Natural Gas Storage at Ahuroa, Taranaki

Derek Long

1. Why?

FlexGas operate a gas storage site in Ahuroa, in a depleted reservoir at 2.5km depth. To meet customer demand, they wish to obtain consent for doubling the injection and extraction capacity of their operation. The relevant regional authority, in this case Taranaki Regional Council, will decide whether or not the resource consent application is to be approved after hearing submissions from potential stakeholders, which include:

- FlexGas, who are looking to double their operations to meet customer demand and maximise revenue.
- Taranaki Regional Council, who are worried that increased operations may cause severe gas leakage and lead to environmental damage and societal discontent.
- Local Farmers, who are concerned that their own properties as well as the surrounding environment may be damaged due to gas leakage from the reservoir.

Possible outcomes of this process include:

- FlexGas reduce the operation.
- FlexGas maintain operations at the current capacity.
- FlexGas double the capacity of their operation.

2. How?

From this modelling study, we wish to capture the relationship between pressure in the reservoir and time, which will help to quantify gas leakage from the reservoir and its severity. We will be developing a model that predicts how the pressure changes in response to the different injection/extraction capacities, which will be used to predict future pressure changes and future gas leakage. These results will provide insight into the which operation capacities allow for non-severe gas leakage.

3. Given?

A Lumped Parameter Model (LPM) is one that simplifies complex systems into a single control volume and describes its average behaviour. Fradkin et al., 1981, uses LPMs to simplify the Wairakei geothermal reservoir into a single 'lump' and obtain relationships between pressure changes and fluid flows.

More advanced formulations of the conventional model include accounting for heat and mass transfers between liquid and gas phases. The corrected model thus considers the thermodynamic properties of the fluid phases (Khalid et al., 2013).

We will be using an LPM to solve for the pressure changes inside the reservoir in relation to the mass flow. The following data describes the mass flow rate and the pressure in the reservoir, since 2019.

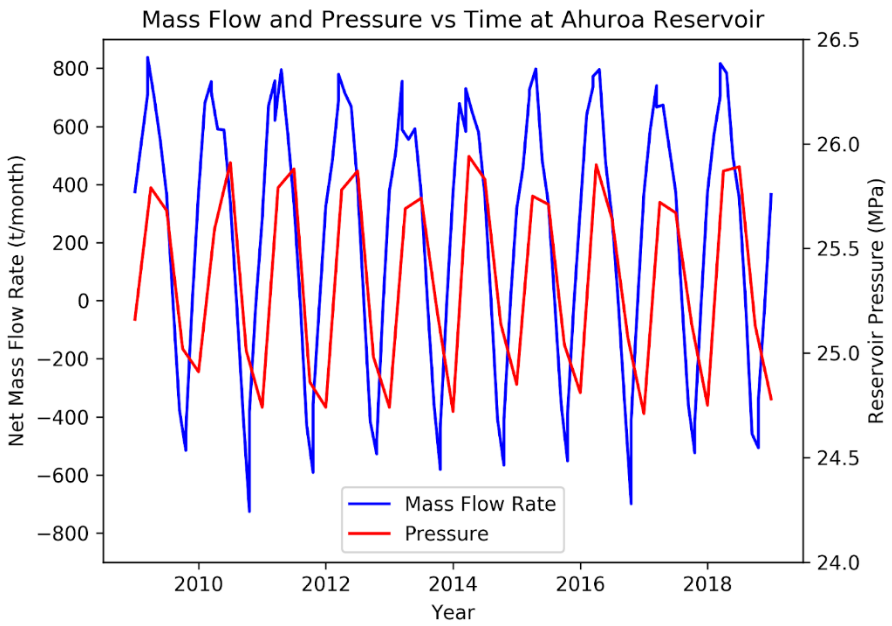

Figure 1: Mass flow rate in the Ahuroa gas reservoir (blue line) against the pressure in the reservoir (red line).

We notice that each year, the monthly mass flow seems to be highest in summer, at around 700 tonnes per month and troughs in winter, at around -700 tonnes per month. This high extraction compared to injection during the colder months is likely due to the increase in demand for natural gas.

It appears that as the net monthly mass flow increases, the reservoir pressure also increases and vice versa. However, the reservoir pressure seems to peak, at approximately 25.9 MPa, slightly after the peak in mass flow rate and seems to be lowest, at approximately 24.8 MPa, slightly after the troughs in mass flow rate.

References:

Fradkin, L. J., M L. Sorey, A. McNabb (1981), On Identification and Validation of Some Geothermal Models, Water Resour Res, 17: 929-936.

Khalid, P, S Ghazi (2013), Discrimination of fizz water and gas reservoir by AVO analysis: a modified approach, Acta Geod Geophys, 48: 347-361.

4. Assume?

For our model, the main physical theory we will consider is the conservation of mass. We will be using an LPM to analyse the pressure changes within the reservoir as a function of time.

Since we are simplifying the gas reservoir into a single control volume, our model's spatial domain is the boundary of the reservoir and does not include the surrounding earth. As such, the model will include the physical processes below, which relate to mass leaving and entering the reservoir's boundaries:

- Injection and extraction of natural gas, which has been given as a net mass flow rate, where injection is positive, from 2009 (Fig. 1). We also see from Fig. 1 that the rate of change in pressure is directly proportional to the net mass flow rate. The future net mass flow rate will be modelled sinusoidally with time.
- Leakage of natural gas, which occurs when the overpressure is higher than a critical value. The rate of change in pressure is also directly proportional to the square of the overpressure.

Any physical processing relating to spatial variation, such as the movement of natural gas and the effects that temperature may have on it within the reservoir, will be excluded.

We will assume that, although some parameters may change in response to the change in pressure, the variation in reservoir pressure will not have a significant effect on the parameter values. Therefore, we can assume that parameters such as porosity, density and compressibility remain constant in the reservoir. The cross-sectional reservoir area will be assumed to remain constant and not vary with height.

The time domain will be from the beginning of the data (2009) to 10 years after the end of the data (2019). Lastly, we will also assume that the natural gas in the reservoir is purely methane (CH_4), as this is its principle component.

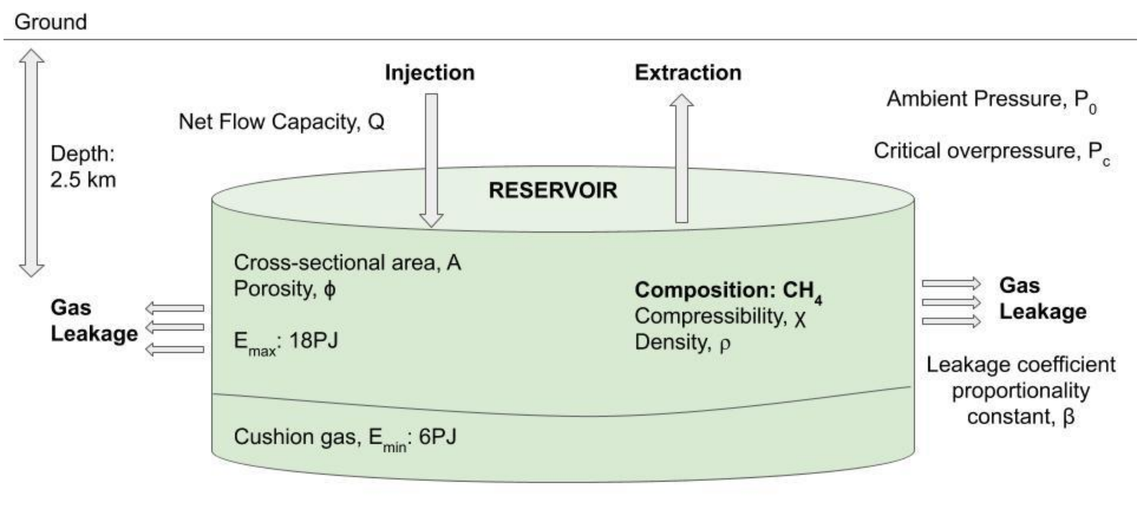

Figure 2: Schematic Illustration of Ahuroa Gas reservoir LPM

5. Formulate?

Our LPM ODE is:

$$\frac{dP}{dt} = aq - b(P - P_0) \qquad b = \begin{cases} 0 & , P - P_0 < P_C \\ \beta(P - P_0) & , P - P_0 \geq P_C \end{cases} \qquad a = \frac{Q}{AD\chi\phi\rho}$$

$$\frac{dL}{dt} = \frac{b(P - P_0)}{a} \qquad \rightarrow \qquad L = \int \frac{b(P - P_0)}{a}\, dt$$

where P is pressure, P_0 is ambient pressure in the reservoir, a is a lumped parameter (mass flow strength), q is the mass flow rate, b is the leakage coefficient, β is the leakage proportionality constant, P_c is the critical overpressure, L is the gas leakage, *Q, A, D, X, Φ, ρ* are, respectively, net flow capacity, cross-sectional area, depth, compressibility, porosity and density.

The analytical solution for a constant q(t) when b = β(P-P_0):

$$P = \frac{\sqrt{a}\sqrt{q}\,\tanh(\sqrt{a}\sqrt{b}\,c\sqrt{q} + \sqrt{a}\sqrt{q}\sqrt{b}\,t}{\sqrt{b}} + P0$$

The analytical solution for a constant q(t) when b = 0:

$$P = aqt + c$$

We will use the Improved Euler method to solve our ODE numerically. The code is given in gs_functions.py.

6. Working?

A unit test has been used to check that the Improved Euler method is working as intended by comparing it to an output calculated on paper. The code is given in test_gs.py. We also implemented a couple unit tests for our pressure model, which includes testing that the analytical solution is being used correctly for different values of pressure.

We have benchmarked the numerical solution of our model against the analytical solution and plotted the results below. These results show that our method is also working as intended.

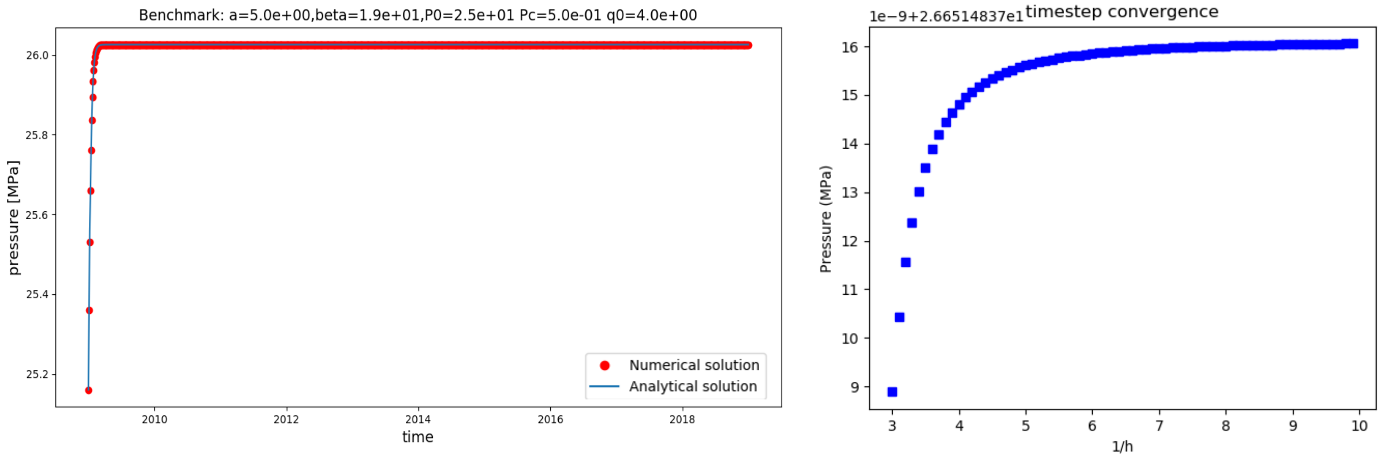

Figure 3: (left) Comparison of numerical solution against analytic benchmark. (right) time-step convergence.

7. Suitable?

Our LPM was calibrated to the reservoir data using the differential_evolution function. The code for this is given in gs_functions.py. The parameters that allowed for a best fit model were:

a = 0.751 Pa/kg, β = 7.116/(MPa yr), P_0 = 24.996 MPa, P_c = 0.249 MPa

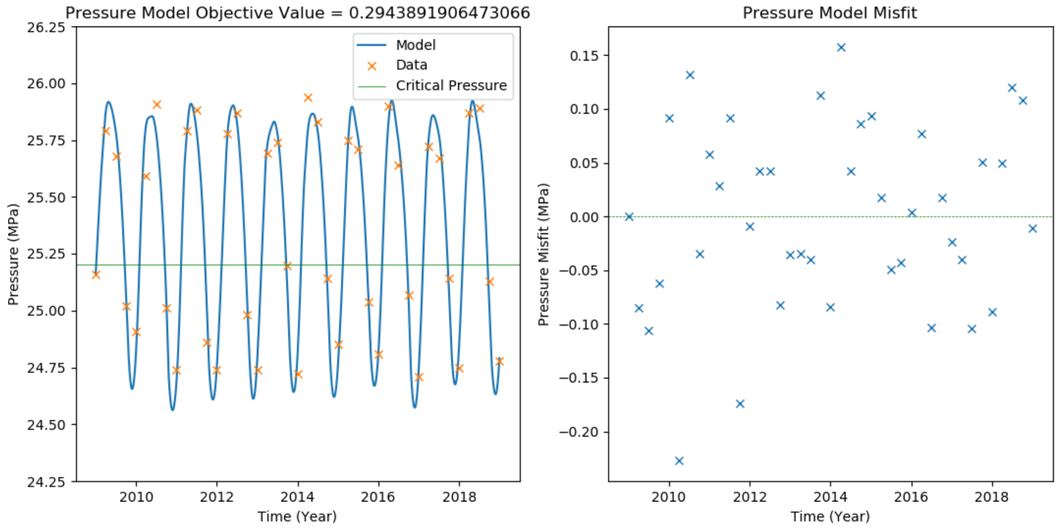

Figure 4: (left) Best-fit model (blue line) compared against the pressure data (crosses). (right) Model misfit against data.

The pressure model seems to capture the sinusoidal pattern of the pressure data well, seen from the small objective value. The misfit is also reasonably spread with few irregularities.

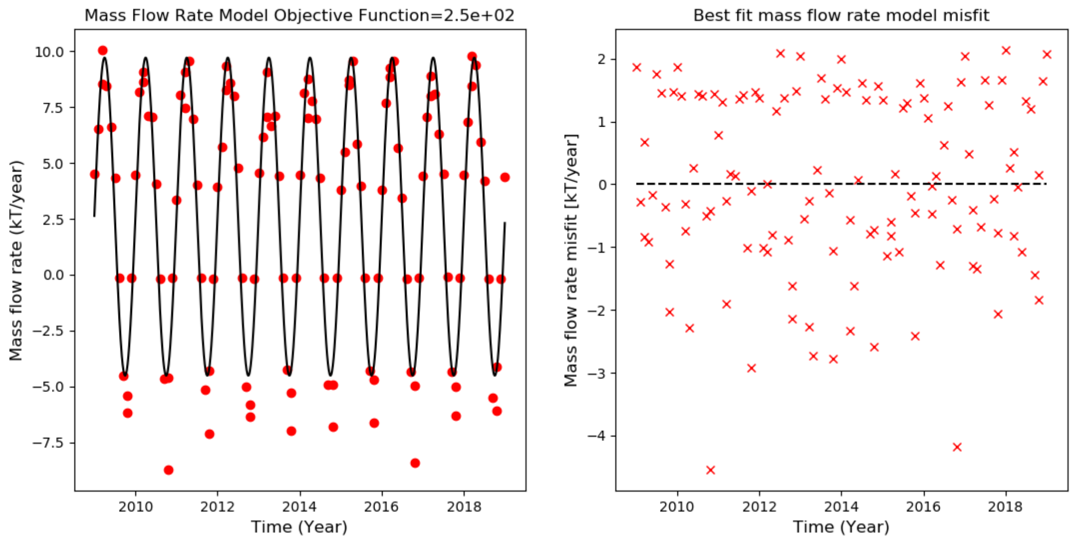

Figure 5: (left) Best-fit model (blue line) compared against the mass flow data (dots). (right) Model misfit against data.

The mass flow rate model does a good job capturing the regular, sinusoidal pattern of the mass flow data. The parameters that allowed for a best fit were:

A = 2.589, B = 7.095, C = 6.292, D = 6.707 in equation q = A + Bsin(Ct + D).

The mass flow rate appears to centre around a positive, constant value, which suggests that there is a net injection. This is expected as there must be underlying gas leakage that has not been accounted for. However, the objective function is quite large, and the model seems to not fit the lower values. This may be due to structural errors in our model formulation. Again, the misfit is reasonably spread with few irregularities.

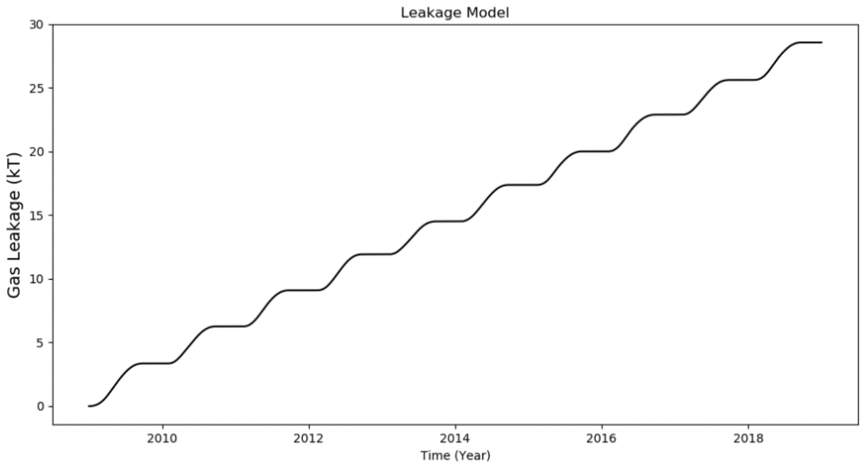

Figure 6: Model for gas leakage out of the reservoir from 2009

The gas leakage appears to have a regular, repeating linear pattern. The steep increase in gas leakage seems to occur around the same time when pressure is high, and levels off when pressure is low.

8. Improve?

The original integration method we used in our solve_ode function, to solve our ODE, was with the explicit Runge-Kutta method of order 5(4) from solve_ivp in the scipy.integrate module. However, using the solve_ivp function to integrate our stiff ODE led to an unstable and inaccurate solution, shown when benchmarking – the numerical solution did not line up with the analytical solution. We also attempted using built-in implicit methods from solve_ivp, such as the Runge-Kutta method, but these methods took too long to run.

We changed the solve_ode function to use the improved Euler method with a small time step. This implementation allowed for a stable solution when benchmarking, as well as being much faster than solve_ivp.

9. Use?

Our calibrated model can be used to consider four possible consent outcomes that may occur in the next 10 years, which are:

i. The capacity of operation is doubled.
ii. The capacity of operation is halved.
iii. The capacity of operation remains at its current value.
iv. The operation is discontinued.

The following plot shows the four possible consent outcomes and we see the range of possible changes in gas leakage:

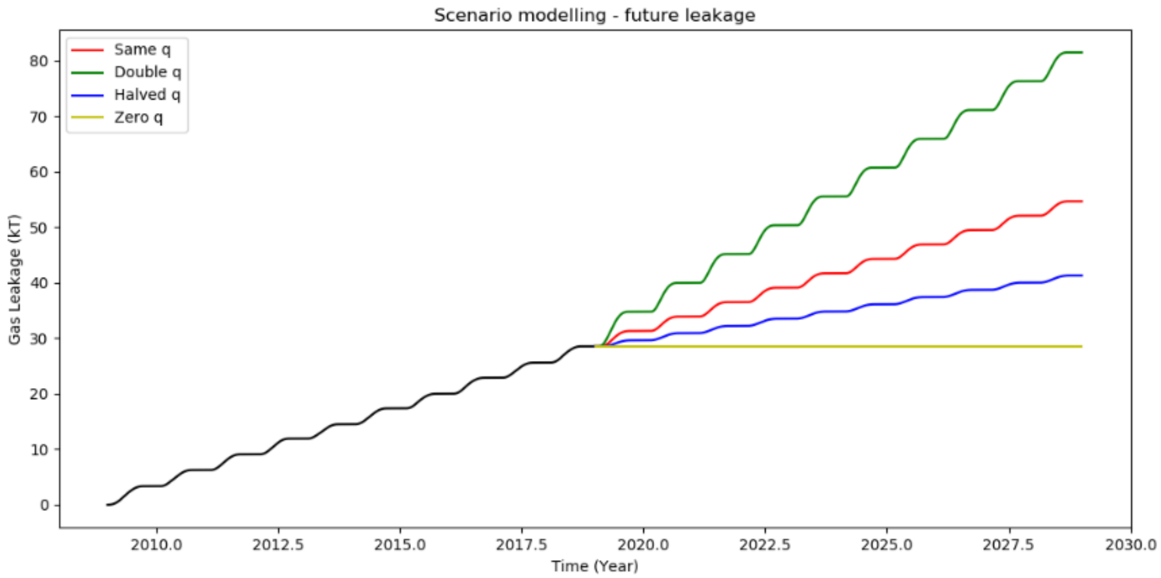

Figure 7: Model predictions for four possible outcomes: capacity is doubled (green), capacity remains at its current value (red), capacity is halved (blue), and operation is discontinued (yellow).

The gas leakage after 10 years for each of the four outcomes is 81.14kT, 54.51kT, 41.23kT and 28.55kT, respectively.

10. Unknown?

There is uncertainty in all data and in this case, there may be some measurement error in the pressure data. As such, we have constructed a range of possible models that account for this uncertainty and approximated the standard deviation of the pressure data to 0.5 MPa.

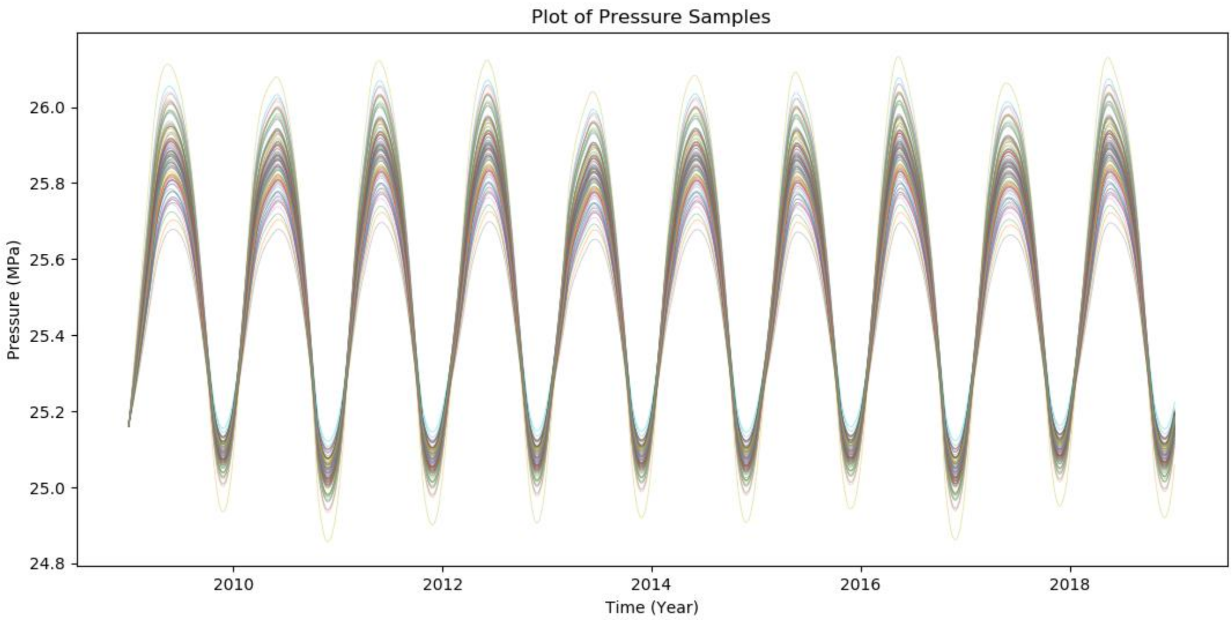

Figure 8: Pressure models across an uncertainty of 0.5MPa from 2009

We also approximated a posterior distribution by conducting a grid search over the parameter space and computing the objective function:

$$S(\theta) = \frac{1}{\sigma^2}\sum(\tilde{p} - p(\theta))^2$$

where $p(\theta)$ is the LPM for parameters θ. We then obtained the set of 100 sample models to the data using the best-fit parameters and covariance matrix.

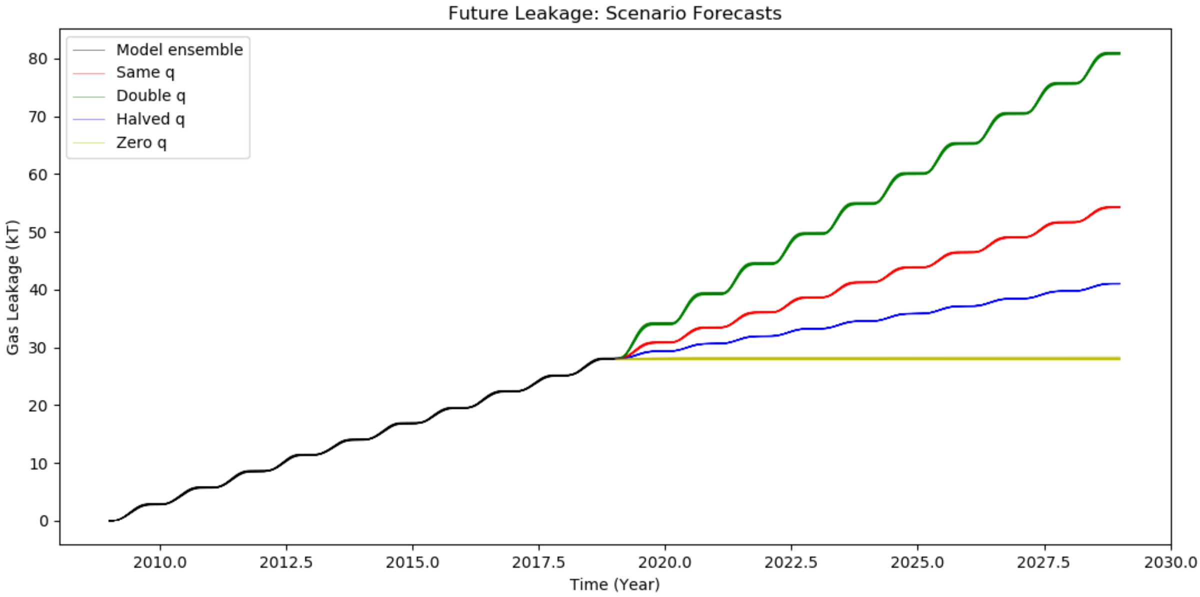

Figure 8: Gas leakage model ensemble and model forecast for possible outcomes: capacity is doubled (green), capacity remains at its current value (red), capacity is halved (blue), and operation is discontinued (yellow).

The 95% confidence intervals for gas leakage 10 years from now for each of the four outcomes are [80.30, 80.61], [53.94, 54.14], [40.85, 41.02] and [27.95, 28.17] respectively.

However, we are suspicious of this model forecast due to the narrow prediction intervals. Our model does not seem to capture a good variation of possible scenarios whereas realistically, we would expect there to be more variation in future leakage. We think that structural error in our model, such as neglecting spatial variation or using an overly simplified LPM, may have led to this behaviour.

11. Recommend?

Four different possible outcomes for gas leakage in the Ahuroa reservoir have been modelled over a future period of 10 years. From this, we were able to assess the relative severity of the gas leakage of the possible scenarios.

Past data shows that the total gas leakage from 2009 to 2019 is approximately 28kT, which translates to 2.8kT per year. If we double the capacity, the total gas leakage over the next 10 years would be approximately 52.4kT, which translates to 5.24kT per year. Similarly, if we were to maintain our current capacity, halve it, or discontinue operation, the gas leakage would be approximately 2.6kT, 1.3kT, or 0kT per year, respectively.

Given a gas leakage threshold value, we can determine which of the four possible scenarios would provide a satisfactory outcome for the potential stakeholders involved. For example, if the threshold value for leakage were to be between 5.24kT and 2.6kT per year, we would recommend maintaining the capacity of operation at its current value, or possibly halving it.

However, possible outcomes will have different consequences and impacts, not only on the stakeholders involved but also other on factors as well. For example, even if the threshold value were much larger than 5.24kT, doubling the capacity may lead to even worse damage on surrounding environment and property. Although FlexGas will be able to meet demands and maximise revenue, local farmers and communities may become more discontent and unsatisfied. On the other hand, reducing the capacity by half or fully discontinuing operation may lead to financial loss and damage to FlexGas. Although this could result in less detrimental effects on surrounding property and environment, this would probably lead to unemployment and significant societal impacts.

The effects of spatial variation and temperature change within the reservoir have not been considered in this modelling study. These processes may have a considerable effect on reservoir pressure and gas leakage, so it would be worthwhile to investigate them in future studies.