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Reservoir Lifetime and Heat Recovery Factor in Geothermal Aquifers used for Urban Heating

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Abstract – Simple models are discussed to evaluate reservoir lifetime and heat recovery factor in geothermal aquifers used for urban heating. By comparing various single well and doublet production schemes, it is shown that reinjection of heat depleted water greatly enhances heat recovery and reservoir lifetime, and can be optimized for maximum heat production. It is concluded that geothermal aquifer production should be unitized, as is already done in oil and gas reservoirs.

Key words: Reservoir lifetime; Heat recovery factor; Doublet; Geothermal aquifer; Reinjection.

Nomenclature

a	distance between doublets in multi-doublet patterns, meters
A	area of aquifer at base temperature, m^2 drainage area of individual doublets in multi-doublet patterns, m^2
D	distance between doublet wells, meters
h	aquifer thickness, meters
H	water head, meters
Q	production rate, m^3/sec.
r_e	aquifer radius, meters
r_w	well radius, meters
R_g	heat recovery factor, fraction
s	water level drawdown, meters
Δt	producing time, sec.
T	aquifer transmissivity, m^2/sec.
v	stream-channel water velocity, m/sec.
$\Delta\theta$	actual temperature change, °C
$\Delta\theta'$	theoretical temperature change, °C
θ	water temperature, °C
λ	heat conductivity, W/m/°C
λ_r	rock heat conductivity, W/m/°C
$\rho_a c_a$	aquifer heat capacity, J/m^3/°C
$\rho_a c_r$	rock heat capacity, J/m^3/°C
$\rho_w c_w$	water heat capacity, J/m^3/°C
ϕ	aquifer porosity, fraction

1. Introduction

One major question in the assessment of regional geothermal potential is the estimation of the quantity of the accessible resource base that can be extracted, and of the time during which such an extraction can be economically maintained (MUFFLER and CATALDI, 1977). These vary widely with the nature of the geothermal system, and various solutions have appeared in literature, mainly for hot water and steam geothermal reservoirs (BODVARSSON, 1974; NATHENSON, 1975). The present paper deals more specifically with geothermal aquifers at intermediate temperatures that are used for urban heating.

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2. *Production without reinjection*

The lifetime of a geothermal reservoir of any type, depends primarily on how it is developed. There is no essential difference with normal groundwater aquifers, or oil and gas reservoirs, except that reservoir life may be shortened because of a lack of heat, in addition to a lack of pressure.

The simplest development scheme for a space heating project (and the one that requires the least investment) consists in producing the geothermal water without reinjecting it. In this case, the water will be produced at a constant temperature – equal to the initial reservoir temperature minus the temperature drop from the bottom to the top of the well – as long as the water supply lasts, i.e., as long as the reservoir pressure is sufficient for the production rate to be sustained. When no flashing can take place, the reservoir pressure is related to the depth of the liquid level in the wellbore, and production will continue until the level drops below the pump inlet. As submersible pump size and required power increase with depth, there is a practical limitation on the admissible well drawdown. Usually, it is of the order of 100 meters, although it is possible to obtain drawdowns as high as 200 meters.

For a certain period after it has been completed, a single well behaves as if it were isolated in an infinite system, but its behavior is ultimately affected by flow conditions at the boundaries of the drainage area. Typically, there can be a recharge (at the outcrop of the formation) or an impermeable barrier (due to sealing faults, or the other pumping wells in the vicinity). Although the geometry of the subsurface permeability is usually complex, the single well behavior with either boundary conditions can often be approximated by simple models leading to analytical solutions that can be used to estimate reservoir lifetime and heat recovery factors.

2.1. *Single well in a constant pressure circle*

The model in Fig. 1 represents a single well intersecting two circular reservoirs with constant pressure (zero drawdown) boundaries. Figure 1(A) is a plane view, showing the outer radius, and the 30°C and 60°C isotherms for the deeper aquifer. Figure 1(B) is a cross section indicating the limits of both aquifers.

If all production from one aquifer is supposed to take place from the single well, the model of Fig. 1 will give the production potential of that aquifer.

Assuming the reservoir to be horizontal, homogeneous, isotropic, of constant thickness and initially at uniform pressure, maximum pressure drawdown at the wellbore will be obtained under steady state conditions as (Dietz, 1965):

$$s = \frac{Q}{2\pi T} \ln \frac{r_e}{r_w}, \tag{1}$$

where s = the water level drawdown, in meters
Q = the constant production rate, in m^3/sec.
T = the aquifer transmissivity, in m^2/sec.
r_e, r_w = the aquifer and wellbore radius, respectively, in meters.

The maximum production rate that can be maintained indefinitely from such a reservoir is thus:

$$Q_{max} = \frac{2\pi T s_{max}}{\ln r_e/r_w}. \tag{2}$$

Where s_{max} is the maximum drawdown at the wellbore; with $s_{max} = 200$ m, $r_e = 300$ km, $r_w = 0.075$ m (6″ diameter hole) and the aquifer data shown in Table 1, one obtains:

$$Q_{max} = 0.083\ m^3/sec\ (298\ m^3/hr)\ \text{for aquifer A},$$

$$Q_{max} = 0.008\ m^3/sec\ (30\ m^3/hr)\ \text{for aquifer B}.$$

It is important to emphasize that these Q_{max} values represent the *maximum total withdrawal rate from the aquifer*, under the specified boundary conditions, which is not dependent upon the number of wells. Greater values will only be obtained with higher T (aquifer of better transmissivity) or smaller r_e (recharge boundary closer to the

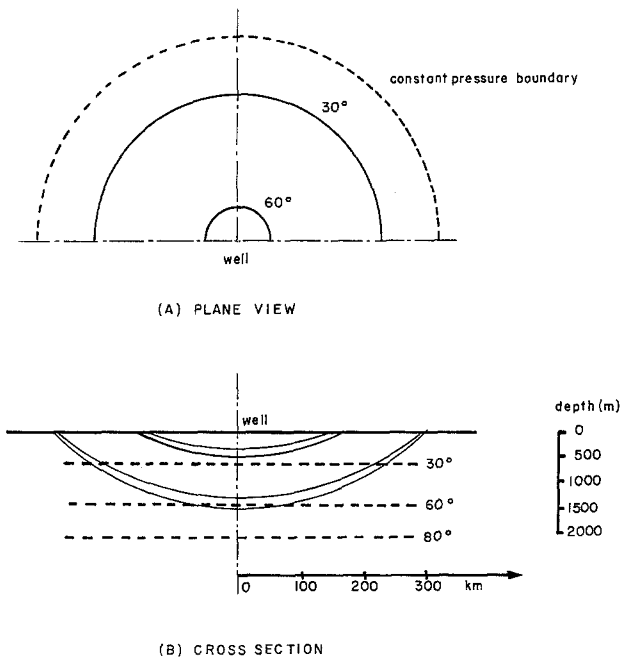

Figure 1
Schematic of a deep aquifer.

production well), but these usually imply a shallower aquifer whose temperature might not be adequate (cf. Fig. 1(B)).

Table 1
Example aquifer data

	Transmissivity (m^2/s)	Storage coefficient fraction	Thickness (m)
Aquifer A	10^{-3}	10^{-4}	100
Aquifer B	10^{-4}	10^{-5}	15

The heat recovery factor can be defined as the ratio of extracted heat, $Q_{\max}\,\Delta t\,\rho_w c_w\,\Delta\theta$, to the total theoretically recoverable heat in place, $\rho_a c_a A h\,\Delta\theta'$. Δt is the producing time, $\rho_w c_w$ and $\rho_a c_a$ are the heat capacity of the water and of the aquifer – $\rho_a c_a = \phi\rho_w c_w + (1 - \phi)\rho_r c_r$, where ϕ is the porosity and $\rho_r c_r$ the rock heat capacity – $\Delta\theta$ and $\Delta\theta'$ are the useful temperature drop that can be obtained with geothermal water (actual and theoretical). A should be taken as the area of the aquifer *corresponding to the appropriate water temperature*, which can be very different from the aquifer areal extent (Fig. 1(B)).

The heat recovery factor is thus equal to:

$$R_g = \frac{\rho_w c_w}{\rho_a c_a}\frac{Q_{\max}\,\Delta t}{Ah}\frac{\Delta\theta}{\Delta\theta'}. \tag{3}$$

If we take $\Delta\theta = \Delta\theta'$ for the sake of simplicity, we are left with a heat recovery factor that only depends upon the production scheme:

$$R_g = \frac{\rho_w c_w}{\rho_a c_a}\frac{Q_{\max}\,\Delta t}{Ah} = \frac{1}{\phi + (1 - \phi)(\rho_r c_r/\rho_w c_w)}\frac{Q_{\max}\,\Delta t}{Ah}. \tag{4}$$

With $\Delta t = 30$ years, $\rho_r c_r/\rho_w c_w = 0.5$, $\phi = 15\%$, $A = 8000\ \mathrm{km}^2$ and the aquifer data of Table 1, one obtains:

$$R_g = 1.7 \times 10^{-4} = 0.017\%\ \text{for aquifer A},$$

$$R_g = 1.2 \times 10^{-4} = 0.012\%\ \text{for aquifer B}.$$

2.2. *Single well in a closed square*

The model shown in Fig. 2(A) represents a single well in a reservoir with impermeable boundaries. The well in Fig. 2(A) has the same behavior as any of the wells in the regularly developed reservoir shown in Fig. 2(B). The model pictured in Fig. 2(A) can thus be used to obtain individual well potential, in addition to the aquifer potential obtained from the previous model.

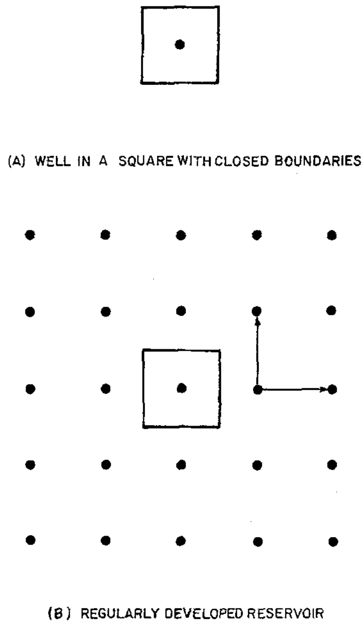

Figure 2
Single well in a closed square.

The long time well drawdown given by the model of Fig. 2(A) is equal to (MATTHEWS and RUSSELL, 1967):

$$s = \frac{Q\,\Delta t}{SA} + \frac{Q}{4\pi T}\ln\frac{A}{3.7 r_w^2}, \tag{5}$$

where S is the aquifer storage coefficient and A is the well drainage area. Equation (5) indicates that no steady-state is reached with this model. Thus, if constant production is to be maintained throughout the total production period Δt, the maximum production rate must be less than or equal to:

$$Q_{\max} = \frac{s_{\max}}{\Delta t/SA + 1/4\pi T \ln A/3.7 r_w^2}, \tag{6}$$

with $A = 1\ \mathrm{km}^2$, $\Delta t = 30$ years, $s_{\max} = 200$ m and $r_w = 0.075$ m, Eqn. (6) yields:

$$Q_{\max} = 2\cdot 10^{-5}\ \mathrm{m^3/sec} = 0.076\ \mathrm{m^3/hr}\ \text{for aquifer A},$$

$$Q_{\max} = 2\cdot 10^{-6}\ \mathrm{m^3/sec} = 0.008\ \mathrm{m^3/hr}\ \text{for aquifer B}.$$

The heat recovery factor is then:

$$R_g = 3.5 \times 10^{-4} = 0.035\,\%\ \text{for aquifer A},$$

$$R_g = 2.4 \times 10^{-4} = 0.024\,\%\ \text{for aquifer B}.$$

3. *Production with reinjection*

It is clear that only very little production and very small recovery factors can be obtained with the type of development that was considered so far. Both models give results of the same order of magnitude; for a total useful area of 8000 km^2, the second model yields a total production rate of 0.167 m^3/s for aquifer A, compared to 0.083 m^3/s with the first model. Of course, this would only be valid in normal sedimentary aquifers. In karstic systems, for instance, with heavy recharge from below, very different results might be obtained.

An alternative to the single well production approach is the use of a doublet type of development (Fig. 3) in which all production is reinjected into the aquifer after the heat has been extracted. Such a procedure maintains the reservoir pressure, prevents subsidence, and insures an indefinite supply of water. It also permits the recovery of the heat contained in the rock, but as a result, it creates a zone of injected water around the injection well at a different temperature from that of the native water. That zone will grow with time, and will eventually reach the production well. After breakthrough occurs, the water temperature is no longer constant at the production well and this may reduce drastically the efficiency of the operation.

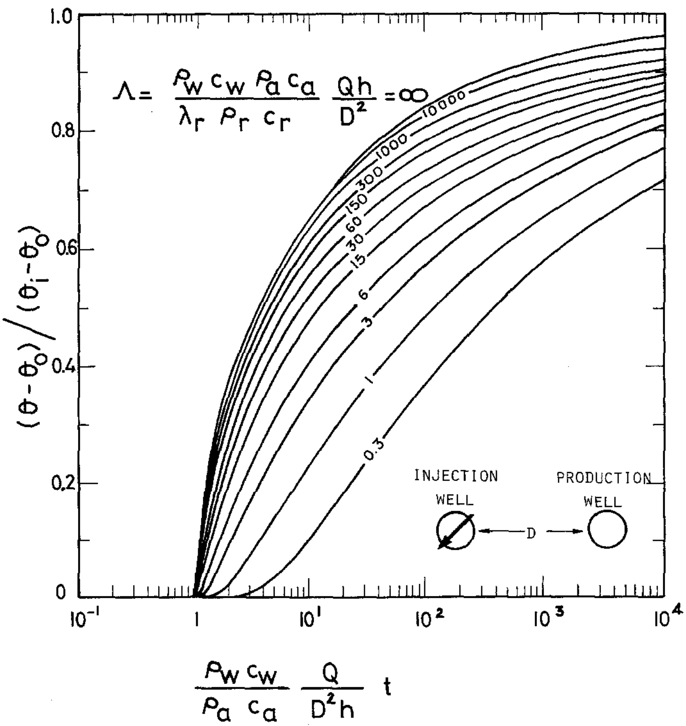

Figure 3
Temperature variation at the production well of a geothermal doublet.

In order to predict the temperature behavior of the aquifer during reinjection, it is necessary to utilize a heat/flow model. In such a model, the heat and flow equations, respectively:

$$\operatorname{div}(K\nabla H) + Q = S\frac{dH}{dt}, \tag{7}$$

$$\operatorname{div}(\lambda\nabla T) - \operatorname{div}(\rho_w c_w v T) = \rho_a c_a \frac{\partial T}{\partial t}, \tag{8}$$

should be solved in a coupled manner, because the permeability K in Eqn. (7) includes the water viscosity and therefore depends upon the temperature, which in turn depends upon the potential field (velocity v in Eqn. (8)). This requires a rather complex computer program, the accuracy of which is usually not very satisfactory because of numerical dispersion. It is possible, however, to analytically approximate the solution, by using hypotheses that result in decoupling Eqns. (7) and (8). Such a simplified solution, published by GRINGARTEN and SAUTY (1975), will be used in this paper.

3.1. *Single doublet*

GRINGARTEN and SAUTY (1975), by neglecting horizontal thermal conduction in the aquifer and the confining rocks, have obtained the curves shown in Fig. 3 for an isolated doublet. In Fig. 3, the production well dimensionless temperature:

$$T_{wD} = \frac{\theta - \theta_0}{\theta_i - \theta_0} \tag{9}$$

is plotted versus a dimensionless time:

$$t_D = \frac{\rho_w c_w}{\rho_a c_a}\frac{Q\,\Delta t}{D^2 h} \tag{10}$$

for various values of a coefficient characteristic of heat exchange with the confining rocks:

$$\Lambda = \frac{\rho_w c_w \rho_a c_a}{\lambda_r \rho_r c_r}\frac{Qh}{D^2} \tag{11}$$

θ_0 and θ_i are the initial and injection temperature, λ_r is the confining rock vertical thermal conductivity, and D is the distance between the wells of the doublet.

It can be seen from Fig. 3 that the time of thermal breakthrough increases with decreasing Λ. It is minimum and equal to $\pi/3$ when $\Lambda = \infty$ (no heat loss to the confining rocks). In this paper, the theoretical thermal breakthrough time corresponding to $\Lambda = \infty$ will be defined as the *lifetime of the doublet*. It is also equal to the water breakthrough time, multiplied by $\rho_w c_w \phi/\rho_a c_a$. The following relationship is thus obtained:

$$\frac{\rho_w c_w}{\rho_a c_a} \frac{Q\,\Delta t}{D^2 h} = \frac{\pi}{3}. \tag{12}$$

Equation (12) yields the *minimum distance* D between the doublet wells for the production temperature to remain constant for a period Δt at a constant injection and production Q.

Another relationship between D, Q, and the steady state well drawdown is obtained from the potential theory:

$$s = \frac{Q}{2\pi T} \ln \frac{D}{r_w}. \tag{13}$$

Equation (13) yields the *maximum distance* D that will maintain the drawdown at the well above the maximum possible drawdown s_{max}.

It is then possible to combine Eqns. 12 and 13 in order to find the distance D that will provide the *maximum constant rate* Q corresponding to a lifetime Δt and to the maximum possible drawdown at the well, s_{max}. For instance, with $\Delta t = 30$ years, $s_{max} = 200$ meters, $r_w = 0.075$ m and the data of Table 1, one obtains:

$$Q_{max} = 0.128\ \mathrm{m^3/sec}\ (459\ \mathrm{m^3/hr}) \quad \text{and} \quad D = 1417\ \mathrm{m}\ \text{for Aquifer A},$$

$$Q_{max} = 0.013\ \mathrm{m^3/sec}\ (47\ \mathrm{m^3/hr}) \quad \text{and} \quad D = 1170\ \mathrm{m}\ \text{for Aquifer B}.$$

These figures are to be compared with those obtained previously with the model of a single well in a constant pressure circle. In this case, however, the *total production* from the entire aquifer could be much higher, because of the possibility of having several doublets in the same aquifer.

3.2. Multi doublet patterns

In order to evaluate the maximum aquifer production that can be reached with a doublet type of development, we will consider different doublet patterns, and calculate for each one the reservoir lifetime and heat recovery factor.

The reservoir lifetime is simply obtained by computing the time required for a water particle to travel from one input to one output well along the streamline of highest average velocity (MUSKAT, 1946) and multiplying it by $\rho_w c_w \phi / \rho_a c_a$.

The results of the calculations are presented in Figs. 4 and 5. Figure 4 shows the ratio of the reservoir lifetime with various *two doublet patterns* to that with a single doublet, as a function of a/D, where a is the 'distance' between the doublets (as indicated in Fig. 4). It appears that the lifetime ratio is always less than unity when the respective positions of injection and production wells are such that an impermeable (fictitious) boundary is created between the doublets (patterns (1) and (2) in Fig. 4). It increases with a/D and approaches unity within 1% when $a/D = 2$. On the contrary, this ratio can be *greater than one* if the well positions are such that a constant pressure

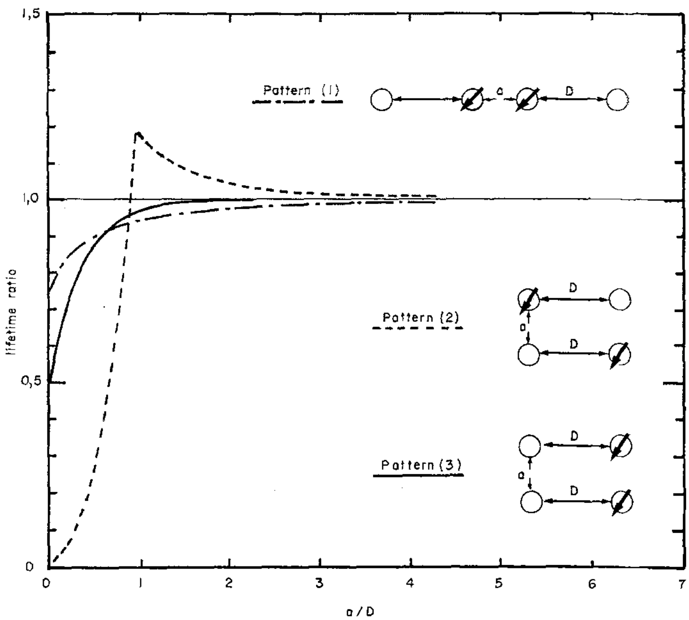

Figure 4
Comparison of reservoir lifetime for various two-doublet patterns.

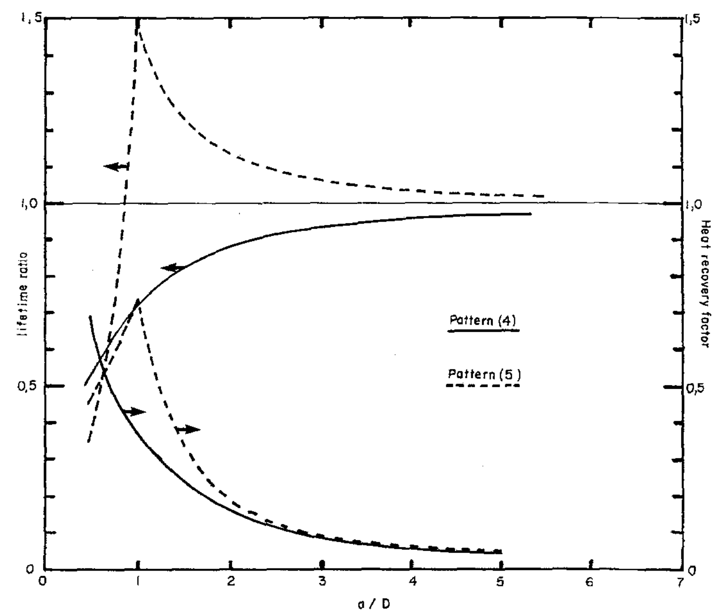

Figure 5
Comparison of reservoir lifetime and heat recovery factor for various patterns of doublet development.

boundary is created between the doublets (pattern (3) in Fig. 4). A type (3) pattern is therefore more adequate in a geothermal aquifer development.

This point is further emphasized in Fig. 5, where a *totally developed* aquifer is considered with the two different patterns shown in Fig. 6, one generating no flow boundaries between the doublets – pattern (4) – and the other generating constant pressure boundaries – pattern (5). With pattern (4) (doublet in a closed rectangle), the reservoir life is always less than that with a single doublet in an infinite system. It increases with a/D, and approaches that with a single doublet within 5% if $a/D \geq 4$ (drainage area equal to $20D^2$).

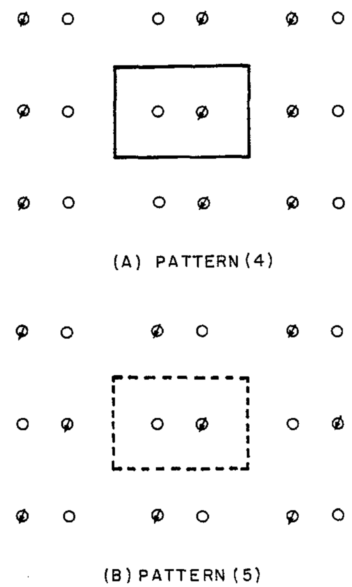

Figure 6
Various possible doublet arrangements in a totally developed reservoir.

On the other hand, with pattern (5) (doublet in a constant pressure rectangle), reservoir lifetime is greater than that with a single doublet for $a/D \geq 0.9$. It is maximum and equal to 1.5 times that with a single doublet when $a = D$ (drainage area equal to $2D^2$). The well arrangement corresponding to pattern (5) with $a = D$ is called a *five spot pattern* in the oil industry.

Heat recovery factors for both patterns (4) and (5) can be obtained from Eqn. (4), which can also be written as:

$$R_g = t_D \frac{D^2}{A}, \tag{14}$$

where t_D (Eqn. 10) is the reservoir lifetime and A the drainage area:

$$A = a(D + a). \tag{15}$$

The results, shown in Fig. 5, indicate that heat recovery is much higher than with no reinjection and can reach 75% with the most efficient pattern (pattern 5).

As an example, with $\Delta t = 30$ years, and the aquifer data of Table 1, and using pattern (5) with $a = D$, the *maximum constant* rate Q_{max} per doublet is:

$$Q_{max} = 0.134\ \mathrm{m^3/sec}\ (481\ \mathrm{m^3/hr}) \quad \text{and} \quad D = 900\ \mathrm{m}\ \text{for aquifer A,}$$

$$Q_{max} = 0.014\ \mathrm{m^3/sec}\ (49\ \mathrm{m^3/hr}) \quad \text{and} \quad D = 750\ \mathrm{m}\ \text{for aquifer B.}$$

The drainage area per doublet is thus 1.62 $\mathrm{km^2}$ for aquifer A and 1.13 $\mathrm{km^2}$ for aquifer B. Assuming a useful aquifer area of 8000 $\mathrm{km^2}$, the total aquifer production rate would be:

$$662\ \mathrm{m^3/sec}\ (2.4 \times 10^6\ \mathrm{m^3/hr})\ \text{for aquifer A,}$$

$$96\ \mathrm{m^3/sec}\ (3.5 \times 10^5\ \mathrm{m^3/hr})\ \text{for aquifer B.}$$

If pattern (4) was used instead of pattern (5), but with the same well spacing, the *maximum rate* Q_{max} *per* doublet would be:

$$Q_{max} = 0.035\ \mathrm{m^3/sec}\ (124.8\ \mathrm{m^3/hr})\ \text{for aquifer A,}$$

$$Q_{max} = 0.005\ \mathrm{m^3/sec}\ (18.7\ \mathrm{m^3/hr})\ \text{for aquifer B.}$$

The total production rate for a total productive area of 800 $\mathrm{km^3}$ would then be:

$$173\ \mathrm{m^3/sec}\ (6.24 \times 10^5\ \mathrm{m^3/hr})\ \text{for aquifer A,}$$

$$37\ \mathrm{m^3/sec}\ (1.32 \times 10^5\ \mathrm{m^3/hr})\ \text{for aquifer B.}$$

4. *Conclusions*

The results presented in this study can be summarized as follows:

(1) Reservoir lifetime and heat recovery factor in geothermal aquifers is very much dependent upon the development scheme.

(2) As a general rule, production with reinjection of heat depleted water increases the heat recovery factor and the aquifer production potential by several orders of magnitude.

(3) When using a doublet type of development (production with reinjection), it does not seem to be a good practice to try to isolate each doublet from the influence of the others. Greater reservoir lifetime and heat recovery factors are obtained by alternating injection and production wells. In other words, geothermal aquifer production should be *unitized*, as is already done in oil and gas reservoirs.

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