# Estimating short-term capacities of geothermal wells

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**Abstract**

In this report a geothermal system with full reinjection is analyzed. The focus is on extreme output situations, where wells are utilized at their maximum mechanical output. Such situations should not be maintained for long periods, a few days or months at the most, since the annual recommended average flow rate for long-term use is usually below these levels. It is assumed that the geothermal reservoir together with production and reinjection wells can be modelled as a series of tanks. Due to a large demand difference between seasons the first degree term of the conventional flow-pressure relationship for geothermal reservoirs is omitted during high demand seasons, leaving only the turbulent term for consideration. Changes in water elevation in production and reinjection wells can be estimated with the full reinjection constraint for different scenarios. Using this constraint, various combinations of production and reinjection wells may be analysed and provide answers to questions like: "What is the optimal combination of production and reinjection wells? At what depth shall the production pumps be placed? When is it economical to add a new reinjection well or a production well? Could we possibly increase the pump pressure instead?" Finally an optimization procedure regarding system setup for a closed geothermal system, is briefly introduced.

***Keywords:*** *Geothermal system, reinjection, well pumping, economical utilization, peak load.*

## 1 Introduction

In this article, a geothermal field will be analyzed using a reinjection constraint of 100%. The field is assumed to be closed and all wells are assumed to work as independent tanks. These suppositions allow for the derivation of equations that connect flows and pressure and, if the amounts of dissolved gases in the water are known, it provides a basis of mechanical performance constraints.

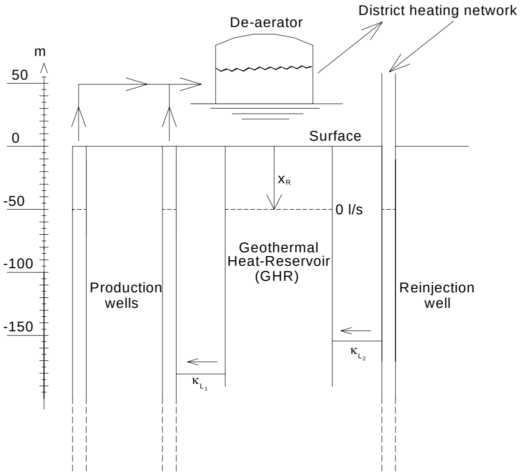
Reinjection of water into geothermal fields is an essential tool for maintaining the reservoir pressure and sometimes a necessary tool for environmental reasons as well. The use of reinjection will hopefully become more widespread as geothermal utilization increases globally.

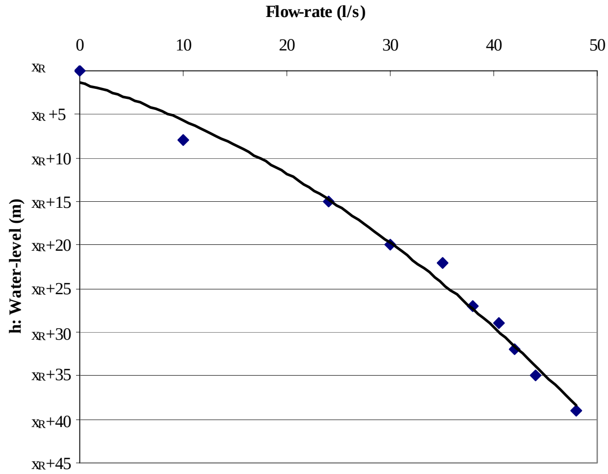
This article includes concepts that might assist those seeking the most economical way of utilizing a geothermal field.

## 2 The Geothermal system

In this study, the geothermal field is assumed to work and function as connected tanks. In its simplest form, the production well is one tank, the field itself a second tank and the reinjection well the third and final tank. The geothermal system is assumed to be closed and isentropic. It is assumed that all wells are of similar depth. Figure 1 depicts a simple schematic picture of a geothermal field. The picture includes 2 production wells and 1 reinjection well. This combination of wells will be called "system 2-1" in future context, for the sake of simplicity.

Test runs have been performed from a single well test, and primary results showing changes in water level of the well for different flow-rates have been estimated. Figure 2 shows typical measurements (and a fitted curve) depicting the water level and flow-rate relationship.




**Figures 1 and 2: A schematic picture of a geothermal system and a typical water level / flow-rate chart with measurements from one production well.**

Figure 1 introduces a few parameters that are used in this report. They are the following:

$x_R$: distance from the surface to the water-level in the geothermal heat reservoir [m].

$k_{L1}$: flow resistance from the reinjection tank to the geothermal heat reservoir (GHR).

$k_{L2}$: flow resistance from GHR to the production tank.

The parameter named $x_R$ is defined to be positive. The larger the distance from the surface to the geothermal reservoir's water level is, the larger the $x_R$.

In Figure 2 a fitted curve has been drawn through the data points. This fitted curve is constructed with the general formula,

$$h = a + b * Q + c * Q^2 \tag{1}$$

Where all parameters have physical interpretations, which are as follows:

h: difference in height when pumping, to scale with the initial $x_R$.

a: describes the initial water-level,

b: describes pressure drop in the reservoir around the well,

c: describes pressure losses resulting from turbulent flow in the flow paths the well intersects.

The coefficients a and b are time dependent, and assumed to change with the passage of time. Constant c however is assumed to be non-dependent of time.

In existing documentations eq. (1) is used either with or without the first degree coefficient "b" (see Árni Gunnarsson, 1997). The second-degree term in eq. (1) becomes dominant due to high turbulent losses, when withdrawal from the reservoir is high and high-flow is experienced. Here the effects of "b" will be omitted, and constant "a" (the height in the well at Q = 0) is added to the initial $x_R$. This results in a considerable simplified version of eq. (1) and it becomes:

$$h = c * Q^2 \tag{2}$$

To find the change in pressure, for a given change in height, the hydrostatic formula:

$$P = \rho * g * h \quad (3)$$

is used. Combining (2) and (3) results in:

$$Q = \sqrt{\frac{1}{c} * h} = \sqrt{\frac{1}{c} * \frac{P}{\rho g}} \quad (4)$$

By arranging terms and defining a constant "$k_L$":

$$k_L = \sqrt{\frac{1}{c\rho g}} \quad (5)$$

the formula describing water-level changes in a well, associated with changes in height and flow, now becomes the following:

$$Q = k_{L1}\sqrt{P}, \text{ and } Q = k_{L2}\sqrt{P} \quad \text{(6.1) and (6.2)}$$

where indices 1 and 2 refer respectively to the production well (=1) and the reinjection well (=2). Note that if the same well serves both as the production and the reinjection well, constant "c" in eq. (1) might be the same for both events, depending on the geological formation or stratum encountered, and thus $k_{L1}=k_{L2}$.

To fit the data to the new equation, i.e. to the polynomial from eq.(1) without the linear term, one has to re-estimate the constant "c". It can, for instance, be achieved using the least-squares method:

$$\hat{\theta} = (X^T X)^{-1} X^T Y \quad (7)$$

where θ is a vector of coefficients, X is the design matrix and Y a vector containing the responses. In this case (where a second order polynomial is required without the first order coefficients) X and Y will be structured in the following way:

$$X^T = \begin{bmatrix} 1 & 1 & 1 & \cdots \\ x_1^2 & x_2^2 & x_3^2 & \cdots \end{bmatrix} \text{ and } Y^T = \begin{bmatrix} y_1 & y_2 & y_3 & \cdots \end{bmatrix} \quad (8)$$

Where the data points from test flows or the $x_i$'s and $y_i$'s can be obtained from Figure 2. For this construction of X and Y the coefficient vector θ will be as follows:

$$\hat{\theta} = \begin{bmatrix} a \\ c \end{bmatrix} \quad (9)$$

That is, vector θ is constructed from the polynomial's intersection of the y-axis (the head at no flow or constant a) and the flow resistance coefficient, "c". The same procedure is followed for all wells, i.e. the production and the reinjection wells.

When parameter "c" has been obtained for all wells, formula (5) can be used to find their respective $k_L$ values. Intuitively, there should not be a large difference between $k_{L1}$ and $k_{L2}$ if the wells lie within the same geological formations or stratum in the earth. After the $k_L$ constants have been evaluated from test flows, pressure losses of surface pipes and fittings should be added to include all losses (natural or mechanical) in the calculations.

The least-squares method places equal weight on all measurement points, and if focus on specific data points is required (e.g. for good fit at specific flows) the weighted least-squares method from statistical theory can readily be applied.

By combining equation (6.1) or (6.2) and equation (3) we obtain a formula for the height in a well for any given flow.

$$h = \frac{1}{\rho g}\left(\frac{Q}{k_L}\right)^2 \tag{10}$$

The $k_L$ value can either be $k_{L1}$ or $k_{L2}$, depending on which side is being evaluated.

# 3 Condition of water in wells

To obtain the settling depth of a deep well pump the following information must be available for the water in each well: pressure and temperature gradient, chemical analysis and calculated gas/water ratio. In the simplified model presented here, it is assumed that the pump intake is placed below the bubble point (in wells with a high gas content) and at least 10 m below the lowest expected water level.

The main assumption here that reinjection of withdrawal is 100%. Given this assumption the design pressure of the surface pipework and equipment connected to the reinjection well becomes an important design parameter when evaluating cost. The relationship between the cost of surface equipment and the design pressure is such that the higher the pressure, the higher the cost.

# 4 Example of use

The situation in Figure 1 can be analyzed further. It is assumed that flow test have already been completed and the constants $k_{L1}$ and $k_{L2}$ have been evaluated. Their values are $k_{L1}$ = 84 $m^3/(h\sqrt{bar})$ for the two production wells and $k_{L2}$ = 92 $m^3/(h\sqrt{bar})$ for the reinjection well. Other assumptions, made for the sake of simplicity, are as follows:

- The initial height of water in the geothermal heat reservoir ($x_R$) is assumed to be the same as the height in the reinjection well and the production wells at all times.
- The minimal submersion depth of pumps in the production wells is assumed to be 10m.

Using these assumptions the maximum flow in the reinjection well(s) for a given pressure can be calculated, using the following formula:

$$Q_{tot} = k_{L2} n \sqrt{p_{gauge,design} + x_R g\rho / 10^5} \quad \text{or} \quad Q_{tot} = \sum_{i=1}^{n} k_{L2i} \sqrt{p_{gauge,design,i} + x_{Ri} g\rho / 10^5} \quad [m^3/h]$$ (11.1 and 11.2)

Where: (11.1) n = total number of reinjection wells (where $k_L$'s and $x_R$'s are constant).

(11.2) n = total number of reinjection wells ($k_L$'s and $x_R$'s vary between wells).

Formula (11.2) is a generalization of formula (11.1), where wells are indexed with "i".

The minimum required depth of pumps in wells at maximum flow can then be found:

$$h_{pump} = x_R + \Delta h_{pump,\min} + ((Q_{tot}/m)/k_{L1})^2 * 10^5 / \rho g, \quad [m] \tag{12.1}$$

$$h_{pump,i} = x_{Ri} + \Delta h_{pump,\min,i} + (Q_{tot,i}/k_{L1})^2 * 10^5 / \rho g \quad \text{and} \quad \sum_{i=1}^{m} Q_{tot,i} = Q_{tot} \quad [m] \tag{12.2}$$

Where: $\Delta h_{pump,\ min:}$ indicates the minimum submersion of the pump, determined either from chemical or hydrodynamic conditions.

m: number of production wells.

$Q_{tot}$: maximum flow, from (11.1 or 11.2)

Formula (12.2) is again a generalization of formula (12.1). Formula (12.1) applies when all production wells have similar characteristics.

Figure 3 shows the maximum flow as a function of $x_R$ and the resulting depth of pumps at maximum flow.

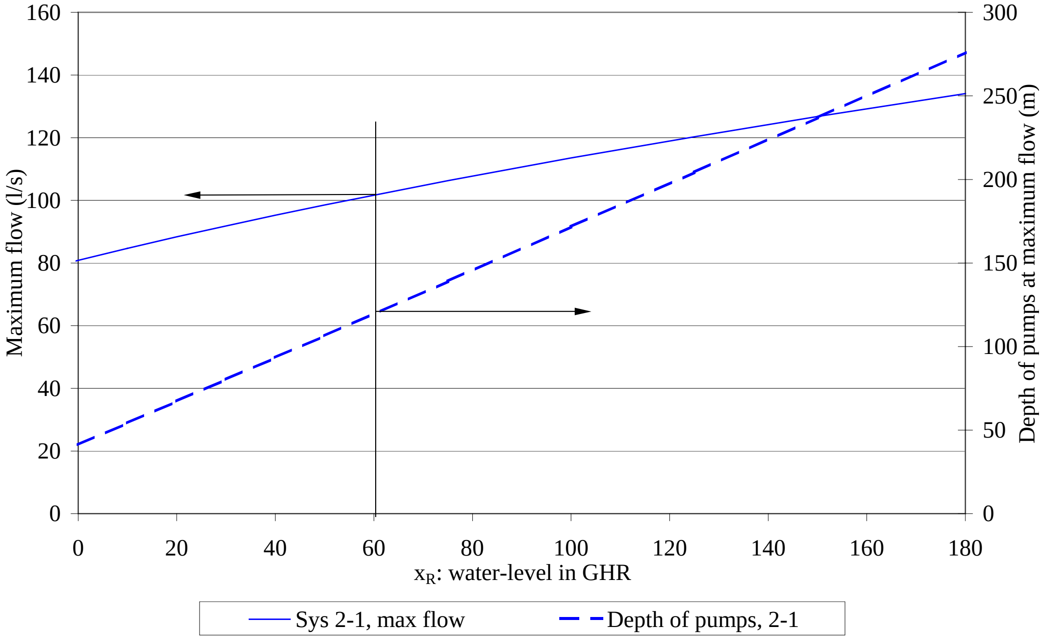



**Figure 3: The maximum flow when the pressure is 10 bar$_{gauge}$ at reinjection well-head and the minimum required depth of pumps in both production wells at these flows.**

The system in Figure 3 is descriptive for two production wells and one reinjection well. As shown, the lower the $x_R$ value, the lower the maximum flow. It also applies that the higher $x_R$ in the reinjection well, the more difficulties are encountered when pumping the water down the well. It is also known that when $x_R$ is low, a large pump is required for the reinjection well, but a small / moderate pump for the 2 production wells, and vice versa when $x_R$ grows. With a 90% reinjection condition, instead of 100% reinjection, the maximum flow from production wells increases linearly 11,1% (to 89,8 l/s for $x_R$=0) while pump depth increases about 17,8% for $x_R$=0, but only 7,3% for $x_R$=180.

The example can be expanded further. If these three wells do not cover the heat load and the maximum annual potential of the field according to geological surveys has not yet been reached, one would typically want to know how to meet demand requirements by adding geothermal wells. Another assumption will be added, for the sake of simplicity:

- All additional wells are assumed to have $k_{L1}$ = 84 $m^3/(h\sqrt{bar})$ (production) and $k_{L2}$ = 92 $m^3/(h\sqrt{bar})$ (reinjection), i.e. additional wells show the same characteristics as the original wells.

Figure 4 shows the changes in an isotropic geothermal field, using the same assumptions as before. It indicates, for different values of $x_R$, what combinations of wells can be used to meet load requirements. Here, for the sake of simplicity, the initial $x_R$ values are assumed to be the same in all wells. The figure is descriptive for a design pressure of 10 $bar_{gauge}$.

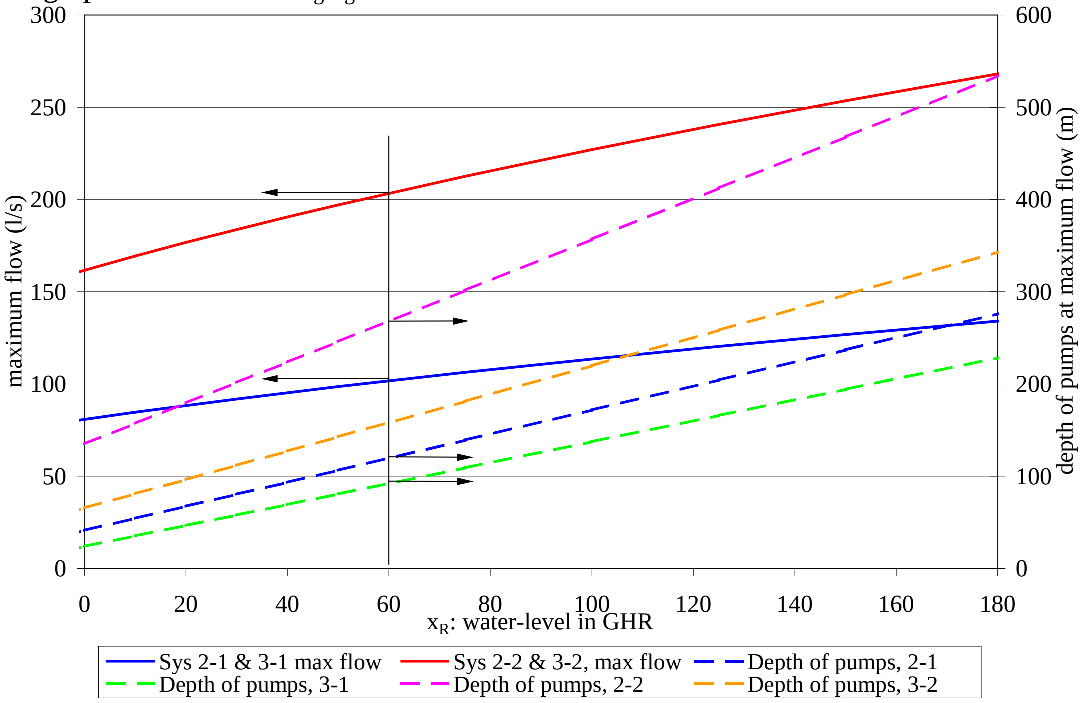



**Figure 4: The maximum flow for either 1 or 2 reinjection wells and the minimum required depth of pumps to maintain maximum flow for 2 or 3 production wells.**

**Figure 4** forms a specific basis for the designer. If the geothermal field has not yet been fully exploited, one can estimate whether a reinjection well, or a production well, should be added to the system. For a given initial $x_R$ the performance of the geothermal system at maximum production can read from the chart. To set up an example, let's assume that a geothermal field is under exploitation and the initial $x_R$ = 60 m. A 100% reinjection condition is forced upon the power provider. The current establishment is sys 2-1 and a demand for additional power for the winter season exists. Geological surveys indicate that intensive pumping will not endanger the production potential of the site. A number of scenarios might apply to this example, namely:

- The need is around 150 l/s and the flow rate/water-level equation indicates that two production wells are able to provide 100 l/s with pumps at levels above 100 m. Thus there is no need to upgrade to sys 3-1. However, this particular reinjection well cannot handle the flow. Thus one reinjection well should be added, upgrading the system to sys 2-2.

- Same as above, but the construction of wells does not allow pumps any deeper than 100 m. In such a situation, sys 3-1 would be the most convenient upgrade.
- If both situations apply, the only way to meet the demand is to add two wells, and in that case sys 3-2 could meet demand requirements, and perhaps even more.

Changes in the design pressure at the reinjection wellhead, will result in different outcomes. In some cases one might not need additional wells, e.g. if the piping equipment could withstand 16 bar. For such cases a powerful pump might do the job.

It is emphasised that the scenarios from Figures 3 and **4** are extreme output situations, and one would typically not design a pumping scheme based on such parameters. The knowledge from these graphs is mainly good for security reasons, for instance, in extreme cold waves. One would typically meet the highest regular seasonal peaks with additional peak load options. See (Þorleikur Jóhannesson and Þrándur Ólafsson, 2003) for a economical case study from site.

# 5 Optimization

In its most global perspective, Figures 3 and 4 only indicate the conditions at a cross section in a three dimensional chart. Figure 5 illustarates very generally the relationship between variables.

The number of wells needed for the cases of 8 $bar_{gauge}$, 10 $bar_{gauge}$, 16 $bar_{gauge}$ etc. could be calculated, as well as the price of wells. The optimum solution, where the total price (investment costs and roughly estimated operational costs over the system's lifetime) is minimal, could be used as an initial layout, in the early stages of geothermal utilization design.

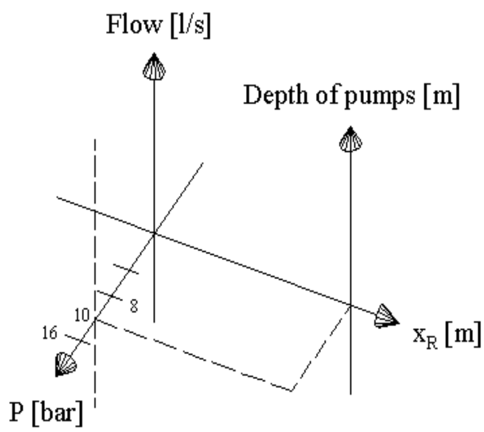



**Fig 5. The relationship between variables.**

For detailed economical optimization the required energy for pumping should be taken into account. The required energy for pumping can be evaluated using the formula:

$$\dot{W} = \dot{m}g(h + h_{deareator}) / \eta_{tot} \tag{13}$$

where: $\dot{m}$ is the mass flow (kg/s),

$\eta_{tot}$ is the total efficiency of pumping (a function of the load)

$h_{deareator}$ is the elevation of the deareator tank intake + pressure losses in the collecting pipeline.

Once the load duration curve has been provided, pumping schedules and simulations should be laid out and the total cost of utilization over the system's lifetime summarized. By taking these costs into account, it is easy to see if another well is economically feasible or not.

If wells are relatively inexpensive compared to their operational costs, i.e. the electricity driving the pumps, one might want to add more wells instead of increasing pumping to the mechanical maximum load. In such a case, the required strength of surface pipework and equipment might not have to be very high.

# 6 Relaxing the 100% reinjection condition

At present few geothermal sites are conditioned upon 100% reinjection. The situation is more likely 50-90% reinjection of water. Figure 6 shows how the situation is in system 3-1 when the 100% reinjection condition is relaxed. Since the system is closed, and all water is not pumped back to the system, $x_R$ will increase with time. The less reinjection over time, the more $x_R$ will increase accordingly.

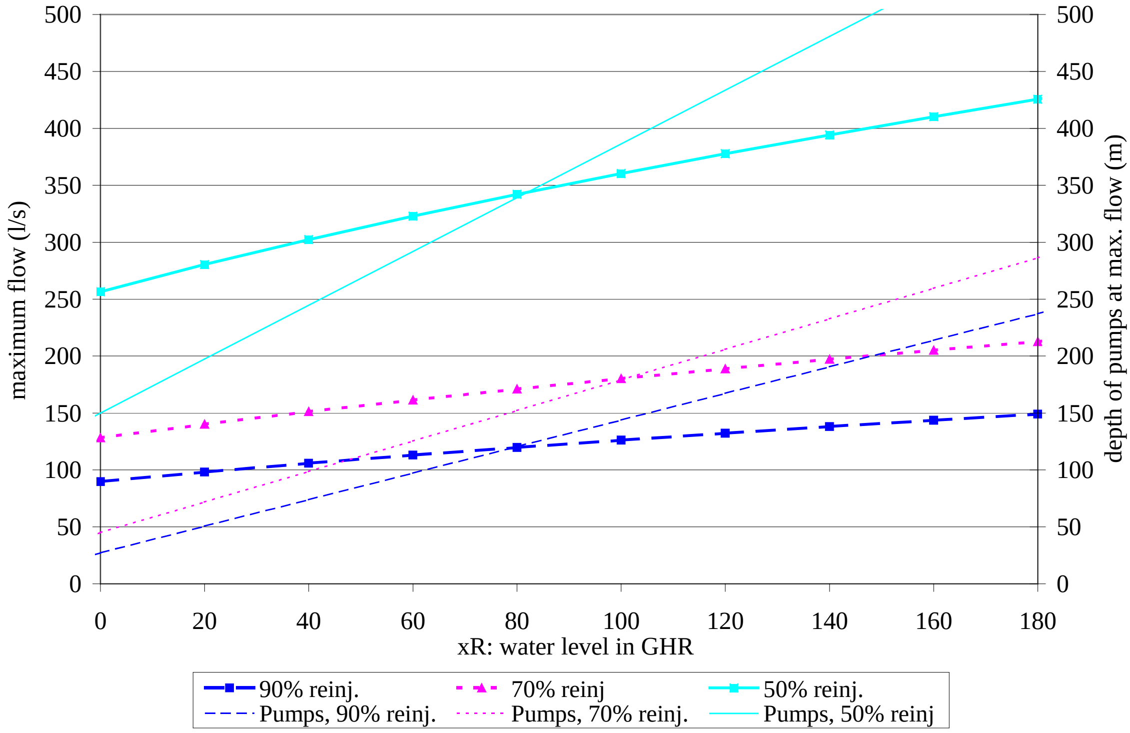



**Figure 4: The maximum flow for 1 reinjection well and the minimum required depth of pumps to maintain maximum flow for 3 production wells at different reinjection %'s.**

# 7 Conclusions

The global use of geothermal utilization is expected to increase substantially over the next years, especially if the Kyoto-protocol becomes a cornerstone in global $CO_2$ policy. The demand for geothermal heat should also increase if absorption chillers or absorption refrigerators substitute cooling devices such as those installed e.g. in air-conditioners.

For district heating and district cooling devices, 100% reinjection is a realistic and responsible way of utilizing the heat. For such cases, the analysis introduced here might prove a useful tool in getting an overview of the maximum well output to see how the wells could meet worst case scenario days in extreme cold waves.

The charts presented here should be used for short-time utilization only. Even though the system is assumed to be closed, i.e. all water removed is pumped back in again, 100% reinjection is not common practice and there is no guarantee that the simple models presented here mirror conditions actually encountered in situ.

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