Journal of Hydrology (NZ) 46 (2): 105-115 2007

The effects of land application of farm dairy effluent on groundwater quality – West Coast 2001

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Abstract

Land application of agricultural effluent is becoming a standard farming practice. The application of farm dairy effluent to land, as opposed to direct discharge to waterways, is the preferred method for disposal in New Zealand as regulatory authorities move to protect and enhance water quality and meet Maori spiritual and cultural values. Land application recognises the nutrient value of dairy effluent; however, it is not without risks. Careful management of land application of the effluent is required because of the potential nutrient and bacterial contamination of groundwater. In 2001, 19 groundwater bores were sampled on four occasions to assess the effects of farm dairy effluent on groundwater quality. Elevated (> 1.6 g m^{-3}) nitrate-nitrogen concentrations were found in 14 of these bores (43 of 74 samples). The available long-term data shows statistically significant increasing trends in nitrate-nitrogen and chloride over the period 1998 to 2007. The nitrate-nitrogen and chloride results suggest effluent is the source of the elevated nitrate-nitrogen; however, the nitrogen isotope analysis indicates that the source of the nitrate-nitrogen may be from fertiliser or soil organic matter (average $\delta^{15}N$ value of 3.5‰). Spatially isolated occurrences of bacterial contamination were also recorded: in 7 bores and 12% of all samples analysed. Groundwater dating, using chlorofluorocarbons, suggested that the groundwater in the region was young (8 to 12 years). Overall, the spatial and temporal data suggests human influences are affecting groundwater quality on the West Coast.

Introduction

Dairy farming is crucial to the New Zealand economy: dairy products constituted 17% of the total export earnings in 2003, while agriculture contributed 4.9% of GDP (Statistics New Zealand, 2004a,b). Over the past ten to fifteen years, dairy farming in New Zealand intensified dramatically: total cow numbers have increased from 2.4 million to 3.8 million – a 60% increase – between 1990/91 and 2005/06 (Livestock Improvement Corporation 2006). The average stocking rate has increased from 2.1 to 2.6 cows per hectare in the 20 years to 1997/98 (Ministry for the Environment, 1999) and, associated with this increase in stock numbers, has been an increase in the use of nitrogen (N) fertiliser (Parliamentary Commissioner for the Environment, 2004). The increasing number of livestock, and the associated processing industries, poses a considerable threat to the environment due to the need to safely dispose of the waste generated.

The rates of intensification in the West Coast Region of the South Island have been similar to the national values. From 1998/99 to 2005/06, the intensification of dairying in the region saw the total number of cows increase 53% (>40 000 cows) to 124 000; the stocking rate increased from 2.0 to 2.15 cows per hectare and the average herd size increase 51% from 218 to 330 cows (Livestock Improvement Corporation 1998 and 2006). While only 3.2% of the 2005/06 New Zealand dairy herds are located in the West Coast region, dairying is the West Coast's most productive agricultural activity.

Farm dairy effluent is the mixture of dairy cow faeces and urine deposited during milking that is subsequently diluted with wash-down water during the cleaning of the milking area and the associated holding yards. Thus farm dairy effluent is a dilute organic effluent. Irrigation of farm dairy effluent onto pasture is increasingly being recognised as a means for biological treatment, and recognises the fact that it is a resource to be utilised for its nutrient content rather than a waste for disposal. Land application of farm dairy effluent can provide valuable nutrients and organic matter for pasture. However, inappropriate application rates or timing can lead to poor utilisation by plants, causing nitrate leaching and groundwater contamination, surface water contamination, anaerobic soil conditions, water-logging of soils, soil nutrient imbalances and/or animal health problems (Wang *et al.*, 2004). In New Zealand, land application of farm dairy effluent has become the preferred treatment method to minimise the risk of contamination of surface waters and to address cultural concerns about the addition of waste material to waterways. For example, since 1993 the proportion of Waikato farmers who irrigate dairy effluent onto pasture rose from 35% to nearly 70% in 1997 to effectively 100% in 2004 (Barkle *et al.*, 2000).

The interaction of farm management practices and the physical environment of the individual farm predominantly control the potential impact of dairying on groundwater quality. The physical environment includes the nature and timing of precipitation, the geology and soil characteristics, the topography, and location of water bodies. Farm management practices include the stocking rate, effluent disposal practices, and fertiliser application timing and rates.

The challenges of effluent application are well recognised. This paper examines the effects of farm dairy effluent application to land on groundwater quality through field monitoring at 19 selected sites, supplemented by data from three National Groundwater Monitoring Programme sites, in the West Coast Region in 2001.

West Coast groundwater resources

Even though the West Coast Region is the third largest Region by land area, there is only limited information on its groundwater resources. Since the region has historically had a relatively reliable supply of surface water, there has been a limited need to access groundwater resources in the region; and thus little need to collect groundwater resource information. However, groundwater is important for some industries, particularly dairy farming, and to certain communities for drinking water supplies (James, 2001).

Most aquifers studied in the West Coast region are located in unconfined recent alluvial gravel outwash adjacent to streams. The thickness of the alluvial gravels is typically 20-40 m, with up to 60-70 m in parts of the Grey Valley. The general hydrogeological setting is one of considerable water availability. Most of the coastal strip of the region receives 2000-4000 mm of rainfall annually, which is reasonably consistent month to month, and there are relatively low evapotranspiration losses (714 mm at Reefton, 1999-2004). These large annual effective rainfall totals, combined with high-relief surface catchments, result in few limitations on the abstraction of groundwater or groundwater allocation restrictions. To date resource consents have not been required for either groundwater abstraction or bore construction for domestic or farm use, and so there is limited information on actual groundwater use. However, a groundwater bore inventory has been compiled. The inventory had over 300 recorded bores in 2001 – 20% in the Grey Valley, 27% in the Hokitika/Kowhitirangi area, and 22% in the South Westland area, with the remainder scattered through the Reefton/Inangahua and Westport areas. Most abstraction is from shallow aquifers with water tables only 5 to 10 metres below the ground surface. During 1998, 374 farms were surveyed to investigate the different types of effluent disposal systems; 20% indicated that they used some form of land-based effluent irrigation system (West Coast Regional Council, 1998).

Methodology

From the 1998 farm survey, bores suitable for sampling were identified. Selection criteria included that the bore was in an area surrounded by farms disposing of farm dairy effluent to land, that clusters of bores would allow a series of bores downgradient to be analysed, and that the total selection should cover the range of sites generally observed in the region. From the initial selection, a total of 22 bores were located – 19 especially for this study and 3 bores from the National Groundwater Monitoring Programme (NGMP). The 19 bores were all farm bores routinely used for water supply, but complete information on the construction of each of the bores was generally unknown. The sites were in four groups (Fig. 1):

- seven bores in the Ahaura Valley, including an NGMP bore (NGMP-1),
- seven bores on Totara Flat and one slightly to the north-east at Ikamatua,
- five bores from Kowhitirangi, including two NGMP bores (NGMP-2 and NGMP-3), and
- two bores from around Reefton (Inangahua Valley).

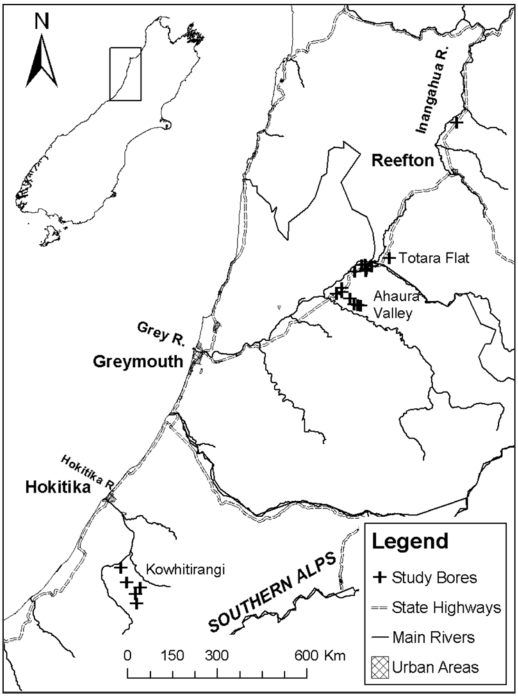

Figure 1 – Location map of study area

For budgetary reasons, only a limited number of parameters were measured at each location. These were field measurements of pH, temperature, dissolved oxygen and conductivity, and laboratory analysis of nitrate-nitrogen, ammonia-nitrogen, chloride, dissolved reactive phosphorus, total iron, and bacteria faecal coliform and *Escherichia coli.* Field measurements of pH, temperature, dissolved oxygen and conductivity were taken using a WTW Multiline P4 meter in a bucket of flowing bore water, not in a flow cell. Sampling was carried out bi-monthly over an 8-month period, starting with autumn (April) and finishing in October. The bores were purged of three volumes of water and samples collected from the closest possible outlet to the headworks. Samples for laboratory analyses were collected in pre-prepared bottles supplied by Cawthron Institute Laboratories in Nelson; stored on ice following collection and were analysed by Cawthron within 24 hours using American Public Health Association standard methods.

Following analysis of the April results, 6 samples were taken, as part of the June sampling, from the locations with the greatest nitrate-nitrogen concentrations for nitrogen isotope analysis, because isotopic analysis may be used to help identify the source of the nitrogen (Kellman and Hillaire-Marcel, 2002). In addition, four samples, covering the whole region, were taken for age dating using chloroflurocarbon (CFC) analysis. Due to the sensitivity of the CFC results the sampling was undertaken by Robert van der Raaji (GNS) according to the appropriate protocols.

Results

Overview

Across four groups and the four sampling occasions there was considerable spatial and temporal variability in the field parameter measurements (Fig. 2). The lack of statistical difference in the results suggests that the natural processes controlling groundwater quality are more-or-less similar across the catchments studied. Hence, variations in nitrate concentrations could be inferred to arise from land-use activities.

Similarly, comparing the data to the results from the National Groundwater Monitoring Programme data offers insights (Table 1). The measured conductivities were low compared to New Zealand as a whole, the ammonia-nitrogen values were similar, and

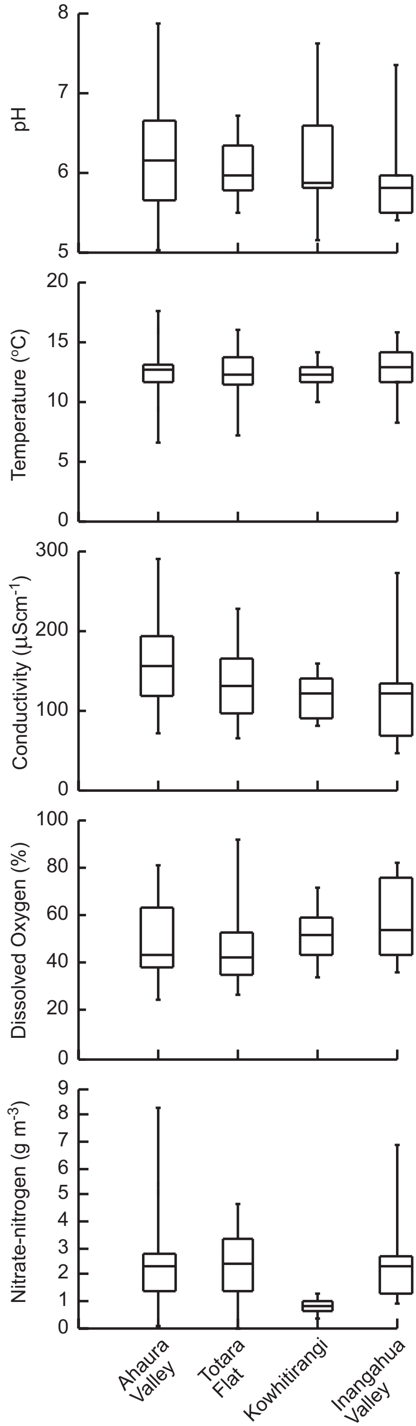

Figure 2 – Summary of the data from the 19 bores sampled

Table 1 – Percentile comparisons of the data from the West Coast and the National Groundwater Monitoring Programme ([1]Daughney and Reeves, 2005; [2]Daughney and Wall, 2007)

	Nitrate-nitrogen		Ammonia-nitrogen		Conductivity	
Percentile (%)	NGMP[1]	West Coast	NGMP[1]	West Coast	NGMP[2]	West Coast
5	0.53	0.47	0.00	0.00	88.5	65.5
25	2.20	0.94	0.00	0.01	144.8	92.3
50	4.68	2.20	0.01	0.01	210.0	134.1
75	8.90	3.00	0.01	0.02	371.1	168.8
95	35.19	4.86	0.07	0.05	1111.0	250.6

the nitrate-nitrogen values exhibited some elevated values. Across the 19 bores, 43 of the 76 samples (from 14 bores) had nitrate-nitrogen values indicative of "probable" anthropogenic impacts and 11 samples (5 bores) had values indicative of "almost certain anthropogenic impacts" (Daughney and Reeves, 2005).

The dissolved oxygen values should be treated with caution, given the difficulty with measuring dissolved oxygen in the field and given that a flow cell was not used. However, when combined with the ammonia-nitrogen results, the data can be used to infer denitrification conditions. That is, in places the low dissolved oxygen, low nitrate-nitrogen and the ammonia-nitrogen values suggest some denitrification; hence, any impact of farm dairy effluent would be hard to detect. Results from this study suggest denitrification is not occurring, as dissolved oxygen concentrations are high (Fig. 2), as are the ratios of nitrate-nitrogen to ammonia-nitrogen in all samples. The low conductivity values obtained are consistent with the groundwater being young and being recharged primarily from rivers or considerable rainfall.

Ahaura Valley

Nitrate-nitrogen concentrations here varied from 0.16 g m^{-3} to 8.2 g m^{-3}. The greatest concentrations (peak value 8 g m^{-3}) were recorded in winter (August) and the greatest concentration recorded on each of the four sampling rounds was at the most down-gradient bore at the lower end of the valley. While all the bores are in the unconfined aquifer, the bore at the lower end of the valley is one of the shallowest, with a total depth of only 10 m and an average depth to the water table of 5 m. The bores at the top end of the valley are 30 and 48 m deep, with water tables around 15-20 m below ground surface. The concentrations of dissolved reactive phosphorus, iron, chloride and ammonia-nitrogen were all consistent and low at all locations over the four sampling rounds, except for high iron concentrations at one location (median 1.96 g m^{-3}). In the April sampling round faecal coliform and *E. coli* were recorded at one location (*E. coli* 5 cfu/100 ml) while in October faecal coliform and *E. coli* were recorded at two locations (*E. coli* 1 and 40 cfu/100 ml).

Totara Flat

Nitrate-nitrogen concentrations here showed a distinct winter peak: the values at the seven locations were between 0.5 g m^{-3} and 2 g m^{-3} in April and between 2 g m^{-3} and 4.5 g m^{-3} in August. The concentrations of dissolved reactive phosphorus, iron, chloride and ammonia-nitrogen were all consistent and low at all locations over the four sampling rounds. Positive results for *E. coli* were recorded at two locations (one once in April and the other three times: in April 8 cfu/100 ml, June 1 cfu/100 ml and October 33 cfu/100 ml). In October faecal coliform and *E. coli* were recorded at two locations (*E. coli* 1 and 40 cfu/100 ml).

Kowhitirangi

Nitrate-nitrogen concentrations here were the lowest of all the study areas; the greatest winter value was only 1.3 g m^{-3}, nonetheless the winter values were greater than the values at other times. The concentrations of dissolved reactive phosphorus, iron, chloride and ammonia-nitrogen were all consistent and low at all locations over the four sampling rounds. No measurable occurrences of either faecal coliform or *E. coli* were recorded at any of the three locations.

Inangahua Valley

Average nitrate-nitrogen concentrations here were 1.28 g m^{-3} and 3.77 g m^{-3} at the two locations; again peak values were recorded in winter. The concentrations of dissolved reactive phosphorus, iron, chloride and ammonia-nitrogen were all consistent and low at all locations over the four sampling rounds. No measurable occurrences of either faecal coliform or *E. coli* were recorded at either of the locations.

National Groundwater Monitoring Programme bores

In addition to the 19 bores sampled for this study, results from the three National Groundwater Monitoring Programme (NGMP) bores can be used to supplement the results. The NGMP-2 bore at Kowhitirangi is located up-gradient of the intensively farmed area, while the NGMP-3 bore is down-gradient. The NGMP-1 bore is located at the down-gradient end of the Ahaura valley. Long-term trends in the NGMP data was investigated using the seasonal Mann-Kendall trend analysis, a non-parametric test that does not depend on the data being drawn at random from a normally distributed population (Gilbert, 1987). The Mann Kendall test does not calculate the magnitude of the trend; it only determines whether or not a trend is present. For bores where a trend is identified, the magnitude of the trend was estimated using Sen's slope estimator, a non-parametric test that is less affected by data errors, outliers or missing data than simple linear regression (Gilbert, 1987).

Over the term of the monitoring programme, nitrate-nitrogen concentrations the NGMP-1 bore has shown a steady increase, and seasonal peaks are also evident. The NGMP-2 and NGMP-3 bores show less apparent trends (Fig. 3). A similar pattern of results is evident in the chloride concentrations recorded at each of these locations. Trend analysis confirms the pattern evident in the figure, i.e., in terms of nitrate-nitrogen concentrations, at NGMP-1 the increase was significant (at the 95% confidence level) with a rate of change of 0.30 g m^{-3} y^{-1}; at NGMP-2 the increase was significant (at the 95% confidence level) with a rate of change of 0.03 g m^{-3} y^{-1}; and at NGMP-3 the increase was significant (at the 90% confidence level, but not at the 95% confidence level) with a rate of change of 0.04 g m^{-3} y^{-1}. Daughney

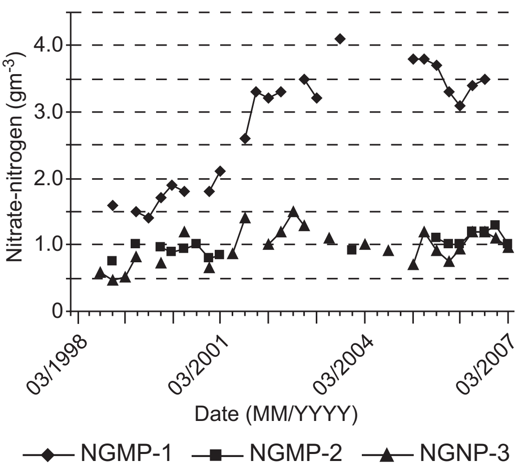

Figure 3 – Nitrate-nitrogen concentrations of West Coast NGMP bores, Sep 1998-Sep 2003.

and Reeves (2006) concluded that the 'normal' rate of change of nitrate-nitrogen in New Zealand groundwater not affected by human activity should be less than ±0.1 mg l^{-1} per year; hence, the data from NGMP-1 almost certainly suggests anthropogenic influences.

Age dating and isotope analysis

Measuring the ratio between the ^{14}N and ^{15}N isotopes ($\delta^{15}N$) potentially allows the source of the nitrogen observed in the sample to be determined, because ^{14}N is derived from natural processes while ^{15}N is derived from anthropogenic processes. Inorganic fertilisers with nitrogen that has been atmospherically derived have a $\delta^{15}N$ similar to that of air, typically -4‰ to +4‰, while nitrate from animal effluent and human waste has a more positive $\delta^{15}N$ value of between +10‰ to +25‰ (Kendall *et al.*, 1995). The $\delta^{15}N$ values (‰) for the 6 samples were between 1.51 and 4.58 (average 3.5‰, Table 2).

Table 2 – Nitrate-nitrogen concentrations and nitrogen isotope results

Group	$\delta^{15}N$ (%)	Nitrate-nitrogen (mg l^{-1})
Ahaura Valley	3.58	2.2
Ahaura Valley	4.18	2.2
Ahaura Valley	1.51	5.4
Totara Flat	3.40	4.1
Inangahua Valley	3.67	4.0
Inangahua Valley	4.58	3.3

The mean residence time of the groundwater was determined using samples from 4 bores using CFC dating analysis. The concentrations of CFC-11 and CFC-12, expressed as equivalent atmospheric partial pressures, corresponded to recharge years between 1984 and 1986 for CFC-11 and 1989-1993 for CFC-12. The CFC-12 mean residence time was shorter than the CFC-11 calculation in all cases. This can be attributed to CFC-11 degradation and adsorption and is consistent with other New Zealand groundwaters (van der Raaij, 2000); hence, the recommended recharge years are based on the CFC-12 model recharge dates. The CFC analysis suggests the groundwater across the region is young, with a mean residence time of between 8 and 12 years.

Discussion

Over the 76 samples, the chloride concentration explains 51% of the variance in the nitrate-nitrogen concentration and the slope of the regression line (0.71) is significantly different from 0 (p=0.0, SPSS, 2000; Fig. 4). As increasing trends of chloride can be a general indication of effluent contamination, this suggests that the source of the nitrate-nitrogen is from effluent, either human or animal (Rosen, 2001); however, the nitrogen isotope results prevent a definitive conclusion (see below).

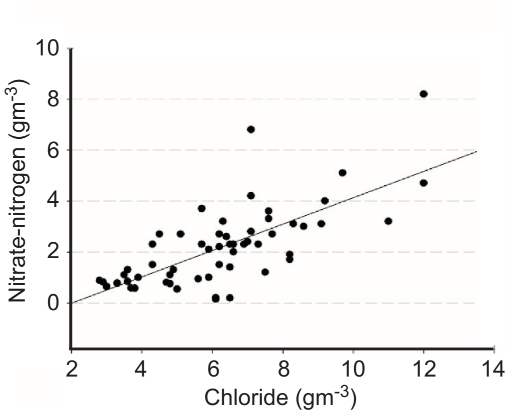

Figure 4 – Nitrate-nitrogen and chloride concentrations of all samples.

Several studies (e.g., Close *et al.*, 2001) have shown that groundwater nitrate-nitrogen concentrations may vary with depth to the water table. While the total depth of the bore is not a measure of the depth to the water table, bore depth was available for all locations (whereas the screened depth was not). A comparison of bore depth and nitrate-nitrogen concentration, over the 76 samples, showed that nitrate-nitrogen concentrations over 3.5 g m^{-3}, the level almost certainly indicative of anthropenic influence (Daughney and Reeves (2005), were recorded only in bores shallower than 10 m (Fig. 5). This suggests a surface source for the nitrate-nitrogen.

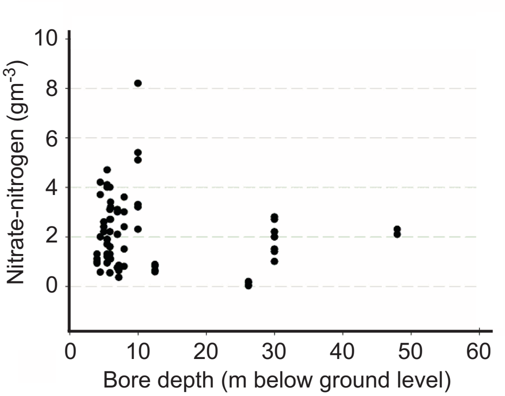

Figure 5 – Nitrate-nitrogen concentrations and depth of bore below ground level.

The elevated nitrate-nitrogen values in the Ahaura Valley were unsurprising. The valley is intensively farmed, with all dairy farms applying their farm dairy effluent to land, and the unconfined aquifer and the fluctuating groundwater levels suggest a rainfall-recharge-dominated system. Bores at the top of the valley are typically 30-50 m deep (with groundwater levels 7-20 m below ground surface), while the groundwater levels in bores at the bottom of the valley were 4-7 m below ground surface. Four bores consistently have nitrate-nitrogen concentrations of over 1.6 g m^{-3}, while one bore consistently has nitrate-nitrogen concentrations of over 3.5 g m^{-3}. These high nitrate-nitrogen values, coupled with the trend analysis (NGMP-1), the winter nitrate-nitrogen values being approximately twice the summer values, and the general correlation between the results for nitrate-nitrogen and chloride suggest some degree of human influence on groundwater quality.

At Totara Flat, the mean nitrate nitrogen concentration was 2.5 g m^{-3} and the similar groundwater levels, hydrogeology, rainfall and land-use practices to the lower Ahaura valley sites allows comparison to be made with the increasing trends evident from the NGMP-1 bore. The positive bacterial results in this study area were of concern. Field investigations at one location noted that, on all four site visits, it appeared that the pump controlling the oxidation pond was not working. Effluent had backed up in farm drains, and one of these drains was only 4 m from the bore head and 1.5 m below the ground surface. The bore was a domestic supply for two houses and also the main stock supply. Apparently a number of calves died at this farm due to a waterborne bacteriological infection (McCleery pers. comm., 2001). In addition, several properties in the area have previously reported health problems (apparently as a result of drinking from groundwater sources); in one case heavy summer pumping had induced drainage of effluent from an oxidation pond into the pumped bore.

At Kowhitirangi, low concentrations of nitrate-nitrogen were observed; however, the results from the NGMP bores in this area suggest that down-gradient there is evidence of increasing nitrate-nitrogen concentrations. The low concentrations may be explained by a number of factors. According to the Dairy Effluent Survey 1998, only 12% of the 50 dairy farms in the area were applying farm dairy effluent to land; the majority were using oxidation ponds and barrier ditches that then drained into surface water. Also, the low-lying nature of the area, high annual rainfall, proximity to the Hokitika and Kokatahi rivers, shallow groundwater tables and the high hydraulic conductivities of the alluvial gravels may allow increased dilution of any nitrate-nitrogen leaching to groundwater.

Across the region, the recharge dates calculated from CFC concentrations indicate that the groundwater sampled was young. This can be attributed to the shallow unconfined nature of the aquifers tapped by the bores. The young age of the water sampled in the Kowhitirangi area is consistent with the shallow water table, high hydraulic conductivities and low conductivities measured.

The 6 bores with elevated nitrate-nitrogen levels analysed for nitrogen isotope composition had an average $\delta^{15}N$ value of 3.5‰, which is consistent with either a fertiliser or soil organic nitrogen source; however, given the nitrate-nitrogen concentrations (Table 2), it is not surprising this value is close to that of soil organic nitrogen. Hence, the nitrogen isotope analysis cannot be used to conclude that the elevated nitrate-nitrogen is due to fertiliser and not farm dairy effluent. The nitrate-nitrogen concentrations and their rate of change suggest that a source other than natural soil organic nitrogen is causing the elevated concentrations. Given that an intensification of dairying, in terms of increased stocking, herd size and number of cows milked, is usually associated with an increase in fertiliser use (Parliamentary Commissioner for the Environment, 2004), and the young age of the groundwater, it is likely the increase in nitrate-nitrogen is due to a mix of fertiliser and farm dairy effluent, rather than one or the other.

Farm dairy effluent management

Prior to the growth in land application of farm dairy effluent, the effluent from New Zealand dairy sheds was typically treated in a two-stage pond (anaerobic followed by aerobic) system, prior to discharge to a surface waterway (Zaman *et al.*, 2002). For example, during 1996/97, about 35% of farms in the Waikato region were using this waste treatment system (Longhurst *et al.*, 2000), and since 1993 the proportion of Waikato farmers who irrigate farm dairy effluent onto pasture rose from 35% to nearly 70% in 1997, to effectively 100% in 2004 (Barkle *et al.*, 2000). From a nutrient recapture perspective, and as a means to reduce environmental effects on surface waterways, farm dairy effluent application to land is of greater value than utilising effluent from oxidation ponds (Longhurst *et al.*, 2000). While effluent irrigation diverts nutrients from waterways, it potentially results in other environmental problems if not carefully managed. These include increased recharge to the groundwater, accompanied by salts and nitrate.

Conclusion

From the point of improved water quality, Houlbrooke *et al.* (2004) concluded that because 80-98% of the nutrients applied in the farm dairy effluent were trapped by the soil land treatment, thus considerably reducing the quantity of nutrients reaching freshwater bodies, land treatment could have considerable positive effects.

Excessive application of farm dairy effluent can, however, also result in a range of detrimental effects. Excessive applications of nitrogen have been shown to result in nitrogen leaching, to levels above the recommended concentration for drinking water (Ministry of Health, 2003); hence the use of rules by most New Zealand regional councils to manage the application of farm dairy effluent. Land application of dairy effluent has the potential to increase microbial contamination, and hence affect human health (Sinton, 2001). An alternative, and important, consideration is that groundwater standards and contamination have important implications on agricultural management and economics (Eco-Link Limited, 2000).

Nitrate-nitrogen contamination of groundwater, and its associated impacts on surface water, continues to be problematic and a significant concern in New Zealand for regulators, land managers and waterway users. It is important that land application of farm dairy effluent does not simply result in the transfer of effluent management from a waterway "problem" to a future land "problem".

The nitrate-nitrogen concentrations observed, the increasing trends (and the rate of change in concentration) in nitrate-nitrogen and chloride, and the bacterial results all suggest human influences on groundwater quality on the West Coast.

Acknowledgements

We thank West Coast Regional Council, especially Trevor James, for the opportunity to undertake this project, funding and field assistance. Thanks also to Rob van der Raaij (GNS) for undertaking the nitrogen isotope and CFC dating analysis. Two anonymous reviews significantly improved the paper.

References

Barkle, G.F.; Stenger, R.; Singleton, P.L.; Painter, D.J. 2000: Effect of regular irrigation with dairy farm effluent on soil organic matter and soil microbial biomass. *Australian Journal of Soil Research 38*: 1087-1097.

Close, M.E.; Rosen, M.R.; Smith, V.R. 2001: Fate and transport of nitrates and pesticides in New Zealand's aquifers. *In* White, P.A.; Rosen, M.R. (*eds.) Groundwaters of New Zealand*. Christchurch, New Zealand Hydrological Society: 185-220.

Daughney, C.; Reeves, R. 2005: Definition of hydrochemical facies in the New Zealand National Groundwater Monitoring Programme. *Journal of Hydrology (New Zealand) 44*: 105-130.

Daughney, C.; Reeves, R. 2006: Analysis of long-term trends in the New Zealand's groundwater quality based on data from the National Groundwater Monitoring Programme. *Journal of Hydrology (New Zealand) 45*: 41-62.

Daughney, C.; Wall, M. 2007: Groundwater quality in New Zealand: State and Trends 1995-2006. GNS Science Consultancy Report 2007/23.

Eco-Link Limited 2000: Implications of groundwater nitrate standards for agricultural mangement. Report commissioned by MAF Policy. Technical paper 2000/15: 177 p. Available from http://www.maf.govt.nz/mafnet/publications/techpap.html [10/10/2005]

Gilbert, R. 1987: *Statistical methods for environmental monitoring*. Van Nostrad Reinhold, New York.

Houlbrooke, D.; Horne, D.; Hedleym M.; Hanly, J.; Snow, V. 2004: A review of literature on the land treatment of farm-dairy effluent in New Zealand and its impact on water quality. *New Zealand Journal of Agriculture Research 47*: 499-511.

James, T. 2001: West Coast Groundwater. *In* White, P.A.; Rosen, M.R. (*eds.), Groundwaters of New Zealand*. Christchurch, New Zealand Hydrological Society: 461-464.

Kellman, M.; Hillaire-Marcel, C. 2002: Evaluation of nitrogen isotopes as indicators of nitrate contamination sources in an agricultural watershed. *Agriculture ecosystems and environment 95*: 87-102.

Kendall, C.; Sklash, M.G.; Bullen, T.D. 1995: Isotope Tracers of Water and Solute Sources in Catchments. In *Solute Modelling in Catchment Systems*, John Wiley and Sons, New York, p. 261-303.

Livestock Improvement Corporation 1999: Dairy Statistics 1998-1999. Hamilton. Livestock Improvement Corporation Limited.

Livestock Improvement Corporation 2006: Dairy Statistics 2005-2006. Hamilton. Livestock Improvement Corporation Limited.

Longhurst, R.D.; Roberts, A.H.; O'Connor, M.B. 2000: Farm dairy effluent: a review of published data on chemical and physical characteristics in New Zealand. *New Zealand Journal of Agricultural Research 43*: 7-14.

McCleery, B. 2001: Personal communications. Brian McCleery, sharemilker, Totara Flat.

Ministry for the Environment 1999: Resource Management Act – Practice and performance: A case study of farm dairy effluent management. Wellington, Ministry for the Environment.

Ministry of Health 2003: Drinking-water standards New Zealand 2004. Available from http://www.moh.govt.nz/moh.nsf/0/f220b2b169b7ea30cc256dce007251c8?OpenDocument [10/10/2005]

Parliamentary Commissioner for the Environment 2004: Growing for good: intensive farming, sustainability and New Zealand's environment. Wellington, Parliamentary Commissioner for the Environment.

Rosen, M. 2001: Hydrochemistry of New Zealand's aquifers. *In* White, P.A.; Rosen, M.R. (*eds.), Groundwaters of New Zealand*. Christchurch, New Zealand Hydrological Society: 77-110.

Sinton, L.W. 2001: Microbial contamination of New Zealand's aquifers. *In* White, P.A.; Rosen, M.R. (*eds.), Groundwaters of New Zealand*. Christchurch, New Zealand Hydrological Society: 221-251.

SPSS Inc. 2000: *SYSTAT Version 10 – statistical software*.

Statistics New Zealand 2004a: Overseas Merchandise Trade (Exports) December 2003. http://www.stats.govt.nz/domino/external/pasfull/pasfull.nsf/0/4c2567ef00247c6acc256e3500122e1c/$FILE/Alltabls.xls [31 January 2004]

Statistics New Zealand 2004b: Gross Domestic Product (Exports) December 2003. http://www.stats.govt.nz/domino/external/pasfull/pasfull.nsf/0/4c2567ef00247c6acc256e620075a269/$FILE/alltabls.xls [31 January 2004]

Van der Raaij, R. 2000: Nitrate contamination in the Te Ore Ore Aquifers: a study using chemical, isotopic and CFC data. Unpublished BSc Hons dissertation, Victoria University of Wellington.

Wang, H.; Magesan, G.; Bolan, N. 2004: Overview of the environmental effects of land application of farm effluents. *New Zealand Journal of Agriculture Research 47*: 389-403.

West Coast Regional Council 1998: Dairy shed effluent database. An internal inventory/database of the West Coast Regional Council, Greymouth.

Zaman, M.; Cameron, K.C.; Di, H.J.; Inubushi, K. 2002: Changes in mineral N, microbial biomass and enzyme activities in different soil depths after surface applications of dairy shed effluent and chemical fertilizer. *Nutrient Cycling in Agroecosystems 63*: 275-290.

Manuscript received 15 April 2007; accepted for publication 17 October 2007