Thermal Recovery of Bitumen from West Coast tar sands

1. Why?

In 2018, the extraction of bitumen from West Coast tar sands was banned due to environmental implications that would come as result of this, such as the leaching of toxins into groundwater. Due to the economy failing as a result of a pandemic, a study has been conducted to assess whether it is safe to undergo further projects for the applicant requesting this information.

This project will provide a recommendation to the applicant in their resource consent application on whether it is safe to keep extracting bitumen from West Coast tar sands or that these processes should end effective immediately. The relevant regional authority, in this case being the West Coast Regional Council will hear proposals from the affected stakeholders before approving or declining the consent application. These stakeholders being:

- Todd Energy, who see this as a potential market that will enable them to profit considerably due to the mass pumping of steam in the process of bitumen recovery.
- Ngai Tahu, who are also interested in the profit that can be acquired via bitumen extraction.
- New Zealand Transport Agency, who believe that by extracting bitumen locally instead of importing from Canada, our nations interests would better be protected.
- Greenpeace, who want to maintain environmental stability in our nation, by limiting the potential leaching of mass toxic organics into groundwater.
- Local Farmers, who are also concerned about the implications that the leaching of toxic organics into groundwater will have on their farms and ability to farm.

The possible outcomes of the consent application process include:

- Consent application is denied and thermal activities in the West Coast must stop immediately.
- Consent application is accepted, and the thermal activities (steam injection) in the West Coast may continue at the same rate.
- Consent application is accepted, and the thermal activities (steam injection) in the West Coast may continue at half the rate.
- Consent application is accepted, and the thermal activities (steam injection) in the West Coast may continue at the double rate.

2. How?

We will be using a computer model to understand how the changes in operation of a thermal system affect its pressure and temperature. The economics of the different possible outcomes will be considered out of scope for this report. From the model, we would expect to learn about the effects of the operations and how we can estimate pressure and temperature appropriately in a system. The model will provide insight to how safe it is to undergo further operations, taking into consideration the temperature point that may cause leaching of toxic organics into groundwater.

3. Given?

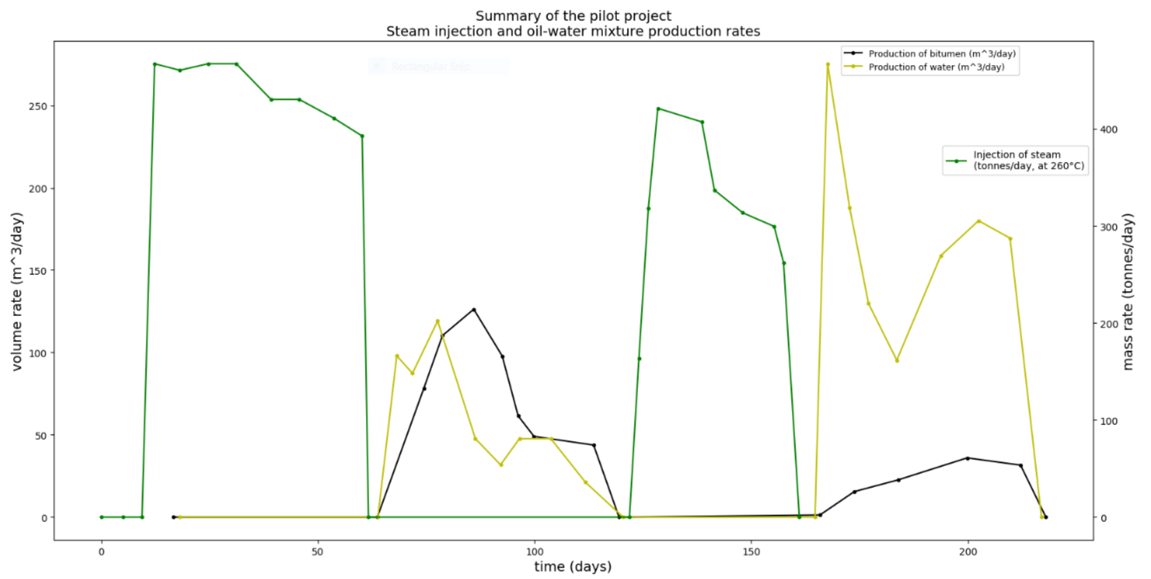


Figure 1: The production rates of Bitumen (black), and water (yellow), and the steam injection rate (green).

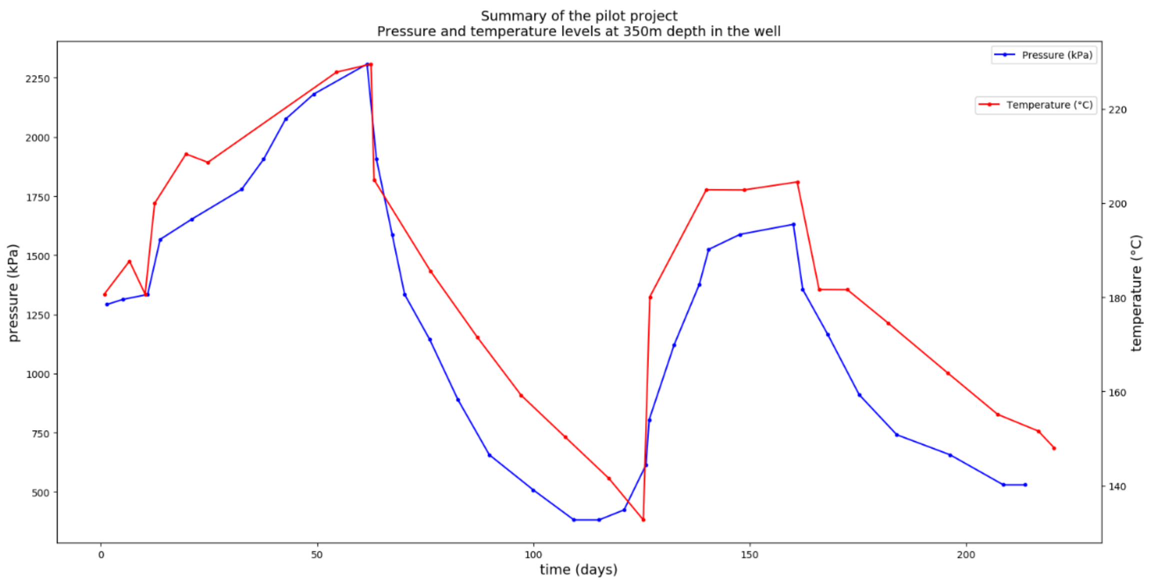


Figure 2: The change in pressure and temperature in the well at 350m depth over time.

The pilot study consists of two separate cycles of steam injection at 260°C, this can be seen on Figure 1 as two separate peaks. The rate of steam injection seems to peak at a rate of just above 400 tonnes/day. The production rates of oil and water seem to peak around similar times, this is when there is no steam being injected, allowing for the extraction of the oil-water mix.

The pressure and temperature levels at 350m depth in the well seem to take similar shapes in the pilot study, this is seen especially in the peaks and troughs occurring around the same time. We can see that during steam injection periods (at 260 degrees C), both pressure and temperature tend to increase, whereas when steam injection halts, the pressure and temperature levels started to decrease. Due to the temperature decreasing the steam cools down when steam injection halts, this causes water to be produced and extracted along with oil (condensation of steam). This explains the large production/extraction of water towards the end of the pilot study.

4. Assume?

In the project the relevant physical theories to be used include:

Fluid Mechanics – pressure mass flow (Conservation of mass, Darcy's law)
Thermodynamics – temperature heat flow (Conservation of energy, Fourier's law).
(Both physical theories are related to the injection of steam into the system).

An LPM model will be used to best study the changes in pressure and temperature within the defined control volume. We have defined the region of space where our model is valid as being from surface, to the bottom of the hole, where the surface is the point of steam-injection. This region of space has been defined this way to remove potential errors that we may encounter to our boundary and initial conditions due to unusual underground circumstances. Thus, the physical processes that we have considered are associated with mass entering and leaving the defined control volume.

The physical processes to be considered in the study:

· Steam injection into the system (displayed as a net mass flow rate)
· Bitumen and water extraction (displayed as a net mass flow rate)
· Well recharge by surrounding water
· The potential leaching of toxic organics into groundwater (when temperature exceeds 240°C)

Physical processes to be excluded in the study:
· Ideal gas law, which assumes the effect of temperature on pressure and density is negligible.

The given data from the pilot study starts in March 2021 and ends in December 2021. The data will then be extrapolated beyond June 2022 until the 2 repeated cycles reach equilibrium. We will assume that the following parameters remain constant in the control volume: porosity, density, dynamic viscosity, permeability, and cross-sectional area.

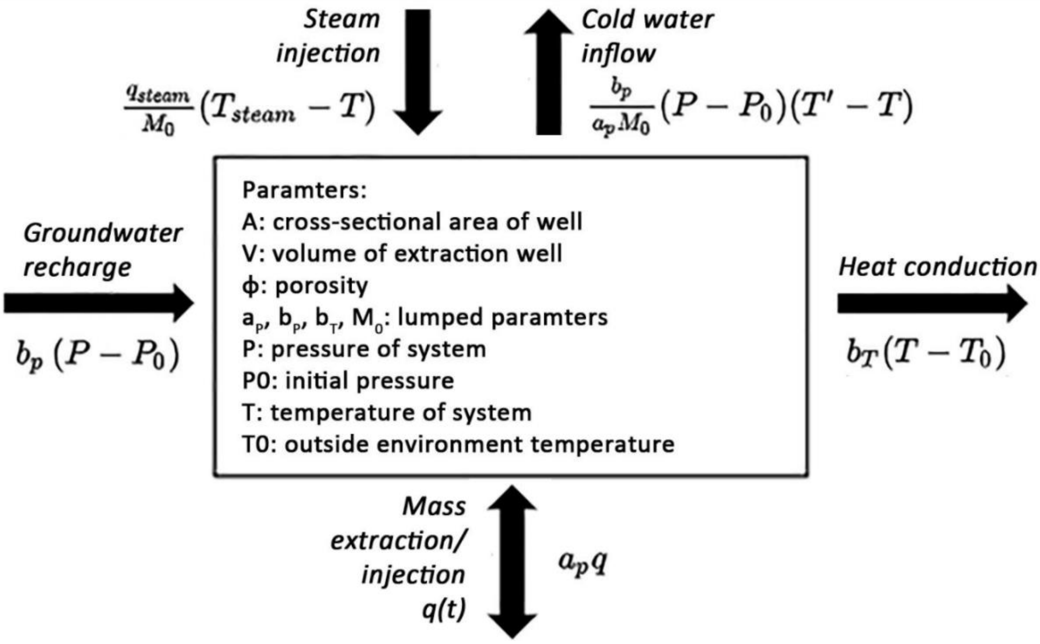


Figure 3: Schematic illustration of the thermal recovery project's LPM.

5. Formulate?

These are the differential equations describing our system. For the pressure differential equation, P is the pressure of steam, P_0 being its initial pressure (atmospheric pressure), q is the mass extraction rate, g is gravity acceleration, A, ø, k, L are, respectively, the cross-sectional area of the well, porosity, permeability and length, µ and p are the viscosity and density of the liquid and a_p and b_p are lumped parameters that depend on the physical parameters of the system.

$$a_p = \frac{g}{A\phi} \qquad b_p = \frac{g}{A\phi}\left(\frac{kpA_{rchg}}{\mu L}\right) \qquad b_t = \frac{\Upsilon}{pcV}$$

$$\frac{dP}{dt} = \underbrace{-a_p q}_{\text{extraction/ injection}} \underbrace{- b_p (P - P_0)}_{\text{recharge}}, \qquad q = q_{water} + q_{oil} - q_{steam}$$

$$\frac{dT}{dt} = \underbrace{\frac{q_{steam}}{M_0}(T_{steam} - T)}_{\text{steam injection}} - \underbrace{\frac{b_p}{a_p M_0}(P - P_0)(T' - T)}_{\text{cold water inflow}} - \underbrace{b_T(T - T_0)}_{\text{conduction}}, \qquad \underbrace{T' = \begin{cases} T(t) & \text{if } P > P_0 \\ T_0 & \text{otherwise} \end{cases}}_{\text{temperature depends on direction of flow}}$$

For the temperature differential equation, q_{steam} is the steam injection rate in the system, M_0 is the total mass in the system (assumed to be same as initial mass in system), T_{steam}, T and T_0 are, respectively, the temperature of steam, temperature of the system, and initial temperature, c, V, ϒ are, respectively, the specific heat capacity, volume and the heat transfer coefficient, b_t is a lumped parameter that depends on the physical parameters of the system.

The pressure analytical solution obtained to the equation was done for constant production, where q(t) = q (constant). Where the analytical solution can be seen in the formula below. The solution heads towards steady states as e goes to 0, causing $P = P_0 - a_p q / b_p$. Using the improved Euler method, numerically the equation was solved for an arbitrary q(t) array which can be seen in the project_functions.py file.

The temperature analytical solution for the equations was also obtained for constant production where q(t) = q (constant). The analytical solution can be seen in the formula below. Numerically we solved the equation using the improved Euler method, for an arbitrary q(t) array which can also be found in the project_functions.py file.

$$\frac{dP}{dt} = -a_p q - b_p (P - P_0), \qquad P = \frac{-a_p q}{b_p}\left(1 - e^{-b_p t}\right) + P_0$$

$$\frac{dT}{dt} = \frac{q_s}{M_0}(T_s - T) - \frac{b_p}{a_p M_0}(P - P_0)(T' - T) - b_t(T - T_0),$$

$$T = \frac{\frac{q_s}{M_0} e^{-t\left(\frac{q_s}{M_0} - \frac{b_p}{a_p M_0}(P - P_0) + b_t\right)} \times \left(T_s\left(e^{t\left(\frac{q_s}{M_0} - \frac{b_p}{a_p M_0}(P - P_0) + b_t\right)} - 1\right) + T_0\right) + T_0\left(b_t - \frac{b_p}{a_p M_0}(P - P_0)\right)}{\left(\frac{q_s}{M_0} - \frac{b_p}{a_p M_0}(P - P_0) + b_t\right)}$$

6. Working?

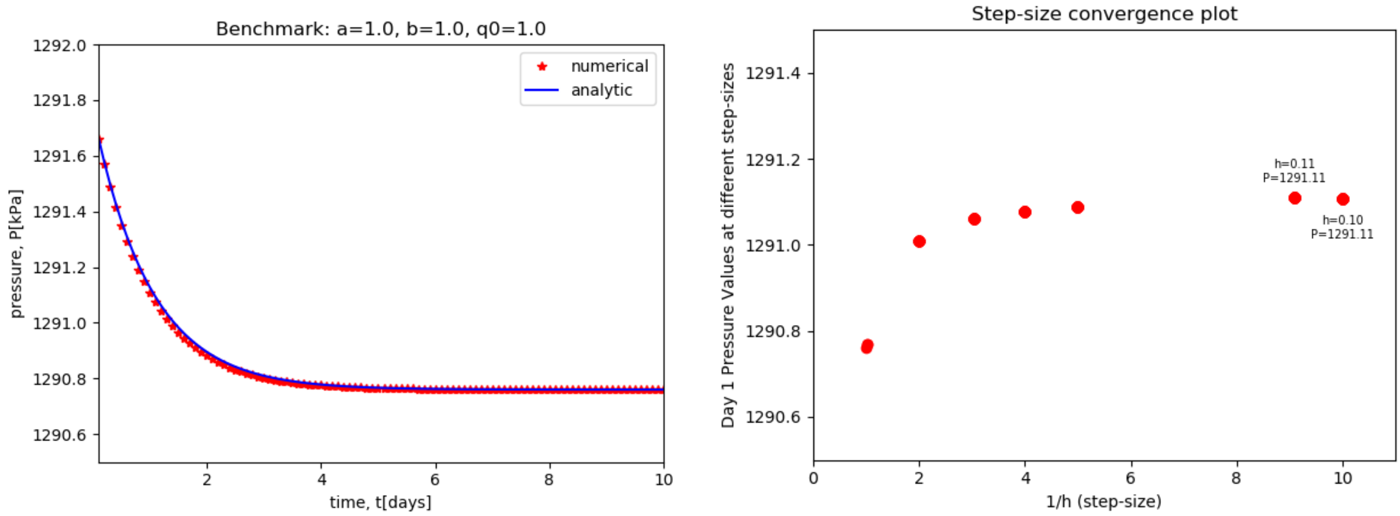
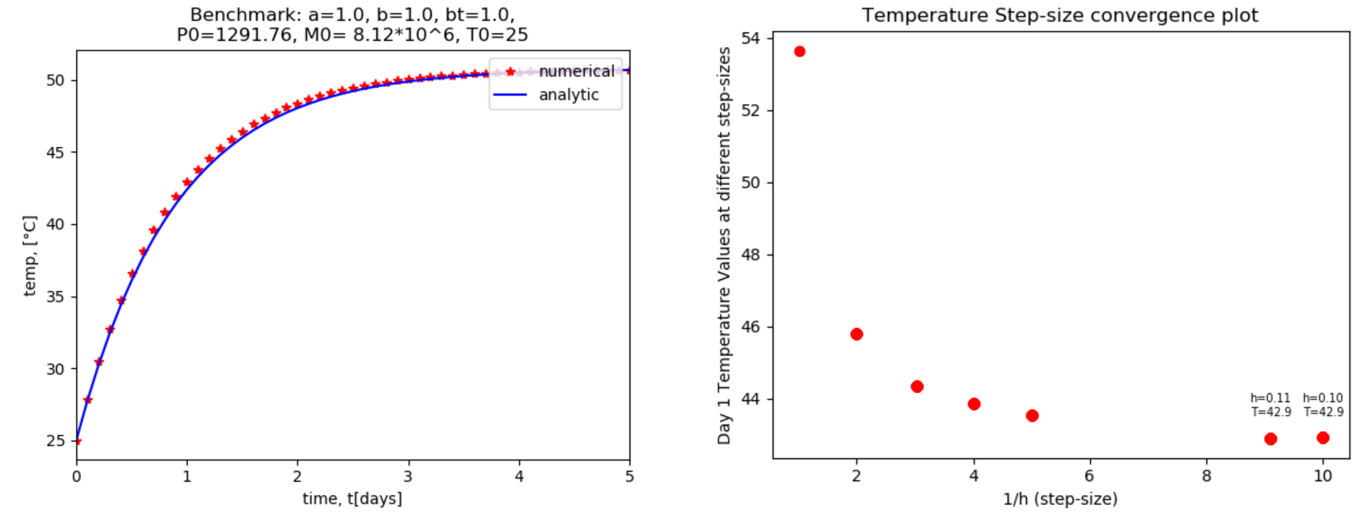


Figure 4: The analytical pressure benchmark compared to the numerical solution (left). Step-size convergence plot



(right).

Figure 5: The analytical temperature benchmark compared to the numerical solution (left). Step-size convergence plot (right).

The correct implementation of the Improved Euler Method has been checked via a unit test that compares the output with a solution worked out by hand. The code can be found in the project_functions.py file.

We have also benchmarked the numerical solution for the Pressure and Temperature LPM's alongside their respective analytical solutions for constant production rates. From figures 4 and 5 (left) above we can see that the solvers are working as intended.

Figures 4 and 5 (right) also shows that we are better off using smaller step-sizes closer to 0.1 as this is where our values tend to converge upon, for the most accurate results.

7. Suitable?

We have calibrated the LPM model to the pilot study data using the curve-fit modelling tool, as well as including a sum-of-squares misfit plot to the data and calibrated values. The best fit model for pressure has parameters as seen as being a_p = 1.6*10^-4 and b_p = 8.8*10^-2. The best fit model for temperature has parameters as seen as being a_p = 1.6*10^-4 and b_p = 8.8*10^-2, b_t = 2.5*10^-2 and M_0 = 2.1*10^6.

Both models (figures 6 and 7) do an unreasonable job of capturing the overall trend of the data, after the first peak they both do not decrease enough to capture the trough of the data which is seen as being too high. The misfit of the pressure plot is seen to reach beyond 800kPA towards the middle of the data. The misfit of the temperature plot is seen to reach beyond 20 degrees Celsius consistently in figure 7. This may be due to the fact that we assumed that P_0 to be the atmospheric pressure and T_0 to be the initial value of temperature in the data instead of calibrating both parameters.

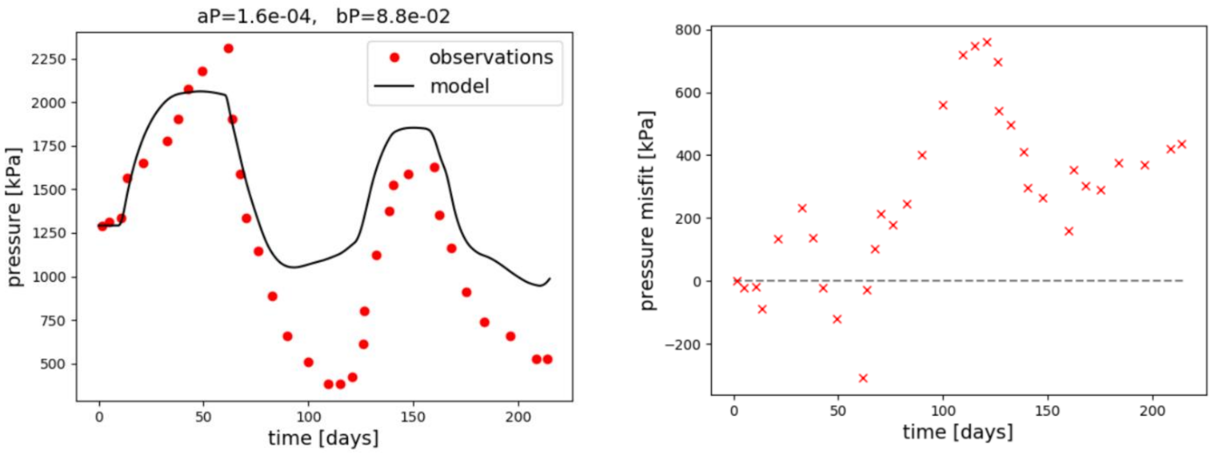


Figure 6: The best-fit pressure model without calibrated P_0 and T_0 values (left). The misfit of the best-fit pressure model with the data (right).

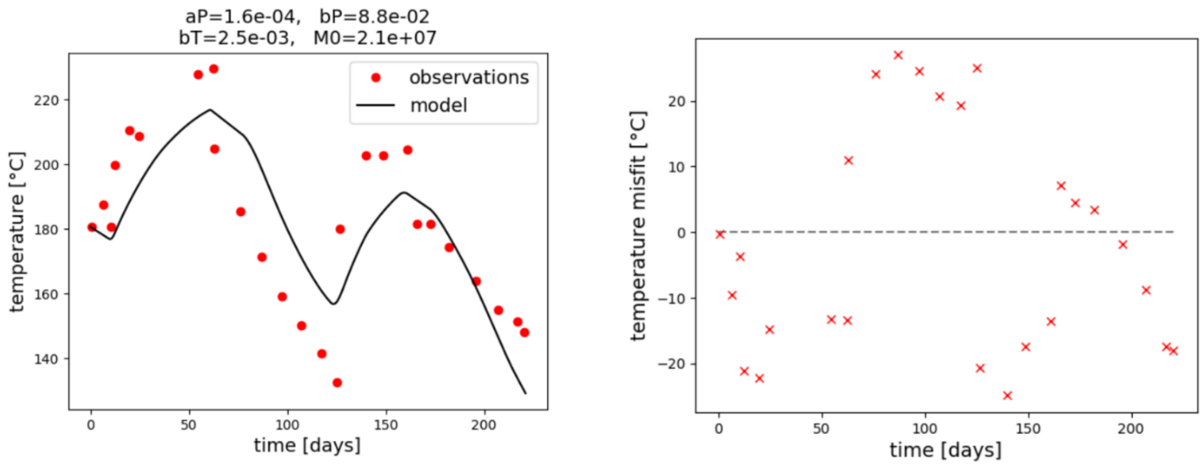


Figure 7: The best-fit temperature model without calibrated P_0 and T_0 values (left). The misfit of the best-fit temperature model with the data (right).

8. Improve?

As we can see from the general trend of the plots beforehand, uncalibrated values of P_0 and T_0 were not enough to model the general trend of the data. However, by calibrating P_0 and T_0, we might expect to see an improved model that is better fitted to the data.

We calibrated the model a second time and the best fit model for pressure had parameters as seen of a_p = 1.7*10^-4, b_p = 5.3*10^-2, P_0 = 8.1*10^2. The best fit model for temperature had parameters as seen of a_p = 1.7*10^-4, b_p = 5.3*10^-2, P_0 = 8.1*10^2, b_t = 3.8*10^-2, M_0 = 5.7*10^6 and T_0 = 1.4*10^2.

The improved model does a better job of capturing the overall trend of the data including the peaks and troughs of the data. The pressure misfit has decreased to be at a maximum of 300kPA, but generally below 200kPA after the initial pressure drop which is an improvement. The temperature misfit generally stays below 20 degrees Celsius more consistently after the initial temperature drop which is also another improvement to our previous model. What we can say for certain is that by calibrating P_0 and T_0 we were able to decrease the misfit quite considerably, seen in figures 8 and 9.

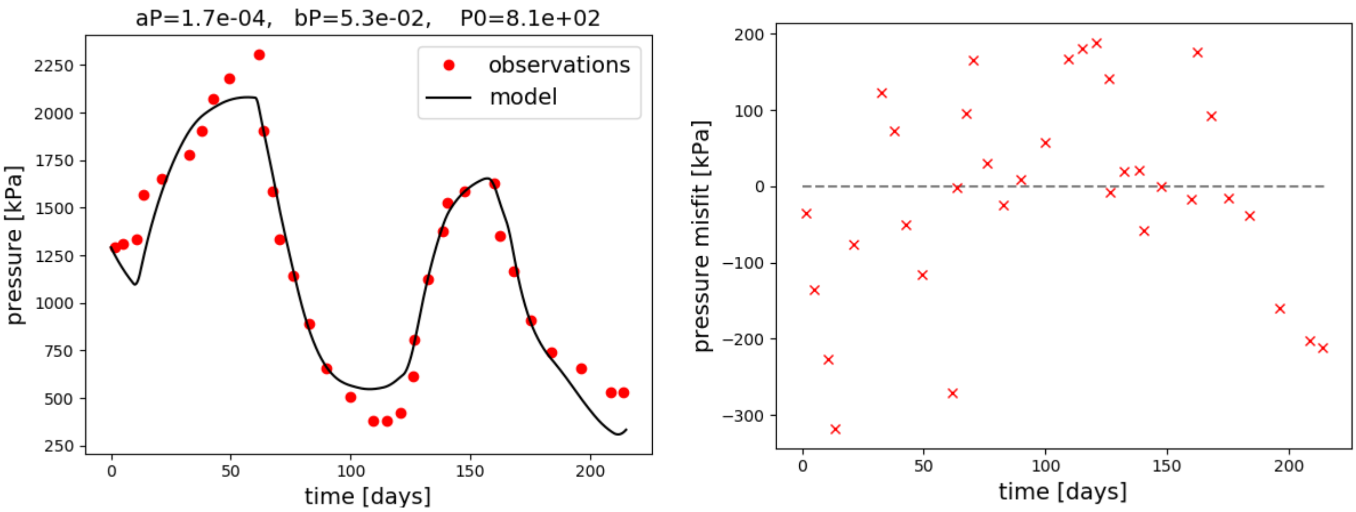


Figure 8: The best-fit pressure model with calibrated P_0 and T_0 values (left). The misfit of the best-fit pressure model with the data (right).

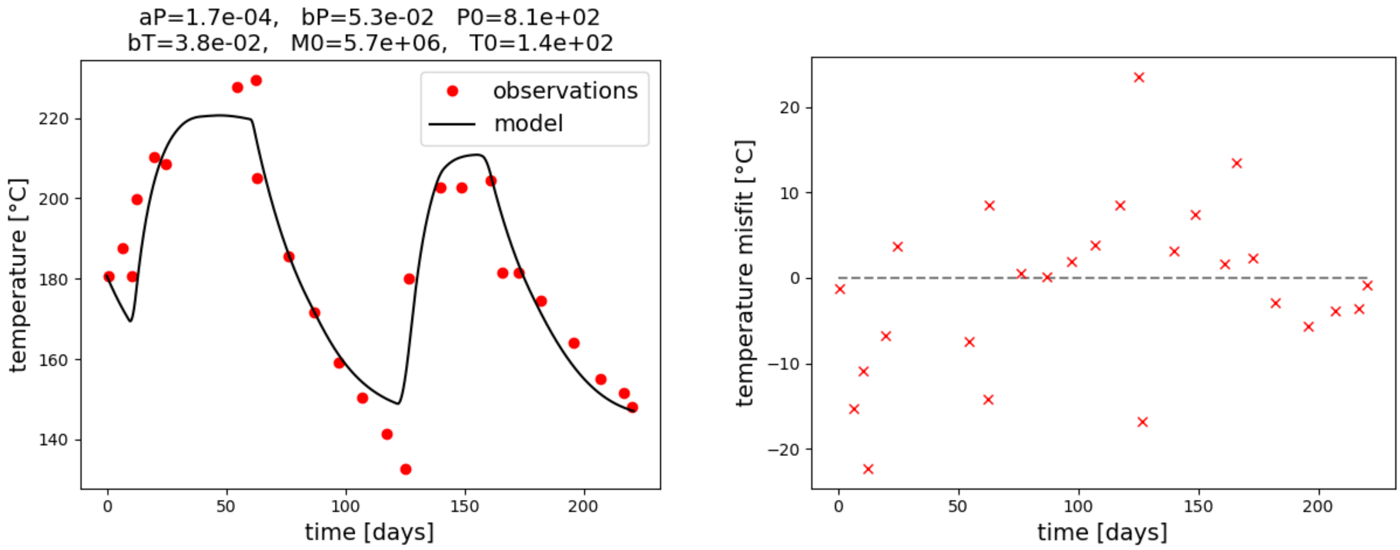


Figure 9: The best-fit temperature model with calibrated P_0 and T_0 values (left). The misfit of the best-fit temperature model with the data (right).

9. Use?

Using the improved model with calibrated parameters for P_0 and T_0, we will consider four different possible scenarios for 2 more cycles, these being:

1. Halting operations (Injecting 0 tonnes/day of steam into the ground)
2. Continued operation at a reduced rate (half the current injection rate) being 250 tonnes/day of steam injected into the ground.
3. Continued operation at similar rate of 500 tonnes/day of steam injected into the ground.
4. Continued operation at an increased rate (double the current injection rate) being 1000 tonnes/day of steam injected into the ground.

These are the four consent outcomes that the West Coast regional council may choose to proceed with. The following models identify the predicted behaviour of pressure and temperature in the system that we may expect to see.

During the two-cycle process, it appears that the temperature values reach a maximum of 228.5, 210.7, 190.7, 147 degrees Celsius in the plot. Therefore, it seems that the continued operation of steam injection at double the rate at 1000 tonnes/day would not appear to threaten the potential leaching of toxic organics in the groundwater as temperature does not exceed 240 degrees Celsius.

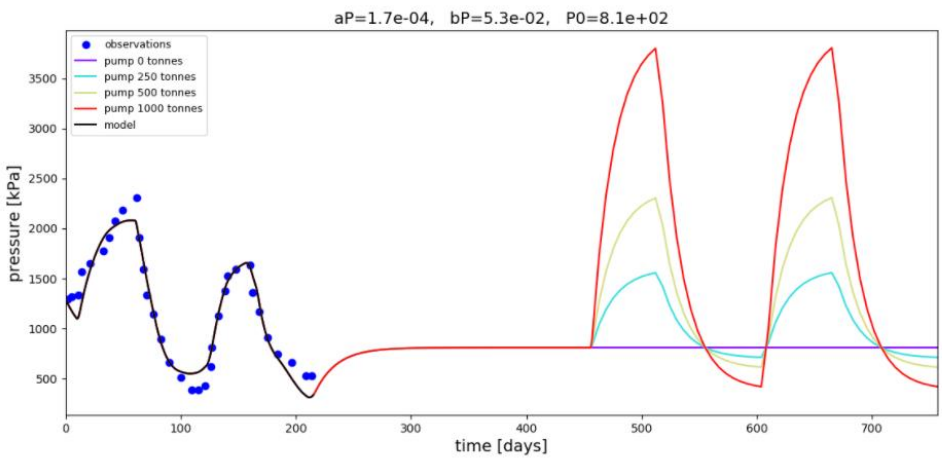


Figure 10: Pressure model predictions for four different steam injection rates, no injection (purple), halved rate (blue), same rate (yellow), doubled rate (red).

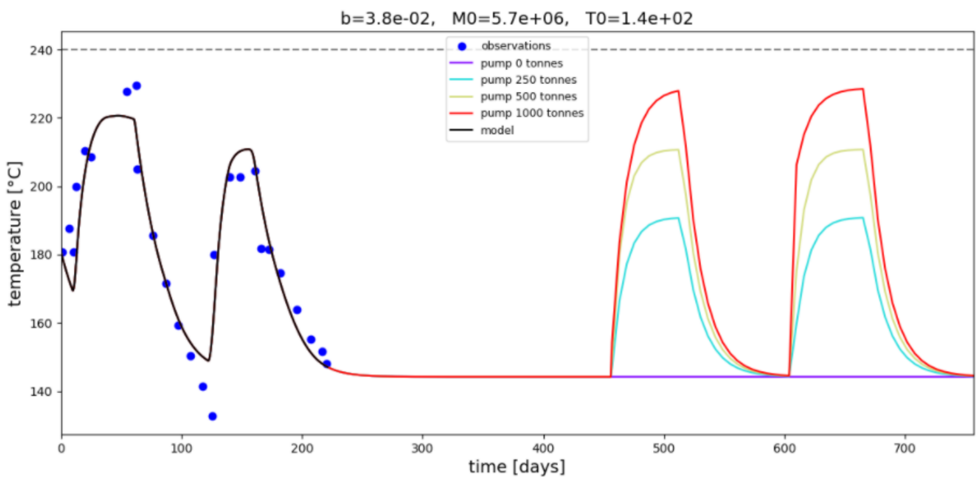


Figure 11: Temperature model predictions for four different steam injection rates, no injection (purple), halved rate (blue), same rate (yellow), doubled rate (red).

10. Unknown?

When dealing with data there will always be uncertainty, hence there may be some errors in the pressure and temperature data. We have undergone uncertainty analysis to better see the range of solutions that have taken into account these possible errors. The best fit parameters and covariance matrix came from using the curve fit modelling tool during calibration, these were used to create 100 appropriate sample models using the np.random.multivariate_normal function.

The four consent outcomes have 95% confidence intervals of [139.4, 156.2], [183.85, 200.3], [203.9, 219.5], [221.1, 236.3], respectively.

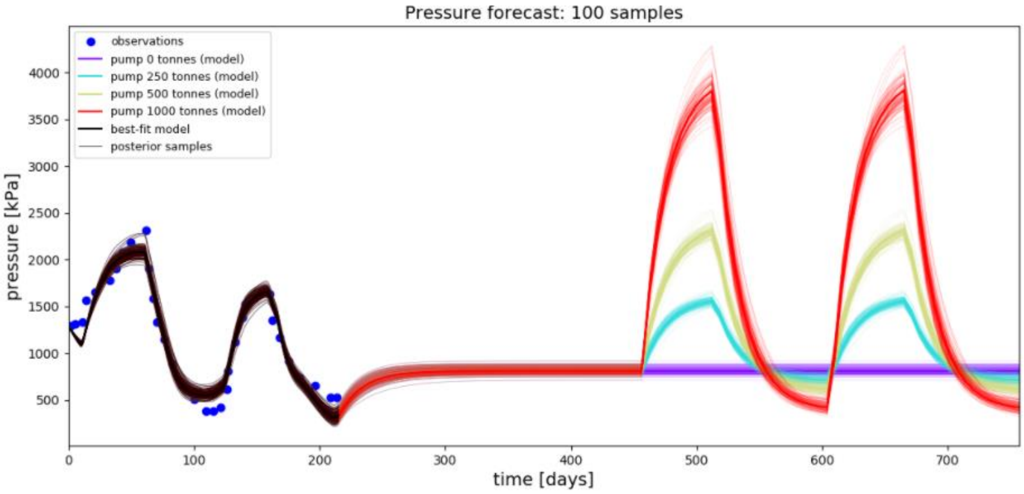


Figure 12: Pressure model forecast for four different steam injection rates, no injection (purple), halved rate (blue), same rate (yellow), doubled rate (red).

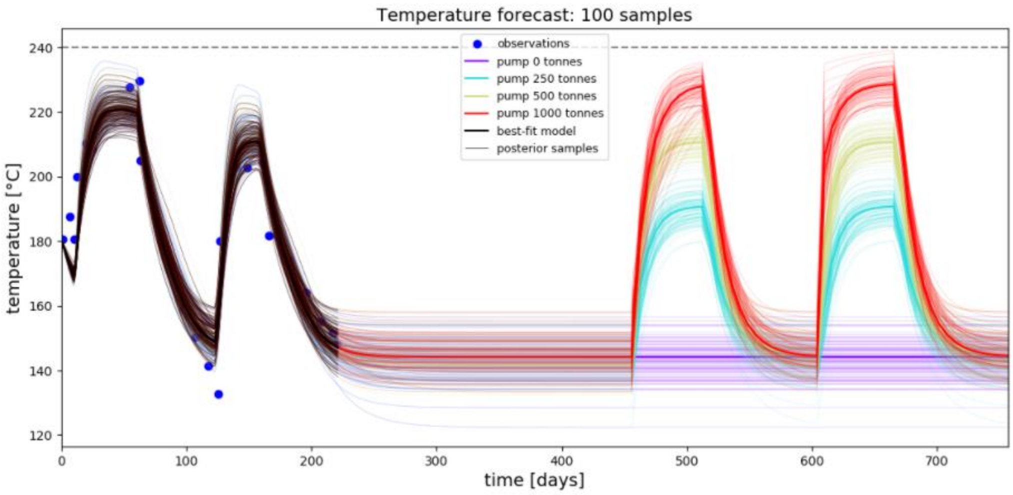


Figure 13: Temperature model forecast for four different steam injection rates, no injection (purple), halved rate (blue), same rate (yellow), doubled rate (red).

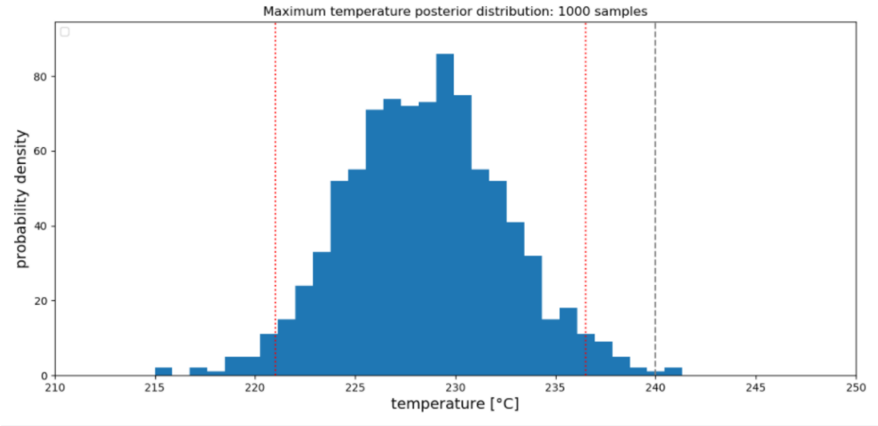


Figure 14: Temperature posterior distribution, generated from 1000 samples. The grey line shows the temperature boundary that would cause leaching of toxic organics into groundwater, red lines show the 95% confidence interval.

We developed a histogram of 1000 appropriate samples using the np.random.multivariate_normal function for the case of 1000 tonnes of steam being injection daily. Figure 14 shows us an approximate normal distribution, with the best fit temperature being 228.5 degrees Celsius, where the 95% confidence interval lies between [220.6, 235.9].

Shortcomings in the model could be due to the effect of pressure on temperature. Being that because pressure and temperature are directly proportional, we may have been understating temperature in the study as pressure increases. The current model has not taken this into account and thus has not accounted for the potential increase of temperature.

11. Recommend?

Pressure and Temperature changes have been modelled over a two-cycle process for four potential production scenarios. It is understood that beyond 240 degrees Celsius, leaching of toxic organics into groundwater may occur. From the models produced we saw that all of the different production scenarios showed that they were below this threshold; with the double production capacity generating a maximum temperature of 228.5 degrees Celsius, the same production capacity generates a maximum temperature of 210.7 degrees Celsius, the reduced production capacity generates max temperature of 190.7 degrees Celsius and halting operations would return the temperature to 147 degrees Celsius. If minimising the potential environmental damages is of the most importance, then it would be recommended to cap the future injection of steam into the ground at 1000 tonnes/day. This is because as seen by our modelling and uncertainty analysis it is unlikely that the temperature exceeds the 240-degree threshold given the 95% confidence interval (seen as being between 220.6 and 235.9 degrees Celsius), where the most likely maximum temperature was seen to be 228.5 degrees Celsius. This will also allow Todd Energy and Ngai Tahu to maximise profits from the processes.

In saying this, the recommendation comes with disclaimer for this scenario that although there is less than 5% chance that the temperature will exceed the 240 degree threshold during the next venture, this does not mean there is no chance it will happen at all. We have also only undergone analysis for the four scenarios mentioned, and if the maximum 1000 tonnes/day of steam injected daily is increased then this model would not support those actions. Also, we have not considered the potential effects of pressure on temperature, meaning we may have been understating the temperature values in our models. In the future, it would be sensible to assess whether changes in pressure have a significant impact on the temperature within a system.