

Perched and leaky layers in complex surface-subsurface flow environments: the Kawerau shallow groundwater aquifer, New Zealand

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Abstract

Perched and leaky geological layers can play an important role in hydrological systems by redirecting land surface recharge and reducing total recharge volume to regional aquifers. The extent of continuity and permeability of perched layers can be key physical parameters in surface and subsurface flow connection to regional groundwater systems. A semi-permeable perched layer with discontinuities, heterogeneity, fractures and faults will inevitably increase the spatial complexity of local recharge in an otherwise simple system. Relatively little is known about how perched and leaky layers might control linkages between surface flow, shallow groundwater flow, and regional groundwater. We describe one such system in the Kawerau shallow groundwater aquifer (New Zealand), where a thin, semi-permeable and fractured layer alternates between leaky and perching behaviour. A numerical groundwater model indicates the perching layer plays a critical role in controlling the volume and spatial pattern of water exchange between surface water and local and regional groundwater systems.

Keywords

perched and leaky, shallow aquifer, surface water groundwater interaction, Kawerau, Rotoiti, Matahina, semi-permeable

Introduction

Perched water tables have long been classified as aquifers (Fetter and Fetter, 2001; Freeze and Cherry, 1979). In addition, surface-subsurface flow interaction has been the subject of many recent research projects (Bayani Cardenas, 2008; Cloke *et al.*, 2006; Ebel *et al.*, 2007; Gauthier *et al.*, 2009; Lemieux *et al.*, 2008; Li and Duffy, 2011; Maxwell and Kollet, 2008; Meyerhoff and Maxwell, 2011; Shokri and Bardsley, 2016; Smerdon *et al.*, 2008). However, the importance of perched aquifers on surface and subsurface flow integration has seldom been investigated in detail.

Perched aquifers can effectively redirect land surface recharge along horizontal impermeable layers to springs, streams, wetlands, and lakes (Amit *et al.*, 2002; Driese *et al.*, 2001; O'Driscoll and Parizek, 2003; Rabbo, 2000; Von der Heyden and New, 2003), consequently decreasing the

volume of vertical recharge to deeper aquifers (Bagtzoglou *et al.*, 2000). Furthermore, the extent of continuity and permeability of perched layers plays an important role in connections between surface-subsurface flow and the regional groundwater system. Where perched layers are fully continuous and impermeable, surface and subsurface flow becomes isolated from the regional groundwater system (Golden *et al.*, 2014; Pirkle and Brooks, 1959). However, a semi-permeable perched layer with internal discontinuity, fractures, and faults is likely to have complex local effects on the hydrologic environment.

Despite their common occurrence, relatively little is known about how perched and leaky aquifers control water exchange in the total hydrological system. As noted by previous authors, the importance of perched aquifers in regional groundwater conceptual models tends to be neglected, due to either lack of information or the scale of the studies concerned (Cable Rains *et al.*, 2006).

Perched aquifers may occur in a range of geological units, particularly in volcanic formations where textures and structures that

affect porosity and permeability may vary laterally over short distances. We describe here one example of a perched aquifer in a volcanic succession – the Kawerau shallow groundwater aquifer in the Okataina Volcanic Centre, in the North Island of New Zealand. We employ a high-resolution, finite element model of this system to illustrate how perched and leaky aquifers can play a critical role in creating groundwater flow complexity as well as influencing travel times, recharge volume, and recharge spatial variation.

Site description

Location and surface flow system

The Kawerau shallow groundwater aquifer in the Rotoiti Pyroclastics covers approximately 14.3 km² to the north of Kawerau township and the west of the Tasman Mill wastewater treatment ponds in the Bay of Plenty region (Fig. 1). The catchment associated with the study area has a gentle eastward gradient and is mainly covered by pine, eucalyptus and native forest. Ground surface elevation varies from 180 m above mean sea level (AMSL) in the west, down to 20 m AMSL at the catchment outlet.

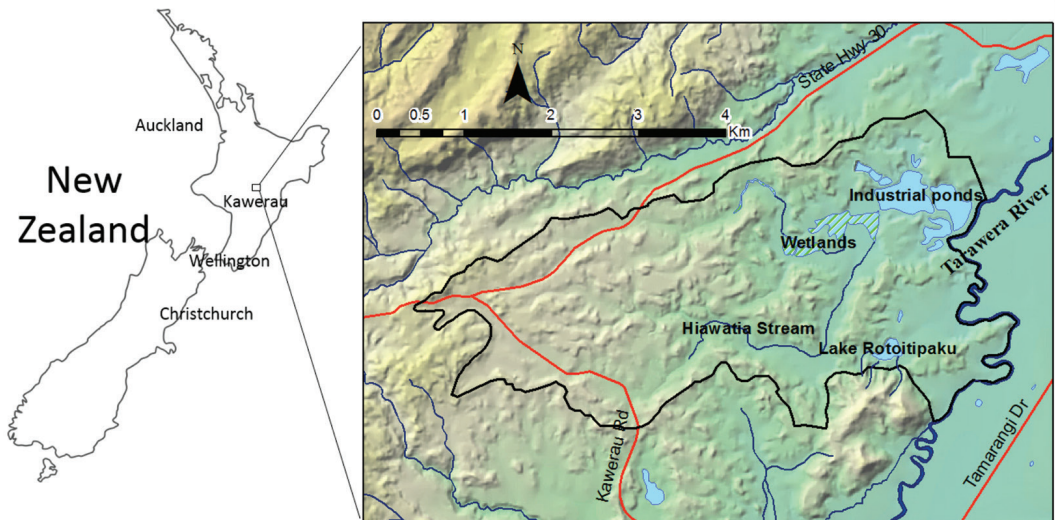


Figure 1 – Overview map of the study area (solid black line).

The catchment is drained by two small streams, which pass through a wetland and discharge into Lake Rotoroa. The lake, in turn, discharges into the wastewater treatment ponds. In addition to this natural inflow, there is discharge to the lake of about 124.3 ML/day (million litres per day) of wastewater and stormwater from pulp, paper and timber industries at the Tasman site enters the ponds. Following diffuser treatment, the combined natural and industrial flux of around 128.9 ML/day is then released into the Tarawera River by a control valve.

Geological and hydrogeological setting

The geology of the study area comprises a succession of pyroclastic units derived from explosive eruptions of the Taupo Volcanic Zone. The main laterally-continuous shallow volcanic unit in the study area is the Rotoiti Pyroclastics Formation (equivalent to Rotoiti Breccia). The Rotoiti Pyroclastics were deposited during eruption of the Rotoiti Caldera at the northern part of Haroharo Caldera at 61.0 ± 1.4 ka (Wilson *et al.*, 2007) with magma volume estimates ranging between 80 and 120 km³ (Nairn, 1971; Shane *et al.*, 2005; Wilson and Charlier, 2009). The formation consists of airfall deposits and non-welded ignimbrite that has a soft to firm consistency (Charlier and Wilson, 2010). It ranges considerably in thickness from 7.5 to 74 m in the observation bores in the study area.

There is little information available in the literature regarding the hydraulic conductivity of the Rotoiti Pyroclastics. However, from results of limited slug tests, it is anticipated to be fairly porous and permeable (Sky *et al.*, 2009; Thompson, 1974; Tschirter and White, 2014).

Underlying the Rotoiti Pyroclastics is the Matahina Ignimbrite (Bailey and Carr, 1994), covering around 2,000 km² with regional variable thickness ranging from 5 to 200 m. The Matahina Ignimbrite is

a 320 ka (Leonard, 2010) pyroclastic-flow deposit that erupted from the Haroharo Caldera, with an eruption volume of about 120 km³. The Matahina Ignimbrite has been identified in some investigation bores in the study area (Milicich *et al.*, 2014; Milicich *et al.*, 2013; Sky *et al.*, 2009). In addition, a low-permeability unit, the 138,000 to 150,000 year-old Onepu Formation, is observable at the south east of the study area (Milicich *et al.*, 2013).

In terms of permeability, previous studies suggest the Matahina Ignimbrite is permeable enough to act as a productive groundwater aquifer (Bailey and Carr, 1994; Tschirter and White, 2014). However, in spite of the permeability of the Rotoiti Pyroclastics and Matahina Ignimbrite, a thin semi-permeable layer (around 2 m thick) between these two formations has been reported in some of the geological surveys (Sky *et al.*, 2009). Similarly, some other studies specify that the upper part of Matahina Ignimbrite has a reduced primary porosity and groundwater yield compared to the lower portion. Moreover, some faults and fractures are reported to cut across both units (Gordon, 2001; Milicich *et al.*, 2013; Nairn, 1971; Tschirter and White, 2014).

The existence of the semi-permeable layer between the two relatively permeable formations causes the development of a perched aquifer in the Rotoiti Pyroclastics. Evidence of perching, including an unsaturated zone between two vertically separated water tables, is observed in three observation bores by Sky *et al.* (2009). However, the semi-permeable layer is patchy and not fully continuous across the site. Also, fractures and faults have developed some hydraulic connection between the Rotoiti Pyroclastics and Matahina Ignimbrite. The perched layer may therefore in fact create a complex connection between the local surface water, shallow aquifer, and the regional groundwater system.

Climate

The climate in Kawerau is warm and temperate (oceanic climate) and classified as Cfb by the Köppen-Geiger system (Peel *et al.*, 2007). In Cfb climates, summers are cool because of cool ocean currents; however, winters are milder than other climates in comparable latitudes.

For the current study the average annual rainfall and potential evapotranspiration (PET) for a three-year period from the beginning of 2008 to the end of 2010 was utilised because of data availability and stability of wastewater ponds managed during this period. The data are supported by NIWA virtual climate stations (VCS) (Tait, 2014; Tait *et al.*, 2006). Figures 2 and 3 show interpolation maps of annual average rainfall and PET, respectively. Catchment actual evapotranspiration (AET) was estimated using the approach of Zhang *et al.* (2004):

$$AET = PET \left(1 + \frac{P}{PET} - \left[1 + \left(\frac{P}{PET} \right)^w \right]^{1/w} \right) \quad (1)$$

where P is precipitation, and w is a dimensionless model parameter. Woods *et al.* (2006) reported that $w=4.35$ gives the best fit to New Zealand sites and this value was utilised here. Local mean annual rainfall varies from around 1750 mm near the wastewater treatment ponds to about 1900 mm in the northeast of study area. PET and AET have much less spatial variation than rainfall, with PET and AET variation estimated to be never more than 50 mm over the whole catchment.

Catchment and shallow aquifer outflow

Comprehensive industry monitoring of treatment pond inflow and outflow was used to estimate catchment and shallow aquifer discharge using a water balance approach. Sources of pond water include industrial discharge (QI), environmental discharge (QE), and direct precipitation (P). Water sinks are direct discharge to the

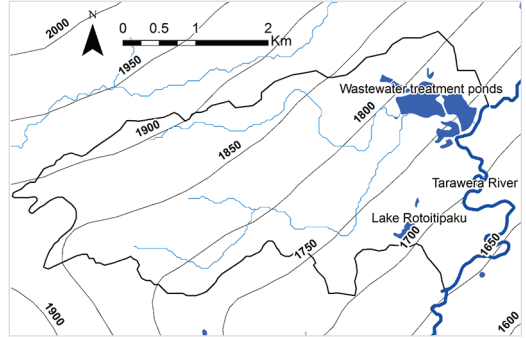


Figure 2 – Mean annual rainfall contours, estimated using NIWA virtual climate station data (Tait *et al.*, 2006; Tait, 2014).

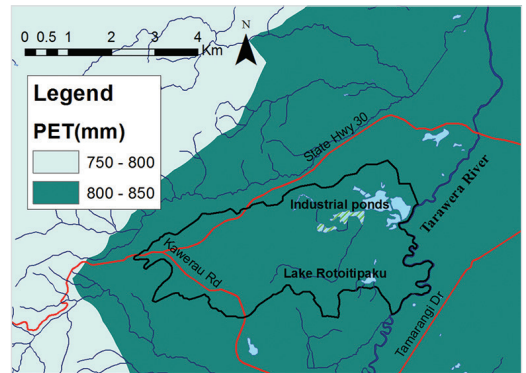


Figure 3 – Mean annual PET, estimated using NIWA virtual climate station data (Tait, 2014; Tait *et al.*, 2006).

Tarawera River (Q_w), evaporation (ET) and seepage loss (S) to the Tarawera River and to groundwater (Fig. 4).

The ponds' total water balance equation can therefore be expressed as:

$$(QI + QE + P) - (Q_w + ET_0 + S) = \frac{\Delta V}{\Delta t} \quad (2)$$

where is the volumetric storage change, assumed to be zero for an annual water budget. Water balance elements are calculated as below:

Q_w and QI : Industrial discharge to the ponds (Q_w) and pond outflow to the Tarawera River (QI) are monitored by a continuous

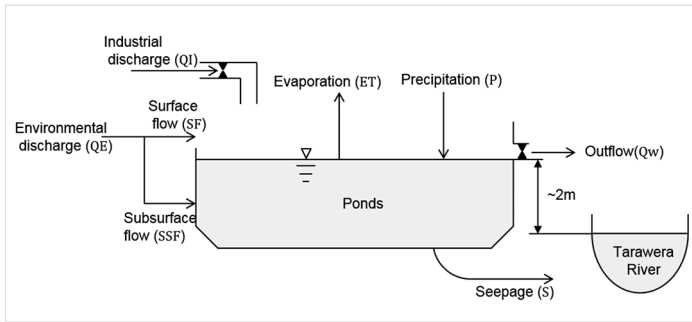


Figure 4 – Schematic diagram showing water sources and sinks for the Kawerau industrial ponds.

flow measurement gauge. For the study period (from the beginning of 2008 to the end of 2010) the difference between mean Q_w and Q_I was $128.9 - 124.3 = 4.7$ ML/day.

P and ET : The direct annual volumetric precipitation (P) and evaporation (ET) for the ponds are estimated to be 1.99 and 0.91 ML/day, respectively, obtained by multiplying the pond area (~ 0.4 km²) and daily VCS data (Tait *et al.*, 2006).

Seepage to Tarawera River (S): The seepage rate between the wastewater treatment ponds and Tarawera River was estimated using the steady-state numerical model. The assumptions that were made to estimate seepage rate are (i) the seepage flow is steady state and flowing slowly, (ii) the seepage domain is non-fractured, and (iii) the sub-pond hydraulic conductivity is homogeneous. The hydraulic conductivity of the material between the river and ponds is assumed to be 0.38 ± 0.28 m/day, based on the slug test results of Sky *et al.* (2009). The seepage rate as obtained from the model was estimated at 0.20 ± 0.14 ML/day.

Comparing this seepage estimate with the pond outflow to the Tarawera River, the upper bound of the calculated seepage rate is less than 0.3% of the surface outflow discharge. Therefore, the uncertainty in estimating the seepage to Tarawera River does not have a significant impact on the pond's water balance.

QE : Using Equation 2, the natural inflow to the ponds (QE) was estimated as 3.8 ML/day. Considering that the average annual rainfall (1800 mm/year) for the catchment area (12.8 km²) equates to a volume of 63.4 ML/day, an approximate estimate is that 6% of the catchment's annual rainfall volume flows into the industrial ponds.

Method and materials

A numerical groundwater model for the shallow aquifer was developed in order to increase understanding of groundwater flow and the effect of the leaky perched aquifer on surface water bodies and the regional groundwater system. The numerical model was constructed in FEFLOW (Finite Element subsurface FLOW system) (Trefry and Muffels, 2007), which is a well-known groundwater software package.

Monitoring bores and slug tests

Data from groundwater level monitoring bores are available in the study area. Given the bore casing depth and measuring point elevation compared to the Matahina Ignimbrite surface elevation, it is evident that some bores are monitoring the perched aquifer and others represent the regional groundwater system. In terms of data quality, in spite of a large number of monitoring bores, the water level records are not continuous and do not cover all the study area (Fig. 5).

Current understanding of near-surface hydraulic properties of the site is based on some slug tests reported by Sky *et al.* (2009), indicating a ‘moderate’ hydraulic conductivity which is consistent with more recent work (Landon, 2014). The results of slug tests by Sky *et al.* (2009) indicate a degree of spatial variability in near-surface hydraulic conductivity (Fig. 6). Though obviously somewhat uncertain, this provides an initial estimation of hydraulic conductivity for the numerical model.

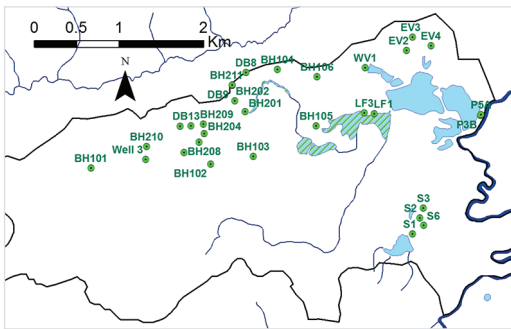


Figure 5 – Shallow observation bores utilised for groundwater model calibration.

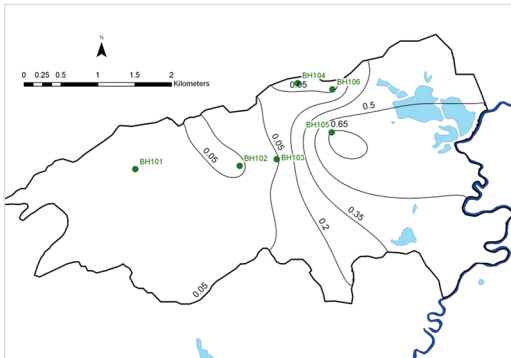


Figure 6 – Interpolated hydraulic conductivity (m/day) of Rotoiti Pyroclastics from available slug test data.

Conceptual model structure

The model aquifer boundaries are a combination of the catchment boundaries of the streams of order 3 and 4, as defined by the river environment classification

(REC) network, reported by Snelder *et al.* (2014), and geological units from Nairn (2002). The shallow and perched groundwater aquifer model includes all saturated and permeable units above the Matahina Ignimbrite, including the four upper units: Tarawera Pyroclastics, Kaharoa Pyroclastics, Taupo Pumice Formation and Whakatane Formation. Each of these have variable thickness and locally discontinuous distribution. The widespread Rotoiti Pyroclastics unit is also included but the impermeable Onepu Rhyolite is excluded from the conceptual model. This single-layer model is only applied to the saturated zone and water movement in the unsaturated area not incorporated.

The thin semi-permeable layer between the Matahina Ignimbrite and Rotoiti Pyroclastics is considered as leaky basement. The elevation of this interface surface is interpolated from available information in the geological bore-logs. Its upper surface boundary is derived from a 5-metre resolution topographic map. Figure 7 gives an overview of the conceptual model for the Kawerau shallow aquifer and Figure 8 illustrates the catchment REC network order 3 and 4 streams as reported by Snelder *et al.* (2010).

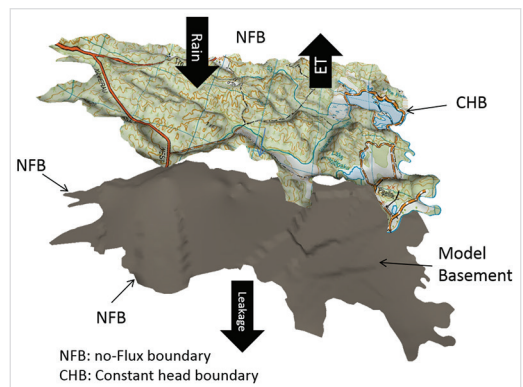


Figure 7 – Conceptual model showing ground surface topography and the top of Matahina Ignimbrite surface as applied in the numerical model.

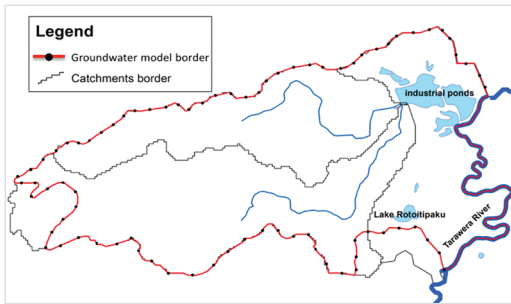


Figure 8 – Catchments of order 3 and 4 from New Zealand river environment classification (REC) (Snelder *et al.*, 2010) (black lines) and the shallow perched groundwater boundary (red lines).

Recharge zones

Field observations indicate that sheet-flow would be unlikely to occur during heavy rainfall, because of vegetation effects, high soil infiltration, and a relatively flat land surface. There are no major irrigation, industrial or domestic water supply wells inside the model boundaries in the Bay of Plenty Regional Council database (White, 2005). Therefore, recharge from the ground surface drains either to streams or to ponds, or recharges to the Matahina Ignimbrite. Six recharge zones were defined (Fig. 9), based on rainfall and PET spatial distribution (Fig. 3) and the annual rate of environmental discharge to the pond.

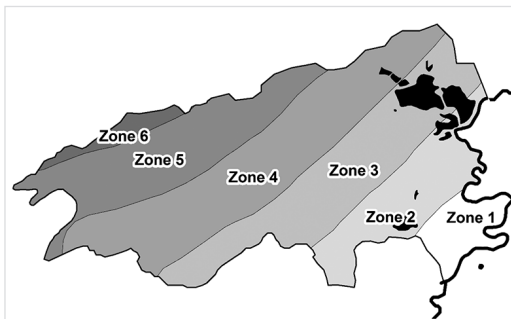


Figure 9 – Recharge zones as specified in the model; annual average recharge is 885, 935, 985, 1035, 1085 and 1135 mm/year for zone 1 to 6, respectively.

The conceptual ‘basement’ is defined here as the semi-permeable layer between the Matahina Ignimbrite and Rotoiti Pyroclastics. It is discontinuous and the assumption is therefore made that a continuous but spatially variable vertical flux must be leaking through to the Matahina Ignimbrite aquifer.

Numerical model

A steady-state finite element groundwater model was implemented for this study, enabling easy definition of complicated boundaries and permitting different mesh geometries and density in different parts the model. Mesh resolution was increased for critical zones, such as near the wastewater treatment ponds and observation bores. Figure 10 shows the generated finite element mesh for the study area.

All water level variations in the ponds and the river were ignored and average water levels of 14, 20, and 24 metres as constant head boundaries to respectively represent the Tarawera River, pond 1 to pond 5 water levels collectively, and Lake Rotoitipaku. These constant head boundaries could create either a local sink or a source, depending on hydraulic gradients arising from the model. All other boundaries were set as zero-flux.

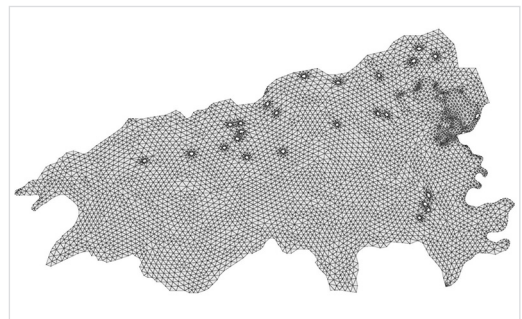


Figure 10 – Finite element mesh of the study area.

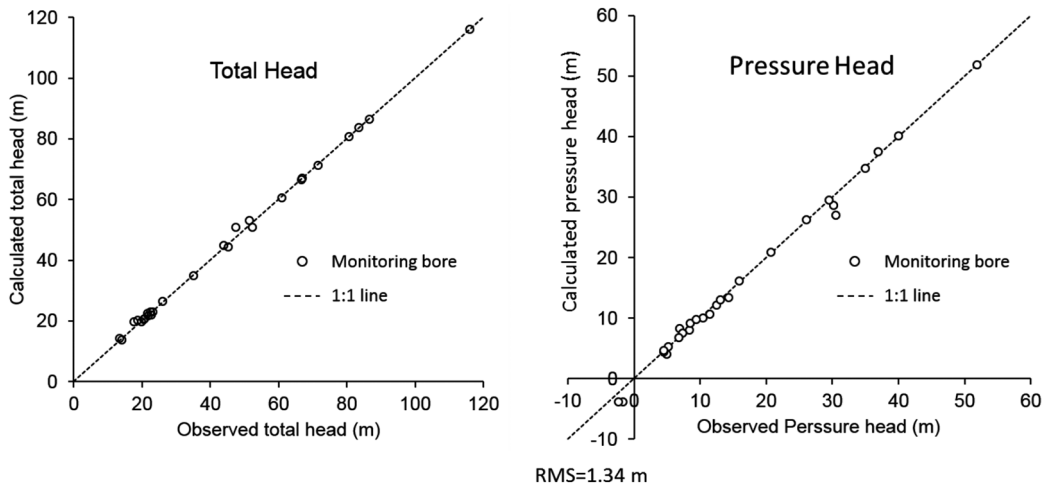


Figure 11 – Calculated (fitted) vs observed total head and pressure head at the monitoring bore locations.

Numerical model calibration

The steady-state model was calibrated against time-averaged groundwater levels in 26 observation bores. An automated calibration procedure was implemented using the parameter estimation software PEST (Dahlstrom, 2015), with 100 pilot points. Using trial and error with PEST, a basement leakage and hydraulic conductivity map was generated by minimising differences between modelled and observed groundwater levels. During this process, the hydraulic conductivities were constrained to remain within 20% of the values obtained through slug tests at the points of measurement. Comparison between observed and computed total head and pressure head at the monitoring bore locations are shown in Figure 11.

Results and discussion

Perched and regional groundwater interaction

The model-derived static water table of the study area is shown in Figure 12. Groundwater flow in the model tends to follow the topographic gradient and becomes shallower closer to the ponds. However, in

the north centre of the domain the static water table contours show a distinctive local pattern of flow convergence, indicating leakage. This area is highlighted in Figure 12 and is referenced hereafter as the basement leakage zone. Possible connection at this site between the Matahina Ignimbrite and Rotoiti Pyroclastics aquifers is also reported by *Sky et al.* (2009).

It is noticeable that the model-generated steady-state water table surface slopes somewhat toward the leakage zone, sometimes

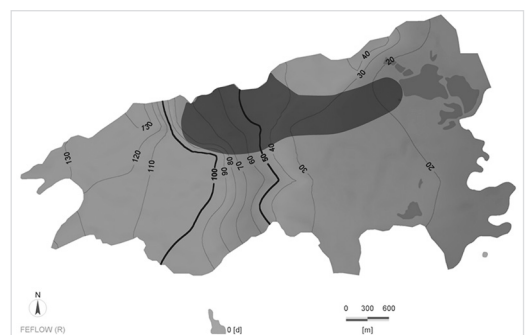


Figure 12 – Simlated steady-state water table from the calibrated numerical model, and the basement leakage zone. Piezometric contours are metres above mean sea level.

against the general eastward piezometric gradient. This strong connection between the perched and regional groundwater table may be due to the existence of a fault, as reported by Sky *et al.* (2009). Because of the increased recharge rate to the Matahina aquifer through the leakage zone, the groundwater level on the Matahina aquifer rises and almost connects to the perched aquifer in the leakage zone.

From the model's water balance the spatially-averaged annual recharge from the ground surface into the perched aquifer is estimated to be 1011 mm, of which 904 mm leaks into the Matahina Ignimbrite and around 107 mm passes to the Tarawera River via the Rotoiti aquifer. Therefore, on average around 11% of the total land surface recharge is predicted to be redirected by the semi-permeable layer to the Tarawera River either directly or through the ponds. Consequently, 89% of the land surface recharge leaks to the regional groundwater aquifer.

The leakage rates to the Matahina Ignimbrite varies spatially. The model predicts about 78% of the leakage to the regional groundwater system passes through the leakage zone. Therefore, the perched layer effectively changes the regional groundwater recharge pattern.

Particle tracking and surface water bodies

The calibrated model was used to estimate flow paths from different points within the spatial domain. Results of particle tracking for a selection of points are shown in Figure 13a. Some flow paths are predicted to travel directly to the Tarawera River, but most reach the river indirectly via the streams and ponds.

The semi-permeable layer causes a separation between shallow and regional groundwater in the study area. Consequently, the shallow groundwater system acts as the source of the surface water bodies including

two streams, wetlands and the natural ponds within the catchment. The water balance of the groundwater model indicates the semi-permeable layer redirects 4.2 ML/day of the land surface recharge to the shallow groundwater system and surface water bodies.

Particle travel times estimated by the model shown are in Figure 13b. Any water particles released in the catchment within 1 km of the ponds may take up to 10 years to appear in the ponds via the shallow groundwater. However, for other areas, travel time to the ponds may take over 50 years.

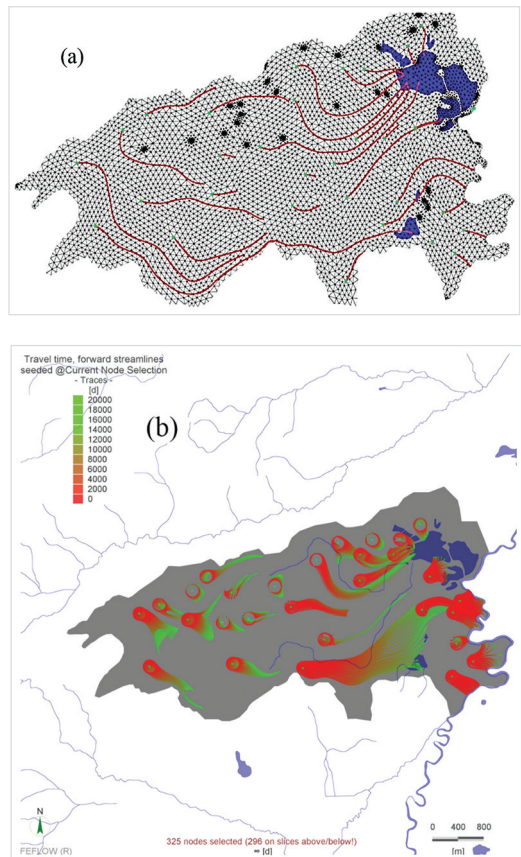


Figure 13 – (a) Particle tracking and (b) travel time results from the FEFLOW model.

Conclusion

Perched and leaky aquifers can have an important role in both constraining and connecting surface water to subsurface shallow and regional groundwater flow systems.

A case study of a groundwater system in the Kawerau area shows that a thin, semi-permeable layer between two volcanic units (the Rotoiti Pyroclastics and Matahina Ignimbrite) results in the development of a shallow water table within the Rotoiti Pyroclastics. Modelling indicates that there is complex water flux interaction between the surface flow, subsurface flow, and the regional groundwater system of the Matahina Ignimbrite. The perched layer plays an important role in the connection and control of the flux exchange between the surface-subsurface flow and regional groundwater system. The semi-permeable layer redirects approximately 11% of the land surface recharge along horizontal pathways to the surface flow network.

The perched and regional groundwater systems across the study area have both strong and weak connection zones vertically. The numerical model indicates the strongest linkage in an area close to the northern boundary, likely due to the existence of a fault through the Rotoiti Pyroclastics and Matahina Ignimbrite. The calibrated model shows around 78% of the total land surface recharge passes through this leakage zone to the underlying layer. There could be additional connections between the perched and regional aquifers within the study area, but their detection would require more monitoring sites.

Ignoring perched aquifers in large-scale regional groundwater models may result in considerable error in defining recharge spatial variation, thus increasing regional groundwater model inaccuracies.

Acknowledgements

This material is based upon work funded by Norske Skog Tasman and Carter Holt Harvey Pulp and Paper.

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