Groundwater Modelling Assessment of Shallow and Deep Geothermal Aquifer Interactions Around Otumuheke Stream, Wairākei-Tauhara Geothermal Field

Jake Scherberg[1], Jon Williamson[1], and Matthew J Sophy[2]

[1]Williamson Water & Land Advisory; 1/10 Putaki Drive Kumeu 0881; New Zealand

[2] Contact Energy, Wairākei Power Station, Taupō, New Zealand

jacob.scherberg@wwla.kiwi

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ABSTRACT

Williamson Water & Land Advisory has collaborated with Contact Energy in a hydrogeological modelling study of the shallow Tauhara Geothermal Field, focused on the Otumuheke Stream area. The stream, fed by geothermally heated groundwater and flowing into the Waikato awa approximately 1 km upstream of Huka Falls, holds significance to local Iwi and is a popular recreation site.

Flow and temperature changes have occurred in the Otumuheke stream since the 1960s in response to reservoir pressure trends. Since 2013, reservoir pressure near Otumuheke spring has increased due to nearby reinjection. Contemporaneously, ground subsidence has declined as has flow from the uppermost spring in the valley. The decline in stream flow has coincided with declining groundwater levels within the shallow aquifer that resides within the Taupō Pumice and Oruanui Formations.

Groundwater level declines are less evident with increasing distance from geothermal features and subsidence anomalies, indicating that declining groundwater levels and streamflow are not due to climate alone. The hypothesis was that the reinjected geothermal fluid partially submerged or quenched the steam zone at the base of the shallow aquifer, reducing the pressure buffer separating shallow groundwater from the deep geothermal reservoir and allowing increased downward vertical leakage.

For this study, a numerical modelling approach was applied to improve understanding of the mechanisms causing the observed changes in the shallow hydrogeological environment. A groundwater model was calibrated with groundwater monitoring data and Otumuheke Stream flows records. Results show that the model is suitable for simulating observed groundwater levels and streamflow, and thereby replicating the interaction between the shallow aquifer and geothermal reservoir.

Results indicate that vertical leakage losses currently range from approximately 15,000 to 24,000 m^3/day (175 to 277 L/s), which is substantial relative to the median flow of the Otumuheke Stream (less than 100 L/s since 2014), though a small effect relative to the 130 Mm^3 estimated for shallow aquifer water storage within the Otumuheke Catchment. The model is suitable for further investigating the shallow aquifer effects of a range of environmental variables and future power plant management options.

1. INTRODUCTION

1.1 Project Overview

Williamson Water & Land Advisory (WWLA) collaborated with Contact Energy Limited (CE) to undertake a hydrogeological modelling study of the Otumuheke Stream and surrounding area. The stream, fed by geothermally heated water, holds cultural significance to local Iwi and is a popular recreation site. The spring has become a well known destination in Taupō, hence changes are often noticed by the general public.

Historic changes and predicted effects of geothermal development on the spring have been documented in resource consents for the Wairākei-Tauhara geothermal field; the list of effects includes subsidence and changes to surface geothermal features (Rosenberg et al., 2009; Bromley et al., 2021). Since 2013, temperature and flow of the spring have declined to the point where the spring now emerges over 200 m downstream from its historic source.

This study seeks to improve understanding of the mechanisms causing these changes within the context of the hydrogeological environment and ongoing management practices related to geothermal development.

The study area extends northeast from the Lake Taupō shoreline at the city of Taupō to the confluence of the Waikato River and the Pueto Stream, with these water bodies defining the boundary of this investigation. Mount Tauhara is a central feature in the study area, surrounded by relatively flat land that is predominantly used for farming, pastures, and geothermal energy production. The model extent was determined to facilitate analysis of present and future development of geothermal resources in the area surrounding Mount Tauhara. Figure 1 shows an overview of the study area.

.2 Study Objectives

This study comprised a modelling investigation where a calibrated numerical model was developed to simulate interactions between deep and shallow groundwater to facilitate an assessment of the hydrological environment in relation to current and proposed activities. The key objectives of the modelling exercise were to:

- Advance understanding of the shallow hydrogeological functionality of the Tauhara geothermal field and Otumuheke Stream system.
- Evaluate current hypotheses with regard to mechanisms that are potentially related to declining flow and groundwater levels.
- Apply model for sensitivity analysis as well as conceptual modelling of future conditions and responses to proposed management options.

1.3 Hydrogeological Conceptualisation

This investigation focuses on the hydrological conditions of the Otumuheke Stream and the shallow aquifer that underlies the stream bed. The Otumuheke Stream is a discharge point for the shallow aquifer in a thermally active area where

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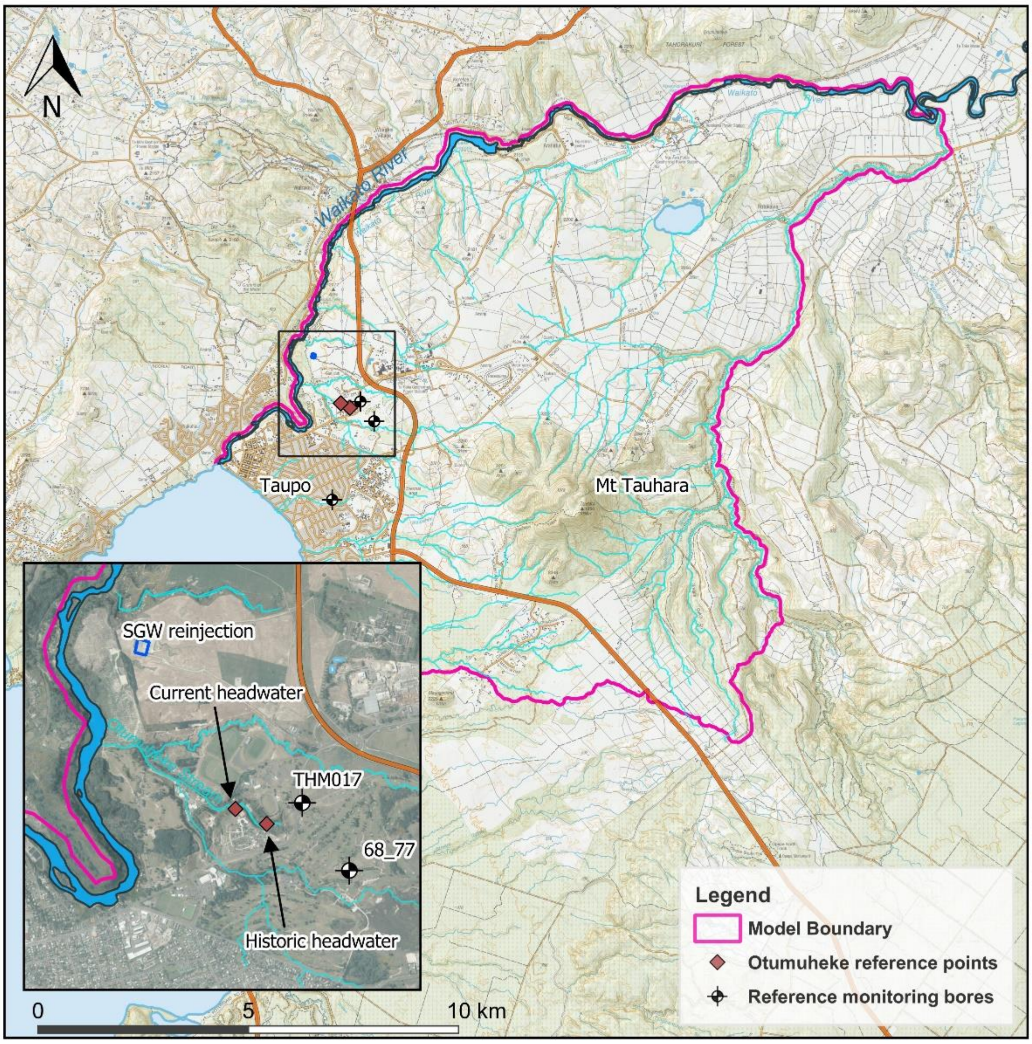

Figure 1. Study area overview with highlight of locations referenced in this paper.

shallow groundwater is heated by steam trapped within underlying strata.

The stream intersects the highly permeable Taupō Pumice and Oranui Formations which comprise the uppermost geologic layer. These layers overly the low-permeability Upper Huka Falls Formation (U-HFF), which itself overlies the highly conductive Middle Huka Falls Formation (M-HFF), low permeability Lower Huka Falls Formation (L-HFF), and the Waiora Formation which comprises the geothermal reservoir used by CE for power generation.

The M-HFF is a moderately to highly permeable aquifer that is mostly confined (SKM, 2010; Bignall et. al., 2010). The M-HFF has historically contained the steam zone that, where present, creates a pressure barrier or buffer to vertical flow which effectively heats shallow groundwater while precluding vertical drainage from the shallow to deep aquifer (Brockbank et. al., 2020). The presence of steam in the upper strata indicates fracturing of the HFF materials in the Otumuheke area. Figure 2 provides a conceptual illustration of the geologic layering and steam residing within the formation.

Prior investigations have noted that the decline in stream flow has coincided with increased reinjection of separated geothermal water (SGW) into the M-HFF that underlies the shallow aquifer. Furthermore, monitoring of bores in the M-HFF and deeper layers has shown that pressure/water levels in these deeper layers has increased over the same timeframe that shallow aquifer has been decreasing. These observations are supported by the converse trends observed prior to reinjection where monitoring data documented declining pressure in the M-HFF was from the onset of abstraction for energy production in the 1960's until SGW reinjection began in the mid-1990's. For reference, historic monitoring data shows that from 1964 to 1996 the temperature of the Otumuheke Spring rose approximately 2°C per year (GNS 2010).

The hypothesis proposed in previous investigations was that the increasing water levels in the deep aquifer have submerged the steam zone within the M-HFF, reducing a pressure barrier that was preventing leakage out of the shallow aquifer to greater depths (Brockbank et. al. 2020; Sophy 2020). This is conceptually illustrated in Figure 3, which shows the decline in shallow aquifer bore 68-77 relative to the increase in water level and decrease in well head pressure (from steam) in the deeper bore (THM017), located 570 m away (both bores are shown in Figure 1).

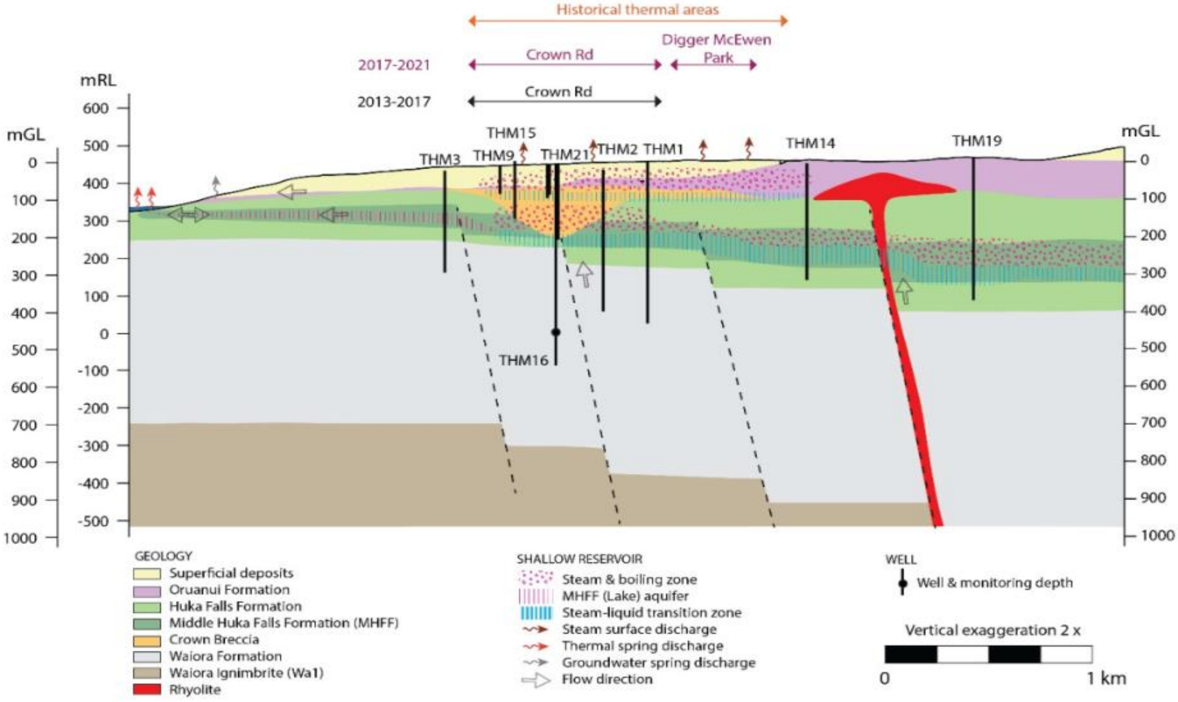

Figure 2 Conceptual illustration of steam distribution through the geologic layers in study area (From Brockbank et. al. (2020)).

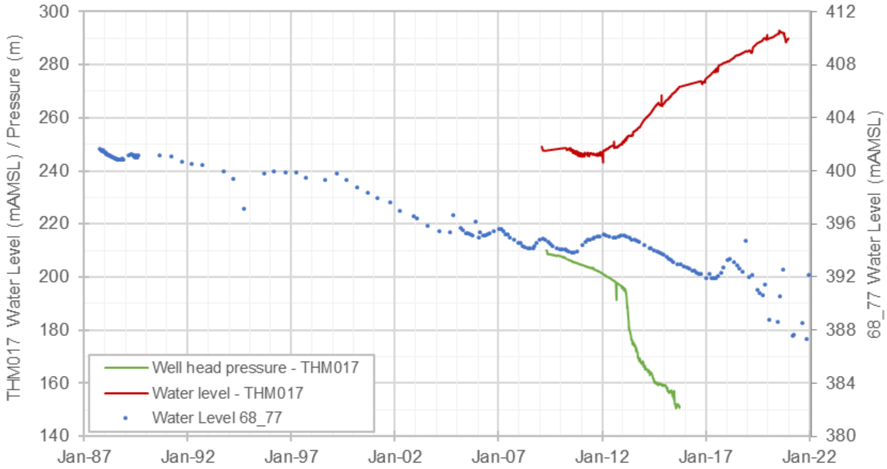

Figure 3. Water level and well head pressure in the deep THM017 bore compared to shallow groundwater levels measured in the 68-77 monitoring bore.

2. MODEL DEVELOPMENT METHODOLOGY

The framework of the numerical model was developed based on a conceptual understanding of the hydrological system. It is known that groundwater recharge in this area occurs through deep percolation of rainfall and that groundwater generally radiates from Mount Tauhara, discharging into Lake Taupō (in the shallow aquifer), the Waikato River, and the drainage network that in turn converges with the Waikato River. The U-HFF forms a lower bound to the shallow aquifer, however there are areas where fracturing allows for interaction between the shallow and deeper aquifer, often manifesting with surface discharge of geothermally heated water (i.e. hot springs and fumaroles).

The Tauhara Groundwater Model (TGM) was developed using an unstructured grid (Figure 4) within the USGS MODFLOW code to simulate groundwater conditions in the shallow aquifer, including interactions with underlying geothermal layers. Geologic data provided by CE and topographic data from Waikato Regional Council and LINZ were used to define aquifer dimensions. Groundwater recharge was calculated using the Soil Moisture Water Balance Model developed by WWLA and applied across 34 sub-catchments within the study area, each parameterised to reflect slope, soil, and geology.

The model was calibrated to shallow aquifer water levels using available data from 91 bores by adjusting hydraulic conductivity over the model area within the known range for the geologic materials based on previous studies and measurements (Rosenberg et al., 2010; SKM, 2010; WWLA, 2019). The model simulated the 50-year period from 1972

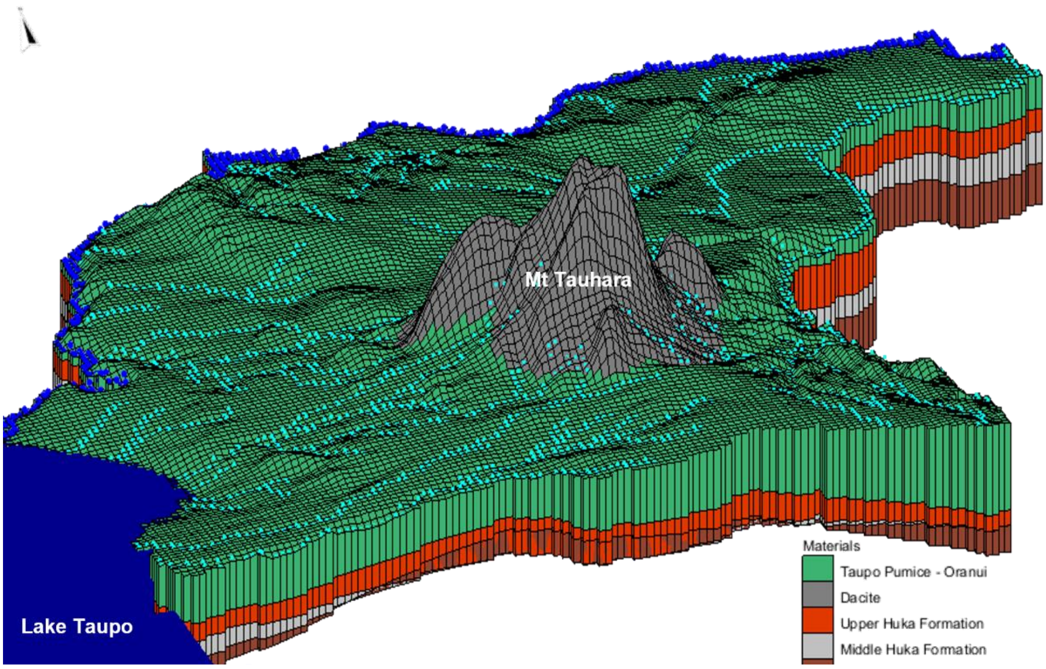

Figure 4 TGM model grid.

through 2021, achieving a root mean squared error (RMSE) of 7.4 m which amounts to 4.4% of the range of observed data. An RMSE that is less than 10% of the range of observations is commonly considered to indicate a good calibration for a regional scale model such as the TGM, hence the model is considered to be fit for purpose.

It was determined that the observed declines in shallow groundwater levels and stream baseflow were not due to climate alone. One notable indication of this is that the bores where water levels are declining are limited to the area around the Otumuheke Stream, while the decline is less evident with increasing distance from the stream. Figure 5 shows an example of two shallow aquifer monitoring sites. At site 68_77, approximately 0.5 km from the current spring, water levels have consistently been in decline since the late 1990's; whereas at site 68_39, 2.3 km from the spring, water levels have been stable over the same period.

A general head boundary (GHB) was applied over the area surrounding the branches of the Otumuheke Stream where groundwater levels have been declining to simulate the pressure reduction at the base of the M-HFF aquifer and consequently mimic the trends in surface water baseflow and groundwater conditions. A GHB condition applies pressure and conductivity parameters to simulate the influence of an external water body (in this case the M-HFF aquifer) on groundwater within the model domain.

The pressure applied to the GHB was held at a constant (345 mAMSL) to assure that water only drained out of the model. Conductivity was adjusted for the six GHB areas based on observed groundwater trends such that the degree and extent of influence from the applied conditions aligned with observed data. This method produced a good agreement between simulated and measured groundwater levels, as shown in Figure 6 for monitoring site 68_77; and for simulated and measured flow in the Otumuheke Streams, as shown in Figure 7.

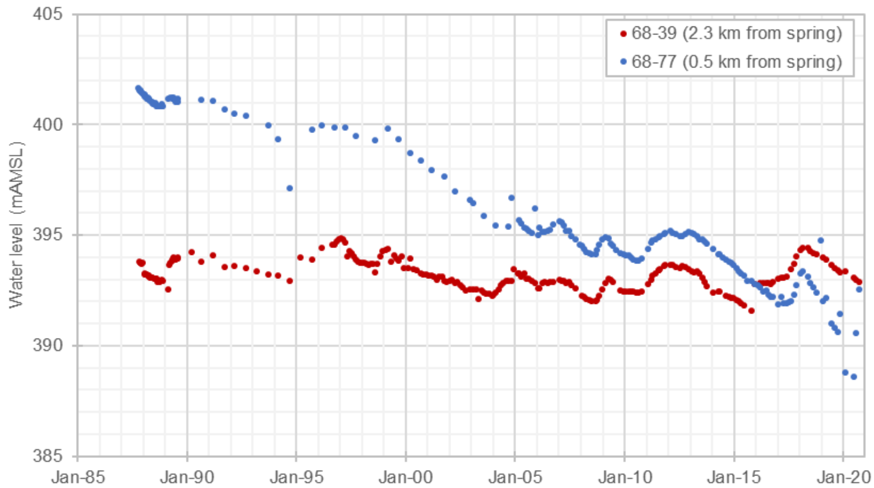

Figure 5. Comparison of groundwater level monitoring data (1987-2021) at varying distances from Otumuheke spring.

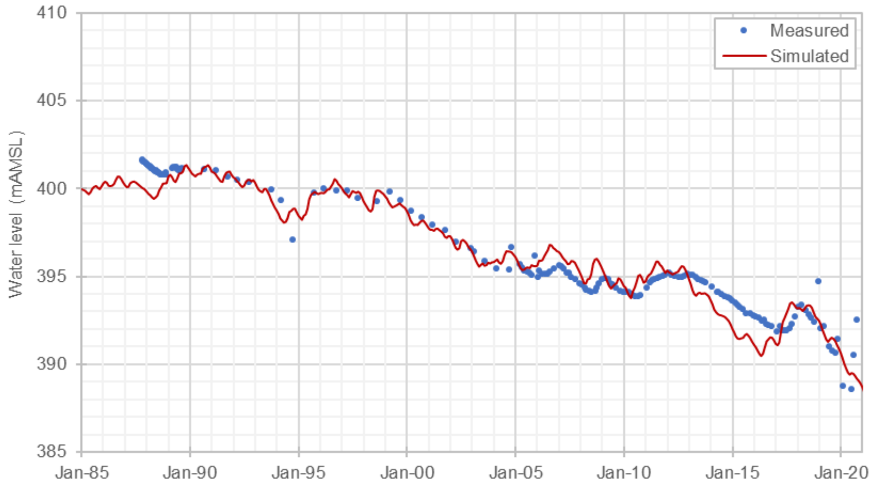

Figure 7. Measured versus simulated water levels for monitoring bore 68_77.

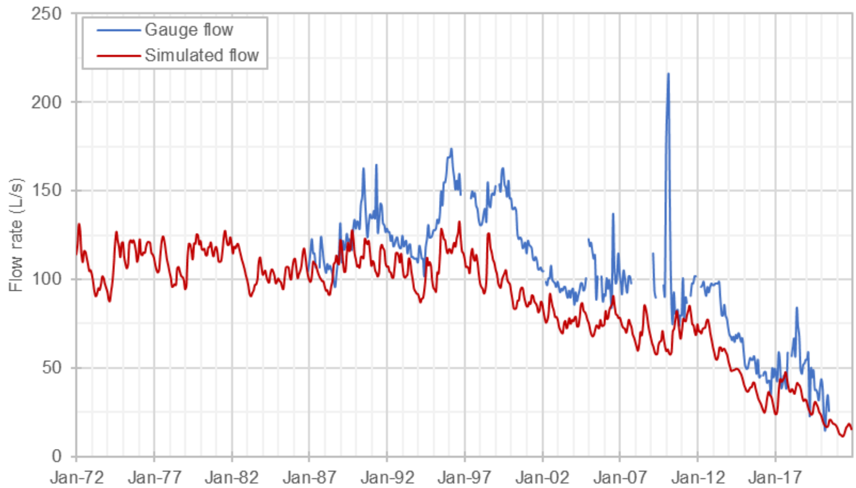

Figure 6. Measured and simulated flow at Otumuheke gauge.

Results from the calibrated model show that drainage through the Otumuheke GHB boundary, representing the connection to deeper layers, is a small part of the water budget over the full simulation period. However, this drainage from the shallow aquifer began increasing after the beginning of SGW reinjection, and in recent years has increased from a negligible amount to approximately 24,000 m^3/day (277 L/s) amounting to 6% of total groundwater outflow for the entire model at the end of the simulation period (Figure 8). For comparison, since 1986 (earliest available data) the median measured flow in the Otumuheke Stream was 105 L/s, though flows have been significantly lower in recent years.

3. CONCLUSION

WWLA and CE have collaborated to develop a calibrated groundwater flow model for the area encompassing the Tauhara Geothermal Field. The modelling efforts have focused in particular on simulating the ongoing changes observed in the Otumuheke Stream over the past 25 years to test current hypotheses related to this phenomenon and better understand the hydrological interactions between the shallow aquifer and the underlying geothermal reservoir. A GHB boundary condition was applied to simulate the connection between the M-HFF and the shallow aquifer. The results showed a successful simulation of declining shallow aquifer groundwater levels and Otumuheke Stream flow corresponding to increased pressure in underlying layers and inundation of the pressurized steam within the M-HFF.

The results of the modelling investigation support the hypothesis that ongoing SGW reinjection is related to an increasing degree of connection between the deep and shallow aquifers in the Otumuheke area. The model demonstrates that increasing conductivity at the base of the shallow aquifer can result in lower shallow aquifer water levels. To put this finding in context, it is considered that pressure in the deep aquifer has increased, presumably due to reinjection, over the same time period that shallow groundwater levels and Otumuheke Stream flow have declined. The inundation of the pressurized steam zone at the base of the shallow aquifer is considered a possible physical mechanism for the increased conductivity that has been incorporated into the numerical model with the GHB boundary condition.

The depressurisation of the shallow aquifer via vertical leakage to the deeper aquifer that is required to simulate the current groundwater levels ranges from approximately 15,000 to 24,000 m^3/day (~175 to 277 L/s) over the last five years. This is a substantial flow compared to the flow of the

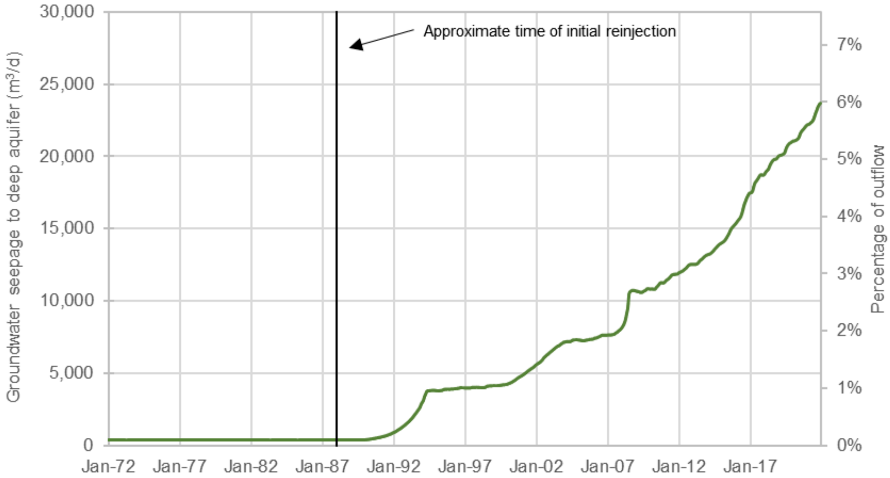

Figure 8. Simulated drainage from shallow aquifer into deeper layers in Otumuheke Stream area.

Otumuheke Stream, which in the 1980's to 1990's ranged from 100 to 175 L/s. If the full effects of the depressurisation have not yet manifested, it could be anticipated that the Otumuheke Stream flows may continue to decline with respect to its groundwater baseflow component.

The model is suitable for investigating the shallow aquifer and its interaction with surface water and underlying geologic materials. Further applications may include sensitivity analysis on the configuration of the model, incorporation of other environmental variables such as consent conditions from nearby industrial sites, and ongoing or proposed CE operations. The model can also be used to test stream flow augmentation or mitigation options, including optimising the location, and potential infiltration rate for shallow aquifer injection bores or soakage trenches.

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