Technical report advising Proposed Plan Change 6A Officer's Report of Decisions Requested

Assessment of Nitrogen Sensitive Zone loading limits

Modelling of Kakanui – Kauru, Ettrick, and Lower Taieri nitrogen accumulation sensitivity

Prepared by Otago Regional Council's Resource Science Unit

August 2012

Background

Plan Change 6A of the Otago Regional Plan: Water contains nitrogen discharge limits in proposed clause 12.C.1.3:

3. *"The discharge of nitrogen from land to groundwater, is a* ***permitted*** *activity, providing:*
   i) *From 31 March 2019, calculated nitrogen leaching by the Council using OVERSEER version 6.0 does not exceed:*
      (a) 10 kilograms nitrogen per hectare per year over any nitrogen sensitive zone identified in Maps I1-I6; and
      (b) 30 kilograms nitrogen per hectare per year elsewhere in Otago; and
   ii) *Upon request …."*

Nitrogen Sensitive Zones

In this manner, the plan change is proposed to make a distinction between "*nitrogen sensitive zones"* and rural land elsewhere in the region. Maps I-1 to I-6 detail the six areas or zones considered to have additional sensitivity to nitrogen contamination:

- I-1 Kakanui – Kauru Aquifer (the northern Groundwater Protection Zone A is pictured).
- I-2 Shag Alluvium Aquifer.
- I-3 Lower Taieri Aquifer - East, (the Groundwater Protection zones A & B surrounding Mosgiel are pictured).
- I-4 Ettrick Basin Aquifer and Roxburgh Basin Aquifer (the respective A Groundwater Protection zones in each aquifer are pictured).
- I-5 Wakatipu Basin Aquifer, and catchment of lakes Wakatipu and Wanaka.
- I-6 Catchment of lakes Wanaka and Hawea.

The aquifer components of the "*nitrogen sensitive zones"* are subject of this report. The major lake catchment of maps I-5 and I-6 are not included in the discussions of this report, although the Wakatipu Basin Aquifer on map I-5 is.

Hydro-Dynamic Conditions favouring Nitrogen Accumulation

The sub-text of the distinction made between "*nitrogen sensitive zones"* and rural land elsewhere in the region is that the specified zones are considered to be more sensitive to nitrogen accumulation than elsewhere. Dissolved inorganic nitrogen species, such as nitrate, nitrite and ammonia, are naturally occurring and occur pervasively in groundwater within 500 m of the land surface. All groundwater systems experience some degree of nitrogen accumulation unless they are confined or if the *in situ* geochemical environment reduces incoming nitrogen from soil drainage. Some groundwater systems or aquifers have particular conditions that favour the compounding accumulation of dissolved inorganic nitrogen over long time frames. These conditions increase the probability of nutrient levels rising towards the drinking water guidelines for nitrate, nitrite or ammonia nitrogen. The most readily definable special conditions are what can be described as hydro-dynamic. Hydro-dynamic conditions that favour nitrogen accumulation are as follow:

- Unconfined aquifer setting, open to soil drainage drizzling through the unsaturated zone above.
- Thin aquifers, containing a relatively small volume of groundwater within the saturated zone.
- Soil drainage dominated recharge.
- Lack of dilution from other sources of recharge having low nitrogen content, such as surface water infiltration directly from a water body.
- Low permeability and/or groundwater flow velocity (flux).

Other risk factors are whether the aquifer has also displayed an accumulation in nitrogen concentration already or the known lack of geochemical conditions that would otherwise suppress the accumulation of nitrate nitrogen.

Nitrogen Guideline Values

The dissolved inorganic nitrogen species of health significance, if taken for water supplies are nitrate and nitrite. The respective drinking water guideline concentrations are as follow:

- Nitrate (short term exposure) 50 gNO_3/m^3 or 11.3 gN/m^3
- Nitrite (short term exposure) 3 gNO_2/m^3 or 0.91 gN/m^3
- Nitrite (long term exposure) 0.2 gNO_2/m^3 or 0.061 gN/m^3

Ammonia has a Maximum Acceptable Value (MAV or guideline value) of aesthetic significance. That is to say, if ammonia in raw water exceeds 1.5 gNH_3/m^3, then there is an odour that reduces palatability, but health significance is not triggered. The associated ammonia nitrogen value is not much less at 1.16 gN/m^3. All forms of nitrogen, including "*organic nitrogen, ammoniacal nitrogen, nitrite nitrogen and nitrate nitrogen"* are referenced in Plan Change 6A, clause 12.C.1.3 for management of soil zone discharges to groundwater.

The water quality of groundwater has long been difficult to classify or provide standards or guidelines for. Since groundwater is commonly used as a source of domestic water in rural communities, without water treatment or ongoing monitoring, it has become customary for authorities to refer to the drinking water standard MAVs when setting water quality guidelines. The most stringent drinking water MAV is that of nitrite nitrogen with a concentration of 0.061 gN/m^3 for long-term exposure. Given that long-term exposure to water from a water bore is an entirely feasible eventuality for long-term members of a rural residential population, the long-term MAV is the most appropriate guideline. Unfortunately, there is little information available from groundwater monitoring to differentiate between nitrate and nitrite despite the large difference in MAV.

The processes of soil nutrient cycling and soil drainage have the effect of *nitrifying* the entrained nitrogen dissolved in any soil leachate. This process is mediated by *Nitrobacter sp.* bacteria in the soil / subsoil and has nitrite as a transitional species with nitrate as the end member. Most nitrogen transiting the subsoil and unsaturated zone is thus nitrate nitrogen. Therefore, most attention on environmental management of groundwater nitrogen goes on the nitrate species of the element. The substantial water quality management programme practised in the European Union, termed the Nitrates

Directive of 2001 and confirmed in the Groundwater Directive of 2006, seeks to limit groundwater nitrate nitrogen concentrations to 11.3 gN/m^3 (European Union, 2012).

Modelling

Ettrick Unconfined Aquifer

Appendix A outlines the process of modelling the Ettrick Aquifer, termed the *Ettrick Unconfined Aquifer* by Bekesi (2006), in order to assess the sensitivity of the groundwater to nitrogen accumulation. Modelling showed a tendency to accumulate nitrogen on the down-gradient side of the flow system, especially adjacent to an area of flow stagnation against a basement margin. Modelling suggested that if uniform rate of nitrogen discharge to the aquifer was practised, then a rate of 20 kgN/ha/y would still maintain the aquifer substantially within the 11.3 gN/m^3 MAV concentration. It should be noted that the hydro-dynamic model using Rushton soil-moisture modelling for recharge, MODFLOW for flow simulation and MT3D for advection / dispersion modelling of nitrogen movement through the aquifer was highly conservative to employ the zero nitrogen inflows of Benger Burn and range-front recharge which diluted nitrogenous soil drainage.

North Taieri – Mosgiel groundwater protection zones

Reporting of Modelling of the North Taieri groundwater System around Mosgiel is given in Appendix B. Modelling of recharge, groundwater flow and nitrogen movement in the multi-layered North Taieri compartment of the Lower Taieri groundwater system strongly suggested that the system was relatively insensitive to changes in nitrogen discharge in the range of 10 to 30 kgN/ha/y, which is also the difference in loading rates proposed between sensitive zones and anywhere else in Otago. The model had a relatively small area in which nitrate could affect groundwater quality (without geochemical reduction) and affect the Mosgiel public water supply. The infiltration losses of the Silver Stream of up to 40 litres per second, which were confirmed by field gauging (Rekker & Houlbrooke, 2010), contributed greatly to the groundwater system's resilience against nitrogen accumulation. The contrasting soil retention properties of the soil classes in the recharge zone were also important.

Kakanui – Kauru Alluvium

The Kakanui – Kauru zone is reported in Appendix C. The northern groundwater protection zone A within the Kakanui – Kauru Alluvium was proposed in the notification of RPW Plan Change 6A as a nitrogen sensitive zone. This zone perhaps stands apart from the foregoing aquifer modelling exercises because the water quality values to be protected are in-stream surface water quality of the Kakanui River rather than groundwater nitrate.

A study of the groundwater – surface water interaction between the alluvium and river was carried out. The study showed that up to 25% of the aquifer could be replenished by peak flow events. The limited groundwater storage available in the riparian gravels makes for a highly responsive aquifer that will not tend to accrue nutrients from year to year. In this way, the Kakanui – Kauru alluvium differs from other aquifers in Otago, which have a much greater storage to annual recharge ratio.

The available data indicates that nitrate concentrations in the river are peaking well above the 0.08 mg/l nitrate-N threshold during winter and spring. This makes sense because there is very little nutrient use within the soil profile during this time. Much of the nutrient – enriched groundwater is flushed into the aquifer by rainfall, and discharged into the river during winter and spring. However, a residual of elevated nitrate continues to discharge to the river during the critical summer period. The gain in river flow from groundwater storage is typically over 10% during a flow recession, so residual nitrate in the aquifer continues to be added to the river during summer. The nitrate concentrations increase during periods of flow recession because the proportion of groundwater contribution to river flow increases as flow decreases.

The conceptual model outlined above suggests that to control river water quality requires controlling nutrient discharge through the soil, particularly during the critical winter leaching period. The ECAN lookup tables for nitrate leaching indicate that wintering of cows contributes an additional 10 to 15 kgN/ha/yr[1]. This implies that winter leaching rates are at least 30% higher than the annual values specified in the lookup tables. Furthermore, the area of greatest groundwater gain from the river has very light soils which are prone to high rates of leaching. This leaching will continue into the summer period on irrigated pasture.

Our recommendation is that the Kakanui – Kauru aquifer remains a sensitive aquifer, with a 20 kgN/ha/y leaching limit.

Re-Evaluation of Nitrogen Sensitive Zones

The following re-evaluation of the six proposed nitrogen sensitive zones that are aquifers was undertaken in the knowledge submissions received in response to Plan Change 6A notification and subsequent modelling of nitrogen accumulation.
Table 1 lists the loading limits within the proposed plan change alongside the suggested new loadings following a re-evaluation, including some nitrogen accumulation modelling.

[1] The majority of the area consists of extra light soils. These soils are predicted to leach between 38 and 65 kgN/ha/y depending on herd density and wintering (Lilburne et al. 2010).

Table 1: Schedule of Notified and Re-Evaluated Nitrogen Loadings.

	Notified Loading Limit (kgN/ha/y)	New Recommended Loading Limit (kgN/ha/y)	Comment
Kakanui – Kauru Alluvium	10	20	Surface water quality controlled
Shag Alluvium	10	20	Surface water quality controlled
Mosgiel – N Taieri GPZ A & B	10	30	Remove from PC 6A map I-3
Ettrick Aquifer	10	20	
Roxburgh Aquifer	10	20	
Wakatipu Basin	10	20	A series of sub-basins couched in schist

It is suggested that the Mosgiel – North Taieri groundwater protections zones can be removed from the initial list of nitrogen sensitive zones on the basis of the conceptual understanding of the stratified aquifer and groundwater modelling results.

Nothing in the foregoing analysis indicates that current land practices can conform to the discharge limits discussed, or otherwise. The analysis has instead focused on the ability of the underlying groundwater system to assimilate soil discharges at the nitrogen limits discussed.

References

Bekesi, G. 2006: Groundwater allocation of the Ettrick Basin. Prepared by Resource Science Unit for Otago Regional Council, December 2006, Dunedin. ISBN 1-877265-42-X.

European Union. 2012: http://ec.europa.eu/environment/water/water-nitrates/index_en.html

Lilburne, L., Webb, T., Ford, R., and Bidwell, V. 2010. Estimating nitrate-Nitrogen leaching rates under rural land uses in Canterbury. Environment Canterbury technical report R10/127

Rekker, J H; and Houlbrooke, C. 2010: Lower Taieri Groundwater Allocation Study. Prepared by Resource Science Unit for Otago Regional Council, December 2006, Dunedin. ISBN 1-877265-42-X.

Appendix A

Deterministic modelling of the Ettrick Aquifer.

Background

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In this manner, the plan change is proposed to make a distinction between "*nitrogen sensitive zones"* and rural land elsewhere in the region. Maps I1 to I6 detail the six areas or zones considered to have additional sensitivity to nitrogen contamination:

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The aquifer components of the "*nitrogen sensitive zones"* and the Ettrick Aquifer in particular are subject of this report. Over sensitive aquifers, the primary values sought for water quality protection are as follows:

- Protection of groundwater quality from rising or excessive nitrate nitrogen concentration, where the potable concentration is 11.3 $gNO_3\text{-}N/m^3$.
- Protection of surface waters receiving appreciable contribution from groundwater where the RPW plan change proposed discharge quality limits are between 0.08 $gNNN/m^3$ and 0.45 $gNNN/m^3$ (Schedule 16).

The first of these values relating to the maintenance of acceptable nitrate nitrogen concentration is more readily assessed and quantified. The second value for maintaining acceptable surface water nitrate and nitrite nitrogen concentrations is addressed explicitly only with great difficulty due to the proliferation in variables contributing to eventual concentrations in surface water. In addition, the Clutha River /

Mata Au, into which the Ettrick Aquifer discharges, is less sensitive to nitrogen contribution due to the mean flow rate of 540 m^3/s (17,000 Mm^3/y), which would substantially dilute any such nitrogen contaminants.

Examination of relevant literature on land use and nitrogen losses suggested that the 10 kgN/ha/yr (soil drainage) discharge limit would be consistent with a drainage concentration of 6.3 gN/m^3 and be typical of the overlying activity of dryland sheep grazing (e.g. Lilburne, *et al*, 2010). However, land use of higher intensity would be likely to induce soil discharges to water exceeding the 10 kgN/ha/yr discharge limit. Accordingly, the imposition of the 10 kgN/ha/yr and 30 kgN/ha/yr limits may have the effect of impinging on the main activities of land after 31 March 2019. Activities would need to be made consistent to the relevant nitrogen discharge limits by land use change if OVERSEER modelling pointed to soil discharges exceeding the limits after that date.

Numerous submissions have been received that question the appropriateness and scientific basis for both the extent of sensitive zones proposed and nitrogen discharge limit proposed. As a response to the submissions, this report is directed towards a re-evaluation of both factors at a technical level.

Approach

Having outlined the background to this report, the approach taken in responding to a Request for Service on the sensitive aquifer question needs to be defined. In this case, a deterministic model was developed for the Ettrick Aquifer to allow comparison of a range of nitrogen discharges to ultimate groundwater nitrogen concentrations. A deterministic model is a simplified facsimile of the aquifer concerned, including its geometry, water balance and boundary conditions. Nonetheless, a deterministic model attempts to replicate the conditions pertinent to the questions being studied. Deterministic models are dimensionally correct and calibrated using measured data obtained from the aquifer. Table 2 lists some comparative parameters and water budgets for the Ettrick Aquifer and selected aquifers described elsewhere in Otago.

Table 2: List of aquifer parameters and sources of recharge for selected Otago aquifers.

		Median Aquifer Parameter (m or m/d)			Percent Recharge Source (%)		
RPW Map*		**Depth of Aquifer**	**Saturated Thickness**	**K_h**	**Rainfall**	**Stream / River**	**Irrigation**
I-4	Ettrick Basin Aquifer	19.1	6.62	100	56%	44%	0%
RPW Map[¥]		**Depth**	**Saturated Thickness**	**K_h**	**Rainfall**	**Stream / River**	**Irrigation**
	Selected "Elsewhere in Otago" Aquifers						
C3	Cromwell Terrace Aquifer	37.2	15.2	400	29%	38%	33%
C1	Wanaka-Cardrona Aquifer	39.1	19.3	250	17%	25%	57%
C9	L Waitaki Alluvium Aquifer	10.9	6.7	130	29%	45%	26%
C4	Dunstan Flats Aquifer	30	7.2	300	4%	23%	72%
C4	Earnscleugh Flat Aquifer	21.2	6.3	300	1.2%	85%	14%
	Median of medians	30	7.23	300	17.4%	37.5%	33.3%
	Mean of medians	27.7	10.9	276	16.2%	43.3%	40.5%

Note:

K_h = approximate saturated horizontal hydraulic conductivity, i.e. permeability.
? means little reliable information is not available.
* proposed plan change 6A to the RPW and appended maps.
¥ operative RPW and appended maps.

The Ettrick Aquifer tends to be generally shallower, less permeable and have a greater proportion of its recharge from rainfall than the norm for many Otago aquifers of its type. This may result in a higher probability of the Ettrick Aquifer exceeding the drinking water standards for dissolve inorganic nitrogen.

The hydrogeology of the Ettrick Aquifer as described in the most recent ORC scientific publication (Bekesi, 2006) and extracted from ORC databases such as the well records database, were used in developing a framework of the aquifer within MODFLOW. The MODFLOW groundwater modelling and MT3DMS contaminant transport codes were implemented within the Groundwater Vistas (Rumbaugh and Rumbaugh, 2007) modelling package. Optimisation of this model was performed with the aid of the PEST optimisation package (Doherty and Hunt, 2011). Contaminant transport was simulated with the MODFLOW component package MT3DMS (Zheng and Wang, 1999).
Modelling followed the following procedure:

1. Calculate land surface recharge for irrigated and non irrigated areas with the Rushton model (see Wilson and Lu, 2011).
2. Calculate the nitrate-N concentration of leachate for each soil group and recharge rate.
3. Construct and optimise a MODFLOW model for observed conditions.
4. Run MODFLOW and MT3DMS to simulate the impact of a range of nitrogen discharge rates on the Ettrick Aquifer groundwater nitrogen concentrations.

This process is shown diagrammatically below:

Recharge Model **Soil Nutrient Model**
↓ ↓
MODFLOW groundwater flow model
↓
MT3DMS groundwater transport model

A soil nutrient modelling exercise was not ultimately carried out by ORC. Rather, leachate values of nitrate-N mass in kgN/Ha/y were taken from the 6A plan change document and Lilburne et al. (2010)[2]. Where Lilburne et al. (2010) was referenced, the leachate mass for Lincoln soils was used for each of the Otago case studies, as this site is considered to be most representative of Otago conditions. Relevant leaching rates for Lincoln soils in KgN/Ha/y are shown below:

Table 3: Nitrogen leaching rates from Lilburne et al. (2010) for Lincoln soils.

Leaching Rates (kgN/ha/y)	**Soil Group:** PAW:	**Extra light** <50	**Very light** 50-80	**Light** 80-110	**Medium to heavy** >110
3 cows/Ha winter on	Spray Irrigation	50	41	31	19
	Border dike		86	76	76
100% sheep	Dryland	10	9	8	5
	Spray Irrigation	25	20	16	9
	Border dike	66	43	38	38

The proposed plan change 6A nitrogen discharge loadings were included in MT3DMS simulations to estimate the effects of leaching on the Ettrick Aquifer. The relevant nitrogen limits were:

- 10 kgN/ha/y (nitrogen sensitive zones)
- 30 kgN/ha/y ("elsewhere in Otago")

Numerical Model

The vital statistics of the Ettrick Aquifer numerical model are introduced in Table 4. Those areas of the model domain that are underlain by schist rock were simulated as No Flow cells, and thus inactivated. Other significant boundary conditions within the Ettrick Aquifer model included the Clutha River / Mata Au, the upper Benger Burn infiltration as it crosses the aquifer and range-front infiltration of surface water as minor creeks soak into the terrace surface.

[2] Nitrate-N masses for different land uses are listed in the green table on page 30 of Lilburne et al.(2010).

Table 4: Vital statistics of numerical model.

Dimension	Value
Top (m AMSL)	90
Bottom (m AMSL)	60
Mean Clutha level (m AMSL)	72
Model Domain Width (m)	5,160
Model Domain Height (m)	6,000
Cell dimension (m)	120 × 120
No. of model cells	2,150
No. of Columns	43
No. of Rows	50
Model area (m^2)	30,960,000
Rainfall recharge area (m^2)	14,299,200

Rainfall recharge was applied over an area of 14.3 km^2 representing the permeable surface of the Ettrick terraces west of the Clutha River. For the simulation of steady state recharge conditions, the soil-moisture modelling of recharge over the Roxburgh Basin was referenced (Wilson and Lu, 2011). This equated to a long-term mean of 88 mm/y. Across the 14.3 km2 surface of the aquifer the rainfall recharge equated to 1.3 Mm^3/y.

Bekesi (2006) estimated recharge from the infiltration of surface water rising as runoff in the 10.7 km2 catchment discharging onto the western flank of the Ettrick Aquifer. This was previously estimated at 2 Mm^3/y (Bekesi, 2006), but had been re-evaluated as 1.6 Mm^3/y for the purposes of the numerical model. The range-front recharge was applied in the numerical model as a series of 45 model cells discharge a mean annual quantity evenly along the 4.8 km length of the western boundary.

Bekesi (2006) also estimated the infiltration of surface water from the Benger Burn at 2.4 Mm3/y based on the equivalent Mean Annual Low Flow estimate. For the numerical model the use of a river (RIV) boundary condition was opted for instead. The river boundary specified the river bed elevation and estimated the bed conductance controlling the rate of infiltration. The bed conductance was further refined during the calibration and parameter estimation process so that a balance was achieved that reflected probable exchanges between the Benger Burn and underlying aquifer. The ultimate rate of infiltration was optimised to an estimated 1.4 Mm^3/y in this fashion.

For the simulation of nitrogen transport and accumulation in the aquifer, nitrogen was included in rainfall recharge only. Typically, nitrogen is most significant in soil drainage vertically through the soil profile, rather than surface water runoff. This is evident in SOE monitoring of dissolved inorganic nitrogen (DIN) as follows.

- Benger Burn mean DIN concentration: 0.2 gN/m^3.
- Ettrick Aquifer mean DIN concentration 3.5 gN/m^3.

Accordingly, Benger Burn and range front recharge were specified as having zero nitrogen content in the numerical model.

The specification of nitrogen discharge to the aquifer in rainfall recharge was made as in Table 5 as follows:

Table 5: Nitrogen loadings and corresponding concentrations.

Nitrogen loading (kgN/ha/y)	**Concentration in recharge (gN/m^3)***
10	11.4
20	22.7
30	34.1

* based on recharge of 88 mm/y

The nitrogen loadings correspond to the proposed sensitive zone limit (10 kgN/ha/y), the "elsewhere in Otago" limit (30 kgN/ha/y) and an intermediate value (20 kgN/ha/y). These concentrations were specified in numerical modelling using MT3DMS.

Model Calibration and Parameter Optimisation

Calibration data was obtained from long-term mean groundwater level measurements at seven selected SOE monitoring bores distributed across the Ettrick Aquifer surface listed in Table 6.

Table 6: List of calibration data points in Ettrick Aquifer.

Easting (NZMG)	**Northing (NZMG)**	**No.***	**SWL[¥]**	**Well No.**	**Owner surname**
2226670	5500998	34	70.84	G43/0004	Vernon
2227194	5501251	15	71.15	G43/0009	Dunnich
2225548	5501355	7	74.91	G43/0018	Aitchison
2226855	5501466	24	71.83	G43/0030	Jane
2226423	5502202	7	72.11	G43/0032	Calder
2225775	5502015	4	72.38	G43/0036	Marsh
2225640	5503620	36	72.17	G43/0043	Hiscock

* No. of groundwater level measurements making up the mean static water level
¥ Mean Static Water Level (SWL) as groundwater level elevation above mean sea level.

These mean static water levels for calibration allowed comparison with steady state model simulations. Subsequently, the modelling process moved into parameter optimisation. The parameter optimisation tools used were those within the PEST code (Doherty and Hunt, 2011). The primary optimisation parameters were the horizontal hydraulic conductivity field across the aquifer, plus river bed conductance.

The process of PEST optimisation proceeded to produce errors between measured and modelled mean static water levels at minor values, indicating a satisfactory calibration outcome. Figure 1 shows the calibration result as a cross plot of measured levels versus modelled levels.

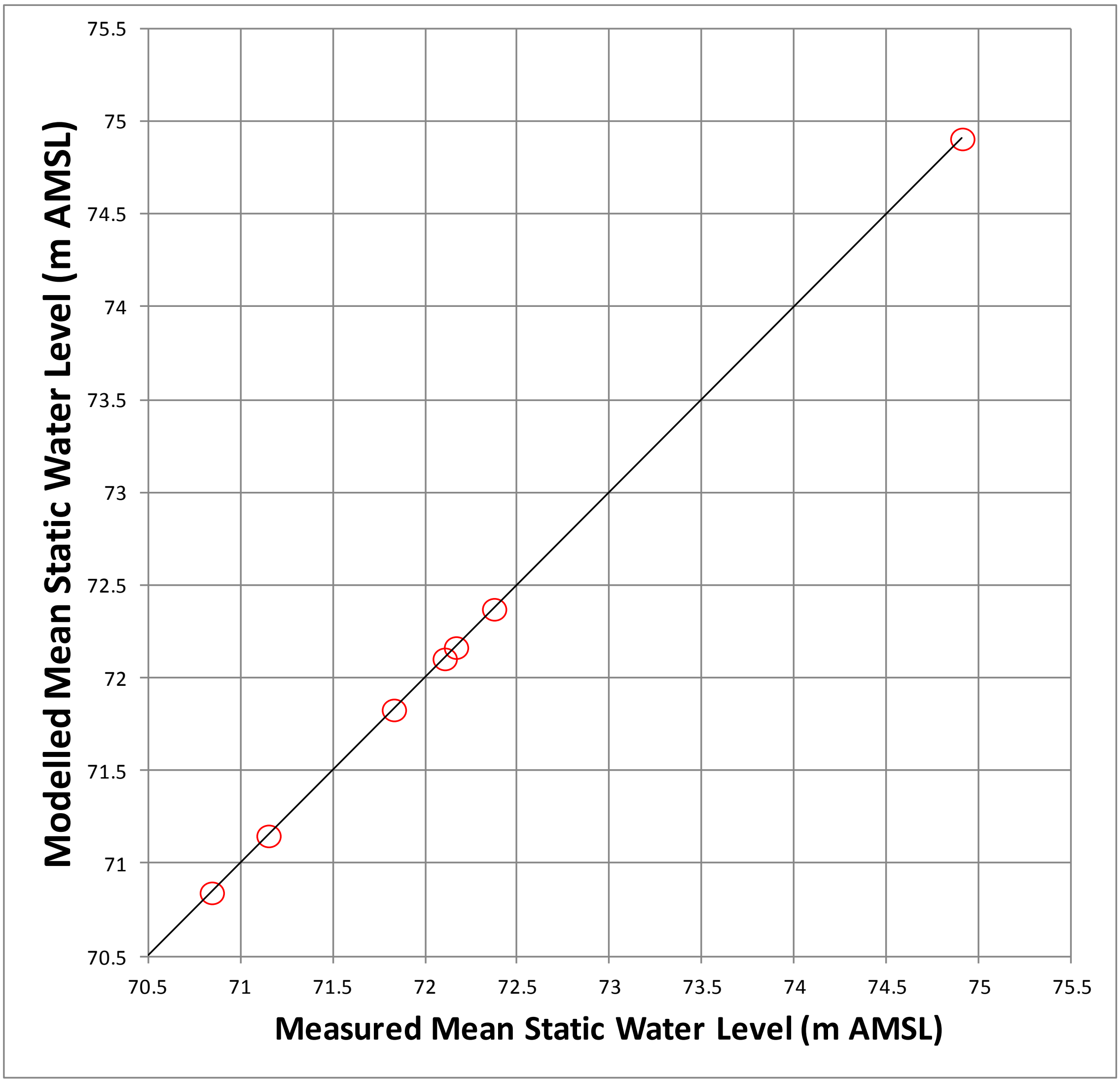

Figure 1: **Plot of measured and modelled mean static water levels following parameter optimisation.**

The resulting optimised hydraulic conductivity across the aquifer fell within a plausible range of values between 4 m/d and 175 m/d. Such absolute values and the range of hydraulic conductivity values are consistent with ORC's understanding of the glacial outwash gravels comprising the Ettrick Aquifer.

Numerical Modelling Results

The scenarios modelled evaluated the essential question posed in relation to nitrogen sensitive zones. What nitrogen discharge limit is sufficiently protective of groundwater nitrogen status? In terms of assessing protection levels, the drinking water standard of 11.3 gN/m^3 for nitrate nitrogen was chosen as the upper limit (see Figure 9).

MODFLOW defined a groundwater flow pattern as shown in Figure 2. The water table contours are in terms of mean sea level. Arrows show inferred flow paths.

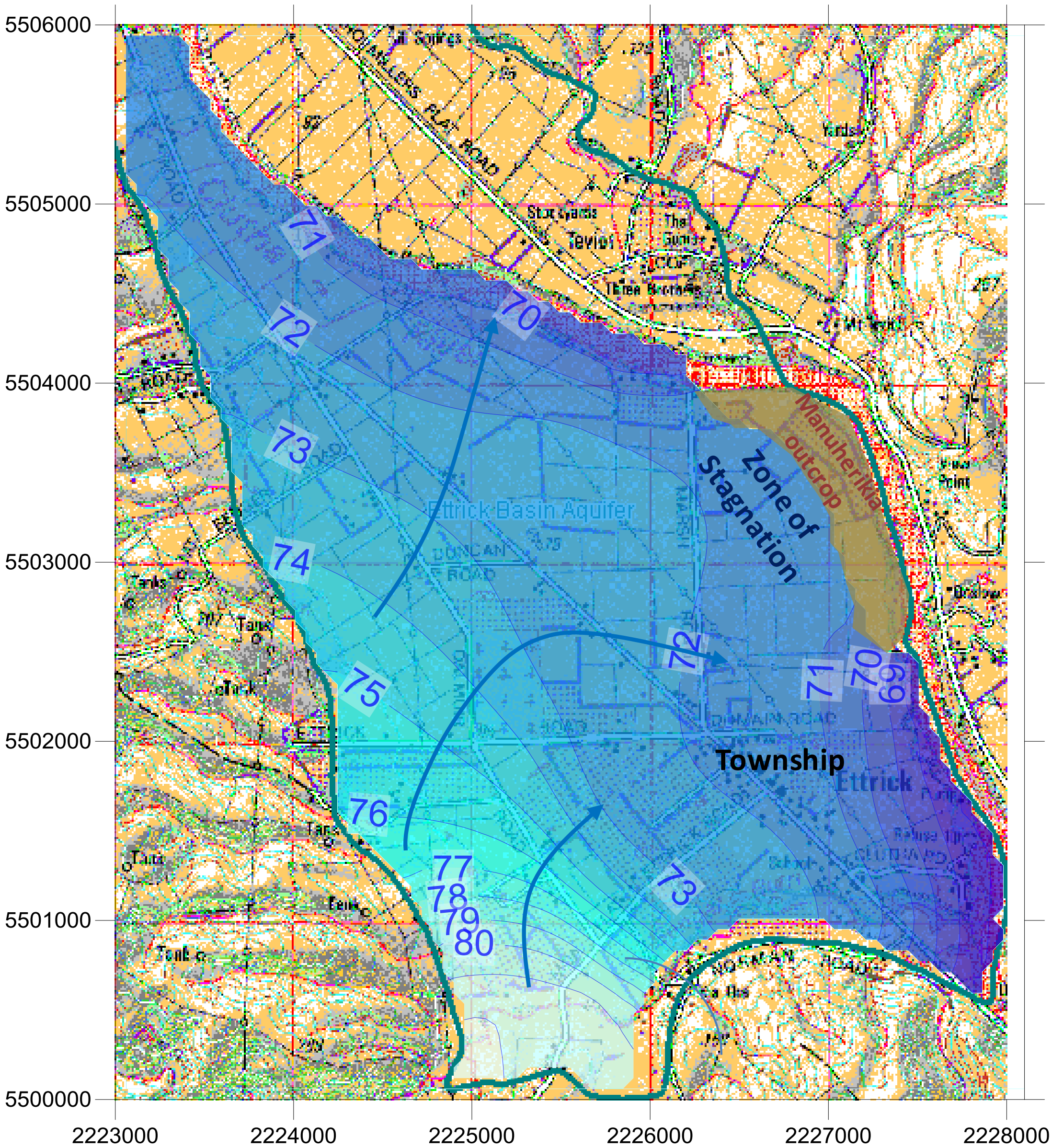

Figure 2: **Groundwater flow pattern defined in MODFLOW simulation of Ettrick Aquifer.**

MT3DMS modelling of the accumulation of nitrogen in the aquifer over 35 years is shown in Figure 3 to Figure 8 as colour floods and graphs. Figure 3, Figure 5 and Figure 7 show contoured nitrogen concentration across the aquifer. Figure 4, Figure 6, Figure 8 and Figure 9 plot nitrogen accumulation through time as 'seen' at the Ettrick monitoring bore (G43/0032) marked in the maps on the northern side of the township.

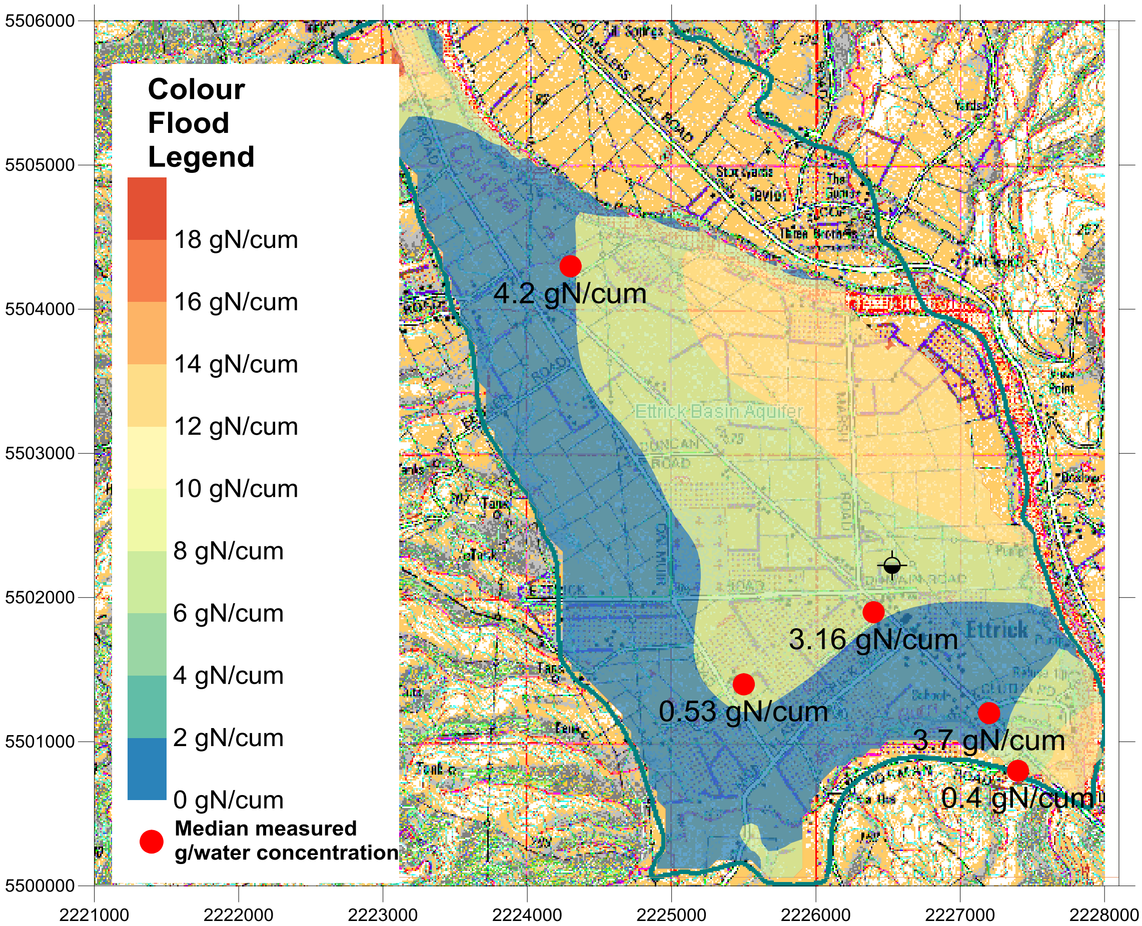

Figure 3: **Modelled nitrogen concentrations in Ettrick Aquifer under 10 kgN/ha/y loading. Measured median nitrate nitrogen concentrations are shown for comparison.**

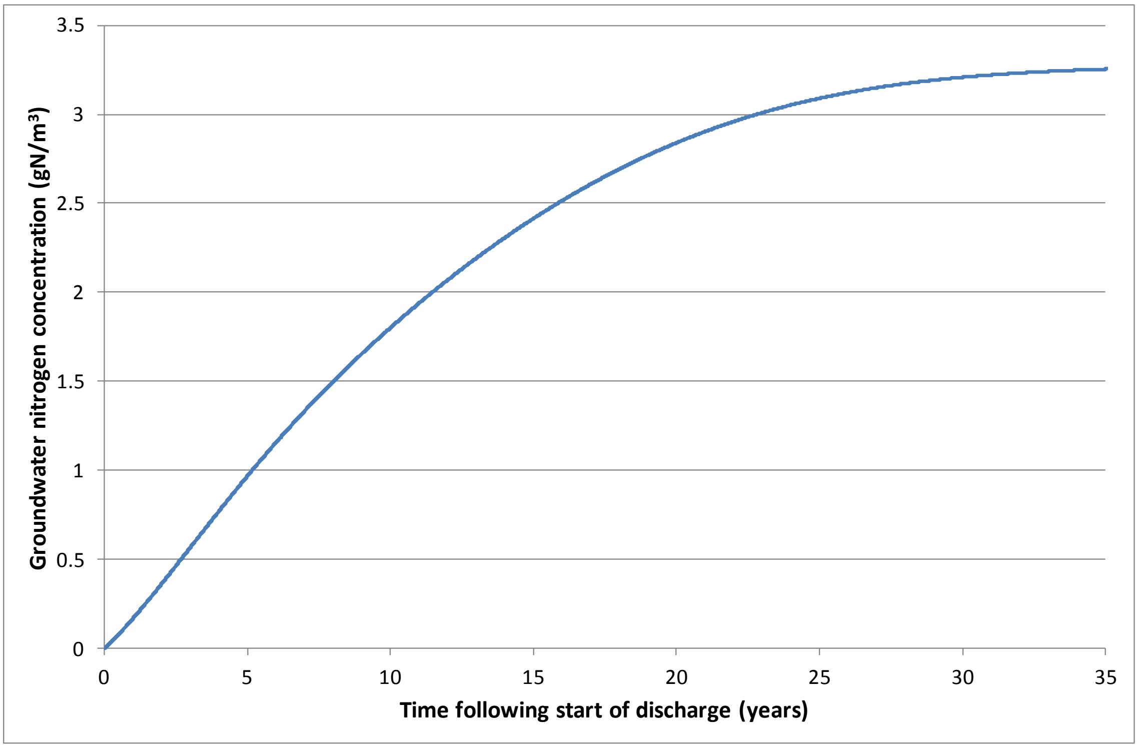

Figure 4: **Modelled nitrogen concentrations as time series under 10 kgN/ha/y loading. The concentration was as 'seen' at the monitoring bore marked ① thus above.**

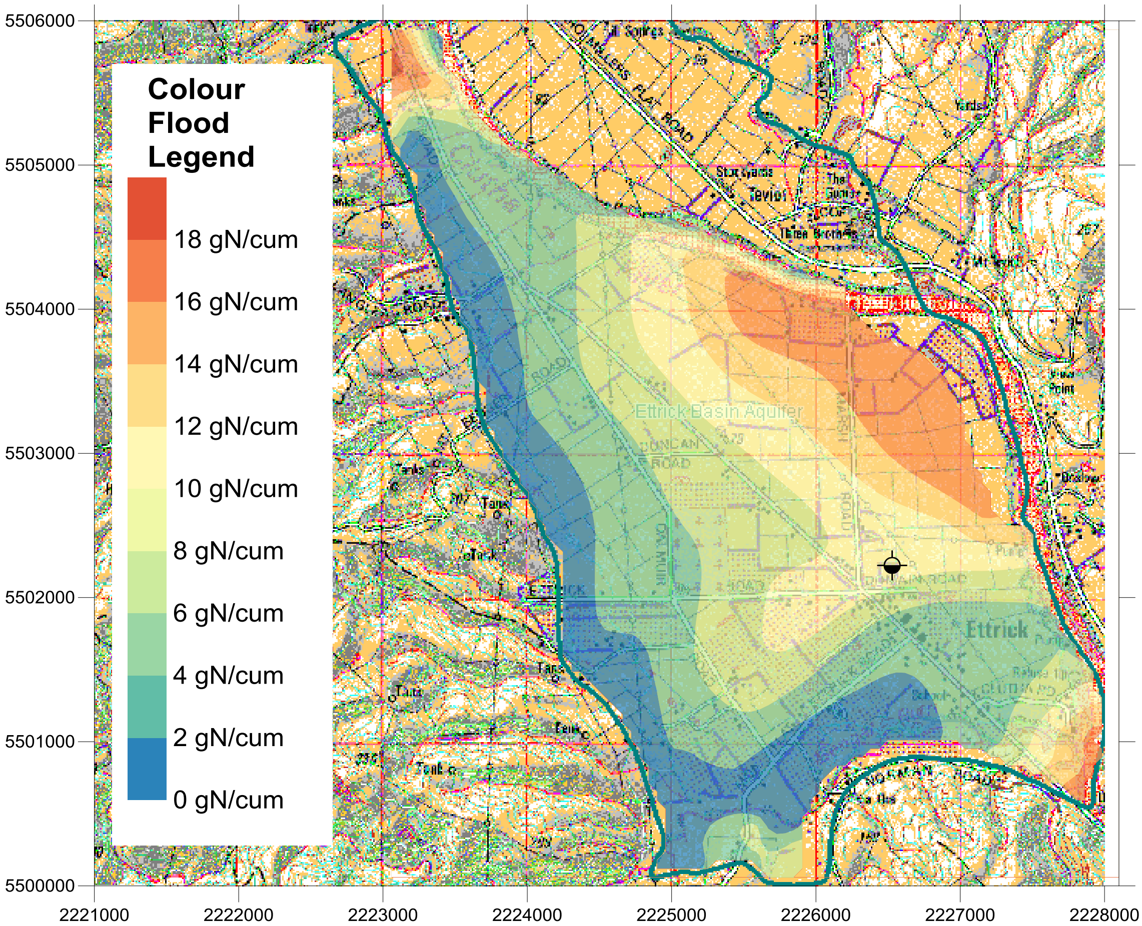

Figure 5: **Modelled nitrogen concentrations in Ettrick Aquifer under 20 kgN/ha/y loading.**

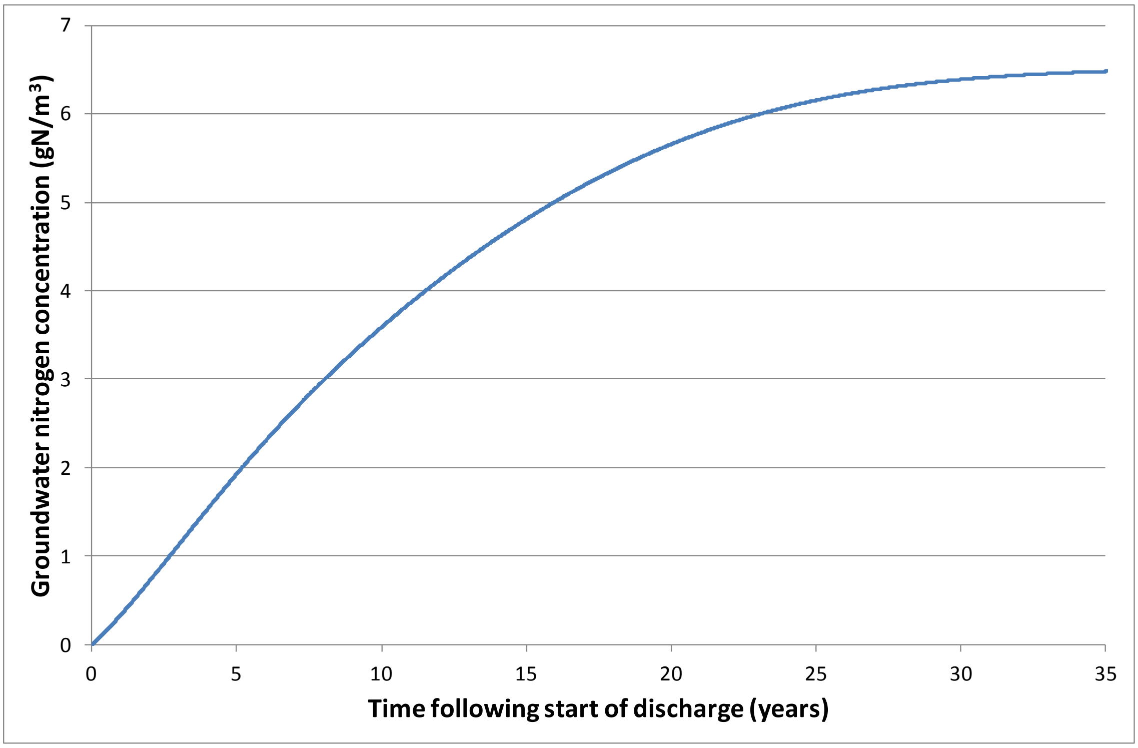

Figure 6: **Modelled nitrogen concentrations as time series under 20 kgN/ha/y loading.**

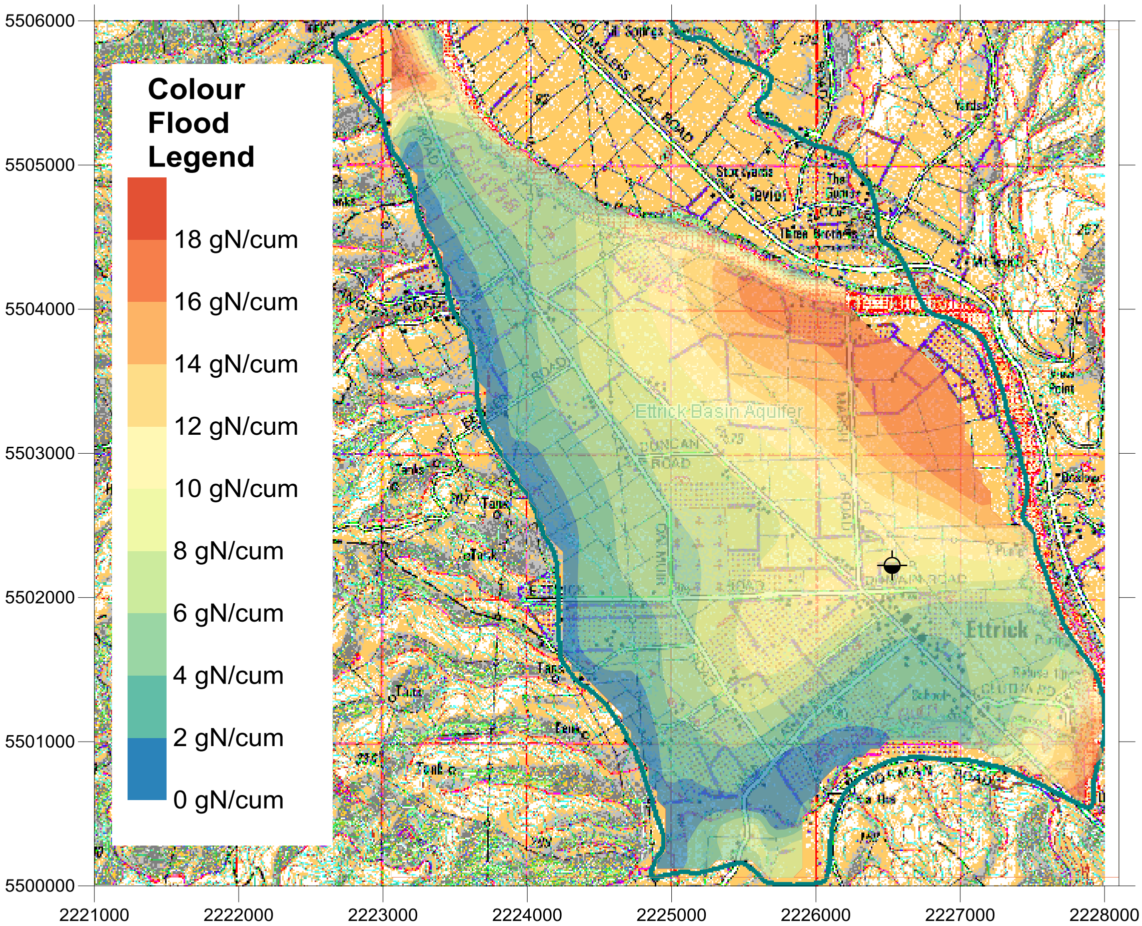

Figure 7: **Modelled nitrogen concentrations in Ettrick Aquifer under 30 kgN/ha/y loading.**

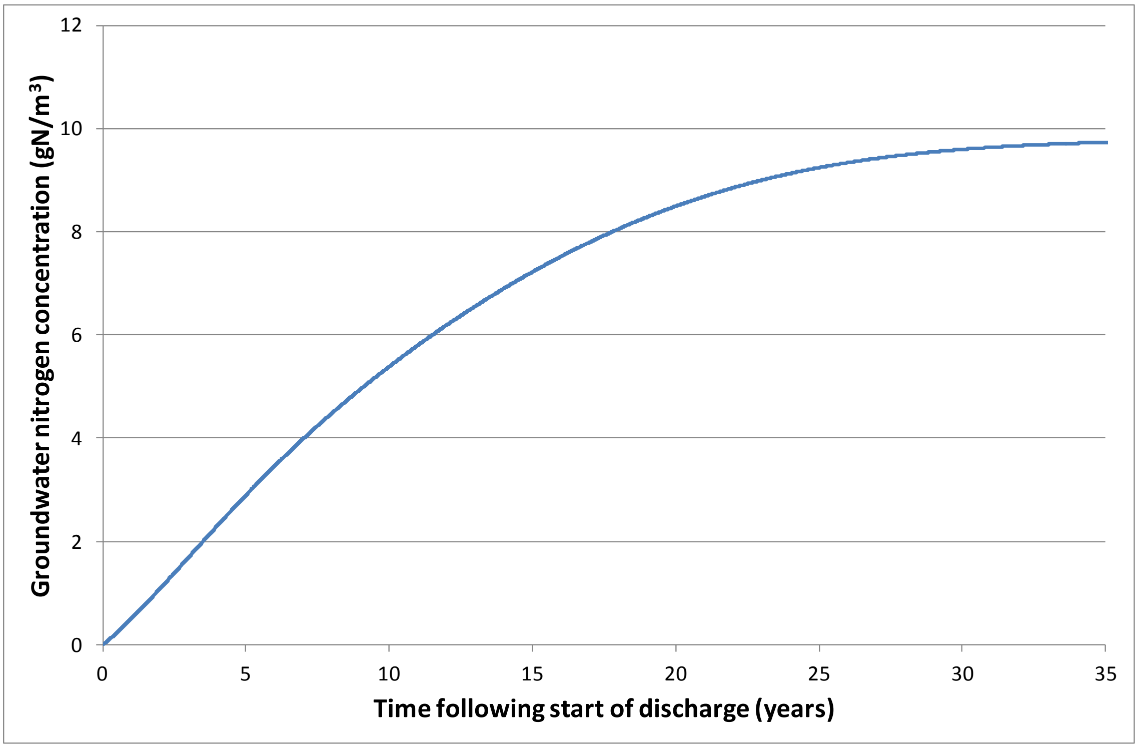

Figure 8: **Modelled nitrogen concentrations as time series under 30 kgN/ha/y loading.**

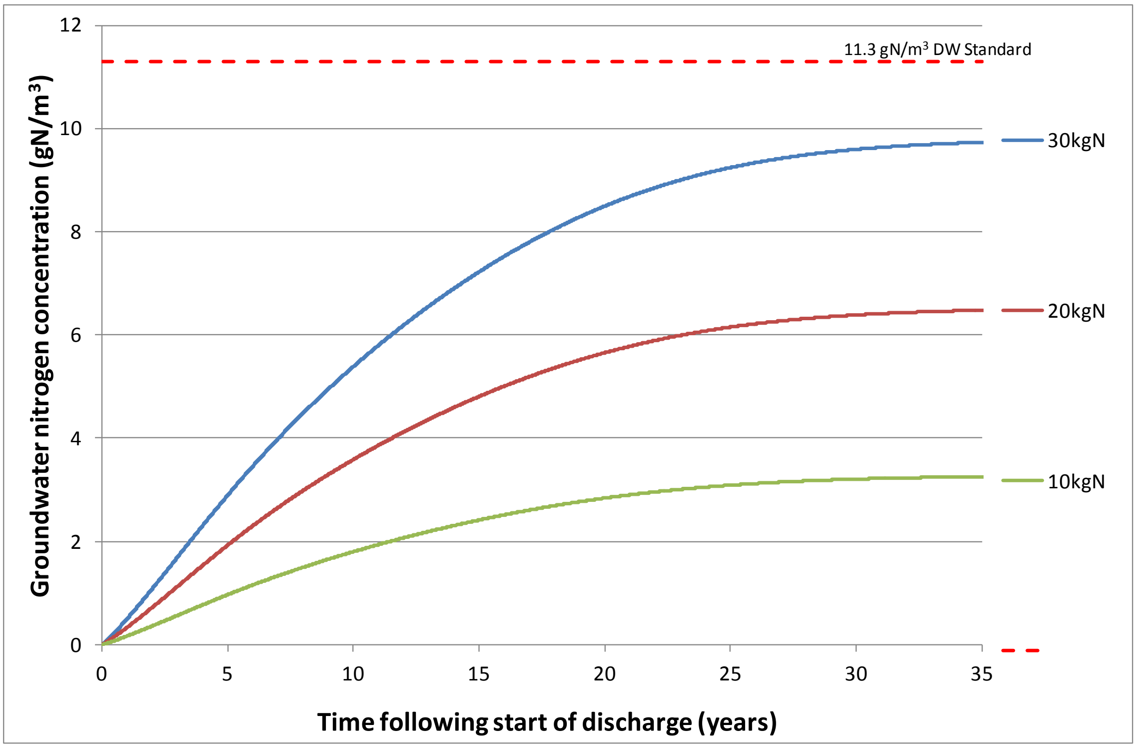

Figure 9: **Modelled nitrogen concentrations at monitoring bore marked ① in Figure 2 as time series under 10, 20 & 30 kgN/ha/y loading displayed for ready comparison.**

When taken together, the MT3DMS modelling results reveal that 20 and 30 kgN/ha/y loadings induce areas of above drinking water standard nitrate nitrogen concentrations in unconfined groundwater, while at 10 kgN/ha/y loading does not. The most affected area coincides with a zone of stagnation abutting the Manuherikia Formation outcrop on the banks of the Clutha River / Mata Au (see Figure 2). The Manuherikia Formation is effectively impermeable thus impeding groundwater flow. Therefore the surface outcrop area of the formation is specified as No Flow boundary cells in the MODFLOW simulation. This cuts the aquifer off from discharge into the river for the length of the Manuherikia Formation outcrop and causes groundwater adjoining the outcrop to stagnate relative to zones north and south.

Discussion

The dilution capacity of surface water recharges at the Benger Burn and the Mt Benger range front have a tempering effect on groundwater nitrogen concentrations. However, as groundwater within the aquifer moves eastward land surface recharge containing nitrogen mixes to raise the concentration progressively as the water moves east. The township area would have the greater number of receptors in terms of drinking water quality. Up to 175 individuals lived in the three Ettrick mesh blocks according to the 2006 census. Most population was centred on the SH8 – Ettrick Road – Domain Road area. Without a communal water supply, this area obtains water from individual water bores. This continues to be the case. ORC recognised the water quality vulnerability in 1998 and instituted a Groundwater Protection Zone A across the Ettrick Aquifer with consequent controls on new septic discharges and disturbance of the soil mantle. A nitrogen sensitive zone would also recognise the modelled vulnerability to nitrate nitrogen accumulation.

Conclusions

1) The Ettrick Aquifer carries a multitude of waters recharged from different sources, and these can be summarised as follow:
   a) Rainfall induced (Land Surface) Recharge (LSR), containing nitrogen
   b) Range-front Recharge from the Mt Benger foothills
   c) Surface water recharge from the Benger Burn

2) The Ettrick Aquifer is glacial outwash gravel aquifer and unconfined, receiving soil drainage LSR with appreciable nitrogen content attributable to agricultural / horticultural land use.

3) Groundwater nitrogen is significantly diluted by low nitrogen surface water from other sources of recharge.

4) A Manuherikia Formation outcrop mapped in geological map sheets of the Ettrick area would impart a zone of stagnation in the groundwater pattern abutting it.

5) The zone of stagnation noted above is significant in MT3DMS modelling results in elevating associated groundwater nitrogen concentrations.

6) Groundwater nitrogen concentrations modelled in the vicinity of Ettrick Township range as follows for the nitrogen loadings selected:
   a) At 10 kgN/ha/y, the township concentration after 35 years was 3.3 gN/m^3.
   b) At 20 kgN/ha/y, the township concentration after 35 years was 6.2 gN/m^3.
   c) At 30 kgN/ha/y, the township concentration after 35 years was 9.7 gN/m^3.

7) It is notable that a considerable lag between soil drainage becoming elevated with respect to nitrogen and the groundwater nitrogen concentrations coming to equilibrium exists and can be approximately defined in advective – dispersive modelling with MT3DMS.

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Appendix B

Modelling of the North Taieri groundwater System around Mosgiel.

Background

Plan Change 6A of the Otago Regional Plan: Water contains nitrogen discharge limits in proposed clause 12.C.1.3:

5. *"The discharge of nitrogen from land to groundwater, is a **permitted** activity, providing:*
    i) *From 31 March 2019, calculated nitrogen leaching by the Council using OVERSEER version 6.0 does not exceed:*
        (a) 10 kilograms nitrogen per hectare per year over any nitrogen sensitive zone identified in Maps I1-I6; and
        (b) 30 kilograms nitrogen per hectare per year elsewhere in Otago; and
    ii) *Upon request ...."*

The North Taieri groundwater protection zones around Mosgiel are listed and pictured in map I-3 as a nitrogen sensitive zone. The rationale for selecting this area can be gleaned from the original report setting forward the justification for nominating seven sensitive zones, as follows:

- *A history of nitrate nitrogen accumulation as measured in local monitoring bores and township water supply bores.*
- *This part of the Lower Taieri Aquifer lacks post-oxic or anoxic redox conditions in the saturated zone or subsoil that would lead to pervasive de-nitrification of incoming nitrate nitrogen.*
- *Unconfined aquifer.*
- *Longer Mean Residence Time (MRT) of groundwater in the aquifer, but significantly younger than 50 years (< 10 to 30 years BP at depths down to 30 m BGL).*

The location and disposition of the areas are shown in Figure 10.

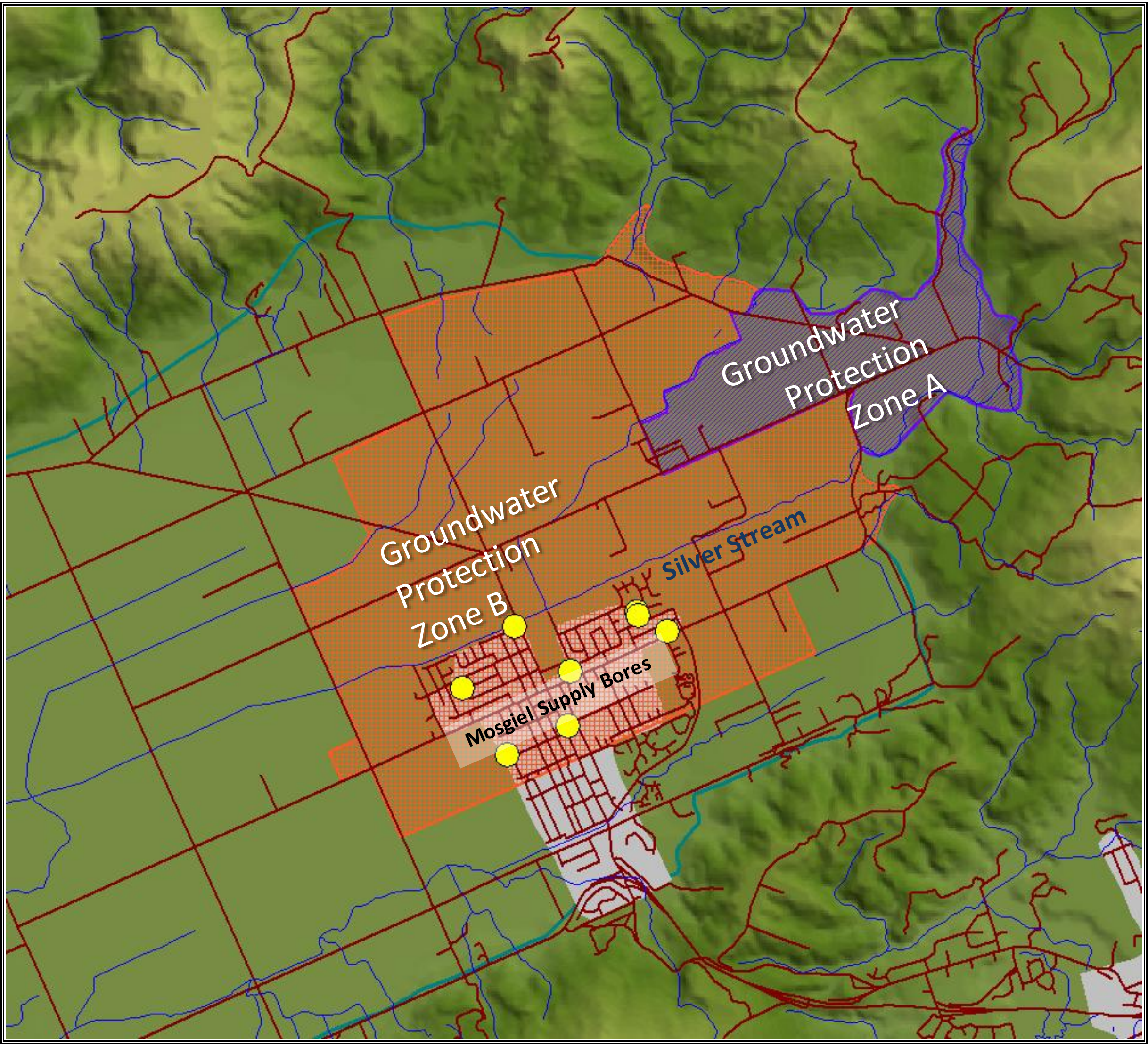

Figure 10: Location of groundwater protection zones making up the Nitrogen Sensitive Zone.

The original rationale for defining groundwater protection zones around and up-gradient of Mosgiel recognised the following facts:

- Mosgiel Township is supplied with water from the water supply aquifer at depths between 30 m and 45 m and 8 bores.
- The township has a population of approximately 9,000 individuals, and resource management needed to consider public health risk in terms of water quality or toxicants entering the water supply aquifer.
- The groundwater protection zone A was considered to cover the clearly unconfined up-gradient portion of the aquifer making up the primary recharge zone.
- The groundwater protection zone B was considered to cover the increasingly stratified portions of the aquifer with its secondary recharge zones, particularly the Silver Stream upstream of Gordon Road.
- The Mosgiel supply bores all displayed elevated nitrate nitrogen to some extent (i.e. >0.5 gN/m^3), implying that modern water could enter the water supply aquifer and was sufficiently young to be affected by post-war land use or waste disposal practices.

The original surveys of the Lower Taieri Aquifers (Irricon & Royds Consulting, 1994; and Irricon & ESR, 1997) found indications of grazing agriculture effects on groundwater quality, plus evidence of lax waste disposal practices at three landfills and a few more contaminated sites in the up-gradient recharge zone to the Mosgiel water supply. Further investigations, monitoring and groundwater protection measures were recommended as a result. The groundwater protection zones as delineated above were included in the 1998 draft of the Regional Plan: Water.

A subsequent groundwater allocation investigation and model project confirmed the critical role of the Silver Stream between Puddle Alley and Gordon Road in augmenting the water supply aquifer at Mosgiel (Rekker & Houlebrooke, 2010). The same report compared the high nitrate and chloride in shallow Mosgiel groundwater with the low nitrate and chloride in the Silver Stream, and speculated that the moderate nitrate and chloride concentrations in Mosgiel bore water was a result of mixing those two primary sources of water. In the face of evidence of infiltration of surface water and subsequent mixing of surface water and soil drainage being pumped as groundwater from moderately deep bores under Mosgiel, the vulnerability of the water supply would appear to be confirmed. The distinction is important because some previous analyses of Mosgiel contaminant hydrogeology (e.g. van der Raaij, 2009) have assumed or inferred confined aquifer conditions at the Mosgiel water supply bores when adopting stratified, unconfined conditions would be more conservative in terms of groundwater quality protection.

The North Taieri area, as for all developed flat pasture in the country, is attractive for the development of intensive agriculture, including cropping and dairy grazing. Shallow North Taieri groundwater has a nitrate-nitrite nitrogen concentration of between 6 gN/m^3 and 12 gN/m^3, while deeper water supply aquifer water has an extraction-weighted mean concentration of 3.2 gN/m^3.

Numerical Modelling

Modelling of the North Taieri compartment of the Lower Taieri groundwater system began with simulation of the soil-moisture of the area’s pasture. This had been undertaken as part of earlier groundwater modelling of the wider basin groundwater system (Rekker & Houlebrooke, 2010). Nine of the twelve previously modelled soil classes resided within the North Taieri area. Four of the nine soil classes were considered to have an active role in leaching of nitrate nitrogen.

The larger Lower Taieri groundwater model extending from North Taieri to Clarendon beyond Lake Waihola (Rekker & Houlebrooke, 2010) was cut down to encompass only the East Taieri zone, including North Taieri and Mosgiel. The groundwater model in MODFLOW included three separate layers simulating depth domains within the groundwater system, linked by groundwater exchanges at their bottom and top surface. The vertical groundwater exchanges were controlled or governed by the vertical hydraulic conductivity and the gradient between each layer. The model had a surface extent of 48.2 km^2 and extended across the Taieri Plain from one flank defined by the North Taieri Fault in the northwest to the Titri Fault in the southeast. The model extended downstream almost to the Taieri River between Outram Bridge and Allanton. This farthest (south-western) extent of the model was considered to be of less importance to the nitrate simulations due to the chemical reduction once groundwater flowed beneath the Waihola Silt/Sand (Barrel et al, 1999 and Litchfield et al, 2002).

The MODFLOW groundwater modelling and MT3DMS contaminant transport codes were implemented within the Groundwater Vistas (Rumbaugh and Rumbaugh, 2007) modelling package. Optimisation of this model was performed with the aid of the PEST optimisation package (Doherty and Hunt, 2011). Contaminant transport was simulated with the MODFLOW component package MT3DMS (Zheng and Wang, 1999).
Modelling followed the following procedure:

5. Calculate land surface recharge for irrigated and non irrigated areas with the Rushton model (see Rekker & Houlebrooke, 2010, Appendix B).
6. Calculate the nitrate-N concentration of leachate for each soil group and recharge rate.
7. Construct and optimise a MODFLOW model for observed conditions.
8. Run MODFLOW and MT3DMS to simulate the impact of a range of nitrogen discharge rates on the Ettrick Aquifer groundwater nitrogen concentrations.

This process is shown diagrammatically below:

Recharge Model **Soil Nutrient Model**
↓ ↓
MODFLOW groundwater
flow model
↓
MT3DMS groundwater
transport model

A soil nutrient modelling exercise was not ultimately carried out by ORC. Rather, leachate values of nitrate-N mass in kgN/Ha/y were taken from the 6A plan change document.

Calibration & Automated Parameter Estimation

The cut-down model was re-calibrated using transient groundwater level data collected as part of SOE monitoring since 1997. The recalibration process included intensive parameter estimation using the PEST. The parameter optimisation tools used were those within the PEST code (Doherty and Hunt, 2011). The primary optimisation parameters were the horizontal hydraulic conductivity field across the water bearing, plus river bed conductance relating to the Silver Stream.

The process of PEST optimisation proceeded to reduce errors between measured and modelled mean static water levels, indicating a satisfactory calibration outcome. Figure 11 shows the calibration result as a plot of measured levels versus modelled levels at the Harley Bore, shallowest (P6, 5.5 m to 7.5 m) piezometer.

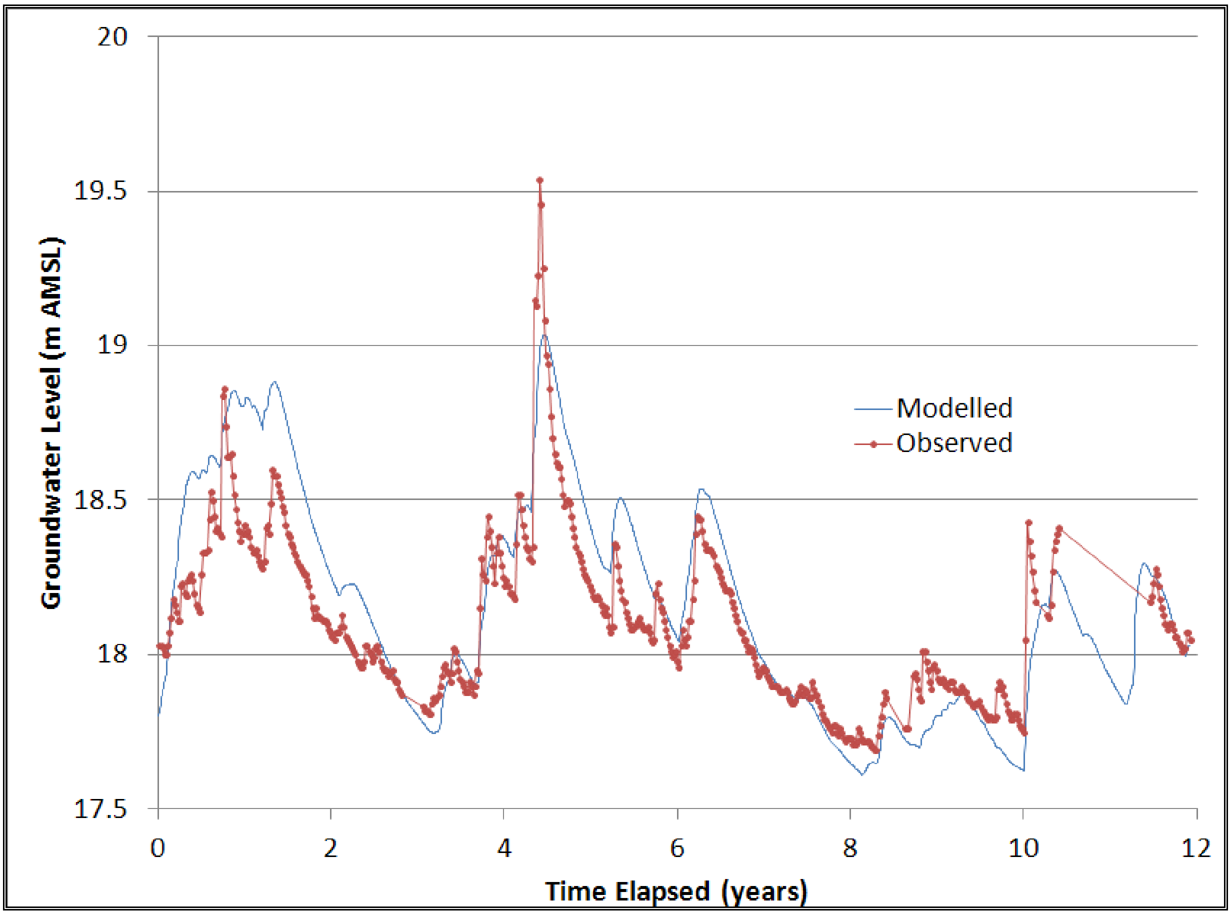

Figure 11: Modelled versus observed groundwater level in shallow groundwater near Mosgiel.

The normalised root mean square error (NRMSE) is the root mean square error (RMSE) divided by the range of observations is defined in the following equation.

$$NRMSE = \frac{RMSE}{X\ obs,max\ -\ X\ obs,min}$$

NRMSE is used in this case as the measure of fit between observed and modelled groundwater levels across the five level monitoring points within the model domain[3]. The calibration period of twelve years from April 1996 to April 2008 allowed five monitoring bores with either continuous or periodically dipped water level records to be used in history matching. The NRMSE for the model was calculated as 0.06 (or 6%), which is considered acceptable.

The cross-plot of observed and measured levels is shown in Figure 12 and differentiates shallow aquifer and deeper water supply aquifer bores.

[3] Anderson, M.P.; Woessner, W.W. 1992: *Applied Groundwater Modeling: Simulation of Flow and Advective Transport* (2nd Edition ed.). Academic Press.

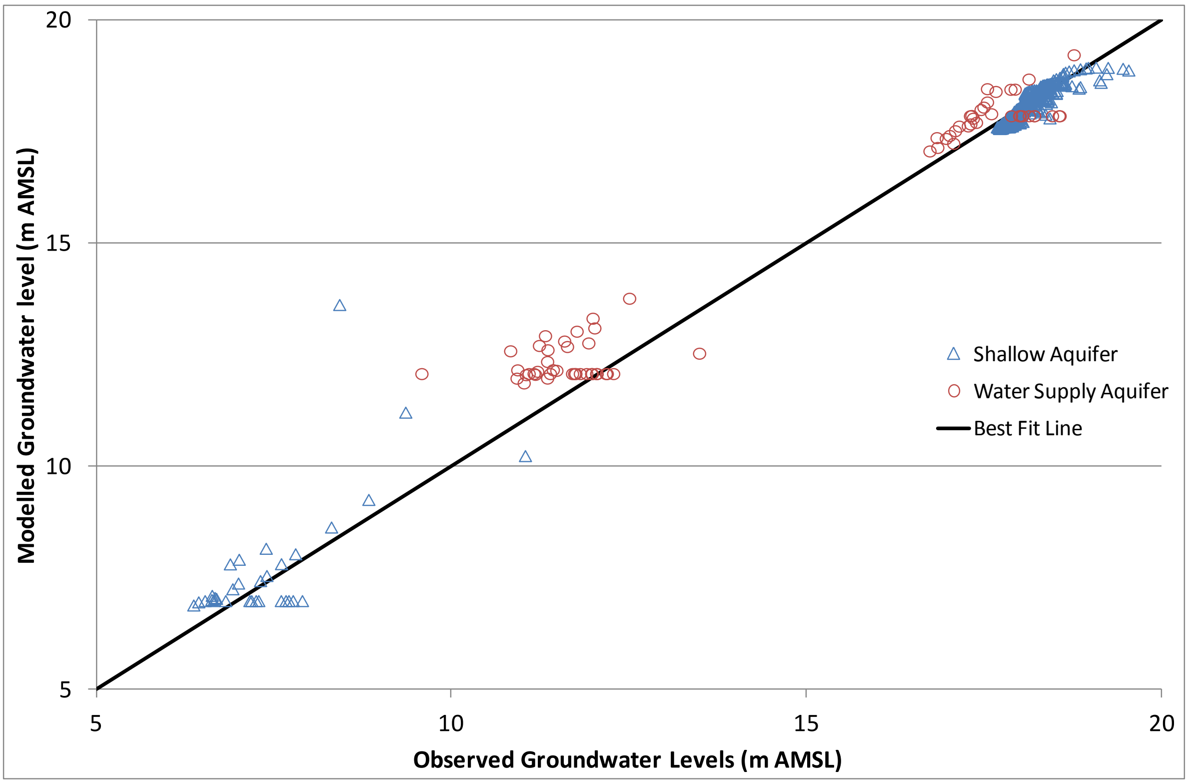

Figure 12: Cross-plot of observed versus modelled groundwater levels in five bore records.

Thus we see in the NRMSE result, time series trace in Figure 11 and the cross-plot in Figure 12 that the calibration arrived at a reasonable fit against reality.

Scenario Modelling

Having developed a groundwater flow model and calibrated it adequately, the next step was to devise nitrogen transport scenarios using MT3DMS. MT3D signifies "mass transport in three dimensions", so the dispersion coefficients in three dimensions were first specified.

- Longitudinal dispersivity = 0.1
- Lateral dispersivity = 0.01
- Vertical dispersivity = 0.001

These coefficients of dispersivity were taken from investigations deriving such coefficients for sandy gravel aquifers in New Zealand (Thorpe et al, 1982; and PDP & ECan 2002). The MODFLOW model was also configured in three layers, allowing the three dimensional movement of nitrogen through the model in additional to three-dimensional dispersion. The scenarios devised followed the range of nitrogen limits that might be deployed to protect the area's groundwater nitrogen status.

- 10 kgN/ha/y
- 15 kgN/ha/y
- 20 kgN/ha/y
- 25 kgN/ha/y
- 30 kgN/ha.y

These loadings were combined with surface recharge as recharge rates (m/d) and concentrations (gN/m^3) to deliver the soil drainage to the water table under four relevant soil classes.

$$Soil\ drainage\ concentration = \frac{Nitrogen\ loading}{Recharge}$$

Soil drainage concentrations were calculated for each recharge zone and each transient stress period using the formula above. The MT3DMS simulation initially traversed the same 12 year time period and used the same data as for the calibration process. The Silver Stream was simulated as having a uniform nitrogen concentration of 0.2 gN/m^3. This is a few orders of magnitude lower than concentrations applied as soil drainage, so dilution with surface water would result.

Seven groundwater monitoring sites have been monitored in North Taieri as part of the SOE programme since 1996. Five of these bores would appear to be screened in the deeper water supply aquifer beyond depths of 25 m. Two bores (Anderton and Morris) are located in the area adjacent to Milners Road landfill and are shallow, probably more readily classed as drawing on the unconfined aquifer. The water supply aquifer monitoring bores are associated with low nitrate/nitrite nitrogen concentration, typically >2.5 gN/m^3. The two shallow, unconfined aquifer bores are clearly associated with higher nitrate/nitrite nitrogen concentrations, up to 11.5 gN/m^3. Figure 13 shows the pattern as a combined concentration – time plot.

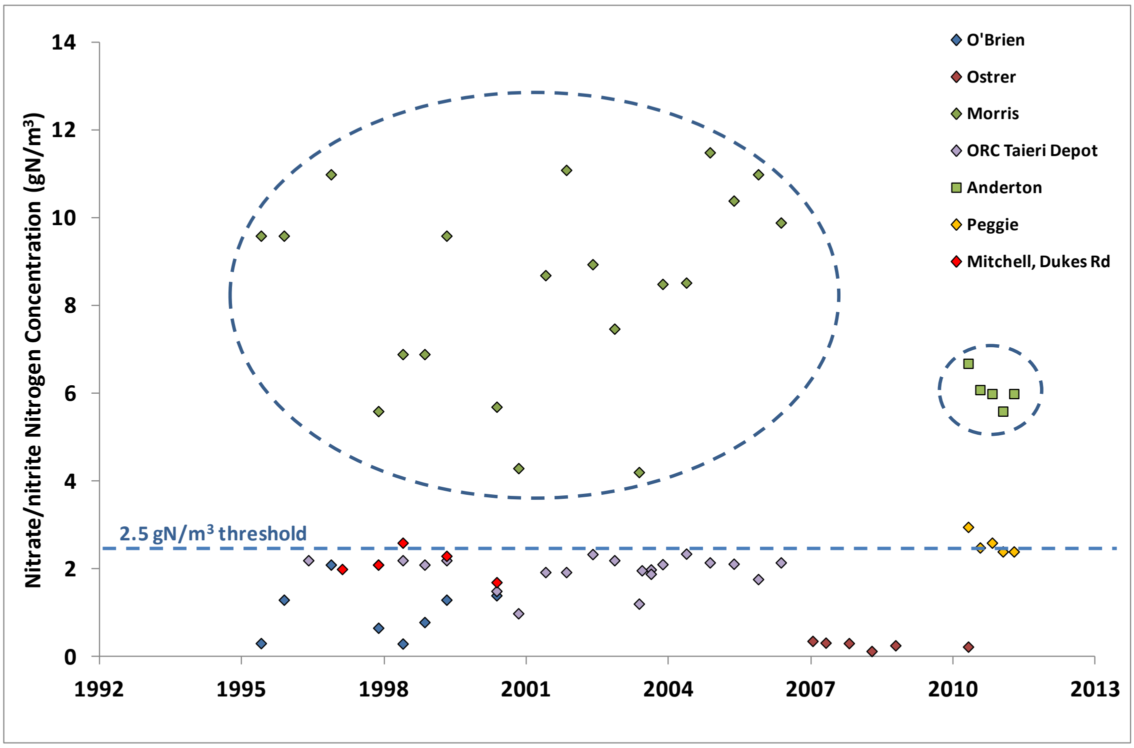

Figure 13: **Concentration versus time plot of SOE monitoring for nitrogen in the North Taieri groundwater system. Differentiation on the basis of concentration is shown with dashed lines.**

The time – concentration plot in Figure 13 also indicates a stable long-term trend in the ORC Taieri Depot record. The Morris nitrate nitrogen record shows significant volatility, but this is evidence for a shallow bore within the wholly unconfined part of the groundwater system.

Examining the Lower Taieri groundwater recharge modelling (Rekker & Houlbrooke, 2010), four soil classes were considered to contribute to nitrate/nitrite nitrogen leaching in the North Taieri area.

- Zone 4 ("Mill Creek")
- Zone 5 ("alluvial fans")
- Zone 6 ("Silverstream – Owhiro")
- Zone 8 ("Janefield and bed of Silverstream")

The Irricon and ESR (1997) report considered the nitrate leaching potential of the Silverstream – Owhiro and Janefield soil zones to be highest overall. Certainly, these zones have the highest overall percentages of mean annual rainfall draining to groundwater of between 22% and 30% (Rekker & Houlbrooke, 2010). An approximate area of 2,100 ha within the 4,800 ha extent of the model's active cells had recharge applied from these four soil zones. The scenarios were arranged to apply the nitrogen loading within recharge in accordance with the recharge rate.

For example, scenario 1 had a loading of 10 kgN/ha/y (10,000 gN/ha/y)) and a mean recharge rate of 87 mm/y (870 m^3/ha/y).

$$Soil\ drainage\ concentration = \frac{Nitrogen\ loading}{Recharge}$$

So,

$$11.5 = \frac{10{,}000}{870}$$

Transient recharge and concentration data sets were compiled for use in the transient simulation based on the uniform application of 10 to 30 kgN/ha/y.

Model Results

Figure 14 illustrates the groundwater flow pattern in the uppermost, unconfined aquifer in the North Taieri area. The first thing to note was that the model north was rotated 38° from true north for optimal orientation of the larger Lower Taieri Basin in the parent model. Groundwater level contours tiered down the East Taieri towards the Taieri River and School Swamp. The Silver Stream was represented as a river (RIV) boundary in the uppermost model layer between Puddle Alley and School Swamp. The upper Silver Stream and soil drainage recharge made up the model water input to the uppermost model layer. The lower Silver Stream and School Swamp received the water output (outflow), as they were observed to do in reality.

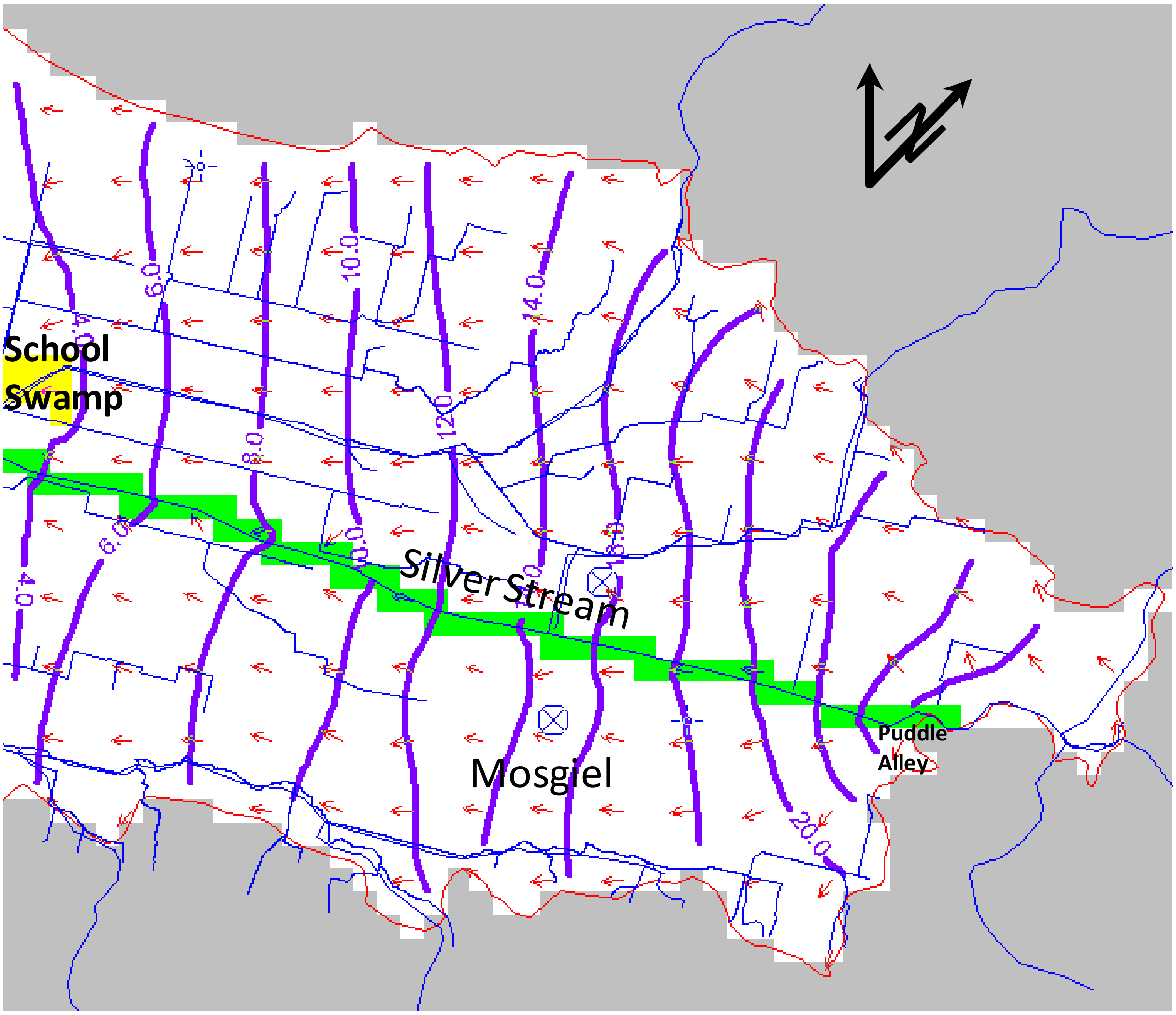

Figure 14: **Model representation of shallow unconfined aquifer flow pattern.**

Land Surface Recharge (LSR) and accompanying nitrogen inputs were applied at the model's uppermost surface as recharge (RCH). Figure 15 shows the areas of the model domain that received LSR during transient simulation in MODFLOW and MT3DMS. The Mosgiel Township area and the immediate vicinity of the Silver Stream were excluded from applied recharge.

The Silver Stream river boundary was assigned a constant nitrogen concentration to emulate the loss of water to the aquifer from the Silver Stream. The median concentration of 0.2 gN/m^3 was determined in SOE monitoring at Blacks Bridge, where the stream enters the model domain. In this manner the low nitrogen inflow from the stream could be accounted for in the nitrogen transport modelling.

Initial nitrogen concentrations were also applied to set the transport simulations to current day conditions and head off any long-term lag effects. The median concentrations in shallow groundwater of 6 gN/m3, and the median concentration in the water supply aquifer of 3 gN/m3, were assigned as initial conditions. A default concentration of 0.3 gN/m^3 was assigned to the lowest model layer in accordance with a small number of measurements beyond 45 m depth.

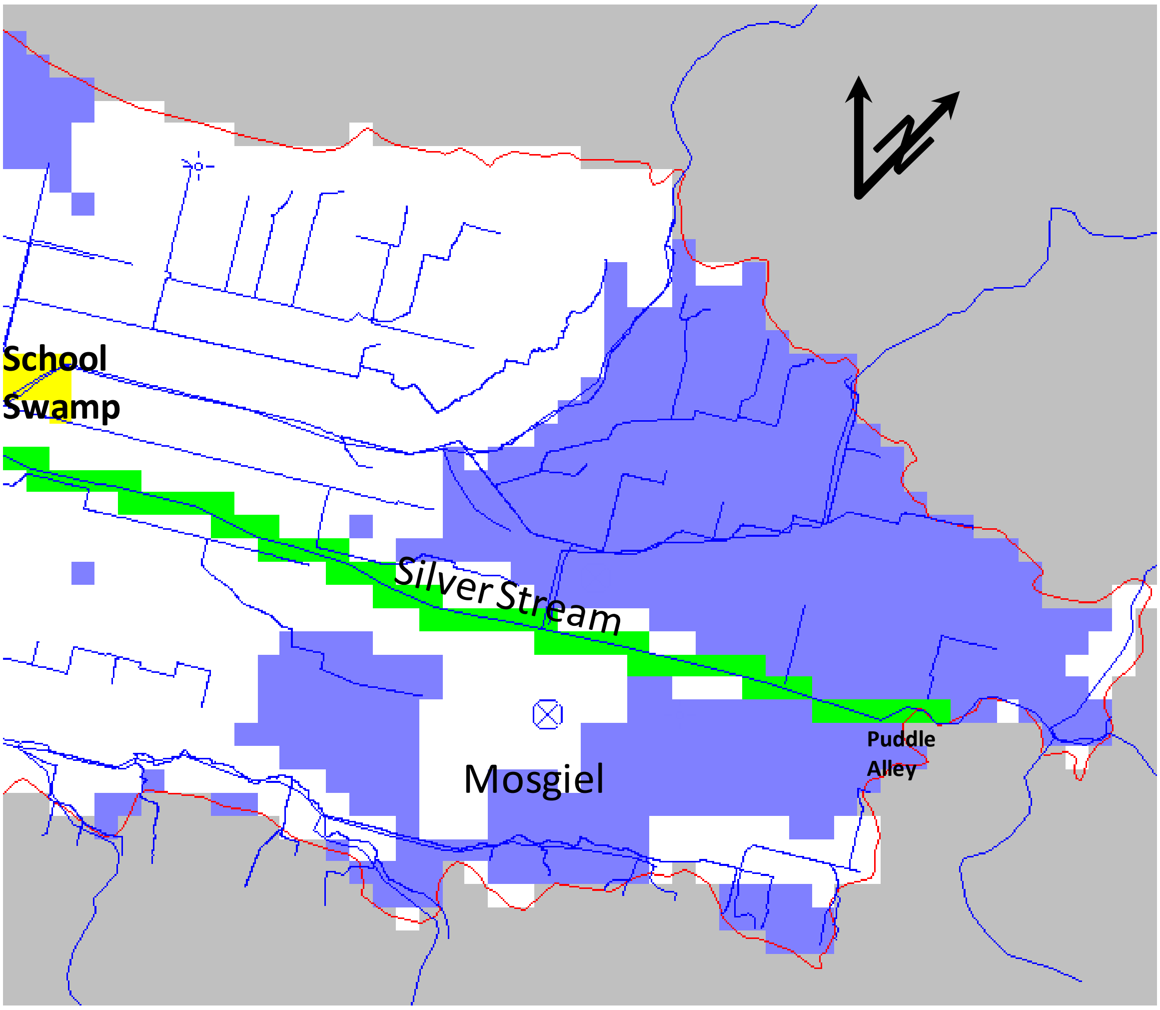

Figure 15: **Locations of applied recharge and dissolved nitrogen in transient model simulation (shown in light blue shading).**

The resulting groundwater nitrogen concentrations can be expressed in snap-shot colour floods of the uppermost aquifer. Figure 16 illustrates the spread of groundwater nitrogen in the shallow aquifer at the point of peak accumulation under the 10 kgN/ha/y rate of loading. From the colour flood pattern of groundwater nitrogen concentrations it is plain to see the diluting effect that the Silver Stream infiltration has on underlying the shallow aquifer.

For another perspective of the accumulation of nitrogen, Figure 17 plots the rise in groundwater nitrogen within the water supply aquifer at the position of one of the water supply bores in Mosgiel under the influence of the low 10 kgN/ha/y loading. As Figure 17 shows, the concentration grows from its initial concentration, peaks and begins a decline. The dynamic variation in nitrogen concentrations is what can be conceptually expected for nitrogen accumulation of a groundwater system in this setting. However, it is extremely difficult to anchor the timing of the accumulation and peak in the historical or current context.

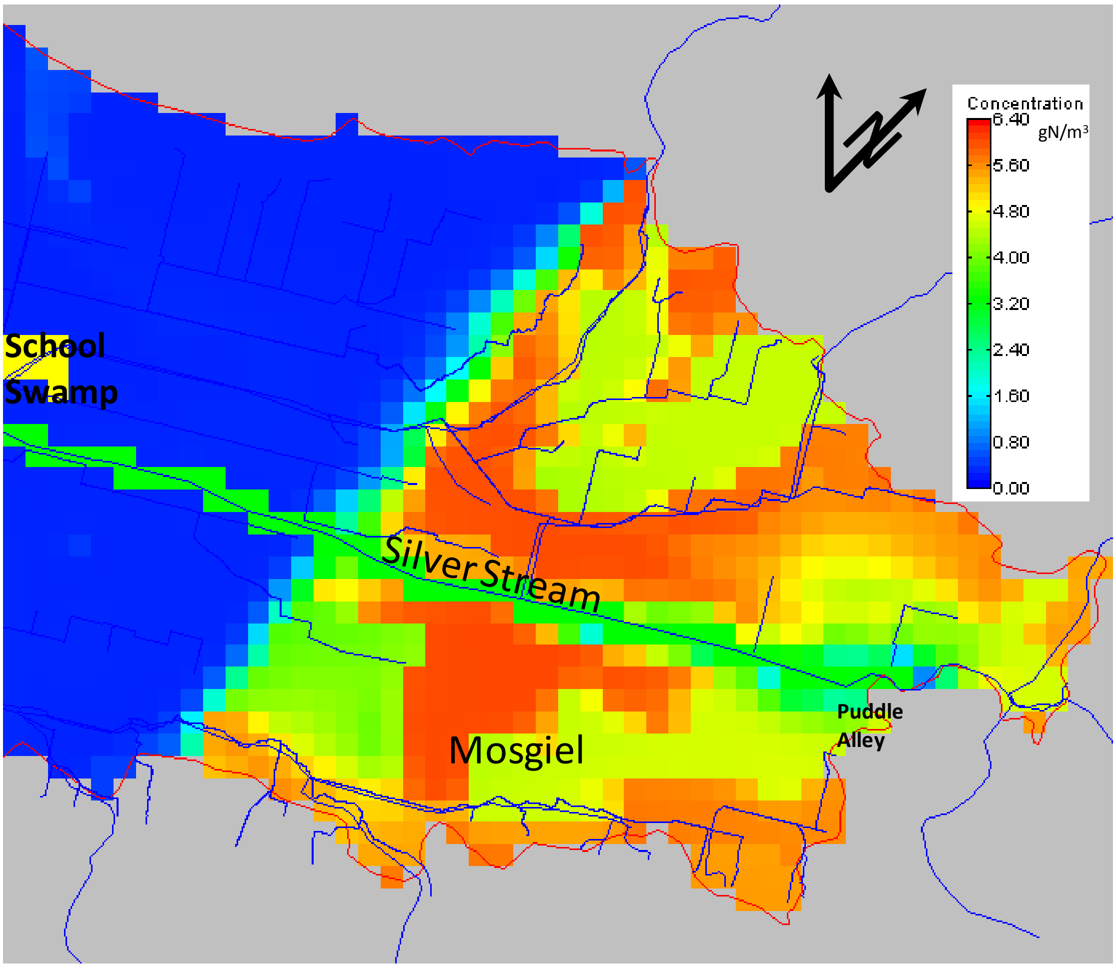

Figure 16: **Peak nitrogen concentrations in transient nitrogen transport simulation for a loading of 10 kgN/ha/y.**

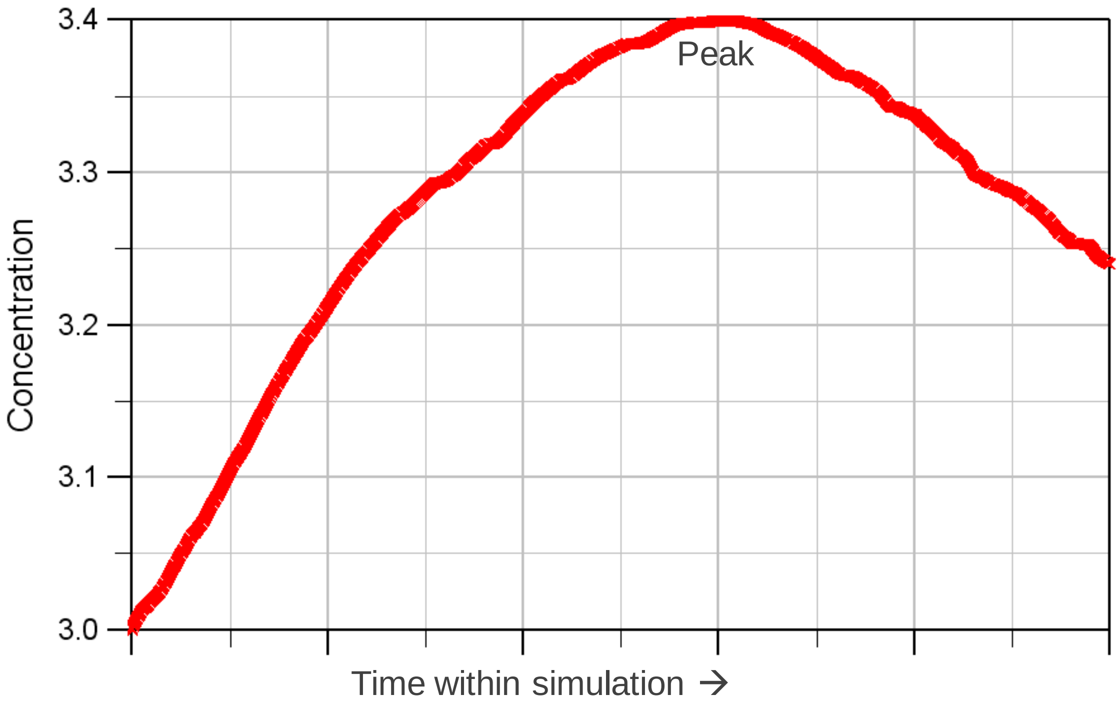

Figure 17: **Groundwater nitrogen concentration in the water supply aquifer at 10 kgN/ha/y.**

One of the surprising findings of nitrogen accumulation modelling with MT3DMS was that nitrogen loading in Land Surface Recharge had little impact on either the shallow aquifer or the water supply aquifer beneath it. Figure 18 illustrates the peak accumulation of shallow aquifer nitrogen for the highest loading of 30 kgN/ha/y, which bears very close resemblance to Figure 16 under the lighter loading of 10 kgN/ha/y. The difference in highest concentrations in the shallow aquifer was about 0.2 gN/m^3, so not very large.

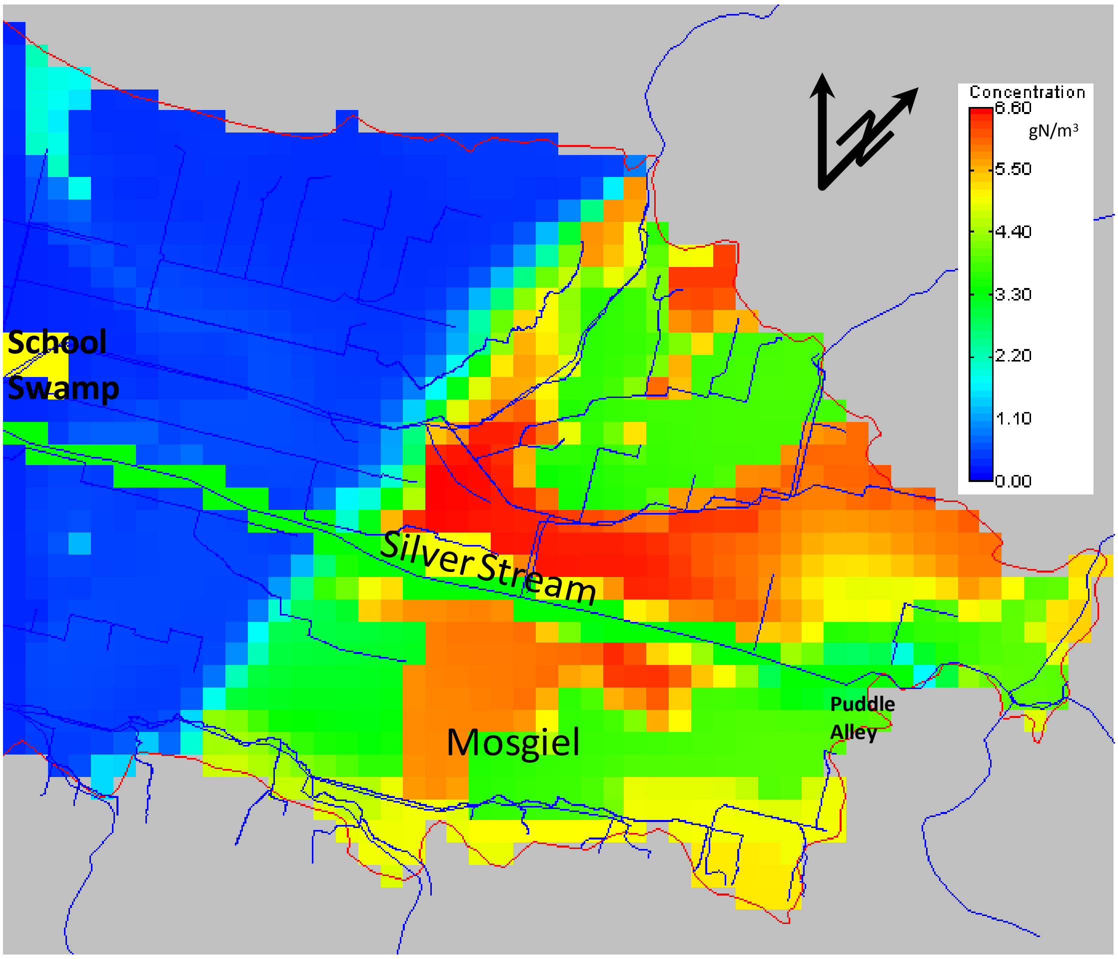

Figure 18: Equivalent nitrogen concentrations for a loading of 30 kgN/ha/y.

The situation is similar for the water supply aquifer beneath the shallow aquifer. Figure 19 for the 30 kgN/ha/y loading plots the rise in concentration from initial water supply aquifer levels to a peak followed by a decline to a level well below initial concentration. The plot suggests that the water supply aquifer really is not significantly affected by Land Surface Recharge sources of nitrogen. When all Mosgiel bore positions are examined a variable pattern of nitrogen impact is evident with peak concentrations lying between 4.4 and 3.1 gN/m^3, while equilibrium concentrations rest at 2.2 and 0.4 gN/m^3.

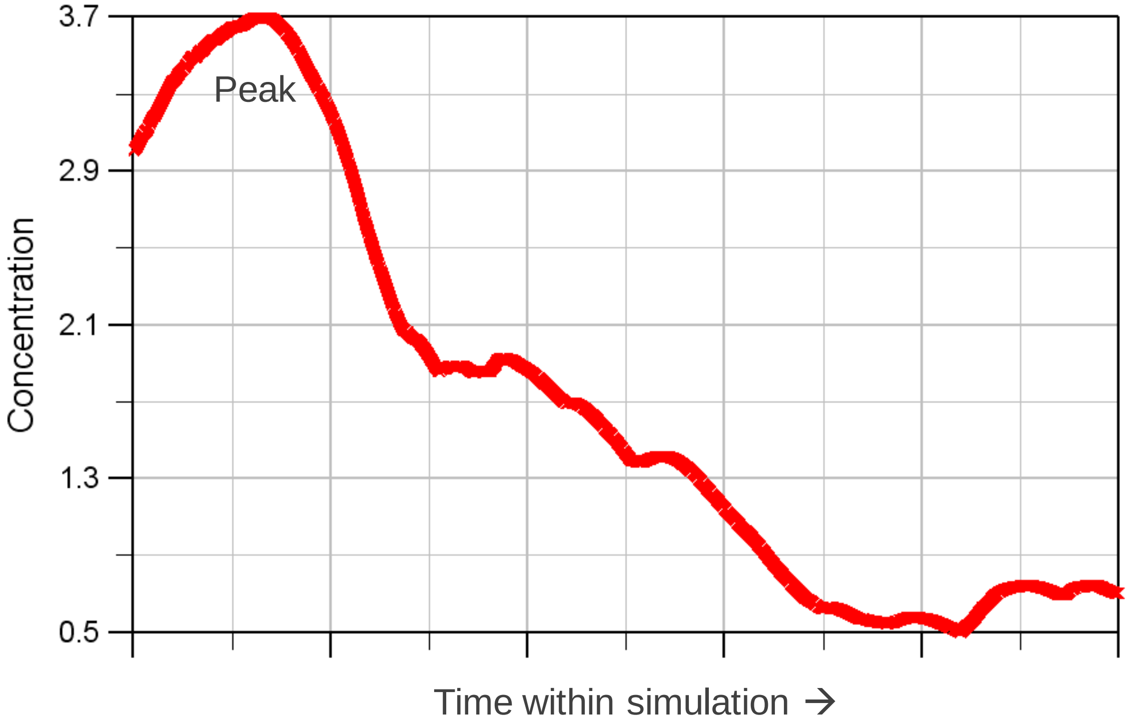

Figure 19: Groundwater nitrogen concentration in the water supply aquifer at 30 kgN/ha/y.

Discussion

The objective in deterministic modelling was to determine the sensitivity of the Lower Taieri groundwater system at North Taieri to Land Surface Recharge induced nitrogen pulses. The subject of the modelling was a laterally restricted pocket of the groundwater system in the recharge zone, upstream of the Waihola Silt/sand aquitard that caps the rests of the Lower Taieri groundwater system. Within this unconfined and stratified set of water bearing layers nitrate nitrogen is able to persist in solution with the groundwater and occurs at concentrations significantly higher than seen in reducing conditions further downstream (i.e. <0.2 gN/m^3 in the presence of reducing conditions).

Since we are most interested in how rural activities such as agriculture affect the nitrogen status, the model scenarios have concentrated on the effect of a range of recharge nitrogen loadings over the shallow aquifer surface. While we are aware that the Milners Road landfills have given rise to (a) nitrogen plume(s), these are not included in the nitrogen modelling. Since the groundwater system would appear to be quite slow to equilibrate and there has been European settlers on the Taieri Plain since the 1860s, it was considered that initial concentrations equivalent to current median nitrogen concentration were necessary to emulate the historic accumulation of nitrogen.

The nitrogen modelling was entirely *conservative*, in that it did not include removal of nitrogen by any other mechanism than outflow. Concentrations could only be altered by dispersion within the aquifer or dilution by sources of groundwater at different strengths. The Silver Stream riverbed infiltration, in particular, acted to dilute surrounding groundwater nitrogen derived from nitrogen-bearing recharge. Thus, we could see a green, low nitrogen strip in the colour flood maps of Figure 16 and Figure 18 where inflowing surface water divided the adjacent elevated nitrogen areas. The presence of the Silver Stream infiltration and the role that it plays in augmenting the groundwater extraction of the water supply aquifer would appear to be significant in suppressing the nitrogen status of that water supply. Indeed, since the Silver Stream infiltration entered the shallow aquifer first before infiltrating into the water supply aquifer, the model suggested that the shallow aquifer was also to a degree ‘capped’ with respect to nitrogen.

Overall, the model simulations showed the groundwater nitrogen concentrations peaking at just over 50% of the nitrate nitrogen drinking water guideline (5.65 gN/m^3) for all nitrogen loadings evaluated. This would be enough to trigger the need for monitoring, but the model results are not indicative of the potential for the North Taieri compartment of the Lower Taieri groundwater system to exceed the drinking water guideline under the influence of agricultural activities alone. Accordingly, while the compartment possessed the risk factors such as a history of nitrate nitrogen accumulation, lack of post-oxic redox conditions, an unconfined aquifer or longer Mean Residence Time (MRT), the nitrogen modelling has pointed to significant resilience against nitrate accumulation. It is suggested that the Mosgiel groundwater protection zones A or B are not appropriate for the setting of a nitrogen sensitive zone.

Conclusions

The following conclusions may be drawn from the foregoing analysis.

1) The Mosgiel groundwater protection zones A and B were considered to have risk factors that highlighted the potential for the accumulation of nitrate/nitrite nitrogen in groundwater to concentrations in excess of the nitrate nitrogen drinking water guideline value, hence they were included as a proposed *nitrogen sensitive zone* with the RPW plan change 6A.

2) The Lower Taieri groundwater recharge and groundwater flow models were 'cut-down' and adapted for operation alongside the contaminant transport package called MT3DMS.

3) Proposed and intermediate nitrogen loading limits in Plan Change 6A were tested within the resulting nitrogen accumulation model, specifically 10, 15, 20, 25 and 30 kgN/ha/y.

4) The hydro-dynamics and temporal characteristics of the model was such that nitrogen concentrations would peak, decline and stabilise to levels often less than the initial concentrations.

5) The peak modelled nitrogen concentrations did not exceed 7.5 gN/m^3, even at the highest nitrogen loading of 30 kgN/ha/y.

6) The nitrogen accumulation model displayed little sensitivity to the value of nitrogen loading within the 10 to 30 kgN/ha/y modelled.

7) The inferred lack of significant sensitivity to nitrogen loading is attributed to balancing and buffering role of Silver Stream riverbed infiltration.

8) The Mosgiel groundwater protection zones A and B may not be suitable candidates for inclusion as *nitrogen sensitive zones*.

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Appendix C

Sensitivity of the Kakanui-Kauru Alluvial Aquifer

Background

Plan Change 6A of the Otago Regional Plan: Water proposes nitrogen discharge limits in clause 12.C.1.3. The Kakanui-Kauru Alluvial Aquifer has been identified as a nitrogen sensitive area on map I-1, and has been attributed a permitted activity limit of 10 kgN/ha/year.

The Kakanui-Kauru aquifer has been identified as sensitive because of its high degree of interaction with the river. The Kakanui River has also been identified as being sensitive to nitrate accrual. Accordingly, the river has been placed in Discharge Area 2 in Schedule 15, wherein a nitrate-N value of 0.08 mg/l is considered to constitute good quality water.

The river threshold of 0.08 mg/l is extremely low compared to nitrate values typically found in groundwater. Typical background nitrate-N values for groundwater in an undeveloped catchment are less than 1 mg/l. Thus, the rationale for including the Kakanui-Kauru system in the list of sensitive aquifers is to place a limit on nutrient contributions to the Kakanui River.

This memo assesses the relationship between nitrate-N accrual in the Kakanui-Kauru Alluvium, and concentrations in the river. The approach is essentially qualitative, and based on a conceptual understanding of the system. Conclusions about the impact of land use on river quality are made based on this conceptual model, and verified with the available monitoring data.

All nitrate values reported in this memo are assumed to be nitrate-N, since *nitrite* is considered to be negligible in most environments.

Basin structure

The Kakanui-Kauru riparian aquifer is a complex groundwater system because it is largely driven by surface water flows. The aquifer is thin, so there is limited storage potential. A large proportion of aquifer storage is expected to be replenished in response to seasonal river flows and also individual events.

Figure 20 shows the main hydrological features of the Kakanui-Kauru system. The perimeter of the Kakanui-Kauru Alluvium is marked by the contact between younger Quaternary alluvium (Q1 and Q2) and older sediments. The young Quaternary sediments are highly permeable. The groundwater flux through the surrounding older marine and volcanic sediments is several orders of magnitude lower than the Quaternary alluvium. These older sediments can be considered fairly impermeable by comparison.

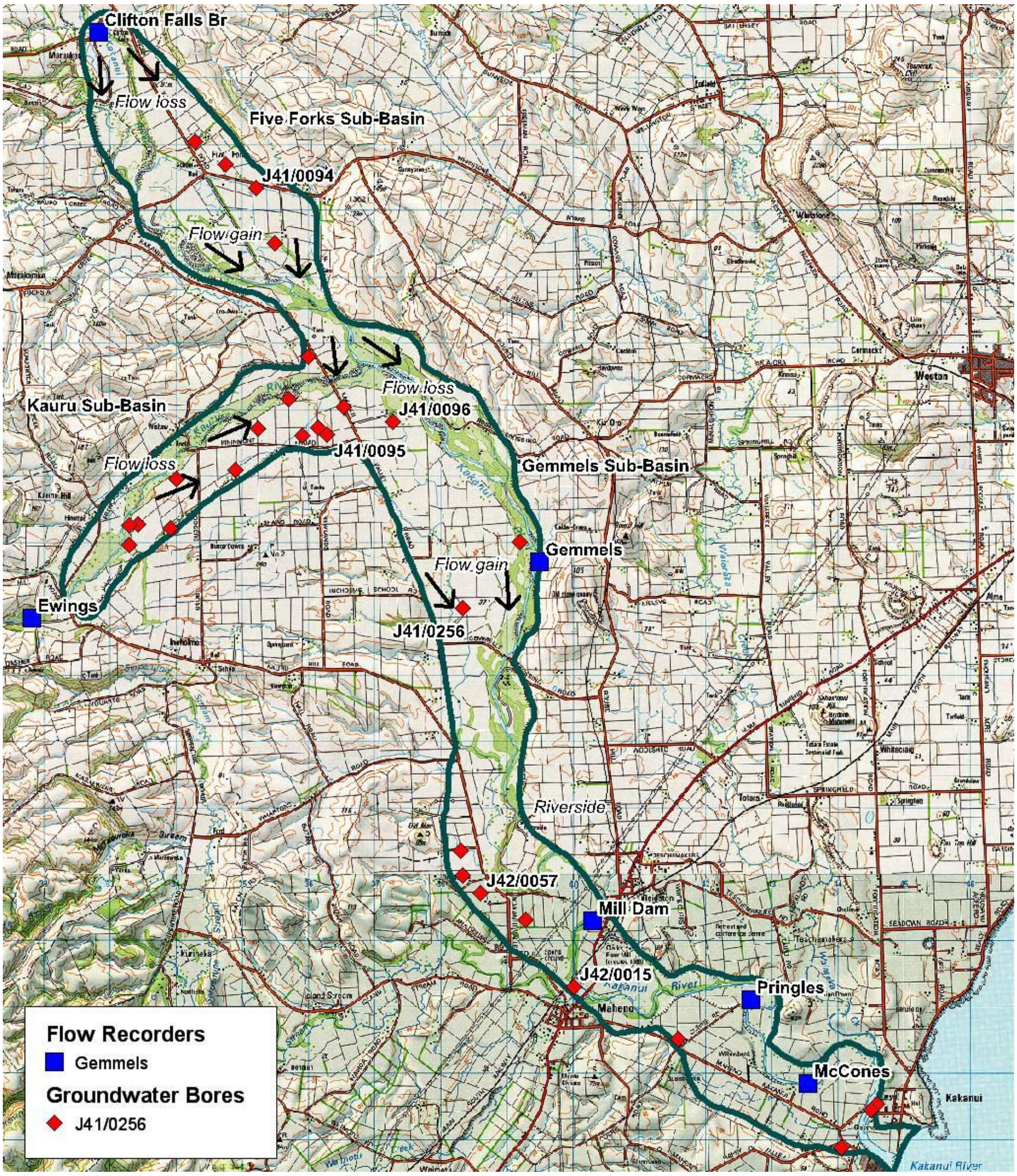

Figure 20. Map of the Kakanui-Kauru alluvium showing monitoring sites, groundwater sub-basins, and regions of river flow gain and loss.

Three main groundwater sub-basins can be identified in the Kakanui-Kauru catchment:

1. *Five Forks*. This is the northernmost basin located between Clifton Falls and the narrows upstream of the Kauru confluence.
2. *Kauru*. This sub-basin comprises the whole of the Kauru arm.
3. *Gemmels*. This basin is centrally located between and the Kauru confluence and Riverside/Gemmels Crossing Road.

To the south of Riverside the valley maintains a fairly regular width, although there are localised areas of widening around Mill Dam, Pringles and McCones.

Earth resistivity survey surveys carried out during summer 1989 indicate an average saturated gravel thickness of 4.9m north Gemmels Crossing, and 2.1m to the south (Pearson, 1989). Table 7 gives estimates of the volume of water held within each sub-basin during summer conditions. These estimates have been based on the contoured sediment thicknesses provided by Pearson (1989). The greatest volume of groundwater storage is found in the Gemmels sub-basin, where the gravels are thickest.

Table 7. Estimated gravel thicknesses and storage volumes during low flow (assuming $S_y = 0.15$).

Sub-basin	Area (ha)	Thickness (m)	Saturated Thickness (m)	Storage (Mm^3)
Five-Forks	821.9	5.5	3.8	4.7
Kauru	596	6	5.5	4.9
Gemmels	935.4	6.5	5.8	8.1
Southern valley	1355	3.3	2.1	4.3
Total	**3708.3**	**5.0**	**4.0**	**22.0**

Significant flow loss to the Quaternary alluvium occurs as the river enters each of the three sub-basins. River flow increases again at the lower end of each basin. There are expected be localised flow losses and gains as the volume of alluvium widens and shrinks, and the sediment permeability increases or decreases.

Surface water-groundwater interaction

There are two main types of groundwater - surface water interaction seen on the Kakanui-Kauru system. The first of these is flow loss and gain that occurs within individual sub-basins. The contribution of groundwater to river flow as it leaves a sub-basin is important, as it has a large influence on the nitrate values observed downstream during low flows. The second type of interaction is the aquifer's response to individual flow events. This determines how nitrate stored in the aquifer is diluted, or flushed out into the river.

Sub-basin interaction

Two concurrent flow gauging surveys were carried out during low flows in March 1992 (ORC, 1993). The Kauru River was dry at this time. Irrigation abstractions were turned off for the second of these surveys. Some conclusions about groundwater-surface water interaction can be made for conditions at the time:

- There was a flow gain of 10-15% between Clifton Falls and Mill Dam. Much of this gain is expected to be provided by groundwater drainage from the Kauru Valley alluvium

- The flow loss and gain in the Five Forks sub-basin was about 10% of river flow

- The flow loss and gain in the Gemmels sub-basin was 15-20% of river flow

The proportion of baseflow contribution to the river is expected to change significantly over time. A major factor is the drying of the Kauru River. This occurs because there is insufficient river flow to keep pace with the storage lost by groundwater drainage to the Kakanui valley alluvium. When the Kauru River becomes disconnected from the Kakanui River, the proportion of groundwater contributing to Kakanui River flow rapidly increases.

While sub-basin gains and losses account for a large proportion of river flow, they only account for a very minor proportion of groundwater storage. The daily flow gains and losses that occur within each sub-basin account for less than 1% of groundwater storage. A much greater turnover of groundwater storage occurs on a seasonal basis, and in response to high flow events. However, sub-basin flow is an important pathway for nitrate in groundwater to enter the river.

Event Responses

Groundwater levels change seasonally and with high flow events. The volume of water that is replenished during a high flow event, and then drained during flow recession, can represent a high proportion of groundwater storage. Monitoring of groundwater levels across the aquifer from 1986-1989 indicates that fluctuations in groundwater levels responding to high flow events could comprise 25% of aquifer storage (ORC, 1993). Fluctuations observed in the two bores with a monitoring record, J41/0096 and J41/0256, show fluctuations of 0.68m and 1.45m, respectively. These fluctuations are 10 to 22% of the average thickness of the Gemmels sub-basin.

The high turnover of groundwater storage in response to high flow events has implications for nitrate accrual in the aquifer. Any nutrients that accumulate in the aquifer can be displaced by high flow events. If the interval between high flow events is long, there may be enough time for the aquifer to accumulate nitrate to moderate concentrations. If this occurs, the water released as baseflow following a high flow event will have sufficient nitrate to exceed the surface water threshold of 0.08 mg/l. The river is particularly vulnerable during the period when the proportion of baseflow contributed from the riparian gravels is greatest. This period is typically towards the end of a long flow recession.

The nature of the relationship between the river and the riparian gravels changes over the course of the year. Recharge from high flow events is stored in the upper part of each sub-basin, and released further down the valley during flow recessions. Thus, groundwater storage fills from the upper part of the system and this recharge front progressively moves down the system towards the coast. Conversely, during a flow recession, the system drains from the lower part of each sub-basin upwards.

The volume of groundwater stored within the alluvial gravels determines the response at the lower valley to flow events higher in the catchment. At the end of each summer, most of the available dynamic groundwater storage has been drained into the Kakanui River as baseflow. At such a time, there is typically little response at Mill Dam to a fresh higher in the catchment. The additional water entering the catchment during a fresh is soaked up by riparian gravels in the Kauru, Five Forks and Gemmels sub-basins, thereby replenishing groundwater storage. This loss of flow to groundwater continues until riparian gravel storage is replenished. When the gravels are fully saturated, Mill Dam becomes more responsive.

At the end of winter groundwater storage is typically at full capacity. Some flow loss to riparian gravels occurs during flow peaks when the river stage is high. However, from spring through to summer the river becomes a draining system for the Kakanui Alluvium.

Figure 21 shows an example of the river response to a fresh during October 1993. This particular period was chosen because the flow is quite low for October, and irrigation demand is also low. The plot shows three curves, combined basin inflow at Clifton Falls and Ewings, the difference between combined inflow and Mill Dam flow, and the flow change at Mill Dam as a percentage of inflow. The Mill Dam curves show some fluctuations in responses to an irrigation demand of 40-100 l/s.

Figure 21 shows that as inflow at Clifton Falls and Ewings drops, the proportion of flow at Mill Dam provided by baseflow increases with time. The contribution from riparian gravels between the top and bottom of the catchment increases over time to at least 15-20% of total flow.

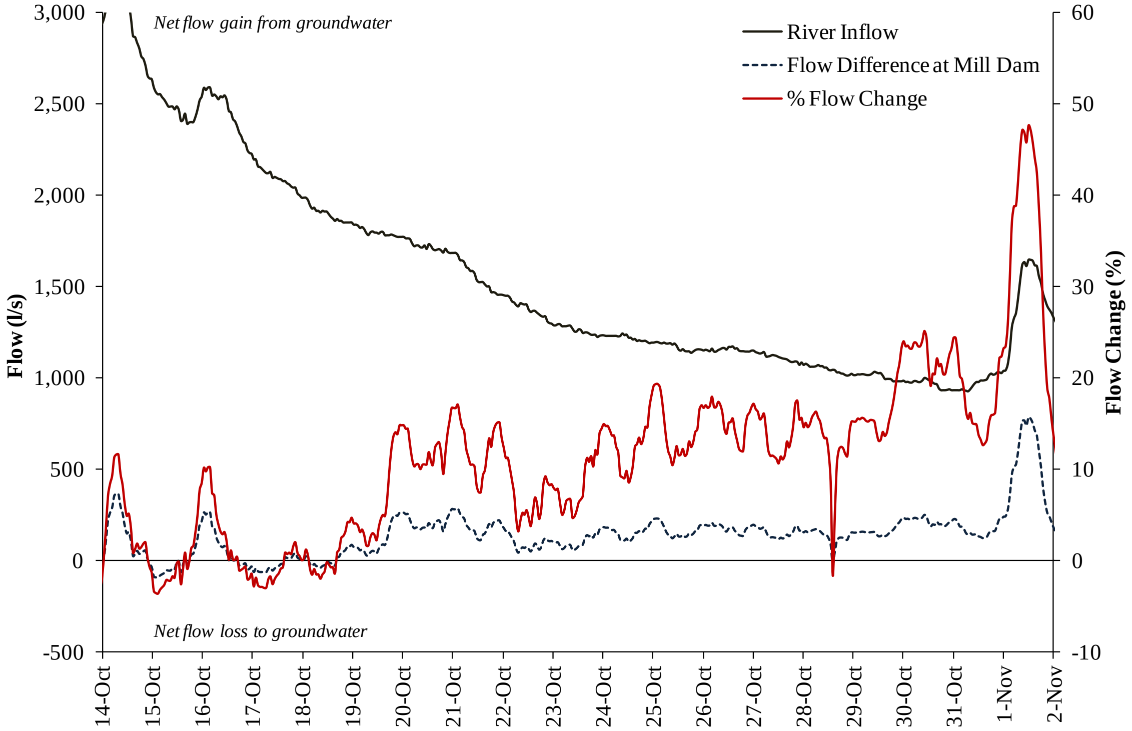

Figure 21. Flow recession of October 1993.

Towards the end of a very long flow recession, the proportion of baseflow contributed to the river is expected to decrease again. This is because the hydraulic gradient towards the river flattens in response to the continued drainage of groundwater storage. It is difficult to definitively show this phenomenon with the available data because of interference effects caused by abstraction.

Influence of the Kauru

The Kauru River has a large influence on groundwater dynamics in the Kakanui Valley. The reason for this is that the Kauru gravels have a large volume of groundwater storage which freely drains into the Kakanui Valley. Furthermore, the Kauru River is ephemeral, which creates large fluctuations in groundwater discharge to the Kakanui.

Figure 22 shows the response of groundwater at J41/0096 to river flow at Clifton Falls. The annual fluctuation in water level is up to 15% of the estimated aquifer saturated thickness. This bore is located opposite the Kauru confluence, and is less than 500m from the Kakanui River. Figure 22 shows that a fresh in the river prompts a rapid rise in groundwater levels. However, the peak in groundwater levels occurs some two to four weeks following the fresh in the river. The reason for this time lag is that the peak in groundwater levels is caused by a pulse of groundwater propagating down the Kauru Valley.

The same delay effect is not caused by the Kakanui River because discharge from the upper Kakanui Basin at Five Forks is restricted by a narrowing of the valley. This restriction maintains high groundwater levels in the Five Forks basin, and mediates groundwater discharge downgradient towards the Kauru confluence.

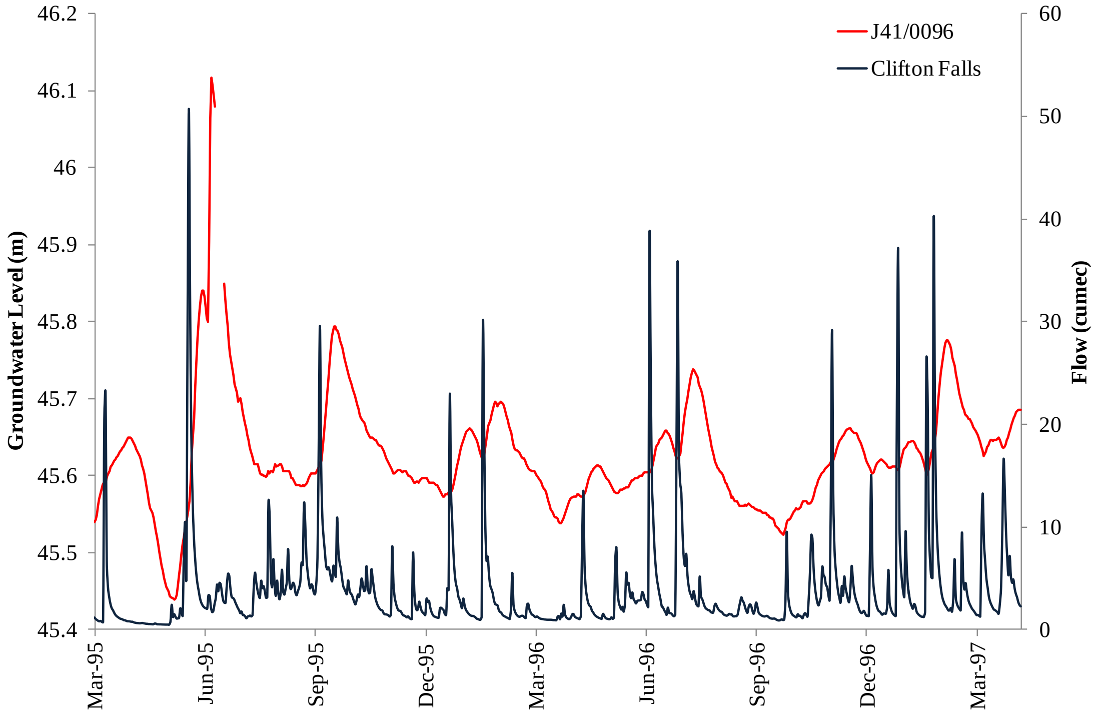

Figure 22. Time series of groundwater level at J41/0096 and Kakanui flow at Clifton Falls.

The rate of Kauru River flow loss to groundwater has previously been estimated to be 150 to 250 l/s (ORC, 2003). Preliminary results from temporary recorders show that the river dries at Kakanui Valley Road if the flow at Ewings drops below 200-250 l/s. There may, or may not, be flow at Rodgers Crossing at the same time, depending on the availability of residual groundwater storage from previous flow events. These flow loss estimates place a lower limit recharge to the Kauru alluvial gravels. At higher flows, the rate of drainage to groundwater is expected to be significantly higher. The temporary recorders indicate that flow losses in excess of 500 l/s can occur during high flow events. Thus, the rate of groundwater discharge from the Kauru into the Kakanui Valley is between 150 - 500 l/s, depending on antecedent conditions.

Land surface recharge

Land surface recharge determines the timing of nutrient leaching through the soil profile. The proportion of land surface recharge compared to river inflow is also important because it determines how enriched or diluted the nitrate leachate will become in the aquifer.

There are five main soil hydraulic classes in the Kakanui Valley (Table 8). The soils with the lowest water holding capacity (Class 4 and 5) are widespread upstream of Riverside. These soils have the highest potential nutrient leaching rates. The heavier soils (Cass 1 to 3) are found in the lower valley, particularly downstream of Maheno. These soils have a lower potential nutrient leaching rate. The majority of soils in the catchment are considered to be either light or extremely light for the purposes of estimating nutrient leaching rates[4].

Table 8. Land surface recharge estimates.

Soil Class	1	2	3	4	5
PAW	133	122	103	68	36
PRAW	66	49	46	41	22
Non-irrigated Area (ha)	58	3	182	503	1,062
Irrigated Area (ha)	275	153	218	668	494
Total Area	**333**	**156**	**400**	**1,171**	**1,556**
Irrigated recharge (mm)	160	488	168	368	423
Rainfall recharge (mm)	34	38	39	72	107
Irrigated recharge (m^3/y)	441,007	744,926	365,487	2,459,184	2,088,309
Rainfall recharge (m^3/y)	19,370	1,239	71,607	364,031	1,135,362
Total Average Recharge (m^3/d)	**1,261**	**2,044**	**1,198**	**7,735**	**8,832**
(l/s)	**14.6**	**23.7**	**13.9**	**90**	**102**

Irrigated and non-irrigated recharge has been calculated for each soil class. Irrigated recharge has been calculated to accord with efficient irrigation schedules for North Otago as outlined by Aqualinc (2006). Irrigation has a huge effect on land surface recharge in the catchment by maintaining soil moisture at elevated levels from October through to April. Mean annual non-irrigated recharge is 17% of rainfall, compared to 77% for irrigated recharge. The additional soil drainage facilitated by irrigation has a particularly large effect on the recharge through the lighter soils in the northern catchment, which is where most of the river baseflow is sourced during low flow.

Nitrate leaching is considered to be greatest during winter when there is very little uptake of nutrients by pasture. However, the increased soil drainage resulting from irrigation will allow continued leaching of nutrients through the summer months. Total average monthly land surface recharge values have been calculated for Table 8 to compare with monthly flow values. This enables a rough groundwater budget to be calculated. Land surface recharge typically comprises around 10% of the median river flow at Mill Dam. However, a light rainfall event during the summer could induce a groundwater recharge event that comprises 15% of the river flow, or a greater proportion at lower flows.

The land surface recharge calculations indicate that the aquifer (and river) are susceptible to elevated nitrate concentrations from leaching throughout the year. The more sensitive lighter soils coincide with the region of the aquifer that contributes the most to river baseflow during the summer. These soils are predicted to leach between 38 and 65 kgN/ha/y, depending on herd density and wintering (Lilburne et al. 2010).

[4] Refer to Lilburne et al. 2010.

The ECAN lookup tables for nitrate leaching indicate that wintering of cows contributes an additional 10 to 15 KgN/ha/yr of leachate[1]. This implies that winter leaching rates are at least 30% higher than the annual values specified in the lookup tables.

While much of the leachate entering the aquifer during winter will be moved through the system quite rapidly, there is expected to be residual nitrate in the aquifer. Ongoing leaching during the summer beneath irrigated pasture will continue to maintain nitrate at elevated concentrations. At a conceptual level, it is difficult to see how an annual leaching limit of 30 kgN/ha/yr would improve water quality in the river unless the cows were also wintered-off.

Existing nitrate data

Groundwater

There are few groundwater sample results available for the Kakanui-Kauru aquifer. Table 9 summarises the available groundwater data. All of the samples except two were taken prior to the mid to late 1980’s and don’t reflect the current state of intensive land use. Bore J41/0096 was sampled from Dec 1985 to March 1995. While pasture was irrigated during the 1980’s and 1990’s, there was very little dairy farming in the catchment. Land intensification started more recently, around 10 years ago, and increased significantly in the last 3-5 years.

Table 9. Nitrate-N values measured in Kakanui-Kauru groundwater.

Site Name	E	N	Samples	Median Nitrate-N	Max Nitrate-N
J41/0095	1426405	5004974	1	0.45	0.45
J41/0096	1427305	5005174	10	1.1	2.5
J41/0094	1425316	5008717	1	2.4	2.4
J41/0256	1428452	5002374	2	0.57	0.92
J42/0057	1429084	4998046	1	12.8	12.8
J42/0015	1430012	4996577	2	2.1	10.8
		Totals:	**17**	**1.6**	**Max 12.8**

A bore survey on 10 July 2012 carried out north of SH1 only found two bores that could be accessed for sampling. Samples from these bores gave nitrate-N concentrations of 2.4 mg/l at Five Forks, and 12.8 mg/l at Maheno. These values are sufficiently high enough that the river threshold of 0.08 mg/ would be exceeded even if the baseflow contribution was very low at the same time.

An estimate of the average groundwater nitrate concentration can be made from the median river concentration if a suitable baseflow contribution is assumed. Applying a range of baseflows of 5-15% of river flow gives an estimated groundwater concentration of just 0.5 to 1.6 mg/l nitrate-N. Groundwater contribution to the Kakanui River has been gauged as being up to 17% of the flow, and the recession curves suggest it could reach 25% of flow. It follows that the surface water threshold of 0.08 mg/l would be breached with a groundwater concentration of less than 0.4 mg/l.

Surface Water

[1] The majority of the area consists of extra light soils. These soils are predicted to leach between 38 and 65 kgN/ha/y depending on herd density and wintering (Lilburne et al. 2010).

Schedule 15 of the proposed plan change outlines nitrate thresholds for good receiving water quality. Group A catchments have a receiving water quality threshold of 0.45 mg/l nitrate-N. The Kakanui catchment has been placed within the more sensitive Group 2 catchments, which have a threshold of 0.08 mg/l nitrate-N.

The median nitrate-N concentration at Clifton Falls and Ewings is 0.012 mg/l. At McCones, this increases to 0.08 in response to the higher intensity of land use on the Kakanui River terraces. Note that these values have been calculate from the whole period of record, and do not reflect trends.

Figure 23 shows the relationship between flow and nitrate values at McCones. The data available is from 2003 to 2012. There is a general relation of increasing nitrate as flow increases. Most of the higher nitrate-N values (> 0.3 mg/l) occur soon after high rainfall events, and are likely to be caused by high intensity rainfall events that produce surface runoff.

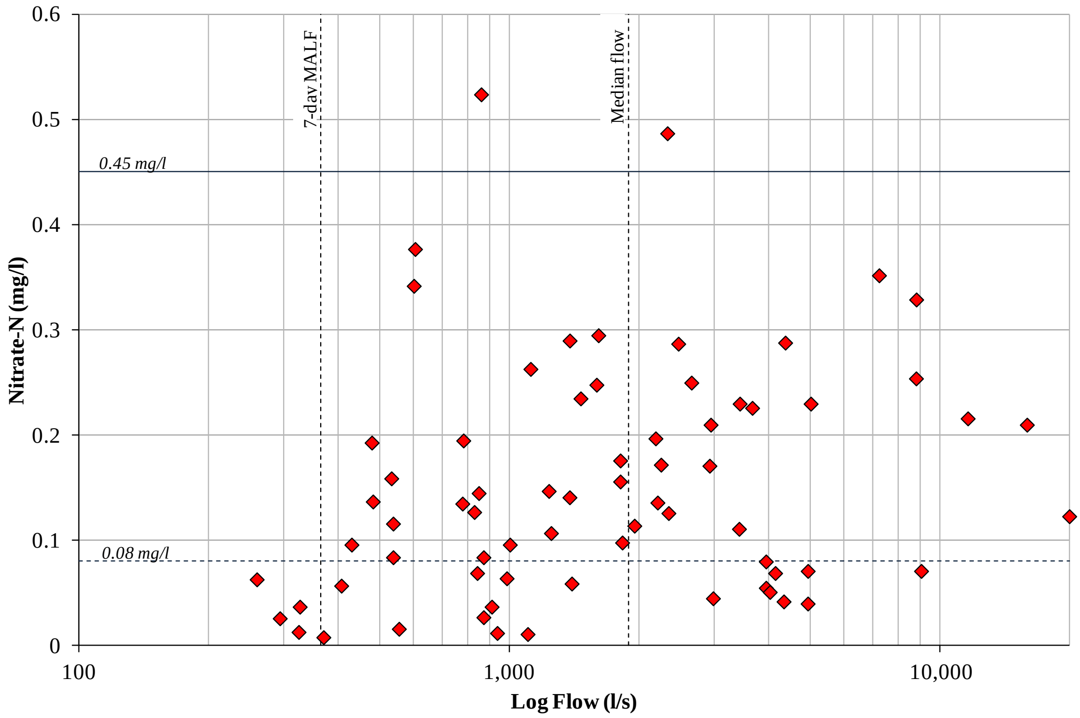

Figure 23. Nitrate-N concentration vs log flow at McCones.

Baseflow from the Kakanui-Kauru Alluvium becomes a significant contributor to river flow when flow falls below the median. There is a notable rise in nitrate-N between flows of 400l/s and 800 l/s. The main reason for this is the drying up of the ephemeral Kauru river bed, which increases the proportion of groundwater contribution to flow at McCones.

Many of the lower nitrate values in Figure 23 have had some nitrogen removed by periphyton growth. An annual cycle can be seen in the McCones data with lower nitrate values recorded each summer. This cycle seems to occur regardless of flow, so it appears there is significant nitrate removal by periphyton. With this in mind, it is clear that McCones is not the ideal SOE site for assessing the effectiveness of the proposed policy.

Despite the removal of nitrate by periphyton, there has been a significant increase in nitrate concentrations through time at McCones. Figure 24 shows the trend of nitrate-nitrite nitrogen concentrations though time at MCones. The nitrogen record has been flow-adjusted using flow at Mill Dam to remove distortions caused by seasonal variance.

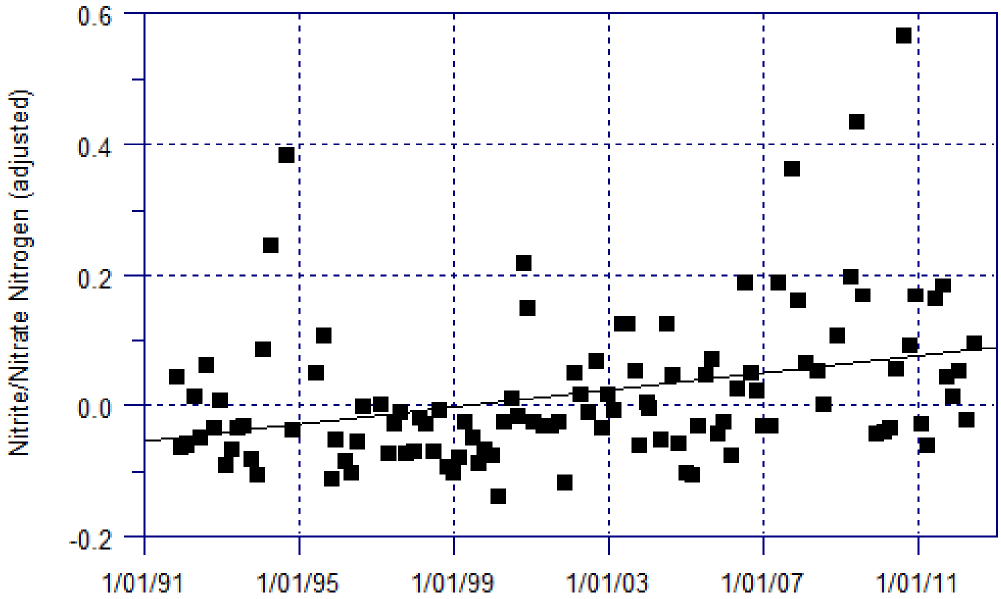

Figure 24. Mill Dam flow adjusted NNN-trend at McCones.

Figure 24 clearly shows that there has been a significant increase in nitrate within the river through time. The annual increase since 1991 has been 6% on average. Samples from the 1980's averaged around 0.04 mg/l, whereas the more recent data shows an average of around 0.17 mg/l. The relationship between land use intensification and river nitrogen is clearly demonstrated by the sampling data despite removal by periphyton during summer. There is still plenty of potential diary expansion in the catchment, so we could see a continuing increase in nitrate into the future.

Figure 25 shows the relationship between flow at Mill Dam and nitrate-N at Gemmels. The period of record available is from 1991 to 2002, and the median is 0.08 mg/l. The Gemmels site is also not ideal for monitoring nutrients in the catchment because it is located in a gaining reach of the river, and does not collect all of the groundwater storage discharging from the Gemmels sub-basin. The river nitrate concentrations are therefore underestimated by samples at this site. However, the site is located upstream of the main area of periphyton growth, so it is a much better indicator of how the stream and aquifer are interacting.

The relationship at Gemmels is quite different to that shown at McCones. If we assume that the highest nitrate values (>0.3 mg/l) are caused by rainfall runoff events, an inflection in the data can be seen where nitrate concentrations are lowest. This inflection occurs at around 6,000 l/s, or three times the median flow. Nitrate values generally tend to increase at higher and lower flows relative to this inflection point.

The increase in nitrate at lower flow suggests that the proportion of baseflow to the river is increasing at lower flow, thereby increasing the nitrate concentrations in the river. Intuitively, this is what we would expect, and it is what the recession curves show (eg Figure 21). The river should become increasingly reliant on groundwater storage to sustain its flow as the inflow at Clifton Falls and Ewings reduces over the summer, hence we see a rise in nitrate values during low flow.

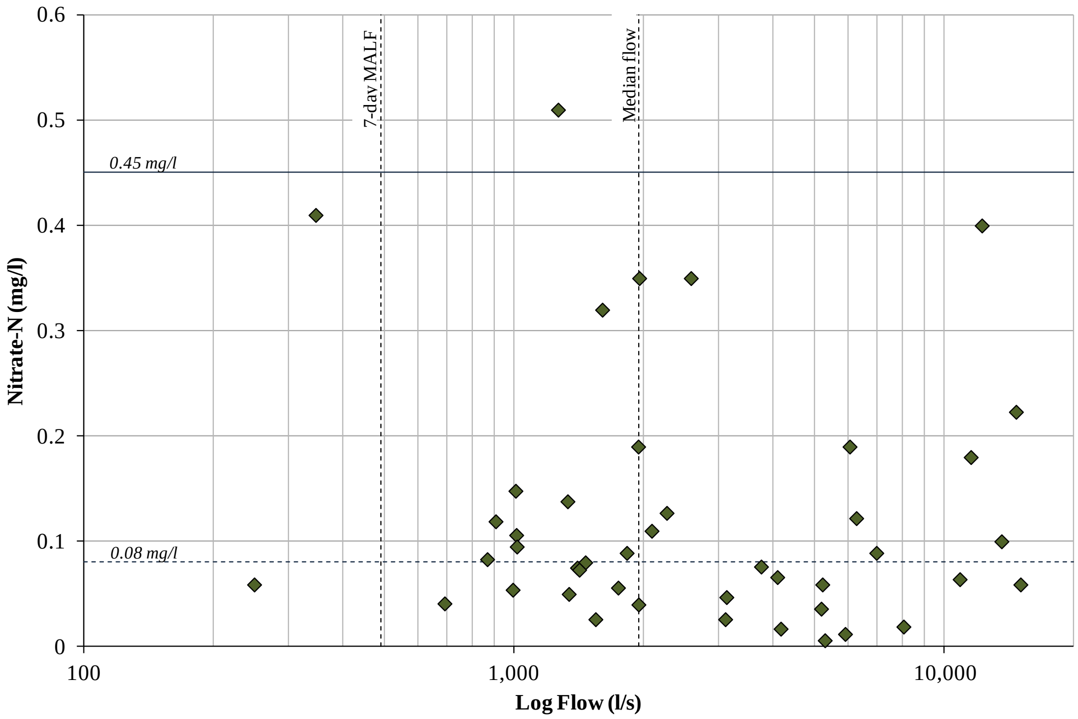

Figure 25. Nitrate-N concentration at Gemmels vs log flow at Mill Dam.

A comparison of nitrate concentrations with the flow record indicates that values over 0.08 mg/l during the summer are caused by small to moderate antecedent rainfall events. This is consistent with the conclusions of the land surface recharge study.

Conclusions

- The available monitoring data confirms that the aquifer is nitrate-sensitive. A leaching threshold of 20 kgN/ha/y is recommended. The degree of soil leaching and groundwater - surface water interaction is very high in the catchment. It is highly unlikely that 0.08 mg/l could be maintained, particularly during the critical period of periphyton growth under a leaching rate of 30 kgN/ha/y.

- Most nutrient leaching is expected to occur during winter if herds are wintered-on. While much of this leached water is removed from the system within a month, there is still considerable residual nitrate in the aquifer during summer.

- The lightest soils are located above Riverside, where most of the groundwater-surface water interaction occurs. Additional nutrient leaching during summer months increases the groundwater nitrate concentration.

- Groundwater in the Kakanui-Kauru alluvium contributes up to 20% of river flow during flow recessions. The area of groundwater storage that contributes this water is above Riverside. This area also has the lightest soils, and is susceptible to nutrient enrichment throughout the year.

- Water quality monitoring shows a clear relationship between land use intensification and nitrate concentrations in the river. Nitrate concentrations have been increasing at a rate of 6% per year. Recent data shows an average nitrate-N concentration of around 0.17 mg/l, and there is still potential for more dairy expansion within the catchment.

- The proposed plan change recommends an instream nitrate threshold of 0.08 mg/l in order to prevent periphyton growth. However, there is currently abundant periphyton growth in the lower catchment, and the median nitrate concentration is 0.08 mg/l. The plan change will clearly not meet its intended objective.

- The sampled median nitrate value at McCones is skewed by the removal of nutrients by periphyton. A more appropriate objective would be a median nitrate-N value of 0.08 mg/l during the summer period as measured upstream of the main area of periphyton growth. An appropriate site would be in Riverside area. This area is downstream of the reach of most substantial groundwater inflow, and upstream of the worst periphyton growth.

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