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Assessment of data driven and process based water management tools for the geothermal reservoir Waiwera (New Zealand)

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Abstract

The reservoir below the village is commercially used since 1863. Due to overproduction in the 1960s and 1970s the water level declined critically. Therefore, abstraction rates were limited, monitoring deployed and models set up to manage the site sustainably. It is shown here that data driven models based on experience and observations are of higher accuracy and provide better prognoses. Process based simulations are more flexible and the foundation for system understanding of the geothermal area. The earlier are "black box" and need regular revision and the latter are the only way for future and prospective scenarios.

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Keywords: water level; abstraction rates; monitoring; models; prognosis; system understanding

1. Introduction

The geothermal hot water reservoir below the village of Waiwera on the Northern Island of New Zealand is used commercially since 1863. The continuous production of 50 °C hot geothermal water, to supply hotels and spas, has a significant impact on the reservoir. Until the year 1969 from all wells drilled the warm water flow was artesian. Due to overproduction the water needs to be pumped up nowadays. Further, within the years 1975 to 1976 the warm

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water seeps on the beach of Waiwera ran dry [1]. In the early 1980s the "Auckland Council" deployed a water allocation and management plan and with that established guidelines to enable a sustainable utilization [2].

Water management tools are essential to ensure the conservation of natural resources. They are based on simple mathematical equations or complex, computer based simulation models and used to determine water quantity and quality or to give insides about underlying processes governing the system. In order to use model outputs for regulation, they need to be scientifically accurate and robust [3].

The work presented here is based on data sets of almost four decades (since 1977 until 2012) of metred water production rates from the Waiwera geothermal reservoir and resulting water levels in an official observation well [4,5]. We applied two data driven regression models and one fully coupled process simulator and assessed their accuracy and prognosis feasibility accordingly.

2. Methods and materials

2.1. Geological setting

The studied site is located on the east coast of the North Island of New Zealand, about 40 kilometres north of Auckland. The village Waiwera is located on the south bank of the estuary of the river on a flat peninsula [6]. An area of approximately 1 km^2 is developed with around 100 bore holes with depths ranging from 8.5 m to 426 m (Fig. 1). The geology of the subsurface is essentially divided into three units: (1) the unconsolidated confining sands, silts and clays of fluvial sediments which form a cover of around 2-20 m for the reservoir; (2) the Waitemata sandstone as actual reservoir of 400 m thickness and (3) the Waiheke greywacke an impermeable base rock with a fault zone through which the geothermal water enters the reservoir (Fig. 1). In addition to the influx of geothermal water from the base, near-surface fresh groundwater from the west and seawater from the east affects the site (Fig. 1).

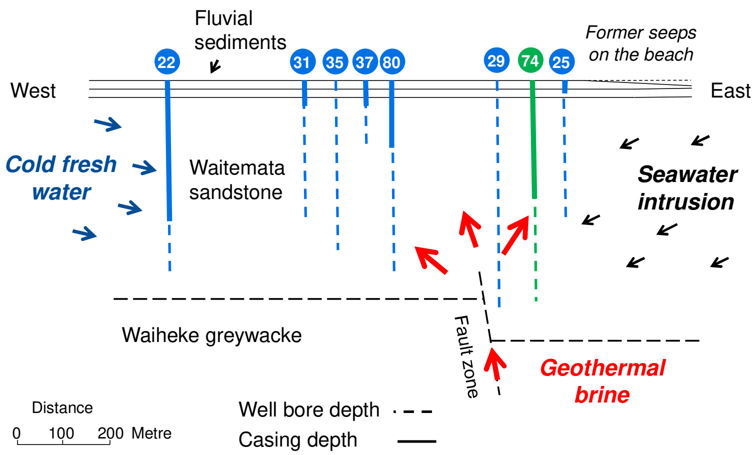

Fig. 1. Conceptual cross section of the geothermal reservoir Waiwera with lithology, well bore locations and depths.

2.2. Data basis

Following the water allocation and management plan [2] abstraction rates from the geothermal reservoir are metred since 1986. Further, regulations demand that the water level in the official observation well of the Auckland Council (74, Fig. 1) is 0.5 m above sea level throughout the year in average. Measurements of the reservoir water level are dating back until 1977 [6]. In that way, almost four decades of data (since 1977 until 2012) are now available [4,5] and are displayed in Fig. 2.

The minimum water level was observed beginning of the 1980s with -1.2 m and the maximum recently with +1.6 m. The higher the production rates from the field are the lower the water level in the observation well is. Highest abstraction rates reached almost 1500 m^3/day and lowest were just above 500 m^3/day (Fig. 2).

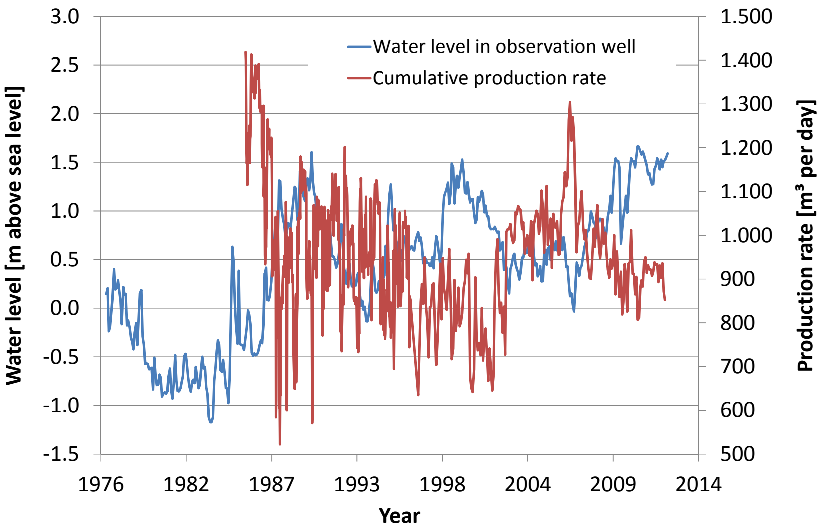

Fig. 2. Abstraction rates from the field with resulting water level in the observation well for the time period 1977-2012.

The metred production rates available for the period 1986 to 2012 [4,5] disclose that most of the water has been pumped from the wells 22, 25, 29, 31, 35, 37 and 80 (Fig. 1). A major change occurred in 1998 when bore 37 was closed and 80 newly drilled and activated as major production well. Within the same context, usage of well 31 has been reduced significantly after 1998. This is the reason why the models, described in the following, were applied on the one hand to the time period 1986-1996 and on the other hand to the years 1998-2012.

2.3. Applied models

We used several models of varying complexity from purely data driven statistical to fully coupled process simulations. They were chosen based on a previous study which compiled the results of all models applied to Waiwera so far [7]. For all three of them at first the available data (Fig. 2) were used for calibration and second the models were then employed for predictive purposes mainly in a retrospective sense.

Univariate regression: The Auckland Council [8] developed this model (Eq. 1) based on the correlation between production rates and measured water levels in the observation well for the period 1986-1991. Underlying principle is the strong and direct anti proportional relationship between the cumulative abstraction rate (in m³/day) from the reservoir and the resulting water level (in m above mean sea level) in bore 74 (Fig. 1).

$$abstraction\ \ rate = \frac{water\ level - 4.22}{-0.00299} \tag{1}$$

Multivariate regression: Chapman [9] performed a time series analysis for the period 1985-1996. The resulting model (Eq. 2) correlates measured water levels in the bore 74 with the production rates (V) of the three major production wells 31, 35 and 37 (all in close proximity to the well 80, Fig. 1). The z values (Eq. 2) take into account a weighted form of the production history of the respective well (Eq. 3).

$$water\,level = -2.85\cdot10^{-3}\cdot V_{35} - 8.78\cdot10^{-4}\cdot z_{35} - 9.82\cdot10^{-4}\cdot V_{31} - 2.18\cdot10^{-4}\cdot z_{31} - 9.75\cdot10^{-4}\cdot V_{37} + 5.66\cdot10^{-4}\cdot z_{37} + 1.64 \tag{2}$$

$$z = \sum_{i=1}^{n}\left[\ln(n+0.5-i)\right]\cdot(V_i - V_{i-1}) \tag{3}$$

Process simulations: Kühn and Stöfen [1] built a three-dimensional numerical model based on available data and the qualitative conceptual understanding of the geothermal reservoir of Waiwera [6]. With the code SHEMAT [10] the quantitative capability of the model was shown. The process simulations take into account fluid flow, heat transfer, species transport and chemical reactions. Compared to the data based models described above it is the most sophisticated one because it takes into account not only the exact location of all seven production wells 22, 25, 29, 31, 35, 37 and 80 but as well bore hole depth and length of the casing.

2.4. Quality assessment

The quality of calibrated models is assessed by comparing their "predictions" (water levels calculated in retrospect based on the metred abstraction rates) for a given set of assumed conditions with observed data. Aim of such a validation process is to demonstrate that a given site-specific model is capable of making "sufficiently accurate" simulations, although "sufficiently accurate" can vary based on project goals [3]. As measure we have used the difference between measured and calculated water levels and the Nash-Sutcliffe efficiency coefficient.

Difference between measured and calculated water level: For each time step we determined the difference between the measured and calculated water level in the observation well of the Auckland Council. From that we deduced the mean of all differences, the respective standard deviation and the maximum value for the time periods 1986-1996 and 1998-2012, respectively.

Nash-Sutcliffe Efficiency: The Nash–Sutcliffe model efficiency (NSE) coefficient [11] is used to assess the predictive power of hydrological models [12]. The NSE (Eq. 4) can range from -∞ to 1. An efficiency of 1 corresponds to a perfect match of modelled discharge (y) to the observed data (x). An efficiency of 0 indicates that the model predictions are as accurate as the mean of the observed data ($\bar{x}$), whereas an efficiency less than 0 occurs when the observed mean is a better predictor than the model. NSE can be used to quantitatively describe the accuracy of model outputs other than discharge as long as there is observed data to compare the model results to.

$$NSE = 1 - \frac{\sum_{i=1}^{n}(x-y)^2}{\sum_{i=1}^{n}(x-\bar{x})^2} \tag{4}$$

3. Results and discussion

With regard to the major change of the production well constellation in 1998 two separate investigation periods were chosen before and after the year when well bore 37 was closed and 80 newly activated. Through well 80 the geothermal water is tapped now from significantly greater depth (Fig. 1). The univariate and multivariate regression models as well as coupled process simulations were applied for the period 1986-1996 and the univariate regression model and the process simulations for the period 1998-2012. Because the univariate regression model is based only on the cumulative abstraction rate of geothermal water from the reservoir it can be applied for both time periods. In contrast the multivariate regression model was deduced for a specific production well constellation [9] and has become obsolete with the implementation of well bore 80. Process simulations based on a three-dimensional geological model can easily be adapted to changed well locations and water production depths. Therefore it has been applied to both time periods under investigation.

3.1. Calculated results for the time period 1986-1996

Fig. 3 shows the calculated water levels of the univariate regression model compared to the actually measured values. The trend of both curves is similar. However, the univariate model overestimates the measured water levels continuously. This would imply that the required water level of 0.5 m above sea level according to the management plan would have been maintained even with higher production rates (Fig. 3). During the years 1991 to 1995 this might have had a negative impact on the geothermal reservoir because the water level in the official observation well went below the demanded limit.

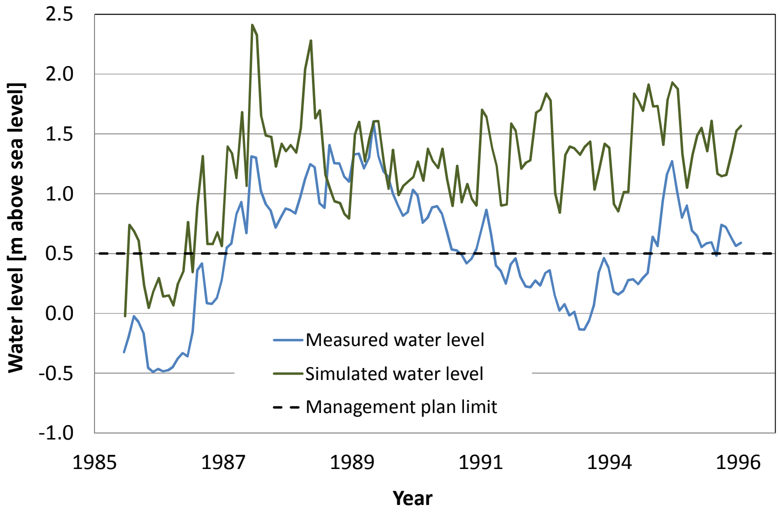

Fig. 3. Measured and simulated water levels for the time period 1986-1996 of the univariate regression model.

Fig. 4 shows the calculated water levels of the multivariate regression model compared to values measured in the observation well. Both graphs are very similar with only small deviations from each other. The quality of the model compared to the univariate regression model is obvious. The comparison outlines very good agreement for the years 1987, 1990-1991 and 1994. Within the year 1989 the model underestimates the measured water level significantly with around 1 m, whereas in 1993 it overestimates it by around 0.5 m.

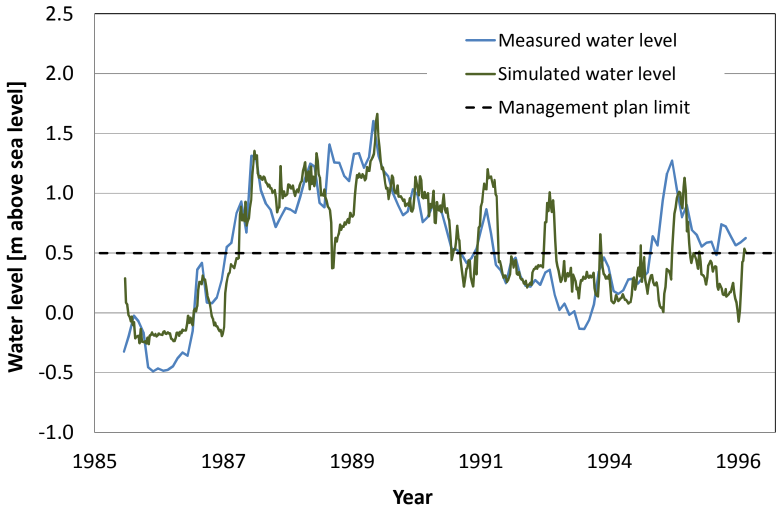

Fig. 4. Measured and simulated water levels for the time period 1986-1996 of the multivariate regression model.

Fig. 5 displays the results of the coupled numerical simulation with SHEMAT for the time period 1986-1996 with only a moderate match between the measured and modelled curves. However, as with the univariate and multivariate regression models, the largest differences occur during the year 1986 and the periods from 1992-1994 and mid-1995. A quite good conformance can be seen within the years 1989-1990. Like the univariate regression model, the coupled numerical simulations overestimate the measured water levels, in this case during the entire time period from 1986-1996. The resolution of the underlying geological model might need further improvement.

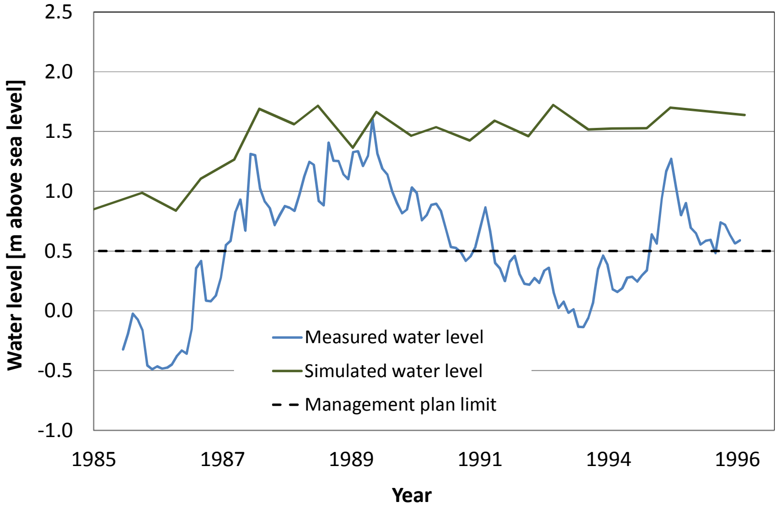

Fig. 5. Measured and simulated water levels for the time period 1986-1996 of the fully coupled process simulation.

The quality assessment of the three models for the time period 1986-1996 is given in Table 1. The numbers underline the visual impression that the multivariate regression model is the most accurate one with a mean difference of only 0.23 m between measured and calculated values and the only one which is able to give a prognosis better than an estimate based on the mean water level with an NSE of 0.64. The univariate model and the fully coupled process simulations show comparable inaccuracy based on the given numbers (Table 1).

Table 1. Quality assessment of the univariate (U) and multivariate (M) regression models as well as the fully coupled process simulations (S) for time periods 1986-1996 and 1998-2012. Given are the means of the differences between measurements and calculations, the respective standard deviations and the maxima as well as the Nash-Sutcliffe efficiency. For the period 1998-2012 process simulations were performed with varying influx of geothermal water from the model base (Fig. 1) with 1000, 1250, 1500 and 1750 m³/day.

Time period	1986-1996			1998-2012				
Model	U	M	S	U	S_{1000}	S_{1250}	S_{1500}	S_{1750}
Mean of differences	0.70	0.23	0.88	0.59	0.75	0.38	0.35	0.49
Standard deviation	0.38	0.18	0.42	0.40	0.47	0.32	0.18	0.32
Maximum difference	1.57	0.89	1.58	1.65	1.63	1.01	0.75	1.11
Nash-Sutcliffe efficiency	-1.60	0.64	-2.97	-1.42	-3.00	-0.30	0.20	-0.80

3.2. Calculated results for the time period 1998-2012

The univariate regression model takes into account the total abstraction rate from the reservoir, without distinguishing between different wells. Therefore, the model can be used for both periods to forecast. Fig. 6 shows the comparison between the calculated and observed data for the time period 1998-2012. The general trend of both graphs again is very similar but, as before, for the entire period the calculated values overestimate the observations. This is particularly evident in 1998 and the period from 2001-2005.

Results of the process simulations with SHEMAT are given in Fig. 7 for the time period 1998-2012. It is the model with the most realistic implementation of production wells 22, 25, 29, 31, 35 and 80 with regard to location as well as depth and length of the casing (Fig. 1). The inflow of the geothermal brine at the base of the reservoir is not yet clearly understood [1,6]. Therefore a parameter study was performed and the influx adopted with 1000, 1250, 1500 and 1750 m³/day. It can be seen that the different fluxes produce exactly the same shape of water level curves which are solely a parallel translation of each other.

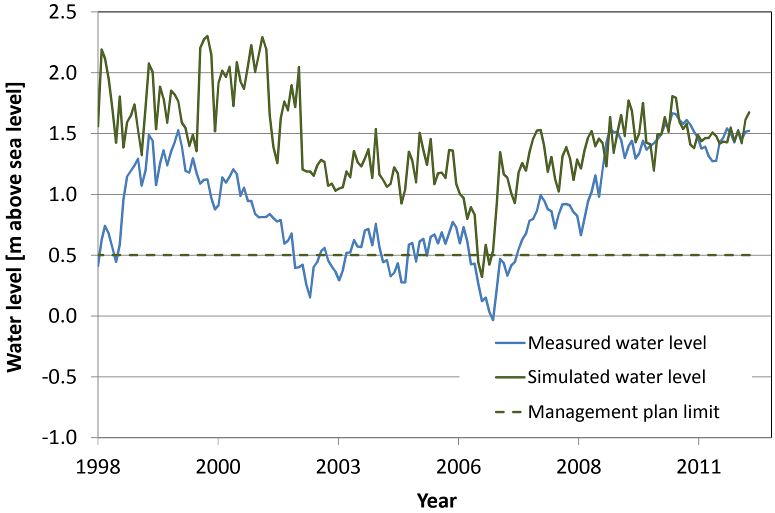

Fig. 6. Measured and simulated water levels for the time period 1998-2012 of the univariate regression model.

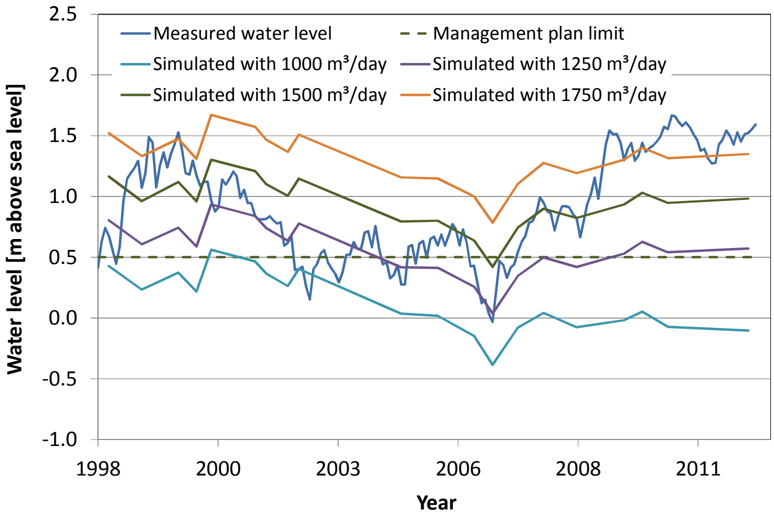

Fig. 7. Measured and simulated water levels for the time period 1998-2012 of the fully coupled process simulations with a scenario analysis about the geothermal inflow rate from the base of the model (Fig. 1).

For the parameter study it is visually not possible to decide which the most accurate case is. However, the quality indices in Table 1 clearly indicate that an inflow rate of 1500 m³/day from the base of the reservoir produces the most accurate model compared to the measured values. The mean of the differences between measurements and calculations is 0.38 m with a standard deviation of 0.18 m. The maximum difference is well below 1 m and the Nash-Sutcliffe efficiency is positive with 0.2. The quality of the model is by far better than the univariate regression model for the period 1998-2012 and almost as good as the multivariate regression model for the period 1986-1996.

4. Conclusions

Management tools are required to regulate water abstraction and ensure sustainable reservoir utilization. Our results show that data driven models, which are based on experience (monitoring), can provide better prognoses than process based simulations because their calibration with water production rates from and resulting water levels in the reservoir can be done with higher accuracy. This is proven by a quantitative quality assessment based on the deviation between monitoring data and modelling results. The multivariate regression model provides significantly better results than the univariate version. Advantages of data based models are their accuracy and robustness. In that way they are suitable to implement conservation programs. However, disadvantage is that they are “black box” and do not tell us anything about system inherent processes. In case significant changes occur, like newly installed major production wells as was the case at Waiwera, they have to be deduced anew. In contrast, three-dimensional fully coupled process simulations are more flexible and the only tool to study processes within the geothermal system as shown for the scenario analysis regarding the base flux of geothermal brine into the reservoir. The quality of a three-dimensional model requires a lot of spatially resolved information, which sometimes are not available. The most suitable model for the period 1986-1996 is the multivariate regression model and the process simulation model for the period 1998-2012. Both show the same standard deviation in the difference between measured and calculated values (Table 1). The multivariate model provides the better mean of the differences and a higher Nash-Sutcliffe efficiency whereas the process simulation model produces the smallest maximum deviation.

Our recommendation for the full implementation of the water allocation and management plan is the revision of the existing multivariate regression model which provides the best water level estimates. Further, we suggest improving the underlying geological model used for the process simulations to provide a more flexible tool for future and prospective scenarios which cannot be covered by data driven models [13].

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