Potential for nitrate contamination of the unconfined aquifer at Cooper's Wells public water supply, Gore District.

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Potential for nitrate contamination of the unconfined aquifer at Cooper's Wells public water supply.

Executive Summary.

Following proposals for the sale of land surrounding Cooper's Wells for dairy conversion, the Gore District Council commissioned an investigation into the potential for contamination of groundwater drawn on by the public water supply bores locate there. An initial field visit by a hydrogeologist found that there to be potential for groundwater contamination arising out of urine deposition of dairy cattle and spreading of dairy shed effluent. Further investigation was authorised in order to assess risk to the groundwater quality posed by dairy conversion of the surrounding land surface through which rainfall percolates to the water table.

Investigation:
The investigation included:

- A pumping test at Cooper's Wells.
- Profiling river and water table elevations.
- Developing a groundwater flow model.
- Developing and calibrating a nitrate accumulation model.
- Forecasting the likely nitrate levels in groundwater following dairy conversion.
- Delineating the extent of the land surface contributing water to groundwater which is pumped at Cooper's Wells.

Findings:
Investigation findings can be summarised as follows:

- The aquifer at Cooper's Wells is found to rest in river gravels which are bounded on the underside and lateral margins by relatively impermeable lignite measures. The part of the aquifer, through which the bulk of groundwater would flow, is very thin by normal standards (about 3 to 4 metres).

- The aquifer is relatively unprotected from surface contamination. The absence of thick soils, or capping of clay or peat measures leaves the groundwater open to infiltration of water and contaminants from above.

- Groundwater flow on the flood plain aquifer has as its source rainfall infiltrating through pasture soil of the flood plain and terraces. On the north bank of the Mataura River the principal direction of flow is north-west towards the river. Groundwater leaves the aquifer as seepage to the river or is pumped to the surface at Cooper's Wells. All of the water
pumped at Cooper's Wells is originally rainwater which has infiltrated directly to groundwater. Such infiltrating groundwater will tend to leach nitrates from the soil as it passes through.

• The groundwater nitrate nitrogen concentration at Cooper's Wells is relatively stable at about 4 milligrams per litre at present.

• Nitrogen is always present in the soil. The soluble form of nitrogen, nitrate is known to leach through the subsoil to join groundwater. Once nitrate joins groundwater as a solute it persists and flows with the groundwater until it arrives at a depth greater than 40 metres (where reduction converts the nitrate to ammonium), or leaves the aquifer as seepage or pumpage.

• Nitrate nitrogen levels in drinking water in excess of 10 milligrams per litre can lead to health problems in humans, particularly infants. The Department of Health stipulates 10 milligrams per litre nitrate nitrogen as the guideline maximum concentration for drinking water.

• Intensification of agriculture is a well-known factor in increasing nitrate leaching to groundwater. This study follows many other researchers in assuming that the increase in nitrate concentration in leachate is a factor of ten higher for dairy pasture than for sheep pasture.

• Nitrate will tend to accumulate in an aquifer with insufficient capacity to buffer the inflow of water with elevated nitrate levels. The thinness of the aquifer at Cooper's Wells and high porosity are factors which may lead to a sharp rise in groundwater nitrate concentration if increased nitrate leaching occurs.

• Groundwater quality is said to "equilibrate" when the rise in concentration slows and stabilises to a level consistent with the concentration of inflowing sources. The degree of mixing with more dilute groundwater and surface water sources will determine the final equilibrium concentration. The groundwater pumped at Cooper's Wells appears to be presently at an equilibrium level of about 4 milligrams nitrate nitrogen per litre. This is consistent with an leachate concentration of 4.4 milligrams per litre estimated for sheep pasture which is the principal land use on the flood plain at present. The estimated leachate concentration for dairy pasture is 44 milligrams per litre.

• If a buffer zone of 24 hectares surrounding the Cooper's Wells were set aside in which no dairy herding was permitted, but the remainder of the groundwater catchment drawn on by Cooper's Wells were converted to dairy use, then the nitrate nitrogen concentration of drinking water sourced at Cooper's Wells would rise above the health threshold within 8 years. If land is converted to dairying to a greater areal extent than 120 hectares, then the pumped nitrate nitrogen concentration will exceed the
threshold at some point in time. If the conversions occur in close proximity to the bores then the impact may be experienced within the first year following conversion.

• Other users of the groundwater resource in the flood plain aquifer may be affected by a rise in the nitrate concentration in groundwater. Domestic bore users drinking the water may be exposing themselves to health risks should the groundwater at their bores rise in nitrate concentration beyond the health threshold. Users of bore water for stock water may expose their farm animals to levels above the 30 milligram per litre nitrate nitrogen limit beyond which toxicity effects should be expected.

• The source area for the 5000 cubic metres per day that is drawn at Cooper's Wells is estimated to be about 850 hectares. While the extent and location of boundaries to the source area are difficult to fix without further investigation, it lies approximately north of Cooper's Wells, and is about 860 to 600 metres wide by about 5 to 6 kilometres long.

• Measures can be taken to prevent nitrate contamination of the groundwater at Cooper's Wells. These generally involve controls on land use to exclude dairy conversion and intensive cropping (also known to induce elevated nitrogen leaching) over the land area contributing groundwater to Cooper's Wells.
Chapter One  Introduction.

1.1  Background.

Gore District Council operates a bore field drawing on shallow unconfined groundwater at a site named Cooper's Wells on the north bank of the Mataura River between the settlements of Whiterigg and Knapdale, north-eastern Southland. The District Council pipes the extracted water to a reservoir in East Gore where it is reticulated for drinking water supply. Some 60% to 70% of Gore's population of about 9000 receives drinking water sourced from Cooper's Wells. Since the end of the Second World War the provision of acceptable drinking water supplies in sufficient quantities to the people of Gore has been problematic (pers. comm. J. Fitzsimons, December 1993). In the 1970's Gore Borough Council opted for complete town supply with groundwater. Crucial to this strategy was the development of a bore field established in a back-filled dredge pond on the Cooper Family property near Whiterigg. This bore field named Cooper's Wells proved to be a high yield, reliable source of high quality groundwater. Two production bores were developed in 1979 and a further bore drilled and developed in the 1980's following the failure of one of the original bores. A nominal 58 litres per second (5000 cubic metres per day) is extracted by the combined pumping of both production bores. The bores are established in a shallow, unconfined flood plain gravel aquifer. This follows the pattern of the majority of groundwater bores in Southland (communication from I.K. Welsh, SRC reported in Smith et al, 1993). the unconfined nature of the aquifer and thin, porous nature of the overlying Recent soils represent a high potential condition for contamination of the groundwaters by a variety of environmental pollutants via surface infiltration.

There is a growing concern among regional water quality officers throughout New Zealand that groundwater beneath agricultural land is being contaminated with nitrates (Sinner, 1992). Far from being a unique problem, nitrate accumulation in groundwater from diffuse agricultural leaching is recognised world-wide in regions of intensive pastoral or cropping land use (Cameron, 1993). The mechanism of nitrate leaching to groundwater and the impacts on water quality of such contamination are detailed in the next chapter. However, it is relevant to providing background information on the situation to make the following points.

1) Intensification of agricultural land use is known to lead to increased leaching of nitrate to groundwater.

2) Pastoral land use change from sheep to dairy farming is known to increase nutrient loss by a factor of at least two in almost all cases (Steele, 1982) and as much as a factor of ten in some situations.

3) Land-based disposal of dairy shed effluent may lead to an increase in nitrate leaching to groundwater in some instances (Cameron, 1993).

4) Once leached from the subsoil (i.e. deeper than 450 centimetres) inorganic nitrate-nitrogen as a solute migrates through the unsaturated zone to the water table without further immobilisation or denitrification (Field et al, 1985).
5) In groundwater, nitrate is carried as a conservative solute by advective-dispersive transport in the direction of principal groundwater flow (Bear and Verruijt, 1987).

In Southland, dairy land use, land disposal of effluent and high densities of septic tank seepage are known to be correlated with elevated nitrate nitrogen levels in groundwater (i.e. over 10 mg/l) (communication from I.K. Welsh, SRC reported in Smith et al, 1993; and Robertson Ryder & Associates, 1993). The Southland Regional Council expects a rapid expansion in conversion to dairy units by an additional 255 separate units by 1997. This represents a doubling of the number of dairy units presently in production. This has raised concerns for further deterioration of already degraded water quality (Robertson Ryder & Associates, 1993). It is observed that catchments with a high proportion of dairying land cover show signs of rising levels of nitrate nitrogen in their groundwater (Robertson Ryder & Associates, 1993). Many of the expected new dairy units will be established on the Mataura Flood Plain north of Gore, which is favoured for its soil drainage properties (Dr P. Williams in Robertson Ryder & Associates, 1993).

The presence of elevated concentrations of nitrate ions in drinking water has serious implications to human health. Nitrate (NO₃⁻) can be reduced in the gastrointestinal tract to nitrite (NO₂⁻). Absorption of nitrite into the infantile bloodstream reduces the oxygen carrying capacity of the haemoglobin in young infants. This can lead to a condition known as methaemoglobinaemia or 'blue baby syndrome'. In some cases this condition has proved to be fatal. In addition, high nitrate concentrations in drinking water has been implicated with the formation of carcinogenic nitrosamines in the stomach and urinary tract. The Ministry of Health, Drinking water standards for New Zealand (Board of Health, 1989) sets the guideline limit for nitrate nitrogen at 10 mg/l and remarks that above this limit the health of infants is likely to be at risk. It has been recommended that stock water not exceed 30 mg/l nitrate nitrogen because of the toxicity risk to farm animals (Smith et al, 1993).

The coincidence of future increased accumulation of leached nitrate in the Mataura Flood Plain aquifer and a public water supply which draws on that groundwater resource leads to a potential resource conflict over groundwater quality. The purpose of this investigation is to assess the groundwater flow system and the potential for diffuse contamination of the groundwaters by nitrate nitrogen. In particular, the investigation will focus on the Mataura Flood Plain aquifer on the north bank of the Mataura River between Whiterigg and Knapdale.
Figure 1.1 Location map of the northern Gore District showing Cooper's Wells and principal localities.
1.2 Study Objectives.

This investigation aims to develop an understanding of the hydrogeology and geochemistry of the Mataura Flood Plain aquifer along the following lines:

- Groundwater flow dynamics; source and fate of groundwater plus solutes.
- Projecting progressive accumulation of nitrate in natural water; the potential for diffuse contamination of the aquifer as a result of induced nutrient loss.

This information is used to evaluate the threat to groundwater quality and to predict future trends in water quality of groundwater extracted at Cooper's Wells and the flood plain aquifer in general.

1.3 Methodology.

Several data gathering techniques were used in the course of this investigation. Initially, a literature search was carried out to locate information relating to groundwater contamination by nitrate in New Zealand and Southland. This was followed by enquiries with Gore District Council and Southland Regional Council for information pertinent to the hydrology and groundwater chemistry. This included a re-interpretation of a 1979 pumping test undertaken at Cooper's Wells. A field visit was made and a new pumping test was carried out to compare with the previous test.

Two principal avenues of data analysis were used. Firstly, the source and fate of the aquifer's groundwater (plus any solutes) needed to be established. A computer groundwater flow model was used to assist in estimating the flow pattern. Analytical flow field calculations were used to estimate the physical extent of the capture zone around the bores at Cooper's Wells. Secondly, solute mass balance calculations were undertaken to approximate steady state nitrate leaching rates to groundwater. These values were coupled with an analytical model for calculating pumped concentration of groundwater as a function of time, thereby estimating the progressive change in nitrate concentration resulting from a change in land use. The groundwater flow model and quality models coupled, give the basis for possible water quality protection measures of the groundwater used by Gore District Council and others.

Possible measures for mitigating the impact to groundwater quality are evaluated and alongside their costs and alternatives.

1.4 Physical Setting and Hydrogeology.

The Matuara River flood plain lying north of Gore Between Whiterigg and Knapdale is contained in a valley flanked on the south-west by the foothills of the Waterfall Range, and on the north-east by low hills crested by Pinnacle Road. Upstream, the valley opens out and extends into the Waimea Plains. To the south on the downstream side, the valley pinches in to confine the Mataura River within the structural high of the
northern limb of the Southland Syncline. The flood plain is approximately three kilometres wide at Cooper's Wells. Figure 1.1 shows the infrastructural setting and the location of Cooper's Wells.

1.4.1 Hydrology.
The Mataura River is the principal drainage for the flood plain. Measured at Gore Bridge, the Mataura River has a mean flow of 76.1 cubic metres per second supplied by an extensive upstream catchment. Flood flows in the Gore area are estimated for the Mataura River as 2000 cumecs or more. Low flows generally occur in late summer and autumn with one of the lowest recorded modern low flow events being 8.7 cumecs on 18 March 1978 (Southland Catchment Board, 1984). Gold Creek is a perennial water course which drains the hills and terraces south of the Chatton-Maitland Road and much of the flood plain's north bank before discharging to the Mataura River 2.5 kilometres upstream of Gore. Gold Creek is either meandering or channelised for much of its course over the low terrace and flood plain. Gold Creek has several tributaries and distributaries which provide drainage for the first terrace above the Recent flood plain surface. No discharge information is available for Gold Creek.

Precipitation is measured as being on average 800 millimetres per year on the Mataura Flood Plain (Southland Catchment Board, 1984). By steady state estimation using measured precipitation and cumulative river discharge, evaporation is estimated at 596 millimetres per year (Southland Catchment Board, 1984). Therefore, on the parts of the Mataura Flood Plain where runoff is negligible, effective precipitation to groundwater could be estimated at about 200 millimetres per year.

1.4.2 Geomorphology.
The Mataura Flood plain is a ribbon surface which slopes sympathetically with the present Mataura river-bed. Terraces are observed on the north side of the Mataura miver (McIntosh et al, 1990). Terrace 1 is found some two metres higher than the flood plain surface and has wide coverage between the flood plain and the Gore-Chatton Road. Observation of the degree of interconnected porosity for the flood plain and terrace gravels indicate abundant large pores in the 1 - 5 millimetre range. Hummocky raised surface feature found east of the Knapdale Homestead are the result of the Pleistocene deposition of aeolian sediments containing silty loess which formed coalesced dunes (McIntosh et al, 1990). These have significance for groundwater hydrology by acting as a barrier to vertical infiltration of precipitation.

1.4.3 Soils.
The distribution of soils on the north bank of the Mataura Flood Plain is to a certain extent governed by the position on the flood plain surface and terraces. The Mataura silty loam covers much of the lower flood plain surface. Gore stony silt loam and Fleming silt loam occupy the upper flood plain surface and terraces (McIntosh, 1992). These soils are classed as excessively drained and slowly accumulating in the case of the Mataura soils, and imperfectly drained in the case of the Fleming soils (McIntosh, 1992).

1.4.4 Geology.
The Gore district has as its lowest exposed basement lithologies the Triassic-Jurassic tuffaceous indurated siltstone / greywacke on the south side of the Mataura Flood Plain,
and Permian argillites and siltstones (Wood, 1966). Infilling the structural contact and depression between the two structural blocks are Tertiary lignite measures of Miocene age (Issac and Lindquist, 1990). The lignite measure form the floor of the Mataura Flood plain from Gore to Knapdale. West of Knapdale, a fault provides structural control causing Permian siltstones to outcrop in places, but mostly covered with a gravel veneer. Over these pre-Quaternary rocks a veneer of Pleistocene-Holocene gravels form the terraces and flood plain surfaces. These gravels contain the aquifer which is the subject of this investigation.

1.4.5 Geohydrology.

The Mataura Flood Plain aquifer rests in Pleistocene-Holocene gravel deposits. The gravels are made up of Recent deposits which formed the bedload of the Mataura River, and the terrace gravels deposited during the outwash phase of the first Otiran glacial period stadial (McIntosh et al, 1990). The lignite measures provide the geohydrological basement for the aquifer, being relatively impermeable at the contact with the gravels.

The Mataura River is cut into the aquifer and in direct hydraulic communication with it. The static groundwater level at Cooper's Wells was measured in February 1979 as being 2.3 metres below ground level or about 76.3 metres above mean sea level. Officers of the Gore District Council have observed that groundwater levels at Cooper's Wells fluctuate mildly with river level (per. comm. Allan Booth, January 1994) leading to deeper drawdowns at lower river flows. Contouring of river profiles and cross sections indicate that the static groundwater level at Cooper's Wells is at least 1.2 metres above that of the Mataura River at its closest point to the production bores (some 600 metres distant from the river). The conceptual model for the groundwater flow system on the north bank of the Mataura Flood Plain places the predominant groundwater flow direction from north to south where the groundwater eventually discharges to the Mataura River. The principal source of groundwater is precipitation infiltrating through the soils of the flood plain and terrace surfaces.

A pumping test carried out at Cooper's Wells in 1979 derived a coefficient of permeability about 300 metres per day using the pumped bore recovery and Theis curve fitting methods. However, when piezometer measurements in three compass directions (not north) were interpreted and their respective coefficients of permeability calculated, the comparison showed a match of 300 m/d only in the southern direction. The infilled dredge channel is oriented north-south and so the 300 m/d level of permeability is likely to reflect the influence of higher porosity in the gravel backfill. A coefficient of permeability on the order of 150 m/d is calculated for piezometer measurements taken 50 metres to the east. This level of permeability is interpreted to reflect more that of the undisturbed gravel aquifer. Details of the pumping test interpretations can be found in Appendix 1.

1.4.6 Water Chemistry.

Analyses of groundwater sourced from Cooper's Wells have been found to have a nitrate nitrogen concentrations as being 4.2 mg/l in 1979 and 3.9 mg/l in 1992 (DSIR Chemistry, 1992). Nitrate nitrogen measured in the Mataura River at Otimita and Gore give mean concentrations of 0.42 and 0.40 mg/l respectively (Southland Catchment Board, 1984).
Chapter Two  
Nitrate Accumulation in Groundwaters.

2.1 Links to Agricultural Practices.

Recognition of the linkage between intensification of agriculture and elevated nutrient loss was initially made following discovery of the eutrophication problem in surface water bodies with low flushing rates and an intensively cultivated and/or fertilised upstream catchment. Attempts at defining and remedying the symptoms of nutrient loss led to progressively more refined studies into the causes. Concurrently, the impact of major intensification in cultivation experienced throughout the developed world for the latter part of this century resulted in nitrate enrichment of many groundwater supplies. Subsurface nitrate contamination first gained attention as pollution of economically important potable water sources. In the United States, despite a massive injection of research funds into pinpointing and remediating industrial point-source groundwater contamination, a greater number of drinking supply wells have been abandoned through agriculture induced nitrate contamination than the total number of wells closed by the discovery of industrial microcontaminants. Subsequently, nitrate accumulation in groundwater was recognised as a vector for solute transport to vulnerable surface water bodies. Accordingly, one revealing indicator of the water quality stress on the ecosystem in an agricultural area is the level of nitrate in shallow groundwater. Aquifers polluted by diffuse leaching of nutrients, particularly nitrate, represent a large, steady discharge reservoir for nutrients. Once ambient nitrate levels have risen to a point as a result of agricultural intensification it takes many years for levels to drop back to original concentrations, even if it were possible to effect a complete halt to elevated nitrate leaching.

2.1.1 The New Zealand situation.

In New Zealand there has been a small amount of research into leaching rates of nitrate through agricultural soils. These studies are summarised by Cameron (1993). The impact of nitrate entry into groundwater was summarised by Burden (1982), including some discussion of saturated zone processes and practicable alternatives where drinking water supplies have been affected. Elevated nitrate levels are recorded in shallow, unconfined groundwater underlying agricultural land in almost every instance that they are monitored (Thorpe et al., 1982; Bowden et al., 1982; Talbot et al., 1986; Hoare, 1986; Dewhurst, 1981; Burden, 1980; Adams et al., 1979; Brougham et al., 1985; O'Dea, 1980; O'Shaughnessy and Hodges, 1992; and Bird, 1987). Recognition of large scale nitrate accumulation in groundwater supplies used for communal or private drinking water has been made for the Waimea Plains, Nelson region (Dicker, Fenemor and Johnston, 1992) and the Hamilton Basin, Waikato region (Hoare, 1986). In both cases the land overlying the aquifers had been intensively cultivated for many years. Interestingly, in the case of the Waimea Plains, the highest nitrate levels (over 30mg/l) were found in confined and semi-confined aquifers while the unconfined aquifer showed quite low nitrate levels. The explanation for the reverse to the usual pattern appears to lie with the source and rate of flow of the respective aquifers. It appears that the confined and semi-confined aquifers derive their recharge from infiltration of precipitation through soils used for market gardening and flow velocities are less than 1 metre per day, while the unconfined aquifer is principally recharged by river water and flows at a much faster 6 metres per day (Dicker, Fenemor and Johnston, 1992).
In Southland, observations have also been made of elevated nitrate levels (> 10 mg/l) in groundwater at the lower Oreti / New River and Oteramika catchments (Robertson, 1992; and Robertson Ryder & Associates, 1993). In both cases land use is characterised by moderate to high dairy farming activity. From what is known, it appears the vulnerability of Southland's groundwater resources is exacerbated by the generally thin, unconfined aquifers and flow pattern, although very little information is yet available on the region's hydrogeology.

2.1.2 Estimates of nitrate leaching.

Nitrogen balances for various agricultural activities have estimated the loss of nutrients as runoff and leaching to groundwater (e.g. Dr P. Williams in Robertson Ryder & Associates, 1993). Direct measurements of leaching losses have been carried out using sampling of tile drain effluent (Mohammed et al, 1987), soil water extraction (Steele et al, 1984), and isotope labelled urine applied to lysimeters (Cameron and Fraser in Cameron, 1993). These studies give data on the level of nitrate leaching associated with various agricultural practices. These studies in general make the following points:

1) Cattle herding provides twice the amount of nitrogen to the pasture than sheep farming (1000 kg/ha/yr compared with 500 kg/ha/yr for sheep) (Steele, 1982).

2) The amount of nitrate leached through the subsoil can be as much as ten times as high for cattle as for sheep (compare 88 kgNO₃-N/ha/yr from Angus steers with 8.3 kgNO₃-N/ha/yr from sheep urine applied at 500 kgN/ha/yr) (Steele et al, 1984; and Cameron and Fraser in Cameron, 1993; respectively).

3) Dairy shed effluent applied to pasture at rates less than 150 to 200 kgN/ha/yr should be capable of being utilised by the pasture and not induce additional leaching (Cameron and Rate, 1992).

4) The greater the recharge flux through the subsoil, the greater the leaching of nitrate into the groundwater (although at a given recharge intensity the leachate will become more dilute).

Nutrient balances undertaken for Southland suggest a nitrate nitrogen leaching rate of between 73 to 95 kgNO₃-N/ha/yr for dairy units (Dr P. Williams in Robertson Ryder & Associates, 1993), the comment is also made that these estimates appear conservative when compared with those for Waikato, Taranaki and Manawatu (94 to 190 kgNO₃-N/ha/yr).

This study adopts the nutrient leaching rate of 88 kgNO₃-N/ha/yr for dairy pasture and 8.8 kgNO₃-N/ha/yr for sheep grazed pasture. No leaching input is added for dairy shed effluent since a regional guideline total nitrogen input limit is set for effluent spreading by way of a rule to require dairy units to have pasture sufficient to spread at a density not greater than 8.2 hectares per 100 shedded cattle. This rule is intended to have the effect of placing a de facto limit of 150 kgN/ha/yr on dairy shed effluent contribution. Taking point 3) above into account it might be supposed that this leads to zero net increase in nitrate nitrogen leaching. However, should the effluent be overly dilute, excess quantities of infiltration water may exceed the soil's field capacity leading to increased leaching. Timing of effluent spreading may also influence rates of leaching, particularly during periods where the soil
is near its field capacity. For this reason spreading is prohibited during winter in Holland and Belgium. Dairy-associated point source discharges such as whey irrigation or land-based milk dumping during industrial disputes may lead to additional leaching. Hoare (1986) estimates the nitrate leaching impact on groundwater quality of dairy factory irrigation wastes to be equivalent to an additional 500 hectares of dairy pasture for the Hautapu dairy factory in the Hamilton Basin, Waikato region.

2.2 Transport in Groundwater.

Once dissolved inorganic nitrate has passed through the subsoil it is assumed that no further immobilisation or denitrification occurs during its passage through the unsaturated zone to the groundwater surface (Field et al., 1985). Field trials on nitrate transport in the unsaturated zone undertaken on the Heretaunga Plains, Hawkes Bay (Thorpe et al. 1982) found no evidence for attenuation of nitrate in the unsaturated zone.

2.2.1 Processes in the saturated zone.

Once in the saturated zone, the nitrate solute is reasonably conservative, although subject to biological processes in some defined situations. Assimilatory ammonification is the reduction of nitrate to nitrite and ammonia (NO₃⁻ → NO₂⁻ → NH₄⁺) by an anaerobic metabolic reaction mediated by subsurface micro-organisms in environments where organic matter is abundant. This has been observed to occur where groundwater passes into confined pressure conditions and the waters become anaerobic (Devlin et al., 1990). Assimilatory ammonification is a reversible process by way of an oxidation metabolis called nitrification, nitrate may re-enter in an aquifer by nitrification when conditions become aerobic once more. Observations of the assimilatory ammonification process have been made in the Heretaunga Plains aquifer, Hawkes Bay where oxygen-rich recharge-derived groundwater flows across of the unconfined / confined transition zone (Thorpe et al., 1982). This is the probable explanation for nitrate contamination of groundwater being a mainly shallow unconfined phenomenon and not being commonly observed lower than thirty or forty metres below ground level (see for example; Smith, 1993). Denitrification, the conversion of nitrate or nitrite to nitrogen gases (NO₃⁻/NO₂⁻ → N₂), is a non-reversible bacterially mediated reduction requiring nitrate or nitrite, labile organic carbon and denitriifying bacteria. Starr and Gillham (1993) observed denitrification occurring in Ontarian unconfined aquifers with the water table lying very close to the surface no deeper than 2 metres below ground level). Neither of these processes are commonly observed to occur in unconfined aquifers with the water table deeper than 2 metres and their base shallower than 30 metres below ground level. In most studies nitrate nitrogen is treated as a conservative anion (i.e is unaltered by in situ processes). This study considers no removal from the aquifer of nitrate nitrogen once it has leached through the subsoil.

2.2.2 Retardation factors.

Nitrate nitrogen is transported advectively as a solute with the groundwater flow. Dicker, Fenemor and Johnston (1992) observed the 15 mgNO₃-N/l isochem arriving at the Richmond urban supply well no. 4 in 1986 following a steady rise from 2.5 mg/l in 1968. They calculate an average velocity of 0.7 metres per day based on the crossing of the nitrogen fronts. However, for the same aquifer and location, a faster flow velocity of 0.92 m/d is reliably calculated by independent hydrodynamic methods. These observations may
allow an inference or retardation of nitrate flowing with the groundwater on the order of about 20%. This study does not consider retardation of nitrate since forward modelling is long-period and because any estimated retardation factors would lie within the bounds of uncertainty already present in the modelling.

2.2.3 Dispersion.
Nitrate nitrogen travels as a solute in groundwater by advective transport. Nitrate as also subject to dispersion leading to mixing of groundwater and solutes at different concentrations. Dispersion occurs at a hydro-mechanical and a molecular level both having the effect of spreading the concentration gradient out across, and parallel to, the path of flow (Bear and Verruijt, 1987). When hydrogeologists consider discrete plumes of contaminated groundwater, dispersive mechanisms are highly significant in defining the level of contamination at any given point, especially at the margins of the plume. However, when considering diffuse contamination where widely distributed sources enter the groundwater continuously at low concentrations, dispersive mechanisms simply ensure that the aquifer is well mixed and that concentration gradient is not steep (i.e. few hot-spots). Therefore, in a highly dispersive aquifer, ambient contamination levels will take some time to rise significantly and an equally long time to fall (if contamination can be halted). This study uses longitudinal dispersivity (4.7 metres) and transverse dispersivity (2.0 metres) for Pleistocene gravels from contamination potential field trials on the Heretaunga Plains (Thorpe et al., 1982).

2.2.4 Advective transport velocity.
Advective transport of nitrate nitrogen proceeds at a rate determined by the following equation:

\[
\nu = \frac{K}{n_e} \cdot \frac{dh}{dx}
\]

\(\nu\) = Advective velocity (m/d)
\(K\) = Permeability (m/d)
\(\frac{dh}{dx}\) = Hydraulic gradient (m/m)
\(n_e\) = Effective porosity (% or as decimal)

Therefore, groundwater flowing in highly permeable, highly porous media at high hydraulic gradients will flow at high velocities. Porosity has the lowest occurring variability (0.01 to 0.40) and so has the lower degree of uncertainty. Porosity can be estimated from the specific yield derived from a pumping test (Devlinny et al., 1990). Permeability can be measured in pumping tests and hydraulic gradients can be calculated from measurements of head throughout the aquifer. This study uses permeability, porosity and hydraulic gradient values from pumping tests and field observations of head in the aquifer.

2.2.5 Nitrate accumulation rates.
The rate of nitrate accumulation in an aquifer is determined by its flow characteristics and the input of nitrate into the saturated zone (the so-called Source-Fate-Dilution consideration). The saturated thickness of the aquifer has a bearing on volume of dilution water available to buffer the entry of nitrate. The thinner the aquifer, the less the buffering. Effective porosity also determines the volume of interconnected groundwater available for
diluting the incoming nitrate (e.g. if in an unconfined aquifer effective porosity is 0.20, then 20% of the total aquifer volume is aqueous and accessible to solutes). Eventually, if conditions of flow and nutrient loss are stable (on the wavelength of several years) the nitrate concentration will equilibrate to a level determined by the concentration of the diffuse leaching and any diluting water entering the aquifer simultaneously.

For example, if a hypothetical aquifer can be considered; having low saturated thickness, high porosity, high permeability and high flow gradients. Consider also the presence of newly established extensive dairy herding over all of the upstream (groundwater) infiltration catchment leaching nitrate at a concentration ten times the present stable concentration (say, a change in leaching from 4 to 40 mgNO₃-N/l). The aquifer is also recharged with a dilute source or surface water by stream infiltration. Given also that the volume of high nitrate recharge is 9,000 cubic metres per day, the stream recharge is 1,000 cubic metres per day and up to 1,000 cubic metres per day is pumped from the aquifer for stockwater. After ten years the aquifer nitrate nitrogen concentration should be in equilibrium and the concentration measured in sampling at almost any point in the aquifer should be about 36 mg/l (i.e. 40 mg/l minus 4 mg/l due to stream recharge dilution). At this point, the groundwater might be declared unfit for stockwater (the guideline limit is presently 30 mgNO₃-N/l) and the stream might be abstracted or diverted to meet the shortfall. The direct consequence of this loss of dilute recharge would for nitrate levels to rise again to 40 mg/l. Water bodies receiving groundwater seepage would experience a rising nitrate concentration as the groundwater seepage component of stream flow increased in concentration and quantity (as a consequence of reduced pumping). This situation would be exacerbated in transient low flows and water shortages when groundwater would contribute a greater portion of baseflow, and subsurface inflow could in fact increase due to lowered base level. In this situation the nitrate concentrations of both groundwater and surface water throughout the catchment might be at critical levels with respect to public health. While this is the worst case scenario, it follows the pattern of steady elevation in the background concentration leading to persistent contamination of water sources observed in many intensively farmed catchments overseas (Burden, 1982).
Chapter Three  Groundwater Flow.

3.1 Estimation of Flow Pattern.

Few bores or observation wells have been drilled in the Mataura Flood Plain aquifer and so there is little information on the distribution of heads or flow pattern. This leads to difficulty in accurately defining the flow pattern with the flood plain aquifer. One option to a hydrogeologist when investigating the flow pattern is to use a numerical groundwater model. While uncertainty remains as to the precise flow pattern in the aquifer and such a model should not be used slavishly, the model can assist in defining approximate flow rates and relationships to certain features.

3.1.1 Conceptual model.
The relative elevation of the water table at Cooper's Wells above the mean river level precludes the possibility that the Mataura River is a major contributor of groundwater recharge to the aquifer drawn on at Cooper's Wells. Accordingly, the conceptual model for groundwater flow in the Mataura Flood Plain aquifer recharge is then infiltrated precipitation. This model is consistent with the water chemistry recorded for groundwater at Cooper's Wells and the Mataura River (see 1.4.6) which suggests that groundwater is recharged by an elevated nitrate source such as leaching from sheep grazed pasture (see chapter 4 for correlation).

3.1.2 Computer groundwater flow model.
A computer groundwater flow model is used to assist in integrating the complex potential field factors of groundwater flow in a manner consistent with the above conceptual model. The model chosen for this simulation of flow pattern is a two-dimensional finite difference model code named Aquifer Simulation Model (ASM) (Kinzelbach and Rauch in Kinzelbach, 1986). The model is used in steady mode throughout the modelling procedure.

3.1.3 Model simulation of flow pattern.
The model domain is a rectangular area 4000 metres wide to the east and 5000 metres long to the north, straddling the Mataura River above Gore. The block centred finite difference model network is made up of less than 2000 cells that are 100 x 100 metres in size. It is considered that the head pattern in the aquifer follows the slope of the land surface at some 2 to 3 metres below ground level. Therefore, the far field specified head boundary cells are set at approximate water table elevations estimated from the land surface elevation. No-flow boundaries are assigned to the physical contact of the flood plain gravels with the lignite measures or undifferentiated, deeply weathered gravels on the eastern margin of the aquifer. River cell elevations are set according to a benchmark water elevation measured at Gore bridge (pers. comm. Noel Hinton, SRC, January 1994) cumulatively multiplied upstream by average gradients taken from river long-sections (Southland Catchment Board, 1974). River elevations are checked using cross sections surveyed in 1985. A coefficient of leakage simulating the conductance of the river with the aquifer is set at 1.0 initially.

This framework provides the basic flow-field information for the computer model. A well cell is added to the model framework in order to simulate the pumping of Cooper's Wells
at a rate of 5100 cubic metres per day (59 l/s). Permeability information is taken from the pumping test of 1979 by assigning 150 metres per day to the majority of the aquifer. Recharge is set at 0.57 millimetres per day for the entire model domain. The model is calibrated using head measurements from bore at Cooper's Wells and one at McDowell's Borehole. These head measurements are only available in the lower part of the north bank of the flood plain aquifer. During calibration specified head boundary elevations and positions were altered, as were river conductances (to 0.02 finally).

Figure 3.1 A diagram of the model framework used in the ASM groundwater flow model. Dimensions and scale are given by the vertex co-ordinates in metres east and north (map 260 Infomap series F45) for this 4000 x 5000 metre model domain. The grid network of cells is 100 x 100 metres in size. The localities of Whiterigg and Gore are marked on the diagram for reference. Diagrams of water table elevation and recharge zone follow this framework in scale and borders.
The model framework as illustrated above with the described parameters is run to give an approximation of the groundwater flow pattern. Figure 3.2 shows the water table elevation contours derived in the model solution.

Figure 3.2 Contour map of water table elevations derived by ASM model solution.
Chapter Four  Nitrate Accumulation Calculation.

4.1 Model Input.

Nitrate accumulation calculations take the form of steady state (equilibrium) formulation of model values and parameters, and time series modelling of nitrate accumulation in the aquifer. The nitrate accumulation model is a set of analytical calculations compiled on a computer spreadsheet programme. The model is intended for prediction of nitrate level in pumped groundwater as a reconnaissance tool (Lerner and Papatolios, 1993). A number of simplifications need to be made in using the model and steady state input values are used. However, spatial and temporal processes, are possible using pre-calculations of nitrate input rates for defined infiltration areas and superposition of simultaneous calculations (Lemer and Papatolios, 1993).

4.1.1 Nitrate Leaching Rates.

As outlined in Chapter 2, nitrate leaching rates have been estimated for different pasture land uses. This study uses 88 kgNO₃-N/ha/yr for dairy herding and 8.8 kgNO₃-N/ha/yr for sheep farming on downlands as the reference nitrate leaching rates. Average leaching rates such as adopted above can be converted to leachate nitrate concentration by dividing by the average recharge rate. In the case of the Mataura Flood Plain aquifer, 200 millimetres per year has been estimated as the recharge rate to the aquifer from precipitation. The following equation derives the concentration:

\[ C = \frac{m}{Q} \]  
\[ C = \frac{8800}{2000} \]
\[ = 4.4 \text{ g/m}^3 \]

Given:
- Annual nitrate leaching = 8.8 kg/ha
- Mass of nitrate leached = 8800 (g/a)
- Annual recharge, 1 hectare = 2000 m³

The concentration of 4.4 mg/l derived above is co-incidentally close to the concentration measured in groundwater pumped from Cooper's Well (3.9 mg/l). The predominant land use in the upstream (groundwater) catchment is sheep farming which suggests that the aquifer may be entirely recharged by infiltration through pasture, and be in equilibrium with respect to nitrate accumulation at present. The leachate concentration for dairy herding can be calculated by the same method.
Given:

- Annual nitrate leaching = 88 kg/ha
- Mass of nitrate leached = 88000 (g/a)
- Annual recharge, 1 hectare = 2000 m³

Nitrate concentrations in the flood plain aquifer might be expected to equilibrate at a level just below 44 mg/l following full mixing and assuming complete coverage of the upstream catchment by dairy units. The above nitrate concentrations are used in time series modelling of nitrate accumulation.

4.1.2 Hydrological zonation.

The nitrate accumulation model for determining pumped concentration at Cooper's Wells can be differentiated spatially by specifying zones of the inflowing groundwater, and hence the timing of its inflow and extent of the infiltration area. Since this study has demonstrated that the source of groundwater drawn by Cooper's Wells is wholly infiltration through pasture, the zonation of the aquifer is simplified. See figure 4.1 for illustration of ideal aquifer zonation.

Figure 4.1 Zonation of an ideal unconfined aquifer pumped by a single well. The t₁ isochrone (line marking flowline starting points of equal travel-time from a pumped well) divides zone A₁ from zone A₂. Each zone receives recharge, Rₚ, and a certain nitrate concentration, Cₚ. The well pumps at a rate, Q, and the water pumped has a concentration, Cₚ. Zonation of the aquifer by this scheme allows superposing of equations defined by isochrones (Lerner and Papatolios, 1993).
The above zonation scheme is applied to the inflow region of Cooper's Wells in order to allow for a buffer zone around the production bores. The radius of a buffer zone described by the 60 day flowline isochrone has been calculated using an analytical model code named Pathlines and Traveltimes (PAT) (Kinzelbach and Rauch in Kinzelbach, 1986). Using a coefficient of permeability of 150 m/d, porosity of 20%, and a hydraulic gradient of 0.2%, the radius of the 60 day zone was calculated to be 280 metres eccentrically centred slightly upgradient of Cooper's Wells along the axis of flow. The $A_1$ zone has an area of 24.6 hectares while the second zone (including all of the infiltration surface upstream of the 60 day isochrone), $A_2$ has an areal extent of many hundreds of hectares.

4.2 Model Formulation.

The nitrate accumulation model is formulated to the scheme set out by Lerner and Papatolios (1993). The basic equation is as follows:

$$C_p = C_o + (C - C_o) \left[ 1 - \exp\left( -\frac{R \cdot t}{b \cdot n} \right) \right]$$  \hspace{1cm} (3)

Where:

- $C_p$ = Pumped concentration (g/m$^3$)
- $C_o$ = Initial concentration (g/m$^3$)
- $C$ = Leachate concentration (g/m$^3$)
- $R$ = Recharge (m)
- $t$ = Time, isochrone (d)
- $b$ = Saturated thickness (m)
- $n$ = Effective porosity (% or decimal)

This basic equation can be superposed with others to simulate non-uniform recharge and concentration. The following equation was developed for the Cooper's Wells situation to simulate the effect of a buffer zone:

$$C_p = \left\{ C_o + Q + Q( C_o - C_1 ) \left[ 1 - \exp\left( -\frac{R_1 \cdot t}{b_n} \right) \right] \right\} / Q$$  \hspace{1cm} \text{zone } A_1, \ 0 < t \leq t_1

$$C_p = \left\{ C_1 \cdot R_1 \cdot A_1 + C_0 \cdot Q'_2 + Q'_2 ( C_2 - C_o ) \left[ 1 - \exp\left( -\frac{R_2 \cdot (t - t_1)}{b_n} \right) \right] \right\} / Q$$  \hspace{1cm} \text{zone } A_2, \ t_1 < t \leq t_2

Where:

- $A_1$ = Area pumped within $t_1$ (m$^2$)
- $Q$ = Pumped discharge (m$^3$/d)
- $Q'_2$ = $Q - R_1 A_1$
The following equations are complied on a computer spreadsheet for ease of computation. The $t_i$ time step is set at 60 days. After 60 days $C_p$ from equation (4b) holds, up to that point equation (4a) applies and both equations are run simultaneously. For this study long term trends hold more interest, so the results of equation (4b) are more pertinent.

4.3 Model Calibration.

Calibration of the model is necessary before nitrate accumulation can be modelled in forward mode (prediction mode). The model is first assessed for sensitivity to change in the input parameters. Out of this sensitivity analysis it appears that changes to the parameters of outer zone recharge, saturated thickness and effective porosity display the greatest sensitivity when nitrate concentrations are held constant. These input parameters are not known with any great certainty since they pertain to average, distant conditions for which there are only estimated values. Therefore it is thought appropriate to adjust these parameters within plausible limits during calibration.

Only one feasible calibration data set can be used. A rise in nitrate concentration has occurred as a result of pastoral land use following the onset of European settlement. An intensification in sheep farming would be expected at about the 1920's due to mechanised transportation, among other factors. Between the 1880's and 1920 a steady rise in nitrate leaching could also be expected at a lower rate. Assuming an initial nitrate nitrogen level of 2.5 mg/l in 1920 and applying a leaching rate of 8.8 kgN$_2$O$_3$-N/ha/yr, the nitrate nitrogen concentration of 3.8 mg/l is reached after 60 years. This is close to the concentration measured at Cooper's Wells in 1979 when pumping was initiated. Equilibrium may have been reached at the present time since the nitrate nitrogen concentration measured in 1992 was 3.9 mg/l. During the calibrations, average saturated thickness is adjusted to 2 meters and average porosity is adjusted to 0.03 (30%) during calibration.

Now calibrated, the model can be used to predict the rise in nitrate concentration as a result of dairy conversion of the upstream (groundwater) catchment.

4.4 Model Predictions.

The nitrate accumulation model is used to assess the impact of dairy conversion in the recharge zone to the groundwater pumped at Cooper's Wells. In doing so, the earlier calculated nitrate concentrations for dairy land use (see 4.1.1) are used as input parameters.

4.4.1 Total dairy conversion of recharge zone, plus buffer zone.

Several assumptions and simplifications need to be made in setting simulation parameters. Firstly, recharge and nitrate concentration used as input are constant. Recharge is set as 0.6 mm per day for both zones. Nitrate concentration is held at 4.4 mg/l for the inner zone on the assumption that a 24 hectare buffer zone is set aside under sheep farming alone. The outer upstream zone is given a nitrate leaching concentration of 44 mg/l (see 4.1). This assumes that the total upstream catchment is converted to dairy production. Secondly, the
model assumes constant pumping at Cooper's Wells. This is close to the real situation at Cooper's Wells since the aquifer is pumped at an average discharge between 58 and 59 litres per second (5000 to 5100 m/d).

Figure 4.2 shows the modelled rise in nitrate nitrogen levels as a result of induced nitrate leaching from dairy pasture. The groundwater source will become unusable for public water supply after about 8 years following dairy conversion. Near equilibration of nitrate input with aquifer concentration (43 mg/l) will be achieved 150 years after dairy conversion using the above model and input.

![Diagram](image.png)

**Figure 4.2** A plot showing the predicted nitrate accumulation curve for groundwater pumped at Cooper's Wells following total conversion of the catchment's pasture to dairy. The upper health guideline limit for drinking water (Board of Health, 1989) is exceeded after 8 years following dairy conversion of the recharge zone upstream of Cooper's Wells. A 24 hectare buffer zone is included as described by the 60 day travel-time isochrone which tends to retard nitrate accumulation.

### 4.4.2 Single dairy unit in close proximity.
The next scenario to be investigated involves dairy conversion of only one dairy unit in close proximity to Cooper's Wells. This hypothetical dairy unit is 60 hectares in size with a herd size of 180 cows. The average pasture nitrate leaching rate is again assumed to be 88 kg/ha/yr with an infiltration concentration of 44 mgNO$_3$-N/l. The outer zone infiltration nitrate concentration is assumed to remain unchanged from the predominant sheep farming level of 4.4 mg/l. Pumping continues at a rate of 5100 m/d and recharge is set at 0.6 mm/d for both zones. The nitrate concentration rises to about 7.2 mg/l and achieves equilibrium within the first year following dairy conversion (i.e. annually, 5200 kg NO$_3$-N leaches into 1.86 Mm$^3$ groundwater pumped, at equilibrium the concentration sums to [4.4 (initial) - 2.8 (dairy unit contribution)] = 7.2 mg/l).
4.4.3 Two dairy units in close proximity.
The third scenario involves two dairy units in close proximity to, and upstream within the recharge zone of Cooper's Wells. The total extent under dairy pasture of the two units combined is 120 hectares carrying 320 cows. Without the buffer zone included in the first scenario the nitrate tends to equilibrate within the first year of dairy conversion. The equilibrium nitrate concentration pumped at Cooper's Wells in this scenario would be just over 10 mg/l.

4.4.4 Conclusions and further discussion.
The conclusion that can be drawn from the above simulations is that dairy conversion of any more than 120 hectares of the upstream (groundwater) catchment feeding Cooper's Wells will lead to the pumped nitrate concentration permanently exceeding the 10 mg/l threshold at some point in time (between the date of conversion and the time of the aquifer reaching equilibrium with respect to nitrate concentration). Clearly, the closer the site of the dairy unit(s) to Cooper's Wells, the sooner the threshold is exceeded. The buffer zone of 24 hectares specified in the first scenario has the effect of slowing the rise in nitrate concentration, but very little effect on the final concentration of pumped groundwater if extensive dairy conversion occurs (only that of the ratio of buffer zone area to total recharge zone area).

Robertson Ryder & Associates (1993) show three dairy units on the Mataura Flood Plain between Whiterigg and Knapdale in a plot of present day dairy unit density (Figure 1c). It is unknown what number of these dairy units (if any) lie within the recharge zone of Cooper's Wells. It seems highly probable that if there is to be a doubling of the number of the number of dairy units in Southland centred on the Mataura catchment that sites will be selected in the recharge zone of Cooper's Wells. Should nitrate be already leaching into the groundwater which is eventually extracted at Cooper's Wells at a rate similar to 88 kgNO₃-N/ha/yr, then the apparent equilibrium observed in pumped concentration between 1979 and 1992 may be only temporary and lead to an eventual rise in nitrate concentration at the point that the elevated nitrate front passes into Cooper's Wells. The velocity of migration of the front(s) is approximately the same as the groundwater flow velocity and can be derived using equation (1). The time at which a front becomes drawn into the production bores at Cooper's Wells will largely determined by the distance to the dairy unit, date of conversion and slope of the hydraulic gradient towards Cooper's Wells.

There are known to be other users of the groundwater resources contained in the Mataura Flood Plain. These are mostly drawn from small bores drilled for domestic drinking water and stockwater. These users will also suffer deteriorating water quality as nitrate accumulates in the groundwater following large-scale dairy conversion. Attention will need to be given to the siting of private bores for human consumption and stockwater since both supplies will be vulnerable to rising nitrate levels. Drinking water bores will reach the potability threshold with only low levels of induced nitrate leaching, while stockwater may become unusable after more than 70% of the bore's recharge is converted to dairy pasture. Careful siting of bores, dairy sheds and feedlots is needed to avoid direct contamination of supplies. Overseas research has found feedlots to have associated plumes of very high nitrate concentrations in groundwater directly downstream before reasonable mixing can occur.
Chapter Five     Well Head Protection.

5.1 Recharge Zone Delineation.

Well head protection and the delineation of well head protection areas (WHPA's) is a well established side-branch of groundwater hydrology (Anderson and Woessner, 1992). Well head protection usually involves defining the areal extent or the position of surface sources for groundwater which eventually passes into an underground water supply. Regulatory measures are usually then employed to implement the protection of the well's capture zone against contamination. Delineation of the recharge zone for the groundwater extracted at Cooper's Wells cannot be precisely determined from the information available at this time. However, since this study concludes that recharge is made up totally of infiltrated precipitation, then estimates of the extent of the bore's recharge zone can be based on the area required for precipitation to recharge the aquifer replacing the 5100 cubic metres per day steady state withdrawal of groundwater by pumping. The recharge area determined by this method is about 850 hectares in extent. Fixation of the boundaries to the recharge zone is more difficult to do accurately. The approximate groundwater flow pattern is used for this exercise since the lateral boundaries of the recharge zone will be described by outside pathlines flowing towards Cooper's Wells. Such an approximation would orient the axis of flow towards the production bores at Cooper's Wells at a bearing of 10° to 20°, subparallel to the Mataura River. The analytical pathline model (PAT) (Kinzelbach and Rauch in Kinzelbach, 1986) using the parameter derived or estimated in the course of this study determined a transition from radial flow to the bores to linear flow at a radius of about 840 metres. This places an estimate on the width of the recharge zone. Pathline plots using the ASM groundwater flow model provides a plot of a recharge zone being about 600 metres in width and over 5 kilometres long. Figure 5.1 shows the pathlines contained within the Cooper's Wells recharge zone and probable boundaries to that zone.

As stated before the location to the boundaries to the recharge zone have a certain degree of uncertainty due to the fact that little is known about the pattern of water table heads north of Cooper's Wells. Studies which would add more certainty would include the placement of observation wells and conducting a piezometric survey of heads in the aquifer, and tracer studies using a conservative tracer suitable for use with public water supply sources.
Figure 5.1 Calculated pathlines towards Cooper’s Wells using the ASM model. A probable recharge zone boundary with an area of 1025 hectare is delineated outside these pathlines.
5.2 Measures to Protect Groundwater Quality.

The obvious measure to protect the quality of groundwater extracted at Cooper's Wells is to promote sympathetic land use in the recharge zone. This study has shown that dairy farming at a density higher than two units (or 120 hectares) in the recharge zone is damaging to water quality to the point of making groundwater at Cooper's Wells unpotable. This study also highlights the situation that the flood plain aquifer is highly vulnerable to surface contamination by merit of the inherent factors including the thin saturated depth of the aquifer, the high porosity and high permeability of the aquifer material. The presence of thin well-drained soils with abundant macropores will tend to promote high leaching rates.

In overseas situations where groundwater supplies are vulnerable to surface contamination regulatory measures are employed to mitigate the threat. The United States Environmental Protection Agency requires well head protection programmes for all public water supplies (Anderson and Woessner, 1992). This usually takes the form of the delineation of a Well Head Protection Area (WHPA) and the implementation of a staged land use regulation plan which has the effect of prohibiting certain activities known to lead to groundwater contamination from past experience.

Such measures may be available in the Cooper's Wells situation. The Resource Management Act 1991 governs water quality and specifies the following restrictions over the discharge of contamination into the aquatic environment:

\[ s.15 \begin{enumerate} [\text{(a)}] \item No person may discharge any- \end{enumerate} \]

\[ \begin{align*} (a) & \quad \text{Contaminant or water into water; or} \\ (b) & \quad \text{Contamination onto or into land in circumstances which may result in that contaminant (or any other contaminant emanating as a result of natural processes from that contaminant) entering water-} \end{align*} \]

unless the discharge is expressly allowed by a rule of a regional plan, a resource consent, or regulations.

\[ s.70 \begin{enumerate} [\text{(a)}] \item Before a regional council includes in a regional plan a rule that allows as a permitted activity- \end{enumerate} \]

\[ \begin{align*} (a) & \quad \text{Contaminant or water into water; or} \\ (b) & \quad \text{Contamination onto or into land in circumstances which may result in that contaminant (or any other contaminant emanating as a result of natural processes from that contaminant) entering water-} \end{align*} \]

the regional council shall be satisfied that none of the following effects are likely to arise in the receiving water, after reasonable mixing, as a result of the discharge (either by itself or in combination with same, similar, or other contaminants):
(c) The production of conspicuous oil or grease films, scums, or foams, or floatable or suspended materials:
(d) Any conspicuous change in the colour or visual clarity:
(e) Any emission of objectionable odour:
(f) The rendering of fresh water unsuitable for consumption by farm animals:
(g) Any significant adverse effects on aquatic life.

Water is defined as follows in the RMA:

"Water"-
(a) Means water in all physical forms whether flowing or not and whether over or under the ground;
(b) Includes fresh water, coastal water, and geothermal water;
(c) Does not include water in any form while in any pipe, tank or cistern.

The present regional plan provision relating to groundwater contamination is contained in the following rule:

Rule 4.4.4.012 Pollution of Underground Water
The discharge of, or depositing on or into land, or allowing to remain on or in any land, any matter which is liable to affect detrimentally the purity of the underground water in the district either directly or indirectly is a discretionary activity.

The final water classifications for Southland enacted under the Water and Soil Conservation Act 1967 and Water Pollution Regulations 1963 have been included in the Regional Plan. In these classifications is a provision for B classification of water of the Mataura River above Gore for water supply purposes put in place in the late 1960's (Southland Catchment Board, 1984). The classification covers the Mataura River between S170:840:428 and S170:838:432 and begins at a point near the gravel pit marked on the topographical map upstream of Cooper's Wells continuing downstream to Gore township. The B classification requires that the quality of the water conform to the following requirement (among others):

(c) The water shall not be tainted so as to make them unpalatable, nor contains toxic substances to the extent that they are unsafe for consumption by humans or farm animals, nor shall they emit objectionable odours.

Human toxicity levels for nitrate begin at 10 mg/l (Board of Health, 1989). It could be argued that natural waters percolating to the Mataura River should share the above classification since groundwater was added to the definition of natural water by later amendment of the Water and Soil Conservation Act (WSC Amendment Act 1981) before the final water classifications were adopted in the regional plan. If it could be shown that a certain intensity of dairy activity had the effect of tainting the water quality so as to make the waters unsafe for consumption by humans (defined by the upper health limit of 10 mgNO₃-N/l), then regional rule 4.4.4.012 could be brought into effect defining such dairy activity as a discretionary activity and requiring application for resource consents.
Further, more specific, groundwater quality protection provisions could be added at a regional level by way of a regional rule or groundwater catchment management plan. At a district level, restrictions on land use could be invoked, by way of a district rule, to protect the quality of water found within the aquifer to the benefit of all private and public users plus the aquatic environment into which the groundwater eventually discharges.

5.3 Evaluation of Costs, Benefits, and Alternatives to Well Head Protection Measures.

While benefits from measures to protect groundwater quality will accrue to the community and also the aquatic environment, the measures will also have their costs to others. Regional or District rules which restrict land use can impinge on the potential for certain activities for which the land would otherwise be suitable. In the case of the Mataura Flood Plain, the potential for conversion to dairy units places an additional premium on the land value.

5.3.1 Costs of Well Head Protection.
The differential between the value of the land as sheep pasture and the potential value as dairy pasture is increasing due to the expansion of the Southland Co-operative Dairy Company's dairy products factory at Edendale. The level of the differential in dollars for one unit has been estimated at $500,000 (pers. comm. Peter Cooper, December 1993). If the entire recharge zone, estimated to be 850 hectares in size (this study) were to be excluded from dairy conversion then the loss in opportunity value due to that exclusion would be about $7,000,000 (i.e. 850/60 ha = 14 dairy units, 14 x $0.5M = $7M). Other long term losses in opportunity value are beyond the scope of this study to estimate. Any extensive exclusion of dairy development on the flood plain aquifer may incur large losses of opportunity costs, felt mainly by producers and secondary industry.

5.3.2 Benefits of Well Head Protection.
Should the groundwater at Cooper's wells become too highly loaded with nitrate for human consumption, then the source would become unavailable for public water supply. This could affect the security of supply for 6000 people in Gore. Reliable supplies of potable water have been hard to find for the Gore township. During the 1970's extensive investigations were made into possible sources for Gore Borough with marginal success. Other sources of water for Gore at present are found in thin gravels at Jacobstown, McDowells' borehole, and Oldham Street. McDowells' borehole is presently closed due to persistent failure. It is also close to Cooper's Wells, sited in the same aquifer, and would be expected to be affected by high nitrate levels at about the same time if Cooper's Wells were closed. The other sources at Jacobstown and Oldham Street are insufficient to meet the town's needs. Increased bore development at these sites is likely to lead to declining groundwater levels and probable failure of supply. Artificial groundwater augmentation to supplement supply during dry periods is carried out at Jacobstown with water piped from the Mataura River. The infiltration bore is approximately 100 metres from the collector bores and has the effect of reducing drawdowns in the collector bores. However, problems have been experienced with suspended solids being carried into the collector bores, suggesting that aquifer filtration may not be sufficient to remove pathogenic bacteria or protozoans.
The benefit to the community in retaining the use of Cooper's wells will be significant. In economic terms, the cost entailed in developing new sources of town water supply and the redevelopment of the bulk distribution system to the comparatively small population at Gore would be a significant financial burden on ratepayers. The alternative sources have a potentially lower supply and bacteriological security, resulting in diminished health standards for the population. This has potential costs in worker absenteeism due to gastrointestinal complaints and increased community health care.

5.3.3 **Alternatives to Well Head Protection.**

Alternatives exist in the Gore District to replace the volume of drinking water sourced at Cooper's Wells in the event that nitrate contamination occurs. All have increased costs to the town and / or lower supply and bacteriological security. They are listed here for completeness.

Treatment options have become recently available using the ion exchange technique. This technique is used in the United States and Europe. Using the cheaper American running cost of 12.25 cents per cubic metre of drinking water treated to remove, say, 6 mg/l excess nitrate nitrogen, the total annual cost to treat Cooper's Wells water would be about $228,000 including capital and operation/maintenance costs. The technology for ion exchange water treatment is not yet available in New Zealand.

Surface water sources are obtainable close to Gore. The Mataura River could provide water with reasonable reliability. Treatment costs are likely to be high given modern drinking water standards. Coagulation to remove suspended solids, filtration and chlorination to remove pathogens will be a minimum requirement. Minimum flow conditions to protect the nationally outstanding sports fishery of the Mataura River may impinge on the security of supply during low flows. Whiskey Creek on the Waterfall Range provides another source of supply if a storage dam or reservoir could be developed to maximise the yield.

Alternative groundwater sources, as yet unproven, may be available from the flood plain aquifer downstream of Gore. Low flow gaugings of the Mataura River suggest measurable recharge to the gravel aquifer between Gore and Mataura (Southland Catchment Board, 1984). These sources remain vulnerable to future dairy conversion.

Artificial groundwater augmentation with river water at a suitable site may be an option. Infiltration bores or basins would be placed at the centre of a ring of collector bores. The injection of river water would be maintained to elevate water pressures in the augmentation area for the collector bores to draw on filtered and aged river water. However, an appropriate site for augmentation has yet to be located.
7.0 References Cited.


Appendix 1.
Report on the Re-interpretation of Pumping Test Data from a Test carried out on Cooper’s Well in 1979 by T.H. Jenkins & Associates.

1.0 Introduction.

Following the establishment of the production bores and observation wells at the Cooper’s Wells site a series of pumping tests were carried out. The pumping test is detailed in the document “Report on Drilling and Testing of Cooper’s Wells for Gore Borough Council” prepared by T. H. Jenkins and Associates in March 1979 (hereafter referred to as the ‘1979 Report’).

The 1979 report gives bore logs, a site plan, time/drawdown plots and distance/drawdown plots of pumping response. Two pumping tests were carried out; one test of well number 1 over 8000 minutes (about 5 and a half days) at a pumping rate of 36.3 litres per second, and a second test of well number 2 over 6000 minutes (about 4 days) at a rate of 44.1 litres per second. Time series measurement of water level (head) was made in the pumped bore for each test. Level measurements were also made in all observation wells at the conclusion of each test. In the report coefficients of transmissibility were calculated, only the value for the “C aquifer” will be valid. Unfortunately, the apparent diameters and zones of transmissibility calculated for the supposedly distinct “aquifer zones” can have no basis in fact, since the observation of distinct zones is due to a mistaken assumption used in curve interpretation.

While the pumping test design was lacking in some respects (lack of time series measurement in observation wells), the overall presentation of raw data allowed a re-interpretation of the pumping test to produce aquifer parameters such as permeability and specific storage coefficients. Since Aquafirma had been engaged to develop a better understanding of aquifer hydraulics at Cooper’s Wells such re-interpretation was thought to be worth the effort. Initial estimates of aquifer parameters will have value in designing subsequent pumping tests in the course of the hydrogeological study of the area. The aquifer parameters derived should be largely independent of the state of the bore screens or the groundwater levels at the time of testing.

2.0 Re-interpretation.

Three separate methods of interpreting test results were available. These methods used drawdown data collected independently of the others. This lack of data dependence in applying the three methods is important in allowing comparison of the derived aquifer parameters. The methods of parameter determination are listed below:

1. Steady State Piezometer Drawdown; Formula of Dupuit.
2. Theis’ Recovery Method for unconfined aquifers.
3. Theis’ Curve Fitting Method for late-time drawdown data.

The parameter which can be derived by all three methods is the coefficient of permeability (more often called hydraulic conductivity). Specific storage can be derived using only the Theis Curve Fitting Method.
2.1 Steady State Piezometer Drawdown; Formula of Dupuit.
This method requires only head or drawdown measured at two different radii
distances from the pumped well. Six observation wells (also called piezometers or tell
tales) were installed at Cooper's Wells. Two observation wells were installed along each
axis in the compass directions of South, East, and West. Therefore the coefficient of
permeability can be determined using the Formula of Dupuit (Kruseman and de Ridder,
1990) as given below:

\[ Q = \frac{2 \Pi K D (s_{m1} - s_{m2})}{2.30 \log(r_2 / r_1)} \]

Where: 
- \( s' \) = corrected drawdown
- \( r \) = radius from pumped well
- \( K \) = Coefficient of permeability
- \( D \) = Saturated depth of aquifer
- \( Q \) = Pumped discharge

The formula is automated in the GW software (United Nations DTCD 1989) and the
drawdown correction is made to allow the input of heads at the observation wells.
Heads for the two pumping tests were taken from those plotted on figures 5, 6, and 7
in the 1979 report and used to calculate the coefficient of permeability in each compass
direction.

\[ \text{Symbols.} \]
- ○ Permeability determined for 8000 min. test.
- □ Permeability determined for 6000 min. test.

\( \text{(Permeability in metres/day)} \)

\text{Figure 2.1 Results of permeability determinations for each compass direction}
\text{using the observation well heads and the Formula of Dupuit. Refer also to}
\text{Figure 2 of the 1979 report for the position of observation wells and distances}
\text{from each other and the pumped bores.}
The derived permeabilities suggest that after 6000 minutes of pumping at a rate of 3810 cubic metres per day (44.1 litres per second) the drawdown has yet to stabilise. However following 8000 minutes of pumping at a rate of 3136 cubic metres per day (36.3 litres per second) the aquifer may be closer to quasi-steady state drawdown. This observation is supported by the flattening of the drawdown curve in figure 3 of the 1979 report. Therefore the 8000 minute test parameters should be used in preference to the 6000 minute test. There is a clear zonation of permeability in the nearest 50 metres from the production bores at Cooper's Wells. The southern quadrant has the highest permeability of any, over 300 metres per day. This high permeability zone could be provisionally attributed to the dredged river channel deposits which form a narrow band of the aquifer trending in a roughly north-south heading. The lowest permeability is found for the western compass direction. The 1979 report observes the western observation wells to be set in raised tailings and speculates that the raised heads are due to capillary action. This quadrant is clearly a low permeability zone for whatever reason. The eastern quadrant has a permeability roughly half that of the southern quadrant. The permeability of 165 metres per day is quite consistent with the expected value for Recent fluvial gravels.

2.2 Theis' Recovery Method for Unconfined Aquifers.

The recovery method involves continuing to measure head in the aquifer following the cessation of pumping; effectively, how well the aquifer recovers from being drawn down by pumping. The response in head can be used to plot a curve on a semi-logarithmic graph. Only late-time data should be used because of the effects of expansion in the aquifer due to reduced water pressure and compaction exerted during the flat intermediate segment of the time/drawdown curve in unconfined aquifers (Kruseman and de Ridder, 1990).

![Diagram of Theis Recovery Method](image)

*Figure 2.2 Plot of t'/t against residual drawdown for the Theis Recovery Method. Data was taken from late-time records of residual drawdown in Figure 3 of the 1979 report.*
A recovery test was carried out for the 8000 minute test on well number 1 at pumping rate of 3136 cubic metres per day. The time from the start of the pumping (t) was divided by the time from the cessation of pumping (t') to give a ratio (t/t'). The ratio was plotted on a logarithmic scale against drawdown on a linear scale.

The change in residual drawdown over one log cycle (Δs') in this case equals 0.51 metres. The Theis Recovery Method has as its' basis the following formula:

\[ Δs' = \frac{2.30 Q}{4πKD} \]

The equation can be transposed to give the KD.

\[ KD = \frac{2.30 Q}{4πΔs'} \]
\[ = 1125 \text{ m}^2/\text{d} \]

\[ K = 281 \text{ m/d} \quad (\text{given a saturated depth of 4 metres}) \]

2.3 Theis Curve Fitting Method.

A special case of Theis' Theorem allows late-time drawdown data to be used for unconfined aquifers (Kruseman and de Ridder, 1990). Figure 3 of the 1979 report shows a drawdown curve for well number 1 while well number 2 is being pumped. The late-time records from this set of observations are used to fit on the Theis type curve. An automated technique is used in this case utilising the GW software (United Nations DTCD, 1989) to optimise the best fit on the type curve. The fit is achieved within three iterations with a standard deviation of 0.025 metres drawdown.

\[ KD = 1235 \text{ m}^2/\text{d} \]
\[ K = 308 \text{ m/d} \quad (\text{given a saturated depth of 4 metres}) \]
\[ S = 0.196 \]
\[ \text{Eff. Porosity} = 19.6\% \]

Clearly, there is reason to believe that the interpreted pumping test results show reasonable agreement between the three methods used. The table below shows how they compare.

Table 1 Comparison of method and permeability derived in this report.

<table>
<thead>
<tr>
<th>Method</th>
<th>Permeability (m/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steady State</td>
<td></td>
</tr>
<tr>
<td>Observation Wells</td>
<td>306 (South)</td>
</tr>
<tr>
<td>Recovery</td>
<td>281</td>
</tr>
<tr>
<td>Curve Fitting</td>
<td>308</td>
</tr>
</tbody>
</table>
3.0 Conclusions.

1. The permeability field of the nearest 50 metres to the production bores at Cooper's Wells show a marked zonation when distance/drawdown plots for observation wells are analyzed. The southern quadrant has the highest permeability at 306 metres per day.

2. The coefficient of permeability derived from measurements of recovery in water levels in well number 1 and drawdown in the same well during pumping of well number 2 is of the order of 300 metres per day with a range of between 308 and 281 metres per day.

3. The specific storage of the aquifer at Cooper's Wells is derived from Theis Curve Fitting Method as being about 0.19. Since specific yield and effective porosity are equivalent for unconfined coarse grained aquifers this implies an effective porosity of 19%.

4.0 References.


Appendix 2.
1.0 INTRODUCTION.

In order to check an earlier pumping test result (see 1979 pumping test results) and secure a more accurate estimate of specific yield / effective porosity, it was decided to conduct a second pumping test utilising existing sensors and telemetry installed at Cooper's Wells recently.

Since the 1979 pumping test a new bore had been installed at Cooper's Wells about 130 meters south of the original bores. This new bore was christened No. 1 Bore, the remaining original bore was renamed No. 2 Bore. The 1994 pumping test used No. 1 Bore as the pumped bore and measured drawdown using a pressure transducer in No. 2 Bore. The pumping test thus designed would estimate the permeability of the backfilled dredge pond and buried tailings.

2.0 TEST DESIGN.

All pumping at Cooper's Wells was stopped on the 18th of February for three days levels at Cooper's Wells to equilibrate. Pumping was started at 9:04 am on the morning of the 21st of February at a continuous rate of 31 litres per second. Pumping continued for five days while water level was recorded in No. 2 Bore. At the close of the pumping period on the 26th of February it was decided to conduct a second pumping test due to surface water interference with groundwater levels. Following a further three day shut-down pumping was restarted at 31 litres per second on the 28th of February. Pumping continued until the 7th of March and the fall in groundwater levels due to drawdown observed in No. 2 Bore.

3.0 ENVIRONMENTAL FACTORS.

A flood occurred on the Mataura River between the 19th and the 22nd of February. At its peak the flood rose 3.8 metres above normal level. Also associated with the flood was heavy rainfall in the Gore area. Both factors led to a measurable rise in groundwater levels at Cooper's Wells.

The flood resulted in river waters transgressing the flood plain terrace surface in places for up to 12 hours. This would have had the greatest effect on groundwater levels as it would have led to a transient pulse of elevated head which propagated through the aquifer at a rate determined by the aquifer storage coefficient. This would be measured as a delayed and smoothed response to surface water rise in a corresponding groundwater rise.

Figure 1 shows the rise and fall in river level between 17 February and 28 February.
Figure 1. A plot of the river level in metres with respect to the gauge datum (68 metres above mean sea level) measured at Gore Bridge between the 17th of February and the 28 of February 1994. The flood peak was experienced at Gore shortly after noon on the 21st of February.

Consequently, the recovery of the water level in No. 2 Bore and drawdown as a result of pumping could not be separated from the change in groundwater level due to the flooding. A second attempt at the pumping test was arranged. The steady and gradual fall of the Mataura River in its flood recession phase was thought to have minimal effect on the groundwater levels.

4.0 TEST RESULTS AND ANALYSIS.

The water levels in No. 2 Bore showed a steady fall during the course of the second attempt at the pumping test. Late-time drawdown was observed in water levels following the 4th of March. The Theis curve fitting method of analysis for late-time data measured in observation wells in an unconfined aquifer is a permitted special case (Kruseman and de Ridder, 1990).

\[ s' = \frac{Q}{4\pi T} W(u) \]

Where:

\[ u = \frac{r^2 S}{4 \cdot T \cdot t} \]

\[ s' = \text{Drawdown (m)} \]
\[ Q = \text{Pump discharge (m}^3/\text{d)} \]
\[ T = \text{Transmissivity (m}^2/\text{d)} \]
\[ r = \text{Radius of observation (m)} \]
The Theis curve fitting method is automated using the GW software (United Nations DTCD, 1989). The following result was obtained.

Permeability \[ 398 \text{ metres per day} \] - saturated thickness 5 metres.

Effective Porosity \[ 9.4\% \]

The permeability calculated is similar to that derived from the 1979 pumping test. However, the effective porosity calculated in this pumping test appears anomalously low given the nature of the aquifer material (unconsolidated clean gravels) at Cooper's Wells. A more plausible value would be the 19.6 \% effective porosity calculated for the previous test.