mixed Sheep & Beef Farming	Annual Cropland	Fine Sandy Loam		
Fruit Growing	Perennial Cropland	Stony Silt		
Emu Farming				
Horse Rearing and Breeding				
Deer Farming				
Vegetable Growing				
Forest				

5. RESULTS

5.1 Regression Results

5.1.1 Effect of Land Use on Nitrate Concentrations

Land use does seem to have a significant effect on current nitrate concentrations in the area. According to the regression model for land use, the area (in hectares) of beef cattle farming, fruit growing, lifestyle blocks, and settlements within a 500m radius of a bore can potentially affect nitrate concentrations within the wells. Minitab results include a Wald test statistic for each coefficient estimate. The absolute magnitude of the Wald's statistic determines the importance of that variable on nitrate concentrations. A summary of results is presented below.Each of the final land use variables in the model a positive relationship with nitrate concentrations.

The Wald statistics for each variable also suggests that the amount of land used for fruit growing within the 500m buffer zone has the greatest influence on nitrate concentrations whereas the area of settlement zone has the least effect on nitrate concentrations. The figure below provides a visual representation of the relative amounts of land use types within the buffer zones. The overall log likelihood test statistic is 257.25, which corresponds to a p-value of <0.005 with 4 degrees of freedom. The null model can therefore be rejected.

Table 3 Summary of Tobit regression results for significant land use variables.

Variable Name	Coefficient (β)	Standard Error	Wald's Stat	p-value
Beef Cattle Farming	0.0509	0.003	19.00	<0.001
Lifestyle Block	0.0956	0.004	24.35	<0.001
Settlement	0.0429	0.003	17.10	<0.001
Fruit Growing	0.4921	0.012	45.33	<0.001
Intercept	-2.825	0.141	-20.07	<0.001

5.1.2 Effect of Land Cover on Nitrate Concentrations

The land cover variables found to influence nitrate concentrations within a 500m radius buffer zone are the areas of high producing grassland, vegetated wetlands, towns, natural forests, annual crops and perennial crops.

Table 4 Summary of Tobit regression results for significant land cover variables

Variable Name	Coefficient	Standard Error	Wald's stat	p-value
High Producing Grassland	-0.196	0.004	-44.50	<0.001
Vegetated Wetland	-0.431	0.017	-24.89	<0.001
Towns	-0.163	0.008	-19.42	<0.001
Natural Forests	0.078	0.014	5.60	<0.001
Annual Cropland	0.087	0.010	8.91	<0.001
Perennial Cropland	0.115	0.008	13.94	<0.001
Intercept	10.029	0.285	35.16	<0.001

Three of the variables, high producing grasslands, vegetated wetlands and towns, appear to have negative effects on nitrate concentrations whereas natural forests, and both types of croplands have a positive effect. The variable with the highest influence on nitrate concentrations is high producing grasslands. Infact, in terms of influence, the variables which show a negative correlation to the latent variable appear to have the biggest Wald's statistics (in terms of greatest deviation from zero). Natural forests seem to have the smallest influence.

R25/5135 is immediately surrounded by an area of perennial cropland. However, since the regression model attributes a higher influence to high producing grasslands and towns, it is expected that these land cover variables will outweigh the positive influence of perennial crops on nitrate concentrations. Bore S25/5256 is surrounded by quite a large area of perennial and annual crops, which have a positive correlation with nitrate concentrations. Indeed, observed nitrate concentrations in this bore are quite high. The overall log likelihood statistic for the land cover model is 261.576. The result is a significance value of $p < 0.005$ with 6 degrees of freedom. This suggests that the land cover Tobit model is a better fit than not having a model.

5.1.3 Effect of Soil Type on Nitrate Concentrations

The soil types which appear to have a significant influence on nitrate concentrations are the loamy soils.

Table 5 Summary of Tobit regression results for significant soil types

Variable Name	Coefficient	Standard Error	Wald's Stat	p-value
Silt Loam	-3.168	0.576	-5.50	<0.001
Peaty Loam	-23.837	4.231	-5.63	<0.001
Fine Sandy Loam	14.922	0.851	17.54	<0.001
Intercept	2.216	0.259	8.56	<0.001

The silt loams and peaty loams have a negative correlation with observed nitrate concentrations whereas fine sandy loam shows a positive correlation. The Wald's statistic is much larger for fine sandy loam, indicating that the presence of this soil type might contribute to higher concentrations of nitrate concentrations at a particular site. Bore number S25/5256 buffer zone contains the highest area of fine sandy loam soil, which fits in with the bore having high nitrate concentrations. Bores S25/5200 and R25/5135 include large areas of silt loam, therefore having lower nitrate concentrations. Again, the exception is bore R25/5190 which has exhibits high nitrate concentrations, but does not contain any of the soil variables which are indicative of high nitrate concentrations.

So far, land use has been the best indicator of nitrate concentrations for bore R25/5190. The overall log likelihood test statistic for the soil type model is 126.67, which corresponds to a p-level of less than 0.005 with 3 degrees of freedom. The null model is therefore rejected.

5.1.4 Effect of TDS and Dissolved Oxygen on Nitrate Concentrations

Out of these two chemical variables, dissolved oxygen was the only significant predictor of nitrate concentrations. Both wells with the highest nitrate concentrations also display the highest dissolved oxygen content. The summary Tobit statistics for this variable are shown in the table below.The intercept was left out of the model equation due to the lack of significance of the intercept coefficient estimate. The overall log likelihood for this Tobit model was 1376.15, which is significant ($p<0.05$) with 1 degree of freedom, so the model will be accepted.Neither of the two climate variables, regional temperature or rainfall, was a significant explanatory variable.

Table 6 Summary of Tobit regression results for significant chemical variables.

Variable Name	Coefficient	Standard Error	Wald's Statistic	p-value
Dissolved Oxygen	0.696	0.064	10.93	<0.001
Intercept	0.128	0.291	0.44	0.661

6 DISCUSSION

Differences in Physical Catchment Properties

Land Cover, Land Use and Nitrate Distribution

Bores located near lifestyle blocks, settlements, beef cattle farms and fruit growing croplands are at a higher risk of being contaminated with nitrate. Previous studies in the area have acknowledged likely contamination to be from agricultural land use activities (Hughes 1997; Kampman & Caldwell 1985; Tidswell 2009) which largely corroborates with the results from this study. The land use type with highest influence on elevated nitrate concentrations was fruit growing. Although land use data was limited to 2008, the land cover map can be used to determine that from 1990 to 2008, the area of high contamination in the northern Hautere and Coastal groundwater zone were covered by croplands, some of which intersect with lifestyle blocks which grow perennial and annual crops. Therefore, it is likely that, for the last 15 years, the highest nitrate concentrations in groundwater were caused largely by crop producing agricultural activities. Nitrate concentrations increased by 20 to 40 percent from the early 1980's to the early 1990's (Hughes 1997) . According to Kampman and Caldwell (1985), large quantities of land were converted from dairy farming areas to horticultural areas, and lifestyle blocks were being established in the 1980's. This description of land use change conforms well to the results of this study and indicates that the original rise in nitrate contaminants in the area was probably due to an increase in market gardening and development of lifestyle blocks. Bores R25/5190 and S25/5256 are located in areas with dense distributions of croplands, lifestyle blocks and beef farming land use activities and therefore have the highest nitrate concentrations.This pattern is possibly caused by the application of nitrate and ammonium based chemical fertilizers in croplands (Spalding & Exner 1993) which tend to be located over areas with well drained soils. In combination with ample dissolved oxygen in aquifers, leached ammonium from chemical fertilizers can also be oxidized to nitrate (Ministry for the Envi. 2007) .

Soil types and Nitrate Distribution

The permeability of vadose zone soils were found to be one of the most important factors determining nitrate leaching to aquifers in other studies (McLay et al. 2001; Spalding & Exner 1993). Soils of high permeability allow the percolation of irrigation water and rainfall into ground water at a faster rate, thereby contributing to high nitrate leaching into soils overlain by crop agriculture (Spalding & Exner 1993). Soil permeability maps created by Landcare Research show that the majority of the area (except for areas overlain by peat and clay soils) are highly permeable. The results of the regression analysis only found fine sandy loam soils to have a significant effect on nitrate concentrations. Bore S25/5256 was located in an area of fine sandy loams, therefore the regression analysis fit the area of high concentrations quite well. However, bore R25/5190 also displayed elevated nitrate concentrations, but was overlain by sandy soils which did not appear to be significant as an explanation for high concentrations. Different results might be yielded if soil permeability had been used as one of the factors in this study.

Changes in Physical Characteristics

Land cover and soil type have not changed since the beginning of the study period, therefore, although the initial distribution in elevated nitrate concentrations may be explained by a combination of land cover and soil type, it does not explain why concentrations have reduced over the last 15 years. Land use was only available for 2008 thus making it difficult to quantify changes in land use over the study period. However, as discussed in the previous section, when descriptions of previous land use are provided in earlier studies, and are combined with land cover data, one can assume land use has not changed too significantly over the last 15 years. Tidswell (2009) indicates that local authorities have implemented improved land use management processes and local farmers are more informed about timing of fertilizer application and optimal irrigation scheduling in order to reduce impacts to groundwater. These improvements in land management practices could explain the reduction of nitrate concentrations over the last decade.

7 CONCLUSION

Results of Tobit regression analysis provide a good regional explanation of bores displaying historically high nitrate concentrations. Elevated nitrate concentrations in the Te Horo area are likely to be found in bores screened in unconfined surface aquifers which are overlain by crop agriculture, beef farming and lifestyle blocks, and which overlie soils of high permeability such as sandy loams. The above land use types provide the highest loads of nitrate and ammonium to highly permeable soils, which facilitate percolation of nitrate and ammonium enriched rainfall and irrigation water down to the water table. High concentrations of dissolved oxygen are found in bores screened in the unconfined aquifers in the study area, with the highest concentrations of dissolved oxygen found in bores overlain by croplands or lifestyle blocks and permeable soils. This allows for additional nitrate production in affected ground waters as available ammonium is readily oxidised to nitrate.

Monitoring bores which do not show any response to land use or soil properties are generally screened in confined aquifers at greater depth. Better land management practices and increased efficiency in irrigation scheduling and fertilizer application is likely to be the main reason behind improvements to groundwater quality observed over the last decade, particularly as other catchment characteristics have not changed over the last 15 years.

ACKNOWLEDGEMENTS

The authors wishes to thank the organizations they work for as well as APN for all the support and assistance provided.

References

Allen, CW 2010, 'Hydrological characteristics of the te hapua wetland complex: The potential influence of groundwater level, bore abstraction and climate change on wetland surface water levels', Victoria University of Wellington, Wellington, New Zealand.

AsureQuality 2008, *Agribase^{tm} enhanced lcbd2*, AsureQuality, 20 May 2012.

Barringer, T, Dunn, D, Battaglin, W & Vowinkel, E 1990, 'Problems and methods involved in relating land use to ground-water quality1', *JAWRA Journal of the American Water Resources Association*, vol. 26, no. 1, pp. 1-9,<http://dx.doi.org/10.1111/j.1752-1688.1990.tb01345.x>.

Cussins, AP 1994, *The hydrology and hydraulic characteristics of the unconfined aquifers of the otaki-te horo area: A thesis submitted to the victoria university of wellington in partial fulfilment of the requirements for the degree of master of science with honours in physical geography*, Victoria University of Wellington.

Gardner, KK & Vogel, RM 2005, 'Predicting ground water nitrate concentration from land use', *Ground Water*, vol. 43, no. 3, pp. 343-52,NLM.

Helsel, DR 2011, *Statistics for censored environmental data using minitab and r*, John Wiley & Sons.

Hughes, B 1995, *Baseline groundwater quality monitoring, hutt valley and kapiti coast: 1994/95*, WRC/CI-G-96/1, Wellington Regional Council, Wellington,<.

Hughes, B 1996, *Baseline groundwater quality monitoring, hutt valley and kapiti coast: 1995/96*, WRC/RINV-G-96/64, Wellington Regional Councnil, Wellington,<.

Hughes, B 1997, *Nitrate contamination of groundwater on the kapiti coast, december 1996*, WRC/RINV-T-97/26, Wellington Regional Council, Wellington,<.

Hydrological Services Group 1994, *Hydrology of the kapiti coast*, Wellington Regional Council, Wellington, New Zealand,<.
Jones, A & Baker, T 2005, *Groundwater monitoring technical report*, GW/RINV-T-05/86, Greater Wellington Regional Council, Wellington,<.
Kampman, I & Caldwell, KJ 1985, *Groundwater resources of the waitohu, otaki and mangaone*, Manawatu Catchment Board and Regional Water Group, Wellington,<.
Landcare Research NZ Ltd 2005, *Soil map of otaki district*, <http://lris.scinfo.org.nz/layer/172-soil-map-of-otaki-district/#/layer/172-soil-map-of-otaki-district/metadata/>.
Liu, S, Lu, J-C, Kolpin, DW & Meeker, WQ 1997, 'Analysis of environmental data with censored observations', *Environmental Science & Technology*, vol. 31, no. 12, pp. 3358-62.viewed 2012/09/13, <http://dx.doi.org/10.1021/es960695x>.
McLay, CDA, Dragten, R, Sparling, G & Selvarajah, N 2001, 'Predicting groundwater nitrate concentrations in a region of mixed agricultural land use: A comparison of three approaches', *Environmental Pollution*, vol. 115, no. 2, pp. 191-204,<http://www.sciencedirect.com/science/article/pii/S0269749101001117>.
Ministry for the Environment 2007, *Groundwater quality in new zealand : State and trends 1995-2006*, ME831, Ministry for the Environment, Wellington,<.
Ministry for the Environment 2009, *The land cover database version 2*, Wellington, <**Error! Hyperlink reference not valid.**.
Ministry of Health, *Drinking-water standards for new zealand 2005 (revised 2008)*, 2008, Ministry of Health, Wellington.
NIWA 2012, *Niwa taihoro nukurangi*, NIWA, viewed 20 September 2012, <http://www.niwa.co.nz/our-science/climate/our-services/virtual-climate-stations>.
Overgaard, K 1984, 'Trends in nitrate pollution of groundwater in denmark', *Nordic Hydrology*, vol. 15, pp. 177-84.
Spalding, RF & Exner, ME 1993, 'Occurrence of nitrate in groundwater—a review', *J. Environ. Qual.*, vol. , no. 3, pp. 392-402,<https://www.crops.org/publications/jeq/abstracts/22/3/392>.
Stackelberg, PE, Barbash, JE, Gilliom, RJ, Stone, WW & Wolock, DM 2012, 'Regression models for estimating concentrations of atrazine plus deethylatrazine in shallow groundwater in agricultural areas of the united states', *J. Environ. Qual.*, vol. 41, no. 2, pp. 479-924 <https://www.agronomy.org/publications/jeq/abstracts/41/2/479>.
Tesoriero, AJ & Voss, FD 1997, 'Predicting the probability of elevated nitrate concentrations in the puget sound basin: Implications for aquifer susceptibility and vulnerability', *Ground Water*, vol. 35, no. 6, pp. 1029-39,<http://dx.doi.org/10.1111/j.1745-6584.1997.tb00175.x>.