GUIDANCE DOCUMENT
FOR THE
AREA OF REVIEW REQUIREMENT

Respectfully Submitted

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Norman, Oklahoma

May, 1985

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I. INTRODUCTION

The Safe Drinking Water Act directs the Environmental Protection Agency (EPA) to develop minimum requirements for State programs to protect underground sources of drinking water (10,000 mg/l TDS or less) from subsurface injection of contaminants. The EPA originally proposed Underground Injection Control (UIC) regulations specifying minimum requirements on August 31, 1976 (41 FR 36 730). Since that time significant changes have been made in the regulations in response to numerous public comments. The regulations were revised as of July 1, 1983 in 40 CFR, Parts 144 through 146. They require that each individual UIC program satisfactorily comply with the minimum requirements set forth.

One of the UIC regulations requires the permitting authority to determine, within an "area of review" (AOR), whether a proposed injection operation has a potential for contaminating underground sources of drinking water through wells, faults, or other pathways that penetrate an injection zone. The AOR -- also known as the zone of endangering influence -- is defined to be that area surrounding an injection well or injection well pattern in which the pressure change in the injection zone, resulting from high pressure injection, is great enough to make possible the migration of fluids out of the injection zone and into an underground source of drinking water.

Two alternative methods for determining an injection well's AOR have been provided in the regulations. One method is by using the Theis equation or an equivalent analytical approach.

The other method is by setting a fixed-radius for the AOR of not less than one-quarter mile. The fixed-radius method is to be based on an evaluation of the hydrogeology, historical practices, and other relevant factors that characterize the area under investigation. Such an evaluation is to guide the selection of an appropriate radius for the AOR.

Once the AOR has been determined, each permit applicant must review the available completion/plugging records for all wells that penetrate the injection zone within the AOR. He must determine whether conditions or pathways exist that might allow the migration of formation or injected fluids out of the injection zone. If he finds such conditions, he must correct the conditions or take preventive action before using the injection well.

Statement of the Problem

During previous research conducted by Engineering Enterprises, Inc. (EEI), two specific problems with applying the AOR requirement were identified. First, it can become extremely difficult to confidently delineate an AOR in situations where the hydrogeology is complex or in situations where little is known about the hydrogeology. Second, in some instances as many as several hundred wells have been identified within an AOR making a review of potential pathways burdensome if not impossible.

Because of the problems associated with delineating an AOR and because there is debate as to the appropriate method or approach to use, this study was carried out to prepare an AOR guidance document. Many of the conclusions and recommendations included in this document came directly from State program experiences and therefore should present useful background information on what criteria and procedures are being used to determine the adequacy of AOR standards.

II. CONCLUSIONS AND RECOMMENDATIONS

One of the research objectives of this study was to evaluate how the AOR requirement is being interpreted and applied. To meet this objective a survey of State UIC Programs was conducted. Specific information solicited from individual UIC programs to accomplish this objective included:

a. the method used to delineate an AOR;

b. problems associated with the AOR requirement specific to each program; and

c. input and suggestions from personnel responsible for the AOR requirement that may be helpful to others.

The survey of UIC programs indicated that the basics of the AOR concept were generally understood in most cases. The survey did, however, show that the application and definition of the requirement needs to become more uniform from program to program. There is also a need to correct the misapplications that were identified and to provide technical assistance to alleviate specific problems with applying the requirement.

Most problems identified with the AOR process dealt with predicting, with confidence, the zone of endangering influence and therefore the area that is to be examined for potential pathways. The two methods for accomplishing this process, given in the regulations, are lenient compared to some methods used for reservoir analyses. These two methods were selected for reasons of simplicity to expedite the AOR requirement. It is reasonable to expect that an AOR determined by either method will vary in accuracy, because of assumptions used to simplify sometimes complex situations. For this reason, it is very important to understand the limitations of the method used and to use professional judgment in determining if the selected AOR is adequate for the situation under investigation.

The methods used to determine an AOR have been the subject of much debate between permitting authorities, industry, and the EPA. A majority of programs are using, or are proposing to use, a fixed-radius approach to the AOR rather than an analytical approach. This is mainly because analytical solutions to the AOR will be limited to areas where the hydrogeologic conditions satisfy the basic assumptions implied by the equations and where adequate information exists that describes the hydrogeologic conditions. Also, the use of a fixed-radius approach will expedite the implementation of UIC programs and has been shown to reflect existing practice for some States.

The major problem identified with the use of a fixed-radius approach involved selecting completely arbitrary fixed radii for the AOR without considering the major factors that may influence it. The regulations imply that judgment should be used to evaluate; hydrogeology, chemistry of injected and formation fluid, groundwater use, and historical practices to guide the selection of an appropriate radius for an AOR. Consideration of these factors will not necessarily give absolute answers to what an appropriate AOR should be. They will, however, provide a few guidelines that Program Directors can use that are adjustable on a case-by-case basis. Obviously a fixed-radius chosen on the basis of past experience with the behavior of a particular injection reservoir is preferable over an arbitrary selection. Previous studies have confirmed that an actual AOR can vary significantly from arbitrarily selected AOR's.

As State programs gain experience with the AOR process, a fixed-radius approach can be refined to reflect more technical consideration. A State program should use all available resources at its disposal to incorporate flexibility, the use of hydrologic intuition, and past experience to guide the AOR process.

When applicable, an analytical approach to the AOR process can be very beneficial if properly used and understood and if the results are qualified within the framework of the assumptions implied by the equations. This can only be accomplished with reliable field data and experience. Personnel who are responsible for the review of AOR applications should be aware of the limitations and the benefits of analytical solutions to well hydraulics as well as knowledgeable on their proper use. For this reason, some critical guidelines are set forth in this document for applying analytical equations to the AOR process. Following these guidelines should remedy many of the misapplications that were identified during the survey of State programs.

Regardless of what method is used to delineate an AOR, States should apply them carefully. The actual zone of endangering influence for a proposed injection well can vary significantly from that of other injection wells even if the wells are located within the same reservoir or well field. Assumptions will have to be made in many AOR determinations because of the lack of basic information. However, assumptions should be technically justified to the greatest extent possible. The degree to which assumptions are validated will play a large role in the accuracy and effectiveness of the AOR process.

The intent of the AOR requirement is to protect underground sources of drinking water. The requirement is not designed to and should not impede oil and gas production activities or disrupt effective State programs unless necessary to protect groundwater. Considering the complexities involved in applying the requirement, the process should be limited to an effort commensurate with the contamination potential of a proposed injection operation. This will require technicians knowledgeable on the subject of reservoir hydraulics and on the relationship between injection wells and reservoir pressure buildup. It would be beneficial to develop an education process -- utilizing either training workshops or seminars -- to ensure the overall effectiveness of the AOR requirement. These seminars could be presented locally and designed to address issues specific to individual programs.

III. DEFINITION OF THE AREA OF REVIEW REQUIREMENT

The AOR requirement was established to provide a means to predict potential problems with pressure buildup resulting from injection operations. While not being necessarily difficult to understand theoretically, the requirement can, in some situations, become quite complex to apply practically.

Three distinct elements of the AOR requirement must be addressed to properly satisfy the intent of the regulations. These elements of the AOR requirement are:

(1) Predicting the AOR or zone of endangering influence;

(2) Reviewing the contamination potential within the predicted AOR; and

(3) Taking corrective or preventive action to reduce the contamination potential.

These three basic elements of the AOR requirement are all necessary to reduce the risk of pollution caused by pressure buildup in an injection zone. The following sections provide an in-depth discussion of each of the basic elements of the AOR requirement.

Predicting the AOR

According to the UIC regulations the AOR is to include the area surrounding an injection well or injection well pattern where pressure buildup in the injection zone creates a potential for contaminating underground sources of drinking water. The potential for contamination occurs within a zone of endangering influence created by and surrounding the injection operation. The zone of endangering influence, resulting from injection, is the area within which the elevation of the initial piezometric surface (fluid level) for the formation fluid in the injection zone is predicted to rise, during the projected life of the operation, to equal or exceed the piezometric surface for any potential underground source of drinking water existing within the same area. Thus, the zone of endangering influence that is expected to result from an injection operation will define the AOR that should be used to satisfy the AOR requirement. To more clearly illustrate this concept, consider the following example.

Example

Consider a typical injection reservoir overlain by a relatively impermeable confining layer. Because of the presence of the upper confining layer, the water of the reservoir is not open to atmospheric pressure. It thus occurs within the pores of the reservoir at pressures greater than atmospheric. Groundwater in such a situation occurs under artesian conditions.

When a well is drilled through the upper confining layer and into an artesian reservoir, water rises in the well to some level above the top of the reservoir. The water level in the well represents the artesian pressure in the reservoir. The elevation to which the water level rises in a well that taps an artesian reservoir is known as the piezometric level. An imaginary surface representing the artesian pressure throughout all or part of the reservoir is called the piezometric surface. When the elevation of the piezometric surface in an injection reservoir is raised above the elevation of the water level in a fresh water aquifer then migration of fluid from the injection zone into the fresh water aquifer is possible.

Figure III-1 illustrates an example of the initial piezometric surface in an injection zone. In this figure, P_i, (the hydraulic head) is the vertical distance from the piezometric surface down to the bottom of the well. For this example a minimum pressure increase equivalent to ΔP would be required to make possible migration from the injection zone into the fresh water aquifer.

When injection into or withdrawal from a reservoir begins the initial piezometric surface will be altered by the development of pressure increases from injection or decreases from withdrawal. In the case of injection, the highest pressure increase will be in the immediate vicinity of the injection well and will decrease when moving radially away from the well. The resulting pressure profile caused by injection into the reservoir is called a cone of impression with its base located on the initial piezometric surface as shown in Figure III-2.

The zone of endangering influence and thus the AOR will be delineated by and depend on the position and dimensions of the cone of impression created during the life of an injection operation. The AOR will include the area within the injection zone

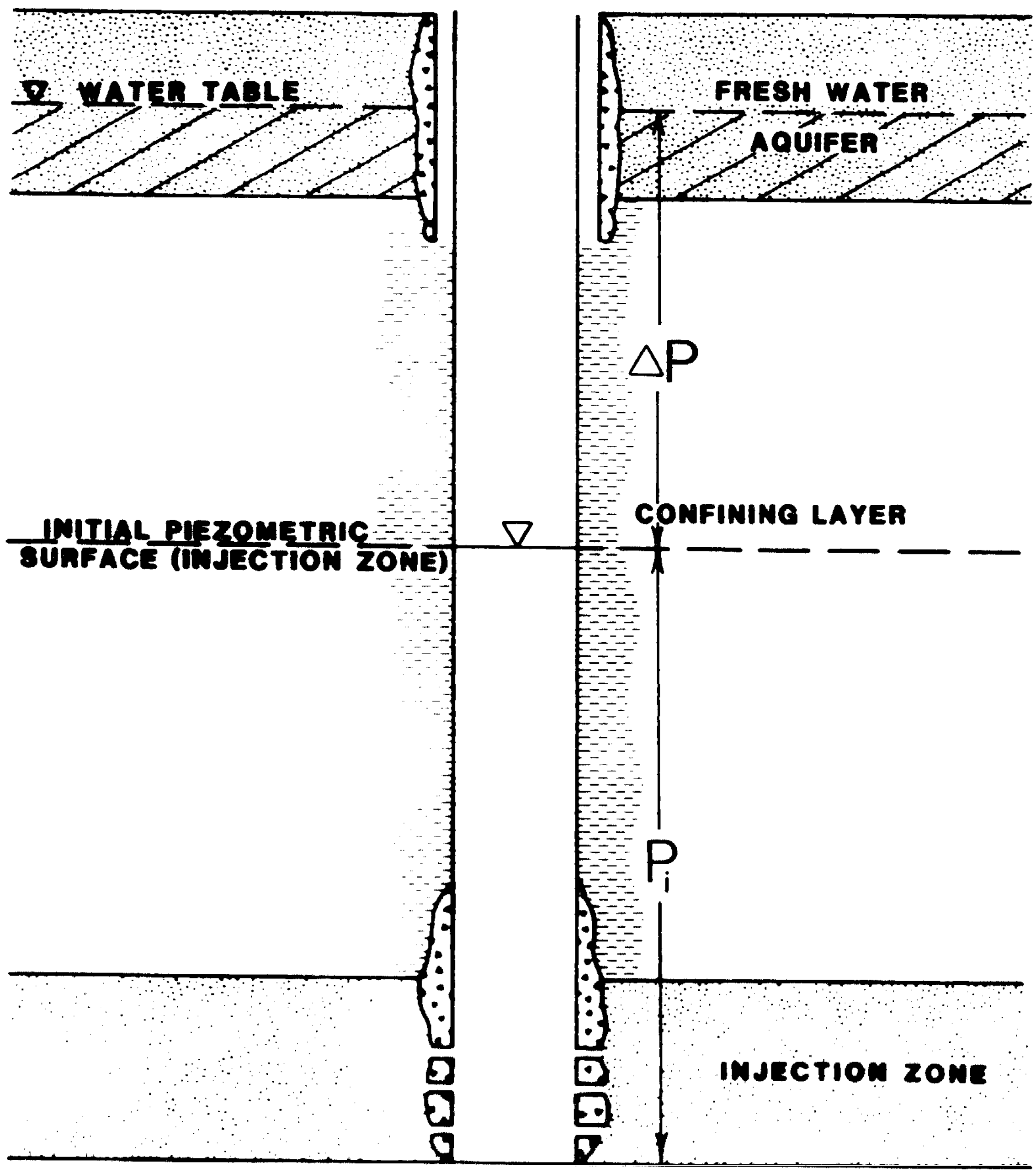


Figure III-1. Example showing the hydraulic head, P_i, of an injection zone and the increase in head, ΔP, that would be required for migration to be possible close to, or at, the injection well.

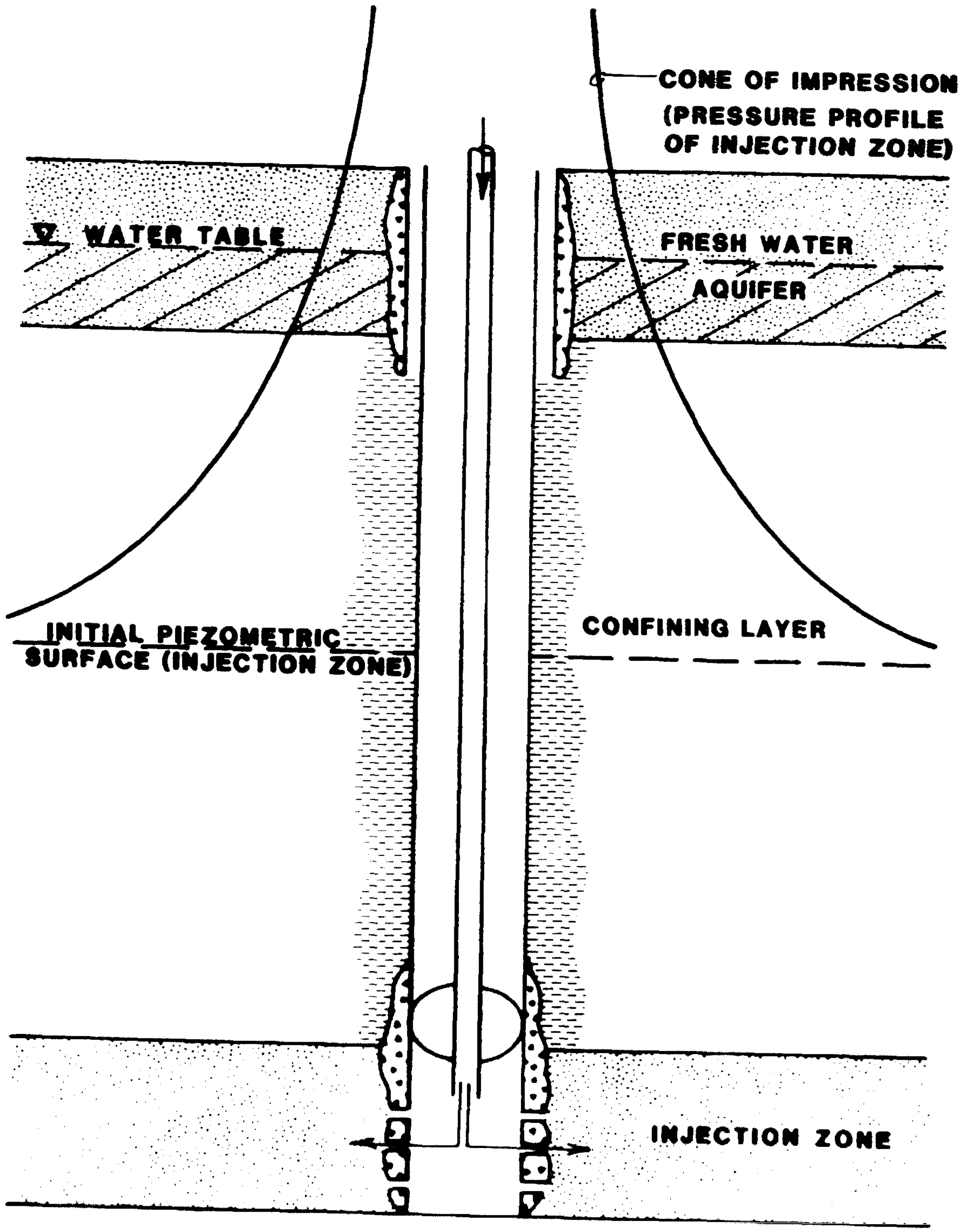


Figure III-2. Idealized example of a cone of impression.

where the pressure change caused by injection raises the piezometric level of the injection zone above the water level (or piezometric level) in the fresh water aquifer. Figure III-3 illustrates how the position of the cone of impression will define the radius of the AOR. In this figure it can be seen that within any distance R from the injection well the resultant pressure in the injection reservoir is greater than the water level in the fresh water aquifer.

Since Figure III-3 is a cross-section view it shows R in only one direction. Actually R will be equally defined any radial direction from the injection well as illustrated in the plan view of Figure III-4.

Within the delineated AOR there is a potential for contaminating the fresh water aquifer because of the pressure differential. Fluids will flow from points of higher to lower pressure if there is a pathway available through which flow can occur. Therefore contamination of the fresh water aquifer shown in the preceding figures can occur when there is a pathway connecting the injection reservoir and the fresh water aquifer within the AOR.

The preceding discussion and examples define how the AOR is described by the boundary of the zone of endangering influence surrounding an injection operation. If a fixed-radius approach for delineating the AOR is used then it should be large enough to encompass the expected zone of endangering influence.

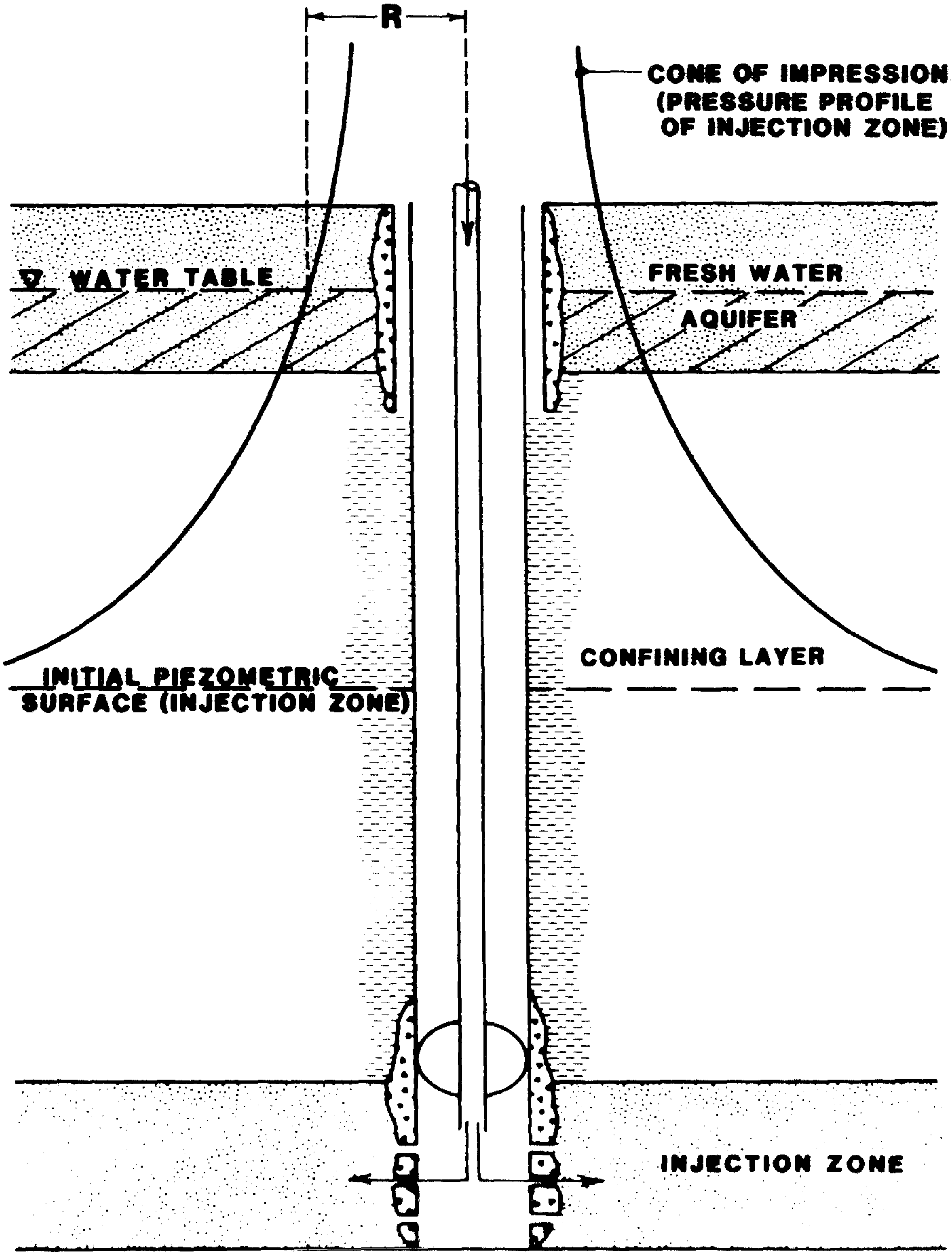


Figure III-3. Example showing how the position of the cone of impression defines the radius, R, of the AOR.

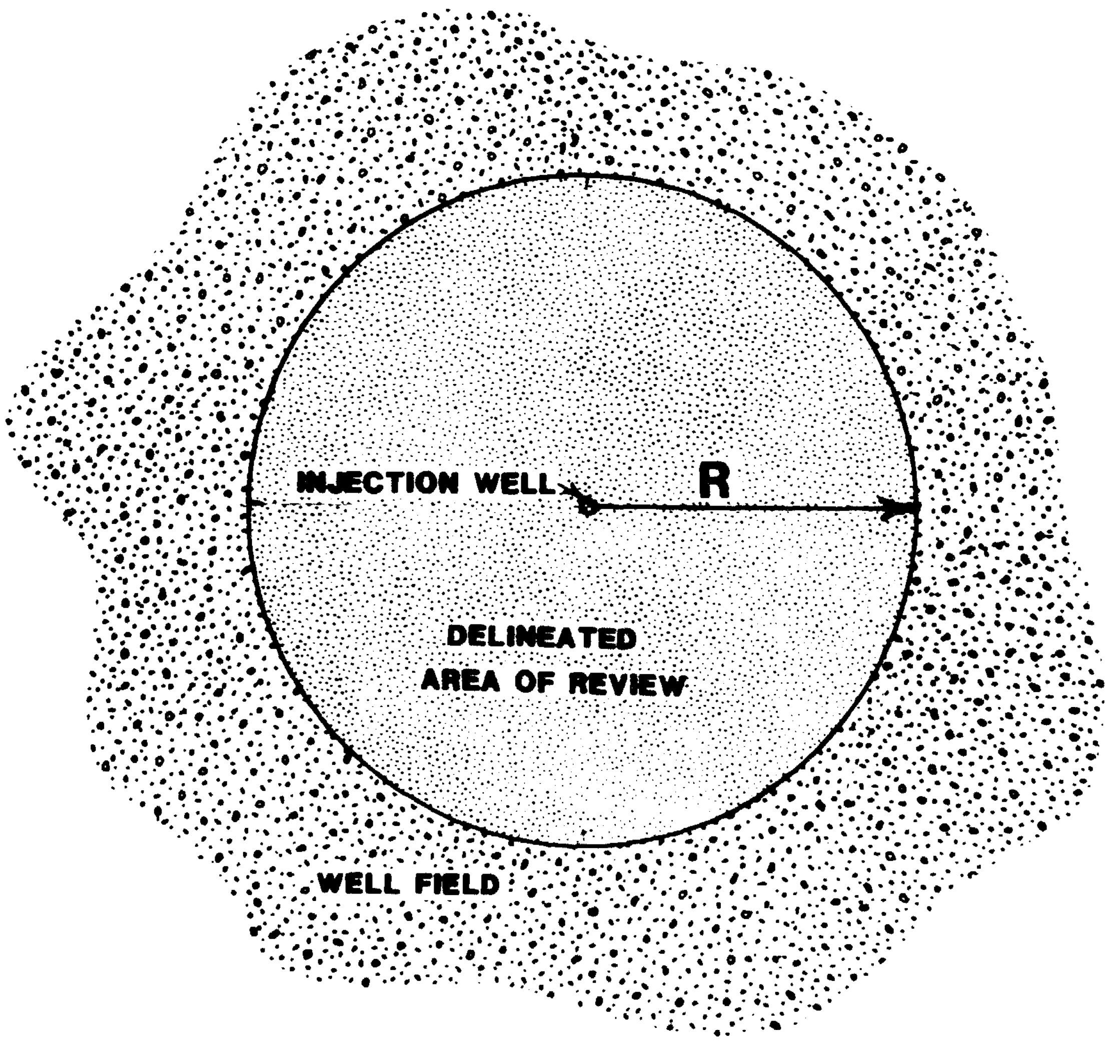


Figure III-4. Plan view of a delineated AOR.

Computing or estimating the zone of endangering influence will require an evaluation of several important factors that include:

a. The initial piezometric surface in the injection zone.
b. The water levels or piezometric levels associated with overlying underground sources of drinking water.
c. The hydraulic properties of the injection reservoir.
d. The hydrogeologic boundaries in the area.
e. The influences of other nearby wells, either injecting or withdrawing from the same reservoir.
f. The injection and withdrawal rates.
g. The proposed life of the injection operation

Any combination of the factors listed above could be critical for establishing an appropriate AOR for a given area. A discussion of how these factors can affect the AOR and how they should be considered is presented in Section V.

Reviewing the Contamination Potential

Once the AOR has been determined, the regulations require that a review be made within the AOR to determine if pathways exist that may allow hydraulic communication between the injection zone and an underground source of drinking water.

Potential pathways for hydraulic communication can include improperly plugged, completed, or abandoned wells that penetrate both the injection zone and fresh water zones. Figure III-5 shows an example of fluid from the injection zone migrating upward into a fresh water aquifer through an unplugged well that

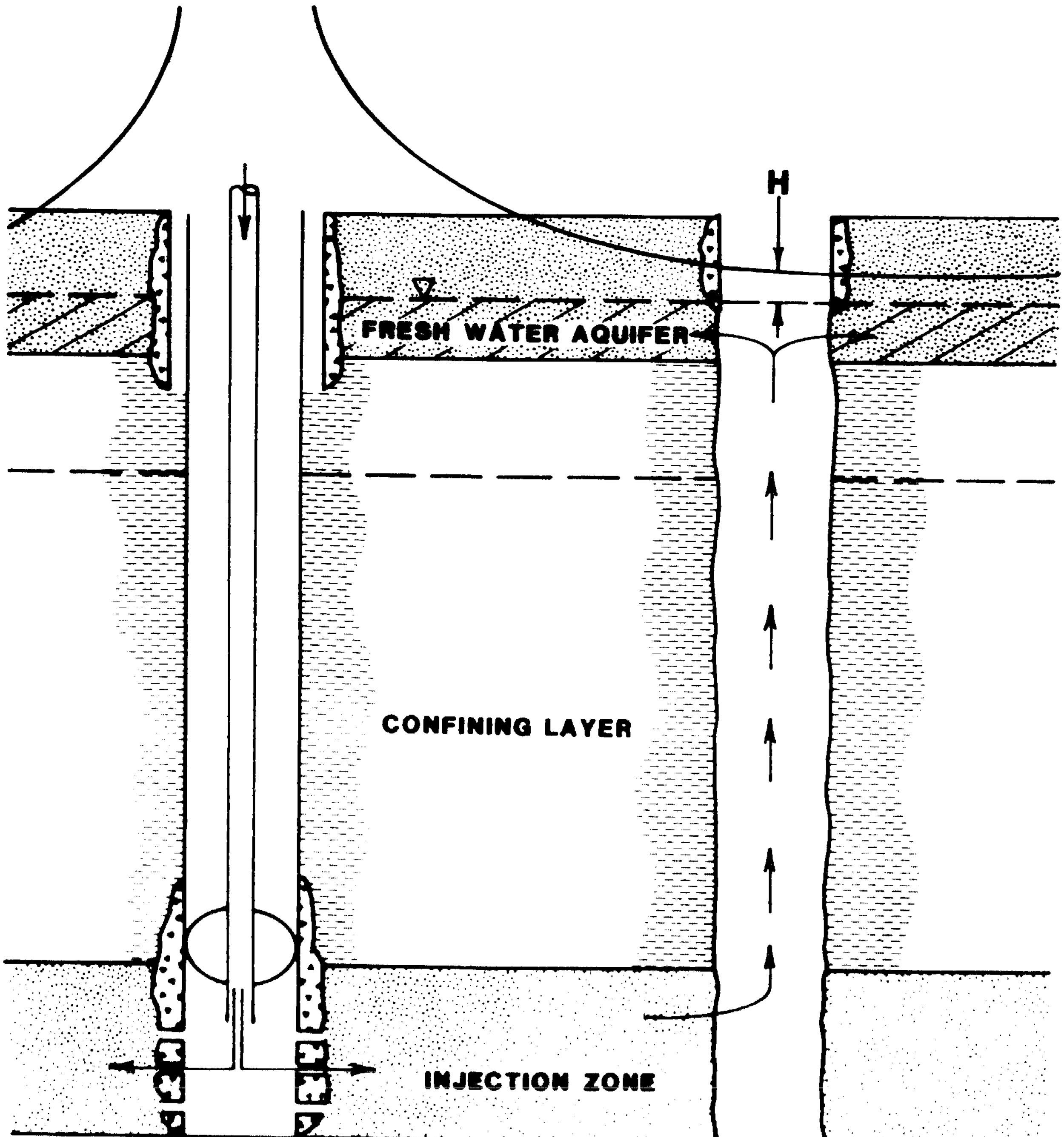


Figure III-5. Example of fluid migrating from the injection zone into a fresh water aquifer through an unplugged well. Migration is made possible because of the pressure differential, shown as H.

penetrates the injection zone within the zone of endangering influence created by the injection operation. In this case migration occurs through the available pathway because the initial pressure of the fluid in the injection zone at the location of the pathway was raised higher than the water level in the fresh water aquifer. The pressure differential shown as H in the figure causes migration of fluid from the injection zone into the fresh water zone. If this pathway were located outside of the zone of endangering influence -- where the fluid pressure in the injection zone is below the water level in the fresh water zone -- then migration would occur in a direction opposite to that shown in the figure.

Other possible pathways can be fractures or faults that provide a means for hydraulic communication between the injection zone and an underground source of drinking water. Figure III-6 shows an example of fluid moving from the injection zone into a fresh water zone through a fault that penetrates the injection zone within the zone of endangering influence of an injection well.

To mitigate potential contamination of underground sources of drinking water the AOR process requires that possible pathways, within an AOR, be identified. Applicants for Class I, II (other than existing), or III injection well permits are required to locate all known wells within the injection well's AOR and which penetrate the injection zone. Information on known faults or fractures is also required. Only information of public

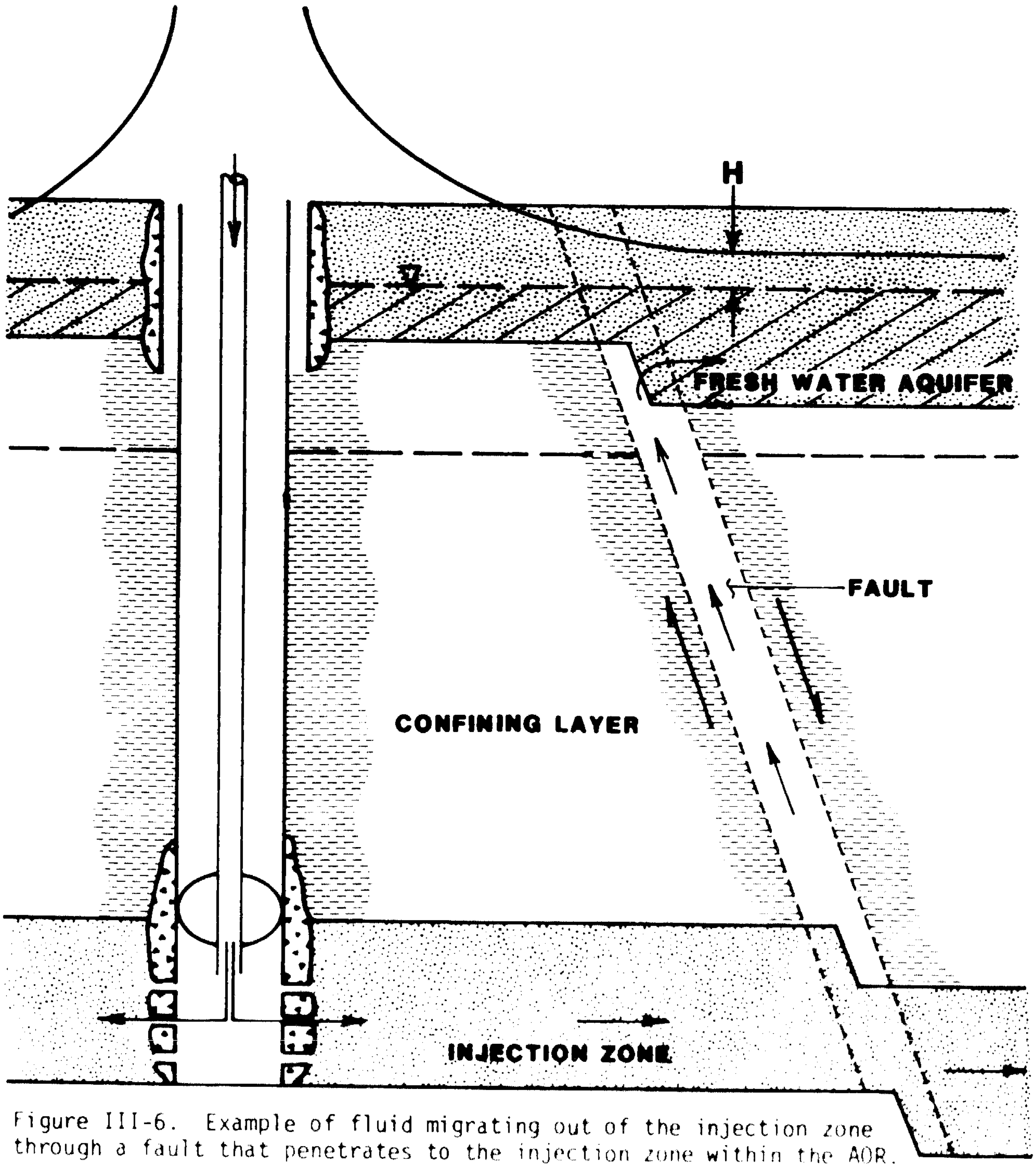


Figure III-6. Example of fluid migrating out of the injection zone through a fault that penetrates to the injection zone within the AOR.

record and pertinent information known to the applicant are required to be included in a permit application. However, the Director of a State program may request any information he believes is needed to review the permit application.

A determination must be made on each well identified on the permit as to whether it is improperly sealed, completed, or abandoned. It does not matter that the wells were completed or plugged according to the best practice at the time. The question remains whether they may provide a pathway for migration to occur.

Wells of all kinds -- producing or abandoned -- that penetrate the injection zone within the AOR have the potential to become pathways for migration. Whether or not they will, in fact, leak, is a function of how the wells were constructed and/or plugged.

While reviewing well completion and plugging records, a judgment must be made as to whether any corrective action is necessary. If problem wells or situations are identified, a plan must be submitted that consists of such steps or modifications as are necessary to prevent movement of fluid into underground sources of drinking water.

Magnitude of Review Process

Based on a 1982 EPA inventory, over two-thirds of the injection wells of record are Class II wells. Class II wells are defined as enhanced recovery or produced - fluid injection wells related to the oil and gas industry. This high ratio of Class II wells over other well classes will likely continue to be the trend because of the nature of oil and gas as a vital resource to the nation. Because of the amount of drilling activity in major oil and gas producing states, the AOR process will have a greater impact in these areas because more potential pathways may exist.

Since oil and gas production began in the United States, over two and one-half million wells have been drilled. It is reasonable to expect that many of these wells may penetrate active or potential injection reservoirs. Although existing Class II injection wells are exempted from the AOR requirement, producing and abandoned wells located nearby the 140,000 existing injection wells are not necessarily exempted. This is because many existing wells associated with the oil and gas industry will likely be in the AOR of new injection wells. In a previous study commissioned by the EPA it was estimated that just over one million producing and abandoned wells would fall within the AOR of newly proposed injection wells. While this may be a gross estimate, it does provide insight into what the magnitude of the review process could be in areas of extensive oil and gas production activity.

Locating possible pathways in which migration could occur, within an established AOR, is an important concept of the UIC regulations. Unfortunately, circumstances can make a realistic application of this concept difficult. For example, the location and exact status of abandoned wells may be difficult to ascertain; or there may be little confidence in completion and plugging records. These types of problems are not surprising, considering that the review process includes wells that were drilled, completed, and abandoned before adequate record keeping systems were established. Intuitively, it can be expected that in areas where there are older wells there will be an increase in the need for corrective action simply because of the methods of construction and abandonment that prevailed in earlier years. Identifying problem wells that may provide a pathway for contaminants can be a major problem to deal with when adequate information on these wells is not available.

The exact impact that problem situations will have on the success of the AOR requirement is difficult to determine. Problems encountered during the review process will have to be handled on a case-by-case basis. For example, assumptions concerning the condition of some wells within an AOR may have to be made. There will always be some risk that problem wells will go unidentified. Therefore, the review process should be handled with considerable flexibility and limited to an effort commensurate with the contamination potential of the proposed injection well.

Corrective and Preventive Action

The third element of the AOR process is to correct or prevent conditions, within an injection well's AOR, that may allow movement of fluid from the injection zone into an underground source of drinking water.

For any identified pathway, within the AOR, the applicant is required to submit a plan detailing the steps to be taken to prevent movement of fluid into underground sources of drinking water. Such a plan may consist of steps to re-cement or replug an improperly abandoned well. Where fractures, faults, and some problem wells are involved, it may not be feasible, or even possible, to prevent the migration. In such cases, it may be necessary to issue conditional permits limiting injection pressures to levels below those required for fluid migration. In effect, this reduces the zone of endangering influence to where the problem pathway lies outside the zone.

If a submitted plan of action is determined to be adequate, the Director of the program may incorporate it into the permit as a condition for approval. Where his review indicates that the plan is inadequate, the Director has several options. He may require the applicant to revise the plan, or he may prescribe another plan for corrective action as a condition of the permit. Finally, the Director may deny the application if an acceptable plan of action cannot be developed.

A major concern for applicants will be the expense involved in taking corrective action. Costs can become substantial and may outweigh the benefits expected from the proposed injection well. If so, relocation of the proposed well may be an alternative. It is obvious that a variety of problems could hinder efforts to take corrective action. Owner/operators, experts, and regulators should therefore work closely together to find optimum solutions.

IV. EVALUATION OF EXISTING APPROACHES TO THE AREA OF REVIEW REQUIREMENT

EPA established a structure for UIC programs that sets forth the permitting, technical analysis, and other program requirements that must be met by UIC programs -- whether run by a State or by EPA. The requirements established by EPA provide a choice of approaches to applying the AOR process. The regulations do not preclude a State from adopting more stringent requirements than those set forth in the EPA structure, so long as the intent of the process is fulfilled.

The purpose of this section is to examine how the AOR requirement is being interpreted and applied by existing UIC programs.

Established Methods for Delineating the AOR

The established methods for delineating the AOR, given as minimum requirements by EPA, can be found in 40 CFR, Part 146.6. The section reads as follows:

> <u>Area of Review</u>
>
> The area of review for each injection well or each field, project or area of the State shall be determined according to either paragraph (a) or (b) of this section. The Director may solicit input from the owners or operators of injection wells within the State as to which method is most appropriate for each geographic area or field.
>
> (a) Zone of endangering influence. (1) The zone of endangering influence shall be:
>
> (i) In the case of application(s) for well permit(s) under § 122.38 that area the radius of which is the lateral distance in which the pressures in the injection zone may cause the migration of the injection

and/or formation fluid into an underground source of drinking water; or

(ii) In the case of an application for an area permit under § 122.39, the project area plus a circumscribing area the width of which is the lateral distance from the perimeter of the project area, in which the pressures in the injection zone may cause the migration of the injection and/or formation fluid into an underground source of drinking water.

(2) Computation of the zone of endangering influence may be based upon the parameters listed below and should be calculated for an injection time period equal to the expected life of the injection well or pattern. The following modified Theis equation illustrates one form which the mathematical model may take.

$$r = \left(\frac{2.25\ KHt}{S10^{x}}\right)^{\frac{1}{2}}$$

where

$$x = \frac{4\pi\ KH(h_w - h_{bo}S_pG_b)}{2.3Q}$$

r = Radius of endangering influence from injection well (length)

K = Hydraulic conductivity of the injection zone (length/time)

H = Thickness of the injection zone (length)

t = Time of injection (time)

S = Storage coefficient (dimensionless)

Q = Injection rate (volume/time)

h_{bo} = Observed original hydrostatic head of injection zone (length) measured from the base of the lowest underground source of drinking water.

h_w = Hydrostatic head of underground source of drinking water (length) measured from the base of the lowest underground source of drinking water

S_pG_b = Specific gravity of fluid in the injection zone (dimensionless)

π = 3.142 (dimensionless)

The above equation is based on the following assumptions:

(i) The injection zone is homogenous and isotropic;

(ii) The injection zone has infinite area extent;

(iii) The injection well penetrates the entire thickness of the injection zone;

(iv) The well diameter is infinitesimal compared to "r" when injection time is longer than a few minutes; and

(v) The emplacement of fluid into the injection zone creates instantaneous increase in pressure.

(b) Fixed radius. (1) In the case of application(s) for well permit(s) under § 122.38 a fixed radius around the well of not less than one-fourth (1/4) mile may be used.

(2) In the case of an application for an area permit under § 122.39 a fixed width of not less than one-fourth (1/4) mile for the circumscribing area may be used.

In determining the fixed radius, the following factors shall be taken into consideration: Chemistry of injected and formation fluids; hydrogeology; population and groundwater use and dependence; and historical practices in the area.

(c) If the area of review is determined by a mathematical model pursuant to paragraph (a) of this section, the permissible radius is the result of such calculation even if it is less than one-fourth (1/4) mile.

While the regulations state that a fixed-radius cannot be less than 1/4 mile, they do not discourage setting a larger radius if circumstances dictate. To help establish an appropriate fixed-radius, the regulations provide a list of factors that need to be considered when the evaluation is made. These factors are:

a. chemistry of injection and formation fluids;

b. hydrogeology;

c. population and groundwater use and dependence; and

d. historical practices in the area.

These factors are to be used as guidelines for fixing an AOR for a given situation. For example, if the groundwater in the area surrounding a proposed injection well is the sole source of drinking water for the area, or if it is an otherwise environmentally sensitive area, then the Program Director may set a fixed-radius for the AOR that is larger than 1/4 mile.

The minimum 1/4 mile fixed-radius is an arbitrarily selected minimum reflecting influence and suggestions from the oil and gas industry. Suggestions from the oil and gas industry are based on past experiences with pressure buildup in reservoirs resulting from enhanced oil recovery operations. Their argument for a small fixed-radius of an AOR is based on the fact that wells producing from the same zones into which injection is occurring will offset pressure buildup caused by the injection process. The pressure relationship between producing and injection wells should be considered, and a 1/4-mile minimum radius for an AOR may well be appropriate for these cases dealing with Class II enhanced recovery wells. The 1/4-mile minimum radius for injection wells used for disposal should be applied with more caution because there are no producing wells to offset the pressure buildup resulting from injection.

State UIC Program Survey

EPA was required to list in the Federal Register each State for which a UIC program may be necessary to ensure that underground injections will not endanger underground sources of drinking water. EPA has listed all 50 States, the District of

Columbia, and the Territories and Possessions of the United States (43FR43420, September 25, 1978; 44FR35288, June 19, 1979; 45FR17632, March 19, 1980).

Each of the listed States had a choice either to apply for primacy of its respective UIC program or have EPA take responsibility for its administration. Table IV-1 lists 23 jurisdictions in which EPA proposed to administer the UIC program.

States that have applied or are in the process of applying for primacy of their UIC program were surveyed during this study to examine how the AOR requirement is being interpreted and applied. Table IV-2 is a list of programs that were surveyed. It lists the methods used to delineate AOR's for specified well classes regulated by the program. As Table IV-2 shows, the fixed-radius approach for delineating an AOR is the most common method.

Fixed-Radius Approach to the AOR

EPA has proposed a fixed-radius approach to the AOR process for several jurisdictions in which it is responsible for UIC administration. For these cases a fixed-radius was deemed appropriate because (1) analytical procedures cannot be applied with confidence to hydrogeological conditions known (or suspected) to exist; (2) the fixed-radius approach reflects existing State practices; or (3) the fixed-radius approach would expedite the AOR process.

Table IV - 1

Jurisdictions in which EPA Proposes to Administer the UIC Program*

Alaska	Missouri (Class I, III, IV, & V only)
Arizona	Montana
Arkansas (Class II only)	Nebraska (Class I, III, IV, & V only)
California (Class I, III, IV & V only)	
Colorado	Nevada
District of Columbia	New York
Idaho	Pennsylvania
Indiana	Tennessee
Iowa	Virginia
Kentucky	American Samoa
Michigan	Northern Mariana Islands
Minnesota	Trust Territory of the Pacific Islands

* The proposed program covers all classes of wells unless otherwise noted.

Table IV - 2

AOR Survey

State	Well Class	Method Used* For AOR
Arkansas	I, III	1/4 mile
Alabama	II I	1/4 mile 5 mile (Equation)**
Florida	I, III	1/4 mile
Georgia	I, II, III	2 mile
Illinois	II	1 mile
Kansas	I, II, III	1/2 mile
Louisiana	II, III	1/4 mile
	I	2 miles
Mississippi	I, III	Theis Equation
Missouri	II	1/2 mile
Nebraska	II	1/2 mile
New Mexico	I, II, III	Theis Equation
North Dakota	II, III I	1/4 mile Equation
Ohio	II	Equation
Oklahoma	II	Theis Equation
South Carolina	II, III	1/4 mile
Texas	II	1/4 mile (Equation)**
Utah	II	1/2 mile
Wyoming	I, II, III	1/4 - 1/2 mile

* Fixed-radius approach used unless otherwise noted

** Equation sometimes used to validate given radius

The survey of State run UIC programs revealed many of these same reasons for choosing a fixed-radius approach. The success of such an approach will depend on the degree of technical consideration that is given to the chosen distance of a fixed-radius. A fixed-radius can be selected and justified in a number of ways. The best method is to evaluate the past behavior of an injection reservoir under investigation. This requires data on past injection activity and how the reservoir fluid pressure was influenced by this activity. This type of data are not always available, however in the case of waterflood injection operations, the oil companies are usually knowledgeable on the influence that injection wells have on reservoir fluid pressure.

Another method for considering the selection of a fixed-radius might be to apply an analytical approach and compare the calculated AOR's from a range of input values expected for a particular reservoir. For example, use a range of permeabilities, injection rates, etc.

In cases where there is a very large pressure differential between the injection zone and fresh water zone, such as may be the case for many deep injection operations, one may feel comfortable using the 1/4 mile minimum radius of review. However, for shallow injection operations, this same radius may not be appropriate. This is why a selected fixed-radius should be evaluated on a case-by-case basis.

The following provides a summary of a few State programs that use a fixed-radius approach to the AOR process and their justification for the radial distance that was chosen.

Kansas

The State of Kansas uses a fixed distance of 1/2 mile for the AOR of Class I, II, and III injection wells. Their justification for using 1/2 mile stems directly from past experience they have had with injection well activity. They may use an equation from time to time if an individual operator chooses. They have used 1/2 mile, when evaluating injection wells, for a long time and consider it appropriate for the AOR process. Kansas currently permits 1200 to 1400 Class II injection wells each year.

Missouri

The State of Missouri uses a fixed distance of 1/2 mile for the AOR of Class II injection wells. This fixed distance was selected on the recommendation of EPA based on shallow injection depths. Missouri currently permits over 120 Class II wells per year.

Texas

The State of Texas uses a fixed distance of 1/4 mile for the AOR of Class II injection wells. This distance was selected on the basis of their extensive experience with injection well activity within the hydrogeologic framework of their State. If suspicious circumstances dictate or if there are unplugged wells known to exist in the vicinity outside of 1/4 mile, then they may choose to use reservoir simulations to determine the adequacy of a 1/4 mile radius. Texas currently reviews as many as 6,000 applications for Class II wells each year.

Georgia

The State of Georgia uses a fixed distance of two miles for the AOR of Class I, II, and III injection wells. This distance was selected based on suggestions and input from EPA.

Illinois

The State of Illinois uses a one mile fixed distance for the AOR of Class II wells. This distance was selected on the basis of past State experience.

Utah

The State of Utah uses a fixed distance of 1/2 mile for the AOR of Class II wells. Equations were used to justify this selected radius. Utah currently permits 40 to 50 Class II wells per year.

The survey revealed some programs using a fixed-radius approach on a completely arbitrary basis. In these cases, it was common for a 1/4 mile fixed distance to be used for AOR's. It should be pointed out that arbitrary choices for the AOR may or may not be appropriate for given situations -- it is complete guesswork. Without any technical evaluation as to the adequacy of AOR determinations it is possible that deficiencies in the AOR process will not be identified until contamination problems occur. Obviously a fixed-radius chosen on the basis of past experience with the behavior of a particular injection reservoir will have a better chance of being appropriate than would an arbitrarily selected radius. As State programs gain experience with the AOR process, a fixed-radius approach can be refined to reflect more technical consideration.

Analytical Approach to the AOR

Analytical approaches used for the AOR process provides the means to actually quantify a zone of endangering influence for a proposed injection operation. Analytical solutions to the AOR will be limited to areas where the hydrogeologic conditions satisty basic assumptions that are implied by the equations and where adequate information exists that describe the hydrogeologic conditions.

Recognizing that analytical results are obtained by assuming properties of an ideal reservoir then it follows that a judgment must be made as to how closely the real reservoir characteristics resembles this particular ideal. Departures from ideal conditions do not necessarily constitute grounds for abandoning the use of analytical equations. Such departures simply emphasize that mere substitution of data into an equation may not in itself provide the assurance that correct results are obtained. Matching calculated solutions to observed results is one practical method to make judgments regarding the applicability of an analytical approach to a given reservoir.

Several forms of analytical approaches to the AOR were identified during the survey of State UIC programs. Most approaches included modified versions of the basic Theis equation. However, one approach used by a couple of programs is not equivalent to the Theis approach and is not valid for calculating the zone of endangering influence. This particular approach is called the volumetric method and is defined as follows:

$$r = \left(\frac{V}{h\phi\pi}\right)$$

where

r = radius of influence

V = volume of fluid to be injected for life of well

h = reservoir thickness

ϕ = reservoir porosity

This equation estimates the radial movement of injected fluid by assuming that the injected fluid will uniformily occupy an expanding cylinder with the injection well at the center. The radius of influence defined by this equation is an estimate of the fluid front radius, assuming flow is in the horizontal direction, and has no relation to the radius of the AOR. This is because the pressure buildup that defines the zone of endangering influence is not considered by the equation. The volumetric method should therefore not be used to delineate an AOR.

Most programs opting for an analytical procedure use a version of the Theis equation. The Theis approach for pressure buildup calculation is useful and provides a method for making

AOR determinations. However, knowledge of its application and limitations are prerequisite to its use. Specific problems, identified during the AOR survey, dealing with analytical calculations of the AOR are discussed in the following:

(a) Failure to consider the initial reservoir pressure -- The base of any cone of impression will rest on the piezometric surface for the receiving reservoir. The cone will build upward from that surface. It follows that a given cone starting from a higher piezometric surface would create a problem sooner and adversely affect a larger area than if it were to start from a lower piezometric surface. Hence the critical importance of knowing the position of the piezometric surface for the receiving reservoir before any injection cone is superimposed.

To calculate the pressure in an injection reservoir at a given point "x" away from an injection well requires the following:

$$P_x = P_i + \Delta P$$

where

P_x = resultant pressure at point x

P_i = initial pressure at point x before injection

ΔP = change in pressure at point x resulting from the injection well.

ΔP is calculated by the analytical equation and depends on the injection rate and the reservoir properties.

P_i is a value that needs to be known or measured before the resultant pressure at point x can be determined.

Some UIC programs do not consider P_i mainly because the data are not required on injection well applications. This can result in misleading pressure calculations and the zone of endangering influence can be significantly underestimated. For these reasons State programs should make P_i required data on injection well applications.

(b) Failure to consider multiple well conditions -- When an AOR is delineated analytically, consideration must be given to all conditions that may alter the reservoir pressure within the influence of a proposed injection operation. For example, suppose the radius of endangering influence for an injection well was calculated to be "x" feet away from the well, but only the effects of the proposed well were considered when making the determination. The radius of endangering influence could therefore be underestimated if there is a resultant pressure increase at point x caused by the effects of other wells injecting into the same reservoir. The radius of endangering influence could also be over-estimated if the effects of withdrawal wells are not considered.

The resultant pressure at any point in a reservoir can be calculated simply by summing the calculated effects of each individual well that influences the pressure at that given point.

Some UIC programs do not consider multiple well conditions. This can nullify the validity of AOR determinations and is especially risky in the case of disposal well fields where there are no withdrawal wells to offset pressure buildup caused by injection.

(c) Equation misuse --
This particular problem was difficult to confirm absolutely because of the lack of detailed information necessary for a case-by-case evaluation. However, based on interviews conducted during the survey of individual programs, it is felt that equation misuse could be occurring.

Two major problems with using analytical equations for AOR determinations should be discussed. First, values for hydrogeologic data -- ie. permeability, thickness, etc. -- that are input into an analytical equation, may not adequately reflect actual hydrogeologic conditions. The data used in analytical equations for the AOR are generally obtained from the applicants of proposed wells and may sometimes reflect regional averages rather than site-specific averages. The most appropriate input values would be those data obtained from actual aquifer pumping and/or injectivity tests performed within a given area. These values would more adequately represent reservoir behavior under stress.

The second problem would be the failure to qualify predicted results within the framework of the assumptions implied in the development of the analytical equations. The assumptions used in developing the equations include the stipulation that the aquifer is homogeneous and isotropic. Even though most naturally deposited sediments do not satisfy this condition, the equations may still be applied and the results qualified according to the extent of nonhomogeneity. This can only be accomplished through observation of actual aquifer behavior. Confidence in the use of analytical equations, for a given aquifer can be achieved by matching calculated results with field results obtained under a controlled set of circumstances. If this is not done, there is no technical justification or qualification for analytical solutions and the predicted results for AOR determinations could be meaningless.

Survey Summary

Considering many of the complexities involved in AOR determinations and the fact that many UIC programs are relatively young, the overall impression of AOR applications is generally good. Many of the problems that were encountered can be resolved through education and experience with the AOR process.

There was evidence to indicate a good working relationship between owner/operators and regulators. One example would be where applicants and regulators compromise on injection rates to minimize the expected zone of endangering influence. Other similar examples were noted during the survey.

One good example of an effective AOR requirement can be found in the regulations developed by the State of New Mexico. Their approach incorporates a fair division of responsibility between applicants and regulators to help ensure adequate AOR determinations. Their AOR requirement, in part, reads as follows:

A. The area of review is the area surrounding an effluent disposal well or in-situ extraction well or the area within and surrounding a well field that is to be examined to identify possible fluid conduits, including the location of all known wells and fractures which may penetrate the injection zone.

B. The area of review for each effluent disposal well, or each in-situ extraction well or well field shall be an area which extends:

1. Two and one-half (2 1/2) miles from the well, or well field; or
2. One-quarter (1/4) mile from a well or well field where the area of review is calculated to be zero pursuant to Subsection B.3. below, or where the well field production at all times exceeds injection to produce a net withdrawal; or
3. A suitable distance, not less than one-quarter (1/4) mile, proposed by the discharger and

approved by the director, based upon a mathematical calculation to determine the area of review........; the discharger must demonstrate that any equation or simulation used to compute the area of review applies to the hydrogeologic conditions in the area of review.

V. GUIDELINES FOR APPLYING THE AOR REQUIREMENT

Application of the AOR requirement can be broken down into four elemental steps. Figure V-1 presents a flow chart illustrating these steps and the following discussion provides a description of the process involved in each.

Step 1 - The first question that must be answered when reviewing an injection well permit is -- What increase in the fluid pressure, ΔP, of the receiving reservoir would be necessary to make migration of injected or formation fluid into fresh water zones possible? To answer this question two parameters need to be known. These are (1) the initial piezometric surface of the injection reservoir, and (2) the piezometric surface, or water levels, of potential underground sources of drinking water overlying the injection reservoir. The difference, in feet of head, between these two parameters defines ΔP. (Refer back to Figure III-1).

For example, suppose the piezometric surface (fluid level) of the injection reservoir was found to be at 1000 feet below ground surface and the piezometric surface (fluid level) of an overlying fresh water aquifer was measured at 500 feet below ground surface.

Then ΔP would be equal to 500 feet of head which would mean that a pressure increase, in the injection reservoir, of about 216 psi would make it possible for

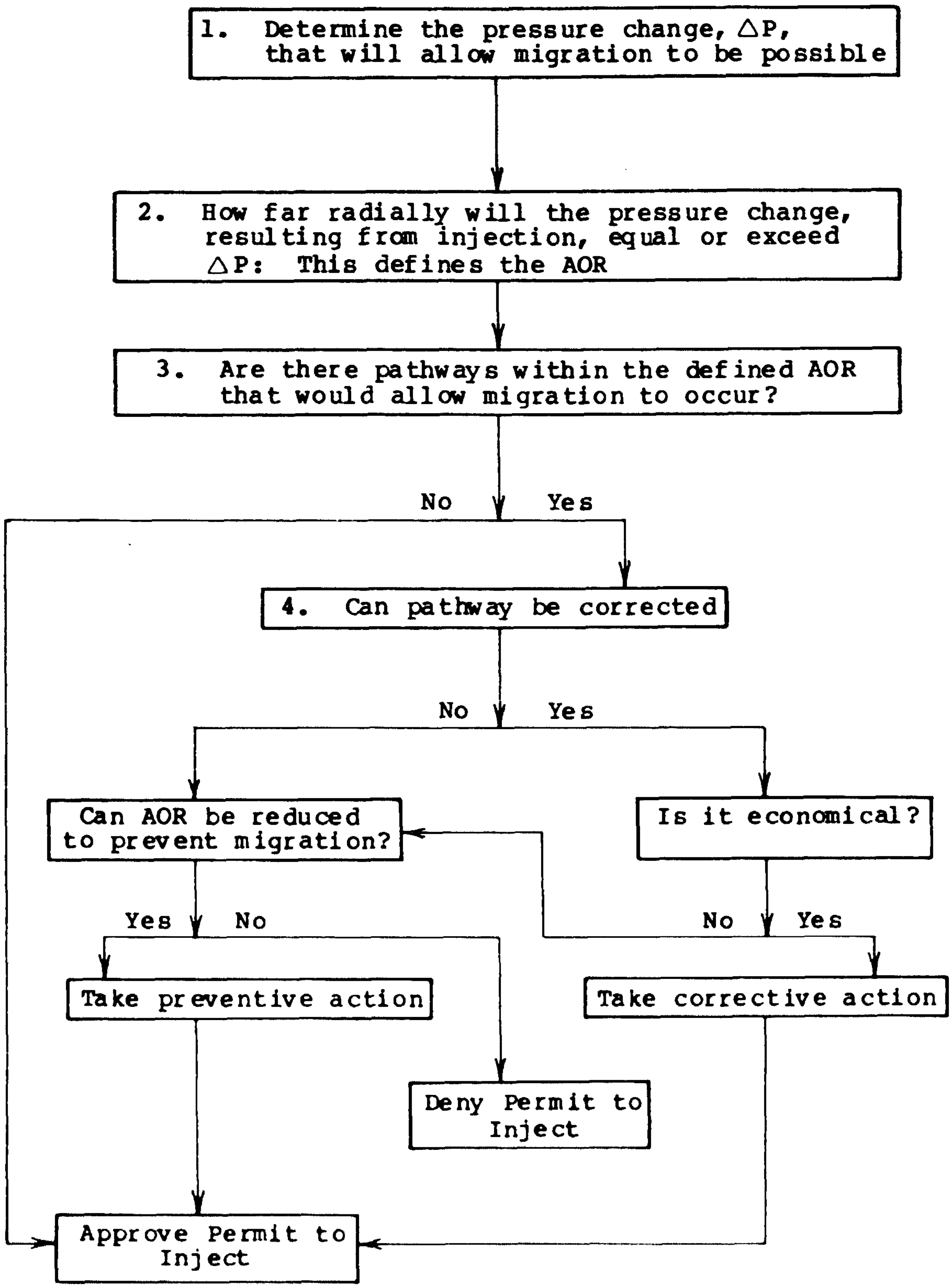


Figure V-1. Flow chart for applying the AOR Requirement.

migration to occur from the injection zone into the fresh water zone. Of course this would require an available pathway in which fluid could migrate.

The base of any cone of impression will rest on the piezometric surface for the receiving reservoir. The cone will build upward from that surface. It follows that a given cone starting from a higher piezometric surface would create a problem sooner and adversely affect a larger area than if it were to start from a lower piezometric surface. This is illustrated in Figure V-2; hence the critical importance of knowing the position of the piezometric surface for the receiving reservoir before any injection cone is superimposed. Before an adequate evaluation described by Step 2 can be made, ΔP must be known.

Step 2 - This step involves predicting how far radially, from an injection well, the pressure increase, resulting from injection, will equal or exceed the ΔP measured in Step 1. This step defines the physical limits of the zone of endangering influence and thus the AOR that should be selected.

This step is perhaps the most difficult to apply because of the nature of such predictions. Many factors have to be considered and a cause-and-effect relationship between injection and aquifer response

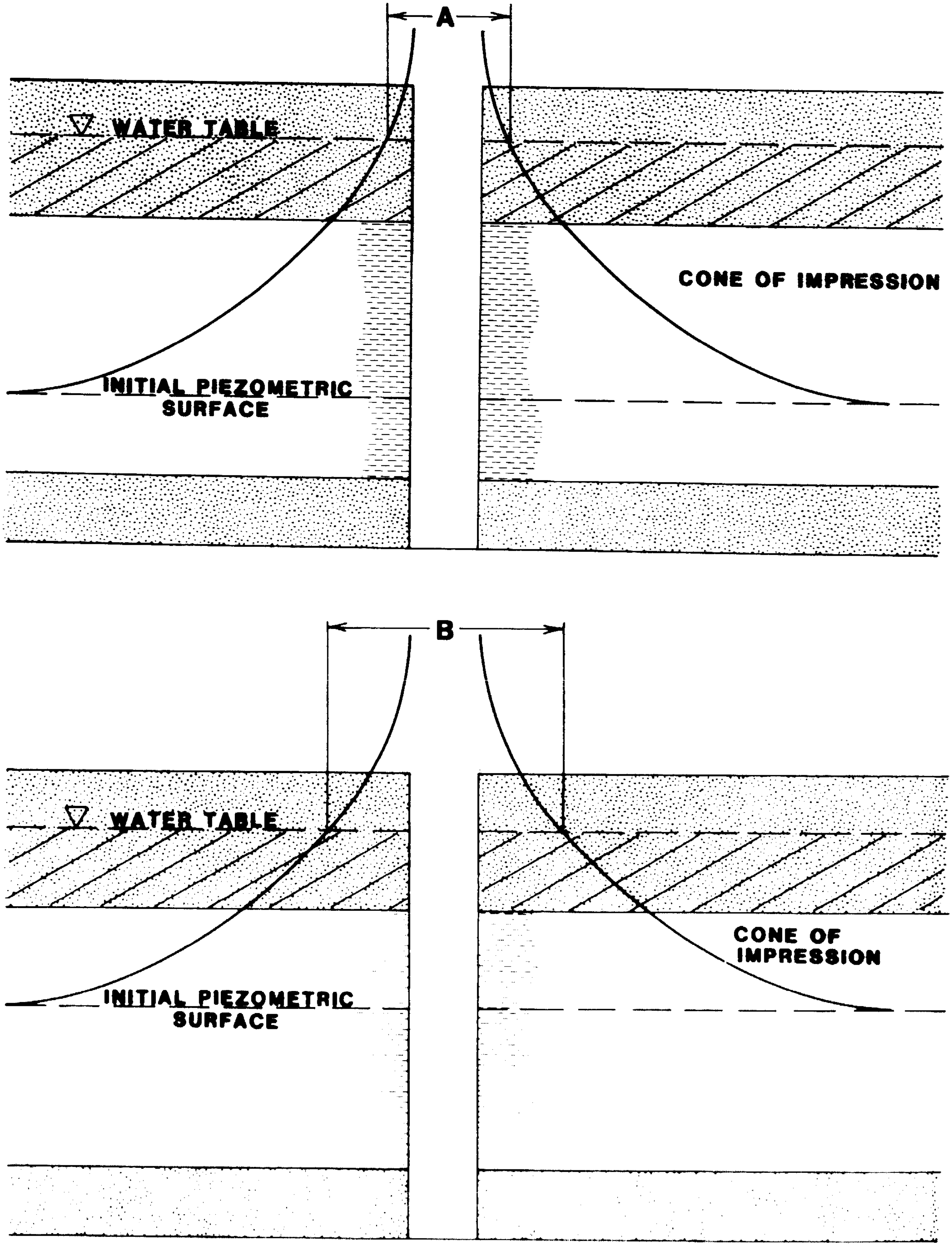


Figure V-2. Illustration to show how a higher initial piezometric surface will increase the zone of endangering influence when everything else is constant (Diameter B is larger).

must be established with a reasonable degree of reliability.

Regardless of the method used to accomplish this step, it is important that due regard be given to basic hydrogeologic principles, the qualification of data describing aquifer characteristics, and in particular the limitations of the method used in the analysis. If a fixed radial distance is selected to accomplish this step, there should be some technical justification for the distance selected. Technical justification can range from analytical techniques to experience with the past performance of the aquifer.

Step 3 - Once the AOR has been delineated, all potential pathways that may allow migration to occur should be identified during this step. All known wells that penetrate the injection zone within the AOR are required to be identified and the records of these wells checked to determine if any were improperly completed and/or abandoned.

Several problems could be encountered when applying this step. First, there may be unidentifiable pathways or wells with little or no information on their completion or abandonment. Second, available records may be inaccurate, incomplete or otherwise questionable. Third, there may be numerous wells within an AOR requiring a time-consuming record review.

In these cases, the Federal Regulations do offer some relief.

The Regulations call for a tabulation of data reasonably available from public records or otherwise known to the applicant. Such data are to include a description of each well's type, construction, date drilled, location, depth, record of plugging and completion and any additional information the Director may require. In cases where the information would be repetitive and the wells are of similar age, type, and construction the Director may elect to only require data on a representative number of wells.

During the application of this step, a determination must be made as to whether potential pathways, within the AOR, would indeed allow migration to occur. If problem pathways are identified, a plan of corrective or preventive action must be developed and implemented in Step 4 of the AOR process.

Step 4 - This step is to determine the best solution for dealing with problem pathways that have been identified within an AOR. The applicant is required to submit a plan consisting of such steps or modifications as are necessary to prevent movement of fluid into underground sources of drinking water. Such a plan may consist of steps to re-cement or replug an improperly abandoned well.

If it is determined to be not feasible or economical to physically modify a problem pathway, the applicant may choose to reduce injection rates and pressures so as to reduce the size of the zone of endangering influence to a point where the problem pathway is no longer within the danger zone.

A major concern for applicants will be the cost of corrective action. Costs can become substantial and may outweigh benefits expected from the proposed injection well. If so, relocation of the proposed well may be a viable alternative.

The preceding discussion has provided a general description of the basic steps involved in applying the AOR requirement. From a technical standpoint, Step 2 is the most difficult to apply because of the theoretical nature of what must be accomplished during this step. The remainder of this section is dedicated to a discussion of guidelines that should be considered when applying acceptable methods for delineating the zone of endangering influence.

Analytical Approach for Delineating an AOR

For decades there has been increasing confidence in the applicability of quantitative methods for solutions to complex hydrologic problems. An important milestone was Theis' development in 1935 of a solution for the nonsteady flow of groundwater, which enabled hydrologists for the first time to predict future changes in groundwater levels resulting from pumping or recharging of wells. A solution of this type is one form of an analytical approach that is obtained by simplifying the basic differential equation,

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} = \frac{S}{T}\frac{\partial h}{\partial t} \qquad \text{(Eq. V-1)}$$

governing the nonsteady flow through porous media.

Theis, in what must be considered one of the fundamental breakthroughs in the development of hydrologic methodology, utilized an analogy to heat-flow theory to arrive at an analytical solution to Eq. V-1. His solution, written in terms of drawdown resulting from a pumping well, is

$$h_o - h(r,t) = \frac{Q}{4\pi T}\int_u^\infty \frac{e^{-u}du}{u} \qquad \text{(Eq. V-2)}$$

where

$$u = \frac{r^2 S}{4Tt} \qquad \text{(Eq. V-3)}$$

h_o = hydraulic head before pumping began

$h(r,t)$ = hydraulic head at time t since pumping began and at a distance r from the pumping well

Q = pumping rate (constant and continuous over time t)

T = aquifer transmissivity

r = radial distance from the pumping well to the point of observation

S = aquifer storativity

t = time since pumping began

Since T is equal to the aquifer permeability (K) multiplied by the aquifer thickness (H), then the term KH often appears in analytical equations in place of T.

The integral in Eq. V-2 is well known in mathematics. It is called the exponential integral. For the specific definition of u given by Eq. V-3, the integral is known as the well function, W(u). With this notation, Eq. V-2 becomes

$$h_o - h(r,t) = \frac{Q}{4 \pi T} W(u) \qquad \text{(Eq. V-4)}$$

Although there is no direct solution to W(u), it can be approximated by the infinite series

$$-0.5772 - \ln u + u - \frac{u^2}{2.2!} + \frac{u^3}{3.3!} - \frac{u^4}{4.4!} \cdots\cdots$$

where u is defined as in Eq. V-3. Tables of values for W(u) are widely available in the literature. Table V-1 provides values of W(u) for various values of u.

If the aquifer properties, T and S, and the pumping rate, Q, are known, it is possible to predict the drawdown in hydraulic head in a confined aquifer at any distance r from a well at any time t after the start of pumping. It is simply necessary to calculate u from Eq. V-3, look up the value of W(u) in the table, and calculate the drawdown, h_o-h, from Eq. V-4. (Note: the term (h_o-h) simply represents the change in the piezometric surface at some distance r from the pumping well at a specific time t since pumping began.)

It is also possible to calculate values of h_o-h at various values of r at a given time t. Such a calculation leads to a plot of the cone of depression (or drawdown cone) in the piezometric surface around a pumping well.

Table V-1 Values of W(u) for Various Values of u

u	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0
X 1	1.219	0.049	0.013	0.0038	0.0011	0.00036	0.00012	0.000038	0.000012
X 10^{-1}	1.82	1.22	0.91	0.70	0.56	0.45	0.37	0.31	0.26
X 10^{-2}	4.04	3.35	2.96	2.68	2.47	2.30	2.15	2.03	1.92
X 10^{-3}	6.33	5.64	5.23	4.95	4.73	4.54	4.39	4.26	4.14
X 10^{-4}	8.63	7.94	7.53	7.25	7.02	6.84	6.69	6.55	6.44
X 10^{-5}	10.94	10.24	9.84	9.55	9.33	9.14	8.99	8.86	8.74
X 10^{-6}	13.24	12.55	12.14	11.85	11.63	11.45	11.29	11.16	11.04
X 10^{-7}	15.54	14.85	14.44	14.15	13.93	13.75	13.60	13.46	13.34
X 10^{-8}	17.84	17.15	16.74	16.46	16.23	16.05	15.90	15.76	15.65
X 10^{-9}	20.15	19.45	19.05	18.76	18.54	18.35	18.20	18.07	17.95
X10^{-10}	22.45	21.76	21.35	21.06	20.84	20.66	20.50	20.37	20.25
X10^{-11}	24.75	24.06	23.65	23.36	23.14	22.96	22.81	22.67	22.55
X10^{-12}	27.05	26.36	25.96	25.67	25.44	25.26	25.11	24.97	24.86
X10^{-13}	29.36	28.66	28.26	27.97	27.75	27.56	27.41	27.28	27.16
X10^{-14}	31.66	30.97	30.56	30.27	30.05	29.87	29.71	29.58	29.46
X10^{-15}	33.96	33.27	32.86	32.58	32.35	32.17	32.02	31.88	31.76

Source: Wenzel, 1942.

For a given aquifer the cone of depression increases in depth and extent with increasing time. Drawdown at any point at a given time is directly proportional to the pumping rate and inversely proportional to aquifer transmissivity and aquifer storativity. Aquifers of low transmissivity develop tight, deep drawdown cones, whereas aquifers of high transmissivity develop shallow cones of wide extent. Transmissivity exerts a greater influence on drawdown than does storativity.

The Theis solution can also be applied to evaluate the flow from an injection well to satisfy step two of the AOR process. The principles are exactly the same as for a pumping well except the sign convention for Q is reversed to express answers in terms of buildup rather than drawdown in the hydraulic head. It is possible to predict the buildup in hydraulic head in a confined aquifer at any distance r from an injection well at any time t after the start of injection. The process is the same as that of a pumping well -- calculate u from Eq. V-3, look up the value of W(u) in the table, and calculate the buildup, $h_o - h$, from Eq. V-4 using -Q. Of course this process still requires that T, S, and Q be known values.

By calculating values of $h_o - h$ at various values of r at a given time t, a plot of the cone of impression (buildup cone) in the piezometric surface can be made. The zone of endangering influence and hence the AOR is delineated where the elevation of the piezometric surface in the injection zone is the same as, or higher than the piezometric surface for any potential underground source of drinking water existing within the same area.

C. E. Jacob observed that after a pumping well had been running for some time, higher values of the infinite series, approximating W(u), became very small, and the Theis nonequilibrium formula could be closely approximated by

$$h_o - h = \frac{2.3\ Q}{4\pi\ KH} \log \left(\frac{2.25\ KHt}{Sr^2}\right) \qquad \text{(Eq. V-5)}$$

Expressing Eq. V-5 in terms of r yields

$$r = \left(\frac{2.25\ KHt}{S10^x}\right)^{1/2} \qquad \text{(Eq. V-6)}$$

where

$$x = \frac{4\pi\ KH\ (h_o - h)}{2.3\ Q}$$

Both Eq. V-5 and Eq. V-6 are modified versions of the basic nonequilibrium formula developed by Theis and thus are subject to the same simplifying assumptions that govern their applicability. Note that Eq. V-6 is the same form of the equation provided in the regulations. The only difference is one of terminology. In the regulations the term $(h_o - h)$ is expressed as the specific value $(h_w - h_{bo})$ where h_w represents the piezometric level in the fresh water aquifer and h_{bo} represents the initial piezometric level in the injection zone, both measured from the same datum point. Therefore $(h_w - h_{bo})$ is equal to ΔP defined in step one of the AOR process. With this value input into Eq. V-6 the calculated r represents the radial distance from the injection well within which the pressure change in the injection zone equals or exceeds ΔP. Thus, the AOR is defined and step two of the process is accomplished. (Note: To calculate the AOR using Eq. V-6, the time t should be the expected life of the injection operation and Q should be the expected average injection rate during this time).

Description of Equation Input Data

Defining, obtaining, and estimating the required input data becomes the controlling factor for adequate determinations if the reservoir does indeed meet the necessary assumptions for the analytical equation to apply. Obviously, the degree of accuracy in any calculated results will depend on the accuracy of the input data.

There are four physical factors that control the size and shape of a cone of impression caused by injection. They are:

T - The transmissivity which is equal to the permeability (K) times the aquifer thickness(H). The transmissivity is the ability of the formation to accept (or deliver) the fluid. (T will many times be expressed in an analytical equation as KH);

S - The coefficient of storage, a measure of the formation's capacity to store (or release from storage) the fluid;

Q - The pumping rate used to inject (or extract) the fluid; and t - The time since the injection (or extraction) began.

Of the four, "Q" and "t" are fixed by us. "Q" is the pumping (injection) rate -- held constant and assumed continuous to satisfy the assumptions upon which the mathematical relationship is based; "t" is the future time of interest and for AOR applications is the proposed life of the injection operation.

"T" and "S" are values that must come from data obtained in the field. Without them, we would only be guessing -- even in ideally homogeneous and uniform geological settings. "S" values are not as critical as "T" values. If an "S" value is available from a pumping test, fine -- if not, one can assume an average value that will give reasonably good results.

In examining logs of wells or test holes in confined aquifers, or in measuring sections of exposed rocks that dip down beneath confining beds to become confined aquifers, the storage coefficient may be estimated from the following rule-of-thumb relationship:

Thickness, H (ft.)	S	$\frac{S}{H}$ (ft.$^{-1}$)
1	10^{-6}	
10	10^{-5}	10^{-6}
100	10^{-4}	
1,000	10^{-3}	

One may either multiply the thickness in feet times 10^{-6}

$ft.^{-1}$ or interpolate between values in the first two columns; for example, for H = 300 ft., $S \simeq 3 \times 10^{-4}$, and so on. Values thus estimated are not absolutely correct, as no allowances have been made for porosity or for compressibility of the aquifer, but they are fairly reliable for most purposes. Such estimates may be improved upon by comparison with values obtained from reliable pumping or flow tests, then extrapolated to other parts of an aquifer with adjustments for thickness if needed.

"T" is a much more critical input requirement. Since the height of the cone of impression is inversely proportional to the value of "T" (i.e., halving the value of "T" doubles the height of the cone), guessing at this value can be very risky. There really is no acceptable substitute for a field-derived "T" value -- preferably by a long-term pumping (or injection) test.

Defining hydrogeologic conditions can be difficult. Available basic data are seldom sufficient to permit rigorous descriptions of aquifers, and economic limitations often prohibit the collection of detailed information concerning the complexities of these aquifers. Insufficient basic data require much interpretation, extrapolation, and application of hydrogeologic principles when preparing the requisite hydrogeologic data.

Important quantitative evaluations of cause-and-effect can frequently be made even when basic data are incomplete. Approximate solutions based on existing data, when properly qualified according to the quality and quantity of data, can be of great importance. Refinement and periodic re-evaluation of solutions after the collection of additional data will be necessary and should be anticipated. Actually, the study of cause-and-effect relationships based on existing data reveals deficiencies in information and indicates whether the collection of additional data is worth the cost.

Unit Consistency

The analytical equations appearing thus far in this report are presented in a non-unitized form. That is, any set of consistent units for equation input parameters must be used. Two examples of consistent units are given:

Q =	$feet^3/day$	$meters^3/day$
t =	days	days
K =	feet/day	meters/day
H =	feet	meters
T =	$feet^2/day$	$meters^2/day$
S=	dimensionless fraction	dimensionless fraction
r =	feet	meters

Injection well applicants will usually report data requirements in practical units such as barrels/day for injection rate and darcys for permeability etc. Therefore, it is necessary to either convert these parameters into a consistent set of units or adjust the equations to correctly handle heterogeneous units by using appropriate constants. For example, in common usage in the United States, hydrologic data are often presented in

American practical hydrologic units:

$Q =$ gallon/minute

$t =$ days

$K =$ gallons/day/ft^2

$H =$ feet

$T =$ gallons/day/ft

$S =$ dimensionless fraction

$r =$ feet

Rather than convert these parameters into a consistent set of units, Equation V-6 can be adjusted with appropriate constants to handle these inconsistent units. For the above American practical hydrologic units, Equation V-6 would take the following form:

$$r = \left(\frac{.3KHt}{S10^x}\right)^{1/2}$$

where

$$x = \frac{(h_o - h)KH}{264Q}$$

Because of the many different variations in the type of units that equation parameters are reported, it is impractical to include an exhaustive list of equations to cover every case. It will suffice to give adequate warning that the use of inconsistent units and/or incorrect unit conversions are a very common source of error when using analytical equations. It would be beneficial for State programs to require that input data be uniformly reported in a consistent unit format.

Graphical Solutions

The Theis equation with its Jacobs "modification" is a popular equation, widely used in the groundwater industry. When solved graphically, it becomes easy to use in an evaluation by the use of two simple expressions. They are:

$$R_o = \left(\frac{0.3KHt}{S}\right)^{1/2} \quad ; \text{and}$$

$$\Delta s = \frac{528\,Q}{KH}$$

The only new terms here are R_o, the so-called "radius of influence" or distance from the point of injection to where no effect can be measured; and Δs, the slope of the straight-line graph of the cone of impression on semi-logarithmic paper (plotting pressure buildup versus distance from injection well).

For the above equations to give correct results, the units for each term must be expressed as follows:

K - gallons per day per square foot

H - feet

S - is dimensionless, and expressed as a decimal fraction

t - time in days

Q - gallons per minute

Δs - feet increase in pressure head for each cycle on the semi-log graph

R_o - feet

Problems can, of course, be solved by computation, using the original equations. But using the above simple expressions and plotting the results on semi-log paper is so simple a process that many investigators prefer this approach. Besides, graphing the results permits one to quickly see how changing "Q", for example, would affect the height and shape of the cone; or affect the period of time during which injection operations may safely continue.

Once we have drawn one curve, it is a simple matter to draw other curves representing the cones for other injection rates. [Note that the term "Q" does not appear in the equation for R_o]. Therefore, changing the injection rate does not change the value of R_o, and a family of curves for different injection rates can all be drawn through the same point R_o.

The second equation tells us that the slope (Δs) is directly proportional to the injection rate (Q). Therefore, reducing the injection rate by, for example, 30% would also reduce the slope (and the pressure buildup) by 30%.

Should the proposed rate of injection produce a pressure buildup that is excessive, one option might be to reduce the rate to one that would be safe.

Example: Graphical Solution

Consider an injection well application with the following data submitted:

Injection Reservoir Properties

S = .0001

K = 2.12 gallons/day/ft^2

H = 30 feet

h_w = 500 feet (measured from bottom of injection zone and represents the piezometric level in the fresh water aquifer)

h_{bo} = 100 feet (measured from bottom of injection zone and represents the initial piezometric level in the injection zone)

Proposed Well Operation Data

Q = 50 gallons/minute

t = 3650 days (proposed project life)

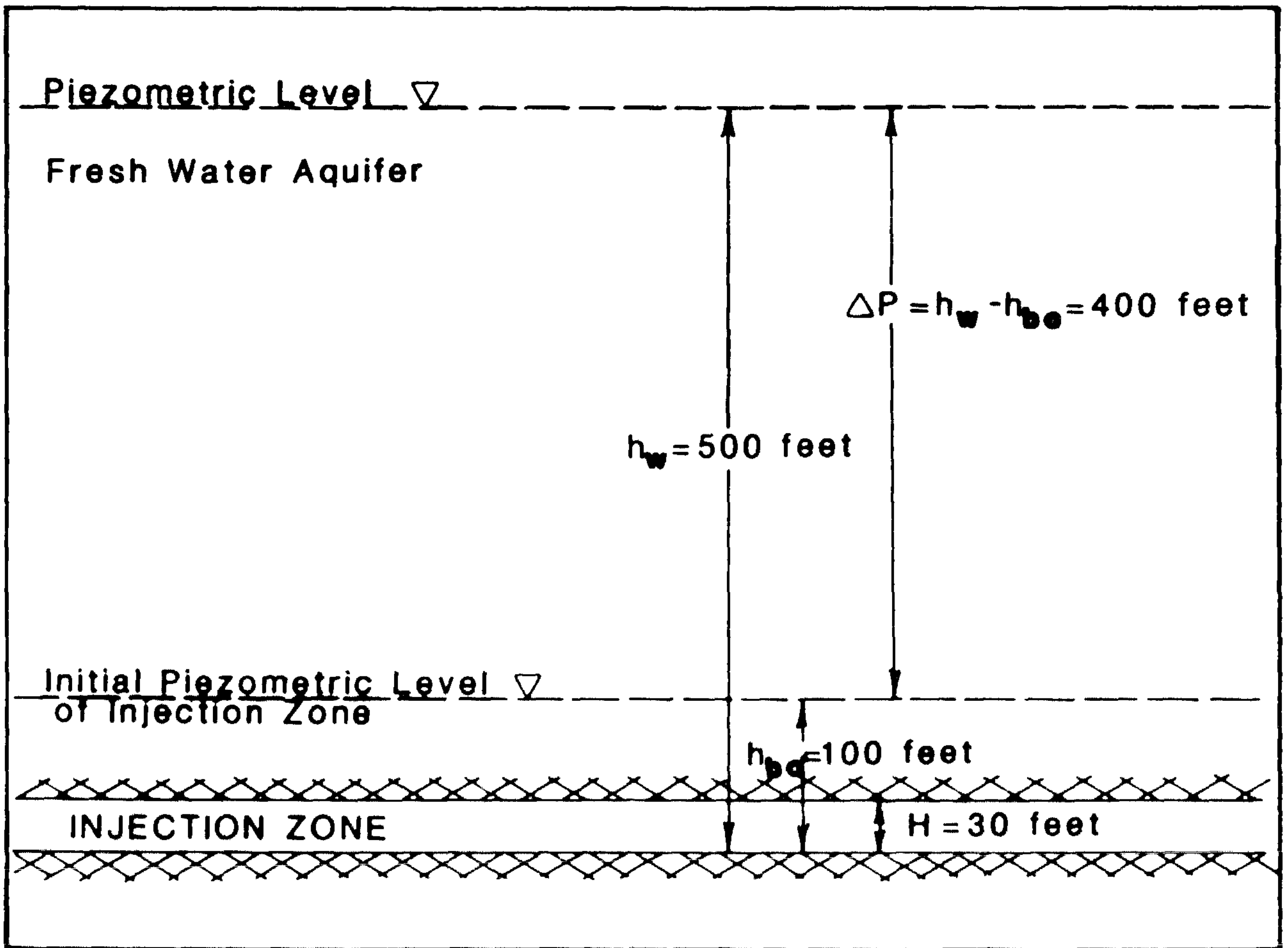


Figure V-3

For this example ΔP, defined in Step 1 of the flow chart in Figure V-1, is 400 feet of head.

To determine the AOR graphically first solve for R_o.

$$R_o = \left(\frac{.3KHt}{S}\right)^{1/2} = \left(\frac{.3(2.12)(30)(3650)}{.0001}\right)^{1/2} = 26{,}390 \text{ feet}$$

At R_o the increase in head caused by the injection well, for the given parameters, is zero. Next plot R_o on semi-logarithmic paper as shown in Figure V-4.

Solve for Δs, the change in head over one log cycle for the specified 50 gallons/minute Q rate.

$$\Delta s = \frac{528(Q)}{KH} = \frac{528(50)}{(2.12)(30)} = 415 \text{ feet}$$

Starting at R_o go back one complete log cycle (for this example go to a distance of 2639 feet from the injection well) and the increase in head should be 415 feet at this distance. This gives another point to draw a straight line through R_o as shown in Figure V-4.

Since 400 feet of head is our critical pressure increase defining the AOR, the appropriate radius for the AOR can easily be picked from the graph. Figure V-4 shows that for this example, the radius for the AOR should be at least 2900 feet from the injection well because at all closer distances the increase in head exceeds 400 feet.

To illustrate the convenience of this method for comparing the AOR for selected injection rates consider the same example data used above and compare the AOR for the injection rates of

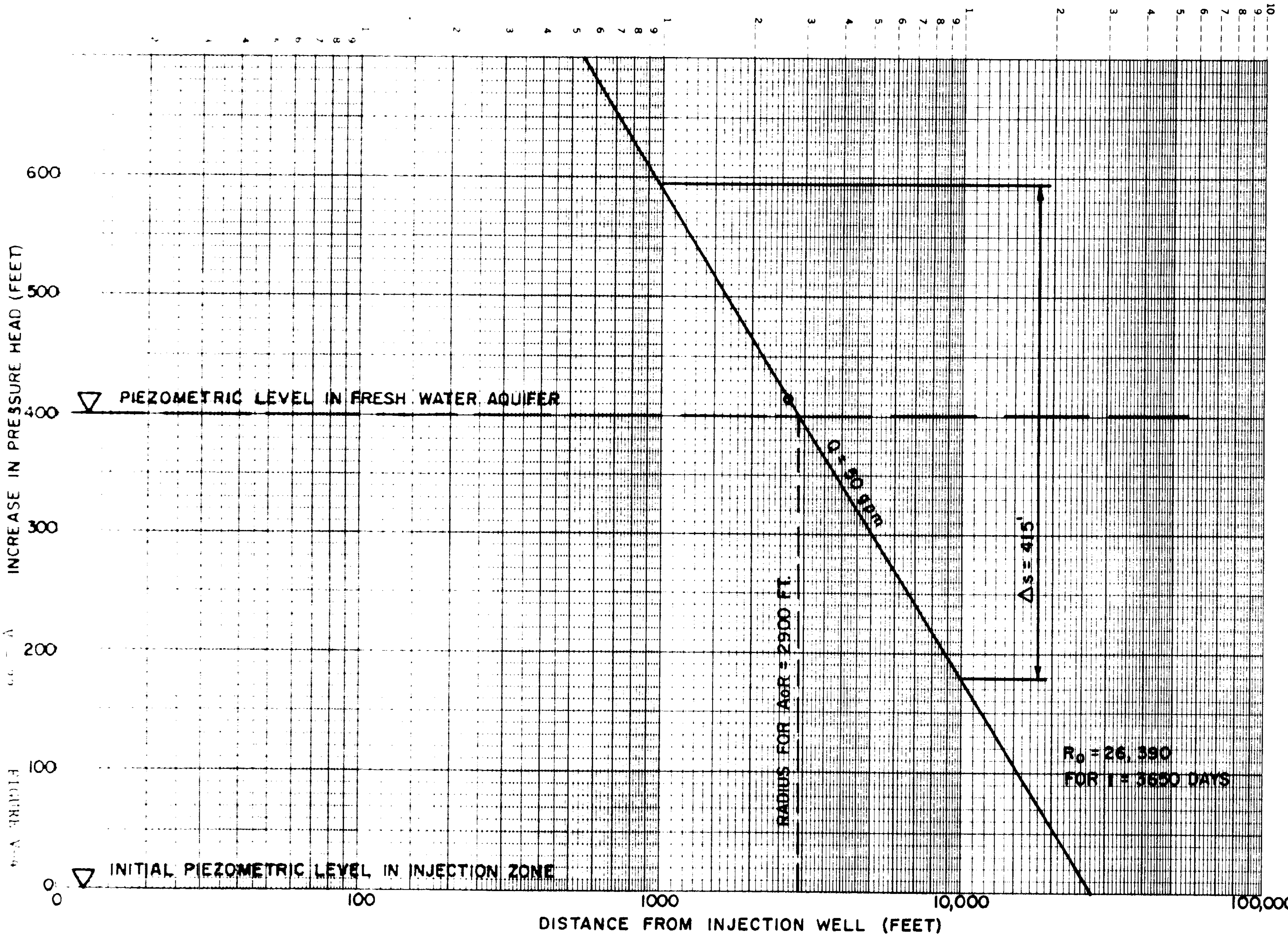

INCREASE IN PRESSURE HEAD (FEET)
600
500
400
300
200
100
0
PIEZOMETRIC LEVEL IN FRESH WATER AQUIFER
INITIAL PIEZOMETRIC LEVEL IN INJECTION ZONE
Q = 50 gpm
RADIUS FOR AoR = 2900 FT.
Δs = 415'
R_o = 26,390
FOR t = 3650 DAYS
0
100
1000
10,000
100,000
DISTANCE FROM INJECTION WELL (FEET)

FIGURE V-4

50, 30, and 20 gallons/minute.

For 30 gpm:

$$\Delta s = \frac{528(30)}{(2.12)(30)} = 249 \text{ feet}$$

For 20 gpm:

$$\Delta s = \frac{528(20)}{(2.12)(30)} = 166 \text{ feet}$$

Repeat the plotting process remembering the R_o has remained unchanged because it is independent of the injection rate. These plots are shown in Figure V-5 and it can be seen that the radius for the AOR should be 100 feet, 620 feet, and 2900 feet for injection rates of 20, 30, and 50 gpm respectively and for a set time of 3650 days.

Dealing with Equation Assumptions

Analytical equations used to predict pressure response from injection into or withdrawal from a reservoir are based on simplifying assumptions that idealize the actual physics of the reservoir. The use of analytical equations for hydrogeologic analysis is based on the following assumptions:

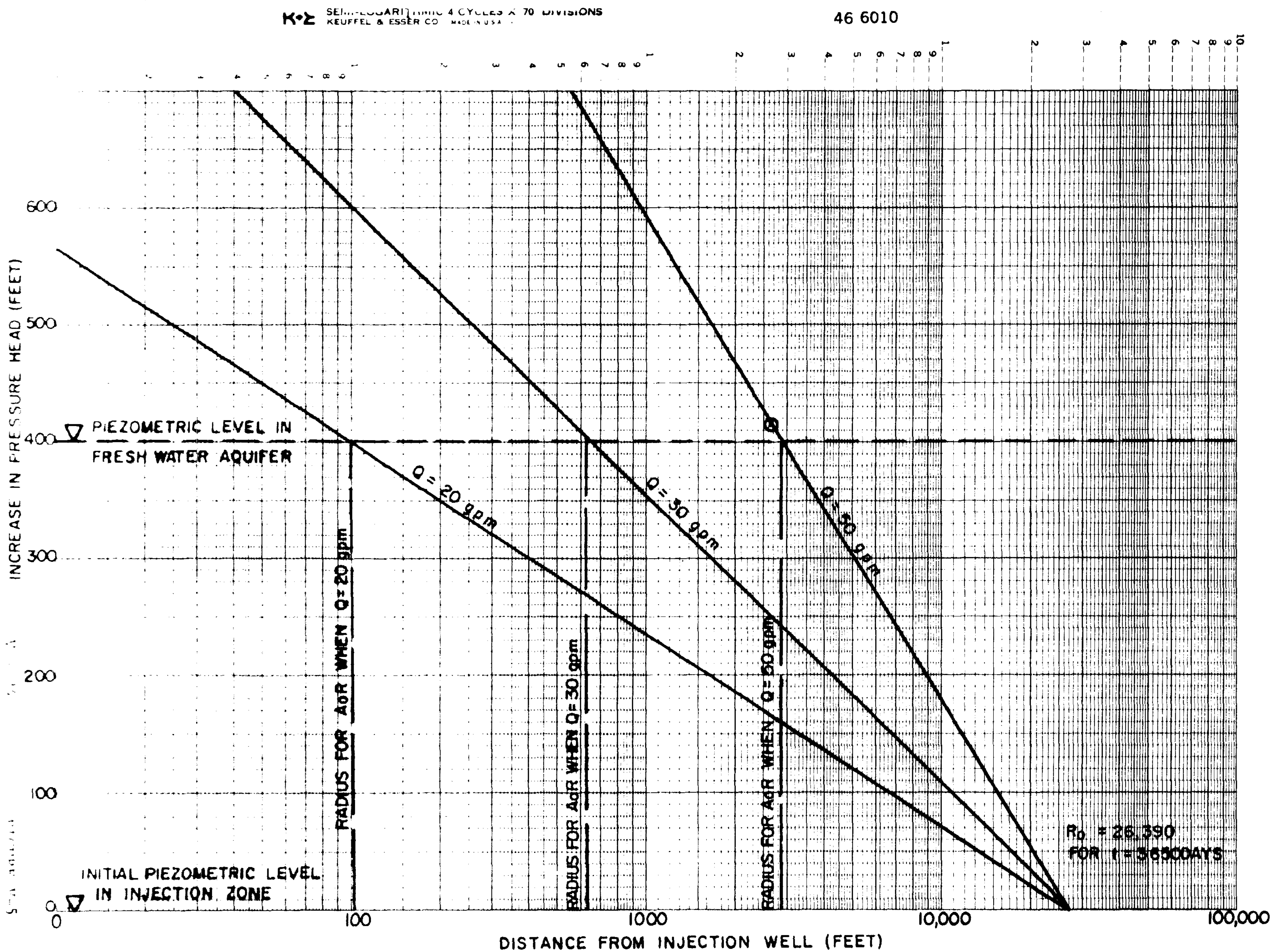
a. the aquifer is homogeneous and isotropic;

b. the aquifer has infinite areal extent;

c. the well penetrates the entire thickness of the aquifer;

d. the well diameter is infinitesimal compared to "r" when pumping (injection) time is longer than a few minutes; and

e. the emplacement of fluid into (or withdrawal from) the


K+E SEMI-LOGARITHMIC 4 CYCLES X 70 DIVISIONS
KEUFFEL & ESSER CO. MADE IN U.S.A.
46 6010
PIEZOMETRIC LEVEL IN
FRESH WATER AQUIFER
Q = 20 gpm
Q = 30 gpm
Q = 50 gpm
RADIUS FOR AoR WHEN Q= 20 gpm
RADIUS FOR AoR WHEN Q= 30 gpm
RADIUS FOR AoR WHEN Q= 50 gpm
INITIAL PIEZOMETRIC LEVEL
IN INJECTION ZONE
R_0 = 26,390
FOR t = 3650DAYS
INCREASE IN PRESSURE HEAD (FEET)
DISTANCE FROM INJECTION WELL (FEET)
0
100
200
300
400
500
600
100
1000
10,000
100,000

aquifer creates instantaneous increase (decrease) in pressure.

In essence these assumptions imply perfectly uniform reservoir characteristics. For example, the aquifer is assumed to have the same permeability, storativity, etc. in all directions and at all points within the aquifer. The assumptions also imply that the aquifer has constant thickness and that the piezometric surface is horizontal (flat).

Because of these simplifying assumptions, analytical solutions describe the response to injection in a very idealized representation of actual aquifer configurations. In other words, the solutions represent what the <u>theoretical</u> response to injection would be if the reservoir were ideal or perfectly uniform. In the real world, aquifers are heterogeneous and anisotropic; they usually vary in thickness; and certainly do not extend to infinity. This is because aquifers are created by complex geologic processes that lead to irregular stratigraphy, interfingering of strata, and pinchouts of both aquifers and aquitards. It is obvious that the worth and applicability of analytical solutions to a particular hydrogeolic environment has to be determined by comparing the deviation between observed response and theoretical response. They have greater worth the more closely the actual hydrogeological environment approaches the idealized configuration.

As an illustration, consider the following example: For this case the injection reservoir is known to have a fairly constant thickness and uniform permeability within an area encompassing 1/2 mile from a proposed injection well. At further distances from the proposed well the permeability is known to decrease dramatically. As long as the area of influence of the injection well remains within the perimeter of the permeability boundary, then the theoretical response to injection, calculated analytically, should be in close agreement with actual reservoir behavior. However, once the area of influence crosses the permeability boundary, the actual flow field will become distorted because of the reduced permeability and actual response will begin to deviate from theoretical predictions. The actual pressure change once this boundary is encountered will be greater than that predicted analytically.

Because of this situation the use of analytical equations, in this case, must be qualified according to the degree of deviation. Such qualifications usually require that field measurements be made of reservoir behavior under stress--for instance, measurement of the pressure change in the reservoir resulting from injection at various distances from the injection well. These data can then be compared with calculated theoretical pressure changes for the same distances and a judgment can be made whether or not the use of analytical equations is justified for future predictions in this hydrogeological setting.

Since all nonhomogeneous and anisotropic conditions will to varying degrees distort the flow field, an important criterion regarding the applicability of the equations discussed in this report is the amount the flow field is distorted when compared to the flow field that would have been observed in an ideal aquifer. This requires that field test data be available.

The selection of equations or computing procedures to be used for analysis is governed largely by the physical conditions of the aquifer studies, insofar as they establish the hydraulic boundaries of the system. Nonhomogeneous and anisotropic conditions combined with the irregularities in the shape of flow systems encountered in many groundwater studies, precludes uninhibited support of calculated results based on vague or meager data. Often the initially calculated results may require revision on the basis of the discoveries resulting from additional testing as the field investigation proceeds.

Circumstance frequently demands that analyses be conducted without prior knowledge of the geology in the vicinity of the test site. To varying degrees, lack of knowledge of the geology in most cases reduces the reliability of the test results to a semiquantitative category until more adequate support is found.

The principal method of groundwater hydraulics analysis is the application of equations derived for particular boundary conditions. The number of equations (and methods) has grown rapidly over the years. These are described in a wide assortment of publications. The essence of many concepts of hydraulics has been presented and briefly discussed in this report but frequent recourse should be made to the more exhaustive treatment given in available publications. A list of suggested publications is presented in the bibliography.

Fixed-Radius Approach for Delineating an AOR

The established requirements for delineating an AOR allow a fixed-radius method to be used. To prevent an arbitrarily selected fixed-radius, the regulations provide a list of factors that need to be considered when the evaluation is made. These factors are:

a. chemistry of injection and formation fluids;

b. hydrogeology;

c. population and groundwater use and dependence; and

d. historical practices in the area.

These factors are to be used as guidelines for fixing an AOR for a given situation. Consideration of these factors will not necessarily give absolute answers to what an appropriate AOR should be; however, they should provide some guidance that is adjustable on a case-by-case basis.

In the previous sections, the reader was warned of using arbitrary data and of applying analytical equations without adequate qualification of the results. These same warnings apply to a fixed-radius approach -- even more so -- and need not be repeated.

In the absence of observed field data, on the behavior of a given reservoir, there are few guidelines that can be given for quantifying an appropriate fixed-radius. That is a basic reason why hydrogeology is listed as a factor for consideration.

The other factors listed above need little explanation. It is obvious that consideration should be given to selecting a larger AOR in areas where many wells penetrate the injection zone and a smaller AOR in isolated injection areas. Other examples would include selecting a larger AOR in areas where groundwater dependence is high or where hazardous substances are being injected. These factors are important and should be considered for all injection operations -- however, they will not quantify what an appropriate radius should be. Without actual field observations and monitoring, the process of selecting a fixed radius for an AOR is reduced to guesswork.

Therefore, the most important guideline that can be given for using a fixed-radius approach for AOR determinations is to use each piece of information that is available on the hydrologic cause-and-effect relationship as a segment of knowledge to refine, as necessary, a chosen radius to an AOR. This may require special field studies or the establishment of monitoring programs for given situations.

Once established, and technically justified for a given hydrogeologic environment, a fixed AOR can be used with greater confidence and more expediently than initial investigations.

BIBLIOGRAPHY

Bear, Jacob, 1979. Hydraulics of Groundwater.

Bouwer, Herman, 1978. Groundwater Hydrology.

Corey, A. T., 1977. Mechanics of Heterogenous Fluids in Porous Media.

Davis, S. N., DeWiest, R. J., 1966. Hydrogeology.

Fetter, C.W., Jr., 1980. Applied Hydrogeology.

Freeze, R. A., Cherry, J. A., 1979. Groundwater.

Hillel, Daniel, 1971. Soil and Water: Physical Principles and Processes.

Johnson Division, UOP Inc., 1966. Ground Water and Wells.

Thornhill, J. T., Short, T. E., and Silka, L., 1982. Application of the Area of Review Concept. Ground Water, v. 20, no. 1, pp. 32-38.

U.S.G.S., 1979. Ground-Water Hydraulics, Professional paper 708.

U.S.G.S., 1963. Shortcuts and Special Problems in Aquifer Tests, Water-Supply Paper 1545-C.

U.S.G.S., 1962. Theory of Aquifer Tests, Water-Supply Paper 1536-E.

Walton, William C., 1970. Groundwater Resource Evaluation.

Walton, William C., 1962. Selected Analytical Methods for Well and Aquifer Evaluation: Bulletin 49 Illinois State Water Survey.

Warner, D. L., et. al, 1979. Radius of Pressure Influence of Injection Wells: EPA-600/2-79-170.

Warner, D. L. and Yow, M. G., 1979. Programmable Hand Calculator Programs for Pumping and Injection Wells. Ground Water v. 17, no. 6, pp. 532-537.