

# **Numerical groundwater flow and transport modelling of the western Lake Taupo catchment**

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**Numerical Groundwater Flow and  
Transport Modelling of the Western  
Lake Taupo Catchment**

Michael Toews

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**GNS Science Consultancy Report 2011/153  
January 2012**

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### **BIBLIOGRAPHIC REFERENCE**

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## CONTENTS

<b>EXECUTIVE SUMMARY</b> .....	<b>II</b>
<b>1.0 INTRODUCTION</b> .....	<b>1</b>
<b>2.0 MODEL DESIGN</b> .....	<b>1</b>
2.1 Conceptual Model .....	1
2.2 Model Grid .....	2
2.3 Hydrogeological Properties .....	2
2.4 Boundary Conditions .....	2
2.4.1 No flow .....	3
2.4.2 Groundwater recharge .....	3
2.4.3 Surface water features.....	3
2.4.4 Nitrate loading .....	3
2.5 Calibration Targets .....	4
2.5.1 Stream flow .....	4
2.5.2 Groundwater levels .....	4
2.5.3 Mean residence time .....	4
<b>3.0 MODEL CALIBRATION</b> .....	<b>5</b>
3.1 Model Run Setting.....	5
3.2 Calibration to Stream Flow .....	5
3.3 Calibration to Groundwater Levels .....	6
3.4 Calibration to Mean Residence Time.....	6
3.5 Sensitivity and Uncertainty .....	6
<b>4.0 MODEL PREDICTIONS</b> .....	<b>7</b>
4.1 Groundwater Flow Results .....	7
4.2 Nitrate Transport Results.....	7
<b>5.0 SUMMARY AND RECOMMENDATIONS</b> .....	<b>7</b>
<b>6.0 ACKNOWLEDGEMENTS</b> .....	<b>9</b>
<b>7.0 REFERENCES</b> .....	<b>9</b>

## FIGURES

<b>Figure 1.</b> The domain of the western Lake Taupo catchment numerical model. ....	12
<b>Figure 2.</b> Cross sections at row 344 of the uniform 80 m wide by 20 m thick grid with 'A' unadjusted DTM and 'B' adjusted DTM. ....	13
<b>Figure 3.</b> Plan view of model, showing the top layer of the hydrostratigraphy.....	14
<b>Figure 4.</b> Cross sections through model showing hydrostratigraphy of materials along rows 129, 186, 299, 330 and 429. ....	15
<b>Figure 5.</b> Boundary conditions for groundwater flow model. ....	16
<b>Figure 6.</b> Nitrate loading used as a constant concentration boundary condition on the topmost saturated cells or water table (Hadfield 2011).....	17
<b>Figure 7.</b> Zones used for ZONEBUDGET (ZBUD) to calibrate stream gauges.. ....	18
<b>Figure 8.</b> Groundwater observation wells in the model domain used for groundwater flow model calibration (Gusyev et al. 2011). ....	19
<b>Figure 9.</b> Simulated vs. observed stream/river flows, units are m <sup>3</sup> /s. ....	20
<b>Figure 10.</b> Calibration plot of modelled vs. observed hydraulic head in the steady-state groundwater flow model. ....	21
<b>Figure 11.</b> Contour-fill map of groundwater table from steady-state flow simulation.. ....	22
<b>Figure 12.</b> Cross sections showing groundwater flow and nitrate simulation results in mg/L. ....	23

## TABLES

<b>Table 1.</b> Data summary of 27 surface water sub-catchments in the western Lake Taupo catchment area (Gusyev et al. 2011).....	25
<b>Table 2.</b> Hydrogeologic properties of materials used for the model development model calibration. ....	26
<b>Table 3.</b> Steady-state groundwater flow budget.....	26

## EXECUTIVE SUMMARY

The goal of this study was to develop a steady-state groundwater flow and transient contaminant transport model to aid with nitrate management in the western Lake Taupo catchment. The model was developed in Visual MODFLOW Pro (VMOD) using available field data and the proposed model design from Gusyev et al. (2011). The model development consisted of two steps: model design and model predictions. The model design included implementation of model grid, boundary conditions, hydrogeology, calibration targets and model calibration. The model predictions included modelled groundwater elevations, water budgets and tentative nitrate concentrations.

The MODFLOW grid covered the modelling area of 1072 km<sup>2</sup> with 500 rows and 335 columns and had a uniform cell size of 80 m by 80 m. The model depth of 320 m incorporated 16 layers with a constant layer thickness of 20 m. The top of the model grid was obtained from modified digital terrain surface and Lake Taupo bathymetry data.

The hydrogeology of the modelling area is comprised of aggregated units of Oruanui, Whakamaru, Pakaumanu and Greywacke (Gusyev et al. 2011). Each grid cell was associated with one hydrogeologic unit and assigned hydraulic conductivity and porosity properties of the unit.

The following boundary conditions (BCs) were applied to the groundwater flow and nitrate transport model: a constant head BC was used to represent water elevations in Lake Taupo; a Cauchy head-dependant BC was used to represent rivers/streams; a flux BC was used to represent groundwater recharge; and a constant concentration specified flux BC was used to represent nitrate loading. These BCs were assigned to layer 1 except the nitrate loading that was implemented to the top-most saturated layer (Gusyev et al. 2011).

The steady-state groundwater flow model was simulated with MODFLOW-2000 and calibrated for stream flows and hydraulic heads by adjusting groundwater recharge, river bed conductance and hydraulic conductivities. The groundwater travel times were simulated with MODPATH and calibrated to Mean Residence Times (MRTs), obtained from groundwater age tracers for the western Lake Taupo area, by adjusting aquifer porosity.

Nitrate transport was simulated as a non-reactive species with MT3DMS 5.2. The transport simulation was conducted for 100 years, with concentrations output every 10 years. Calibration of the nitrate transport model was not undertaken as it was beyond the scope of this study. Modelled nitrate concentrations extend down through Oruanui and Whakamaru units after 80 years.

The results from the groundwater flow model indicate groundwater elevations ranging from 357 m at the Lake Taupo lakeshore to over 1000 m in the northern part of the model domain. Modelled groundwater elevations are sensitive to hydraulic conductivities of Oruanui and Whakamaru units. Decreasing hydraulic conductivity of the Oruanui unit resulted in higher groundwater mounding along Karangahape Road (centre of domain), and consequently fewer dry cells in the flow model. The modelled MRTs for Waihaha River, Wanganui Stream, Whareroa Stream, and Kuratau River sub-catchments, using cumulative frequency distribution curves, were 36 years, 30 years, 51 years and 35 years, respectively. Preliminary

results of the transport model indicate that nitrate plumes extended through the Oruanui and parts of Whakamaru units and reached Lake Taupo after 80 years simulation time.

The following five items are recommended for the next phase of the nitrate transport model development:

- 1) Areas of high modelled nitrate concentration need to be refined. Such plumes may introduce errors in nitrate transport model calibration unless model refinement is undertaken.
- 2) Calibration targets for nitrate concentration need to be implemented in the transport model.
- 3) Groundwater tracer concentrations such as tritium should be implemented as primary calibration targets for the transport model.
- 4) Sensitivity analysis and uncertainty analysis should be conducted on the calibrated transport model.
- 5) Modelling of management scenarios for the western Lake Taupo catchment should be undertaken using the calibrated groundwater flow and transport model.



## 1.0 INTRODUCTION

The goal of this study was to develop a steady-state groundwater flow and transient contaminant transport model to aid with nitrate management in the western Lake Taupo catchment. This study is a continuation of the study by Gusyev et al. (2011) and provides a detailed description of the constructed model for the western Lake Taupo catchment (Figure 1). Gusyev et al. (2011) summarized available field data and proposed a suitable model design for the western Lake Taupo catchment using Visual MODFLOW Pro (VMOD) (Schlumberger Water Services 2010).

An effective modelling exercise consists of four general steps. In the first preliminary step, the purpose of the modelling is defined (Bear et al. 1992). A conceptual model is constructed for the area of interest and the modelling code selected. In the second step, the model is designed. In the third step, the model is calibrated to field observations and is tested with a sensitivity analysis, which determines the variability in modelling results due to the change in calibrated parameters. In the final step, the parameter uncertainty analysis determines the bounds of the uncertainty interval for model outcomes associated with different sets of parameters (Hill and Tiedeman 2007).

This report follows these steps and is divided in three sections: model design, model calibration and model predictions. The model design consisted of grid design, selection of boundary conditions, implementation of hydrogeology, and implementation of calibration targets. Each step of the model design required simplifying assumptions to represent the complexities of the natural flow system that are addressed by Gusyev et al. (2011). Model calibration consisted of calibration, sensitivity and uncertainty, and determined the effect of parameters on the modelling results. The steady-state groundwater flow model was calibrated to median values of stream flows and groundwater levels and to Mean Residence Times (MRTs) obtained from groundwater age tracer data. The calibration of transient nitrate transport to measured concentrations was beyond the scope of this study and not undertaken. The sensitivity analysis was carried out for hydraulic conductivity values in the groundwater flow model. The uncertainty analysis was not implemented at this stage of the project and will be conducted for the groundwater flow and transport model using automated Parameter Estimation software (PEST). The calibrated groundwater flow model was used to simulate contaminant transport and to predict nitrate concentrations discharging into Lake Taupo. Model predictions consisted of modelled groundwater elevations, water budgets and tentative nitrate concentrations. Modelling results of nitrate transport are presented to provide understanding of nitrate movement in the groundwater system. The effects of groundwater flow model assumptions on the modelling results for contaminant transport are also discussed.

## 2.0 MODEL DESIGN

### 2.1 Conceptual Model

A conceptual model for the western Lake Taupo catchment was presented by Gusyev et al. (2011). In summary, the aquifer system is assumed to be bounded by the Lake Taupo surface catchment boundary in the west and by the lake bed in the east (Figure 1). The north and south sides of the model are also surface catchment boundaries (i.e. the conceptual

model assumes no hydrologic connection with neighbouring surface catchments). The aquifer system receives groundwater recharge from rainfall and drains into Lake Taupo through either streams or directly through the lake bed. A spatially varying nitrate concentration is applied at the groundwater table (Gusyev et al. 2011).

## **2.2 Model Grid**

The grid design includes horizontal and vertical cell size in the modelling area and follows recommendations from Gusyev et al. (2011). The modelling area of 1072 km<sup>2</sup> is represented by the modelling grid of 500 rows by 335 columns by 16 layers with a uniform grid cell size of 80 m×80 m×20 m. The vertical discretization of 20 m in 16 layers results in a total model thickness of 320 m and represents the entire Oruanui unit in the model (Hadfield 2011; Gusyev et al. 2011).

The top elevation of the model grid was obtained from modified Lake Taupo bathymetry and digital terrain model (DTM) data. In order to maintain constant thickness of the model layers, the elevation data were processed to reduce steep slopes in areas such as mountain peaks, cliffs and ridges and to preserve low elevation features such as floodplains and valleys. The vertical structure of the grid with the unadjusted and adjusted DTMs is shown in Figure 2 'A' and 'B', respectively. The differences between the original DTM and adjusted DTM are most apparent along steep slopes or isolated topologic high-points that are expected to become dry cells and to be excluded from the groundwater flow and transport solution (Hadfield 2007, 2011). Processing reduced higher elevations in adjacent cells that exceed a specified vertical difference of 10 m in adjacent finite difference cells. The resulting elevation data have slopes no more than 12.5% (maximum 10 m vertical difference per 80 m of cell width). When the adjusted DTM was translated to a uniform thickness grid, the overlap between adjacent cells in layers was no less than 50% (maximum 10 m per 20 m cell height).

## **2.3 Hydrogeological Properties**

The hydrogeology of the model area is comprised of aggregated units of groundwater-bearing Oruanui, Whakamaru, Pakaumanu and Greywacke units (Figure 3). Cross sections through the model showing hydrostratigraphy of materials along rows 129, 186, 299, 330 and 429 are shown in Figure 4. In the model, each grid cell was assigned hydrogeological properties of one unit. Where more than one unit was present in a grid cell, the most abundant unit was selected and its hydrologic properties assigned to the cell. A detailed description of these four units and their hydrogeological properties is provided by Gusyev et al. (2011). Median value of hydrogeological properties reported by Gusyev et al. (2011) were initially assigned to the model and then adjusted during calibration.

## **2.4 Boundary Conditions**

The numerical model incorporates no-flow, groundwater recharge, surface water features such as rivers and lakes, and nitrate loading as boundary conditions (BCs). Groundwater flow and contaminant transport is simulated by the numerical model, which incorporates available data and appropriate simplifying assumptions. The selection of boundary conditions is an essential component of translating a conceptual model into a numerical model.

### **2.4.1 No flow**

Grid cells outside of the modelled groundwater catchment are assigned no flow boundary condition (inactive cells in MODFLOW), and therefore are not included in the groundwater flow and contaminant transport solution (Figure 3 and 4). In order to improve stability of the finite difference solution, the border of the active/inactive interface was analysed to ensure that all active cells had at least two active adjacent cells. As the result, 16 border active cells were identified in each layer and changed to inactive cells.

### **2.4.2 Groundwater recharge**

The difference of average annual rainfall and actual evaporation data between 1960 and 2006 was used as groundwater recharge in the model (Gusyev et al. 2011). The groundwater recharge values were gridded to 80 m cell model resolution and reclassified into 10 zones (Figure 5). Each zone has a discrete recharge value from 400 to 1300 mm/year with 100 mm/year increments. These values were assigned to the topmost saturated model layer using the MODFLOW recharge option #3 (McDonald and Harbaugh 1988; Harbaugh et al. 2000).

### **2.4.3 Surface water features**

The Lake Taupo water level is incorporated in the model as a constant head boundary condition and was set to an elevation of 357 m. The constant head boundary cells were implemented at the lake bed in layer 1 of the model.

Rivers and small streams are incorporated in layer 1 of the model as a Cauchy boundary condition with the use of drain cells. In MODFLOW, a drain cell is a head-dependant Cauchy boundary that removes water from the groundwater system only when the modelled hydraulic head is greater than the drain bottom elevation. Water elevations in the drain cells were obtained from the top elevation of layer 1 and the assigned drain bottom elevation was 1 m below the top elevation of layer 1. A uniform conductance of 80 m<sup>2</sup>/day was assigned to all drain cells in the model. The locations of the drain cells were obtained from the 1:50 000 topographic dataset based on vector data of the streams.

### **2.4.4 Nitrate loading**

Zones of constant nitrate application rates were implemented in the groundwater table as specified flux boundary condition with constant concentration. The flux boundary condition was applied to the uppermost active (non-dry) cells in the model. This procedure was accomplished with a custom computer code that uses the flow solution results to write a MTN constant concentration boundary condition file for VMOD. This file is translated by VMOD for processing with MT3DMS. The nitrate loading rates in kg/ha/year were provided by Hadfield (2011) and were re-projected to the 80 m cell size using a nearest neighbour method to preserve original values (see Figure 6). In this version of the transport model, the constant concentration boundary was 1.6 times higher than supplied field data for demonstration purposes.

## **2.5 Calibration Targets**

Generally, data sets of stream flow, groundwater levels and chemical concentrations obtained from field measurements are used as model calibration targets. Recently, mean residence time (MRT) estimated from groundwater age tracers has also been used for the calibration of aquifer porosity in groundwater flow models (McGuire & McDonnell 2006). The following calibration targets identified by Gusyev et al. (2011) were used in this study: 30 stream gauging stations with non-zero flow measurements; 24 boreholes with adequate groundwater level observations; and 5 surface water sub-catchments with MRT values. In this study, chemical concentrations are not implemented as calibration targets for the transport model.

### **2.5.1 Stream flow**

VMOD does not allow stream flow data to be implemented as calibration targets and the stream flow calibration was conducted outside of VMOD. This was done as follows. A surface water catchment analysis of the original DTM was conducted with ArcGIS Spatial Analyst to define catchment areas that contribute flow to each gauging station, which resulted in thirty-one zones (Figure 7). Zone 1 is a composite zone that does not represent any gauging station. Zone 2 is set to Lake Taupo. Zones 3 to 32 are selected for each stream gauge sub-catchment. These zones were selected in the model domain using ZONEBUDGET (ZBUD). ZBUD is a post-processing utility in VMOD that reports the water flow budget for zones that cannot overlap and have to be selected *a priori* of the model simulation. Flows from the stream/river (drain) component of the groundwater simulation were extracted from the ZBUD output. Stream gauges that included more than one upstream zone (i.e., downstream gauging locations of other gauging station zones in the same catchment) were added to accumulate total upstream flows, as overlapping zones are not permitted in ZBUD. Median value of measured stream flow was used for model calibration (Gusyev et al. 2011).

### **2.5.2 Groundwater levels**

Groundwater levels are implemented in the VMOD model as calibration targets and assigned median values of the groundwater elevation data reported by Gusyev et al. (2011). Groundwater level data from Gusyev et al. (2011) were imported into the model as head observations (Figure 8). The screen depth of the borehole was set to the borehole depth. Most of the head observation wells are in layer 1, with the deepest borehole of 58 m in layer 3. Of the 24 boreholes, four were removed as they were located outside the active model region (near Otupoto Stream, a sub-catchment north of the simulated catchment). In VMOD, the borehole is excluded from calibration if the modelled groundwater elevation falls below the screen depth.

### **2.5.3 Mean residence time**

Mean Residence Time (MRT) obtained from groundwater age tracer data can be used as a calibration target for aquifer porosity in groundwater flow and transport models (McGuire & McDonnell 2006; Sanford 2010). The calibration to MRT is conducted outside of VMOD using results of forward particle tracking in MODPATH. The groundwater particles that discharge in a selected sub-catchment are collected and are used to construct the

cumulative frequency distribution curve at the sub-catchment outlet. The cumulative frequency distribution curve is a mixture of groundwater ages, reflecting the different transit times along all of the flow paths that converge at the sampling point such as outflow from a surface water sub-catchment (McDonnell et al. 2010).

### **3.0 MODEL CALIBRATION**

#### **3.1 Model Run Setting**

Groundwater flow was simulated with MODFLOW-2000, using the LPF flow package. All layers were set as variably confined/unconfined with harmonic mean interblock transmissivity. Cell wetting was enabled from below (WETDRY < 0), with a threshold of 0.1, interval of 1, and wetted head calculated from neighbours. The WHS solver was used with a factorization level 0, damp factor 0.5, maximum inner iterations 25, head change criterion 0.02 m and residual criterion 0.01 m. For the final calibrated model parameters, the flow model converged after a few minutes with 35 outer iterations. Particle tracking was implemented with the use of MODPATH (Pollock 1994). A groundwater particle was assigned in the centre of each active cell of the modelling domain.

Nitrate transport was simulated with MT3DMS version 5.2 (Zheng and Wang 1998), which is part of VMOD. The transport variant for nitrate was specified as a single mobile species with no sorption or kinetic reactions. The default VMOD value for longitudinal dispersivity is 10 m and ratios of horizontal to longitudinal dispersivity and of vertical to longitudinal dispersivity are 0.1 and 0.01, respectively. An implicit GCG solver with upstream finite-difference advection was used. The time steps for the MT3DMS simulation were specified with a default Courant number of 0.75, a step multiplier of 2.0, a maximum step size of 365 days, and total simulation run of 36500 days (100 years, where each year is defined as 365 days) with 115 transport steps. Concentration results over the model domain were shown every 3650 days (10 years) and allowed visual comparison of modelled concentrations at different time steps in the uncalibrated transport model.

#### **3.2 Calibration to Stream Flow**

The best-fit line of simulated vs. observed flows with a slope of 0.9922 is shown in Figure 9. To achieve a calibration between observed and simulated stream flow, a factor of 0.88 was multiplied for each recharge zone to decrease recharge values described in Section 2.4.2. Several drain conductance values between 0.8 m<sup>2</sup>/day and 6400 m<sup>2</sup>/day were tested for the calibration and 80 m<sup>2</sup>/day was used as the final calibration value. Gauging station ID 282\_2, located downstream of Lake Kuratau (zone ZBUD 5), has a controlled low flow gauge for power generation and was removed from the calibration process. In total, 29 observation gauge locations were used for the final stream flow calibration. This step was completed outside VMOD because MOD does not have the capability to allow calibration of the groundwater model to stream flows.

### **3.3 Calibration to Groundwater Levels**

In the calibration to groundwater levels, hydraulic conductivity values were adjusted to achieve a match between modelled and observed groundwater levels. This step was conducted with the use of VMOD. A trial-and-error method was used to adjust conductivities for each material until a good fit and minimized residuals of head observations were established. This fit is shown in Figure 10. Parameter combinations of hydraulic conductivity and drain conductance were tested in the manual calibration process. The calibrated values of hydraulic conductivity are reported in Table 2.

### **3.4 Calibration to Mean Residence Time**

Aquifer porosity values were adjusted to match MRT obtained from groundwater age dating for the Waihaha River, Wanganui Stream, Whareroa Stream, Kuratau River and Omori Stream sub-catchments. MRT values for these sub-catchments are reported in Table 1. Whareroa Stream and Omori Stream have ambiguous MRTs due to a mixture of old and young waters (Morgenstern 2007, 2010). The MRTs for Waihaha River, Wanganui Stream, Whareroa Stream, and Kuratau River sub-catchments calculated using cumulative frequency distribution curves were 36 years, 30 years, 51 years and 35 years, respectively. The grid cell resolution of 80 m by 80 m was too crude to model MRT for the Omori sub-catchment. The calibrated aquifer porosity values are 0.2, 0.1 and 0.05 for Oruanui, Whakamaru and Pakaumanu units, respectively (Table 2).

### **3.5 Sensitivity and Uncertainty**

In groundwater flow and transport models, sensitivity and uncertainty analysis is usually accomplished by trial-and-error or with the use of an automated parameter estimation model such as PEST. The PEST model returns a set of values of estimated parameters that fit field observations. In VMOD, groundwater elevation and concentration values are available as PEST targets and stream flow cannot be included. This limits the use of PEST in VMOD. Therefore, a trial-and-error sensitivity analysis was conducted at this stage. A preliminary sensitivity analysis for the groundwater flow model was conducted to determine the influence of model parameters such as hydraulic conductivity on groundwater elevation. Groundwater elevations are sensitive to hydraulic conductivities of Oruanui and Whakamaru units. Decreasing hydraulic conductivity of the Oruanui unit resulted in higher groundwater mounding along Karangahape Road (centre of domain), and consequently fewer dry cells in the flow model. In addition, sensitivity analysis was conducted to determine the influence of aquifer porosity on MRTs calculated from the model. As a result, it was found that modelled MRTs were most sensitive to aquifer porosity of the Whakamaru unit. The uncertainty analysis should be tailored to the modelling objective, which in this study was the modelling of nitrate concentrations. Therefore, the uncertainty analysis will be conducted for the calibrated groundwater flow and transport model to be developed in a later stage of this project.

## 4.0 MODEL PREDICTIONS

### 4.1 Groundwater Flow Results

Modelled groundwater elevations and the water budget obtained from the calibrated groundwater flow model are shown in Figure 11 and Table 3, respectively. In Figure 11, the modelled groundwater elevations vary from 357 m at the Lake Taupo lakeshore (shown by a light blue line) to over 1000 m in the northern part of the model domain. Dry cells occur along ridges and at topographic high points, and are often found in the Oruanui unit. Dry cells extend from layer 1 down to layer 10, where the water table is approximately 200 m below the top of the model. Cells with either greywacke or Pakaumanu units are normally always saturated as the hydraulic conductivities of these units are relatively low. In Table 3, the modelled In and Out water balance indicate good model convergence, which was a requirement of the study (Hadfield 2011).

### 4.2 Nitrate Transport Results

Modelling results for nitrate transport simulation at 80 years simulation time are shown in Figure 12 for cross sections along rows 129, 186, 299, 330 and 429. In Figure 12, relative concentrations of simulated nitrate are colour-coded and contoured with light green lines from 0 (background) to 64 mg/L using a  $\log_2$  scale. Nitrate concentrations are relative in Figure 12 as the specified concentration from nitrate loading (Figure 6) is not scaled from the original units of kg/year/ha to more appropriate units of concentrations (i.e., mg/L). The groundwater table is shown as a thick blue line and the relative groundwater flow velocities are represented by arrows. The magnitude of modelled groundwater velocity up to a maximum velocity of 0.75 m/day is indicated by the size of arrows. Arrows point upwards out of the top surface where groundwater is discharging. The dry cells that occur in the top layers of the flow model are shown by light grey regions. The hydrostratigraphy of cross sections is shown by faded thick lines in the background and is described earlier in this report (Figure 4).

Modelled plumes of nitrate extended through the Oruanui and parts of Whakamaru units at 80 years simulation time. In the cross sections at row 299 and 330 of Figure 12, the extent of the nitrate plume follows the hydrostratigraphic boundary between Oruanui and Whakamaru units. This phenomenon is due to the different hydraulic conductivities used for the two units, where preferential flow is in the more permeable Oruanui unit, and some flow is refracted at a shallower angle in the less permeable Whakamaru unit (Freeze & Cherry 2003).

Nitrate concentrations in modelled plumes are sensitive to nitrate loading data, as shown in row 129 on the map in Figure 6 and in profile in Figure 12. In this profile, a few cells along parts of Western Bay Road (SH32) have approximately 60 kg/year/ha. These few cells of high concentration are shown in the cross section as elongated subsurface plumes of nitrate.

## 5.0 SUMMARY AND RECOMMENDATIONS

A groundwater flow and nitrate transport model has been developed for the western Lake Taupo catchment using cutting-edge groundwater modelling techniques. The resolution of the model grid was selected to provide accurate nitrate transport simulations and to include small surface water features such as streams (Gusyev et al. 2011). Aquifer hydrogeology

was incorporated in the model based on representation of the geologic units. The nitrate flux boundary condition was applied to the uppermost active (non-dry) cells in the model. The groundwater flow model was calibrated to median values of groundwater elevation and stream flow data (Hadfield 2011; Gusyev et al. 2011). In the calibration to stream flow, groundwater recharge and drain conductance values were adjusted to match median values of observed stream flows at gauging stations outside of VMOD. In addition, particle tracking with MODPATH was implemented in the model and used to calibrate aquifer porosity to MRT obtained from groundwater age tracers (Gusyev et al. 2011). Calibration of the nitrate transport model was not undertaken as it was beyond the scope of this study.

The results of this groundwater flow model indicate groundwater elevations ranging from 357 m at the Lake Taupo lakeshore to over 1000 m in the northern part of the model domain. Modelled groundwater elevations are sensitive to hydraulic conductivities of Oruanui and Whakamaru units. Decreasing hydraulic conductivity of the Oruanui unit resulted in higher groundwater mounding along Karangahape Road (centre of domain), and consequently fewer dry cells in the flow model. The modelled MRTs for Waihaha River, Whareroa Stream, and Kuratau River sub-catchments, using cumulative frequency distribution curves, were 36 years, 51 years and 35 years, respectively. Preliminary results of the transport model indicate that nitrate plumes extended through the Oruanui and parts of Whakamaru units and reached Lake Taupo after 80 years.

The following five items are recommended for the next phase of the nitrate transport model development:

- 1) Areas of high nitrate concentration need to be refined. For example, the high nitrate concentration areas situated along Highway 32 resulted in local plumes of high nitrate concentration in groundwater. These plumes may introduce errors in nitrate transport model calibration.
- 2) Calibration targets for nitrate concentration need to be implemented in the transport model.
- 3) Groundwater tracer concentrations such as tritium can be implemented as primary calibration targets for the transport model. The calibration to MRTs does not account for dispersion and advection of chemicals in groundwater. The calibration to nitrate concentrations is limited due to the lack of information about input nitrate concentrations at the groundwater table and denitrification rates in groundwater. On the other hand, tritium concentrations in rainwater are well defined from 1940 and remain in the groundwater system as a conservative tracer at the sub-catchment outflow.
- 4) Sensitivity analysis and uncertainty analysis should be conducted on the transport model.
- 5) Modelling of management scenarios for the western Lake Taupo catchment should be undertaken using the calibrated groundwater flow and transport model.

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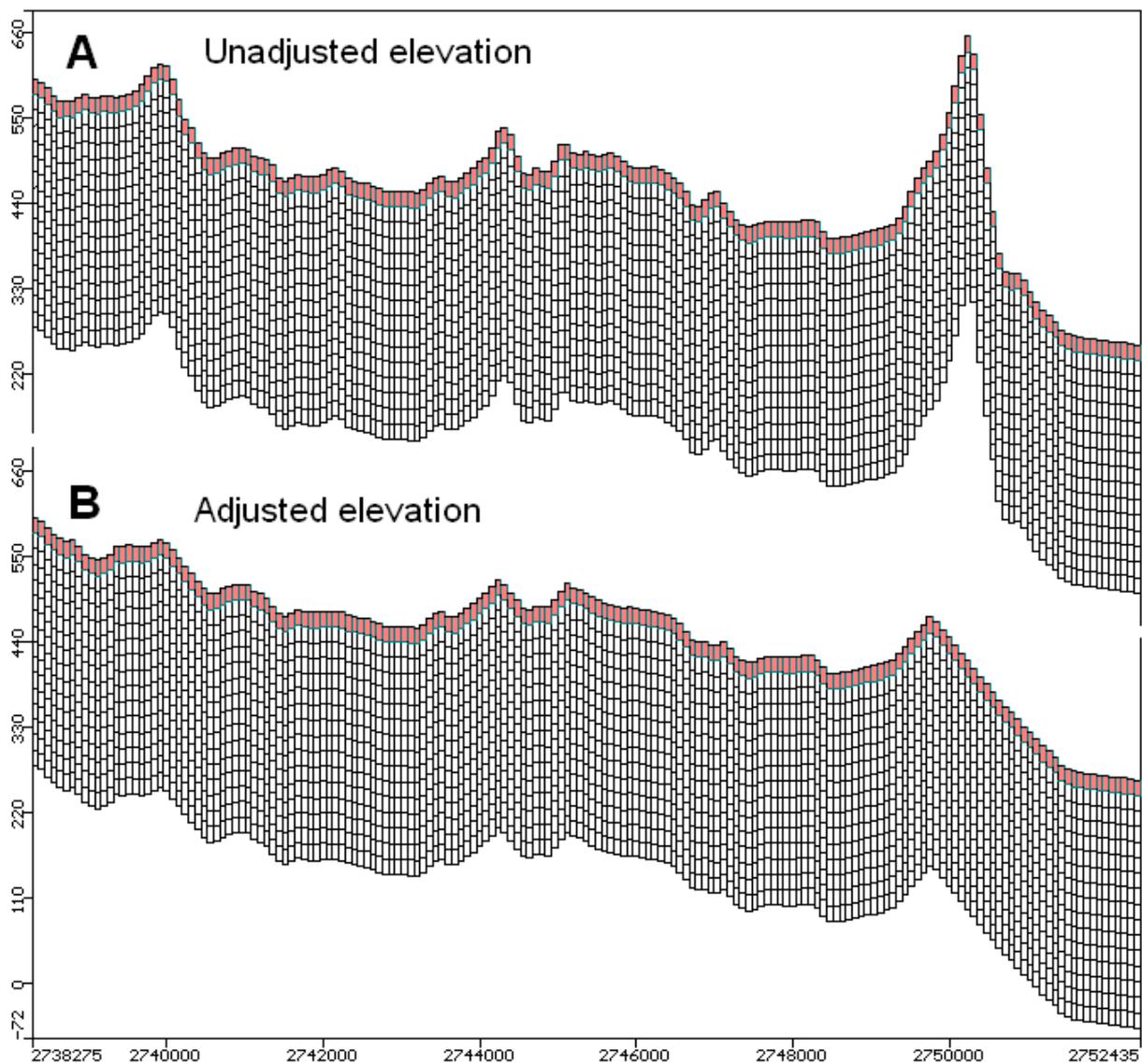
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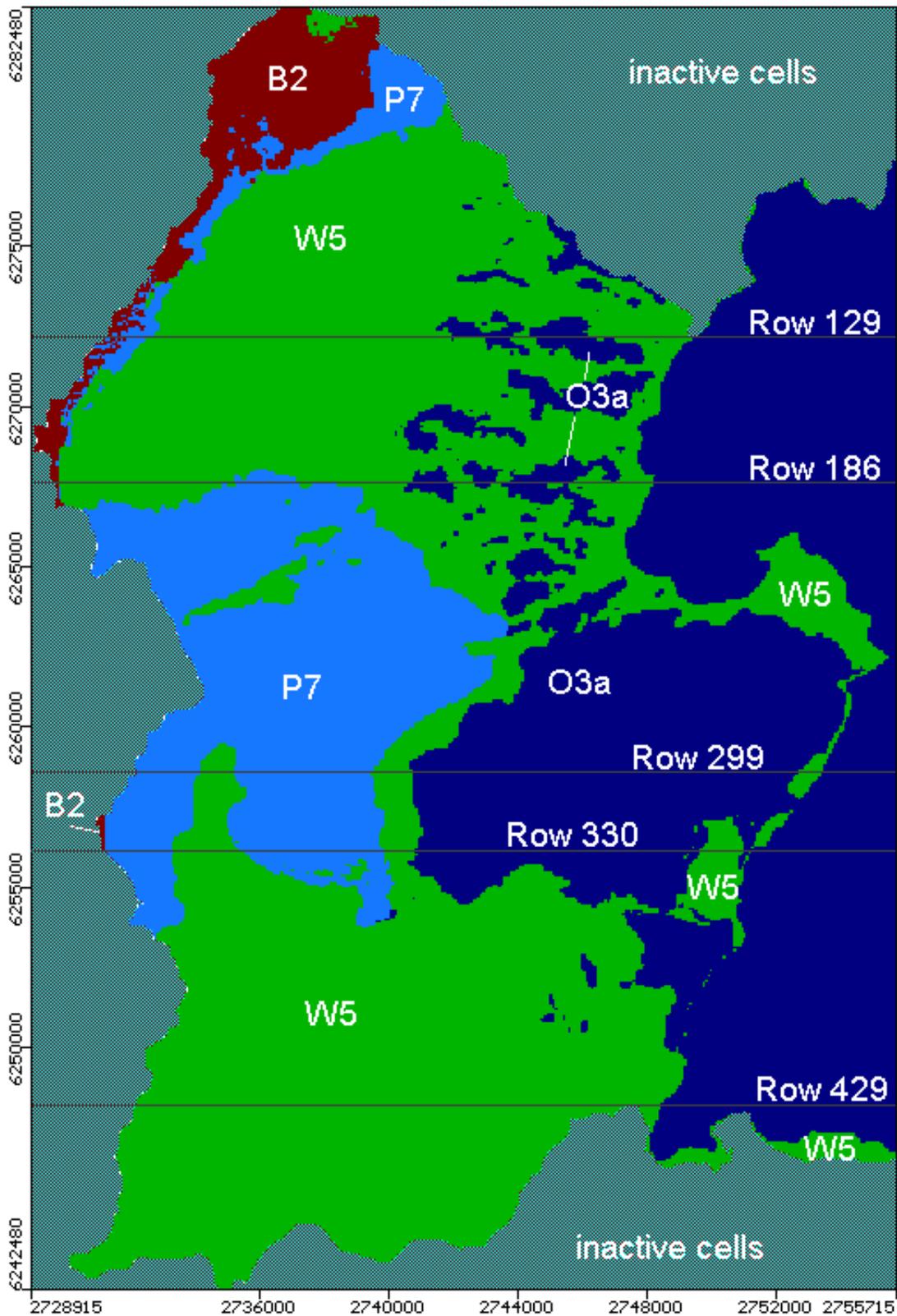
## FIGURES



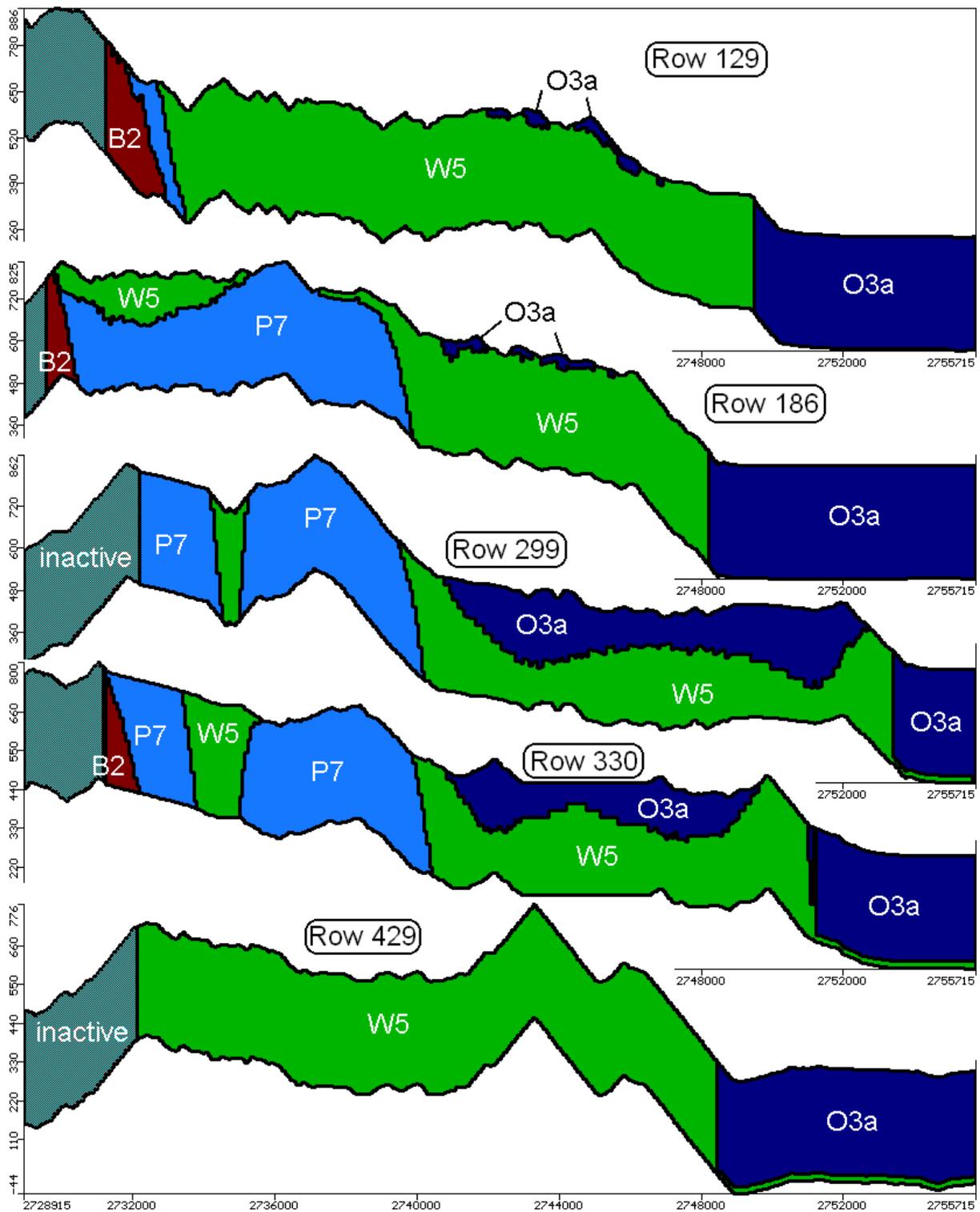
**Figure 1.** The domain of the western Lake Taupo catchment numerical model. The numbered polygons are surface water sub-catchments delineated by EW and numbers refer to sub-catchment names in Table 1.



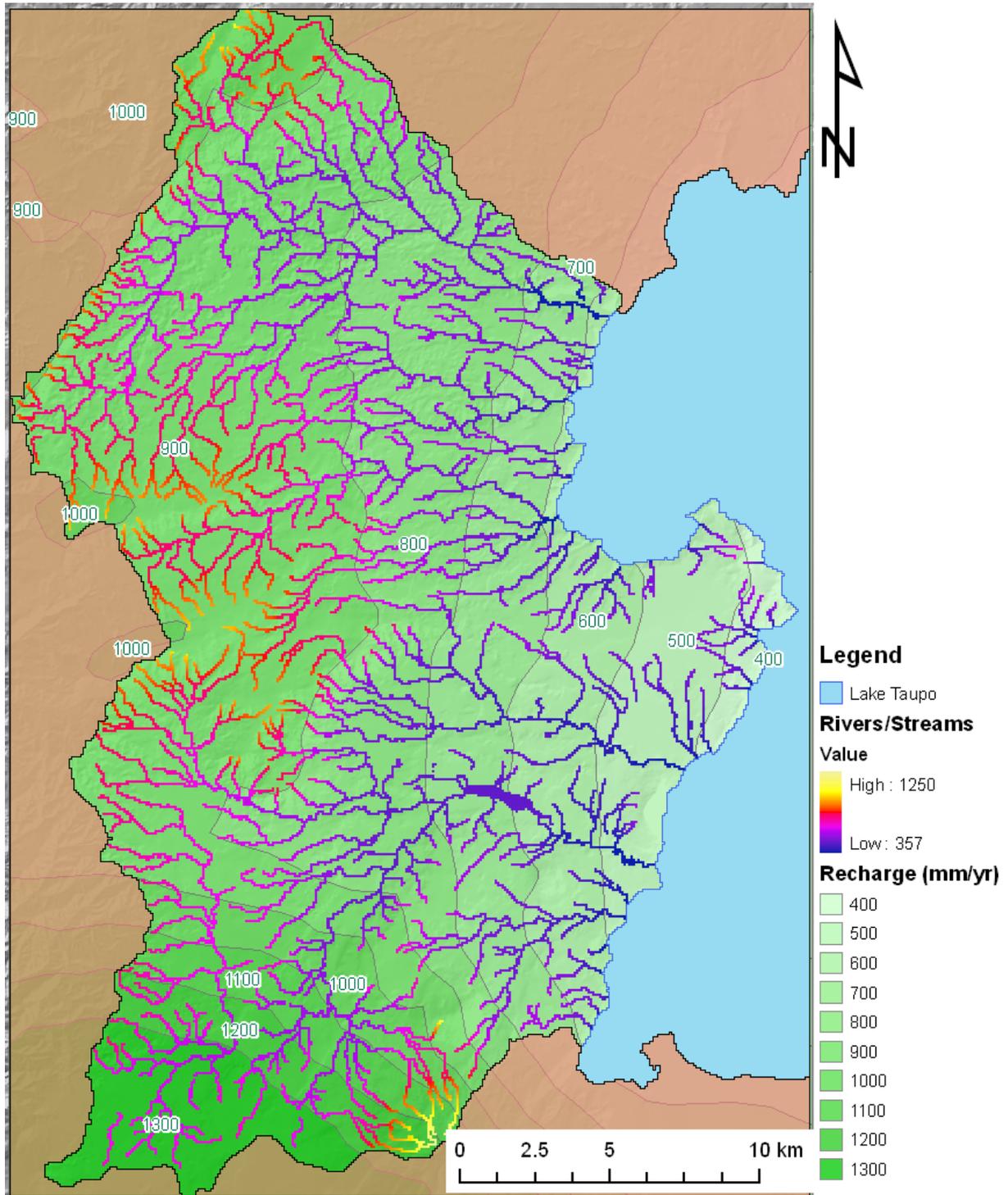
**Figure 2.** Cross sections at row 344 of the uniform 80 m wide by 20 m thick grid with 'A' unadjusted DTM and 'B' adjusted DTM. The upper grid, which was generated using an unadjusted DEM, has several areas where there is no lateral overlap along layers. The lower figure shows corrections (detailed in text) to drop elevations in cells that exceed 10 m difference from their lower elevation neighbours. This ensures that there is a minimum of 50% overlap between adjacent cells in each layer.



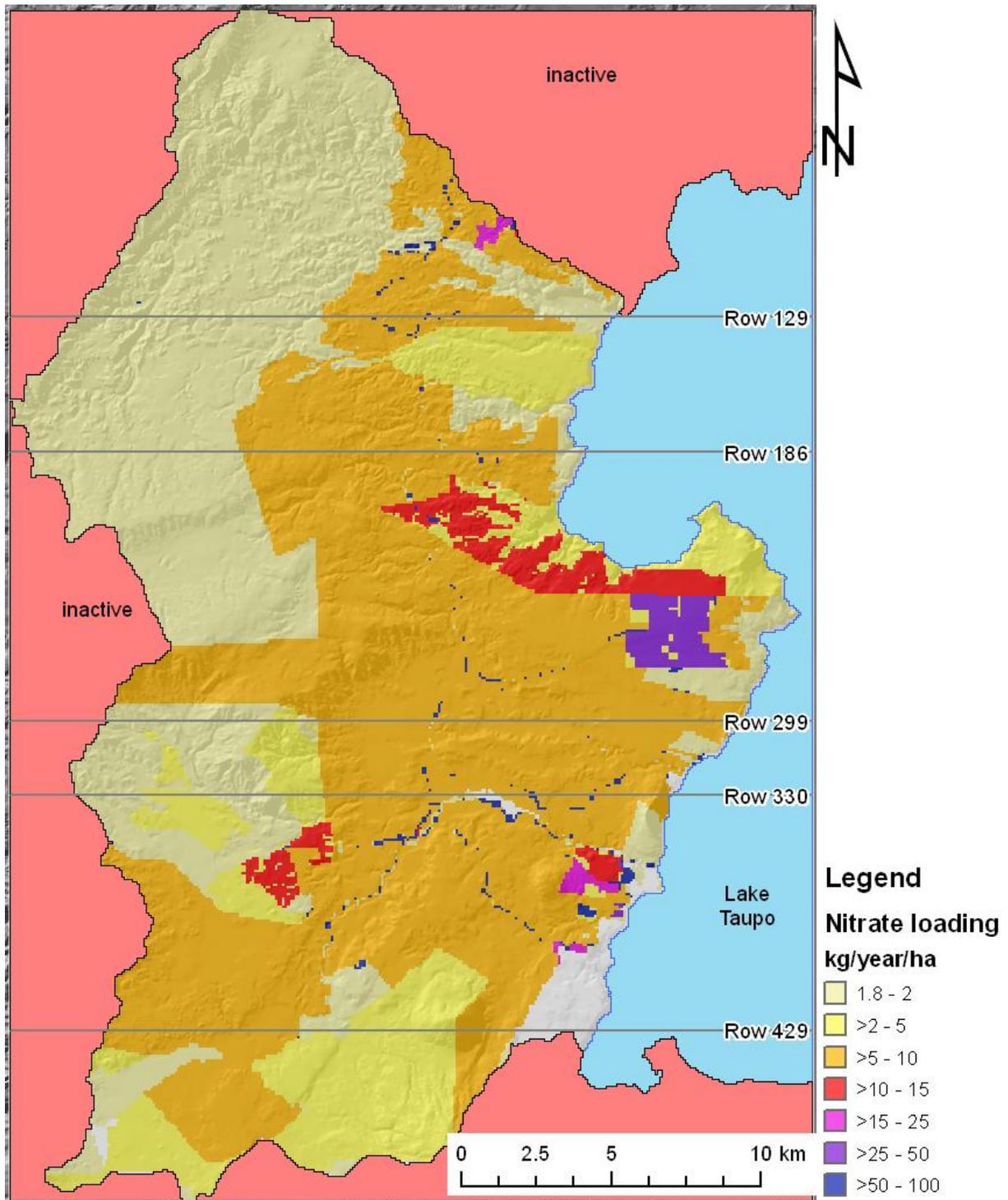
**Figure 3.** Plan view of model, showing the top layer of the hydrostratigraphy, where 'B2' is the greywacke basement unit, 'P7' is the Pakaumanu unit, 'W5' is the Whakamaru unit, and 'O3a' is the Oruanui unit. Grid cells that are not included in the groundwater flow and contaminant transport solution are marked as 'inactive cells'. Cross sections along rows 129, 186, 299, 330 and 429 are shown in Figure 4.



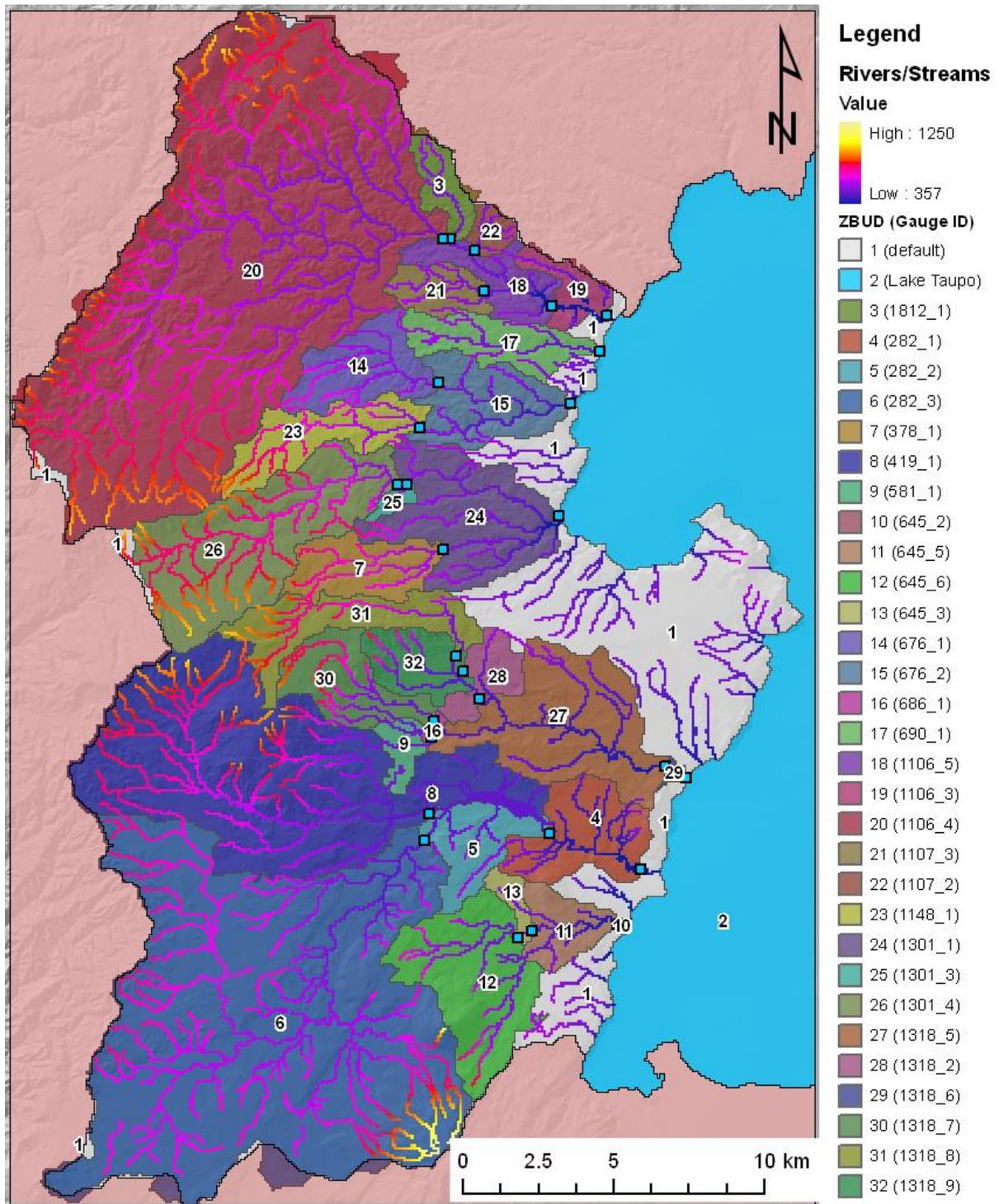
**Figure 4.** Cross sections through model showing hydrostratigraphy of materials along rows 129, 186, 299, 330 and 429. Refer to Figure 3 for cross section locations and material names. Vertical exaggeration is 10 times.



**Figure 5.** Boundary conditions (BC) for groundwater flow model, showing Lake Taupo simulated as a constant head BC, rivers/streams simulated as Cauchy head-dependant drain BCs, and annual groundwater recharge simulated as specified flux BC.



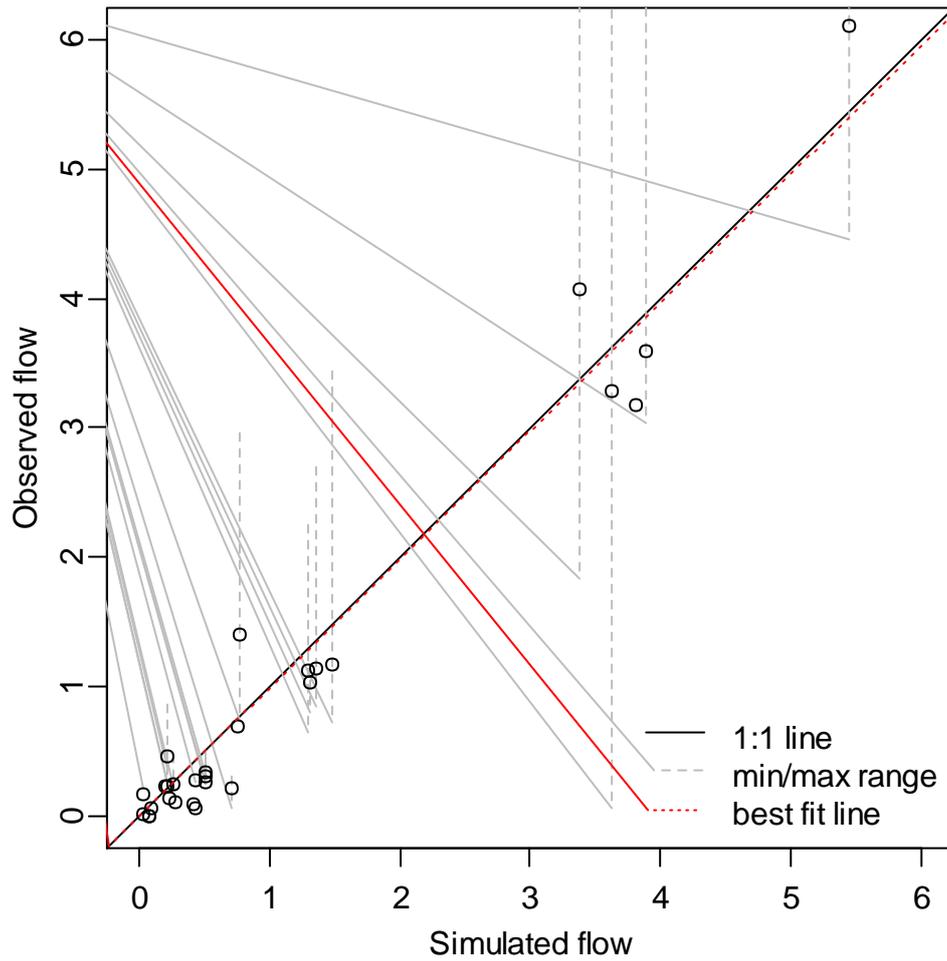
**Figure 6.** Nitrate loading used as a constant concentration boundary condition on the topmost saturated cells or water table (Hadfield 2011). Cross sections along rows 129, 186, 299, 330 and 429 are used to report modelled nitrate concentrations in Figure 12.



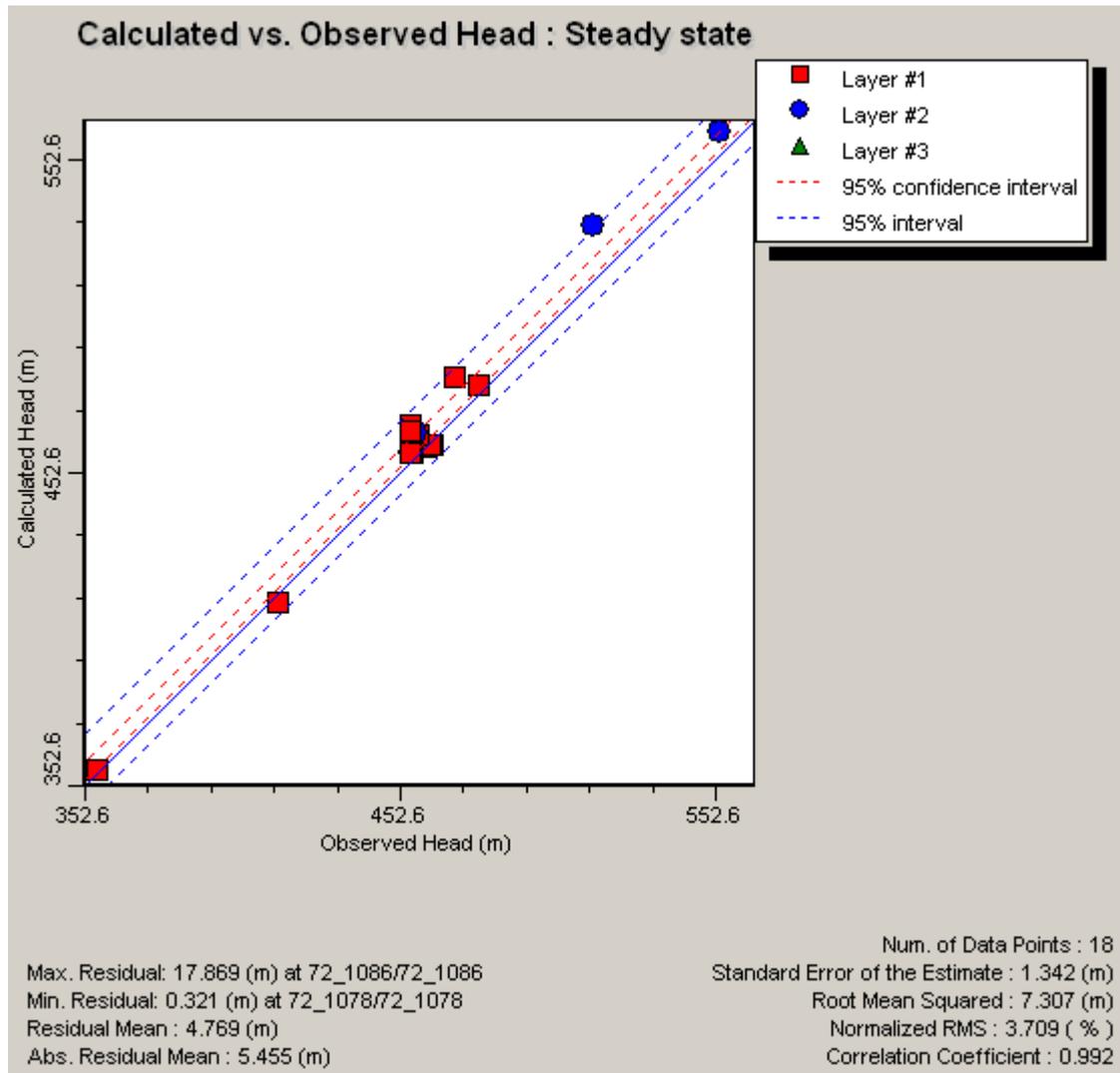
**Figure 7.** Zones used for ZONEBUDGET (ZBUD) to calibrate stream gauges. Zones are determined as the surface water catchment to each gauge location. Zone 1 is a default zone where no other zone has been specified, such as some parts of layer 1, and all of layers 2 to 16.



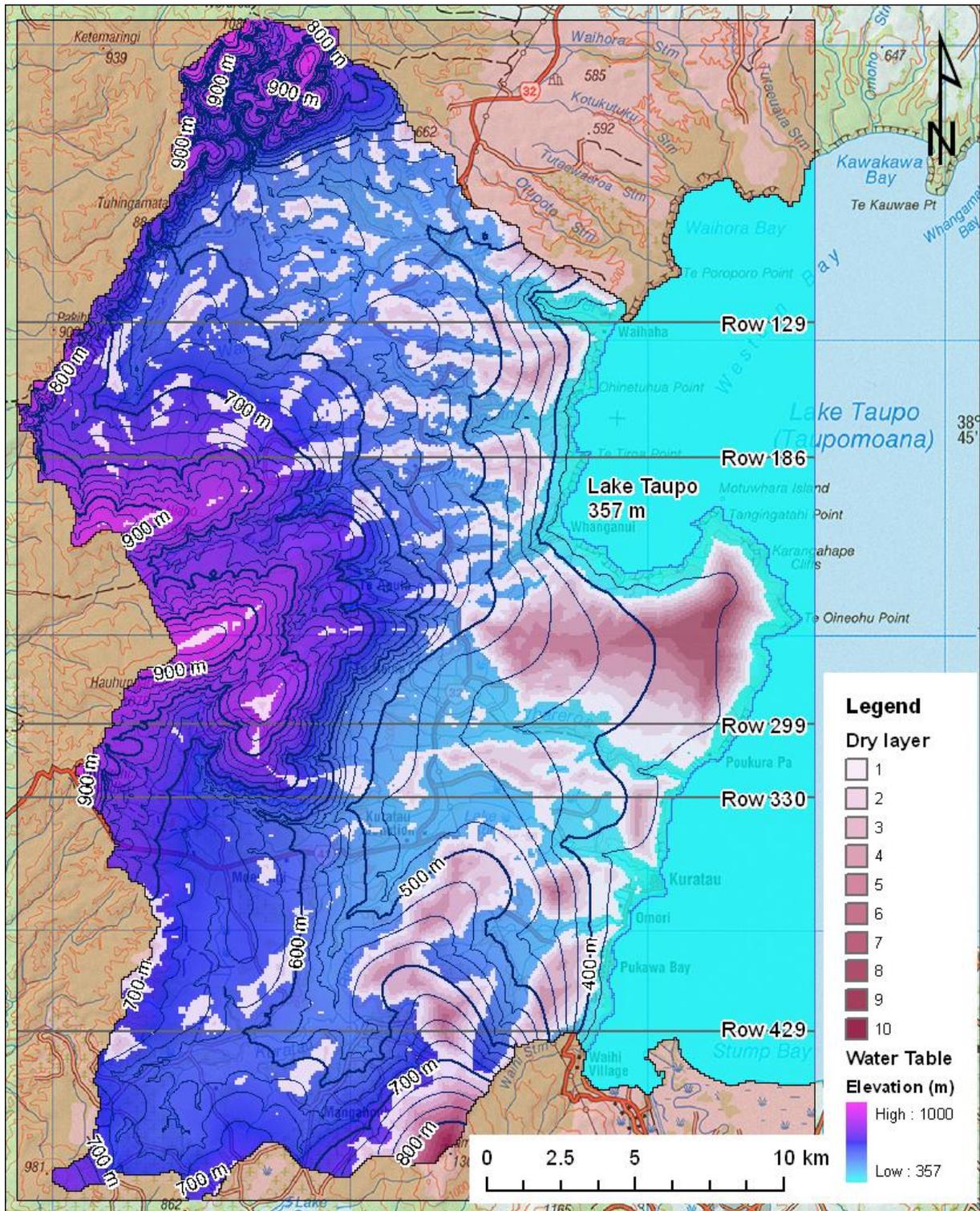
**Figure 8.** Groundwater observation wells in the model domain used for groundwater flow model calibration (Gusyev et al. 2011).



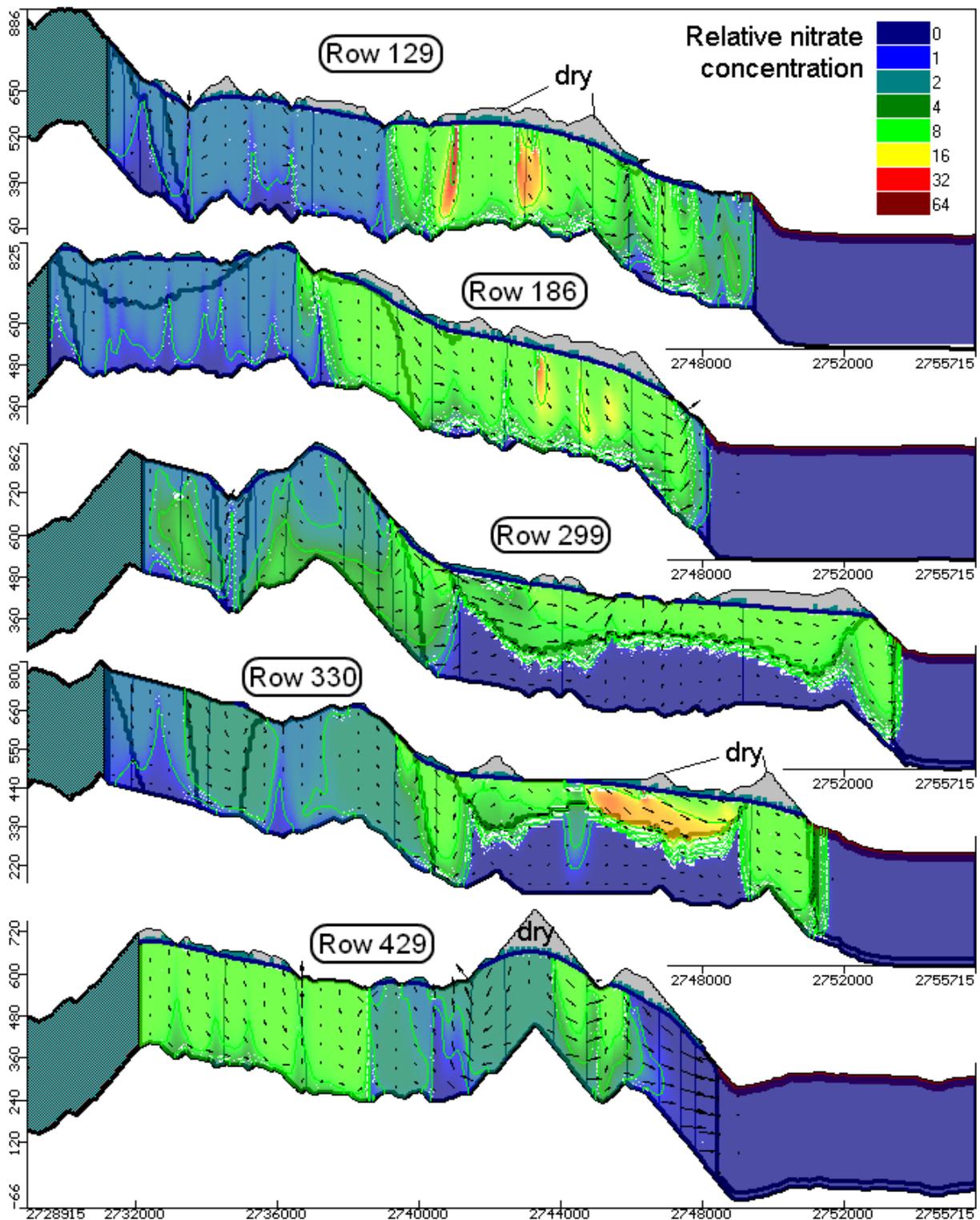
**Figure 9.** Simulated vs. observed stream/river flows, units are m<sup>3</sup>/s. Observed flows are represented with a vertical dashed line to show the minimum and maximum observed flows, while the middle symbol is represented by the median flow. Note that the simulated flows are within the min/max range for almost all gauging locations. The best-fit line has a slope of 0.9922 and R<sup>2</sup> of 0.9695.



**Figure 10.** Calibration plot of modelled vs. observed hydraulic head in the steady-state groundwater flow model.



**Figure 11.** Contour-fill map of groundwater table from steady-state flow simulation. Dry cells, and their layer number are overlaid, illustrating regions with a deep water table. The contour interval for the groundwater table elevation is 25 m, starting at 375 m. A light blue line shows the shoreline for the constant head boundary of 357 m for Lake Taupo.



**Figure 12.** Cross sections showing groundwater flow and nitrate simulation results in mg/L. See Figure 4 for reference to hydrostratigraphy at the same locations in the model. The figures show the water table (thick blue line), with light grey regions of dry cells above (where applicable) to the top of the model. Within the saturated aquifer, shading and light-green contours show a log distribution of relative concentrations of nitrate after 80 years of simulation time. Arrows show relative groundwater flow velocities. Faded thick lines in the background show boundaries of hydrostratigraphy (same as Figure 4).

## TABLES

**Table 1.** Data summary of 27 surface water sub-catchments in the western Lake Taupo catchment area (Gusyev et al. 2011).

No.	Sub-catchment Name	Area, [km <sup>2</sup> ]	Average recharge, [mm/year]	MRT, [years]	# of observation wells	# of gauging stations
13	Waihaha River	155.443	890	49	1	6
14	Otaunga Stream	8.269	786	-	0	1
15	Waikino Stream	31.718	826	-	1	3
16	Te Awaroa Stream	3.085	721	-	0	0
17	Whanganui Stream	65.382	847	49	2	4
18	Orongopioi Stream	6.886	683	-	0	0
19	Kotukutuku 2 Stream	7.309	602	-	2	0
20	Awatapu Stream	7.584	496	-	0	0
21	Whareroa Stream	59.270	709	9 or 53	9	8
22	Kuratau River	199.571	985	30	6	4
23	Te Puke	3.187	568	-	0	0
24	Omori Stream	27.405	744	0.5 or 40	1	4
54	Ohinetuhua	2.752	684	-	0	0
55	Te Tawai	2.643	666	-	0	0
56	Te Papa	0.710	653	-	0	0
57	Taupo U6	0.224	639	-	0	0
58	Te Poroporo	2.963	644	-	0	0
59	Whekenui	0.122	622	-	0	0
60	Wharekaho	1.261	595	-	0	0
61	Te Hapua	5.690	459	-	0	0
62	Karangahape	11.059	487	-	0	0
63	Te Koromiko	5.466	441	-	0	0
64	Te Hape	0.160	458	-	0	0
65	Rangitukua	1.542	494	-	1	0
66	Te Rae	0.250	510	-	1	0
67	Taupo U7	0.051	533	-	0	0
68	Pukawa	7.373	636	-	0	0

"-" stands for "No available data".

**Table 2.** Hydrogeologic properties of materials used for the model development model calibration.

Unit	Code	Hydraulic conductivity value, [m/day]			Calibrated Effective porosity
		Min	Max	Calibrated	
Oruanui	O3a	1.0	3.0	2.0	0.2
Whakamaru	W5	0.04	0.3	0.02	0.1
Pakaumanu	P7	0.03	0.06	0.04	0.05
Greywacke	B2	0.01	0.01	0.01	0.05

**Table 3.** Steady-state groundwater flow budget, where 'IN' refers to water entering the groundwater domain and 'OUT' refers to water exiting the groundwater domain.

Zone ID	IN Flow Budget			OUT Flow Budget		
	Recharge, [10 <sup>3</sup> x m <sup>3</sup> /day]	Fraction of total recharge	Constant head, [10 <sup>3</sup> x m <sup>3</sup> /day]	Drains, [10 <sup>3</sup> x m <sup>3</sup> /day]	Fraction of drains out	Constant head, [10 <sup>3</sup> x m <sup>3</sup> /day]
Zone 1 (remainder)	101.3	8.1%	0	81.7	6.7%	0
Zone 2 (Lake Taupo)	0.085	0.0%	16.6	10.0	0.8%	56.0
Zones 3-32 (Gauged)	1152.8	91.9%	0	1123.1	92.4%	0
Total	1254.2	100.0%	16.6	1214.8	100.0%	56.0
	1270.8			1270.8		