



# Onehunga Aquifer Contamination

RESOURCE CONSENT PROJECT

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## Why?

The Onehunga Aquifer has been a significant source of water in the Auckland region, providing up to 20 million litres per day since the year 2000. However, due to the growing drought in the Auckland region, Watercare has proposed to increase the water extraction from the aquifer to satisfy increased demands. There are potential environmental impacts concerned with this proposal:

- Pressure decline in the aquifer: As the rate of water extraction increases, the pressure in the aquifer decreases as water flows across the aquifer under a pressure gradient.
- Contamination of water: Contaminants, such as copper, dissolve into stormwater at the surface and then leaches down to pressure lows in ground water. The contamination correlates to the pressure decline as a result of increased water extraction. Water extracted can therefore be unsafe to drink if the level of copper exceeds a certain threshold.

Watercare have applied to the Auckland Regional Council (ARC) for resource consent to double their maximum take from its current limit of 20 million litres per day. Auckland Regional Council, the regional authority, approves or declines the consent application after hearing the views from the following affected stakeholders:

- Ngāti Whātua, the local Iwi. Their priority is ecosystem restoration and sustainable harvest of Mahinga Kai – which relates to the traditional value of food resources, as well as the practices involved in producing these resources.
- Watercare, the Auckland Council Organisation that manages drinking, storm, and wastewater within the city. Their primary concern is to maximize the water uptake from the aquifer to meet increasing demands from the city.
- Auckland residents. The residents are in demand for safe drinking water.

The Auckland Regional Council wish to obtain a recommendation before supporting or opposing Watercare's consent application. Possible outcomes of the consent hearing include:

- Consent application is approved, and water extraction is doubled from 20 million litres per day to 40 million litres.
- Consent application is approved, but the water extraction level is reduced to a recommended safe level.
- Consent application is turned down, and no change to the water extraction is made.
- Consent application is turned down, and indefinite moratorium on aquifer usage.

## How?

A computer model can be constructed to capture the water flow through the aquifer. This will allow us to understand how the pressure and concentration of copper will change depending on various water extraction rates.

We expect to get quantitative insights from this model. By modelling and visualising the data of how the concentration of copper and pressure in the aquifer behaves with different volumes of fluid flow through the control volume, we can formulate a mathematical relationship between the two. This model can then be used to predict changes in pressure and concentration in the future.

The model will provide insight in determining how much water can be extracted while maintaining a safe concentration of copper in the water and meeting the increased demand for water.

## Given?

One approach to model an aquifer model is to run a simulation. The aquifer system is defined by a set of differential equations, and the parameters embedded in the differential equations are determined from observations of system input and output. This mathematical process is referred to as 'parameter identification' (Bobba & Singh, 1995).

Another approach is to use a lumped parameter model. The first geothermal models were modelled this way. A lumped parameter model allows us to capture a system and treat it as a single control volume and analyze the pressure changes in response to varying fluid extraction (Fradkin et al., 1981). The model can be represented with a set of ordinary differential equations that can be solved numerically, and the parameters calibrated by computational means.

Using a lumped parameter model is the preferred approach in modelling the aquifer, as we can treat it as a single control volume. The model formulation will solve for copper concentration and pressure changes in response to varying water extraction rates. Previous experimental data has been given to us to assist in the modelling, and these include yearly extraction rates, pressure in the aquifer, and copper concentration level in the water – all starting from the year 1980. The data is plotted in figure 1.

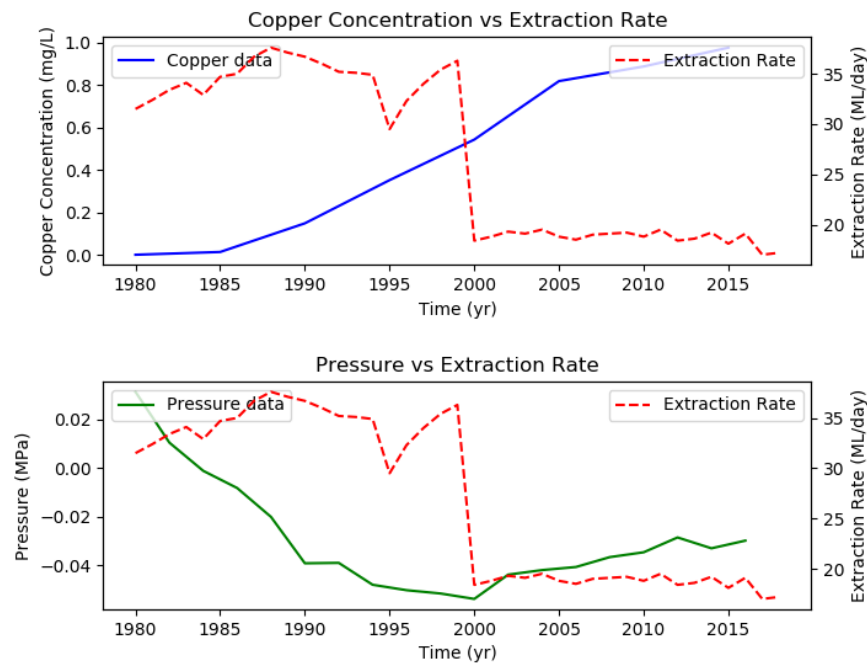


Figure 1: Copper concentration with extraction rate (above), pressure with extraction rate (below).

There is a negatively correlated relationship between water extraction and pressure. The increased water extraction during the early years reflected a steady pressure drop. The reduction of water extraction beginning in 2000 sees a slow but steady recovery of pressure in the aquifer. Following the decreased volume of extraction in 2000, we see a reduction in the rate of increase in copper concentration. However, the effect is currently insufficient, and the rate of change of copper concentration in the aquifer remains positive. We can assume that a higher pressure is required for a reversal of copper concentration in the aquifer.

Research shows that the concentration of copper in water should be about 2.0 mg/litre to be safe to drink (Donohue, 2004). We will use this as a measure in recommending future water extraction rates.

#### References:

Bobba A.G., Singh V.P. (1995) Groundwater contamination modelling. In: Singh V.P. (eds) *Environmental Hydrology. Water Science and Technology Library*, vol 15. Springer, Dordrecht.

Donohue, J (2004). *Copper in Drinking-water*. WHO

Fradkin, LJ, ML Storey, & A McNabb, (1981). "On Identification and Validation of Some Geothermal Models", *Water Resources Research*, 17, 929-936.

## Assume?

The relevant physics and laws to the aquifer model are:

- Conservation of mass: Governs the changes in fluid pressure. The relevant constitutive law is Darcy's law, which will be used to derive a pressure differential equation.
- Conservation of energy: Governs the changes in temperature of the fluid and the aquifer. The relevant constitutive law is Fourier's law of heat transfer.
- Conservation of chemical species: Governs the changes in concentration of chemical species in the fluid. The relevant constitutive law is Fick's law of diffusion.

The main concern for this model is the concentration of copper and the pressure of the aquifer. The concentration will affect the safety of the water supplied to local residents, and the change is directly related to the pressure levels of the aquifer. Therefore, for this model, we will neglect conservation of energy.

We will also neglect the conservation of chemical species, as we are not interested in any other chemical species in the water other than copper. We are not interested in the diffusive movement of copper, but rather how much copper is accumulated as a result of being drawn to the pressure low region, which is governed by the conservation of mass. The pressure will be modelled using a Lumped Parameter Model, and the concentration of copper will be derived with respect to pressure. Hence this model will be a coupled model.

The spatial domain of our lumped parameter model will be the single control volume of the aquifer. The time domain of the model will be from the year 1980 (when the data was first recorded) until 2018 and is extended 32 years to predict different future scenarios up to the year 2050. The initial conditions of pressure, extraction rate, and concentration are given by the first entry of the experimental data recorded in 1980. The strength of adjacent recharge flows from low and high pressure boundaries are also taken into account, and effectively act as boundary conditions. The strength of the recharge is unknown and must be calibrated to be determined.

The conceptual model sketch is shown in figure 2.

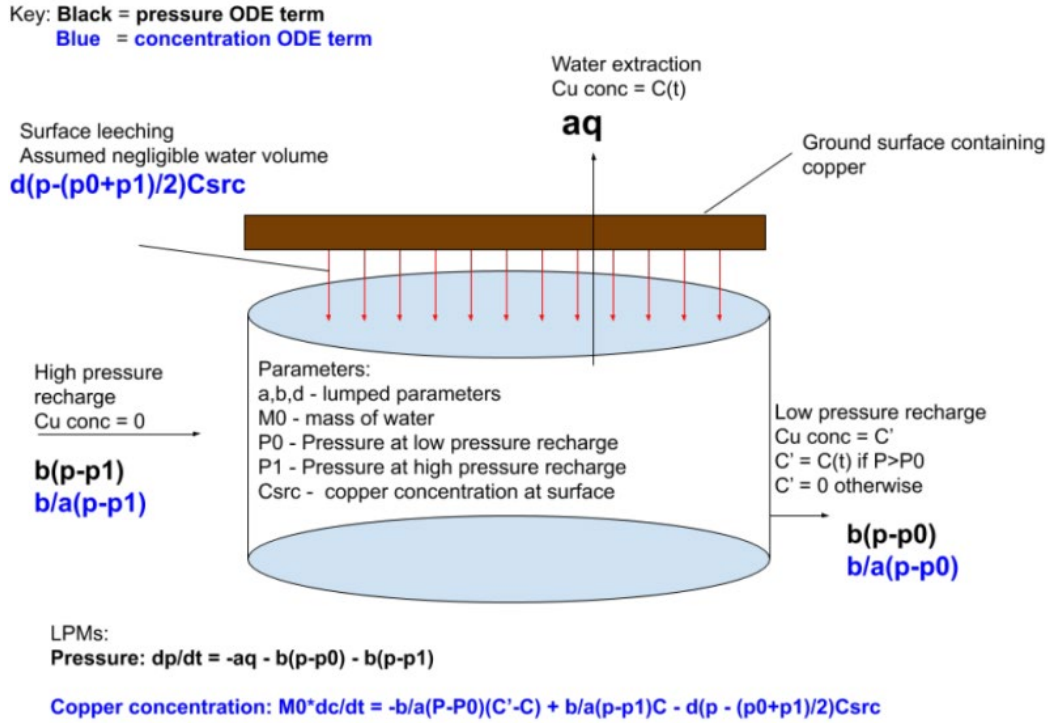


Figure 2: Conceptual model illustration of the aquifer model. Key parameters are listed.

## Formulate?

From Darcy's law, the pressure differential equation is as follows:

$$\frac{dp}{dt} = -aq - b(p - p_0) - b(p - p_1)$$

Rewriting the conservation of copper mass, the concentration differential equation is:

$$M_0 \left( \frac{dc}{dt} \right) = -\frac{b}{a}(p - p_0)(C'' - C) + \frac{b}{a}(p - p_1)C - d \left( P - \frac{p_0 + p_1}{2} \right) C_{src}$$

$$\text{where } C'' = \begin{cases} C(t), & p > p_0 \\ 0, & \text{otherwise} \end{cases}$$

$p$  is the aquifer pressure,  $q$  is the extraction rate,  $p_0$  is the pressure at the low pressure boundary,  $p_1$  is the pressure at the high pressure boundary,  $M_0$  is the total system mass,  $C$  is the concentration of copper, and  $C_{src}$  is the concentration of the source. Since concentration depends on the direction of water flow,  $C''$  is a concentration term that depends on the pressure relative to the low-pressure boundary.  $a$ ,  $b$ , and  $d$  are lumped parameters that are dependent on the system's physical parameters.  $a$  resembles the source strength and  $b$  resembles the strength of the recharge.

$$a = \frac{g}{A\varphi} \quad b = \frac{gk\rho A_{rchrg}}{A\varphi\mu L} \quad d = \frac{b_{src}}{a_{src}}$$

$g$  is the Earth's gravitational constant,  $A$  is the cross sectional area of the aquifer,  $\varphi$  is the porosity,  $k$  is the permeability of water flow through the aquifer,  $\rho$  is the density of water,  $A_{rchrg}$  is the area of recharge,  $\mu$  is the viscosity of water, and  $L$  is the length of flow by the contaminant.

The analytical solution to pressure is obtained by treating  $q(t)$  as a constant, i.e.  $q(t) = q_0$ . Then treating the initial pressure to equal what is given in the experimental data,  $p(0) = 0.0313\text{MPa}$ , we obtain:

$$p(t) = -\frac{aq_0}{2b} + \left(\frac{aq_0}{2b} + 0.0313 - \frac{p_0 + p_1}{2}\right)e^{-2bt} + \frac{p_0 + p_1}{2}$$

As for concentration, we set  $b = 0$ ,  $q(t) = q_0$  then obtain:

$$c(t) = \frac{dC_{src}aq_0t^2}{2M} + c(0)$$

The differential equation is then numerically solved using improved Euler's method using the extraction rates given. This was conducted in python and is implemented in *project\_functions.py* and is run on the main script *main.py*.

## Working?

The code which numerically solves the differential equations using improved Euler's method were tested against critical unit tests that are implemented in *unit\_test.py*. The solutions to the tests were all checked by hand and online sources.

The numerical solution of pressure and concentration was benchmarked against their analytical solution. Extraction rate was set as a constant, and guess parameters were used. The benchmarking is also implemented in *unit\_test.py* and returns the plot shown in figure 3.



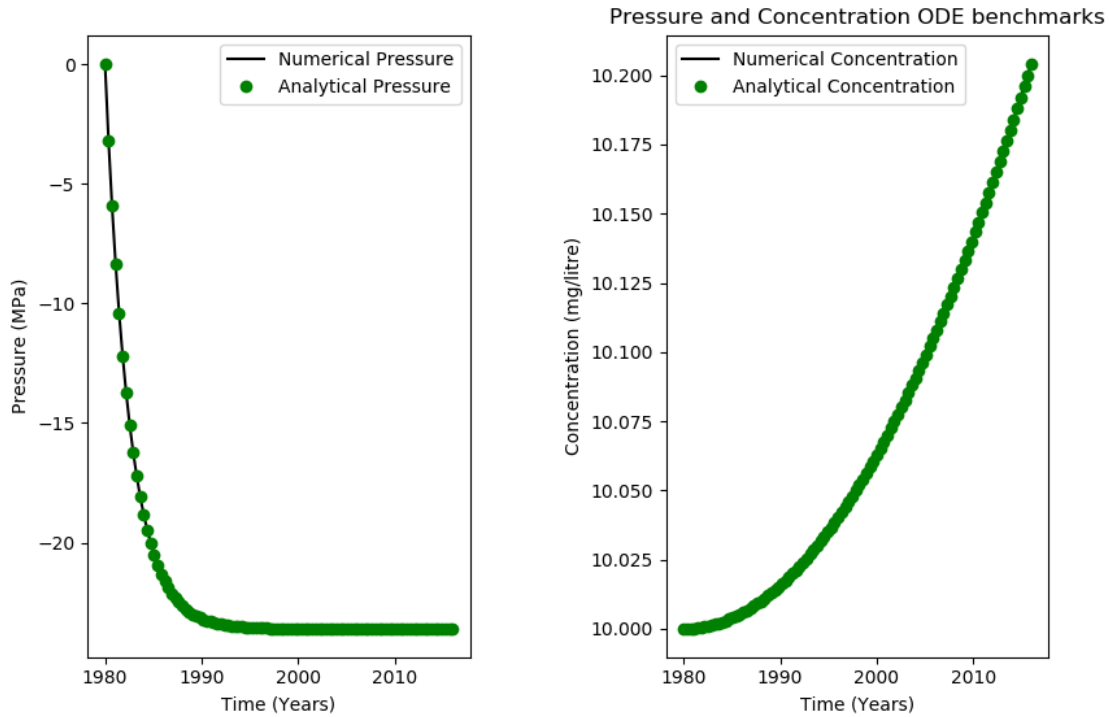


Figure 3: Comparison of numerical solution to the analytical solution given a constant extraction rate. Pressure (left) and concentration (right)

## Suitable?

The lumped parameter model was then automatically calibrated using Python's built in `curve_fit` function. There were a total of 7 parameters to calibrate. Out of these 7 parameters, three of them are independent to the pressure. Therefore, when the model was fitted to the pressure with some guess parameters, only four of these parameters would be calibrated and the other three unchanged. We used the parameters obtained as guess parameters to fit the model to concentration, while fixing the already calibrated parameters with a lower and upper bound. The parameters turned out to be:  $[0.025, 0.054, 0.3, 50000, 48436, -48436, 81]$  ( $[a, b, d, Mo, Po, P_1, C_{src}]$  respectively). The best fit plot is shown on figure 4.



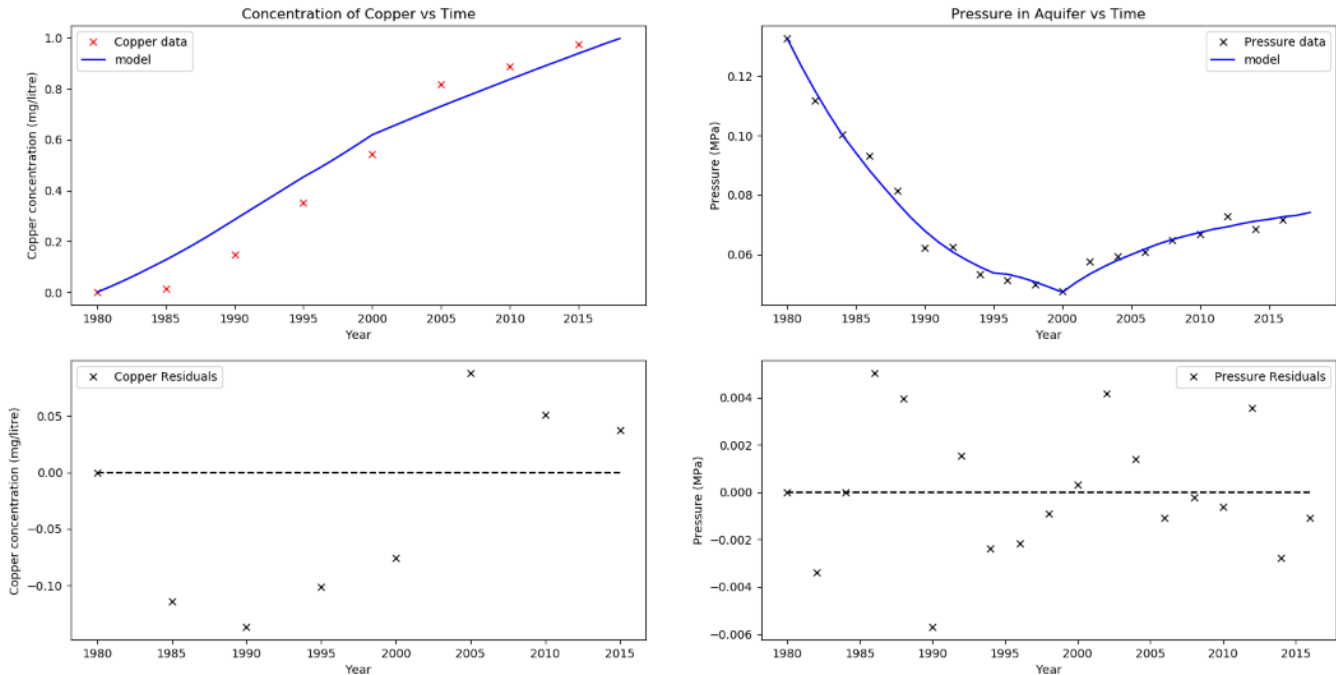


Figure 4: Best fit model of pressure and concentration (above) and misfit plot respectively (below)

The residual plots look consistent and small. There is a misfit correlated in time due to the experimental inaccuracies when measuring values, in particular, the concentration. Concentration can vary within the aquifer, so the sample used to test the concentration will have a fair amount of uncertainty.

## Improve?

Although the best fit model did come out reasonable, the fit to the concentration data could be improved. We can also see from the calibrated parameters that  $P_1$  is the negative of  $P_0$ , which first does not make physical sense and second, it is not consistent with the assumption that all pressures are positive. We had to find another method of automatically calibrating all the 7 parameters, and so we made the following improvements.

- In the differential equation for pressure, we rewrote the equation and introduced a new variable that takes in the sum of  $p_0$  and  $p_1$ .

$$\frac{dp}{dt} = -aq - 2bp + bp_{sum}, \text{ where } p_{sum} = p_0 + p_1$$

This was done to minimise the number of parameters the system had to calibrate, and to cause less confusion within the calibrating function. The same principle was applied to the concentration equation. The product of  $d$  and  $C_{src}$  were combined into one parameter,  $d_c$ .

$$M_0 \left( \frac{dc}{dt} \right) = -\frac{b}{a}(p - p_0)(C'' - C) + \frac{b}{a}(p - (p_{sum} - p_0))C - d_c \left( P - \frac{p_{sum}}{2} \right)$$

- Now with the rewritten equations, we have a total of 6 parameters to calibrate. We implemented further adjustments to our approach to calibration. As only three of these 6 parameters were dependent to the concentration, we replicated our concentration function so that it only takes in the three dependent parameters, meaning that the three pressure dependent parameters would be left unchanged. This was achieved by using Python's *lambda* and *partial* function.

The 6 parameters were first automatically calibrated by fitting to the pressure data with some initial guess parameters. This left us with 3 of the 6 parameters being calibrated, them being  $a, b, p_{sum}$ . The remaining three parameters  $p_0, M_0, d_c$  were automatically calibrated by fitting it to the concentration data using the new concentration function. The new parameters obtained were [0.00029, 0.054, 1300, 2200, 0.053, 0] ( $[a, b, d, M_0, P_{sum}, P_0]$  respectively). The new best fit model and misfit plot is shown in figure 5.

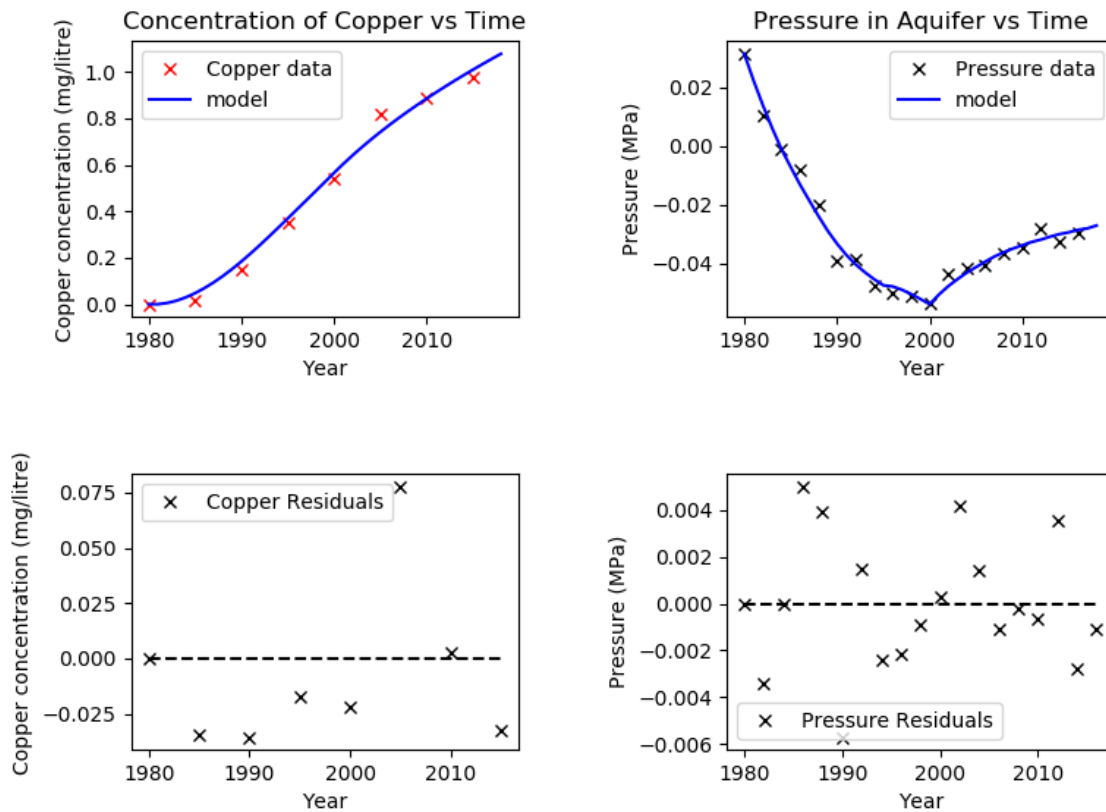


Figure 5: New best fit model of pressure and concentration (above) and misfit plot respectively (below)

Compared to figure 4, the fit has been improved for the concentration model. We can confirm that this is the improved model as our parameters have changed to make more physical sense, with no negative values.

## Use?

With the improved model, we will use it to make predictions of the four possible discussed consent outcomes:

- No change to the water extraction (20 ML/day)
- Doubled extraction (40 ML/day)
- Reduced consent
- Indefinite moratorium

The predictions (excluding reduced consent) are all shown on figure 6 below. The dotted line at 2.0mg/litre indicates the safe concentration limit of copper. The plot predicts 32 years into the future from the last year of given data, i.e. until the year 2050.

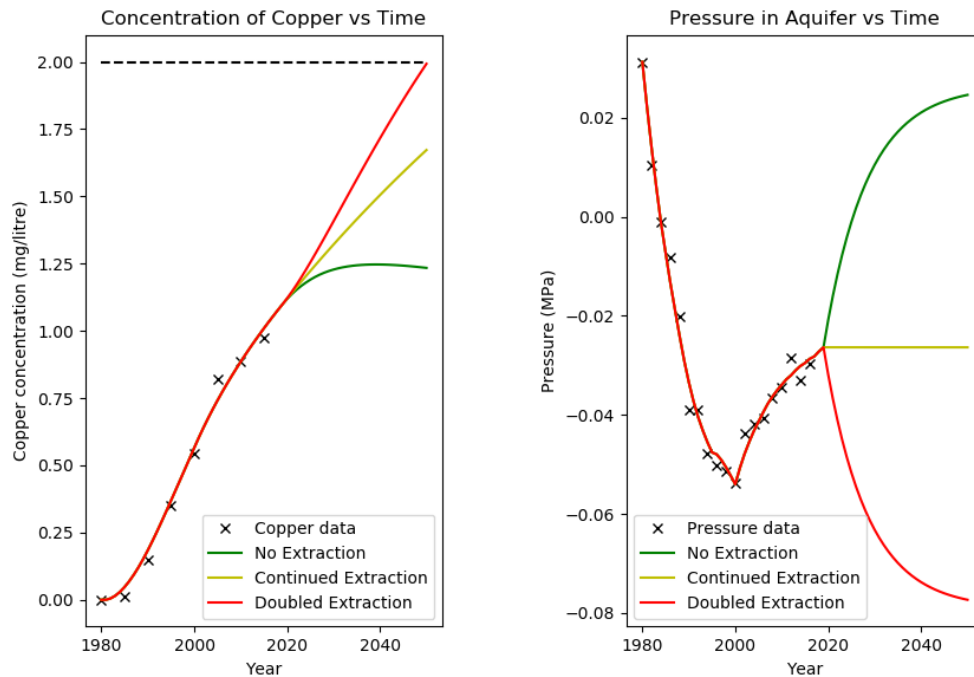


Figure 6: Scenario modelling for 3 cases. No extraction (green), continued extraction at 20ML/day (yellow), and doubled extraction at max 40ML/day (red)

It is observed that continued and no extraction will be safe to proceed for the next 30 years, reaching copper concentrations of 1.675 and 1.2mg/litre respectively by the year 2050, and this directly correlates to the stabilization of pressure for no extraction and no pressure change for continued 20ML/day extraction. However, for the case of doubled extraction, the concentration meets the 2.0mg/litre limit by the year 2050. This suggests that doubling the extraction may threaten safety concerns in the future.

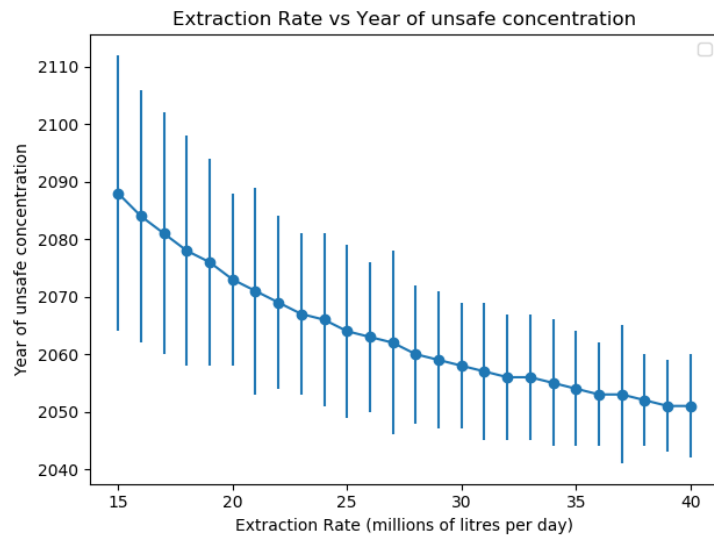


Figure 7: Years of unsafe concentration against varying extraction rates, with error bars of 90% CI.

## Unknown?

The model is not 100% accurate, which means we will sample a range of parameters to consider the uncertainty in the model. This was implemented by taking the covariance matrix output from *curve\_fit* and the 6 calibrated parameters to create a sample of 100 fitting models from the posterior using the *numpy.random.multi\_variate* function. These samples were then plotted and shown in figure 8.

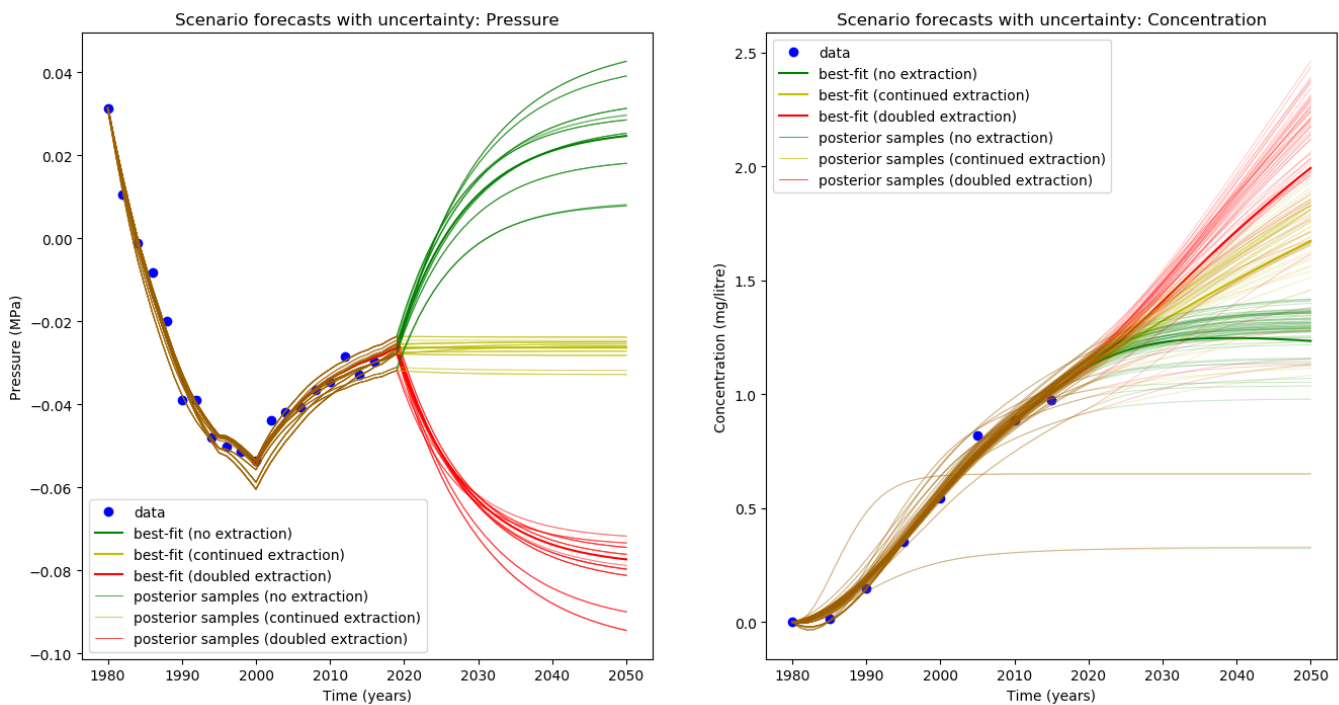


Figure 8: Scenario forecasts with 100 samples of model parameters. Pressure (left) and concentration (right).

The 95% confidence interval for the concentration levels by the end of 2050 for the above scenarios are [1.17, 1.28], [1.47, 1.68], [1.84, 2.12] respectively for no extraction, continued 20ML/day extraction, and doubled extraction.

A shortcoming identified in this model is the effect of other chemical species that may be a contaminant present at the surface of the water. Depending on the type of environment that surrounds the aquifer, level of contaminants other than copper could be present which increases the risk of unsafe water. The current model only accounts for the presence of copper as a contaminant. In addition, the model neglects any temperature changes. Temperature changes may affect the quality of water as it would trigger changes in physical, chemical, and microbial processes in the subsurface environment (Saito et al., 2016).

*Reference: Saito T, Shoichiro H, Ueki T, Ohkubo S, Moldrup P, Kawamoto K & Komatsu T, (2016). "Temperature change affected groundwater quality in a confined marine aquifer during long-term heating and cooling", Water Research, 94, 120-127.*

## Recommend?

Pressure and concentration changes in the Onehunga aquifer have been modelled over a thirty-year period and subject to four different consent outcomes. Two of these (No extraction and continued extraction at 20ML/day) maintained a concentration below the safe limit by the year 2050. Reducing the consent resulted in a later unsafe year of contamination and doubling the extraction rate to 40ML/day would result in a possible contamination by the year 2050.

If the ideal objective is to maintain the safety of the drinking water and meet increased demands, we would recommend to reduce the consent, and let the regional authority to decide which extraction rate is suitable by referring to the plot of unsafe years in figure 8. This recommendation is reliable given the uncertainty in the concentration data. Incorporating this in the analysis suggests that it is almost minimal for extraction rates below 40ML/day to exceed 2.0mg/litre of copper by the year 2050.

This forecast however, is specific to and only valid with the above scenario. Any deviations from this scenario such as the presence of other contaminants may invalidate the forecast. Moreover, the model does not account for the change in water quality as a result of temperature change. Therefore, it would be sensible to consider the effects of temperature change and the presence of other chemical species in future studies.