專 論

地下水污染物回收之井位設計

Wellfield Design for Groundwater Waste Recovery

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（民國81年3月至81年6月）

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摘 要

地下水污染整治計劃最終目標是將污染之地下水清理，其首要的工作是防止污染物繼續向下游延散。在能夠控制地下水污染物流動的情況下，可以將一部份的污染物由井中抽出，加以處理；其餘殘留在水層中之污染物很難抽出，必需在現場處理。處理的方法包括：地下水推動、化學處理、微生物處理或者將這幾種方法合併運用。一個良好的井位設計計劃，可以增加計劃的可行性與經濟效益。本文將討論回收井之設計規範，並探討幾個現場實例。

ABSTRACT

The objective of a groundwater restoration program is ultimately to clean up the polluted groundwater, but first to stabilize the pollutants and prevent them from spreading further in the direction of natural groundwater flow. After the contaminant movement it stabilized, we will remove part of the pollutants in the groundwater system by pump and treat process, Wells will be drilled to the polluted zone and a pumping/injection scheme will be implemented. A good percentage of contaminants can be pumped out and treated on the surface. The remaining residual contaminant will be treated in-situ, by groundwater sweeps, chemical sweeps, bioremediation or a combination of these in-situ processes. A good wellfield design will enhance significantly the economics of in-situ waste recovery. This paper discusses the criteria for a good wellfield design and presents several field examples.

Introduction

After contaminant migration with the groundwater flow is contained, the next step involves the treatment of the contaminant. A good percentage of contaminants can easily be pumped out and treated on the surface. We have to treat the remaining residual contaminant in situ, either by groundwater sweeps or chemical sweeps or a combination of these in-situ procedures. These in-situ waste recovery procedures will speed up the release of the contaminants from the soil.

A good wellfield design will enhance signi -ficantly the economics of in-situ waste recovery. Figure 1 shows the hypothetical recovery curves from two different wellfield designs- one good and one inefficient. There are basically three major concerns in wellfield design:

- waste concentration in the recovered solution,
- amount of recovery of waste,
- duration of operation,

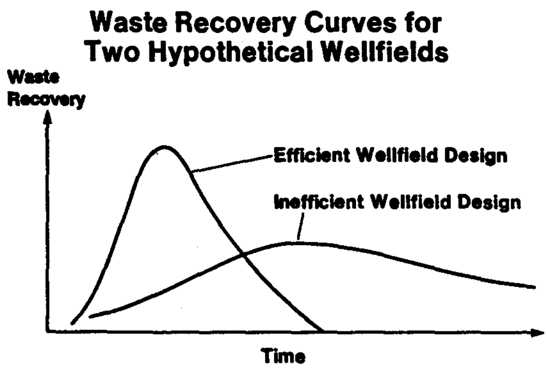


Figure 1. Hypothetical contaminant recovery from two wellfield patterns-one good and one inefficient

Basic Wellfield Pattern

In developing good wellfield design for in-situ waste recovery, we use the technology developed from enhanced oil recovery and in-situ mining. Figure 2 shows the basic wellfield patterns (Craig, 1971). These patterns are used when the contaminated formation has large areal extent in all directions. Special wellfield patterns have to be used for long and narrow strip or odd shape contaminated formations. One of the special wellfield patterns will be shown in the field examples later. Table 1 shows the ratios of recovery to injection wells and areal sweep efficiency at breakthrough in an isotropic homogeneous formation for basic wellfield patterns. The areal sweep efficiency is defined as the percentage of area contacted by injected solution at a given time. For example, Table 1 shows areal sweep efficiency at the time of solution breakthrough at the recovery well for isotropic permeability. For Table 1, very large wellfield patterns have been

Table 1

Wellfield Pattern	Ratio of Recovery to Injection Wells	Areal Sweep Efficiency at Breakthrough
Regular Four-spot	2	73-82%
Skewed Four-Spot	2	70-80%
Five Spot	1	67-73%
Direct Line Drive (d/a = 1)	1	55-60%
Staggered Line Drive (d/a = 1)	1	74-78%
Seven-spot	1/2	73-80%
Inverted Seven-spot	2	73-82%
Normal Nine-spot	1/3	65-80%
Inverted Nine-spot	3	65-80%

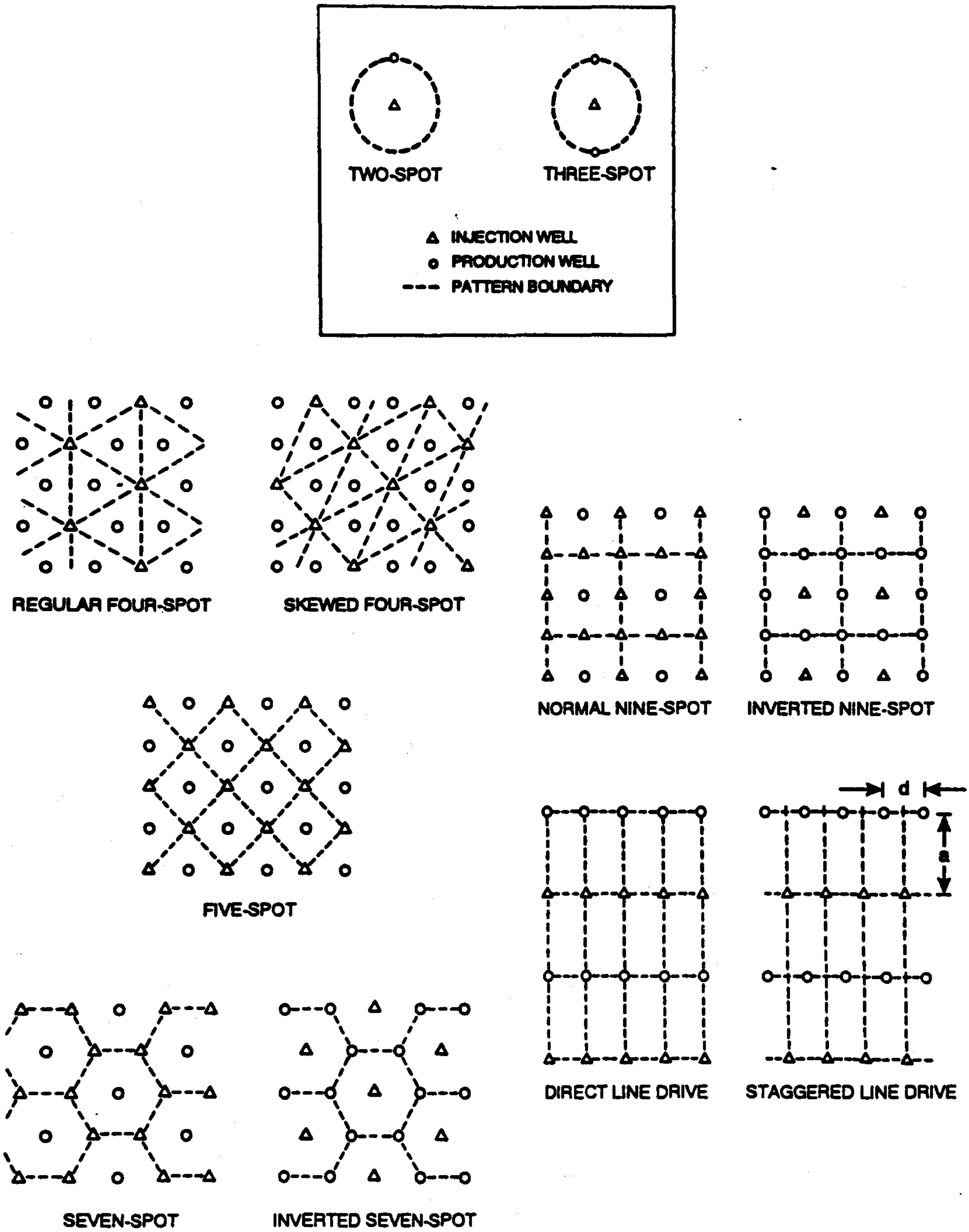


Figure 2. Standard wellfield patterns (craig, 1971)

assumed. A range has been shown for areal sweep efficiency. Different authors have obtained different values for sweep efficiency depending on the method of simulation (Craig, 1971).

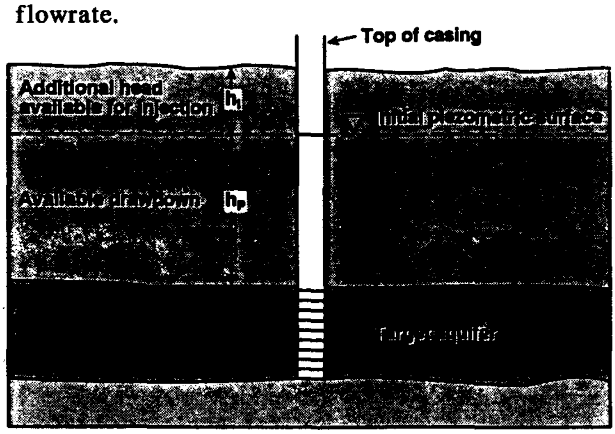
In addition to areal sweep efficiency and breakthrough time, there are several other controlling factors in wellfield design:

- Well productivity and injectivity,
- Formation anisotropy,
- Streamlines and recobery curves.

Well Productivity and Injectivity

Individual well productivity and injectivity provide a good indication of what kind of basic wellfield pattern to consider. Ideally, the ratio of production to injection wells allow all production wells and injection wells to operate near their hydrologic limits. For example, if a well can produce 50 liters per minute but only inject 25 liters per minute, then twice as many injection wells are needed to operate the wellfield at the production well limit. (It is common to be able to pump more from a well than can be injected into the same well.) Checking Table 1, one may want to consider using a seven -spot pattern. Additionally, injectivity and productivity of individual wells determine the breakthrough time and hence, impact economics. Greater well spacing increases the time to breakthrough by lengthening the flow path.

Individual well injectivity is directly proportional to the wellhead injection pressure and the additional head resulting from the distance from the static water level to the top of the casing. Individual well productivity is proportional to the available drawdown. The wellhead injection pressure is the pressure applied at the top of casing during injection. Higher injection or wellhead pressures result in higher injection rates. Injection perssures should not exceed the pressure at which hydraulic fractures would begin to develop which would short-circuit flow between injection and production wells or cause vertical excursions. Likewise, the water level in the production well should not fall below the top of the formation (or the submersible pump suction!). The flow between injection and production wells is caused by the difference in pressure in the formation caused by the production well drawdown and the bottom hole injection pressure. Figure 3 illustrates this point for an artesian situation. Note that if the static water level is near the top of casing, then there is little additional static head to increase the downhole injection pressure and one might expect injection flowrate to be less than the production flowrate, and conversely with the static water level near the top of casing, the possible drawdown is much greater and the production flowrate should be greater than the injection flowrate.



Injection flow rate, Q_I, is proportional to h_I + wellhead injection pressure

Production flow rate, Q_P is proportional to h_P

Figure 3. Injection pressure and production drawdown for an artesian aquifer

Well efficiency is the ratio of actual flowrate compared to the theoretical flowrate. For example, if a well is capable of producing

100 liters per minutem, but is only actually producing 80 liters per minute, then the well efficiency is 80%. It is important for wells to operate as efficiently as practical. Properly designed and developed wells should have a well efficiency above 80%. Well drilling and completion techniques can impact well efficiency. It is common for well efficiency to slowly decrease during operation due to an assortment of reasons and periodic cleaning is required to maintain design flowrates.

Formation Anisotropy

Directional permeability is one of the geologic properties of the formation, It shows the preferential groundwater flow direction. In order to optimize the area coverage, it is suggested to orient the direction of flow along the direction of minor permeability. Figure 4 presents two different cases for direct-line drive well patterns. In case 1, direction of minor permeability is perpendicular to the flow direction, and the areal coverage is small. Case 2 provides better coverage because the direction of minor permeability is parallel to the general flow direction.

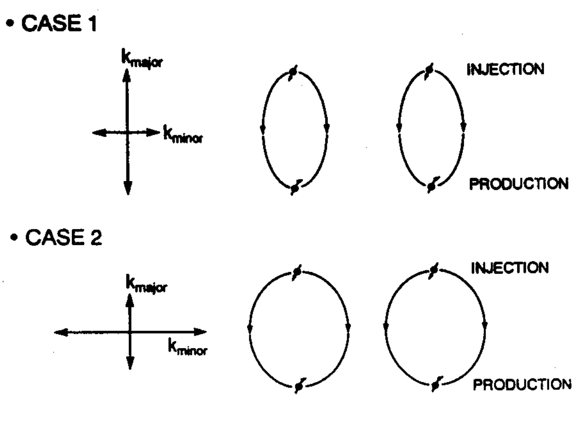


Figure 4. Effect of horizontal directional permeability

Streamlines and Recovery Curves

How long the chemicals or nutrients can stay in the ground and how far they can travel without losing their effectiveness needs to be examined before the well spacing can be determined. A laboratory "stream tube" experiment and/or computer simulated streamline model will be very helpful in selecting the proper chemical mix or nutrients. The idea is to minimize the number of streamline pore volumes to affect the contaminant.

One pore volume is the amount of liquid that will fill up the pore space of a specific volume. For example, in a tube with a capacity of 10 liters and effective porosity of 25%, one pore volume is equivalent to 2.5 liters. The streamline pore volume is the volume of the pore spaces associated with a particular streamline. Theoretically, streamlines have no volume. For practical purposes, all the pore space between two adjacent streamlines is equally divided and considered to be associated with each of the streamlines. The streamline pore volume refers to this pore space.

Let's assume that it takes continuous passing of 25 liters of chemical to leach out the target contaminant in the stream tube considered here. We could also say that it takes 10 pore volumes of chemical to accomplish the clean-up. Obviously, the smaller number of pore volumes required for clean-up the better, since this means less chemical and less time to achieve clean-up.

Using the data shown on Table 2, a series of cases were run using the TRACER computer program. The effect of different wellfield spacing, flowrate per well, and the streamline pore volume on the production from a hypothetical wellfield were investigated by changing one variable at a time and holding the other input parameters constant.

Table 2

Input Variables to TRACER Model

Well/Wellfield	Wellfield size: 122m × 122m
	Well diameter: 0.1m
	Well efficiency: 85%
	Production bleed stream: 1%
Aquifer	Transmissivity: 7.5sq. m/day isotropic
	Storage coefficient: 5×10^5
	Porosity: 20%
	Static water level: 76m above top of sand
	Maximum drawdown: 61m
	Depth to top of sand: 152m
	Thickness of sand: 15.2m

TRACER is an analytical particle tracking model and has been used extensively for designing wellfields for uranium solution mines and is applicable to all porous saturated deposits. TRACER calculates and plots the movement of injected solutions from the injection well(s) to the production well(s) using a series of particles.

TRACER solves two-dimensional and three-dimensional ground water flow problems. The following are the equations for a two-dimensional case:

$$Txx \frac{\partial^2 h}{\partial x^2} + 2\ Txy \frac{\partial^2 h}{\partial x\ \partial y} + Tyy \frac{\partial^2 h}{\partial y^2} = S \frac{\partial h}{\partial t}$$

$$v_x = -\frac{Txx}{b\phi_e}\frac{\partial h}{\partial x} - \frac{Txy}{b\phi_e}\frac{\partial h}{\partial y}$$

$$v_y = -\frac{Txy}{b\phi_e}\frac{\partial h}{\partial x} - \frac{Tyy}{b\phi_e}\frac{\partial h}{\partial y}$$

where,

Txx, Txy and Tyy are the components of transmissivity (L^2/T)
h is aquifer thickness (L)
x, y are coordinates (L)
t is time (T)
v , v are x-, y-component of particle velocity (L/T)
ϕ is effective porosity (dimensionless)

The examples discussed below are based on typical fivespot patterns (Figure 5). All the examples shown reate to a 122 meters by 122 meters area inside a large homogenous formation.

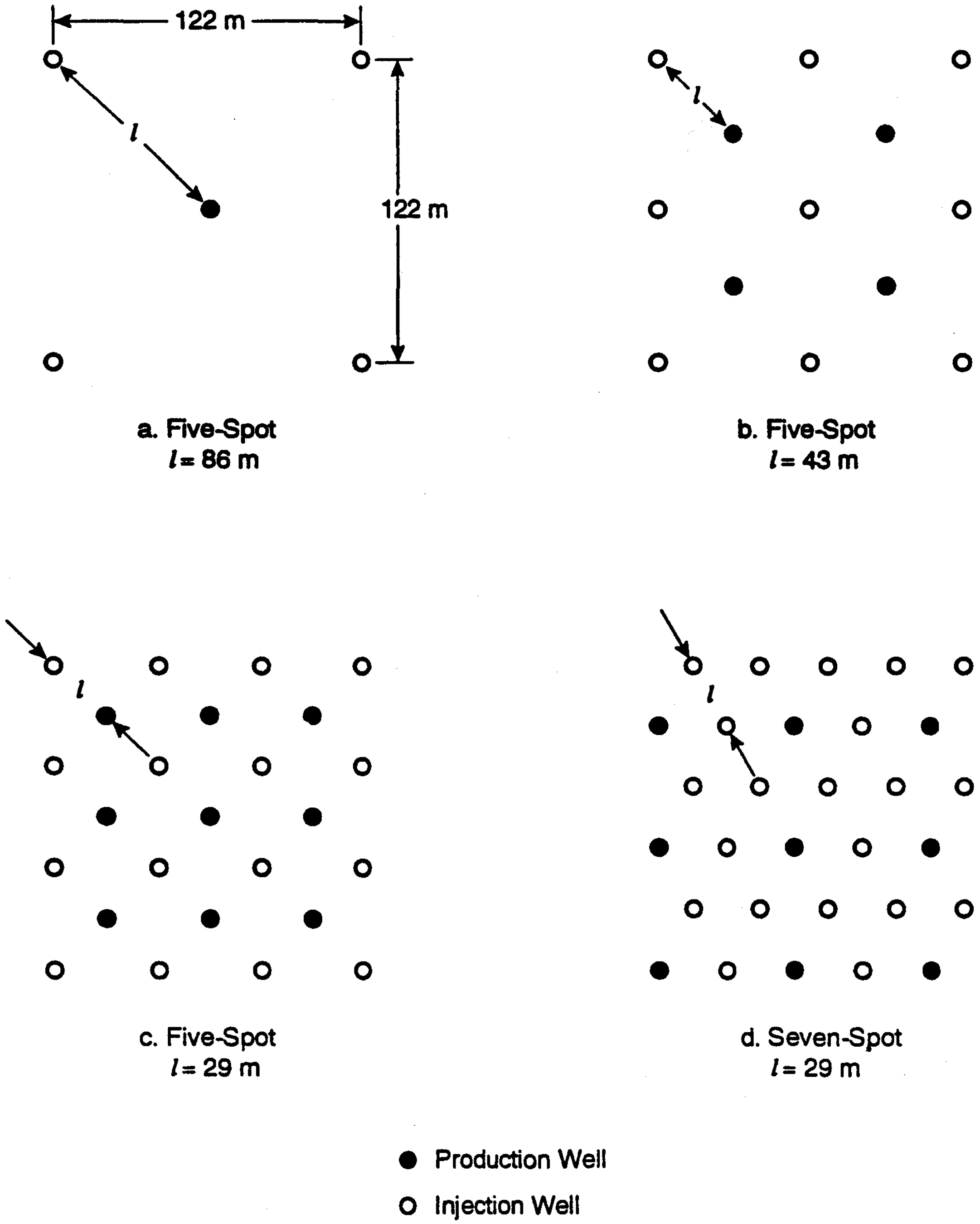


Figure 5. Wellfield patterns used in computer simulation

Figure 6 illustrates the effect on production of varying well spacing. For this example, each production well produces 75 liters-per-minute and the chemical amenability was estimated at 12 streamline pore volumes required to extract the contaminant in the stream tube. As the distance between wells decreases more wells are needed and the total volume of solution circulated in the wellfield increases which results in faster contaminant recovery from the wellfield. The case where one production well and four injection wells (spacing = 86 meters, Figure 5a) are used to clean up the entire wellfield takes a very long time. The case with four production wells and nine injection wells (spacing = 43 meters, Figure 5b) performs better because the wellfield area is being swept with four times more volume of lixiviant. Naturally, the case with nine producing wells and sixteen injection wells (spacing = 29 meters, Figure 5c) cleans up the contaminant in the shortest time.

Figure 7 shows the hypothetic contaminant recovery curves for a 5-spot well field pattern (Figure 5c) operating under various flow rates (37.5 liters per minute, 75.0 liters per minute, and 112.5 liters per minute). As expected, larger flow rate would increase the contaminant reco -very concentration and reduce operational time.

A simple, effective chemical model is used in modelling wellfield production. The model assumes that injected chemical solutions are of sufficient chemical strength to leach contaminant all along the streamline area. The effectiveness of the chemical solution is reflected by the number of "streamline pore volume".

Some contaminants are simply more difficult to clean up than others and a greater volume of lixiviant must be circulated to extract the contaminant. The effect of having to circulate a greater volume is given in Figure 8. The streamline pore volume is a modelling number and represents the number of times lixiviant must circulate through a streamline to extract the contaminant. For example, in a laboratory column test if it took 6 pore volumes to extract the contaminant along the streamline defined by the column for one type contaminant and 12 pore volumes for another type contaminant it would be reasonable to expect the first contaminant to leach with fewer pore volumes of lixiviant in a wellfield than the second contaminant due to differences in the contaminany's chemical amenability.

The advantage of selecting the best available chemistry (lowest streamline pore volume is evident in Figure 8).

All of the cases discussed so far have been for five-spot patterns. Figure 9 does compare a five-spot wellfield (Figure 5c) to a seven-spot wellfield (Figure 5d) and shows very little difference. Why? The production well flowrates are the same and there are the same number of producing wells in the five-spot wellfield and the seven-spot wellfield. When the volume of lixiviant circulated per unit time is the same, the performance will be similar. There is a slight difference in the production curves due to the swept area differences between a five-spot and a seven spot.

The decision in selecting an optimum wellfield is usually an economic issue. Too many wells increases the capital expenditures and too few wells lengthens the operating time.

Field Examples

The above discussion provides some fundamentals in designing wellfields for waste recovery.

The same concepts and fundamentals apply to in-situ mining as well as to in-situ waste recovery. Because of the anisotropy, heterogeneity, and spatial variation of formations, we

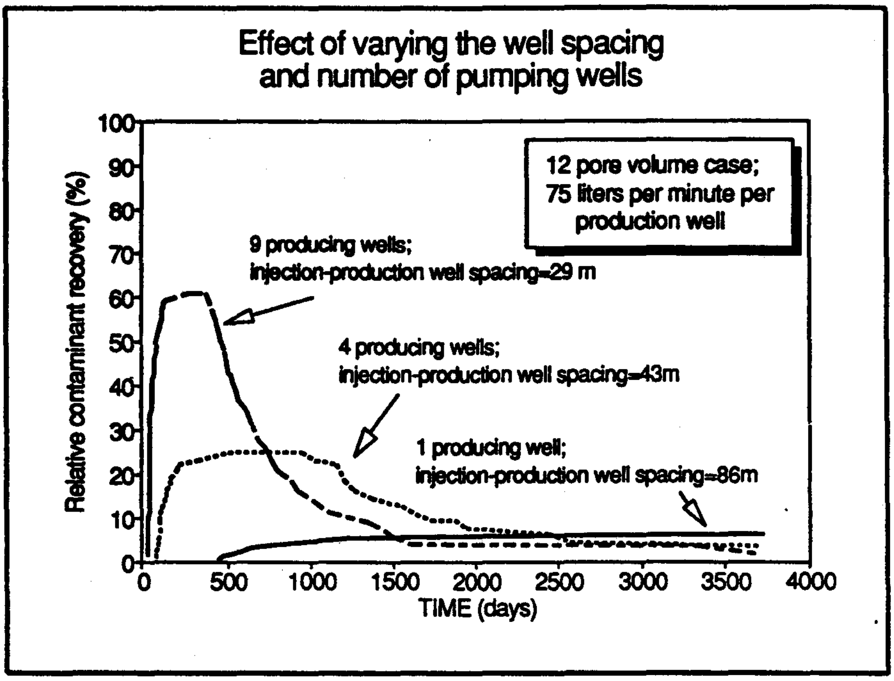


Figure 6. Effect of varying the well sacing and the number of wells in five-spot wellfield patterns

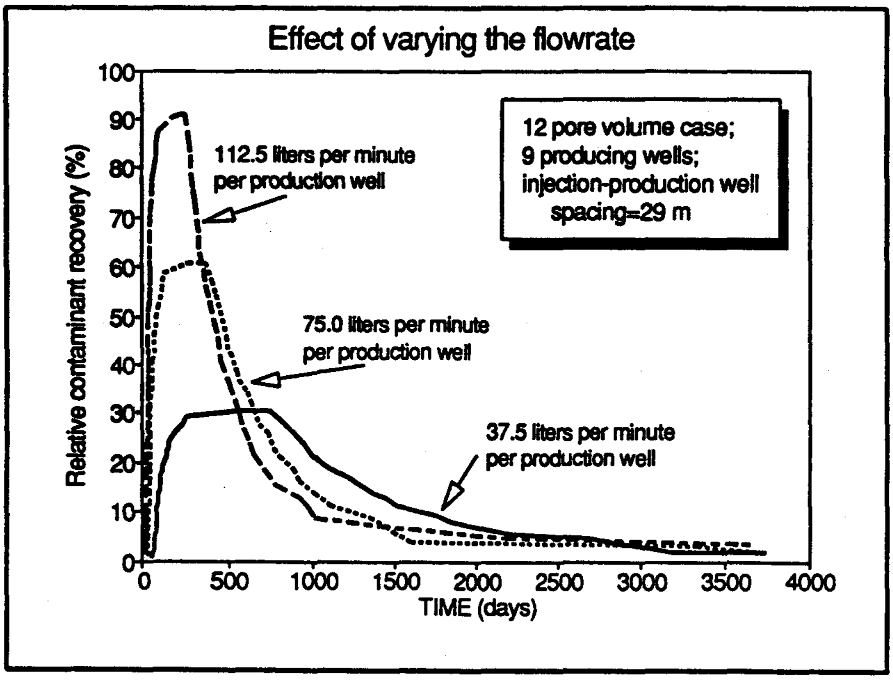


Figure 7. Effect of varying the flowrates in a five-spot wellfield pattern

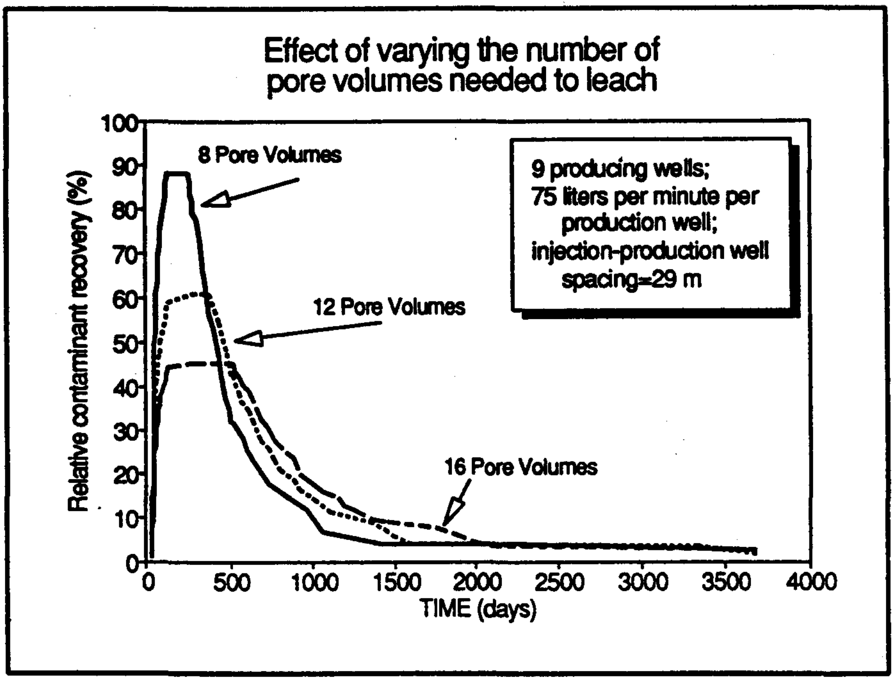


Figure 8. Effect of varying the number of pore volumer in a five-spot wellfield pattern

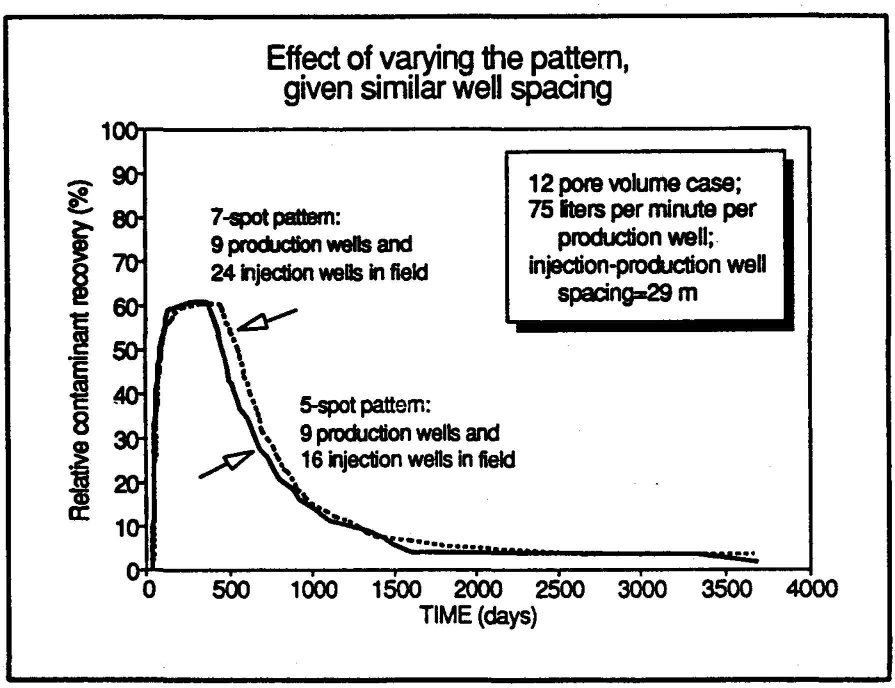


Figure 9. Relative contaminant recovery curves in a five-spot and a seven-spot wellfield pattern

suggest the use of computer models to optimize the wellfield design. We will use three wellfield designs for in-situ uranium operations as examples to illustrate the importance of wellfield design in effective mineral recovery, and by implication, contaminant clean-up.

Case 1: Fourteen Well Pattern (Texas)

This was one of the earliest in-situ uranium operations (Figure 10). The wellfield was consisted of seven injection wells and seven recovery wells. Figure 10 shows a particle plot. In this example, 12 hypothetic particles are released by each injection well (at the beginning of the operation) and their movement plotted each day. After 1 day the injected solution has moved a short distance away from the injection wells as shown by the first rings of particles which have formed around the injection wells and after approximately 7 days the first particles have reached one of the production wells. Each particle represents a portion of the daily injected volume and the distance between each represents the distance travelled in one day. The path a particle takes from the injection to the production well is called a " streamline". Note that the length of various streamlines are different and the time for injected solution to travel to the pumped well varies for each stream line. It is important to remember that not all injected solution arrives at the production well at the same time. The phenomenon impacts the contaminant recovery curve.

Theoretically, streamlines have no volume, but for practical purposes it is assumed that streamline pore volume is the pore volume associated with each particular streamline and all the pore space between streamlines is equally divided with each of the streamlines. The streamline pore volume refers to this pore space.

The wellfield was designed based on intuition rather than engineering considerations. It was not a good design. Part of the injected solution was never recaptured by the production wells. Unrecovered injected solution caused excursion and allows water dilution to occur. The large amount of lixiviant leakage to the NW, W, and SW side of the wellfield contributed to poor recovery of this operation (Figure 11).

Case 2: Five-spot Well Pattern (Wyoming)

The isolated five-spot pattern (four injection wells and one production well) is a very popular design for pilot in-situ uranium operations, especially in formations where well injectivity is limited (Figure 12). The use of a computer model gave an excellent view of the flow paths that the lixiviant moved through in the aquifer (Figure 12). Figure 13 shows the computer match of the production curve.

Case 3: Eleven Well Direct Line Drive (Texas)

This is a very interesting wellfield design (Figure 14). The high grade uranium was deposited in a long and narrow strip. Conventional wellfield designs would not work very well in this case. With the help of a computer model, the wellfield was designed to accommodate the deposit and the production curve (Figure 15) reflected the effectiveness of the operation-high uranium concentration and short operation duration.

Conclusion

A good wellfield design will significantly enhance the economics of groundwater waste recovery. The controlling factors in wellfield design includes sweep efficiency, breakthrough time, well productivity and injectivity, formation anisotropy, streamline and recovery curves. The idea is to maximize the contaminant concentration and minimize the operational time.

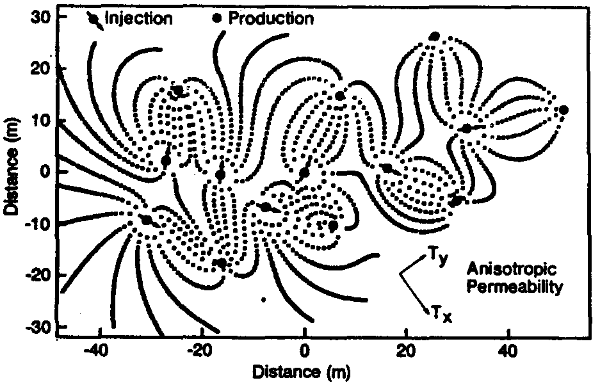


Figure 10. Subsurface flow paths in a fourteen well pattern. Texas

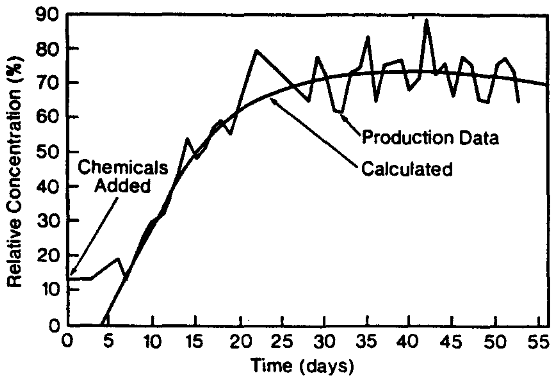


Figure 11. Production match to a fourteen well pattern (Texas) assuming that 10 stream-line pore volumes are required to leach uranium

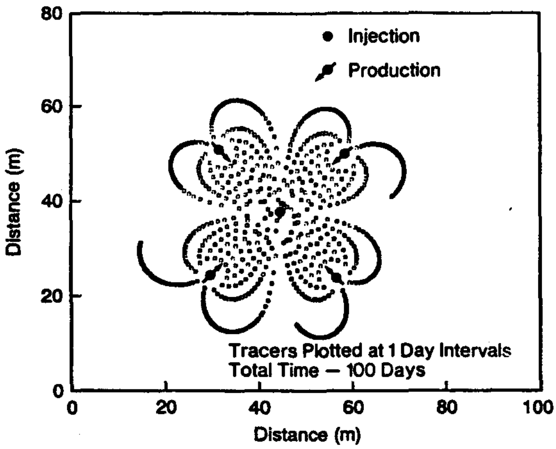


Figure 12. Subsurface flow paths in a five-well pattern, Wyoming

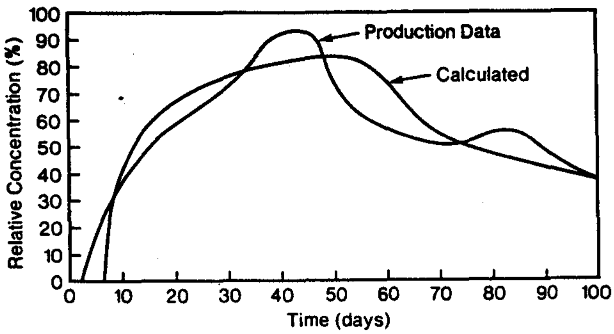


Figure 13. Production match to a five-well pattern (Wyoming) assuming that 8 stream-line pore volumes are required to leach uranium

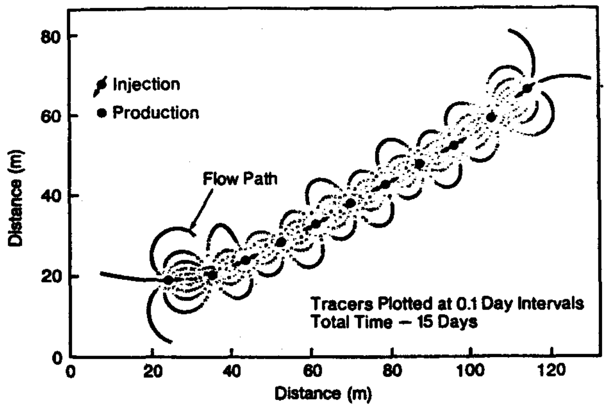


Figure 14. Subsurface flow paths in an eleven-well pattern, Texas

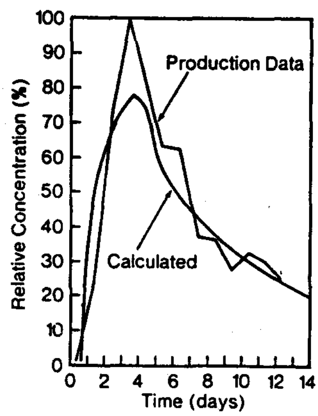


Figure 15. Production match to an eleven-well pattern (Texas) assuming that 6 pore volumes are required to leach uranium

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