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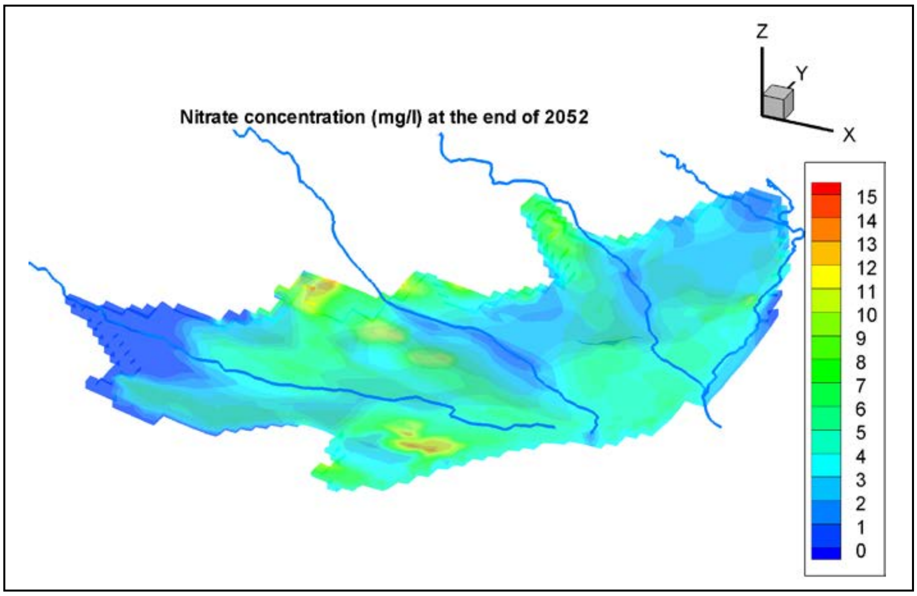

Ruataniwha Basin Nitrate Transport Modelling

Report prepared for HBRIC Ltd
May 2013
EMT 13/06
HBRC Plan No. 4470

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SAFEGUARDING YOUR ENVIRONMENT + KAITIAKI TUKU IHO

Resource Management Group

Environmental Science

Ruataniwha Basin Nitrate Transport Modelling

Report prepared for Hawke's Bay Regional Investment Company Limited

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EXECUTIVE SUMMARY

The proposed Ruataniwha Water Storage scheme will create the potential to irrigate approximately 25,000 hectares of the Ruataniwha Plains. This is almost four times that of the 6,000 hectares of land currently irrigated. Increased irrigation generally favours intensification of farming practices, which increases the potential for nitrogen loss to groundwater through leaching. As a consequence, adverse impacts on groundwater quality may be anticipated, in particular from increasing nitrate concentrations.

Contaminant transport modelling was used to explore the fate of nitrogen in groundwater and help identify areas where greatest risk of nitrate contamination is likely. The modelling used a three-dimensional groundwater flow model (Baalousha, 2009, 2010) to provide input to a solute transport model (Zheng, C. and Wang, 1999), which was used to simulate advection (horizontal and vertical movement) and dispersion (dilution) within the aquifer.

The concentrations of nitrate in the aquifer recharge (a key transport model input) were prepared by NIWA (Rutherford 2013), from leaching losses predicted for future land use. Groundwater flow and contaminant transport models were run for a 35 year period starting in 2017, the date proposed for commencement of the irrigation scheme.

The contaminant transport model predicts the likely concentration of a solute (in this case nitrate), at any point within the model domain and at any time within the model timeframe. Three groundwater layers were defined in the model in terms of depth.
The modelling process predicted:

- Concentrations were predicted to increase in all three groundwater layers over time.
- Highest nitrate concentrations were predicted in layer 1 (shallow groundwater).
- In general, the predicted nitrate concentrations are below the MAV.
- Nitrate concentrations were likely to exceed the Maximum Acceptable Value (MAV) of the New Zealand Drinking Water Guidelines (11.3 mg/L as nitrate-N) at three locations.
- The maximum nitrate concentration predicted is 16.4 mg/L, likely to occur 35 years from the start of the simulation.

It must be noted that groundwater attenuation has not been considered in this modelling, which is conservative approach (i.e. predicts a worst-case scenario for nitrogen reduction).
Although this approach is suitable to identify areas where there is a risk of exceeding the NZ Drinking Water Guidelines (in certain isolated areas where slightly elevated nitrate concentrations are predicted), there are significant uncertainties involved in this study, as in all solute modelling approaches. Therefore, the model-derived estimates of likely future nitrate concentrations should be used qualitatively to guide monitoring and management of future land use intensification and related groundwater nitrogen concentrations. The monitoring activities will provide data to validate the model and will confirm areas where nitrate leaching is occurring and the extent and magnitude of any groundwater contamination. If necessary, mitigation strategies may be developed in response to land use change and groundwater contamination.

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1.0 INTRODUCTION

1.1 Overview

This study has been commissioned by Hawke's Bay Regional Investment Company (HBRIC) to investigate the potential impact of future land use intensification on groundwater. This anticipated intensification is a result of Ruataniwha Water Storage Scheme (RWSS). The report will support the RWSS consent application process.

The Ruataniwha Plains (with approximately 40,000 hectares of irrigable land) are located in central Hawke's Bay overlying the Ruataniwha Basin, within the Tukituki River catchment (approximately 250,000 hectares). They have significant agricultural potential which is currently restricted by access to water. Approximately 6,000 hectares of the Tukituki River catchment are currently irrigated. In the plains, irrigated land is principally supplied by groundwater abstracted (pumped) from the Ruataniwha Aquifer. Water is also abstracted from the Tukituki River and its tributaries. The provision of additional irrigation water from a potential community water storage scheme located on the Upper Makaroro River (a tributary of the Waipawa River, the main tributary of the Tukituki River) is being investigated. Studies have identified approximately 25,000 hectares of potentially irrigable land within the Tukituki River catchment that could be supplied from the RWSS.

Additional irrigation will change land use within the catchment is likely to increase nitrogen leaching rates. Likely changes in land use have been used by AgResearch Limited to create a future land use scenario, from which estimates of future nitrogen leaching rates were derived. These nitrogen leaching rate estimates were provided to NIWA, who developed a geospatial nitrogen loss template. This nitrogen loss template was used by HBRC (Hawke's Bay Regional Council) to predict the future distribution of groundwater nitrogen concentrations using numerical modelling tools.

The New Zealand Drinking Water Guidelines identify a maximum acceptable value for nitrate-nitrogen concentrations in drinking water (11.3 mg/L as nitrate-N, Ministry of Health, 2005). This report describes a semi-quantitative, risk-based method that was used to predict the likely future spatial (3D) distribution of groundwater nitrogen concentrations. This information is designed for application to develop monitoring, management and/or mitigation strategies.

1.2 Existing State

Results from a five-yearly nitrate-N monitoring programme conducted by HBRC covering the entire area of Hawke's Bay identified existing high nitrate concentrations in groundwater (Baalousha, 2008). All wells identified with high nitrate were shown to be shallow (less than 20 m deep) and not being used for drinking water. Most drinking water supply wells penetrate the deeper aquifers which are unlikely to be contaminated by on-land activities. A recent nitrate survey was undertaken in 2012 and showed there is a slight decline in the average nitrate concentrations (Gordon, 2013).

1.3 Modelling Options

To assess the effect of land use activities on groundwater quality, three approaches were considered.

- vulnerability assessment
- groundwater risk mapping
- contaminant transport modelling.

Vulnerability assessment considers the extent to which an aquifer may be affected following exposure to contamination. Vulnerability mapping is normally based on the hydrogeological settings of the aquifer under consideration, such as hydraulic conductivity and depth to water table. The assessment provides an indexed map, classified according to vulnerability to contamination (Aller et al 1987). The map does not predict the contaminant concentration likely as a consequence of the contamination.

Groundwater risk mapping provides a map with a risk factor at each grid point. Preparation of the risk map requires contamination probability mapping and an assessment of the likely impact of contamination. The product of probability and impact is the contamination risk. As with the vulnerability approach, risk mapping provides comparative analysis; that is, it does not provide likely contaminant concentration values.

Contaminant transport modelling simulates the likely fate of a solute (e.g. nitrate-N) in groundwater, based on advection and dispersion processes, assuming that the contaminant is "conservative". "Conservative" implies that loss or removal associated with chemical reaction, biochemical transformation or adsorption to aquifer materials is ignored. This modelling is normally based on groundwater flow model results, where the flow matrix from a groundwater flow model is used as an input to a contaminant transport model. Additional data, such as recharge concentration of the contaminant(s) of concern, are required for the transport model. The model results provide 3D distributions of likely contaminant concentration values, and changes with time.

Contaminant transport modelling was selected over the vulnerability and risk mapping approaches because it predicts the likely concentration of a contaminant along the groundwater flow path. This information allows appropriate future actions (such as targeted groundwater quality investigation or surveys) to be undertaken at locations where they are likely to be most useful.

1.4 Scope

This report describes the implementation of nitrate transport modelling to predict likely future nitrate concentrations in groundwater in the Ruataniwha aquifer. The process takes into account provision of additional irrigation water from the RWSS and the resulting land intensification.
The groundwater flow modelling on which this work is based has been described in detail (Baalousha, 2009, 2010). These reports provide full details regarding model conceptualisation and parameterisation.

This report provides an overview of the conceptual model, with emphasis on contaminant transport modelling. This work simulates the movement of nitrate in groundwater over the period 2017 to 2052 (35 years, the term proposed for the consents being sought to authorise operation of the storage dam that forms part of the Ruataniwha Water Storage Scheme).

2.0 MODEL DEVELOPMENT

The contaminant transport model (MT3DMS) was based on the flow model developed by Baalousha (2010). It is a finite difference groundwater model covering the Quaternary geology in the Ruataniwha Plains (Figure 1). The boundaries are termed "no-flow" and the recharge is mainly from rainfall. "No flow" implies there is no hydraulic connection between water within the basin and any other water body outside the boundary. Groundwater exits the basin via seepage to the Waipawa and Tukituki Rivers. The flow model (Baalousha 2010) spans the period from 1990 to 2010, and predictive modelling covers the period from 2010 to 2022 (Baalousha 2011). The flow model of Baalousha (2010) has been extended to 2052, with the MT3DMS model then being used for contaminant transport modelling.

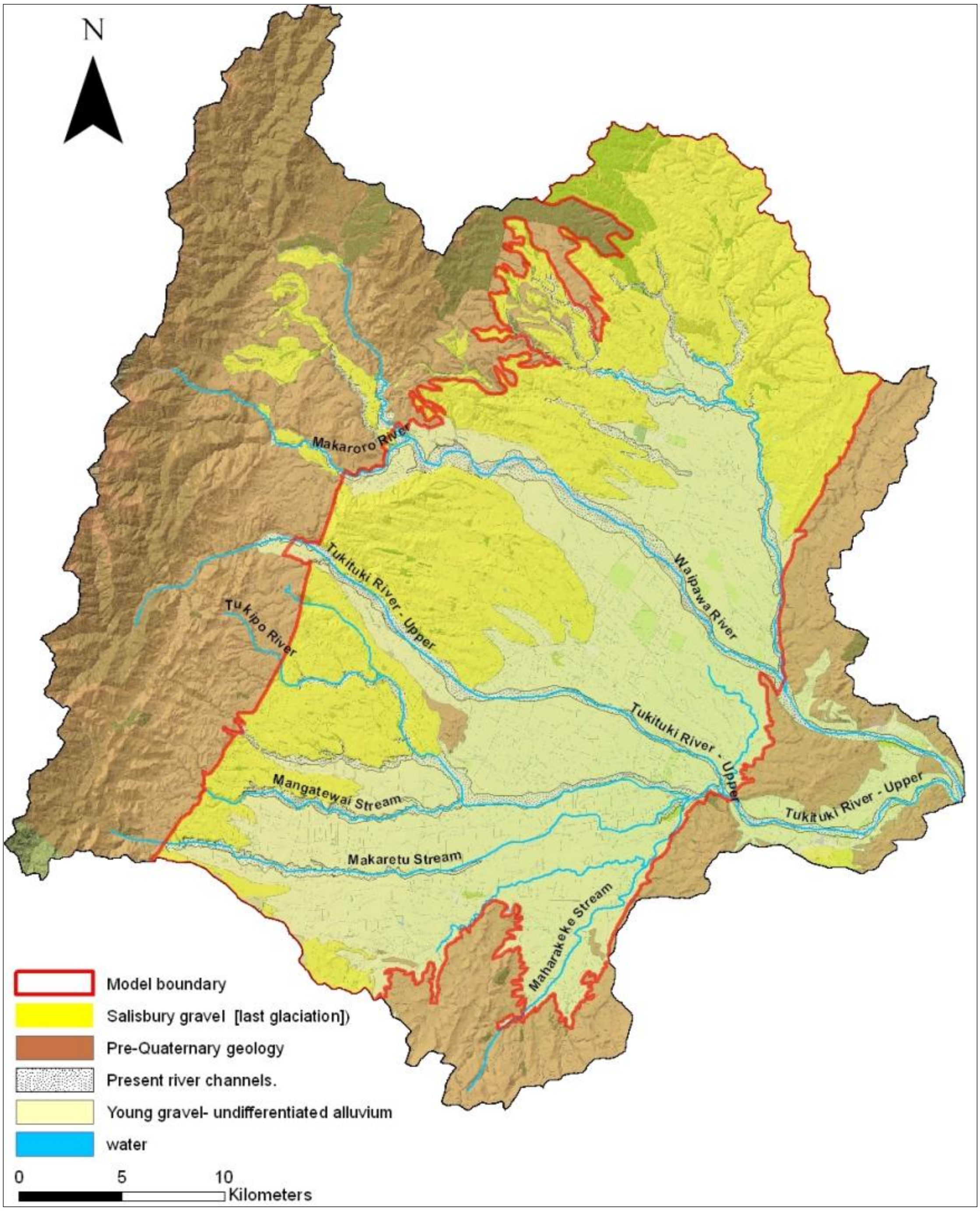

Figure 1: Model boundary and geology (Baalousha 2010)

MT3DMS is a modular three-dimensional transport model for the simulation of advection, dispersion, and chemical reactions of dissolved constituents in groundwater systems (Zheng, and Wang 1998). MT3DMS uses a similar structure to MODFLOW, and is linked with it via the groundwater heads and cell-by-cell flux terms computed by MODFLOW during the flow simulation. Visual Modflow pre and post-processing software was used for the flow and solute transport modelling.

2.1 Groundwater Recharge

The groundwater flow modelling investigation (see Baalousha 2010) provides details on the estimates of groundwater recharge applied, and Figure 2 shows the distribution of recharge over the model area as a rate (m/d).

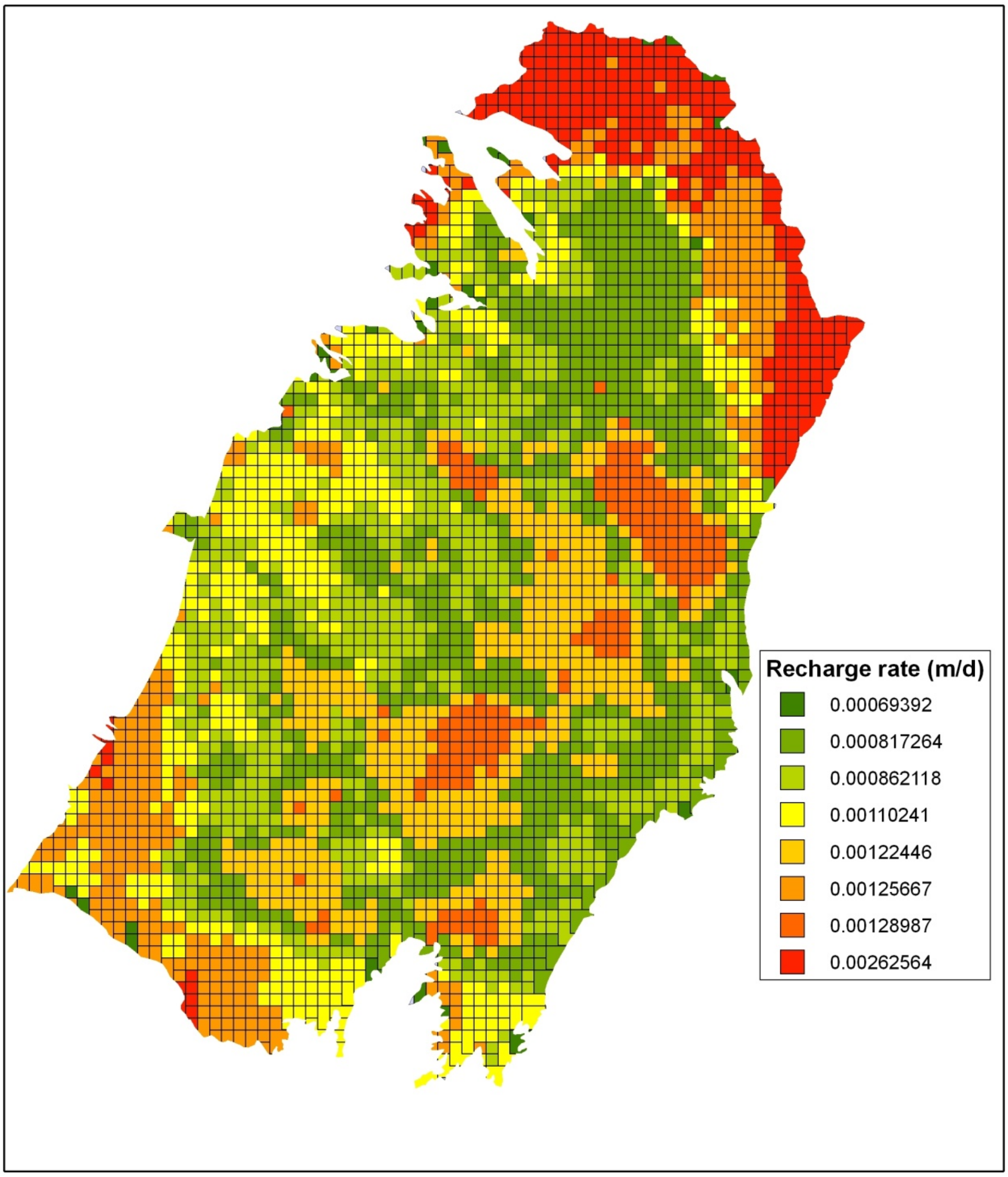

Figure 2: Rainfall recharge over the model domain (m/d)

Additional recharge resulting from irrigation return infiltration was considered in the flow model investigation, but the process was not modelled specifically, as an environmentally conservative approach. Recent work conducted by the National Institute of Water and Atmospheric Research (NIWA) identified a 14% to 20% return irrigation flow, excluding on-farm water losses (Leaching Losses on the Ruataniwha Plain Letter Report NIWA 15 Feb 2013). At full uptake, this equated to between 10 and 15 million m^3 per year (greater if on-farm losses are included), which corresponds to 3.9% to 5.8% of the estimated average annual recharge from rainfall in the Ruataniwha Basin. This is not significant, especially in the context of uncertainties relating to rainfall recharge estimation. It was recommended that this positive effect of return irrigation on the groundwater flow model and low river flow statistics be investigated further in future studies.

2.2 Groundwater Abstraction

As for the predictive modelling work (Baalousha 2011), the annual groundwater abstraction was assumed to be the same as in 2010 (approximately 25 million m^3). Abstraction was distributed into three intervals as shown in Table 1. These intervals represent late summer (January to March), winter (April to September) and early summer (October to December) to reflect fluctuations of groundwater abstraction over a calendar year.

2.3 Spatial Resolution

The spatial resolution of 500 by 500 m for the contaminant transport model is the same as the flow model (Baalousha 2010).

2.4 Temporal Resolution

The temporal resolution of the model is the same as the flow model, approximately three months for each stress period. Adaptive time stepping was used to control numerical dispersion of the finite difference (see page 359, Schlumberger, 2008) The model was run for 35 years (the consent period) post 2017, the date when the proposed Ruataniwha Water Storage Scheme is likely to commence operation.

2.5 Recharge Concentration

The nitrate concentration in the water percolating into the aquifer is a specified model input. In this case, the nitrate concentration was obtained from NIWA[1] for the planned irrigated zones and the proposed future land uses, and assuming that there is no attenuation effect to reduce concentrations in the sub-surface (again, this is a conservative approach). Figure 1 shows a map of recharge concentrations in spatial format.

[1] Dr Kit Rutherford, personal communication, NIWA Hamilton.

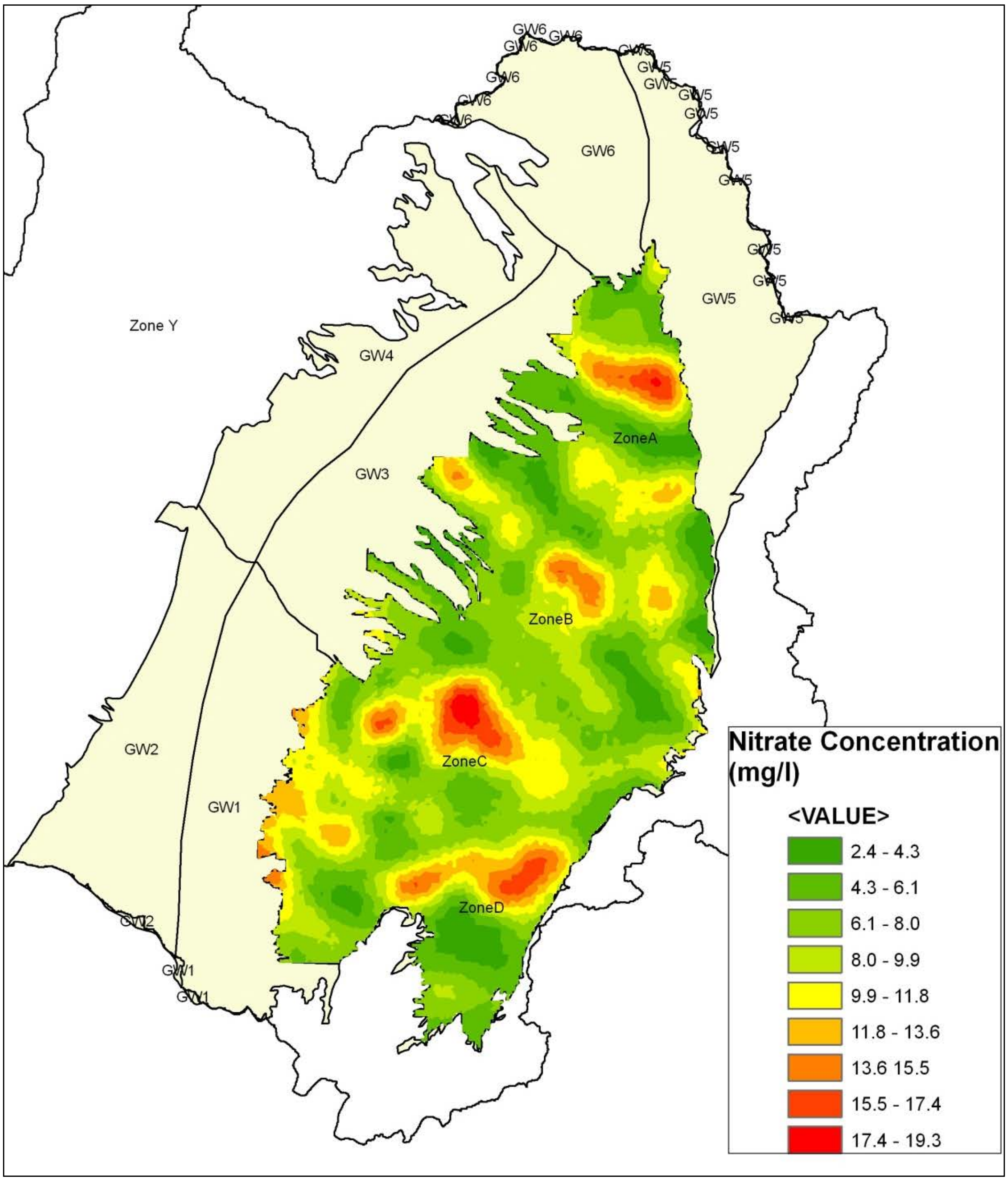

Figure 3: Recharge nitrate-N concentration (mg/L) predicted for future landuse (source: NIWA)

2.6 Hydraulic Properties

Calibrated hydraulic properties were unchanged from the flow model, including calibrated hydraulic conductivity, storativity and streambed conductance (Baalousha 2009, 2010). The solute transport model also requires specification of effective porosity and dispersivity.

2.7 Effective Porosity

Measured values of effective porosity are not available for the Ruataniwha Basin. Accordingly, a value was selected from literature. According to Freeze and Cherry (1979) and Gelhar et al (1992), the porosity for gravels ranges between 25% and 40% and it is higher for clay and silt. A uniform value of 25% for porosity was assigned in this study.

2.8 Dispersivity

Dispersivity is a property of porous media that affects the dilution of a solute in both longitudinal and lateral directions. No measured dispersivity values exist for the Ruataniwha Basin. Values selected from the literature (10 m for longitudinal dispersion and 1 m for lateral dispersion (Gelhar et al. 1992)) were assigned in the model. These literature values are considered appropriate because they are based on field measurements made in similar geological material.

2.9 MT3DMS Settings

The contaminant transport model used a finite difference method for advection and the implicit GCG solver. The Visual MODFLOW user manual (Schlumberger2008) provides more detail on this solver, and the software settings that were applied (including adaptive time stepping), to constrain the numerical dispersion of solute simulation subject to the Peclet and Courant criteria. This is consistent with best practice (Barnett, 2012).

2.10 Uncertainty

Modelling results are always subject to uncertainty. Groundwater modelling has inherent uncertainties because of our inability to observe natural processes going on underground. A model is a relatively crude and therefore inherently limited approximation of the complex natural processes being simulated.

Aside from that inherent uncertainty, the most significant potential source of uncertainty is the selection of parameter values when field-measured values are not available.

Key parameters subject to uncertainty in this case are: (1) Hydraulic Conductivity; (2) Aquifer Storativity; (3) Streambed conductance; and (4) porosity. The first three parameters are elements in the groundwater flow model, on which the contaminant transport model is based. The process used for the flow model was previously described (Baalousha 2011). Uncertainty in the selection of parameter values for this model was minimised to the point where any change of these three parameters would disturb the calibration process, making the flow model unfit. Porosity is the only new parameter in the latter model (nitrate model). Uncertainty arising from selection of a porosity value was minimised through a sensitivity analysis associated with parameter calibration. This was done using PEST (an acronym for Parameter ESTimation and uncertainty analysis). This modelling tool assists in data interpretation, model calibration and predictive analysis, principally by adjusting model parameters until model-generated numbers fit a set of observations as closely as possible.

For parameters used in contaminant transport models (such as porosity and dispersivity), conservative values were selected from the literature. This ensured that model predictions were not biased or extreme.

Modelling uncertainty may result in nitrate concentrations taking longer or shorter times to reach the levels predicted by this model. The locations where increases in nitrate concentrations are predicted are dependent on the location and nature of future land use intensification. Contaminant transport also requires a conceptualisation of the underlying geology. Predicted future landuse intensification is necessarily speculative; conceptualisation of the geology at a small scale is associated significant uncertainty. Actual future intensification will be monitored and real data will help inform potential future nitrate elevations, reducing uncertainty from this source.

It is emphasised that modelling undertaken in this report is consistent with best practice. While it is acknowledged alternative approaches to modelling exist, these may involve different levels of uncertainty and are likely to have different strengths and weaknesses than the modelling methods used in this report.

3.0 MODEL RESULTS

Contaminant transport model output includes estimates of the 3D spatial distribution of nitrate concentrations. The model consists of three layers (see Baalousha 2009, 2010) representing the top Young Gravel, the second thin layer of intermittent aquitard and the lower layer, which represents the Old Gravel Formation.

Figure 4 shows the nitrate concentration predicted at the end of 2052 in the top layer (Layer 1). It predicts that the maximum permissible limit of 11.3 mg/L has been exceeded at four reasonably isolated locations, with an absolute maximum predicted nitrate concentration of 16.2 mg/L. This is not unexpected, given the input concentrations (Figure 1).

Figures 5 to 13 show the simulated groundwater nitrate concentration at five-year time interval between 2017 and 2052. This time period covers the 35 years consent period of the water storage project. Each figure shows concentrations within layer 1 (the shallow layer), layer 2 and layer 3 (the deep layer). The highest nitrate concentrations are predicted to occur in the surface layer because is closest to the contaminant source (land surface). The deeper layer (3) displays the lowest nitrate concentration. It is also noted that nitrate concentrations increases in all three layers over time.

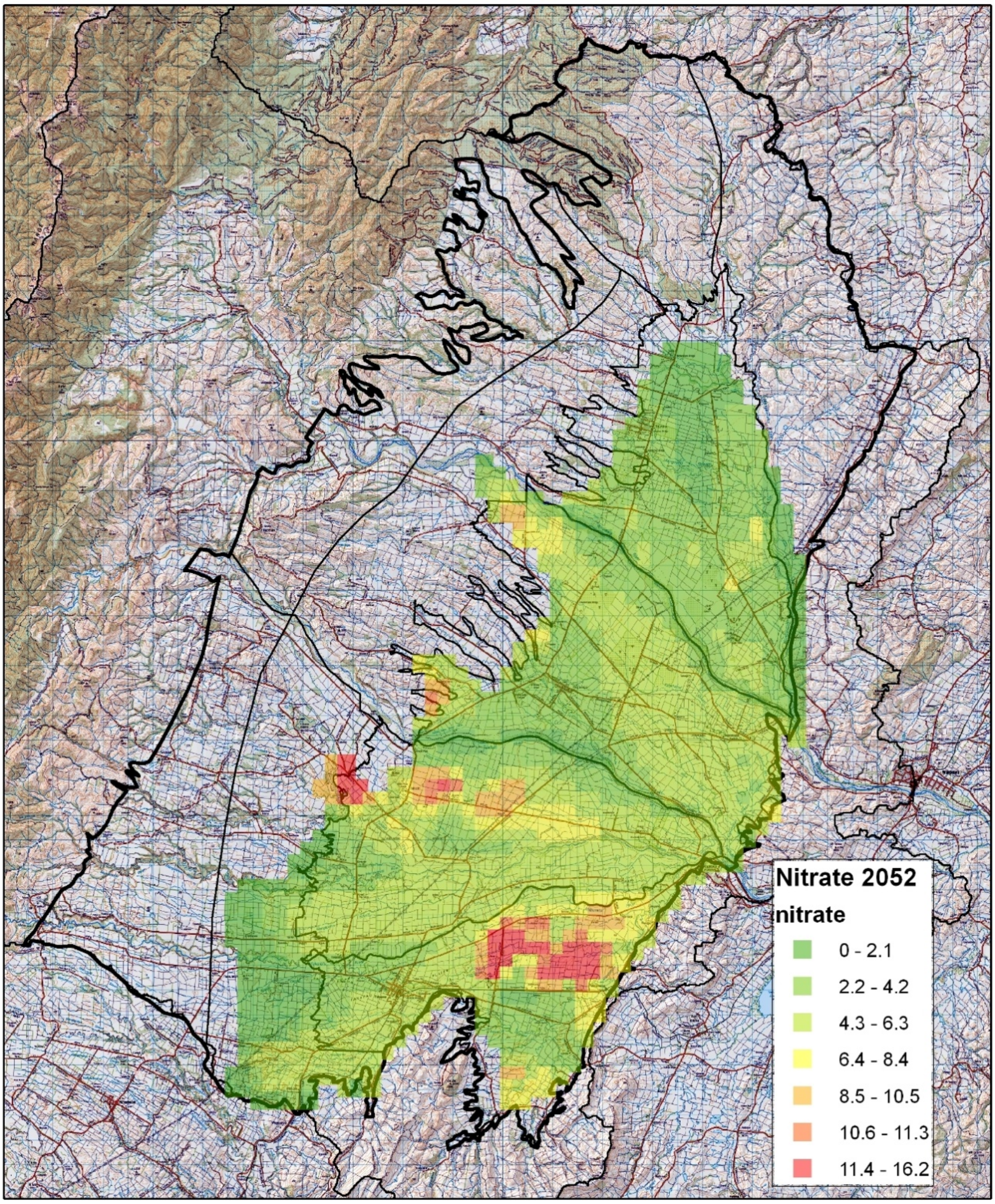

Figure 4: Nitrate concentration at layer 1 (mg/L) at the end of 2052.

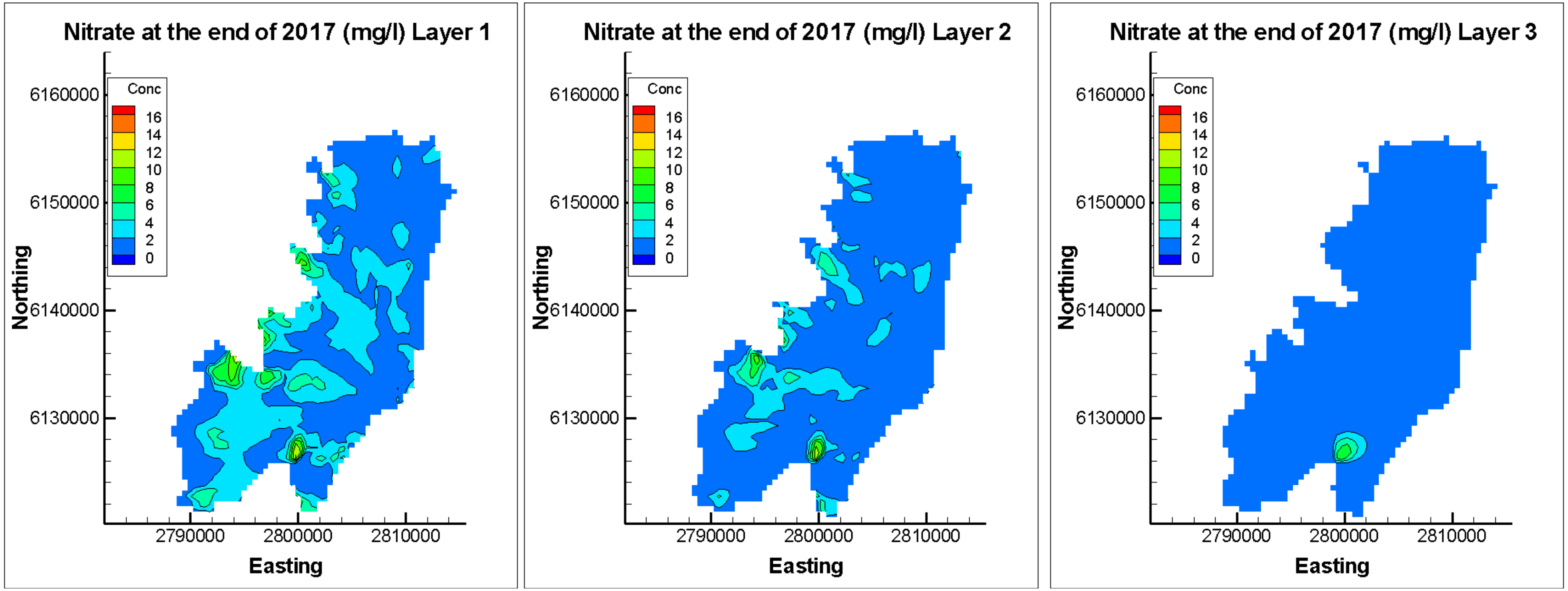

Figure 5: Nitrate concentration at the end of 2017

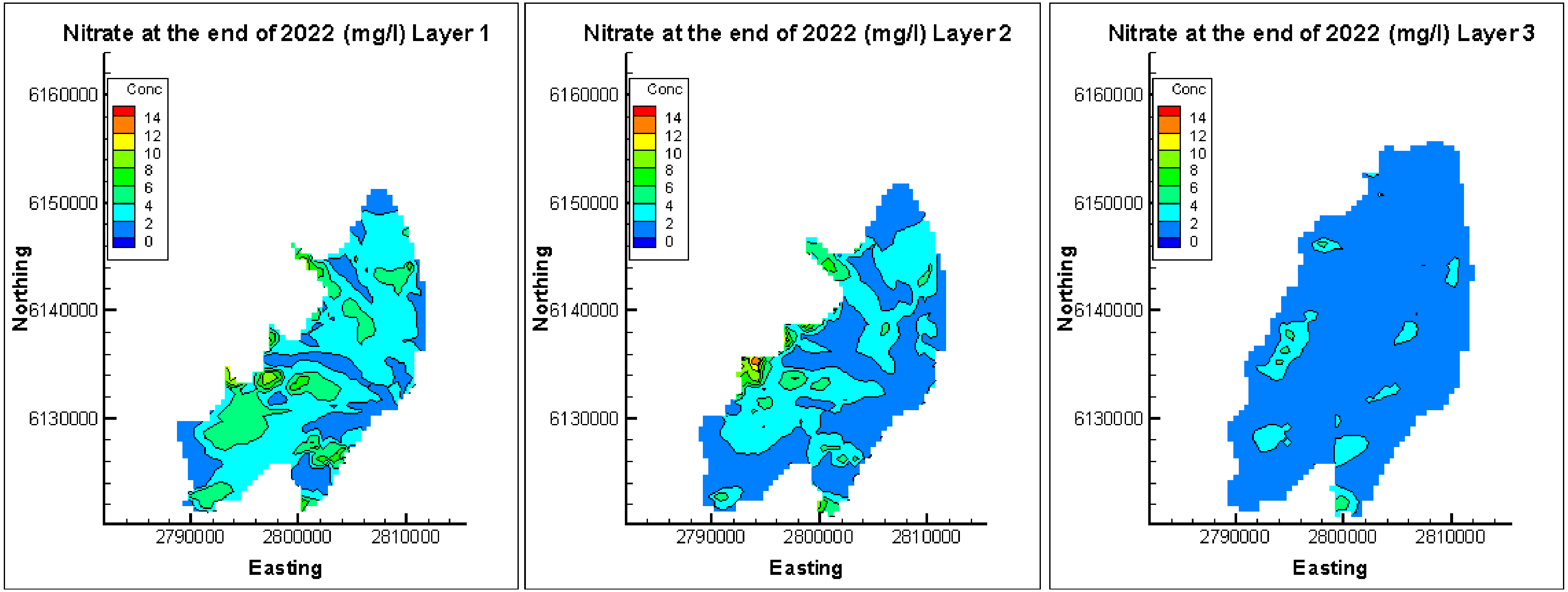

Figure 6: Nitrate concentration at the end of 2022

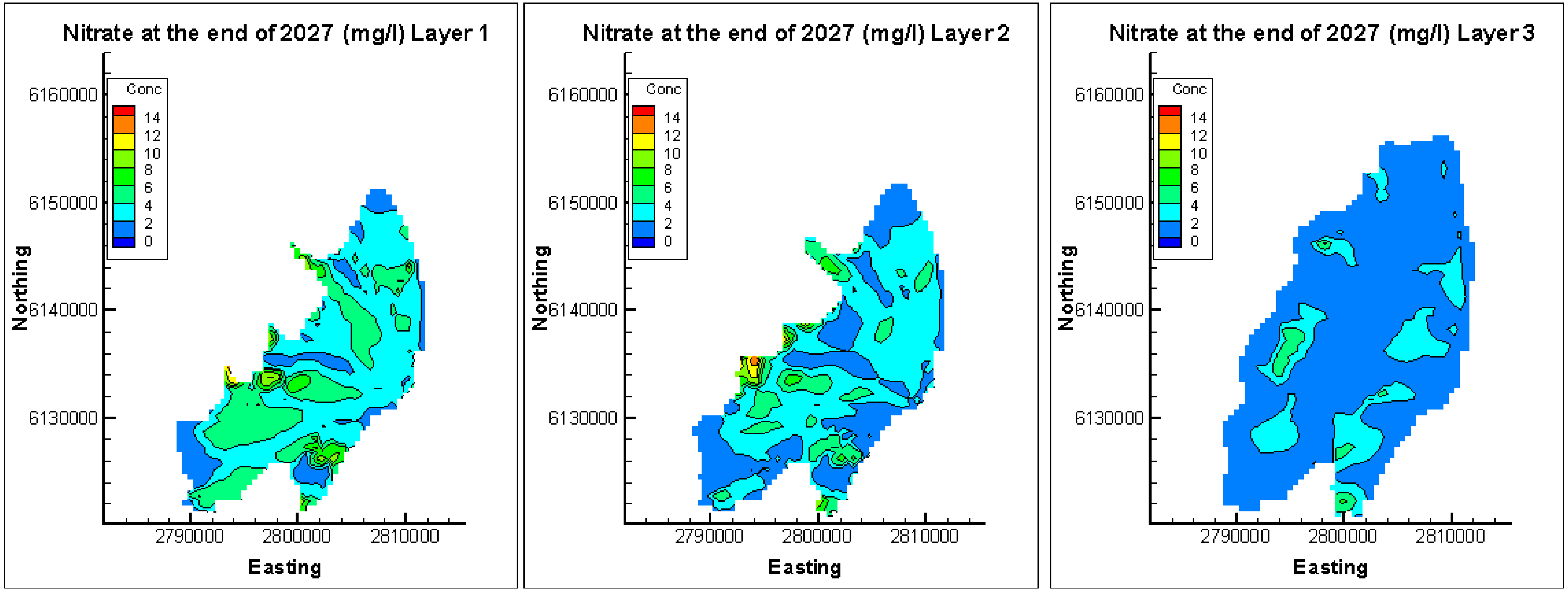

Figure 7: Nitrate concentration at the end of 2027

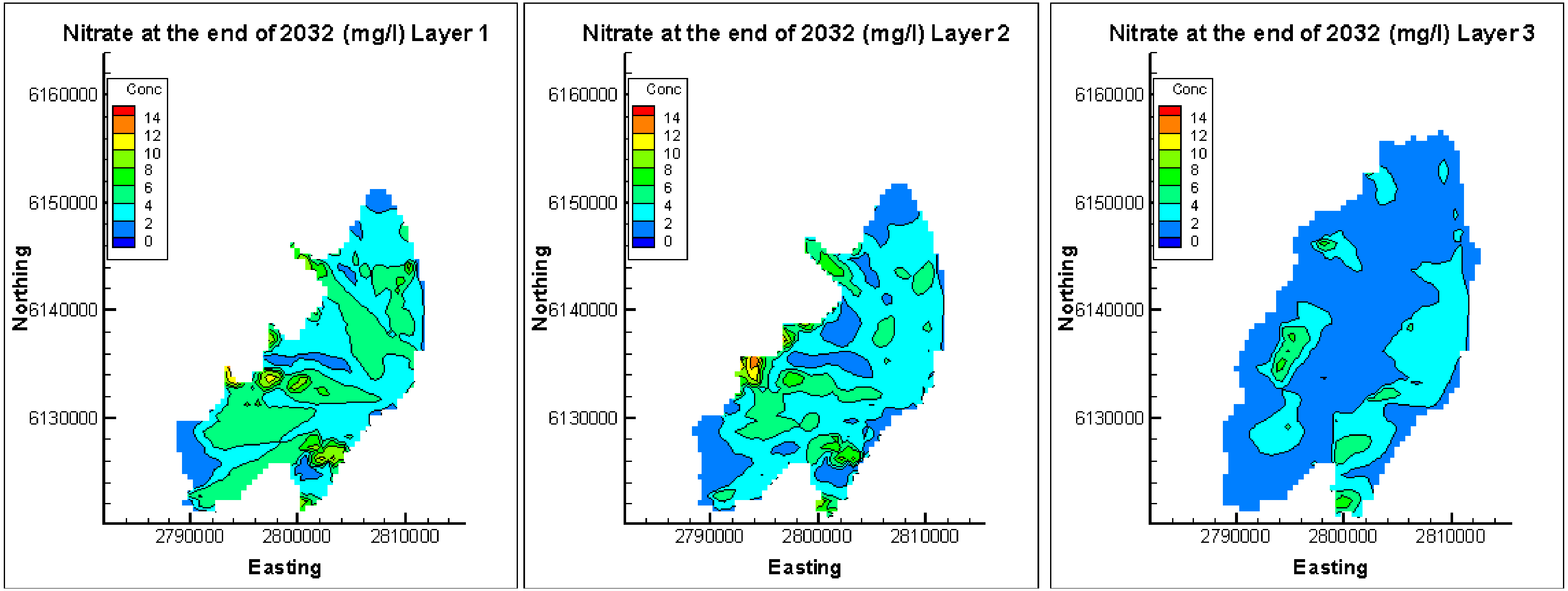

Figure 8: Nitrate concentration at the end of 2032

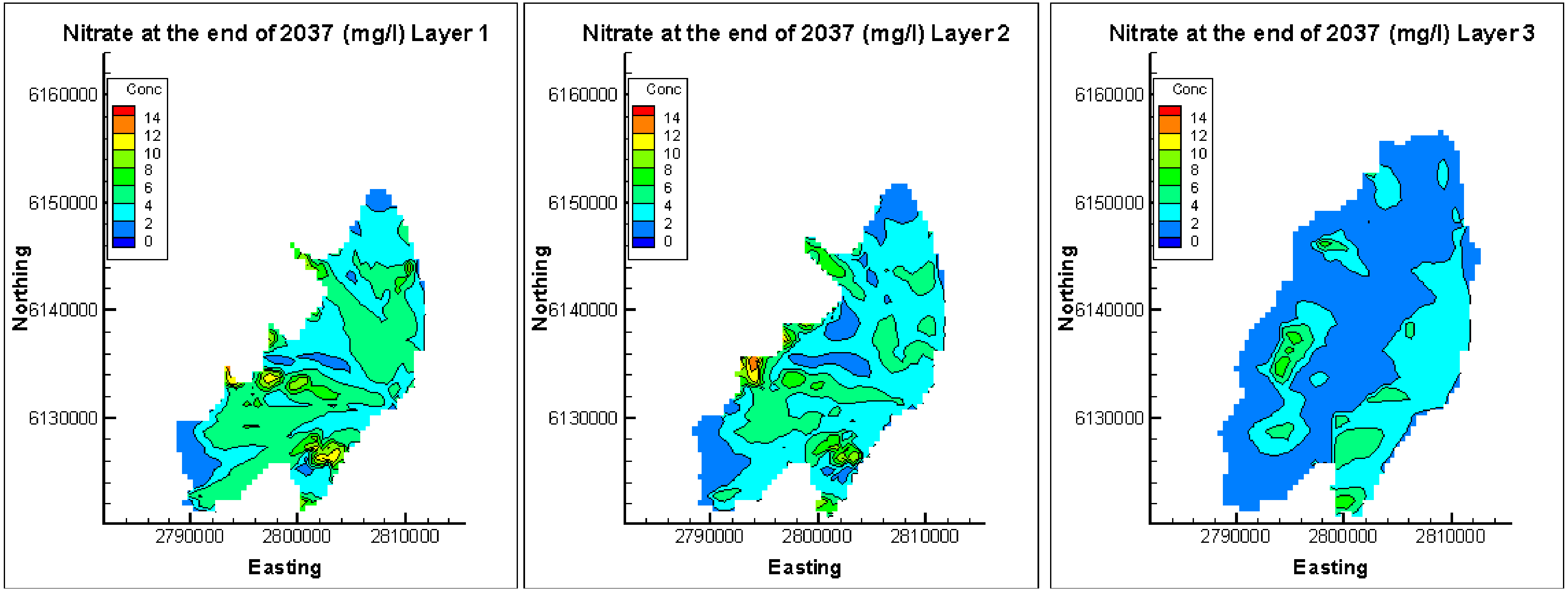

Figure 9: Nitrate concentration at the end of 2037

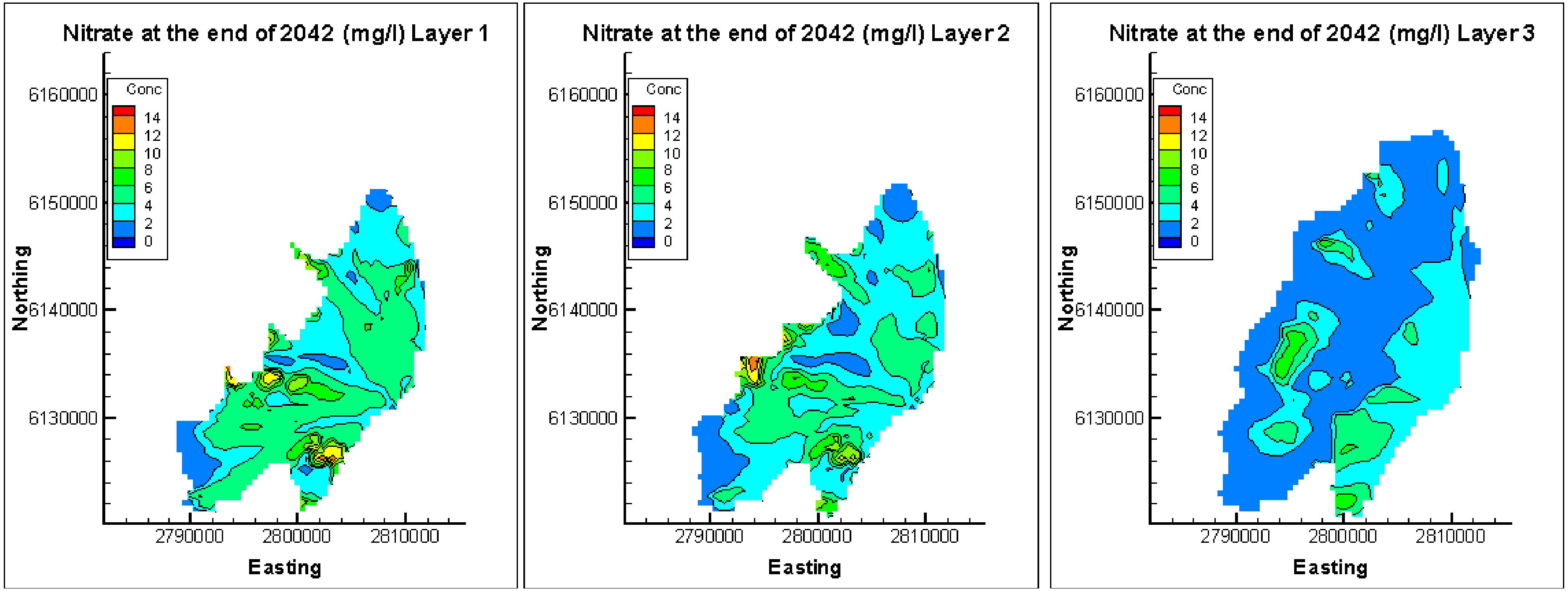

Figure 10: Nitrate concentration at the end of 2042

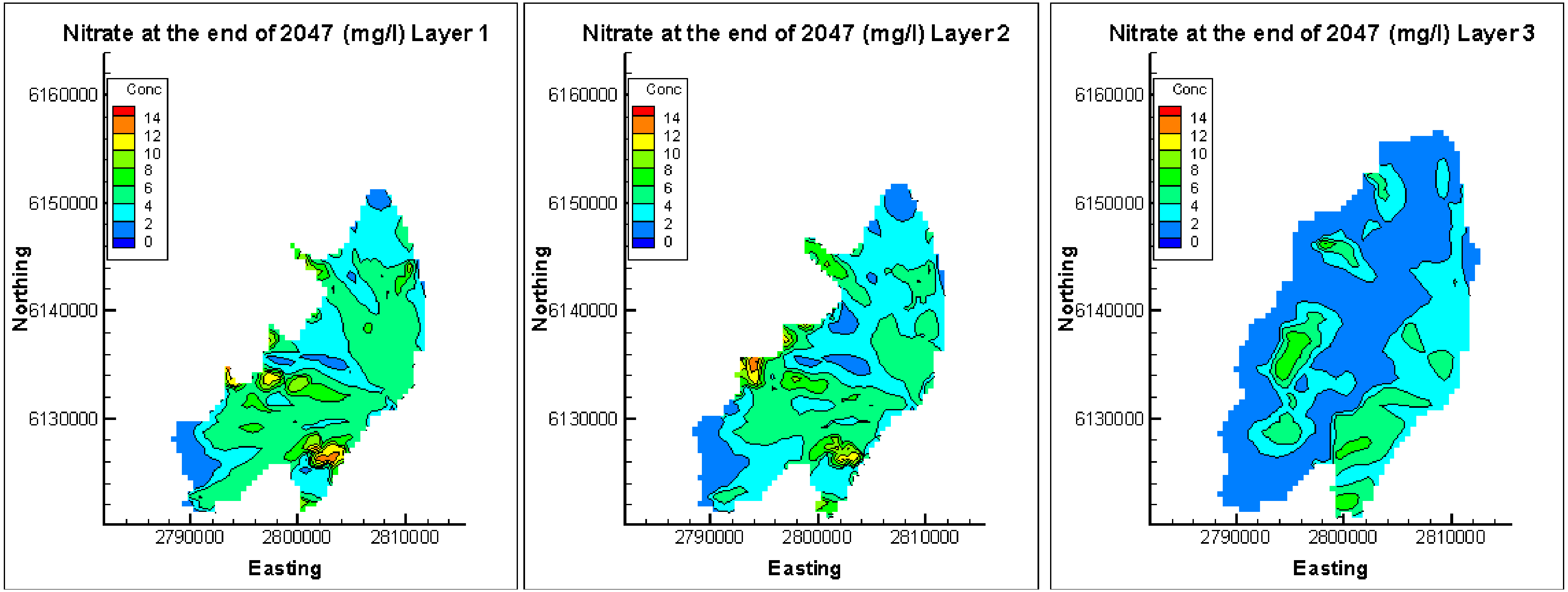

Figure 11: Nitrate concentration at the end of 2047

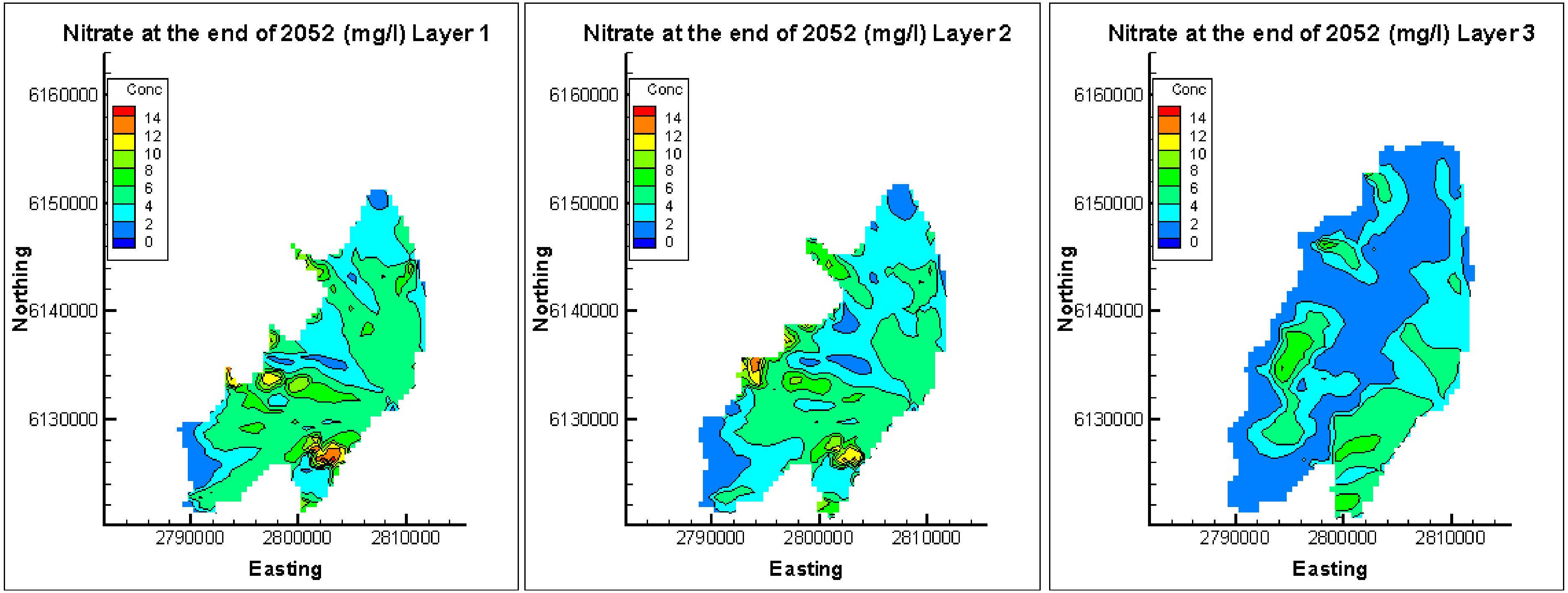

Figure 12: Nitrate concentration at the end of 2052

3.1 Discussion

This semi-quantitative risk assessment was undertaken to identify (on a macro scale) areas of the Ruataniwha aquifer likely to be at highest risk of nitrate contamination based on groundwater modelling results. The solute modelling approach applied, is designed to identify areas where there is a risk of exceeding the NZ Drinking Water Guidelines. There are significant uncertainties involved in this study, as in all solute modelling approaches. Therefore, the model-derived estimates of likely future nitrate concentrations should be used qualitatively to guide monitoring and management of future land use intensification and related groundwater nitrogen concentrations. Monitoring activities will provide data to validate the model and will confirm areas where nitrate leaching is occurring and the extent and magnitude of any groundwater contamination. If necessary, management and mitigation strategies may need to be developed in response to land use change and groundwater contamination.

The contaminant transport modelling is based on flow modelling, which includes sensitivity analysis (Baalousha 2010). Additional parameters used in contaminant transport modelling include input nitrate concentration, porosity and dispersivity.

Nitrate input concentrations were derived by NIWA from a predicted future land use with assumed nitrogen loading. A representative value for porosity was selected from literature, assuming a uniform gravel medium. Sensitivity testing on the porosity parameter value identified that the rate of increase in nitrate concentration was slowed as the porosity value was increased, and thus a parameter value at the low end of a realistic range was specified. A value for dispersivity was also selected from the literature. Sensitivity testing showed that, as dispersion increases, dilution increases and nitrogen concentrations decrease. Accordingly a relatively low value of dispersivity was selected to provide conservative estimates of nitrogen dilution.

The model starts at 2017 and assumes that no nitrogen is present in the groundwater (no lag effect). We know this is not the case and in some areas high nitrogen concentrations exist, the consequence of historical land use. This is not considered critical, however, because high initial nitrate concentrations will only serve to bring forward in time the occurrence of maximum nitrate concentrations. The simulation time of this model is designed to identify the potential future risk zones created by intensification, the time to onset, and thus design appropriate monitoring plans. Results from monitoring should be used to validate the model and also confirm decisions about when intervention is required to mitigate adverse impacts on groundwater being used for drinking water supply.

Attenuation was not considered in this modelling, as a conservative measure. It is likely that in some areas of the catchment almost complete nitrogen attenuation may occur, while at others no attenuation is anticipated. Factors such as the REDOX potential of the groundwater, the aquifer geology and the presence or absence of specific minerals will determine the importance of geochemical attenuation. Assuming that no attenuation is therefore a conservative approach (assumes worst-case conditions).

3.2 Conclusion

Contaminant transport modelling provides estimates of the likely concentration of a solute (in this case nitrate) at any point within the model domain, at any time covered by the modelling period. From the process followed, at the conclusion of the modelling period, nitrate concentrations are likely to exceed the maximum permissible value of 11.3 mg/L at four locations, shown in Figure 4.

Modelling indicates:

- the maximum nitrate concentration will be approximately 16.2 mg/L,
- will occur in the southern part of layer 1 (Figure 12) and
- is likely to be observed in about 2052.

It must be noted that groundwater attenuation has not been included in this modelling and that the concentration predicted is an average figure over the depth of the layer and over the year.

3.3 Recommendation

This modelling exercise should only be used in a semi-quantitative manner, to identify areas where there is a risk of exceeding the NZ Drinking Water Guideline values. Estimates of future groundwater concentrations in these and other areas should also be regarded as indicative. It is recommended that the impact of future land use intensification on groundwater resources should be determined by monitoring groundwater nitrate concentrations. A suitable groundwater nitrogen monitoring programme should be developed for the Ruataniwha basin, with a focus on those areas determined to be at greatest risk. The monitoring programme design should have regard for spatial resolution and the depth of groundwater. The results should be used to validate the model in future and to design further sensitivity testing of parameter values to explore any areas of uncertainty in the predictive results.

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APPENDIX 1 - PEER REVIEW LETTER

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Our Ref: A262B/R005c
Date: May 2013

Rob Christie
Hawkes Bay Regional Investment Company Ltd
Private Bag 6006
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Dear Rob,

RE: Ruataniwha Groundwater Model – Solute Transport Application – Review Comments

1. Introduction

This brief letter provides independent technical review comment by Hugh Middlemis on documents related to the application of the Ruataniwha Basin groundwater flow model to a solute transport assessment purpose to identify areas with a risk of elevated nitrate concentrations due to proposed irrigation development (Baalousha, 2013).

The review was undertaken consistent with the Australian groundwater modelling guidelines (Middlemis et al, 2001; Barnett et al 2012). The review did not involve a complete re-investigation of the studies completed, simply a review of the reports with a focus on the modelling. A detailed audit of the data files was not requested or conducted.

The context is the development and refinement of the Ruataniwha Basin groundwater model by Hawkes Bay Regional Council (HBRC) since 2009, including addressing issues raised in the independent review process undertaken since November 2011on the groundwater flow model (Middlemis, 2012abc). The model was designed for water resources management scenario simulations. The primary purpose of the model may be paraphrased as providing a predictive tool for scenario modelling of groundwater extraction, aquifer responses and river-aquifer interactions.

The outcome of the review process (Middlemis, 2012abc, and this document) is that the groundwater model is considered to be fit for the purpose of predictive scenario modelling of groundwater extraction and assessment of aquifer responses and river-aquifer interactions. The review has further concluded that the flow and solute model is suitable for a semi-quantitative application to identify areas where there are risks of high nitrate concentrations due to the proposed irrigation developments. The Ruataniwha model is however not suitable at the current time for definitive solute transport modelling to comprehensively and accurately predict the 3D distributions of nitrate concentrations and changes with time. Improvements are warranted in several areas before the model would be suitable for highly complex modelling beyond semi-quantitative risk-based approaches.

The future development of an improved and fully integrated model was outlined in Middlemis, 2012b as the next natural step in the development of the Ruataniwha modelling framework from effectively best practice, to a leading practice level. The latest report on solute modelling (Baalousha, May 2013) has been reviewed and found to be consistent with best practice, notably that the work has been used in a risk-based method as suggested above. The use of tritium data to calibrate the particle tracking model capability (and/or solute modelling) is commended. It would also be worthwhile to undertake some calibration and/or sensitivity testing on porosity to get a match with tritium (and possibly also on the K/Sy or T/S parameters/ratios, to test sensitivity to this “diffusivity” parameter). Until the model is further upgraded and refined to address the limitations identified during this independent review process (Middlemis, 2012abc, and this document), and it is validated with field data, any solute transport modelling results should be regarded as indicative only.

2. Selected Review Issues

Examples of some notable aspects of the model for this solute transport application are considered briefly in the points below.

- **Geological structure.** This reviewer considers that the geological structure is adequate for the water allocation and management purpose indicated, including semi-quantitative solute transport. Groundwater models are usually developed with a substantial degree of simplification of the actual geology. This is sometimes referred to as a "lumping" process in that geological units that act in a similar manner hydrologically and hydraulically are lumped into the one layer. This is recognised in the 2012 Australian groundwater modelling guidelines (which includes guidance on solute transport) as an appropriate approach to develop a parsimonious model. The guidelines goes as far as to suggest that the "less is more" approach… "provides a good philosophy for hydrogeological conceptualisations" (Barnett et al, 2012, p.25 last para). For the more complex purpose of solute transport, it could be argued that the structural complexity could be improved, but there is no information available on vertical gradients in piezometric level or salinity that could be used to warrant further refinement. More layers and complex structure may be required in areas where there are substantial vertical hydraulic gradients, or possibly concentration changes with depth (Barnett et al 2012), but this is something that should be considered during future model upgrades. In any event, an increase in complexity would require additional study resources (data, time, budget), which is a decision for consideration by HBRC. The existing approach is considered suitable for semi-quantitative solute transport modelling to identify risks relating to nitrate concentrations.
- **Steady State Model Parameters.** It was noted that the steady state flow model has different parameters to the transient model. However, this is not material to the model performance, as the purpose of the steady state simulation is to define the initial head distribution for the transient simulations (this is stated several times in the transient flow model report). It is common practice to use steady state heads for this purpose (Barnett et al, 2012). While it is also standard practice to ensure they have the same parameters, this is not critical as the transient model soon re-equilibrates the head distribution to match the transient model parameters and stresses (which are also different to the steady state, as they should be). Provided the early time results are not critical to the decision-making (and I believe they are not, as it is more the long term trends and predictions that are key), then the approach adopted is acceptable and broadly consistent with best practice.
- **Digital Terrain Model.** The model has acknowledged limitations in relation to the DTM, and this has implications for surface-groundwater interaction processes, especially in regard to springs, and to a lesser extent in relation to stream-aquifer dynamics, which impacts the model's fitness for purpose to ecological management. It cannot be assumed that the model results in relation to springs are reliable without first considering the model performance in terms of time series groundwater levels for nearby monitoring bores (because springs are highly sensitive to groundwater levels, whereas rivers are arguably less sensitive), and also evaluating the model performance in terms of the spring flux (even if there is poor monitoring data on fluxes). In this context, it is understood that the DTM is based on SRTM data, which is known to have routine errors in the order of several metres and up to tens of metres in some cases, which could potentially reduce model accuracy, especially for the representation of surface interaction dynamics. For example, the rivers are assigned to appropriate model layers semi-automatically by the software when the modeller inputs the river feature levels. The fact that river features occur in shallow and deeper layers is not of concern in itself, unless hydrogeologists confirm that the river is not hosted in the aquifer layer assigned by the model. The DTM may also be the cause of artesian heads in areas near the river, reported by GNS. These issues are worthy of more detailed investigation to identify where action may be required to refine the model (i.e. the extent of the problem may not be large and may be remote from the key areas of interest).
- **Stress period setup.** An arrangement of annual rainfall recharge and 6-monthly river levels is a little incongruous in the model, but not critically so for model performance. While recharge is the main element of the water balance, the model performance is not evaluated in relation to rainfall-recharge responses, but more to river-aquifer interaction responses. Further analysis may be required to confirm whether seasonal rainfall recharge is of great importance for certain areas (e.g. cumulative rainfall deviation (CRD) analysis on rainfall and relating that to groundwater level variations). Otherwise, current arrangements may be acceptable.

- **Solute Transport Investigations.** The report on the solute transport modelling (Baalousha, 2013) has been reviewed and the approaches described are consistent with best practice, in the context of the qualifications regarding risk-based methods and semi-quantitative results mentioned herein. Further investigations are warranted with the flow and solute modelling tool, as particle tracking and solute transport is not a simple one-step process. Substantial “investigative modelling” is required to determine exactly where to put the particles in 3D (even within a particular cell, the 3D location can be important). This takes time though a trial and error process to find the right arrangement, especially if analysis at the sub-catchment scale is required and to improve our understanding of the key processes before the model complex solute transport modelling is warranted. For example, if the particle tracks are calibrated to tritium, then it should be possible to use speciation models such as PHREEQ-C to evaluate nitrate attenuation along those flow paths, which would help validate the solute transport results. Further solute modelling can identify areas where elevated concentrations are predicted, and monitoring should be used to obtain data to validate the model before the results are relied upon for important/critical management decisions.

3. Conclusion

The review has concluded that the flow and solute model is suitable for a semi-quantitative application to identify areas where there are risks of high nitrate concentrations due to the proposed irrigation developments. The Ruataniwha model is however not suitable at the current time for definitive solute transport modelling to comprehensively and accurately predict the 3D distributions of nitrate concentrations and changes with time. Improvements are warranted in several areas before the model would be suitable for highly complex modelling beyond semi-quantitative risk-based approaches.

Areas of improvement for the model have been identified to firmly establish its best practice performance for the complexities of integrated surface and groundwater modelling (Middlemis, 2012abc).

We trust this information is sufficient for your purposes; however should you require any further details or clarification, please do not hesitate to contact our office.

Yours sincerely
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