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CHEMICAL ZONATION IN GROUNDWATER OF THE CENTRAL PLAINS, CANTERBURY

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ABSTRACT

The extensive groundwater beneath the Central Canterbury Plains is an important source of domestic water. In some areas the potability of groundwater is at risk from high nitrate-N concentrations. Nitrate contamination originates from both point and non-point sources. Grazed pastureland and cropland (non-point sources) contribute about 92 percent of the total nitrate-N load (4,171,000 kg per yr) on Central Plains groundwater. Major point sources, including septic tanks, piggeries and meatworks, contribute the remainder. Sewage farms and dairy farms make a relatively insignificant contribution.

Central Plains groundwater has been divided into three chemical zones. Zone (1) lies in regions of recharge from rivers; zone (2) includes unconfined and semi-confined groundwater down to 60 m below the water table, and some shallow confined groundwater; and zone (3) comprises all deep circulating groundwater. Nitrate-N concentrations in zones (1) and (3) are less than 1 g m^{-3}. These concentrations exhibit little seasonal variation and no long-term variation. Zone (3) appears to be protected naturally from contamination originating at the land surface. Concentrations range between 4 and 8 g m^{-3} over large regions of zone (2) and exceed 10 g m^{-3} in parts of the Islington — Burnham — Lincoln area. The magnitude of seasonal fluctuations in nitrate level depends on depth below water table and proximity to point sources. Longer-term fluctuations (during the period of study) appear to result from variation in the amounts of recharge and not from changes in land use.

The apparent separation of shallow and deep groundwater has important implications for groundwater quality management. Zone (2) groundwater cannot be maintained at a potable level if non-point sources remain uncontrolled. Major land-use changes will probably not, however, affect the existing high quality of groundwater in zones (1) and (3). A programme for domestic water reticulation from zone (3) groundwater should be initiated across the Central Plains.

INTRODUCTION

The Central Canterbury Plains cover an area of 202,200 ha. (Fig. 1). Groundwater beneath the plains is an important source of domestic, industrial and agricultural water (Bowden *et al.*, 1983). Each use of groundwater requires a certain minimum level of water quality. Water used for human consumption has the most stringent quality requirements (W.H.O., 1971). Households on

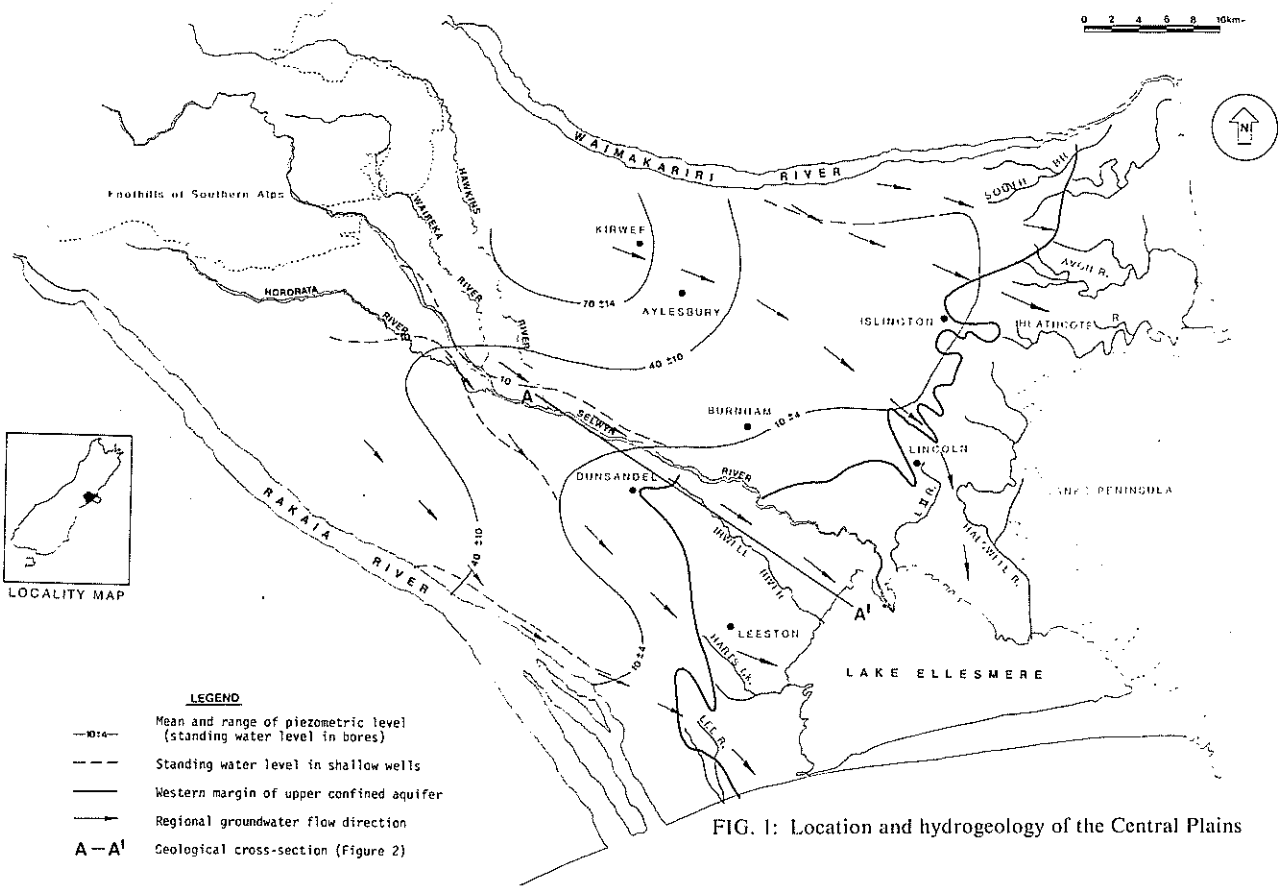

FIG. 1: Location and hydrogeology of the Central Plains

the Central Plains obtain water from individual wells (pop. 15,000) or reticulated supplies (pop. 330,000). Some of the private wells are grouped in small communities but many are scattered throughout the study area. Individual household wells generally draw on the shallowest available groundwater. In areas with unconfined aquifers shallow wells penetrate less than 20 metres into the water table. These wells are particularly susceptible to contamination from various land uses.

The Central Plains is one of a number of areas in New Zealand where intensified agriculture has resulted in a deterioration of adjacent groundwater quality (Burden, 1982a). In several places the potability of Central Plains groundwater is already at risk due to high nitrate levels. A regional management plan for groundwater quality is now needed to balance competing demands of agricultural and domestic uses of groundwater. This paper describes the relationship between land use and nitrate levels in Central Plains groundwater, quantifying the principal sources of nitrate and describing the movement and accumulation of nitrate in groundwater.

METHODS

Groundwater samples were obtained from approximately 600 wells over the period 1977 to 1983. Samples were collected during regional surveys, site investigations, and surveys of public water supplies. Regional surveys of groundwater quality were conducted by the North Canterbury Catchment Board. Sampling between June 1977 and December 1980 included about 400 wells located in a region of unconfined and semi-confined groundwater (generally to the west of the line shown on Fig. 1). Each well was sampled twice, and 40 percent were sampled on four or more occasions. Between June and December 1982 about 200 wells were surveyed including some not previously sampled. Since 1977, the North Canterbury Catchment Board has conducted a number of site investigations near major point sources of groundwater contamination. Unfortunately, this data has proven difficult to interpret on a regional scale. Public water supply wells on the Central Plains have been sampled by the Department of Health and analysed by the Department of Scientific and Industrial Research, Chemistry Division (Christchurch) as part of an annual rating of water supplies in New Zealand. Some of the wells supplying pumping stations in Christchurch City have been analysed since the 1930's. Only in the last 2–3 years has it been possible to sample all the water supply wells in Christchurch individually.

Major-ion analyses were conducted on water from approximately 300 wells in the study area. Most of these wells were located near Christchurch City or near suspected point sources of contamination. The remainder were analysed for both nitrate and chloride, or nitrate alone. All analyses were conducted by the Department of Scientific and Industrial Research, Chemistry Division (Christchurch) and by the North Canterbury Catchment Board, using recognised methods.

HYDROGEOLOGY

The Central Canterbury Plains (Fig. 1) consist of a vertical sequence of

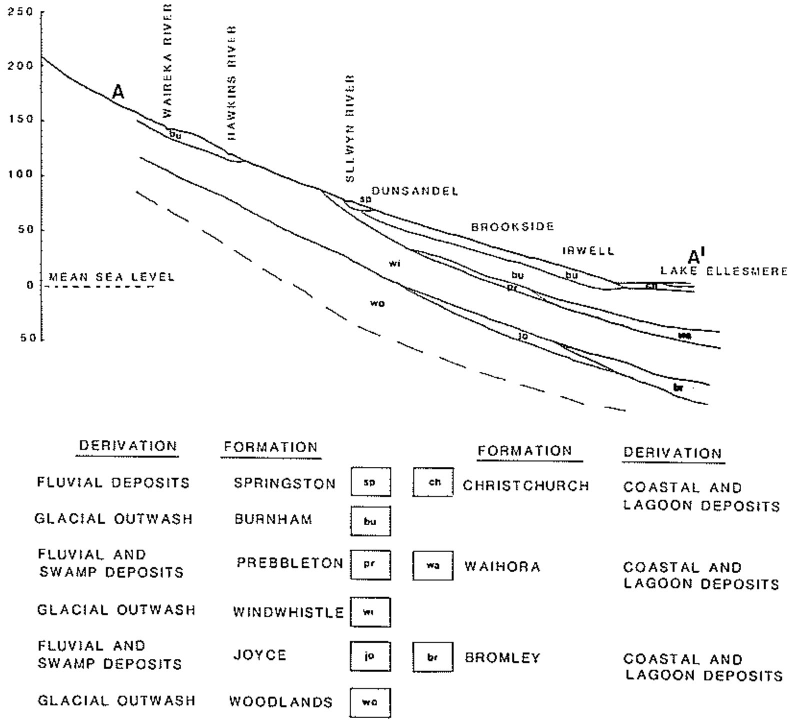

FIG. 2: Schematic geological section down the Plains (after Bowden et al., 1983; Brown and Wilson, 1984)

coalesced glacial outwash and postglacial alluvial fans deposited by the Rakaia, Selwyn and Waimakariri Rivers (Fig. 2). The Quaternary alluvium overlies an irregular basement of indurated Tertiary sediments to a depth of several hundred metres near the coast. The depth of unconsolidated sediments decreases rapidly towards the foothills of the Alps (Suggate, 1973; Wilson, 1973). Relatively low-permeability fluvioglacial outwash near the foothills becomes interbedded with progressively higher-permeability interglacial and postglacial alluvial deposits near the coast. Permeability of this alluvium is greatest sub-parallel to the direction of river flow (west to east), lower transverse to flow, and lowest in a vertical direction (Wilson, 1984). This geological model suggests that Central Plains groundwater may flow preferentially through discrete layers separated from each other by relatively impermeable alluvium (i.e. semi-confining layers). Near the coast, the fluvial gravels are separated by a vertical sequence of fine-grained estuarine and marine sediments (Wilson, 1976). At least four distinct fine-grained beds (i.e. confining layers) have been identified near the coast and more may be located at greater depth.

The Central Plains may be sub-divided into two hydrogeological regions (Fig. 1) — an inland region of unconfined to semi-confined groundwater, and a coastal region of confined groundwater. The unconfined /semi-confined

TABLE 1: Major components of a water balance for the Central Plain groundwater systems.

Inflows	Mean annual recharge rate (m^3s^{-1})	Source	Outflows	Mean annual discharge rate (m^3s^{-1})	Source
Rainfall	16.0	Bowden et al., 1983	Irrigation	4.0	Bowden et al., 1983
Irrigation	1.5	Bowden et al., 1983	Industry	1.5	N.C.C.B., unpublished data
Water races	4.0	N.C.C.B., unpublished data	Domestic	1.0	N.C.C.B., unpublished data
Rakaia R.	4.0	Scott and Thorpe, 1984	Sth. Branch R.	3.0	Christchurch Drainage Board unpublished data
Selwyn R.	3.0	Bowden et al., 1983	Styx R.	2.0	Christchurch Drainage Board unpublished data
Hawkins R.	1.0	Bowden et al., 1983	Avon R.	2.5	Christchurch Drainage Board unpublished data
Waireka R.	0.5	Bowden et al., 1983	Heathcote R.	0.5	Christchurch Drainage Board unpublished data
Hororata R.	0.5	Bowden et al., 1983	Halswell R.	3.0	Lineham, 1983
Waimakariri R.	?		L II R.	3.5	Lineham, 1983
Foothills run-off	?		Selwyn R.	5.5	Lineham, 1983
			Irwell R.	1.5	N.C.C.B., unpublished data
			Harts Ck.	3.0	Lineham, 1983
			Lee R.	3.0	N.C.C.B., unpublished data
			Marine outfall	?	
TOTAL INFLOWS	>30.5		TOTAL OUTFLOWS	>34	

region consists of a major water-table aquifer overlying several deeper aquifers. The fine-grained beds near the coast separate the groundwater system into a vertical series of confined aquifers. There is a hydraulic connection between the two hydrogeological regions but its nature is not clear (Bowden *et al.*, 1983).

Depth to groundwater, as determined by piezometric levels (i.e. the level at which water stands in a bore tapping the water-bearing layer), varies maredly in both space and time (Fig. 1). Water levels of the coastal confined aquifers are sub-artesian or artesian. Farther inland the depth to groundwater (i.e. the piezometric level) is up to 70 metres. Levels fluctuate seasonally by up to 15 metres. The magnitude of the seasonal fluctuation increases with depth below ground level. Long-term (20 year) changes in water level may be as much as twice the seasonal variation (Bowden *et al.*, 1983).

Regional groundwater moves from the inland foothills towards the coast (Fig. 1). The indicated flow directions were based on piezometric levels in wells of all depths (Bowden *et al.*, 1983). No attempt was made to determine flow directions at different depths. On a local scale, permeability differences may result in a complex flow pattern (Thorpe *et al.*, 1982). Groundwater seepage velocities range between 0.1 and 250 m d^{-1} (Bowden *et al.*, 1983). Tracer studies indicate average flow velocities of between 200 and 300 m d^{-1} in shallow groundwater at Burnham (Sinton, 1980; Barry and McCabe, 1979).

Central Plains groundwater is recharged by seepage from surface watercourses and by infiltration of rainfall and irrigation water. Rainfall on the inland foothills may make a further significant contribution to groundwater, particularly to the deeper aquifers. Mean annual recharge from known sources totals about 31 m^3s^{-1} (Table 1). The bulk of this inflow results from rainfall and irrigation surpluses. Groundwater levels in the inland plains indicate that the upper reaches of the Rakaia and Waimakariri Rivers are perched. Seepage from the lower reaches of these rivers affects only the coastal region of the groundwater system. A relatively impermeable stratum, located about 15 m below ground, restricts the downward movement of recharge from the Rakaia and minor inland rivers (Bowden *et al.*, 1983; Scott and Thorpe, 1984). The low permeability stratum appears to correlate with the top of the Burnham formation which may also restrict recharge from the Waimakariri River (Fig. 2). Recharge from the Waimakariri River has not been reliably estimated.

Mean annual discharge from known outlets amounts to about 34 m^3s^{-1} (Table 1). Spring-fed rivers account for about 27.5 m^3s^{-1} of the total outflow. Rainfall and irrigation on the confined aquifer region and run-off from Banks Peninsula may contribute as much as 1 to 2 m^3s^{-1} to flows in the spring-fed rivers. These inflows may be offset by discharges from small springs that have not been included in the present figures. The apparent inflow/outflow balance for the groundwater system may be fortuitous because of uncertainty in the estimates of the water-balance components. Nevertheless, annual recharge does appear to be approximately balanced by known discharges without the need to invoke significant losses beyond the coastline.

SOURCES OF NITRATE

Several sources contribute to nitrate concentrations in Central Plains

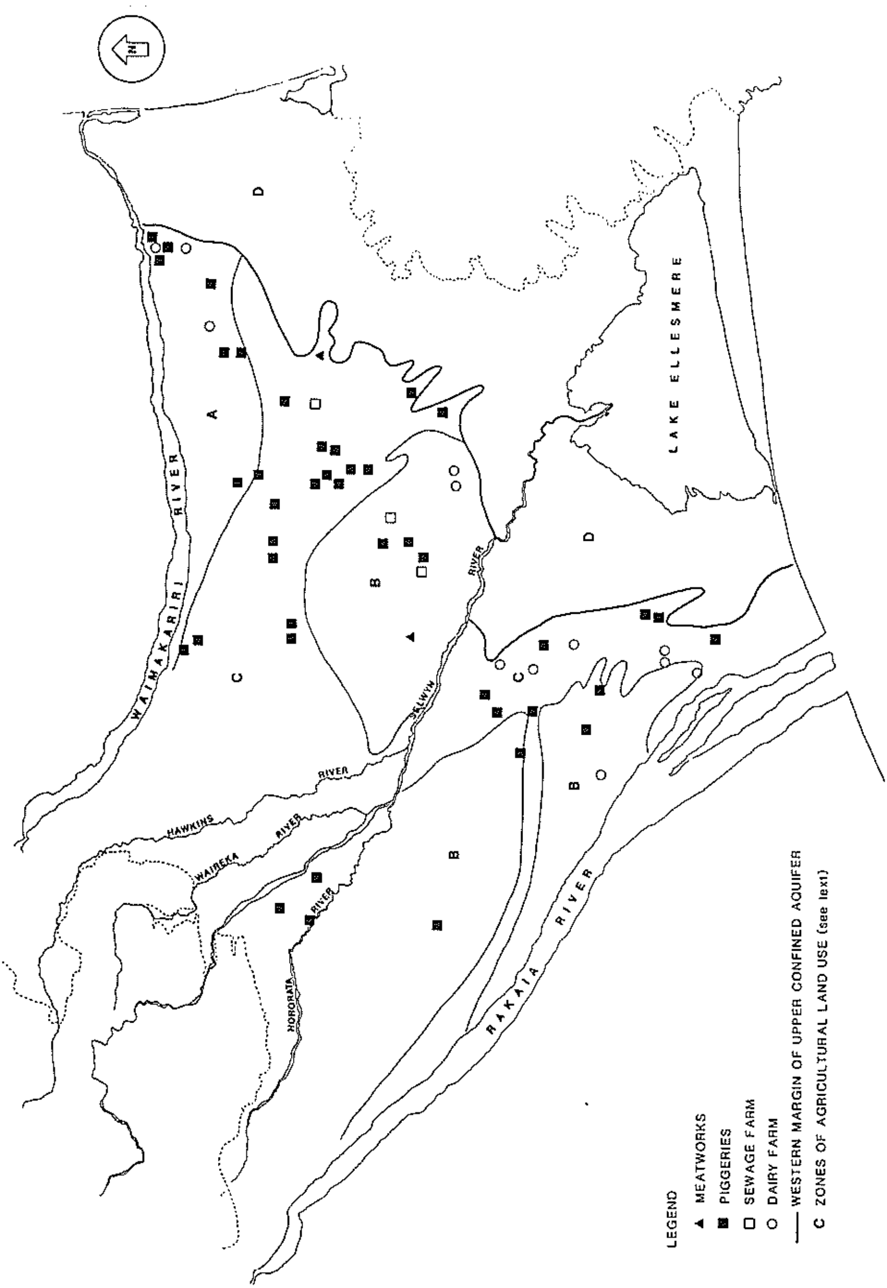

FIG. 3: Agricultural land use and major point sources of nitrate above the unconfirmed groundwater region

TABLE 2: Major sources of nitrate above the unconfined region of Central Plains groundwater.

	+Nitrate-N Leaching Rate (kg $ha^{-1}yr^{-1}$)	Nitrate-N Conc. in Drainage (g m^{-3})	*Nitrate-N Load on Groundwater (kg yr^{-1})	Land Area (ha)	Source
Non-point Sources					
Dryland Pasture	~5–20 (12.5)	5–10	1,500,000 (36)	120,000	Bowden et al., 1983 and Quin, 1979
Irrigated Pasture	~45–100 (63)	15–20	1,200,000 (29)	19,000	Bowden et al., 1983 and Quin, 1979
Dryland Cropping	~10–90 (35)	10–20	700,000 (17)	20,000	Bowden et al., 1983 and Quin, 1979
Irrigated Cropping	~30–100 (57)	10–15	400,000 (10)	7,000	Bowden et al., 1983 and Quin, 1979
Point Sources					
Piggeries (41)	ˆ10–2500 (160)	—	160,000 (3.5)	1,000	N.C.C.B. unpublished data
Septic Tanks (3250)		140–180	130,000 (3)	—	Sinton, 1982
Meatworks (2)	ˆ60–1000 (375)	10–100	75,000 (1.5)	200	Burden, 1984; and N.C.C.B. unpublished data
Sewage Farms (3)	ˆ25–85 (70)	—	3,500	50	Martin & Noonan, 1977; and N.C.C.B. unpublished data
Dairy Farms (10)	—	—	2,500	—	N.C.C.B. unpublished data
		Total	4,171,000		

\+ mean rate of leaching per hectare in parenthesis
* % of total N load in parenthesis
~ range for variation in soil moisture capacity and/or mode of irrigation
ˆ range for differences in disposal site management

groundwater (Fig. 3). These sources may be classified either as point or non-point (Table 2). Non-point sources affect the regional quality of groundwater, and include extensive areas of pastureland (139,000 ha) and cropland (27,000 ha). Point sources of nitrate have a more localised impact. On the Central Plains the major point sources are disposal sites for human and animal wastes. Individually, septic tanks may be regarded as point sources. Collectively, however, septic tanks could have significant regional impact.

The impact of both point and non-point sources on nitrate levels in groundwater is partly controlled by biogeochemical reactions affecting nitrogen. Two crucial factors are the formation of nitrate in the soil and the subsequent stability of nitrate in the soil/groundwater system. For the listed sources, only a small proportion of the nitrogen applied to the land is in the nitrate form. Excess nitrogen is applied to pastureland in the form of urea excreted by grazing stock. On cropland, nitrogen is applied as urea or ammonium fertilisers. Human and animal effluent irrigated onto land contains ammonium nitrogen and various forms of organic nitrogen. If the applied nitrogen were not converted to nitrate, the potability of Central Plains groundwater would not be at risk. Excess nitrogen is, however, almost completely converted to nitrate in the soil zone and unsaturated zone (Adams, 1981; Keeley and Quin, 1979; Quin, 1979; Quin and Burden, 1979). The unsaturated zone of the Central Plains is well aerated. Under these conditions nitrate is the stable form of nitrogen (Champ *et al.*, 1979). There would be no reduction in the amount of nitrate leached to groundwater even if subsurface drainage took several years to pass through the unsaturated zone (Burden, 1984a).

Dryland pasture is the principal source of nitrate affecting Central Plains groundwater quality (Table 2). Grazing stock excrete high concentrations of nitrogen in patches that are then readily leached from the soil zone (Quin, 1979). The rate of leaching is relatively low, but the land area covered by pasture is extensive. Irrigation significantly raises the rate of nitrate leaching by increasing both stock levels and drainage through the soil (Quin and Burden, 1979). Dryland and irrigated pasture together account for approximately 65 percent of the total nitrate load in Central Plains groundwater.

Cropping is widespread on the deeper soils of the Plains. The amount of nitrate leached from cropland is dependent upon soil depth and the timing of irrigation and fertiliser applications. Irrigation increases the rate of leaching by more than 50 percent (Table 2). Nitrate leached from dryland and irrigated cropland together accounts for about 27 percent of the total nitrate load in groundwater. In combination, pastoral and arable agriculture (non-point sources) contribute approximately 92 percent of the nitrate entering Central Plains groundwater.

The intensity of agriculture on the Central Plains is governed mainly by soil depth (Adams, 1981). Soils on the plains may be divided into four classes (Fig. 3). Class A soils are stony and shallow (<80 mm) and support only very light stock grazing. Stock numbers are higher on the deeper (80–200 mm) class B soils and some areas are cropped. Pastoral and arable agriculture is most intensive on the relatively deep (200–600 mm) class C soils. The rate of nitrate leaching to groundwater increases dramatically from class A to class C soils. Class D soils support quite intensive agriculture but are very poorly drained. The low permeability of class D soils probably prevents nitrate leaching to groundwater.

Domestic and industrial sewage from most of the Christchurch metropolitan area and from Lincoln township is disposed, via treatment plants, to surface water and therefore does not affect groundwater quality. However freezing works and abbatoir wastes at Islington and Burnham, and treated domestic sewage from Templeton and Leeston townships, Rolleston Prison and Burnham Military Camp are disposed of by land irrigation on free-draining soils. Most other housholds over the region of unconfined groundwater (approximately 3250) are served by individual septic tanks. Until very recently emphasis was placed on disposal of septic tank effluent rather than concern for the effect of effluent on groundwater quality. The boulder-hole system of disposal in common use removes less than 50 percent of the effluent nitrogen (M. Close, pers. comm.). Collectively, septic tanks contribute only a small proportion (3 percent) of the nitrate entering Central Plains groundwater (Table 2). Individual septic tanks may however, pose a risk to nearby domestic wells because most households lacking sewers are supplied from shallow wells. The problem of local contamination is heightened in rural subdivisions where households are closely grouped (Sinton, 1982).

The major point sources of waste and irrigated animal effluent (Fig. 3) together contribute only about 5 percent of the total nitrate load in Central Plains groundwater (Table 2). The 41 piggeries located over the region of unconfined groundwater contribute 3.5 percent of this. Other sources of nitrate include septic-tank sludge, poultry effluent and urban refuse. Disposal of these wastes probably contributes less than 1 percent of the total load. These figures suggest that point sources of nitrate make an insignificant impact on the regional quality of Central Plains groundwater. On a local scale, however, these point sources may affect the potability of adjoining existing and future sources of domestic water.

CONTAMINATION OF GROUNDWATER

Central Plains groundwater may be sub-divided into three major chemical zones (Fig. 4). These are: (1) river-recharged groundwater, (2) shallow groundwater remote from river recharge zones, and (3) deep groundwater. These zones appear to be characteristic of alluvial groundwater systems throughout New Zealand (Burden, 1982a). The location and spatial extent of the zones are governed by the relative volumes and compositions of different sources of groundwater.

Zone (1)

Zone (1) groundwater lies adjacent to regions of recharge from the Rakaia, Selwyn and Waimakariri Rivers (Fig. 4). Seepage from the rivers is the dominant source of this groundwater. The low nitrate-N concentrations (<1 g m^{-3}) characteristic of zone (1) groundwater reflect, therefore, the nitrate content of local river water. Mean annual low-flow losses to Central Plains groundwater from the lower reaches of the Rakaia River are about 5 m^3s^{-1} (Scott and Thorpe, 1983). The narrow extent of zone (1) near the river suggests, however, that the Rakaia is not a regionally-important source of groundwater.

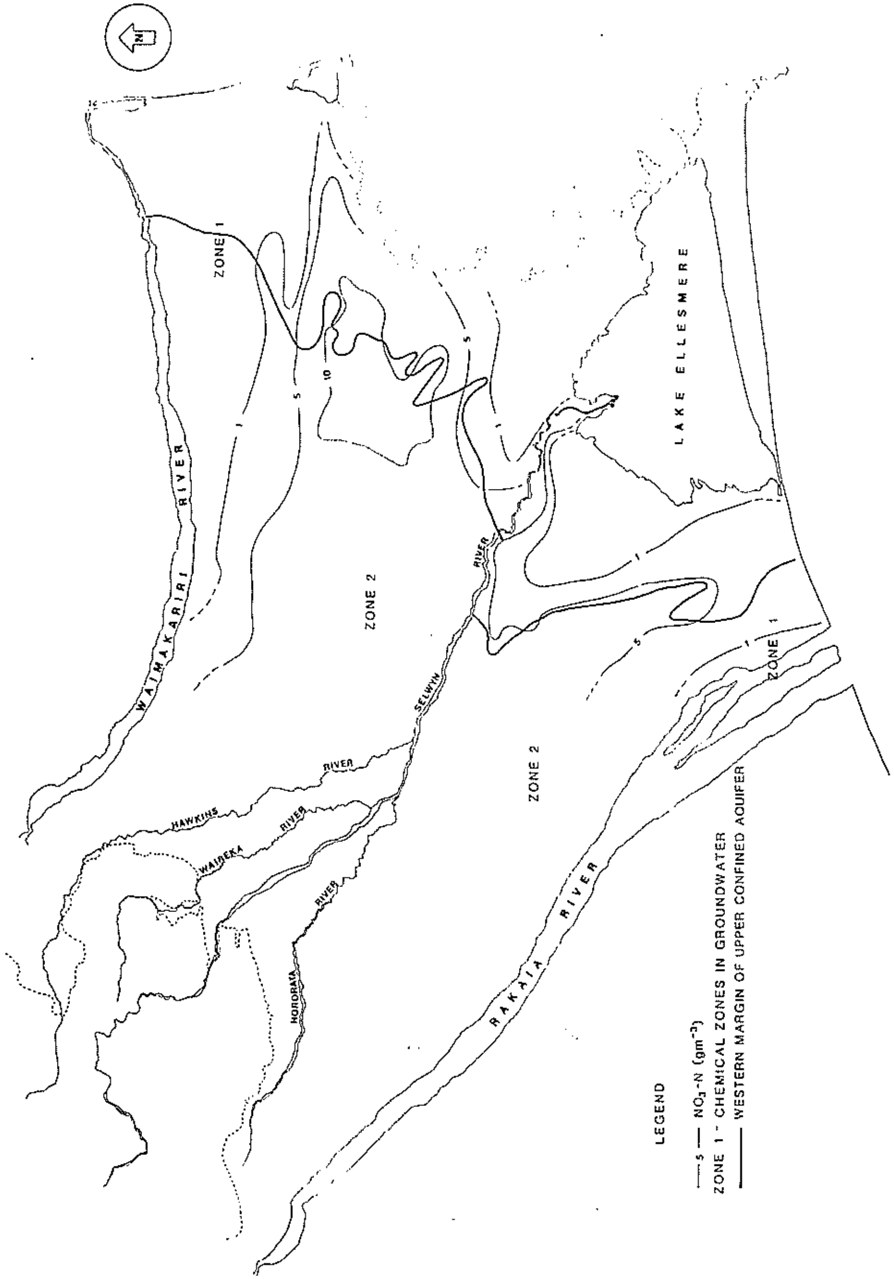

FIG. 4: Nitrate-N concentrations in shallow (<50–60 m below water table) groundwater and zones of different chemical composition.

Seepage to groundwater from the upper and middle sections of the Selwyn River totals about 3 m^3s^{-1} (Bowden *et al.*, 1983). Low-nitrate water from the Selwyn River was detected in adjacent groundwater but there were too few wells in the area for the extent of zone (1) to be clearly defined.

Recharge from the lower reaches of the Waimakariri River appears to have an appreciable impact on nearby groundwater (Fig. 4). The spatial extent of zone (1) groundwater near the Waimakariri is significantly greater than near the Rakaia River. The relatively large area of low-nitrate groundwater adjacent to the Waimakariri River probably results from a combination of a higher rate of river recharge, less nitrate leached from overlying land, and the presence of confining beds. Unfortunately, the rate of recharge from the Waimakariri River has not been accurately estimated so a comparison with the Rakaia River is not possible. Soils in the area are characteristically shallow and stony, and support extensive agriculture (Fig. 3). The amount of nitrate leached from this land is probably lower than from the rest of the Central Plains. Seepage from the Waimakariri River will, therefore, tend to maintain nitrate-N concentrations below 1 g m^{-3} in groundwater over a relatively large area. Finally, once low-nitrate groundwater moves into the confined coastal aquifers no further nitrate contamination is likely to occur. A large part of the zone (1) groundwater near the Waimakariri is located in the upper confined aquifers (Fig. 4). Hydrological evidence suggests that the Waimakariri and Rakaia Rivers are perched in their upper reaches (Bowden *et al.*, 1983), but there were too few observation wells near the rivers to confirm this with chemical data.

Zone (1) groundwater is generally located at shallow depths because the vertical penetration of river recharge appears to be hindered by a layer of relatively impermeable alluvium. Recharge from the Rakaia and inland rivers is restricted by a low permeability stratum about 15 to 20 m below the ground (Scott and Thorpe, 1983; Bowden *et al.*, 1983). This low permeability layer appears to correlate with the top of the Burnham formation (Fig. 2). If the correlation with the Burnham formation is valid, the downward movement of recharge from the Waimakariri River is probably also quite limited.

Zone (2)

Zone (2) includes all unconfined groundwater outside zone (1), some shallow semi-confined groundwater beneath the unconfined areas and some shallow confined groundwater near the coast (Fig. 4). Nitrate-N concentrations ranged between 4 and 8 g m^{-3} throughout most of the zone. Results from a limited number of wells sampled on the inland plains suggests that nitrate-N leaching into groundwater may extend well back towards the foothills of the Southern Alps. Nitrate-N concentrations in shall groundwater match those in drainage from agricultural land (Table 2). This close match indicates that zone (2) groundwater consists almost entirely of subsurface drainage from the plains. Irrigation of crop and pastureland may increase concentrations in drainage by between 50 and 100 percent (Quin and Burden, 1979; Bowden *et al.*, 1983). Widespread irrigation on the plains may, therefore, raise nitrate-N concentrations above 10 g m^{-3} throughout most of zone (2).

Nitrate-N concentrations in shallow groundwater generally increased from the foothills to the eastern margin of the unconfined groundwater region

(Fig. 4). The rate of increase down the plains is probably dependent upon variations in the intensity of agricultural land-use. Nitrate-N concentrations in the Islington — Burnham — Lincoln area often exceeded the safe limit for potable water (10 g m^{-3}) recommended by the World Health Organisation (W.H.O., 1971). Only slightly lower concentrations were recorded in the Dunsandel-Leeston area. Agricultural land-use is particularly intensive in both these areas (Fig. 3). High rates of nitrate leaching from the intensively-utilised agricultural land would be superimposed on base-level contamination from farther up the plains.

Elevated nitrate-N levels have penetrated the coastal shallow-confined aquifers in some places (Fig. 4). The presence of nitrate-N in the confined aquifers results exclusively from the down-gradient movement of unconfined groundwater. Nitrate leached from land near the coast is prevented from entering confined groundwater by a relatively impermeable capping bed. Nitrate-N levels do not, therefore, continue to increase after groundwater enters the confined aquifers. The three areas of confined groundwater containing elevated nitrate levels may represent points of lateral outflow from the shallow groundwater system of the Central Plains. Low nitrate-N concentrations (<1 g m^{-3}) in the rest of the shallow confined groundwater suggests lateral flow does not occur in these regions. Much of the groundwater containing nitrate-N may discharge through springs located along the western margin of the coastal confined aquifers (Fig. 1). The nitrate content of the springs reflects the composition of adjacent shallow groundwater. Also, the mean annual flows of rivers fed by the springs appear at this stage of investigations to account for most of the known inflows to the Central Plains groundwater system (Table 1). It appears, therefore, that zone (2) groundwater follows a shallow circulation path that starts with recharge by rainfall and irrigation on the plains and ends in discharges through springs near the coast.

Elevated nitrate-N concentrations in zone (2) groundwater extend to a depth of about 50–60 m below the water table as determined by piezometric levels (Fig. 5). At about this depth concentrations decrease rapidly and then remain at a low level. A similar drop-off occurred at about the same depth south of the Rakaia River (Quin and Burden, 1979). The depth to which elevated nitrate-N levels extend does not appear to increase with distance down the plains. This is surprising because the nitrate-N-bearing water might be expected to move to greater depths as progressively more drainage accumulates in groundwater. Downward movement of nitrate-N below 50–60 m may be prevented by layers of low permeability alluvium. The presence of such layers has been postulated in a recent geological model of the Canterbury Plains (Wilson, 1979).

Zone (3)

Zone (3) includes all groundwater in the Central Plains located more than about 50–60 m below the piezometric level. Nitrate-N concentrations in deep groundwater beneath the inland plains were generally less than 1 g m^{-3} (Fig. 5). Near the coast, concentrations were less than 0.5 g m^{-3} down to depths of 150 m below ground. These low nitrate-N concentrations suggest that zone (3) groundwater has a different source and flow path to the shallow contaminated groundwater. Infiltration from the inland foothills may be the

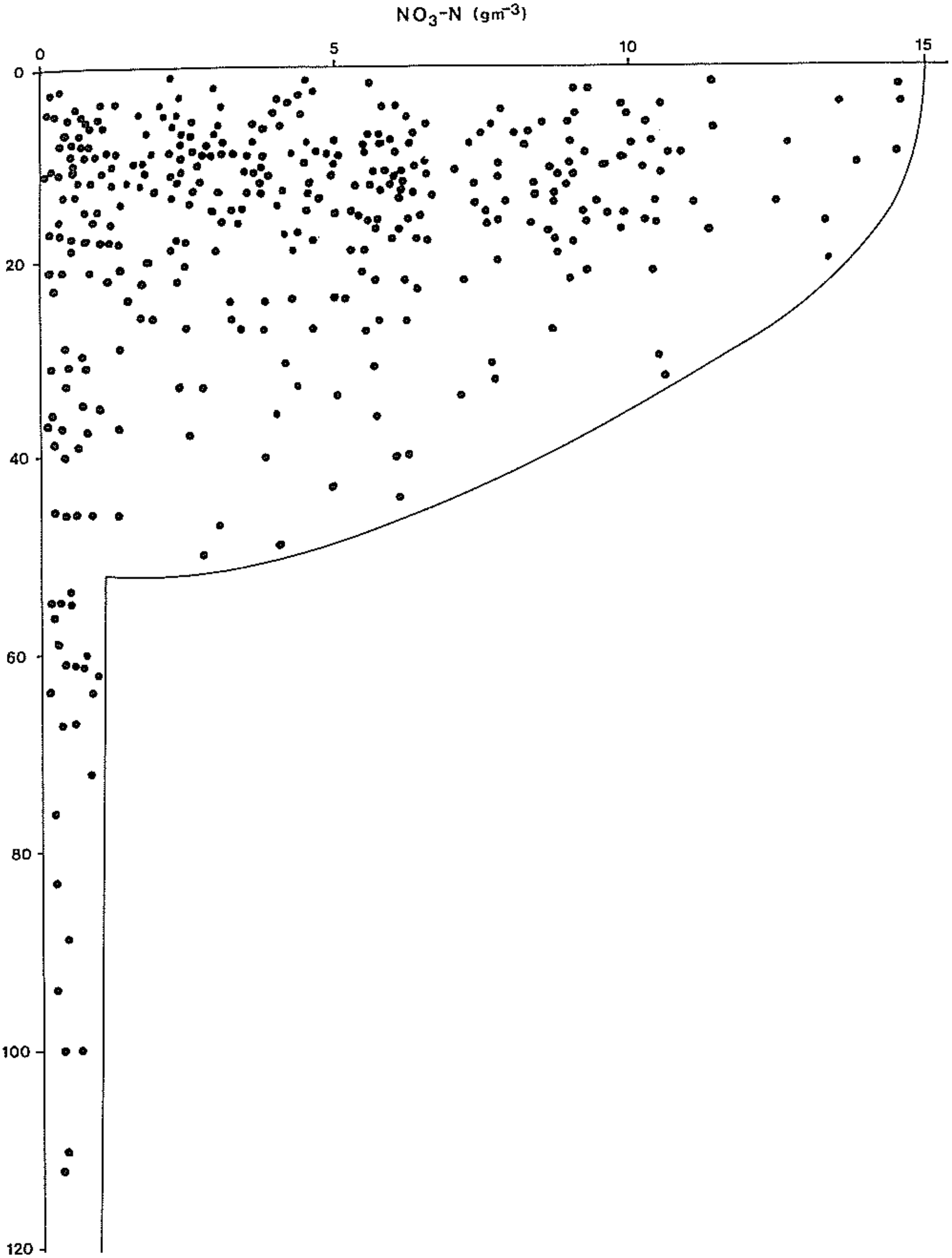

FIG. 5: Nitrate-N concentrations vs. depth below the water table for Zones (1) and (2) groundwater.

TABLE 3: Typical chemical composition of groundwater from Zones (1), (2) and (3)

Zone	Zone (1)	Zone (2)	Zone (3)
Bore Reference	M35/936	M36/70	M35/2132
Location	Halkett	Rolleston	New Brighton
Bore Depth	27.4 m	41.4 m	152.4 m
Average Depth to Standing Water Level	17 m	15 m	Artesian +9 m
pH	7.3	6.8	7.9
Na ($g\ m^{-3}$)	3.0	—	8.7
K ($g\ m^{-3}$)	0.6	—	0.5
Ca ($g\ m^{-3}$)	11.0	—	12.5
Mg ($g\ m^{-3}$)	1.3	—	2.5
HCO_3 ($g\ m^{-3}$)	38.0	44.0	59.0
Cl ($g\ m^{-3}$)	2.6	19.0	5.5
NO_3-N ($g\ m^{-3}$)	0.3	7.1	0.2
SO_4 ($g\ m^{-3}$)	5.3	7.7	4.0

source of low-nitrate water feeding deep groundwater. The relatively high pH (7.5 — 8.0) and low chloride and nitrate-N concentrations in deep groundwater (Table 3) indicate a source of recharge from high up on the plains (Burden, 1982b). Large volumes of run-off from the foothills may recharge groundwater during periods of high rainfall.

Deep groundwater flowing beneath the plains appears to remain isolated from the shallow nitrate-N-elevated groundwater (Fig. 5). On the inland plains, zone (3) groundwater may be confined beneath beds of relatively-impermeable glacial alluvium (Wilson, 1979). Deep groundwater may be confined at successively greater depths by progressively older formations of glacial alluvium. Groundwater at each of these depths may retain an essentially separate flow path. In the Kirwee — Aylesbury area, however, nitrate levels were similar in deep and shallow groundwater. Nitrate-N concentrations in the deep groundwater in this area probably originate at the source of recharge. Recharge may result from infiltration through agricultural land that extends far inland up the south side of the Waimakariri River (Fig. 3).

Zone (3) groundwater appears to flow upwards near the margin of the coastal confined aquifers (Wilson and Hunt, 1975). A groundwater balance for the Central Plains system suggests there may be little lateral flow through the coastal confined aquifers (Table 1). Deep groundwater is probably either discharged from springs or abstracted for human use. Low-nitrate zone (3) groundwater appears to feed all the deep coastal confined aquifers and parts of the shallow confined aquifers. Appreciable quantities of low-nitrate water must be available to replenish major domestic and irrigation abstractions because, to date, groundwater containing elevated nitrate-N levels has not been drawn into the deep coastal aquifers.

TEMPORAL FLUCTUATIONS

Zone (2) groundwater alone exhibited significant temporal fluctuations in nitrate-N content. Interpretation of these fluctuations is complicated by two factors. Firstly, records of groundwater quality (1977–1983) are too short for long-term trends to be clearly established. Secondly, regularly-sampled wells were generally located near suspected sources of contamination. Fluctuations in the quality of water from these wells may not, therefore, reflect regional changes.

Nitrate-N concentrations in zone (2) groundwater were high in late 1979 and then declined gradually through to mid-1983 (Fig. 6). The observed decline appears to result from reduced rainfall recharge and not from changes in land-use. The period 1980 to 1983 was characterised by lower than average rainfall recharge (Bowden *et al.*, 1983). The water table fell as recharge decreased (Fig. 6). Nitrate-N levels increased again late in 1983 in response to increased rainfall recharge.

Seasonal changes in nitrate-N concentration were superimposed upon the long-term trend. Seasonal fluctuations result principally from changes in the volume of subsurface drainage entering groundwater (Burden, 1980). In areas affected by non-point sources, nitrate-N concentrations varied by between 0.5 and 2.0 g m^{-3} throughout a year. The magnitude of seasonal variation often decreased with depth below the water table. In higher nitrate-N level areas such as near townships or piggeries concentrations fluctuated by 5 to 10 g m^{-3}. Down-gradient of the main effluent disposal site for Waitaki N.Z.R. Freezing Works, concentrations changed by up to 20 g m^{-3} (Burden, 1984). Seasonal changes in nitrate-N concentration make it difficult to compare samples from different years unless they were collected in the same month. Two major regional surveys of groundwater quality were conducted by the North Canterbury Catchment Board between 1977 and 1980 and in 1982. Wells were resampled in 1982 in different months than in the earlier survey, making it impossible to indentify a long-term change in regional groundwater quality.

Uniformly-low nitrate-N concentrations in zone (1) and zone (3) groundwater indicate that these regions were not significantly affected by overlying land use. The amount of river water recharging zone (1) groundwater appears to mask the seasonal impact of contaminated drainage (Burden, 1982). In deep (60–150 m) confined groundwater beneath Christchurch City concentrations have not varied by more than about 0.1 g m^{-3} since the 1930's (Chemistry Division, D.S.I.R., unpublished data).

IMPLICATIONS FOR MANAGEMENT

A recent review of the Water and Soil Conservation Act (1967) and subsequent amendments interpreted the overall objective of the Act as "to

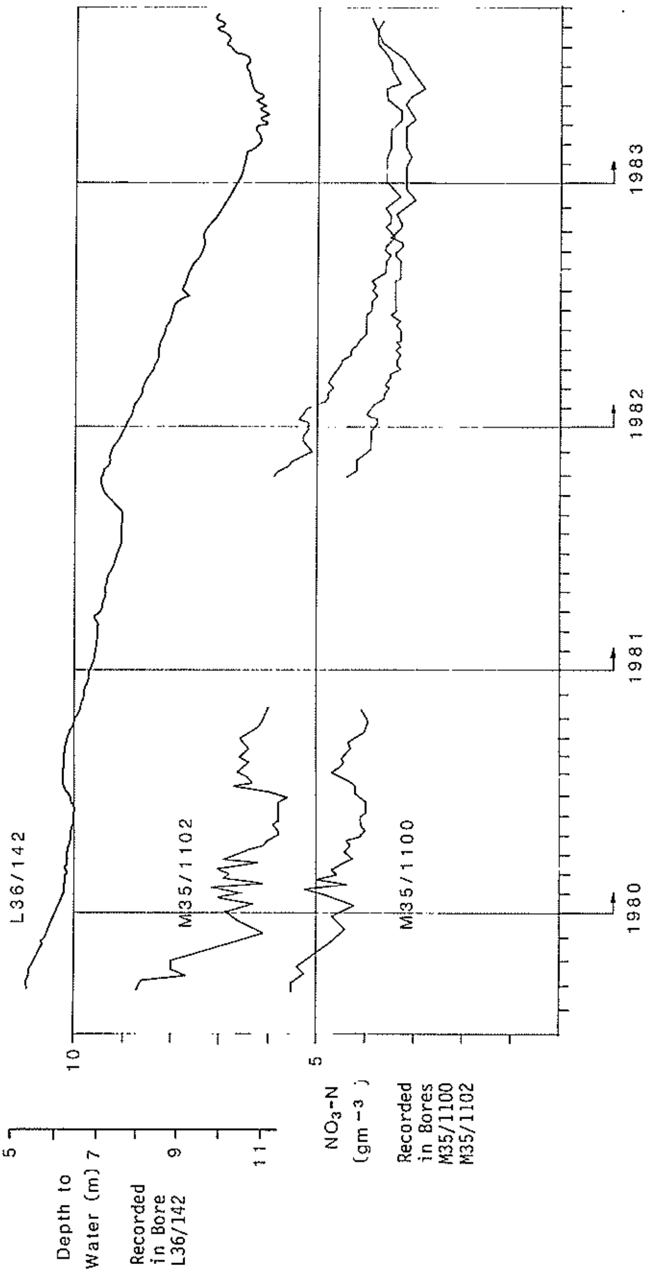

FIG. 6: Comparison of Nitrate-N concentrations in shallow Zone (2) groundwater, with variation in groundwater level for the period September 1979 to September 1983.

maintain and, where necessary, improve the quality of all waters" (Ward, 1984). This objective implies that effective legislative procedures exist to control any potential sources of contamination. In fact, the management tools incorporated in the Water and Soil Conservation Act are quite limited. Under the existing legislation, point sources of contamination can be regulated by way of the water right procedure. Non-point sources, however, cannot be directly controlled. The lack of legislative control over non-point sources has important ramifications for the management of Central Plains groundwater quality, because non-point sources contribute more than 90 percent of the nitrate load of Central Plains groundwater (Table 2). Planned irrigation of agricultural land may more than double the concentration of nitrate in groundwater (Bowden *et al.*, 1983). It is evident that zone (2) groundwater cannot be maintained at a potable level (<10 g m^{-3} NO_3-N) if non-point sources remain uncontrolled.

Zone (3) groundwater has remained in almost pristine condition despite widespread contamination of shallow groundwater (Fig. 5). Investigations to date indicate that further contamination of zone (2) groundwater is unlikely to penetrate beyond about 50–60 m below the water table. Zone (3) groundwater appears to be naturally protected from contamination by successively deeper layers of low-permeability alluvium. Deep groundwater is, therefore, likely to maintain a high level of water quality in the foreseeable future. This high quality groundwater could be tapped to provide reticulated supplies to households throughout the plains. A programme of reticulation could be initiated in the areas of zone (2) groundwater at greatest risk. Development of the programme could then follow in areas where nitrate-N levels are lower at present, but which can be expected to increase with increasing agricultural development. Reticulation would seem to be unnecessary in regions of zone (1) groundwater because of a large throughput of high-quality river water. Land-use intensification appears unlikely to significantly affect nitrate-N concentrations in zone (1) groundwater.

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