Nitrate discharge to groundwater from agricultural land use: an initial assessment for the Canterbury Plains

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1. Purpose

This is a technical report to the Steering Group of the Canterbury Water Management Strategy. It arises from public concern about the effects of agricultural land use on groundwater quality. It applies existing tools and information to provide a strategic view of the issue of nitrate discharges to groundwater on the Canterbury Plains. The tools are being continually improved by scientists in consultation with Environment Canterbury and primary sector industries.

The report addresses nitrate. Nitrate is one of the contaminants for which a threshold is set in the New Zealand Drinking-Water Standards of 11.3 mg/L nitrate-nitrogen. Nitrate-nitrogen is referred to as nitrate in this report. Existing monitoring of nitrate in groundwater is not an accurate indicator of the effects of existing land-use because of time lags. It can take up to several decades for the effect of a land-use change to be seen in groundwater. Nitrate concentrations also vary over a year, from year to year and are very influenced by day-to-day land use practices.

The purpose of this report is to provide an initial assessment of:

- the average effects of existing land-use on groundwater quality if existing land-uses and land-use practice was to continue in the long-term.
- the scale and patterns of change in groundwater quality if there was a reduction in nitrate inputs from existing land uses.
- the scale and patterns of change in groundwater quality from a widespread increase in nitrate (land-use intensification).
- the difference in water quality between shallow and deep groundwater, and the role of river recharge in dispersing nitrate concentrations.

The results are based on a standardised land-use practice for each type of land-use – for example, all arable farms on the same soil and with the same climate will use the same value for nitrate. Because each property is not individually modelled, care should be taken in drawing conclusions about specific locations. The results are intended to give an indication of spatial patterns, and more detailed work would be required to make management recommendations for any specific location.

2. Key findings

Nitrate discharge from agricultural land use on the Canterbury Plains has the potential to cause levels of nitrate concentration in shallow groundwater (<20metres below the groundwater surface), at some localities, that exceed the drinking water standard.

Groundwater quality generally improves with depth below the groundwater surface because of dispersive mixing with high quality groundwater from river recharge.

Reduction of nitrate discharge by improving existing practices has the most effect on the availability of drinking water from shallow groundwater.

On the alluvial plains of Canterbury access to high quality groundwater is dependent on river recharge – clean water flowing into the aquifers from large rivers. The model predictions for Central Canterbury indicate that access to high quality drinking water would be achievable from deep wells almost anywhere on the plains. The actual well depth required for a particular location would need further investigation. The model predictions of the effects of an example of relatively widespread land use intensification suggested that deep groundwater would remain a high quality source of drinking water.

There is considerable potential for incorporating additional knowledge into the current models and refining the resulting model predictions. The effect of groundwater quality on the quality in groundwater-fed springs and streams is not addressed in this report.

3. Introduction

Nitrate is leached by water draining from the soil into the groundwater below, and is referred to as nitrate discharge. The amount of nitrate transported into the groundwater surface depends on the type of land use and the associated management practices. This soil-water drainage is one of the major sources of recharge to groundwater, called land surface recharge. The other major source of groundwater recharge is leakage from rivers, and this river recharge is a significant feature of the groundwater resource of the alluvial aquifers of the Canterbury Plains.

All groundwater eventually discharges into surface waters such as springs, wetlands, streams, lakes or directly to the sea, and supplies most of the freshwater flow to these water bodies in the lowland and plains area of Canterbury. Direct surface runoff is a relatively small contributor to the total flow. The concentration of nitrate in surface waters is determined by the nitrate concentration in the contributing groundwater after any “denitrification” effects have been taken into account.

Denitrification is the conversion of nitrate into other nitrogen compounds that are not of concern from a drinking water or ecological perspective. This conversion of nitrate can occur by means of several processes associated with poorly-drained agricultural land, and chemical and biological reactions within aquifers or within the riparian areas near surface waters. There is little known about the occurrence and magnitude of denitrification in Canterbury. The monitoring data for nitrate concentration in some lowland streams suggests that denitrification may not be a significant process at a regional scale. For the nitrate modelling work in the present study the processes of denitrification have been ignored, as a precautionary response to the lack of evidence.

In the absence of denitrification, the total mass of nitrate leached from land eventually appears in surface waters. The actual concentration of nitrate in a particular surface-water body depends on the contribution from the land surface catchment of the water body and the contribution from river recharge. In Canterbury, the recharge from the large rivers of the Canterbury Plains is considered to be nitrate free, for the purposes of the current modelling.

The average nitrate concentrations of soil-water drainage from some agricultural land uses are higher than acceptable concentrations in groundwater for drinking water quality, and are also higher than acceptable concentrations in surface waters based on toxicity levels for aquatic life. Therefore, a mix of land uses which includes those with low nitrate discharge is desirable for maintaining drinking water quality in groundwater, and the contribution of nitrate-free river recharge is important for maintaining the even lower nitrate concentrations required for a healthy aquatic environment in surface waters.

The purpose of the following modelling approach is to account for nitrate discharge from land and its transport and dispersion in the underlying groundwater. The influence on surface water quality from groundwater discharge is not included in the present report.

Two levels of results are presented in this report:

- Nitrate discharge from agricultural land use, and assessment of shallow groundwater quality on the Canterbury Plains

- Assessment of deeper groundwater quality, as influenced by river recharge, for Central Canterbury

4. Modelling approach

4.1 Nitrate discharge from land – GIS databases

Modelling of nitrate discharge from land to groundwater is achieved by combining a GIS-based map of land use and a "look-up table" of nitrate discharge rates for each type of land use, soil type and climate zone. The range of land use types corresponds to those available on the land use databases and is supplemented by additional information from the ECan consents database and some remote sensing data. There is some uncertainty in the resulting land use type map, and also in the soil and climate maps.

The look-up table has been assembled by consulting scientists who are experts in modelling nitrate leaching from rural land uses. They have produced long-term average values of soil-water drainage and associated nitrate concentration for each feasible combination of land use, soil type, and climate zone. The practices represent a standard practice for each combination of soil, climate and land use. There is some uncertainty in these values due to the need to make assumptions about management practices, and the complex nitrogen cycling system that is being modelled.

The combination of GIS land use database and look-up nitrate discharge table is a modelling procedure that enables convenient updating of the spatial distribution of nitrate discharge from land use as well as examination of the effects of land use change scenarios. The standard data processing tools within GIS can be used to obtain regional maps of nitrate contamination effects such as drinking water quality in shallow groundwater. The underlying uncertainties mean that the results give an indication of spatial patterns but may not be reliable at specific locations.

4.2 Shallow groundwater quality – smoothing the GIS nitrate discharge map

When land surface recharge reaches the groundwater surface it becomes part of the groundwater flow that moves primarily in a horizontal direction towards surface waters. Below the groundwater contributed by land surface recharge there is a layer of groundwater contributed by river recharge. Figure 1 shows a vertical cross-section, generated by a groundwater model, along the direction of groundwater flow through an aquifer.

Figure 1 uses different scales for the horizontal (land surface) and vertical (aquifer thickness) dimensions. The ratio of land surface dimension (50 km) to aquifer thickness (300 m) in this example is such that the recharge from several square kilometres of land surface forms a layer of groundwater that may be only several metres thick. If groundwater is abstracted with a shallow well, the water quality is a sample of the recharge from a strip of land along several hundred metres upstream of the well. This well sampling effect on land surface recharge can be simulated by smoothing the GIS nitrate discharge map with inbuilt mathematical tools. The effect of this procedure is to create a map of samples of the average nitrate discharge concentration corresponding to the area that would be the "catchment" of a shallow well at any location on the map.

For the purposes of this report, the map of nitrate discharge was smoothed with a moving area "window" that is circular with a radius of 1 km. The smoothing procedure provides a value of average nitrate concentration that takes account of the soil drainage contributions from each land unit in the window.

This GIS map smoothing procedure is valid only for obtaining an estimate for shallow wells to about 20 m below the groundwater surface. At greater depths, the catchment area is further upstream and the map becomes less accurate in designating concentration hotspots. Figure 1 also shows that, as depth increases, the nitrate concentration effect from land surface recharge becomes modified by dispersion into the groundwater sourced from river recharge. Prediction of the magnitude and location of this dispersive interface between groundwater from land surface recharge and river recharge requires sophisticated mathematical models of groundwater flow and contaminant transport.

4.3 Groundwater flow – regional groundwater model

The quantity and direction of groundwater flow is determined by the pattern and magnitude of land surface recharge, quantity and location of recharge from the rivers, aquifer properties, and the geography of surface waters. The pattern and magnitude of land surface recharge is provided by the GIS nitrate discharge map, which incorporates the values of soil-water drainage from the look-up table. Magnitudes and location of river recharge is, however, a more difficult problem. It is very difficult to measure accurately by field techniques, especially for the large braided rivers. The alternative is to obtain estimates of the river recharge contribution by means of calibrating a groundwater model to groundwater level data in conjunction with the predictions of land surface recharge.

ECan is developing a regional groundwater flow model for most of the Canterbury Plains. A steady flow version of this model has been calibrated to the groundwater level database for the purposes of the present study. This is a very complex modelling exercise that involves some uncertainty about the location and amount of river recharge contribution, and aquifer properties and boundary conditions.

In order to assess the effects of this uncertainty two groundwater budget scenarios have been considered for modelling the deep groundwater quality for Central Canterbury:

1. "Low river recharge", for which river recharge is 52% of the total recharge

2. "High river recharge", for which river recharge is 68% of the total recharge.

These two scenarios span the range of proportions of river recharge and land surface recharge that are feasible under current understanding of the Central Canterbury aquifer system, according to calibration of the ECan groundwater model. A third scenario, for the case of lower groundwater discharge to the ocean, was also modelled but the proportion of river recharge was similar to that of the Low river recharge scenario. The relative proportions of river and land surface recharges is the critical factor for the quality of deep groundwater.

4.4 Deep groundwater quality – AquiferSim model

Prediction of the 3D pattern of nitrate concentration in groundwater requires the GIS nitrate discharge map in conjunction with knowledge of river recharge, surface water discharge, and aquifer properties provided by the groundwater flow model. These are combined in a nitrate transport model “AquiferSim” that has been developed specifically for rapid computation of the long term pattern of groundwater nitrate concentration for a specified pattern of land use. The current status of the model is that it can predict the spatial pattern of groundwater nitrate concentration at specified depths, as well as vertical views similar to Figure 1.

The capabilities of the AquiferSim model are quite extensive and the principal limitations on prediction are the quality and amount of detailed knowledge that can be put into the model from various sources. One of the unknown factors is the depth of the base of the Canterbury Plains aquifers and how this depth varies with location. For the present study, the depth was set in the AquiferSim model at a value of 250 m below groundwater level everywhere. This means that model results presented as averages for the depth bands of 0 – 50 m and 100 – 150 m are to be taken as indicative of “moderately deep” and “deep” groundwater.

For assessment of the deep groundwater quality of Central Canterbury in this report, model predictions of nitrate concentration are presented as maps of average values for the depth ranges of 0 – 50 m and 100 – 150 m below the groundwater surface. Comparison of these maps demonstrates the influence of river recharge in dispersing the pattern of shallow groundwater nitrate concentration resulting from land surface recharge.

The Christchurch aquifers are a special zone within the Central Canterbury aquifers, which lie within the “sandwich” of confined aquifers along the coastal margin of this region. These confined aquifers are not specifically represented in the current form of the aquifer model. The high groundwater quality of these confined aquifers is due primarily to the influence of river recharge that moves upwards in this groundwater discharge zone. The presence of confining layers is a secondary feature. The Christchurch aquifers also benefit from protection of the recharge zone that contributes the land surface recharge component.

5. Model results and discussion

3.1 Nitrate discharge on the Canterbury Plains

Figure 2 shows a map of the nitrate concentration of soil-water drainage beneath the root zone, before entering groundwater, for the Canterbury Plains. There are many locations where the map legend indicates that predicted values of nitrate concentration are close to or above 12 mg/L, which means that this recharge water is at or above the drinking water limit.

3.2 Shallow groundwater quality on the Canterbury Plains

Figure 3 shows the model predictions of nitrate quality in shallow groundwater, obtained by smoothing the map of Figure 2 as described in section 2.2. Comparison of Figure 3 with Figure 2 demonstrates that the high nitrate values for soil water drainage have been attenuated in a manner that simulates the effect of some dispersion in groundwater and the sampling effect of abstracting groundwater from a well. Locations with smoothed values above 10 mg/L, according to the map legend, could be considered worthy of more refined investigation if access to drinking water from shallow wells (say, less than 20 m below the groundwater surface) is an issue.

3.3 Effect of improved practice on shallow groundwater of Canterbury Plains

An indication of the likely effect of improved practices for reduction of nitrate discharge from agricultural land is presented in Figure 4. This map was produced by applying a 20% reduction to the nitrate concentration component of the nitrate discharge data for Figure 2, but maintaining the values of drainage volume for each land use. This approach is approximate because improved practices would involve changes to both concentration and soil-water drainage (from improved irrigation management, for example).

Comparison of Figure 4 with Figure 3 shows a visually detectable change in shallow groundwater quantity, in general, and a decrease in localities where access to drinking water quality might be an issue.

3.4 Deep groundwater quality in Central Canterbury

Figure 5 shows predicted groundwater nitrate concentrations, averaged over two depth ranges, for Central Canterbury, for the "Low river recharge" case. Figure 6 presents the same information for the "High river recharge" case.

For each river recharge case, Figure 5 and Figure 6 both show the decreased nitrate concentrations in the 100 – 150 m depth band, in comparison with the 0 – 50 m depth band. This difference illustrates the influence of uncontaminated river recharge flowing beneath the nitrate-contaminated recharge from the land surface. This influence results in dispersive "mixing" at the interface between these two sources of groundwater recharge, so that there is an expectation, in general, of decreasing nitrate concentration with increasing depth from the groundwater surface.

Comparison of Figure 6 (high river recharge) with Figure 5 (low river recharge) shows that there is a greater extent of low-nitrate groundwater (dark blue areas), at both depth bands, for the high river recharge case. These model results illustrate the important role of river recharge in determining access to high quality groundwater in these alluvial plains.

3.5 An example of the effect of improved nitrate discharge practice

Figure 7 shows the effect of improved nitrate discharge practice, as described in section 3.3, on the deep groundwater of Central Canterbury (100 – 150 m) for the low river recharge case. Therefore, Figure 7 should be compared with Figure 5(b) to obtain an appreciation of the change in groundwater quality. These changes occur primarily in the areas where the dispersive and diluting influence of river recharge is showing as a transitional interface at these depths.

3.6 An example of the effect of land use intensification

The effect of land use intensification on the deep groundwater of Central Canterbury is illustrated in Figure 8. In this modelling example, 30% of extensive land use was randomly selected and changed to a more intensive land use. Again, Figure 8 should be compared with Figure 5(b). The difference does not appear to be significant, in comparison with the effect of the more widespread reductions in Figure 7. This result may be just a function of the locations of the original extensive farming areas and the location of their nitrate plumes.

3.7 Assimilative capacity of the Central Canterbury aquifers

"Assimilation" of nitrate into the Canterbury Plains aquifers can occur only by means of dispersion and dilution, given the assumption that there is little evidence of denitrification. Dispersion and dilution can result in blending of nitrate plumes from intensive land uses with those from less intensive land use. This is the primary process that determines shallow groundwater quality, as illustrated in Figure 3, for example. However, in the deep alluvial formations of the plains the dominant source of diluting water is recharge from rivers. As previously discussed, the dilution effect generally increases with depth below the groundwater surface. Figure 9 illustrates this process with model predictions of the average concentration in the 100 – 150 m depth band, for Central Canterbury, resulting from a constant value of nitrate concentration across the plains. The map of concentrations in deep groundwater (Figure 9) is therefore expressed in relative terms. The map in Figure 9 really shows the zones of influence of river recharge on the quality of deep groundwater.

6. Conclusions

Nitrate discharge from agricultural land use on the Canterbury Plains has the potential to cause levels of nitrate concentration in shallow groundwater, at some localities, that exceed the drinking water standard. Groundwater quality generally improves with depth below the groundwater surface because of dispersive mixing with high quality groundwater from river recharge.

The actual depth of this dispersive interface at any particular location is probably not predicted accurately by the current versions of the groundwater models. This is because there are still many physical properties of the aquifers, as well as hydrological water balances, which are not yet well understood. There is considerable potential for incorporating additional knowledge into the current models and refining the resulting model predictions.

The current state of groundwater knowledge and modelling capability has enabled predictions about the quality of deep groundwater only for the Central Canterbury zone, for this report. However, it is reasonable to expect that the general principles of groundwater quality illustrated by model predictions for this zone could also be applied to other zones within the alluvial plains that have significant recharge from the rivers that formed them.

The model predictions for Central Canterbury indicate that access to high quality drinking water would be achievable from deep wells almost anywhere on the plains. The actual well depth required for a particular location would need further investigation. The model predictions of the effects of an example of relatively widespread land use intensification suggested that deep groundwater would remain a high quality source of drinking water.

Reduction of nitrate discharge by improving existing practices has the most effect on the availability of drinking water from shallow groundwater. This is an issue for occupants of individual rural properties because of the cost of sinking deep wells. Shallow groundwater also contributes to the quality of surface waters, which is not addressed in this report.

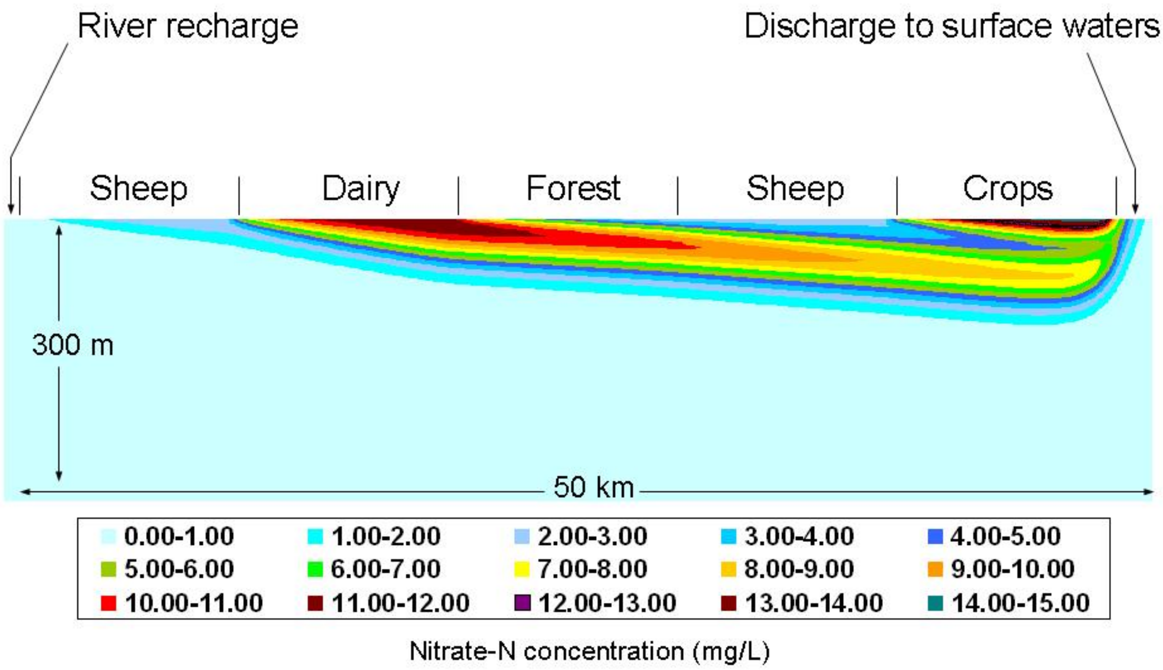


Figure 1. Vertical cross-section of an aquifer, illustrating nitrate plumes from land surface recharge and the underlying layer of groundwater from river recharge.

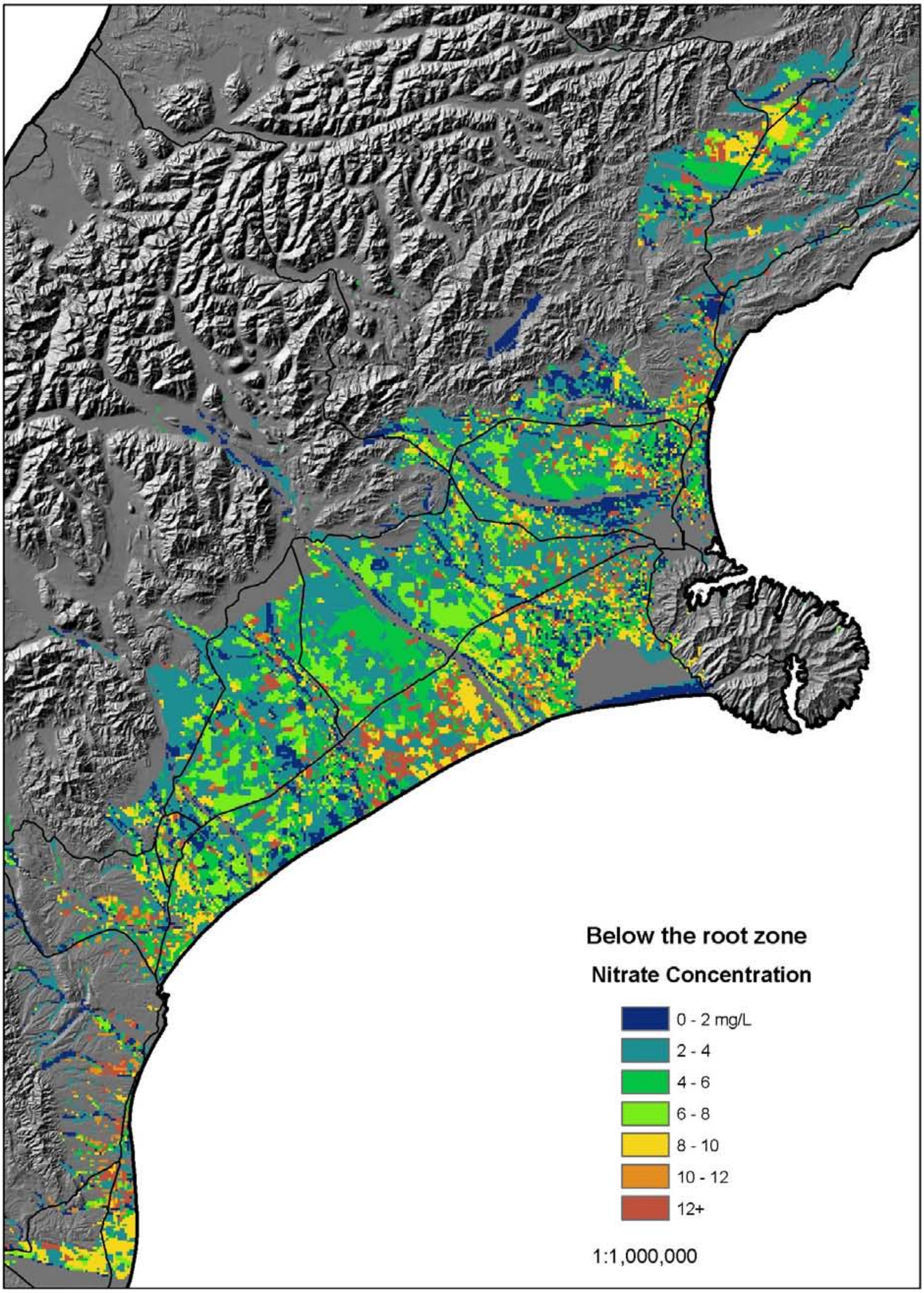


Figure 2. Nitrate concentration of soil-water drainage from agricultural land use on the Canterbury Plains.

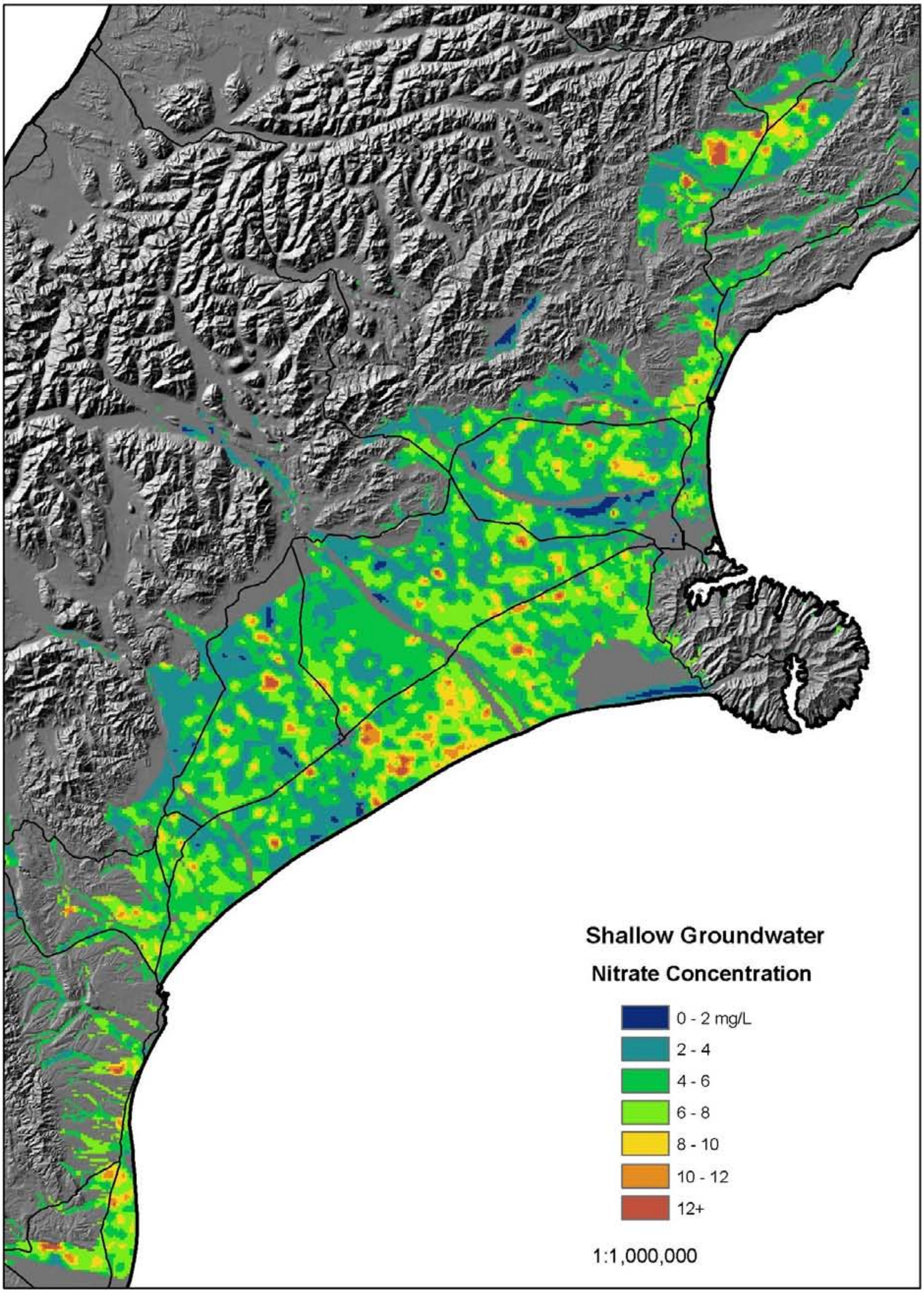


Figure 3. Model prediction of nitrate concentration in shallow groundwater, for Canterbury Plains, by applying a 1 km smoothing window to the nitrate discharge map in Figure 2.

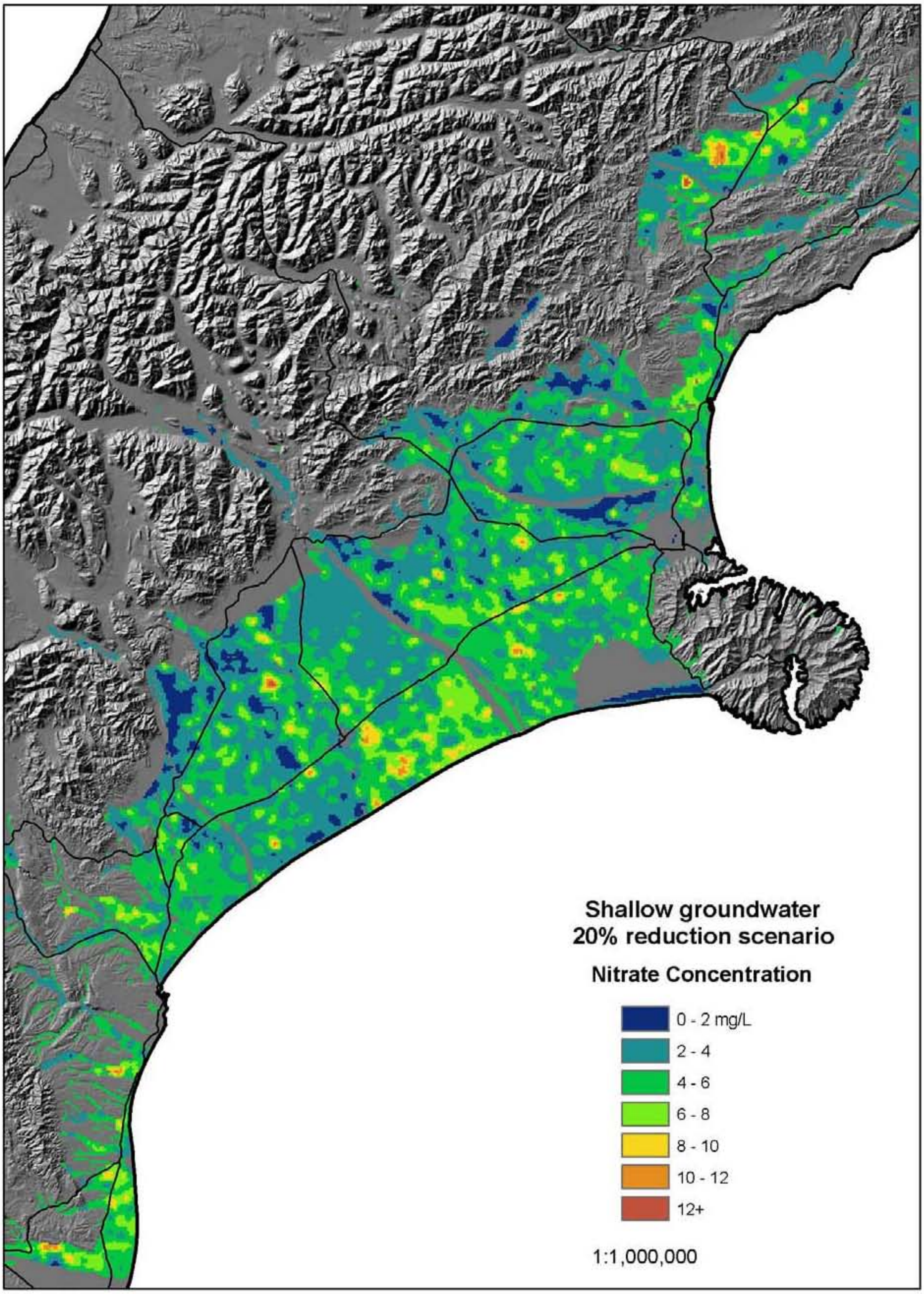
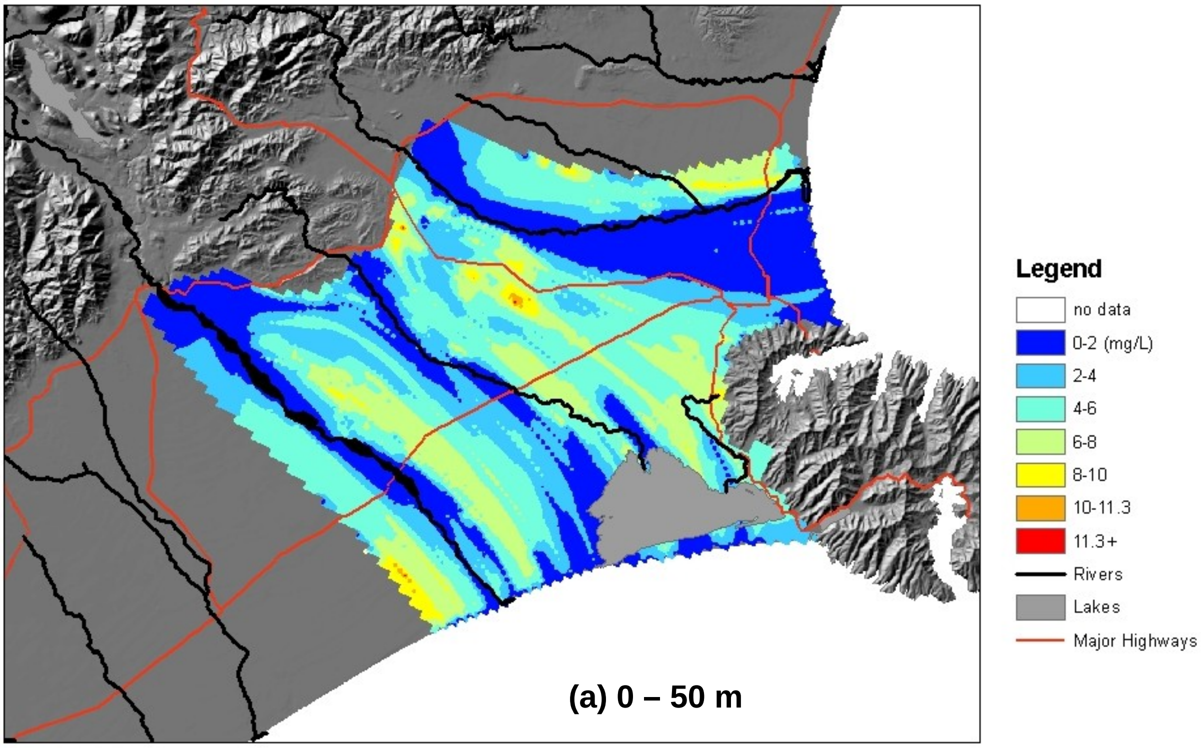


Figure 4. Model prediction of nitrate concentration in shallow groundwater, for Canterbury Plains, by applying a 20% reduction in the nitrate concentration of the nitrate discharges in Figure 2, and applying the smoothing window as in Figure 3.



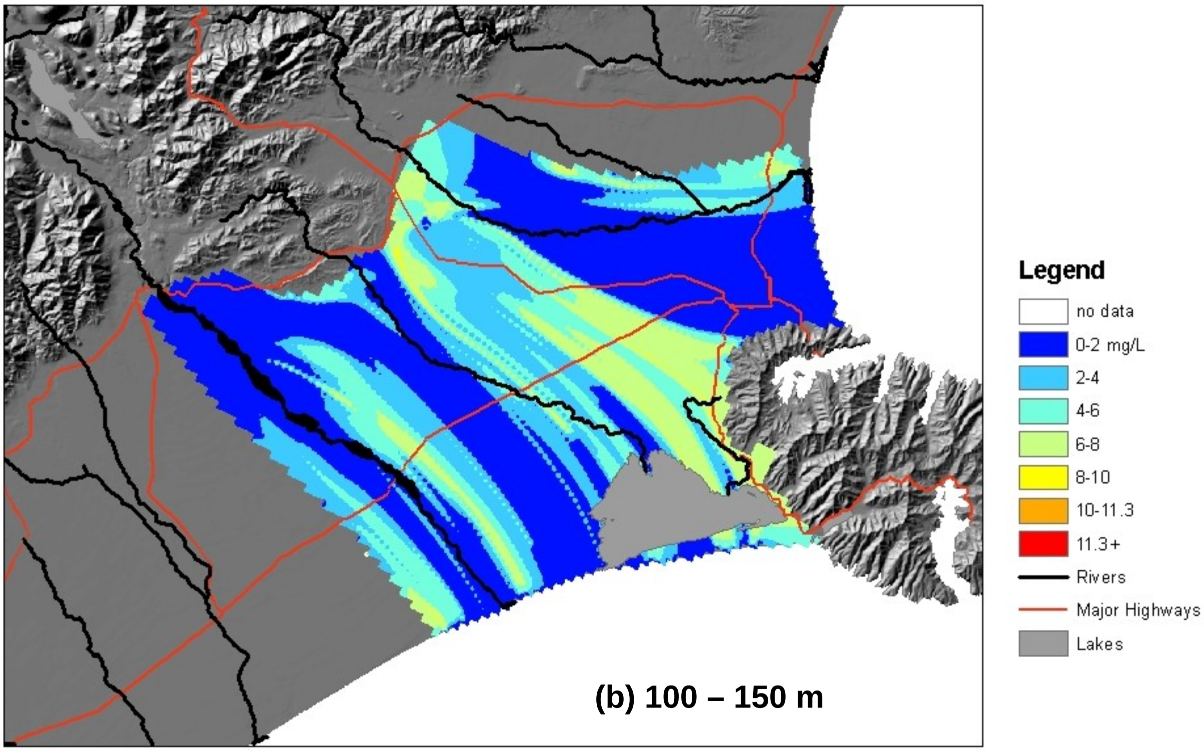


Figure 5. Model predictions of average nitrate concentration for depths of: (a) 0 – 50 m, and (b) 100 – 150 m in the groundwater of Central Canterbury, for the case of low river recharge (52% of total).

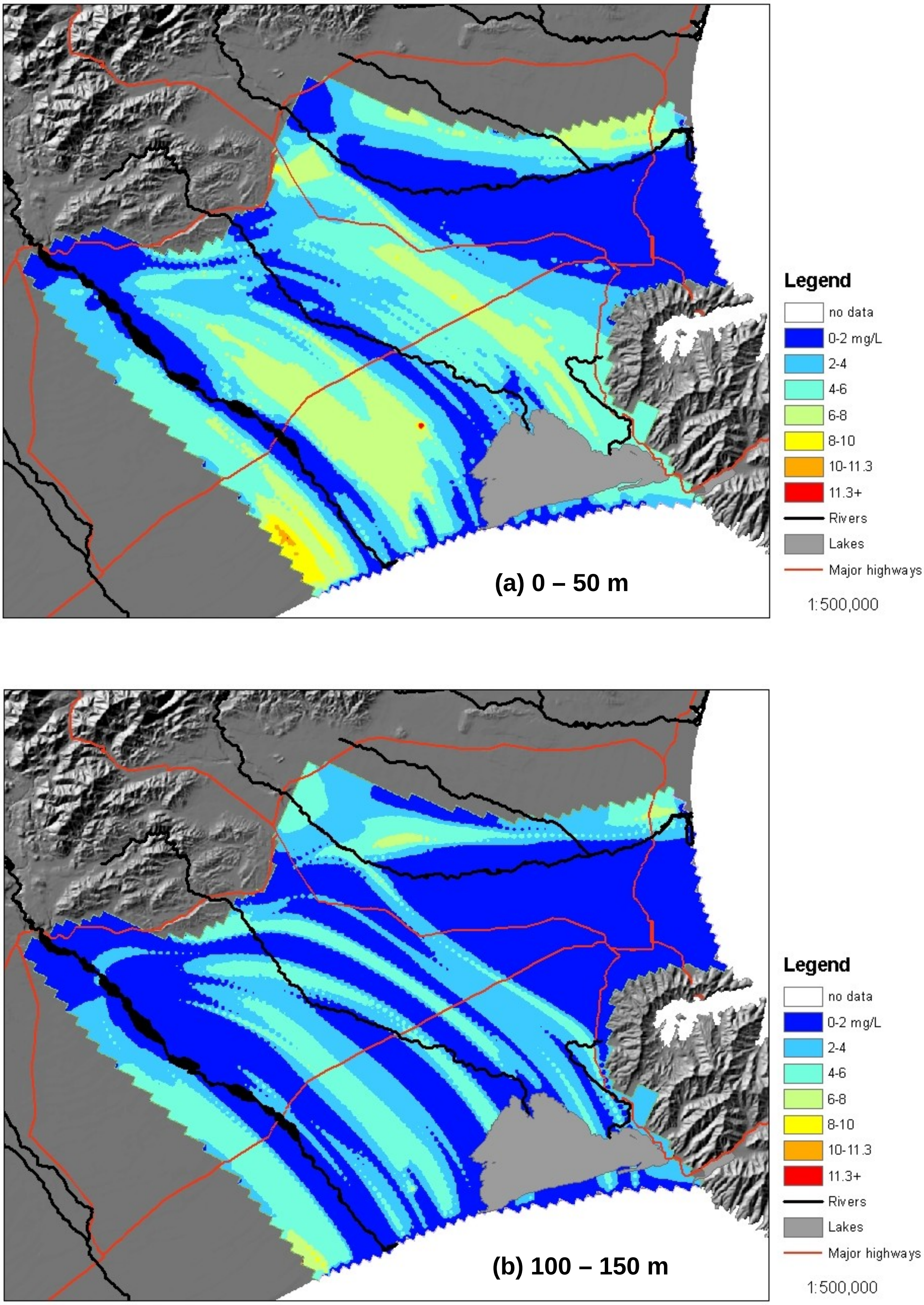


Figure 6. Model predictions of average nitrate concentration for depths of: (a) 0 – 50 m, and (b) 100 – 150 m in the groundwater of Central Canterbury, for the case of high river recharge (68% of total).

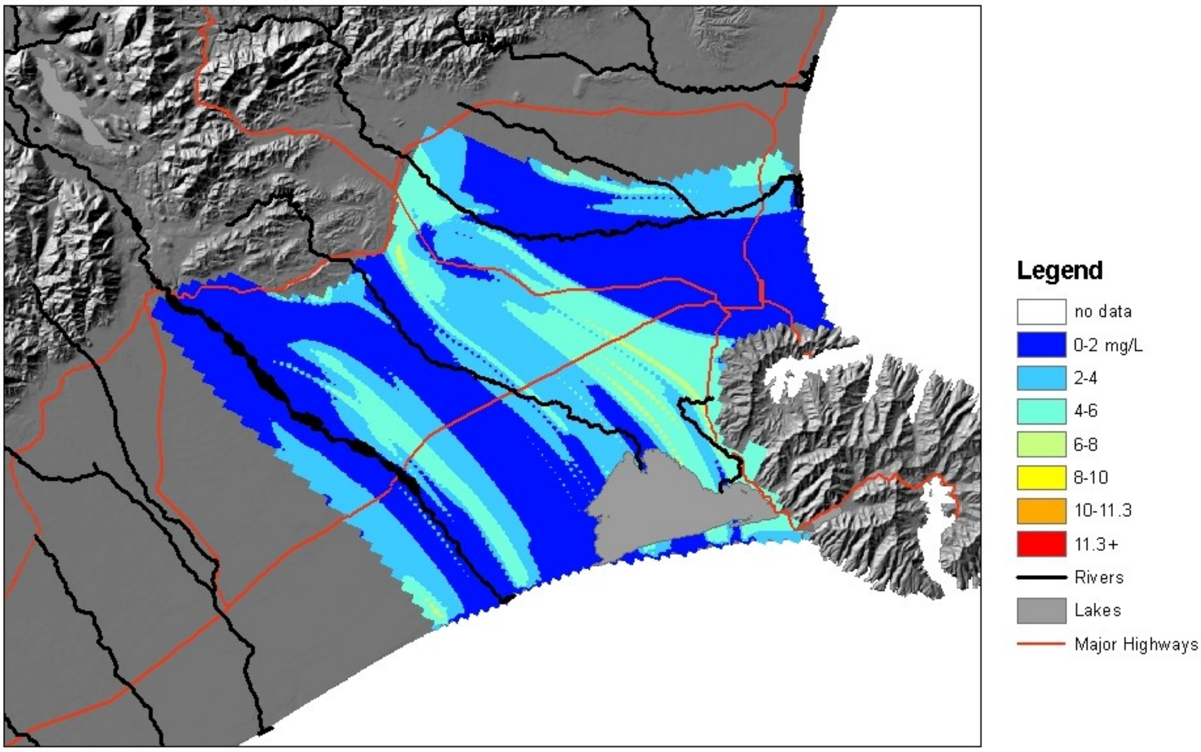


Figure 7. Model prediction of average nitrate concentration in deep groundwater (100 – 150 m), for Central Canterbury with low river recharge, by applying a 20% reduction to the nitrate concentration of the nitrate discharges.

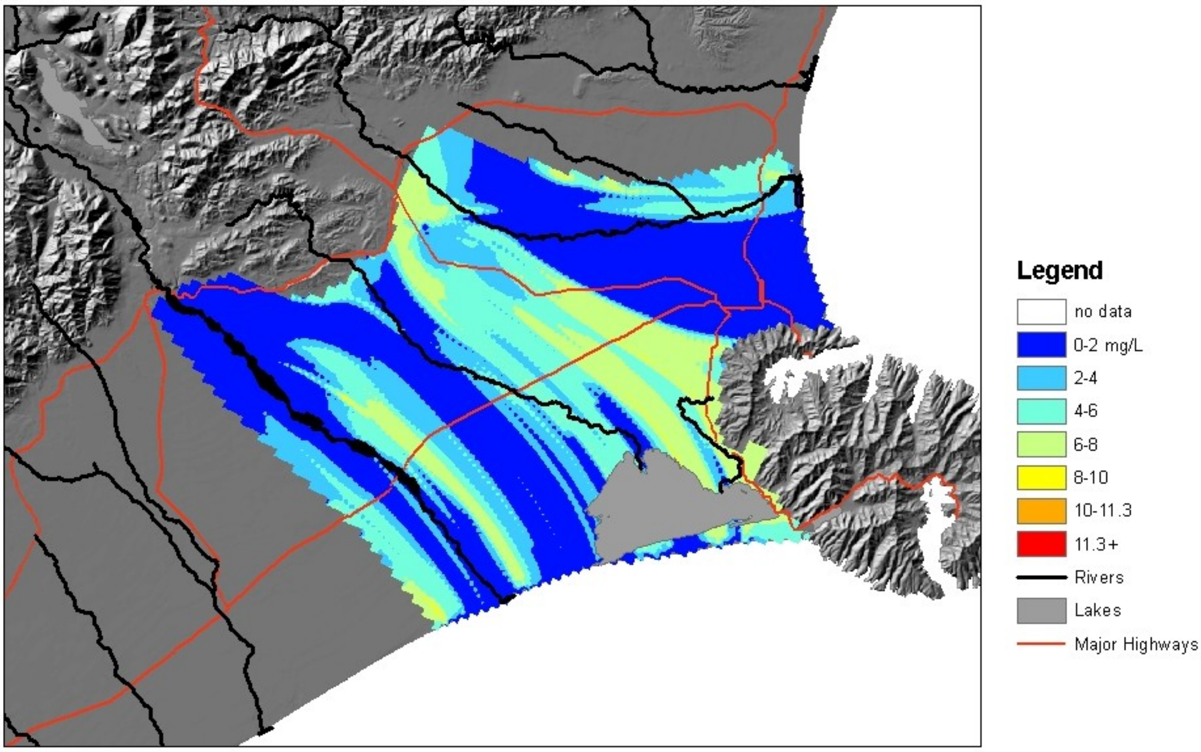


Figure 8. Model prediction of average nitrate concentration in deep groundwater (100 – 150 m), for Central Canterbury with low river recharge, by converting a randomly selected 30% of extensive land use to intensive land use.

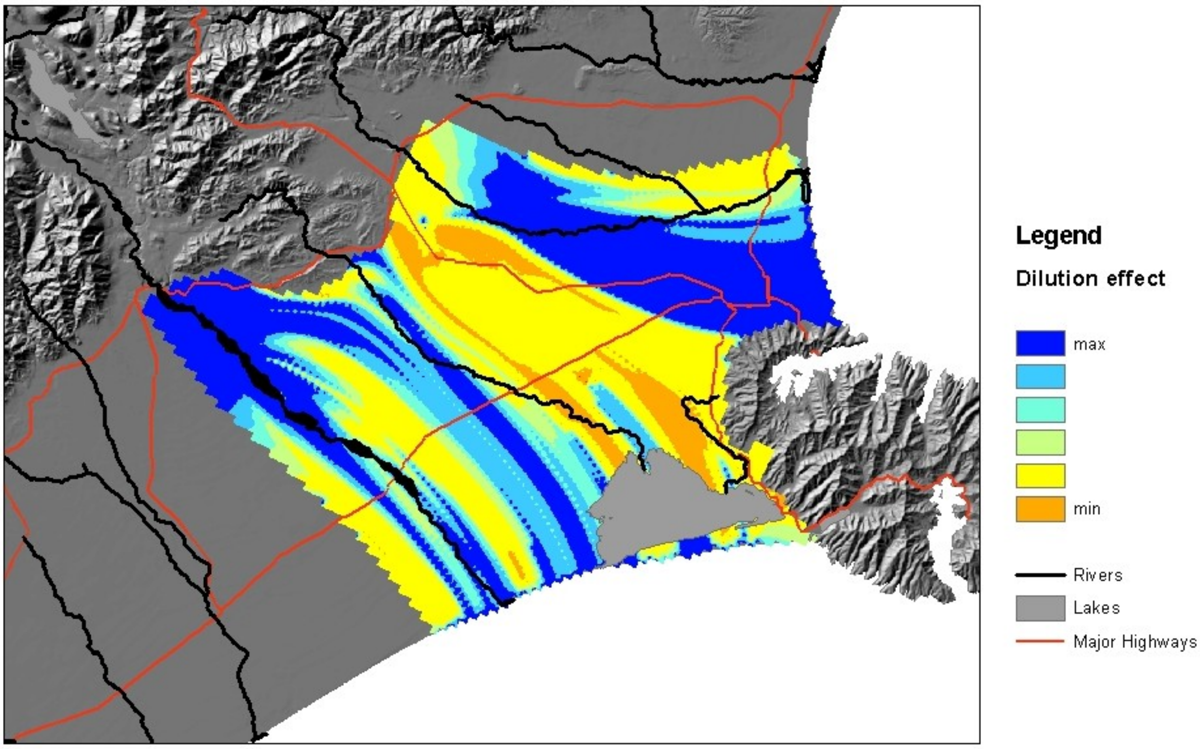


Figure 9. The relative dispersion and dilution effect on deep groundwater (100 – 150 m) from a uniform value of nitrate concentration across Central Canterbury, for the low recharge case.