Lab 3: Forecasting Geothermal Impacts

(Note, while not directly assessed, the final exam will make explicit reference to your experience with this lab and the tasks completed.)

Problem introduction

Utilisation of geothermal resources can sometimes conflict with our enjoyment of their natural beauty. In 1987, geothermal bores (used for indoor heating) were closed throughout Rotorua due to the decline and disappearance of geysers in the geothermal field. Some have still not returned.

Compared to the Oil & Gas industry, operation of a geothermal resource occurs on a shoestring budget. The reason is simple: oil is more valuable. The all-time high for the price of a barrel of oil was $135 in 2008, whereas a barrel of hot water is never worth more than a few dollars. However, the costs associated with drilling and operating wells that access the underground reservoir are largely similar for the two industries.

Given the difficult economic climate and the need to consider environmental impacts, it is important to explore all aspects of risk in geothermal decision-making. Mathematical models play an important role in this regard. In this lab, we will use a simple model to assess whether or not to drill a geothermal well into a reservoir that has uncertain properties. The model idealizes the situation in a similar way to the discharging well model considered in the last lab (Fig. 1). We assume a radial geometry about a horizontal reservoir at depth, $z_r = 1.5$km, with thickness, $h = 200$m, uncertain porosity, ϕ, and permeability, k, initial temperature, $T_i = 250°$C, and pressure, $P_i = 20$MPa.

Hot water is produced from the reservoir at a rate $q(t)$ that changes over the time. Water is extracted by maintaining the pressure at the top of the well, $P_{WHP} = 1$MPa, lower than that in the reservoir. In which case, $q(t) \propto (P_{WHP} - P_i)$. Thus, as pressure in the reservoir declines, the extraction rate also drops[1]. The mass extraction rate is used to compute an equivalent electricity generation rate, which is then converted to an income stream. This income is offset against the fixed upfront cost of drilling and operating the well over a ten-year period, after which it would be nice if our well has turned a profit. Total pressure decline, which affects the health of geothermal surface features like geysers, will also be considered.

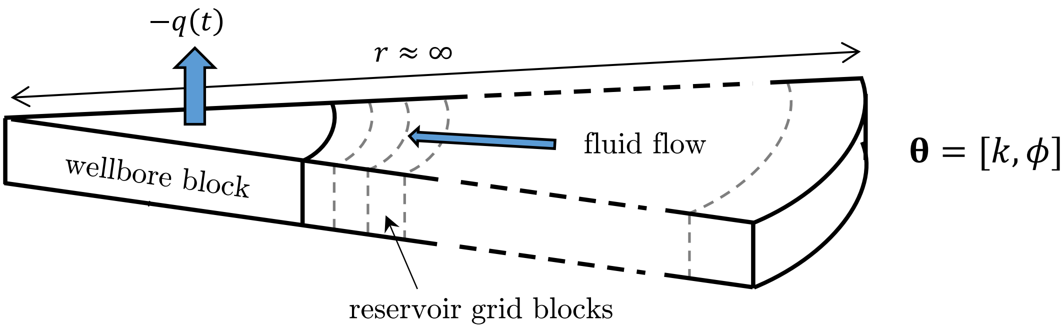


Figure 1: Schematic of modelled geothermal well. The centre block has the same radius as the well. Mass is extracted at a rate, $q(t)$, from the wellbore block, which modifies the pressure in the reservoir, P_i.

The rate at which water flows out of a geothermal well depends on how fluid flows in the reservoir. This in turn is controlled by ϕ and k. Some drill core was taken from a number of wells intersecting the same

[1] Similar to Newton's law of cooling: replace pressure with temperature, and mass flow with heat flow.

reservoir formation, but at different locations. Testing of these samples for porosity and permeability (a procedure similar to the Gingernut experiment) has provided a number of data-points, $[\tilde{k}_i, \tilde{\phi}_i]$.

The tasks for you to complete in the lab are:

1. Run the geothermal extraction model for an arbitrary parameter set, $\mathbf{\theta}$. Try to understand how your choice of inputs affects the outputs.
2. Using the measurements $[\log(\tilde{k}_i), \tilde{\phi}_i]$, develop a normally distributed prior for each of the unknown parameters, $\log(k)$ and ϕ.
3. Sample N parameter sets $\mathbf{\theta}_i = [\log(k_i), \phi_i]$ from the prior and simulate ten years of geothermal extraction for each.
4. For each model in the ensemble, calculate its environmental and economic performance and use this information to determine whether drilling should proceed.

Tasks

As you complete the tasks below, you will encounter several *italicised* questions. While there is nothing to submit for this lab, you may nevertheless wish to write down answers to these questions as an aid for your end of year exam revision.

Download *lab3_files.zip* from Canvas and extract the contents. You will be making modifications to the file *main.py*, which in turn will call functions from *wellbore_model.py*. Open these files in Visual Studio Code. The other files are related to execution of the discharging well model and plotting. You can run python scripts by hitting Ctrl+F5 or just F5 to enter debugging.

"HELP! Visual Studio Code won't run my Python File!" See end of document for troubleshooting.

1. Model familiarization

Before applying a model to a particular situation, it is useful to get a feel for how the forward model is performing, e.g., execution time, parameter sensitivities, etc.

Choose values for reservoir permeability, k, and porosity[2], ϕ. You should also research[3] a reasonable value for the price of electricity. Run the forward model and inspect the plot (Fig. 2).

Why do flow rate and pressure change over time? (blue line in top plot)

Why does power output change over time? (black line in bottom plot)

Why do earnings increase over time? (black dashed line in bottom plot)

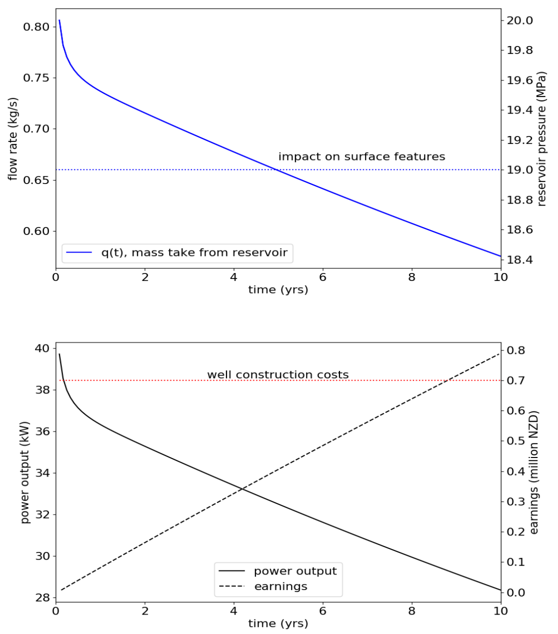


Figure 2: Plot generated for Task 1. Note, depending on the values you selected for k, ϕ and electricity price, your plot may differ. (Top) Mass extraction and reservoir pressure drop over time. (Bottom) Power output and total earnings.

[2] Note, in this lab, porosity is specified as a percentage, e.g., 0.5 ≡ 50%.
[3] Google.

For the parameters you have specified, does the well return a profit in less than ten years? Describe how "well profitability" is sensitive to reservoir and economic parameters.

For the parameters you have specified, does the well adversely affect impact surface features in less than ten years? Describe how "environmental impact" is sensitive to reservoir and economic parameters.

2. Construct prior distributions

At the bottom of *main.py*, comment and uncomment appropriately to execute the function for Task 2 and inspect the plot that is generated (Fig. 3). The histograms summarize the available data: measurements of permeability (on a log scale) and porosity, $[\log(\tilde{k}_i), \tilde{\phi}_i]$[4]. We shall use this information to develop a *prior*, a statement of our belief about the true parameter values in the reservoir, should we decide to drill another well. We shall use a normal distribution to quantify the prior and this requires that we choose a mean, μ, and standard deviation, σ, for each of the two parameters.

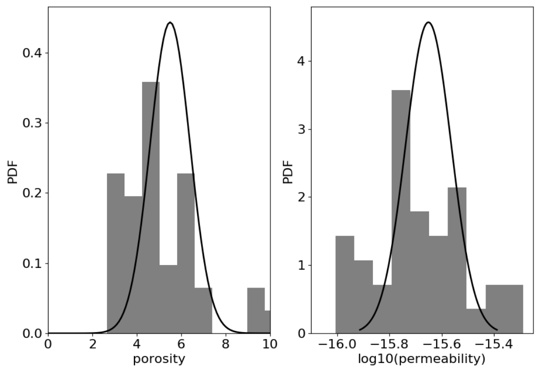


Figure 3: Measured values of porosity, ϕ, and log permeability, k, overlaid by approximating normal distributions representing the prior parameter distribution. Note, the values of ϕ and k above are derived from 39 Gingernut experiments 2016-2018. The data have been rescaled to a range appropriate for geothermal reservoirs.

Modify the prior parameters, all of which are initially set to `None`, and execute the code again. Normal distribution curves are now overlaid over the parameter histograms. Try to generate prior distributions that are a good match to the data.

Do the data even look like they should be described by normal distributions? Suggest an alternative approach.

The prior expresses our uncertainty and ignorance of the true parameter value. If we were absolutely certain *of a parameter's value, what form would the prior take?*

If more data were collected and the uncertainty of a parameter's value decreased, how would this be reflected in μ and σ?

3. A short detour into random numbers

To generate parameter samples, we will need to make use of computer random numbers. Open the file *fun_with_randoms.py* and toggle the True/False switches to execute different code blocks. Once you have answered the questions, continue with Task 4 in *main.py*.

4. Create an ensemble of models

The reservoir parameters k and ϕ are not known with certainty. Therefore, in modelling the future performance of the well, we should sample the priors and create an ensemble of models with different parameters. We will then make a prediction for each model.

[4] In fact, these are the values the class obtained calibrating k and ϕ for the Gingernut experiment. The data have been rescaled to a range appropriate for a geothermal reservoir (less permeable, less porous than a Gingernut!)

At the bottom of *main.py*, comment and uncomment appropriately to execute the function for Task 3. Complete the code for the function *model_ensemble()*, which implements a loop that runs multiple models and then plots their combined output (Fig. 4). For each loop, you are required to:

1. Construct a random parameter set, $\boldsymbol{\theta}_i = [k_i, \phi_i]$.
2. Confirm that the parameter set $\boldsymbol{\theta}_i$ does not fall outside a permissible range.
3. Run the forward model for $\boldsymbol{\theta}_i$ and save the output.

Test the code and inspect the plotted outputs for model ensembles of N between 1 and 1000.

As $N \to \infty$, what do the histograms in the upper two plots of Fig. 4 tend towards?

Describe how the uncertainty in the predicted quantity "total money earned" changes over time by comparing the curves at 3 and 6 years.

For N larger than 5, we switched to using a surrogate model – what's that?

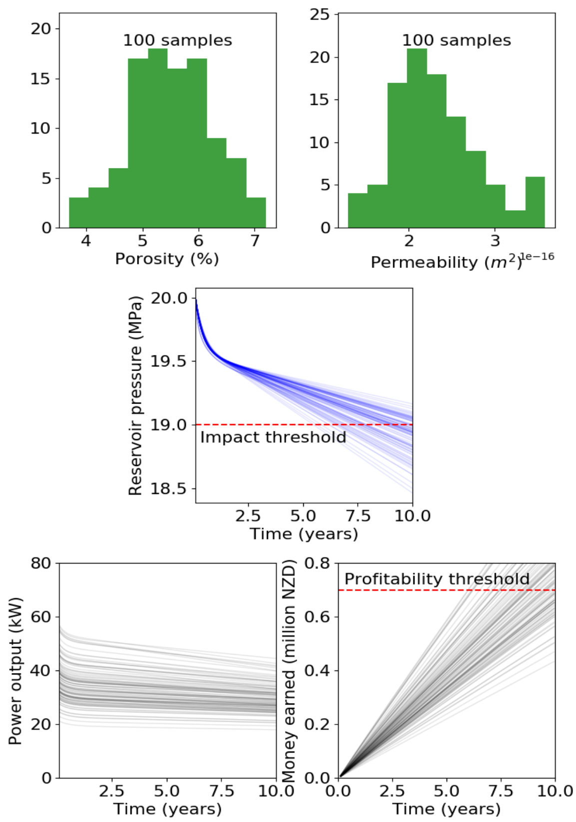


Figure 4: Summary of model ensemble, including histograms of 1000 porosity and permeability samples (top row), 10-year reservoir decline (middle) and power output predictions for the samples (bottom left), and income earned vs. well operation costs (bottom right).

Surrogate models

The first five simulations were performed using an industry-standard geothermal simulator: TOUGH2. However, even for these simple models and a fast, optimized code, the simulations take so long that to run an ensemble of 1000s of models is not practicable within our lab slot (especially if you screw things up the first, second, third… times and have to rerun it).

To speed-up the analysis, we earlier selected a large number of parameter combinations – a grid spanning the 2D space $[\boldsymbol{\theta}_{min}, \boldsymbol{\theta}_{max}]$ – and ran a TOUGH2 simulation for each. This took about eight hours. For each model, we then fitted a simple analytic function with four parameters to the power output curve, P (bottom left curves in Fig. 4):

$$P = a\, e^{-bt} - ct + d,$$

and saved the values of the parameters $[a, b, c, d]$ for each combination. This is the *surrogate model*.

Now, when a parameter value $\boldsymbol{\theta}_i$ is chosen that falls within the grid-search range, we can rapidly compute P by (1) looking up the appropriate parameters, $[a, b, c, d]$, interpolating between grid points if necessary, and (2) computing the analytic function. There is no need to run the comparatively slower TOUGH2 model.

Can you think of any disadvantages that could arise in the use of a surrogate model?

5. Forecast well profitability

To assess whether a well is profitable, we need to know (1) how much income has been earned from electricity generation over the ten-year life of the well, and (2) how much it has cost to operate the well over that time (including the upfront capital cost of drilling). The latter has been estimated at $700,000 and the former depends on how much steam the reservoir can produce and the price that we can sell electricity generated from it.

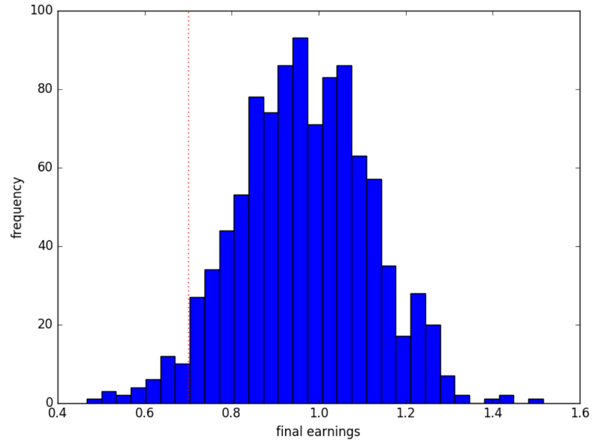


Figure 5: Histogram of ten-year earnings of all models in ensemble. The profitability threshold is plotted as a red line.

At the bottom of *main.py*, comment and uncomment appropriately to execute the function for Task 5 (which depends on the output of Task 4, so DON'T comment these commands). The function *decision()* plots a histogram, and space has been left for you to derive a probabilistic assessment as to whether or not a well that is drilled will be profitable.

On the basis of this modelling analysis, would you recommend drilling the well?

What future uncertainties might impact whether your decision is the right one?

*How would your assessment have been different if we had used a uniform prior? Hence, what is the "*value*" of collecting data,* $[\tilde{k}_i, \tilde{\phi}_i]$*?*

6. Forecast environmental impact

Profitability is not the only concern when drilling a well. There is also the possibility that our drilled well will adversely impact geothermal surface features. Assuming that a 1 MPa pressure drop in the reservoir represents a threshold at which these impacts could be reasonably expected to occur, modify the analysis of Task 5 to estimate the likelihood of adverse environmental impacts.

On the basis of this updated modelling analysis, would you recommend drilling the well?

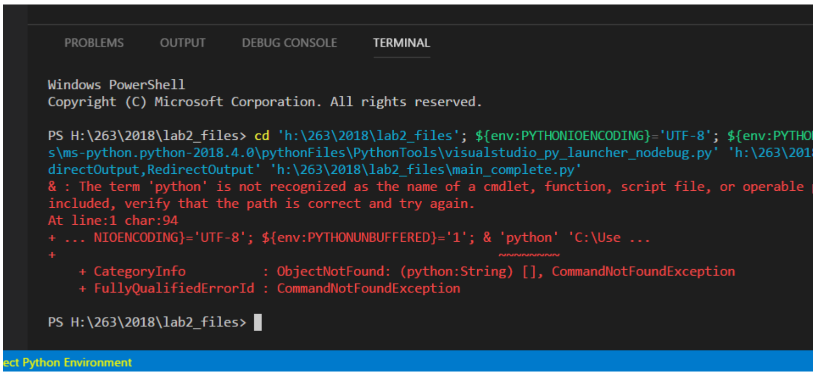
If your answer to the question above is DIFFERENT to Task 5, explain how these two recommendations can be combined or balanced.

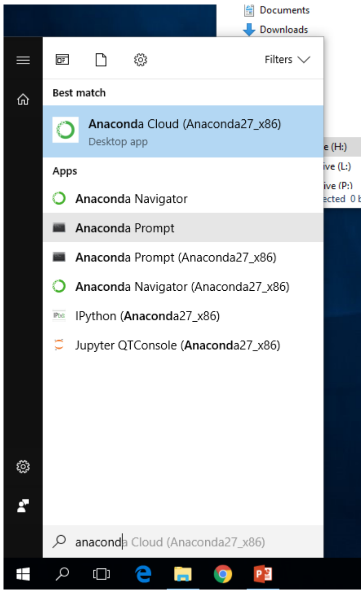
Explain the statement below:

"Models don't make decisions: people do. However, models support informed decision-making."

Troubleshooting Visual Studio Code (VSC)

A common error when trying to run a Python file within VSC looks something like the below





Basically, VSC is telling you it cannot find a Python executable. We'll need to tell it where to look.

1. **Close** Visual Studio Code.
2. **Open** an Anaconda Command Prompt by typing "Anaconda" in the Start Menu. This will open a terminal with a cursor beginning `(C:\Anaconda) C:\Windows\system32>` Environment variables have been defined in this terminal that tell Windows where to find Python.
3. **Open** a new instance of Visual Studio Code from the terminal by typing
   `"C:\Program Files\Microsoft VS Code\Code.exe"`
   Note the quote marks around the entire command. This is because the people who originally designed Windows put a 'space' between the words "Program" and "Files". Operating systems are remarkably fragile.
4. You should now be able to open and run Python files from within VSC. If it's still not working, call me over to share in the misery.