

ARTIFICIAL RECHARGE OF
CONFINED PRAIRIE AQUIFER

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ABSTRACT

Artificial recharge of a confined aquifer was successfully conducted through a 30 m deep small diameter well.

The study site selected was located north of Saskatoon, Saskatchewan, over the Dalmeny aquifer system. Farms and towns in the area obtain water from wells developed into the aquifer and from manmade and natural surface water sources. The aquifer covers an 800 km² region between the North and South Saskatchewan rivers.

Treated fresh water was injected into the aquifer formation by maintaining the water level in the well standpipe above the static water level of the aquifer. The groundwater quality exceeded 2000 mg/L total dissolved solids and was aesthetically displeasing to the well owner because of dissolved iron concentration in excess of 10 mg/L. The injected water contained less than 0.5 mg/L iron, and less than 1000 mg/L total dissolved solids.

Water injected into the aquifer was subsequently recovered by pumping the injection well. The recovery efficiency ranged from 44% to 85% of the theoretical recovery volume, as measured by inorganic chemistry and electrical conductivity. 15% to 36% of the injected water mixed with the natural groundwater and its recovery could not be measured by the adopted methods.

The specific capacity of the aquifer during injection was calculated to be less than 1 m³ day⁻¹ m⁻¹. The calculated specific capacity of the aquifer during recovery was estimated to be greater than 4 m³ day⁻¹ m⁻¹ in 1987, but decreased to less than 2 m³ day⁻¹ m⁻¹ at the end of the field trials.

A preliminary site assessment procedure was established through review of previous work and the findings of the field program.

The field program was limited because the well was over ten years old and had begun to show signs of decreased capacity prior to this

research, and because no monitoring wells could be installed in the study area. Supplementary information relating to artificial recharge was obtained through laboratory and mathematical models.

Tests conducted using a laboratory scale sand model demonstrated that density induced flow occurs after fresh water is injected into brackish water. The fresh water front migrated from a vertical to a horizontal position over a period of 100 minutes. This observation, applied to the field site, may partially account for less than 100% recovery efficiency under artificial recharge.

The fresh water storage in a brackish aquifer was estimated mathematically as a function of hydraulic gradient, aquifer parameters and water density. The model indicated density induced flow may contribute to decreased recovery efficiency of stored fresh water, but the model capabilities was limited to demonstrating the process, rather than application and analysis of field data sets.

The net increase of dissolved calcium in the injected water was calculated to be less than 1 mg/L. The increased calcium concentrations of the recovered water quality over time was attributed to the mixing of brackish water with the injected water, not to calcite dissolution from the aquifer matrix.

Artificial recharge and recovery efficiency of fresh water into a confined aquifer in Saskatchewan was estimated assuming changes in water quality due to dispersion. Some additional losses occurred that may be due to density differences between the injected and original groundwater, or due to the regional groundwater gradient.

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NOMENCLATURE

A	= cross sectional area (m^2)
a	= aquifer compressibility (m^2/N)
α	= dispersivity (m)
B	= complimentary error function coefficient
b	= aquifer thickness (m)
β	= fluid compressibility (m^2/N)
C	= concentration (mg/L)
c_r	= concentration ratio ($\frac{\text{mg/L}}{\text{mg/L}}$) or ($\frac{\mu\text{S/cm}}{\mu\text{S/cm}}$)
ϕ	= tilting angle
D	= diffusion coefficient (m^2/s)
D_m	= coefficient of dispersion (m^2/s)
DG	= density gradient (kg/m^4)
EC	= electrical conductivity ($\mu\text{S}/\text{cm}$)
g	= gravitational acceleration (m/s^2)
h	= hydraulic head (m)
η	= porosity (m^3/m^3)
I	= injection capacity ($\text{m}^3 \text{ day}^{-1} \text{ m}^{-1}$)
ϕ	= density ratio of groundwater to fresh water
K	= hydraulic conductivity (m/s)
κ	= effective permeability
k	= permeability (m^2)
μ	= absolute viscosity (Pa s)
p	= pressure (Pa)
Q	= flow rate (m^3/s)
Q'	= stable injection rate (m^3/day)
q	= unit discharge (m^2/s)
r	= radial distance (m)
ρ	= density of fluid (kg/m^3)
s	= injection head (m)
S	= storativity (m^3/m^3)
T	= temperature ($^{\circ}\text{C}$)
t	= time (s)

T = transmissivity (m^2/s)
TDS = total dissolved solids (mg/L)
 ν = viscosity ratio ($\frac{\text{Pa s}}{\text{Pa s}}$)
V = volume (m^3)
 Ψ = recovery volume ratio
 v = average linear velocity (m/s)
x = distance (m)
Y = distance (m)
z = height above datum (m)

Subscripts

fw = fresh water
gw = groundwater
h = horizontal direction
i = injection
max = maximum
min = minimum
p = recovery
t = time
r = relative
pw = pumped water
u = density induced flow

1.0 INTRODUCTION AND OBJECTIVES

In Saskatchewan, a potential application of artificial recharge is to transfer excess volumes of surface water available in the early spring into brackish aquifers, temporarily improving the quality of water available from the aquifer and conserving water.

Fresh water injection into and recovery from an aquifer may be measured as a function of groundwater flow, dispersion and water density. Field trials have demonstrated that site specific properties relating to well construction and method of injection also influence the injection process, although those factors are more difficult to quantify (Asano, 1980; Cole, 1985).

The objectives of this research were to:

1. Determine if surface water could be injected into a confined aquifer and subsequently recovered with minimum change in water quality.

Permission to use a water well in the Saskatoon area was obtained for the summer of 1987 and 1988. A portable water treatment system developed by the University of Saskatchewan was used to pump and treat surface water and inject the water into the aquifer. The water well pump was used to recover water one to six weeks after injection.

2. Estimate the volume of water available for recovery using basic information of initial water quality and aquifer properties, and compare estimated volumes to field results.

Analytical mathematical groundwater flow equations and a laboratory scale physical model were used to represent the artificial recharge process. Field results regarding the volume and quality of water injected and recovered from the well was then evaluated by comparing to the analytical solution and laboratory observations.

3. Assess changes in water quality using available equilibrium models, and compare results to experimental data.

Groundwater chemistry was analyzed prior to and during recovery. Regional groundwater data was input into a geochemical model to estimate theoretical changes that may be expected from the recharge, estimated changes were compared with observed groundwater chemistry changes.

4. To develop selection criteria for artificial recharge sites to aid in locating a study site.

Selection criteria noted from available literature was used evaluate potential sites. The results from the field trials were then reviewed to assess the relevance of the criteria.

2.0 BACKGROUND

2.1 Natural Recharge in Southern Saskatchewan

Groundwater recharge is the movement of water into the saturated soil zone. Recharge of confined and unconfined aquifers replenishes water removed by pumping, springs, evaporation and plant uptake.

Natural recharge to confined aquifers is less than 5% of annual precipitation; recharge to unconfined aquifers may be greater than 30% of annual precipitation (Rey, 1982). Beneath ponds, natural recharge may be up to 80% of the annual precipitation (Keller, 1985). Figure 2.1 illustrates a typical seepage pattern under ponds.

Groundwater withdrawal greater than natural recharge will result in a net decrease of water held in storage. The long term impact of this practice includes land settlement, decreased storage capacity and transmissivity of the aquifer, and increased levels of dissolved constituents in the groundwater (Driscoll, 1986).

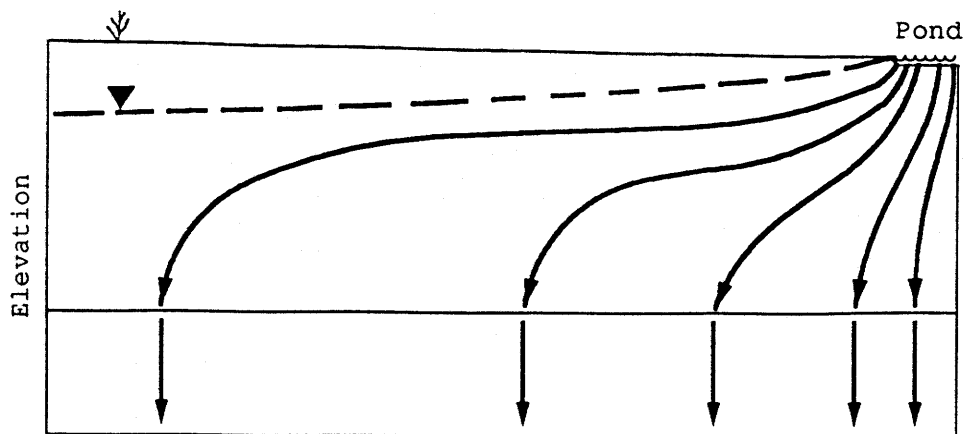


Figure 2.1: Natural recharge in ponds: schematic cross-section (Keller, 1985)

2.1.1 Water Quality

Groundwater available from confined aquifers in Saskatchewan generally contains concentrations of total dissolved solids over 1000 mg/L (Rutherford, 1967). Precipitation may contain trace amounts of dissolved solids, but water is a strong solvent that reacts with calcareous minerals and with sulphate bearing gypsum and anhydrite, common constituents of Prairie soil (Rozkowski, 1967; Freeze and Cherry, 1979). Cool temperature, neutral to acidic pH and high carbon dioxide partial pressure of the soil water enhances the dissolution process (Stumm and Morgan, 1970; Drake, 1980).

Total dissolved solids of groundwater sampled at the same site will vary slightly on a seasonal and yearly basis, depending on the volume of natural recharge (McMonagle, 1987).

The equilibrium concentration of ionic constituents in water is defined by the pH, Eh, and temperature of the water, and the ionic constituents already in solution (Stumm and Morgan, 1970). Water in a confined aquifer exists in a closed system, commonly an anaerobic environment (Stumm and Morgan, 1970, Freeze and Cherry, 1979). Figure 2.2 presents the general change in water's ionic constituents moving through till (Rozkowski, 1967).

Under most conditions, water in a surface reservoir is at equilibrium with available oxygen and carbon dioxide in the atmosphere. An anaerobic environment may develop in the winter beneath the frozen reservoir surface, or in the summer with abundant plant growth.

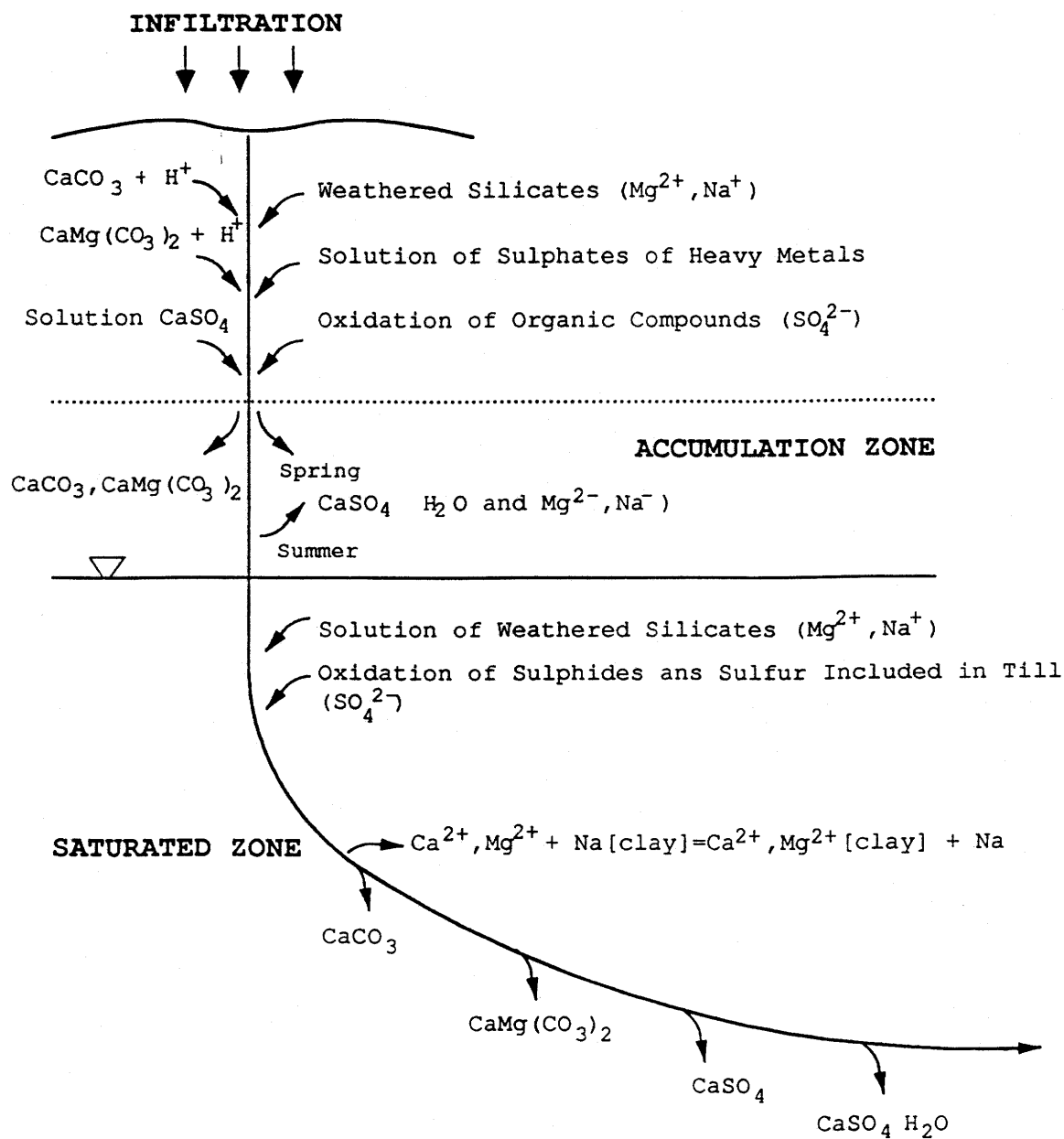


Figure 2.2: Ion cycles in local groundwater recharge zone in till in southern Saskatchewan, in the Moose Mountain region 300 km southeast of Saskatoon (after Rozkowski, 1967)

2.1.2 Availability

The availability of a surface water supply for domestic use depends on drainage patterns, annual precipitation, evaporation rates and storage conditions. In areas where natural reservoirs do not exist, people have constructed reservoirs to enhance runoff and snow catchment.

Ninety percent of Saskatchewan's communities with populations less than 4000 and over 75% of farms depend on groundwater as their source of supply. Several larger communities, including Regina, supplement their surface water supplies with groundwater (Saskatchewan Research Council, 1983). Provincial water quality objectives presented in Table 2.1 reflect the low quality of Saskatchewan's groundwater (Saskatchewan Environment and Public Safety, 1991). The Canadian Water Quality Guidelines (1990) presented in Table 2.2 have comparatively lower acceptable concentrations.

Water quality objectives regarding chemical, biological, radiological and aesthetic characteristics reflect health, cost of water treatment, and aesthetic concerns. Only the primary water quality constituents are presented in Tables 2.1 and 2.2. Primary water constituents that pose a potential health risk are nitrates and sulphates. Nitrate levels above 40 mg/L are dangerous to infants and livestock.

Sulphate levels above 500 mg/L cause temporary minor health problems until the body adjusts to the increased sulphate intake. High sulphate levels remain an aesthetic problem, however the cost of treatment to reduce the concentration of sulphate to 500 mg/L is often prohibitive. Other constituents presented in Tables 2.1 and 2.2 are based on cost of treatment and aesthetic characteristics.

Table 2.1: Municipal Drinking Water Quality Objectives
(Saskatchewan Environment and Public Safety, 1991)

Parameter	Maximum Acceptable Concentration (mg/L)	Aesthetic Objectives (mg/L unless specified)
total dissolved solids	-	1500
total hardness (as CaCO ₃)	-	800
magnesium	-	200
iron (Fe ⁺²)	-	0.3
manganese (Mn ⁺²)	-	0.05
copper (Cu ⁺)	-	1.0
sodium (Na ⁺)	-	300
zinc (Zn ⁺)	-	5.0
total alkalinity (as CaCO ₃)	-	500
chloride (Cl ⁻)	-	250
sulphate (SO ₄ ⁻²)	-	500
sulphide (as H ₂ S)	-	0.05
nitrate (NO ₃ ⁻)	40	-
pH (units)	-	7.0 to 9.0

Table 2.2: Canadian Water Quality Guidelines (Environment Canada, 1989)

Parameter	Maximum Acceptable Concentration (mg/L)	Aesthetic Objectives (mg/L unless specified)
total dissolved solids	-	500
total hardness (as CaCO ₃)	-	500
chloride (Cl ⁻)	-	250
sulphate (SO ₄ ⁻²)	500	150
nitrate (NO ₃ ⁻)	10	-
iron (Fe ⁺²)	-	0.3
manganese (Mn ⁺²)	-	0.05
pH (units)	-	6.5 to 8.5

Groundwater that does not meet water quality objectives may affect water well performance and increase maintenance costs. During pumping, the head in the well decreases, causing a pressure drop across the well screen. Waters that are near saturation or super-saturated with carbonate minerals will tend to precipitate the carbonate at the well screen, encrusting the well screen slots. Remedial acidification of the well removes carbonate from the slots (Driscoll, 1986).

Iron bacteria may develop around the well screen in the presence of dissolved iron in the water, forming a slime that plugs pore spaces around the well and in the screen slots. Shock chlorinating the well may control iron bacteria growth (Smith, 1981).

2.2 Artificial Recharge Processes

Artificial recharge is a planned activity that conveys surface water directly to an aquifer, commonly at rates and quantities greater than natural recharge (Huisman and Olsthoorn, 1983). Surface methods of artificial recharge include spreading ponds, canals and shallow wells to enhance the natural recharge to unconfined aquifers. Subsurface methods include horizontal and vertical wells to displace the original groundwater from the well region or to restore depleted aquifers (Asano, 1980). Artificial recharge involves injection and recovery. Retention time is measured from initial injection to initial recovery (Huisman and Olsthoorn, 1983).

2.2.1 Site Selection

A direct means for selecting a suitable site for artificial recharge was not found in the literature. Available textbooks on the subject (Asano, 1980; Huisman and Olsthoorn, 1983) identify general limiting conditions that have been identified through field programs. The majority of the research conducted has involved saline aquifers, and has identified sodium adsorption on clay particles as a primary limiting factor (Esmail and Kimbler, 1967).

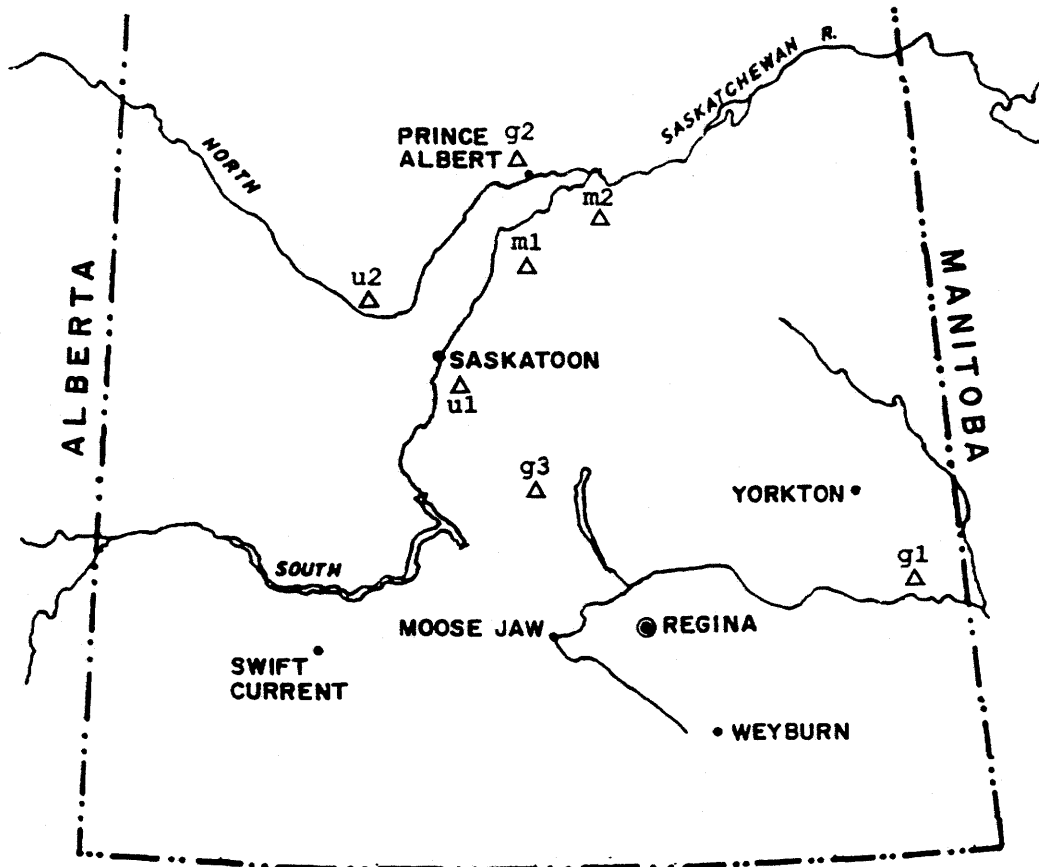
Other factors to consider when injecting water into an aquifer include (Kimbler et al., 1975):

1. Efficiency of the well to aquifer connection,
2. Extent of mixing by diffusion and dispersion,
3. Aquifer capacity, homogeneity, discontinuities, slope, existing gradients, and the relationship between land surface and potentiometric head, and
4. Segregation of water due to density differences.

Several field programs and site appraisals have been documented in Saskatchewan. Interest in artificial recharge in Saskatchewan has been active since the late 1960's, with research and field trials conducted by various agencies (Figure 2.3). Recharge projects are summarized in Table 2.3; project locations are shown in Figure 2.3. At sites u1, u2, g1 and g2, the proposed or intended means of recharge was by water injection through wells, while at sites g3, m1 and m2, the proposed or intended means of recharge was by surface infiltration.

Table 2.3: Artificial recharge studies in Saskatchewan

Site	Details
u1	University of Saskatchewan field site 1 (Gillies, 1983)
u2	University of Saskatchewan field site 2 (Cole, 1985)
g1,g2	National Hydrology Research Institute feasibility study, two of six Prairie sites (Wasiuta, 1987)
g3	Prairie Farm Rehabilitation Association recharge enhancement through snow management (Jackman, 1989)
m1	Wakaw municipal water supply enhancement (UMA, 1989)
m2	Kinistino municipal water supply enhancement (Bullee, 1989)



2.3 Transport Processes

Transport processes affecting artificial recharge include groundwater velocity, diffusion, dispersion and density stratification (Figure 2.4).

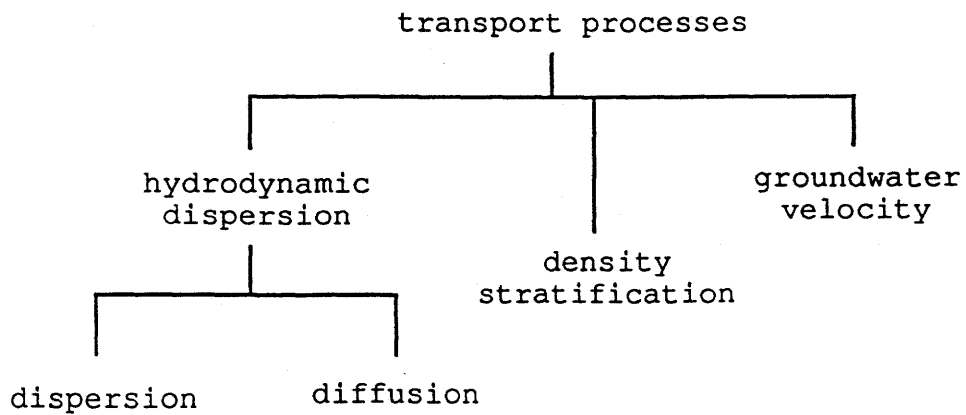


Figure 2.4: Groundwater movement (after Lam et al., 1987)

2.3.1 Groundwater Velocity

Darcy's equation defines flow of water in porous media as:

$$Q = -K \frac{dh}{dx} A \quad (2.1)$$

where: Q = flow rate (m^3/s)

K = hydraulic conductivity (m/s)

h = total head (m)

x = distance in the horizontal direction (m)

A = cross sectional area (m^2)

Hydraulic conductivity is a function of properties of the porous media and of the fluid flowing through the media:

$$K = \frac{\rho g}{\mu} k \quad (2.2)$$

where: k = permeability of porous medium (m^2)

ρ = density of the fluid (kg/m^3)

g = gravitational acceleration (m/s^2)

μ = absolute viscosity of the fluid ($Pa \cdot s$)

The energy equation expresses total head as the summation of velocity head, pressure head and elevation:

$$h = \frac{v^2}{2g} + \frac{p}{\rho g} + z \quad (2.3)$$

where: v = average linear velocity (m/s)

p = pressure (Pa)

z = height above datum (m)

For flow through porous media, the velocity head as expressed by $\frac{v^2}{2g}$ is negligible (Freeze and Cherry, 1979).

Groundwater flow in an aquifer is commonly measured by pump testing an installed well. This test is of primary importance to the well owner in determining the suitability of the well to meet the volume and flow requirements of the user.

Water pumped from a vertical well induces horizontal hydraulic gradients towards a well, as a result the hydraulic head decreases in the aquifer. The flow rate per unit of drawdown is termed specific capacity, a comparative measure of well performance.

The partial differential flow equation for water pumped from a well screened across a confined aquifer is (from Jacob, 1940):

$$\frac{\partial^2 h}{\partial r^2} + \frac{1}{r} \frac{\partial h}{\partial r} = \frac{S}{T} \frac{\partial h}{\partial t} \quad (2.4)$$

where: S = storativity (m^3/m^3)

h = hydraulic head (m)

T = transmissivity (m^2/s)

r = radial distance (m)

t = time (s)

Storativity, S , is defined as the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head.

$$S = \rho g b(a + \eta \beta) \quad (2.5)$$

where a = aquifer compressibility (m^2/N)

b = aquifer thickness (m)

η = porosity (m^3/m^3)

β = fluid compressibility (m^3/kg)

Transmissivity, T , is the bulk hydraulic conductivity across the thickness of the aquifer:

$$T = K b \quad (2.6)$$

Equations 2.6 to 2.8 assume that the aquifer is:

1. Horizontal,
2. Confined between two impermeable formations on top and bottom,
3. Infinite in horizontal thickness,
4. Of constant thickness, and
5. Homogeneous and isotropic with respect to its hydrogeological parameters.

The non-equilibrium solution to Equation 2.1 was developed by Theis (1935).

$$h_0 - h(r,t) = \frac{Q}{4 \pi T} \int_{\mu}^{\infty} \frac{e^{-u}}{u} du \quad (2.7)$$

$$u = \frac{r^2 S}{4 T t} \quad (2.8)$$

The exponential integral, Equation 2.7, is the well function $W(u)$, with u defined by Equation 2.8.

Curve matching of the $W(u)$, u function curve and the data curve determines values of S and T . The curve matching technique is shown in Figure 2.5.

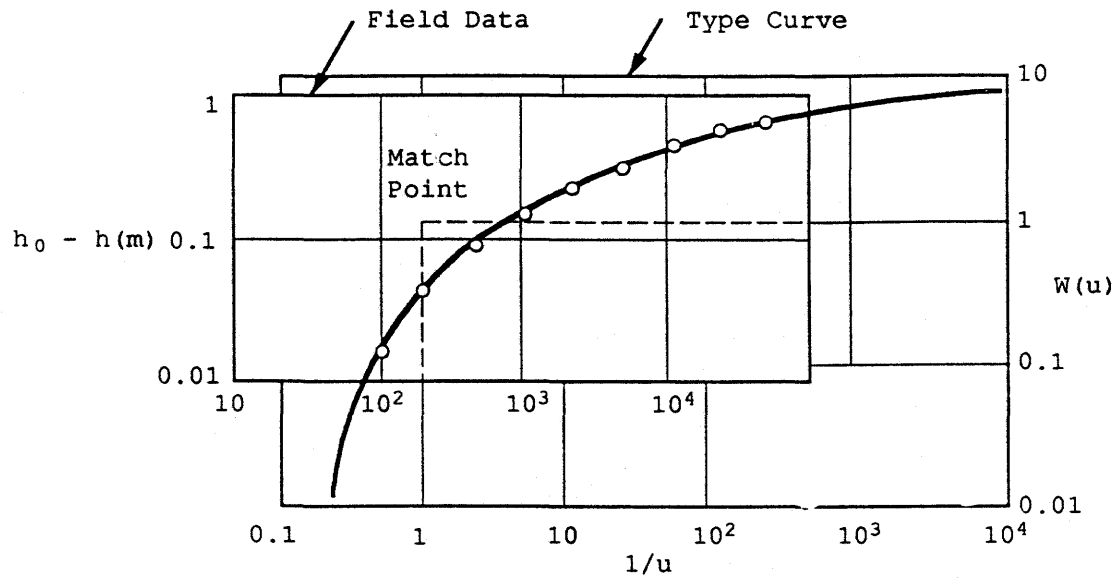


Figure 2.5: This curve matching technique

The groundwater flow equations are reversible and applicable to defining groundwater velocity due to artificial recharge. Water injected into a well induces horizontal hydraulic gradients away from a well and increases the aquifer hydraulic head (Figure 2.6).

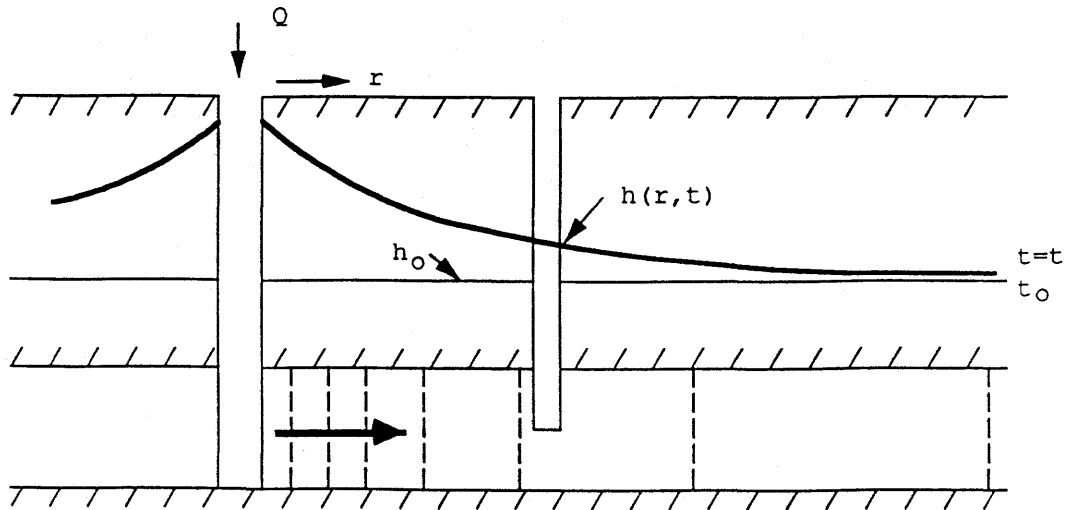


Figure 2.6: Groundwater flow into a confined aquifer

The hydraulic head required to transfer water into the aquifer may increase due to clogging available pore spaces. Clogging mechanisms include air binding, suspended matter, geochemical reactions, mechanical jamming and bacteria (Figure 2.7).

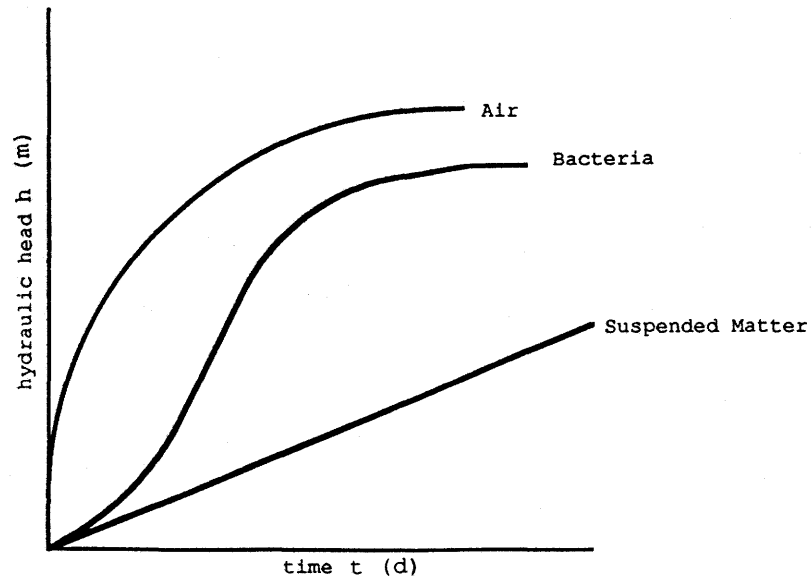


Figure 2.7: Effect of clogging mechanisms on injection head (Huisman and Olsthoorn, 1983)

2.3.2 Diffusion

Diffusion is the process whereby ionic or molecular constituents move under the influence of their concentration gradient.

Fick's second law defines the rate of diffusion through a given cross section per unit time as:

$$\frac{\delta C}{\delta t} + \frac{q}{r} \frac{\delta C}{\delta r} = \frac{Dr^2}{q} \frac{\delta^2 C}{\delta r^2} \quad (2.9)$$

where: D = diffusion coefficient (m^2/s)

C = concentration (mg/L)

and
$$q = \frac{Q}{2 \pi \eta b} \quad (2.10)$$

Diffusion coefficients are commonly 10^{-8} to 10^{-10} m^2/s , but diffusion ceases only when concentration gradients become non-existent (Freeze and Cherry, 1979).

2.3.3 Dispersion

Dispersion occurs under flow through porous media when the concentration front mixes with the native water due to the different flow paths available in the pore spaces. The extent of mixing that occurs as the concentration front moves through the media depends on the dispersivity of the medium:

$$D_m = \alpha v \quad (2.11)$$

where:
$$v = \frac{q}{r} \quad (2.12)$$

and: $D_m =$ coefficient of dispersion (m^2/s)

$\alpha =$ dispersivity (m)

The dispersivity increases as the volume and heterogeneity of the porous medium increases (Figure 2.8).

For non-reactive dissolved constituents in saturated, homogeneous, isotropic materials under uniform flow, the radial differential equation describing the combined effect of diffusion and dispersion is:

$$\frac{\delta C}{\delta t} + \frac{q}{r} \frac{\delta C}{\delta r} = D_m \frac{\delta^2 C}{\delta r^2} + \frac{D}{r} \frac{\delta}{\delta r} \left(r \frac{\delta C}{\delta r} \right) \quad (2.13)$$

The steady state solution to Equation 2.13 is:

$$\frac{C}{C_{gw}} = \frac{1}{2} \operatorname{erfc} (B) \quad (2.14)$$

where: (B) =
$$\frac{q_i t_i - \left(\frac{r^2}{2}\right)}{\sqrt{\frac{4}{3}\alpha r^3 + \frac{Dr^4}{q}}} \quad (2.15)$$

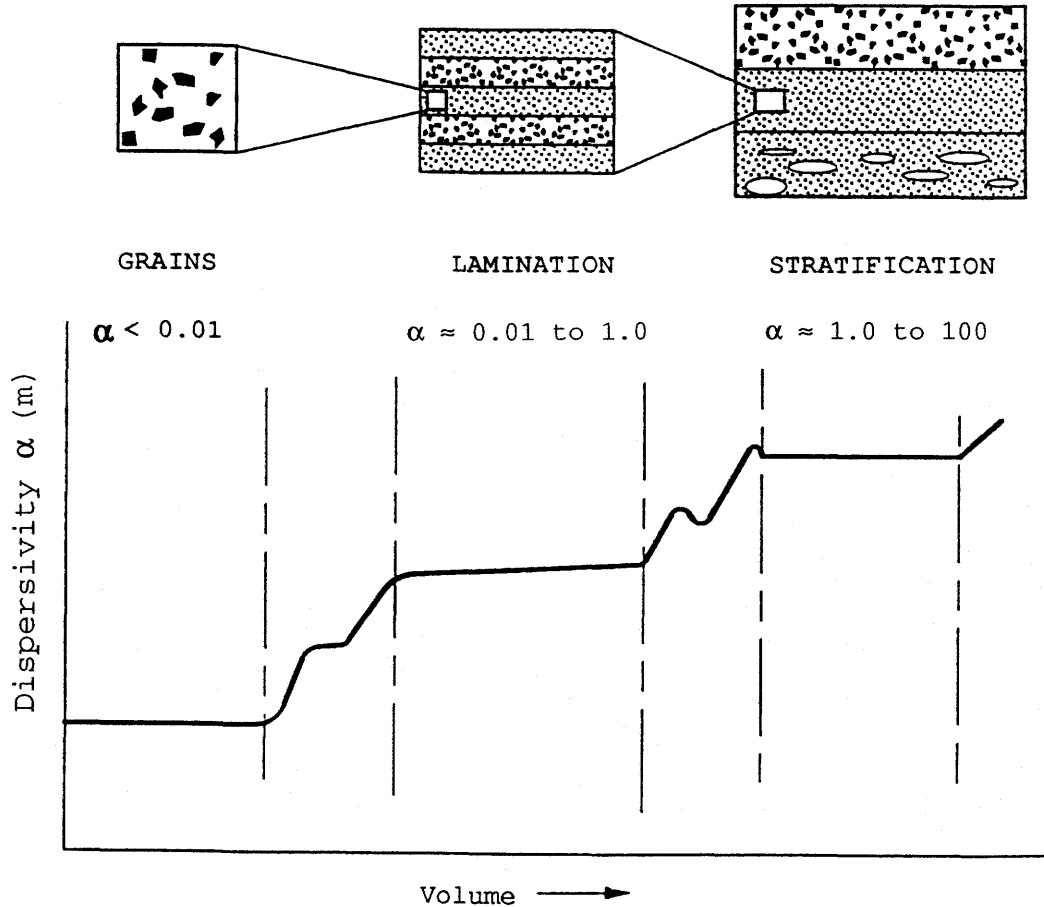


Figure 2.8: Variation in dispersivity with volume of soil (after Lam et. al., 1987)

Gelhar and Collins (1971) developed an equation describing the movement of the concentration front towards a well for injection and withdrawal through a single well. The equation is based on the following assumptions:

1. The front has moved away from the well.
2. Diffusion is negligible.

3. The dispersed zone thickness is small compared to the distance traveled by the front.
4. Initial (groundwater) concentration is zero.

The Gelhar equation relates change in the concentration of dissolved constituents to the recovery volume:

$$B = \frac{\Psi - 1}{\sqrt{\frac{16\alpha}{3P} [2 - |1 - \Psi|^{1/2} (1 - \Psi)]}} \quad (2.16)$$

where: $\Psi = \frac{Q_p t_p}{Q_i t_i}$ = recovery volume ratio (2.17)

and: $R = \sqrt{\frac{Q_i t_i}{\alpha \eta b}}$ = radius of injection (2.18)

The development of the concentration front during recovery is shown in Figure 2.9. Equations 2.14, 2.15 and 2.16 define the breakthrough curve observed in contaminant transport and tracer studies, when the indicator constituent in the recovered water is initially at a greater concentration than the constituent is present in the groundwater, so that $\frac{C}{C_{gw}}$ decreases to 1.0. For artificial recharge, the concentration of the recovered water is initially at a lower concentration than the background groundwater, so that $\frac{C}{C_{gw}}$ increases to 1.0.

$$\frac{C}{C_{gw}} = 1 - \frac{1}{2} \operatorname{erfc}(B) \quad (2.19)$$

The relationship may also be used to estimate the coefficient of dispersion under single well injection and withdrawal (Pickens and Grisak, 1981):

$$B = \frac{3 (\Delta\Psi)^2 \sqrt{Q_i t_i}}{32 \pi^{3/2} \sqrt{\eta b}} \quad \text{at } \frac{C}{C_{fw}} = 0.5 \quad (2.20)$$

where: $\Delta\Psi = (\Psi_{C=1}) - (\Psi_{C=0})$ (2.21)

Field trials and application of the USGS mass transport model conducted by El Kadi (1988) verified the solution to the radial differential equation for steady state flow as described by Equations 2.13 to 2.21.

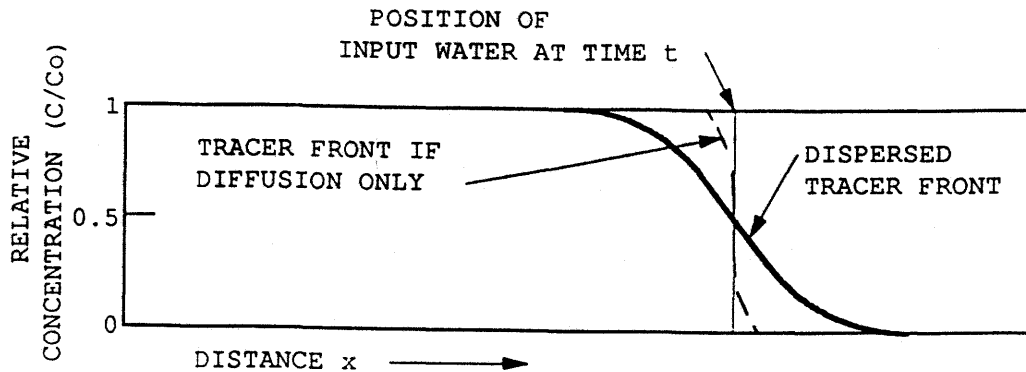


Figure 2.9: Breakthrough curve (after Pickens and Grisak, 1981)

2.3.4 Density Induced Flow

Density induced flow occurs along the mixing front of two fluids, due to differences in fluid density. The problem was first analyzed in the later part of the 19th century by Ghyben and Herzberg (Freeze and Cherry, 1979), for ideal static conditions in coastal aquifers, based on the energy equation.

Hydraulic conductivity, K , aquifer storativity, S , Darcy's equation and the continuity equation are dependent on fluid density. Hydraulic conductivity and aquifer storativity are more dependent on aquifer properties than on fluid properties in a groundwater environment, so that small changes in density would not significantly affect K and S values in Darcy's equation (Bear, 1972; Frind and Palmer, 1980).

$$\alpha_x = -K \left(\frac{\delta h}{\delta x} + \rho_r \right) \quad (2.22)$$

$$\rho_r = \frac{\rho_{pw}}{\rho_{fw}} - 1 \quad (2.23)$$

where: ρ_r = density ratio $\left(\frac{\text{kg/m}^3}{\text{kg/m}^3} \right)$

and: ρ_{pw} = density of recovered (pumped) water (kg/m^3)

ρ_{fw} = density of injected (fresh) water (kg/m^3)

Dissolved constituents contribute to the water density. For example, sea water salts at a concentration of 35,000 mg/L increase water density by 2.5% (Freeze and Cherry, 1979). The relative concentration of the fluid is related to density by the expression:

$$C_r = \frac{\rho_{pw} - \rho_{fw}}{\rho_{gw} - \rho_{fw}} \quad (2.24)$$

where: C_r = relative concentration (unitless)

ρ_{gw} = density of native groundwater (kg/m^3)

The density ratio may then be expressed as:

$$\rho_r = \phi C_r \quad (2.25)$$

where: $\phi = \frac{\rho_{gw}}{\rho_{fw}} - 1 \quad (2.26)$

so that flux may be defined in terms of concentration, by Darcy's equation:

$$q_x = -K \left(\frac{\delta h}{\delta x} + \phi C_r \right) \quad (2.27)$$

Other researchers into artificial recharge have defined density stratification as gravity segregation. Viscosity and density terms define the dimensionless density stratification term, ϕ , based on dimensional analysis and experimental data (Esmail and Kimbler, 1967):

$$\phi = \frac{0.1 k_h g (\rho_{gw} - \rho_{fw}) t}{\eta \mu_a} \sqrt{\frac{\mu_a^{2/3} (DG)}{(\rho_{gw} - \rho_{fw})^{5/3} g^{1/3}}} \quad (2.28)$$

where: $\mu_a = \frac{\mu_{fw} + \mu_{gw}}{2}$

and: DG = density gradient (kg/m^4)

$$DG = \frac{\rho_{gw} - \rho_{fw}}{2Y} \quad (2.29)$$

where: $2Y$ = projection of fluid interface on the horizontal (m)
 ($2Y$ is illustrated in Figure 2.11)

Gardner et al., (1962) defined density stratification as a function of the position of the two fluid interface in the aquifer:

$$f(\phi) = \frac{2Y}{b} \quad (2.30)$$

Figures 2.10 and 2.11 illustrate the interface developed from dispersion alone, and from dispersion and density stratification.

Kumar (1968) and Kimbler et al., (1975) related Gardner's function (Equation 2.30) to the density stratification term, ϕ :

$$2Y/b = 20\phi \quad 0 \leq \phi \leq 0.1 \quad (2.31)$$

$$2Y/b = 0.8 + 12.5\phi - 4.8\phi^2 \quad 0.1 \leq \phi \leq 1.0 \quad (2.32)$$

$$2Y/b = 6.5 + 2\phi \quad \phi > 1.0 \quad (2.33)$$

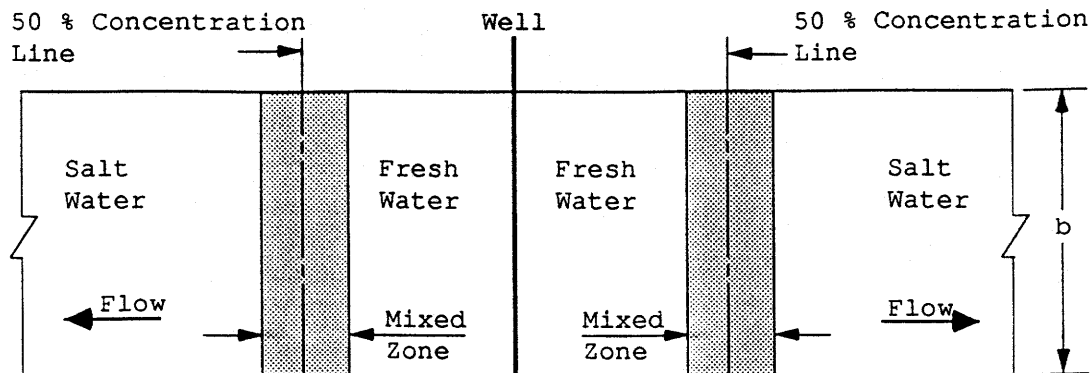


Figure 2.10 Fresh water movement into a salt water aquifer with mixing due to dispersion (Kimbler et al., 1975)

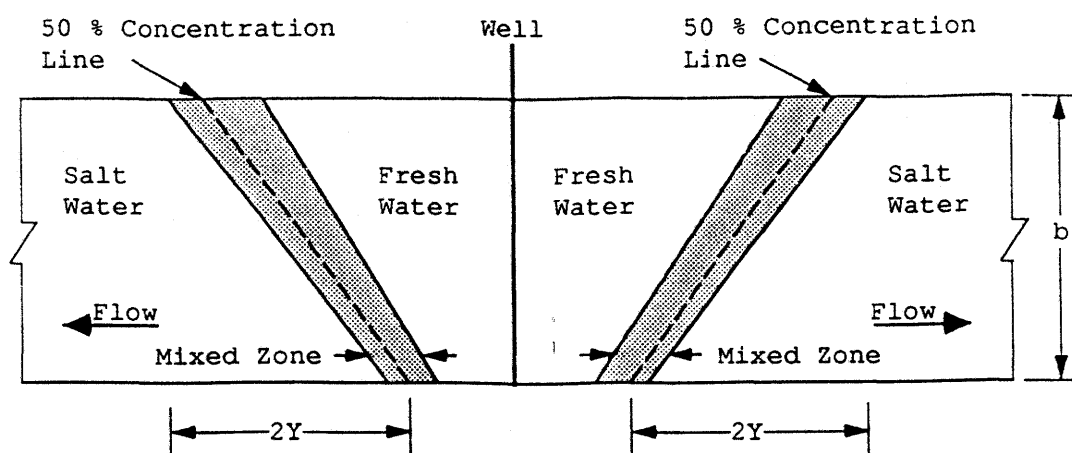


Figure 2.11: Fresh water movement into a salt water aquifer with mixing due to dispersion and density stratification (Kimbler et al., 1975)

Equations 2.28 to 2.33 have not gained wide use in the development of mathematical modeling of artificial recharge programs. It has been shown through analytical solutions and mathematical modeling that under density dependent flow, the mixing front profile varies with time as a function of aquifer thickness and properties of the porous media, and is independent of viscosity (Segol et al., 1975; Frind and Palmer, 1980).

Mathematical models allow input parameters to be varied or held constant to test the relative significance of velocity, dispersion, diffusion and density processes on the groundwater flow regime. The effect of density is difficult to differentiate from other processes under field conditions due to the natural variability in aquifer properties. Segol et al. (1975) and Hellstrom (1988a, 1988b) determined that aquifer anisotropic conditions influenced the shape of the density stratification front with time. Frind (1982) determined that a small increase in density significantly increased computing time and costs, but had little effect on the development of the leachate plume in a fresh water aquifer. Hellstrom (1988a, 1988b) determined that the development of the dispersion front and heterogeneous or anisotropic conditions of the porous media retarded the development of the tilting angle.

2.4 Geochemical Mass Transfer

Geochemical mass transfer processes affecting groundwater quality include adsorption, precipitation and dissolution. These processes occur as the water approaches chemical equilibrium with the porous media in a dynamic environment.

Several geochemical models are currently available to model the equilibration of water with given minerals in a defined environment. Drever (1988) presents an overview of available geochemical models including the PHREEQE (pH-redox-equilibrium equations) computer program developed by the United States Geological survey (Parkhurst et al., 1980). PHREEQE is a program currently available to simulate the mixing of two solutions under artificial recharge conditions. A data base providing thermodynamic data for aqueous species, elements and minerals is available to use with the program.

The process of artificial recharge occurs at a much faster rate than natural recharge, transferring water immediately from the aerobic environment to the anaerobic environment. Therefore, recharge water may react with the native groundwater or with the aquifer material (Huisman and Olsthoorn, 1983). For confined aquifers in Saskatchewan, reactions may occur as water passes through the well screen and contacts the aquifer material, at the mixing zone between the injected water and the native groundwater and during storage between the mixed water and the aquifer material.

Iron and manganese exist in a reduced, soluble state in the anaerobic aquifer environment. The injection of surface water may lead to the precipitation of iron and manganese in the mixed zone (Smith, 1981; Gibson and Cusion, 1980). Groundwater modification studies have sought to precipitate iron within the aquifer, under controlled conditions. The precipitation is promoted through the addition of oxygen or oxygenated water.

Sodium in fresh water may exchange with calcium and magnesium adsorbed onto clay particles within the aquifer. Hydrated sodium on the clay particles takes more space, causing the particles to swell, thus

reducing pore space and permeability of the aquifer (Huisman and Olsthoorn, 1983). The sodium adsorption ratio (SAR) defines the proportion of sodium to calcium and magnesium. SAR values less than 6.0 are desirable to avoid sodium exchange.

$$SAR = \frac{Na^+}{\sqrt{\frac{Ca^{+2} + Mg^{+2}}{2}}} \quad (2.34)$$

where Na^+ = sodium ion concentration (meq/L)

Ca^{+2} = calcium ion concentration (meq/L)

Mg^{+2} = magnesium ion concentration (meq/L)

2.5 Theoretical Artificial Recharge

Research to date indicates that artificial recharge into confined aquifers is a feasible means of storing fresh water.

Transport processes that influence injection, storage and recovery of water are primarily dispersion and density induced flow. Detrimental effects of artificial recharge include clogging the aquifer pore spaces with air, bacterial growth or suspended matter, and reducing the aquifer permeability by altering the clay chemistry. These effects can be reduced or prevented by maintaining the recharge system during recharge and evaluating water chemistry before injecting water.

Artificial recharge of confined aquifers has not been tested in Saskatchewan, although trials have been conducted on unconfined aquifers. Saskatchewan is dependent on groundwater for much of its water supply, although the available water is generally of poor quality that does not meet the Canadian water quality guidelines.

3.0 SITE SELECTION AND DEVELOPMENT

Seventy-five percent of farmers depend on groundwater as their source of supply (Saskatchewan Research Council, 1983). The first practical step in researching artificial recharge was to locate a site that met the theoretical artificial recharge requirements and was owned by farmer that would permit access to that site during the research period.

In the process of locating a site for the artificial recharge field trials, a method of evaluating site conditions was developed. The method was research oriented, but factors identified may also apply to long term practical application. This section discusses the site selection process and presents general conditions of the research site.

3.1 Site Selection Process

A method for evaluating sites was developed based on factors of surface water storage, aquifer and water well properties and water quality. The screening method is summarized in Table 3.1.

3.2 Regional Subsurface Conditions

The Dalmeny regional aquifer system encompasses an 800 km² area immediately north of Saskatoon, Saskatchewan (Figure 3.1). The Dalmeny Aquifer stratigraphy is presented in Figure 3.2. Groundwater flow of the aquifer in the area of the field site is in a south - southeastern direction at a rate from 4 m/yr to 7 m/yr. The regional flow pattern, according to Fortin (1989), is presented in Figure 3.3.

Table 3.1: Site Selection Factors

Factor	Selection Criteria	Comments and References
Permission	Owner is willing to participate in program	
Surface water storage	> 50% of annual domestic demand	Sufficient water must be available for injection and sufficient volume injected to justify the program (Cole, 1985).
Lift to pump water	lift < treatment pump capacity	Surface water source is located in the proximity of the injection well, with the required lift compatible with the pump capacity, so the water is readily pumped to the well head for treatment and injection (Longenbaugh and Duke, 1983).
Treatability	Available surface water may be treated prior to injection	Availability of power source, adequate water quality to minimize treatment requirements (Gillies, 1983).

Table 3.1: Site Selection Factors (Con't)

Factor	Selection Criteria	Comments and References
Injection water after treatment	Meets drinking water quality objectives quality AND is chemically compatible with aquifer	Performance problems have been related to poor quality injection water, including suspended matter, excessive oxygen and the introduction of bacteria (Driscoll, 1986; Huisman and Olsthoorn, 1983). Flocculation of clay particles due to excessive levels of sodium will reduce available pore space (August, 1986).
Water well to aquifer connection	Efficient connection, of perforated casing OR machine slot, gravel packed annulus	Cribbed and large diameter storage wells, and wells over 20 years old tend to have a poor connection to the aquifer due to the nature of construction (Asano, 1980; Cole, 1985; and Driscoll, 1986).
Water well performance	No maintenance problems OR performance problems that may be controlled through treatment	(Smith, 1981; Huisman and Olsthoorn, 1983 and Driscoll, 1986).

Table 3.1: Site Selection Factors (Con't)

Factor	Selection Criteria	Comments and References
Groundwater quality	Chemically compatible with injection water	Excessive dissolution or precipitation of minerals will alter water quality and damage the well screen (Driscoll, 1988 and Drever 1988).
Regional groundwater flow	<0.15 m/day	Regional groundwater flow gradient reduces recovery efficiency of injected water as the water is displaced from the well's zone of influence (Bouwer, 1978).
Recharge head	Depth to static water level in the well + maximum recharge head is below ground surface,	The injection head required to obtain the desired injection rate and injection period must not cause flooding or wet surficial soil conditions in the recharge field (Huisman and Olsthoorn, 1983).

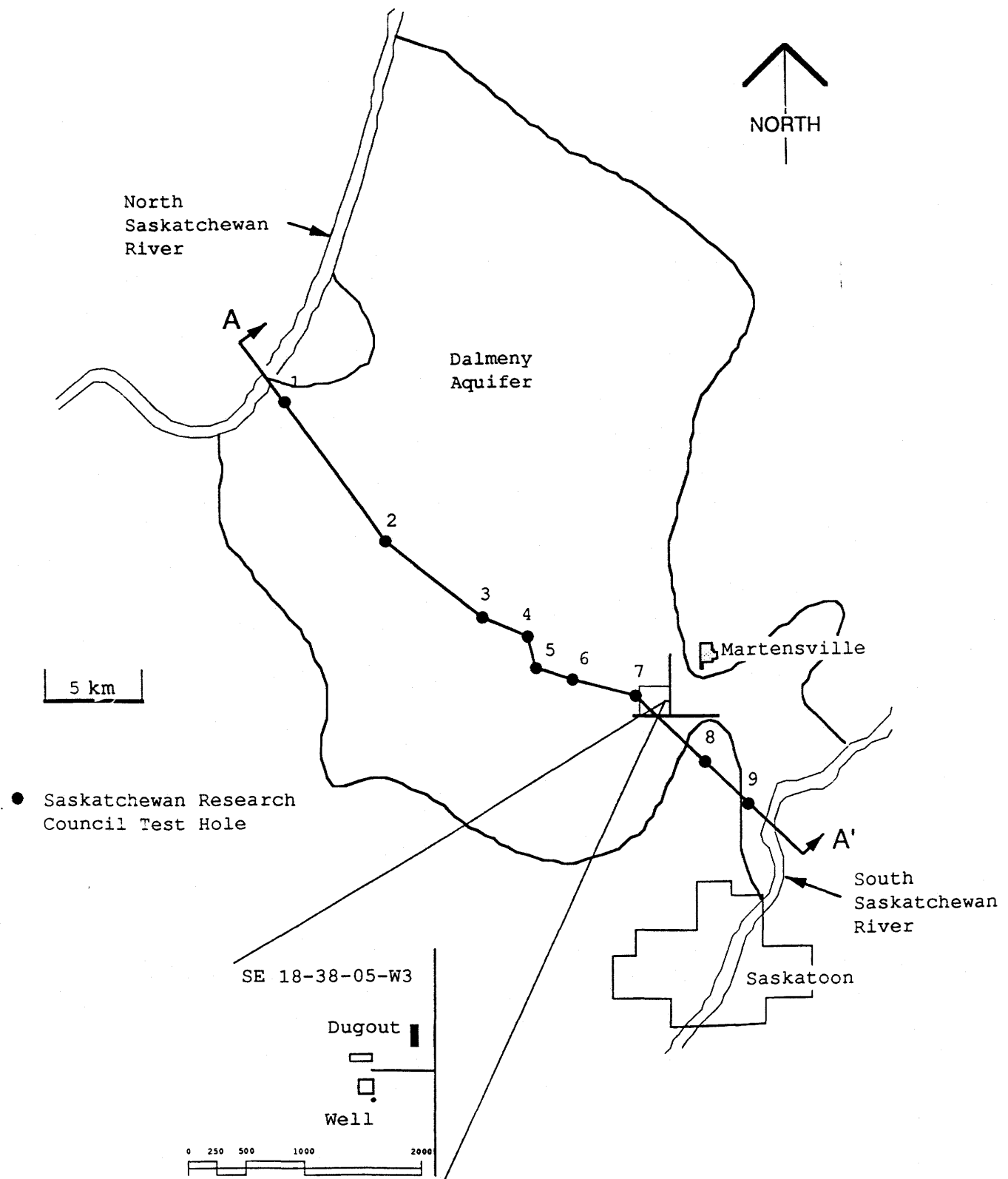
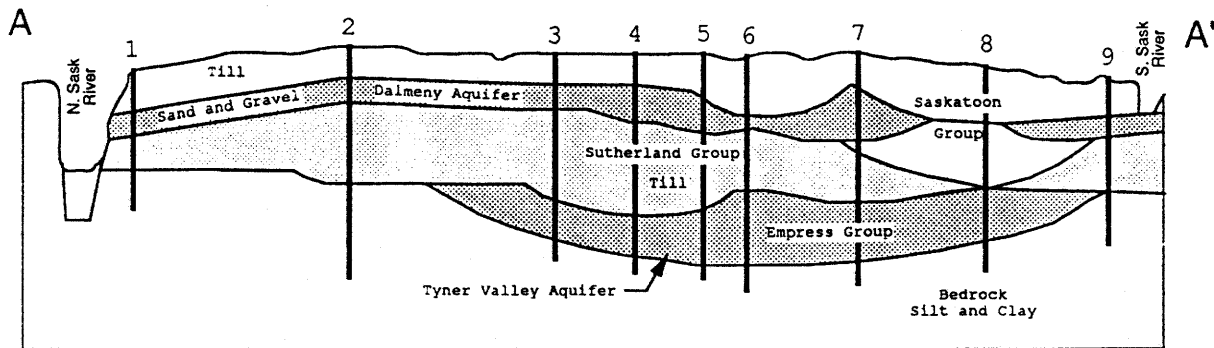


Figure 3.1: Dalmeny aquifer and location of field site (after Keller, 1985)



TEST HOLE #7

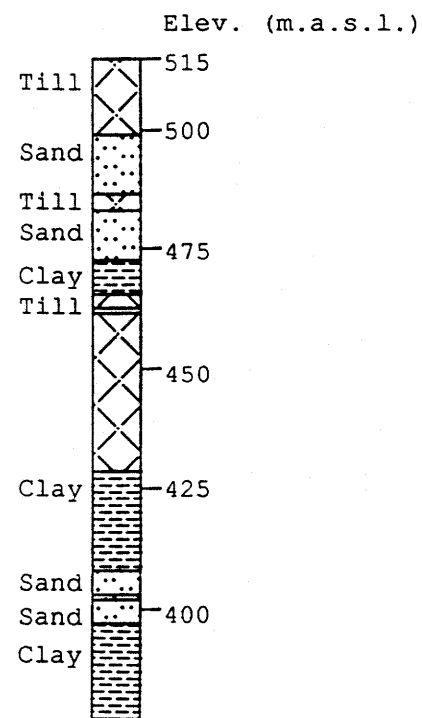
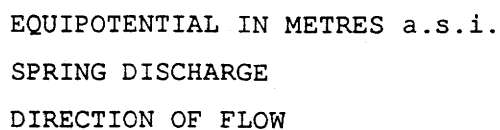


Figure 3.2: Stratigraphic cross section of area, and reference log (Keller, 1985)



Dalmeny aquifer (after Keller, 1985; Fortin, 1989)

Water quality within the aquifer and the overlying till indicates naturally recharging water does not react chemically with the aquifer material or with the water in the aquifer (Fortin, 1989). The variation of electrical conductivity observed in water samples collected from wells located within the aquifer region is due to the extent of leaching that has occurred in the till immediately overlying the aquifer (Fortin, 1989). In unleached settings, where a high concentration of sulphate is still present in the till, diffusion of sulphate into the aquifer due to the concentration gradient may also account for the spatial variability of the water quality (Fortin, 1989).

The groundwater is supersaturated with calcite (CaCO_3), aragonite (MgCO_3), dolomite ($\text{CaCO}_3 \cdot \text{MgCO}_3$) and siderite (FeCO_3). Measured Eh values of 130 to 168 mV suggest slightly reducing conditions in the aquifer. Iron in the groundwater is in a reduced state (Fortin, 1989).

3.3 Local Subsurface Conditions

An acreage 8 km north of Saskatoon, land location SE 18-38-05 W3 (Figure 3.1), was selected for the artificial recharge program during 1987 and 1988.

The water well was constructed in 1975. The driller documented construction details and pump test results at the time of installation. Details of the well construction are presented in Table 3.2.

Well stratigraphy presented in Figure 3.4 was interpreted as part of this research. Available stratigraphic cross-sections suggests that the well penetrates the upper portion of the Dalmeny aquifer system.

The surface reservoir located 200 m northwest of the well was constructed in 1975 with a design capacity of 4000 m³. The property owner pumped well water into the reservoir to precipitate iron and manganese and to increase the storage volume if there was insufficient runoff in the spring. The water obtained from the dugout was potable, based on the Saskatchewan Municipal Drinking Water Quality Objectives.

Water analyses are presented in Appendix B, Table B.1.

Table 3.2: Well completion details from 1975 installation records
(Department of Environment, 1975).

Category	Specifications	
	Value	Description
pump test	8.9 m ³ day ⁻¹ m ⁻¹	specific capacity
borehole	16 cm	diameter
	30 m	deep
	23 m	water struck
	6.4 m	water level in well at time of installation
casing		black iron
	25 m	length
	13 cm	diameter
screen stainless	steel	
	27 m	depth
	1.5 m	length
	13 cm	diameter
	#15	slot size
pump test	26 hours	
	4.2 m	drawdown
	0.5 L/s	flow rate
recommended pumping	0.45 L/s	design flowrate
pump intake	15 m	depth

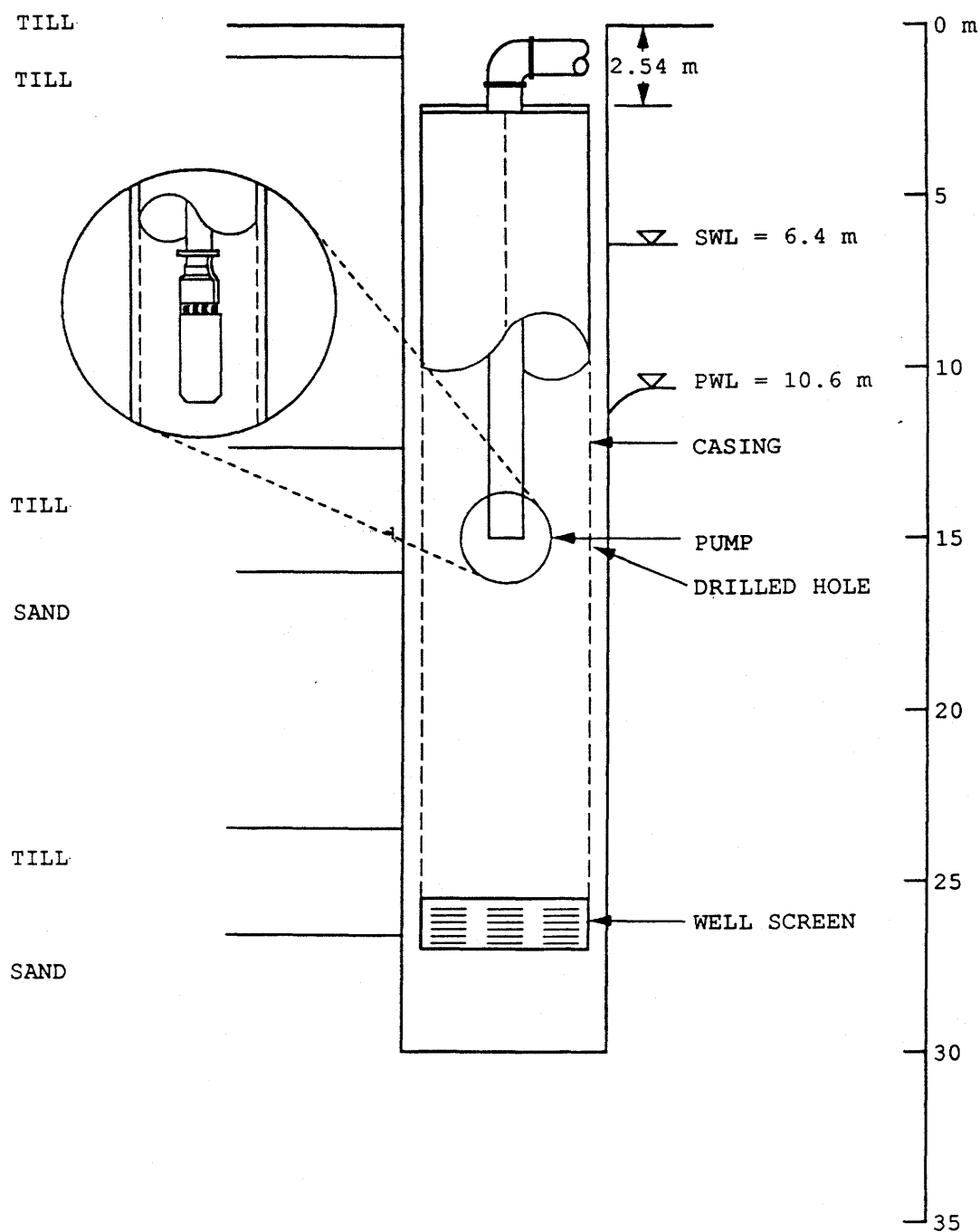


Figure 3.4: Water well lithology and pump detail (Department of Environment, 1975)

4.0 FIELD METHODS

4.1 Introduction

The field study was conducted to develop a relationship between the volume and quality of fresh water injected and recovered from a confined aquifer, and to assess changes in well performance due to the artificial recharge process.

The study used a single well for both injection of treated fresh water and recovery of the stored water at a later date. The time between the start of injection and the start of recovery was the retention time of stored water in the aquifer.

4.2 Artificial Recharge Injection System

The artificial recharge field equipment used in this study was designed by Gillies (1983) and owned by the University of Saskatchewan. Cole (1985) constructed and tested the system for pumping, treating and injecting surface (fresh) water down a well.

With reference to Figure 4.1, the system operates as follows:

1. Water from a surface water reservoir (1) is pumped (2) and held in a surge tank for storage prior to treatment (3).
2. Chlorine is added to the water (4, 5) and the water is circulated through a retention coil to provide time for chlorination (6).
3. The water is treated to remove iron and manganese (7) and organics (8).
4. The treated water is injected into the water well, controlled by the electrical control system presented in Figure 4.2.
5. Volume of water passing through the system is metered (9).

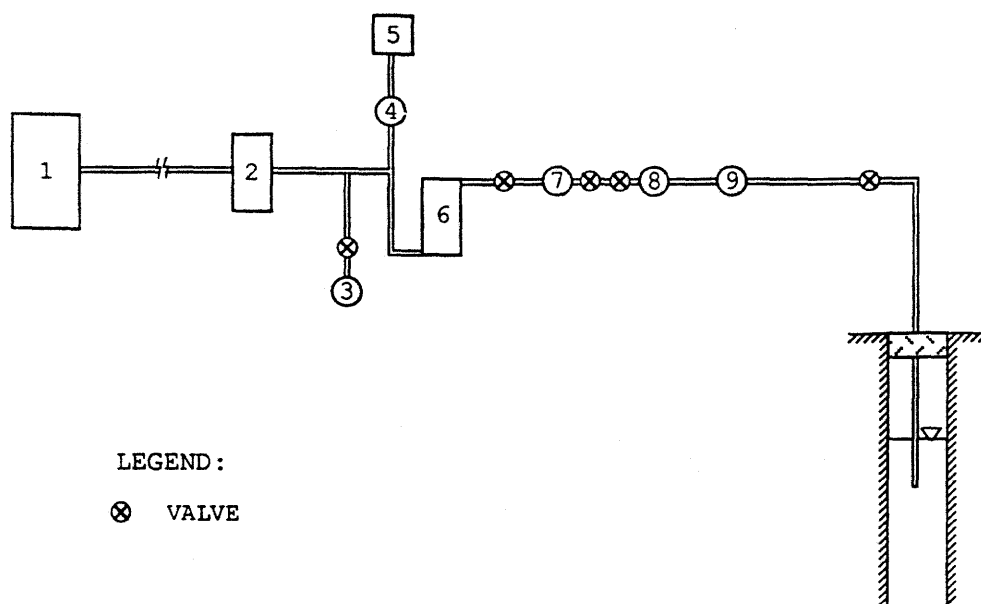


Figure 4.1: Artificial recharge system (Gillies, 1983)

With reference to Figure 4.2, the control system operates as follows:

1. The pump up control (1) responds to electrical sensors placed in well to open and close the solenoid valve (2). The valve is open and water flows into the well when the water level is below sensor (3); the valve is closed and flow stops when the well water level reaches the sensor (4).
2. A difference in water levels between the well and the aquifer induces water to move into the aquifer.

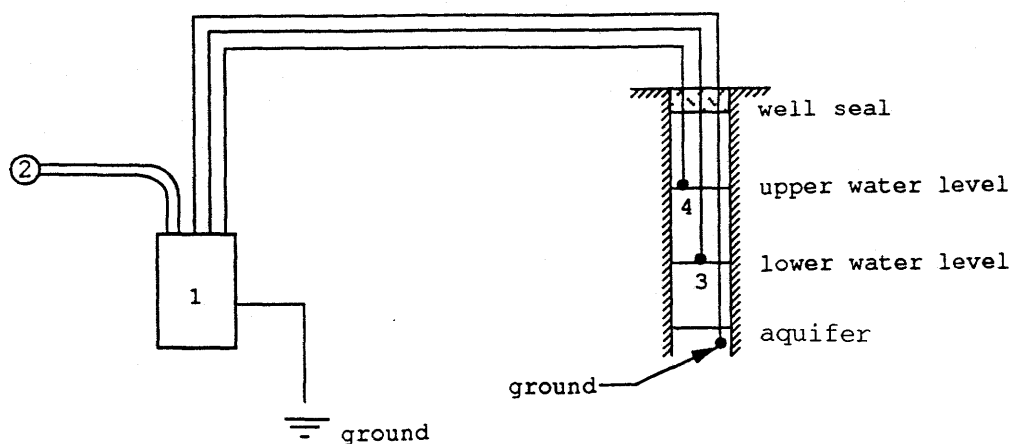


Figure 4.2: Electrical controls for artificial recharge system (Gillies, 1983)

4.3 Field Activities

The system operated during the summer and fall months of 1987 and 1988. Activities related to the field study are listed in Table 4.1.

Table 4.1: Chronology of Field Testing

Date	Activity
14, 16 July 1987	Pump tests
27 July to 14 August 1987	Trial 1 injection
17 August 1987	Trial 1 recovery
20 to 24 August 1987	Trial 2 injection
01 September 1987	Trial 2 recovery
02 to 04 September 1987	Trial 3 injection and recovery
04 September to 07 October 1987	Trial 4 injection
03 to 08 November 1987	Pump test, Trial 4 recovery
16 June 1988	Pump test
24 June 1988	Shock chlorinate well
26 June 1988	Owner began pumping well to replenish surface reservoir
28 July 1988	Pump test
20 August to 16 September 1988	Trial 5 injection
28 September to 02 October 1988	Pump test, Trial 5 recovery

4.4 Data Collection

4.4.1 Water Quality

The surface water quality and well water quality were tested prior to injection in both 1987 and 1988. Water was tested for major ions, pH and electrical conductivity, and the sodium adsorption ratio was calculated. Results are presented in Appendix B, Table B.1 and Table B.2. The sodium adsorption ratio was less than 6.0, indicating that surface water injected into the aquifer would not cause swelling and dilation of clay particles within the aquifer (Huisman and Olsthoorn, 1983).

Water quality during the treatment stages is presented in Appendix B, Table B.3. Trace concentrations of iron and manganese less than 0.5 mg/L were present after treatment.

Total dissolved solids were estimated in the field from electrical conductivity readings according to methods described by the USDA (1954) and Freeze and Cherry (1979). The relationship between electrical conductivity and ionic concentration varies with the type of ionic constituents dissolved in the water (USDA, 1954).

USDA has developed an empirical solution to correlate electrical conductivity to total dissolved solids for irrigation water based on averages from a large sample of surface and groundwater:

$$\text{TDS} = \text{EC} \times 0.64 \quad (4.1)$$

where: TDS = total dissolved solids (mg/L)

EC = electrical conductivity ($\mu\text{S}/\text{cm}$)

Fortin (1989) developed an empirical conversion based on values measured from 52 water samples collected from the Dalmeny aquifer.

$$\text{TDS} = -338.9 + 1.2 \times \text{EC} \quad (4.2)$$

Equation 4.2 is intrinsically dependent on the proportional levels of dissolvable constituents common to the Dalmeny aquifer system, and would probably not apply to other groundwater environments.

4.4.2 Pump Testing

Pump tests were completed on the well before and after injection of water to record changes in the calculated transmissivity and storage coefficient at the well since installation and during the field program.

At the time of the preliminary site assessment, the owner noted a decrease in well performance over the years which he attributed to the low quality of the aquifer water. The well had been periodically treated over the years by shock chlorination and in the spring of 1987 prior to the first injection trial.

All pump test data are presented in Appendix C, Tables C.1 to C.6, inclusive. Pump testing indicated the submersible pump inlet was not set at 15 m, as recorded in the filed well log shown in Figure 3.4. Pumping lowered the water level in the well to a maximum depth of 19.65 m at which depth the pump began drawing air. The bottom of the well was 28.5 m below surface.

4.4.3 Injection Trials

During the injection trials the treatment system performance and the volume of water injected were monitored (Appendix D, Tables D.1 to D.5, inclusive).

The volume injected was manually recorded on a regular basis from the flow meter installed on the portable treatment system. Several problems were encountered during the 1987 trials. The pump did not maintain sufficient water pressure and flow rate until worn gaskets and valves were replaced. Figure 4.3 illustrates pump valve wear. The water line between the surface reservoir and the treatment system was found disconnected near the farm access road several times during summer, resulting in the pump losing prime and the system shutting

down. After the line was moved away from the road the vandalism ceased.

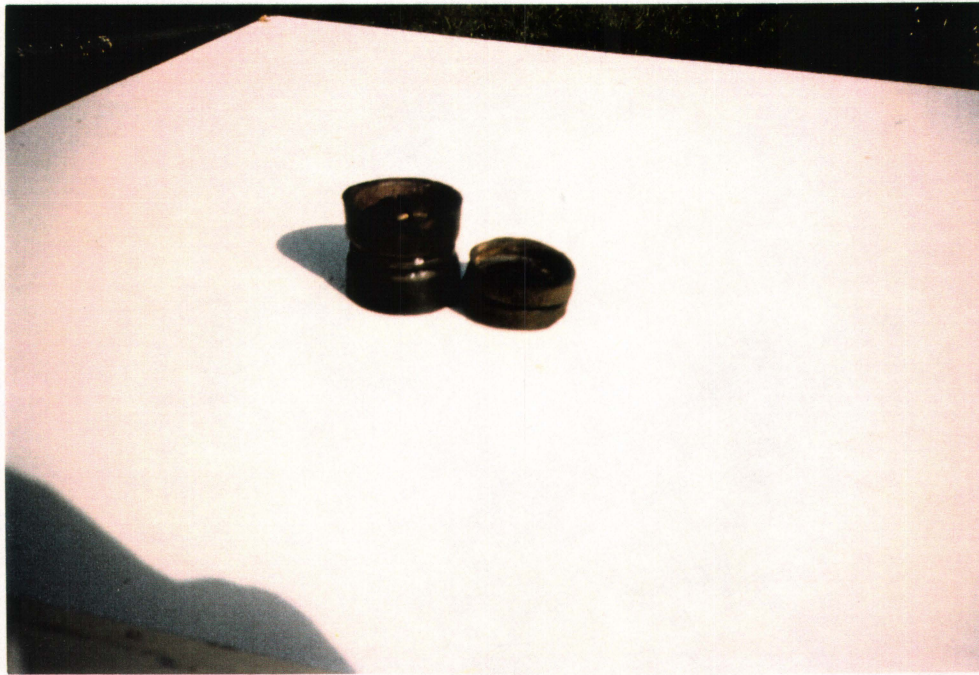


Figure 4.3: Valve wear in piston pump. Worn valve is on the right.

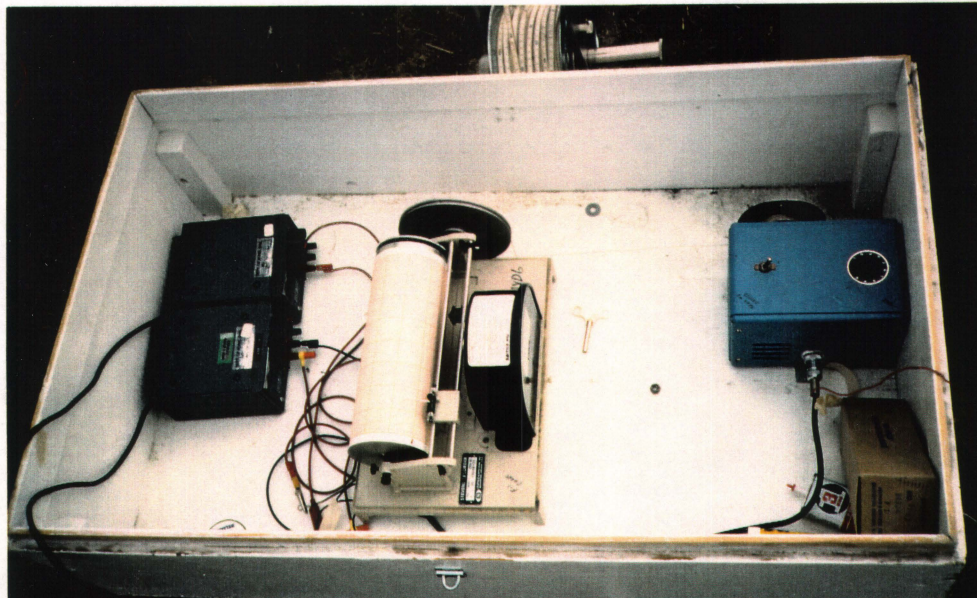


Figure 4.4: Instrumentation, clockwise from top: water level indicator, electric drive for water level bob, F-1 recorder and power supply.

During injection trials 1 to 4 inclusive, the well water level was continuously monitored with a Steven F1 drum recorder, Model 86 Serial Number 64840-74, illustrated in Figure 4.4. The drum recorder gear ratio was 25.4 mm chart pen displacement to 25.4 mm groundwater elevation displacement. The chart was set on a 24 hour time scale. The small diameter of the well and the presence of the submersible pump, injection hose and electronic sensors left little space for the recorder float to freely follow the water level. A slotted plastic conduit, 3 m long and 25 mm inner diameter, was placed in the well to serve as a float guide.

During injection trial 5, an Homiega field data recorder was modified and installed to monitor changes in water levels during injection. The recorder had been built by the Saskatchewan Research Council to meet long term monitoring requirements of the provincial observation wells. The recorder gear ratio was 10 mm chart pen displacement to 90 mm groundwater elevation displacement. The data recorder was not able to respond quickly to the sudden changes in water level under the field conditions, so monitoring was completed for the trial using the Steven F1 drum recorder.

4.4.4 Recovery Trials

During recovery, the quality and volume of recovered water was recorded. The water level was monitored if the discharge flow began to surge, indicating the drawdown water level was near the pump intake.

Water quality was monitored during recovery by measuring electrical conductivity and temperature (Appendix D, Table D.6 to Table D.10 inclusive). During trials 1 and 5, periodic water sampling was conducted to allow a comparison between the field trials and the geochemical model PHREEQE. Water sampled during trial 1 was analyzed for major ionic constituents of calcium, magnesium, sodium, potassium, iron, manganese, alkalinity, nitrates and sulphates using the HACH field testing kit. Water sampled during trial 5 was analyzed for calcium, magnesium and iron using the HACH field testing kit.

The volume of water recovered was determined periodically by measuring the flow rate at the outlet and calculating the volume pumped over the time interval (Appendix D, Tables D.5 to D.8 inclusive). The discharge flow rate was decreased during trials 1 and 4 because the well water level was drawn down near the pump inlet level. A totallizing flow meter, installed at the pump outlet, was read periodically during recovery trial 5. Recovery trial 5 lasted several days and was not extended to complete recovery of injected water volume because of time constraints.

5.0 LABORATORY TRACER STUDY

5.1 Introduction

The tracer study examined the movement of fresh water into a gravel layer saturated with saline water. The development of a density dependant mixing front between fresh and salt water was analyzed in the 19th century (Freeze and Cherry, 1979) and studies in this area have continued, primarily in dealing with salt water intrusion of coastal aquifers (Huisman and Olsthoorn, 1983). For the purposes of this research, the laboratory observations complimented field data, because the field program did not provide direct information on water movement within the aquifer.

5.2 Description of Physical Model

The physical model used in the study was constructed in 1983 by the University of Saskatchewan Agricultural Engineering Department. The model consisted of a plexiglas box 2.4 m long, 0.14 m wide, and 0.58 meters high (Figure 5.1), encased in a metal framework of channel, angle and flat iron. Twenty-four piezometers, numbered A1 to F4, were positioned in the face of the box to monitor changes in the hydraulic head. Three observation wells, W1, W2 and W3 situated as shown in Figure 5.1, were used to fill and drain the model of water. The wells had plastic well screens extending from the bottom of the model to 0.175 m. Wells W2 and W3 were 30 mm diameter hose and could be drained by foot valves. Well W1 was 55 mm diameter hose, with no bottom drainage.

The model was filled with a layer of gravel 0.2 m thick overlain by a layer of No. 40-60 silica blasting sand 0.38 m thick. A thin layer of fine sand between the layers restricted vertical water movement (McGeough, 1983). The model is presented in Figure 5.2. Saturated hydraulic conductivity of the gravel was 0.02 m/s; saturated hydraulic conductivity of the silica sand was 0.0003 m/s (McGeough, 1983).

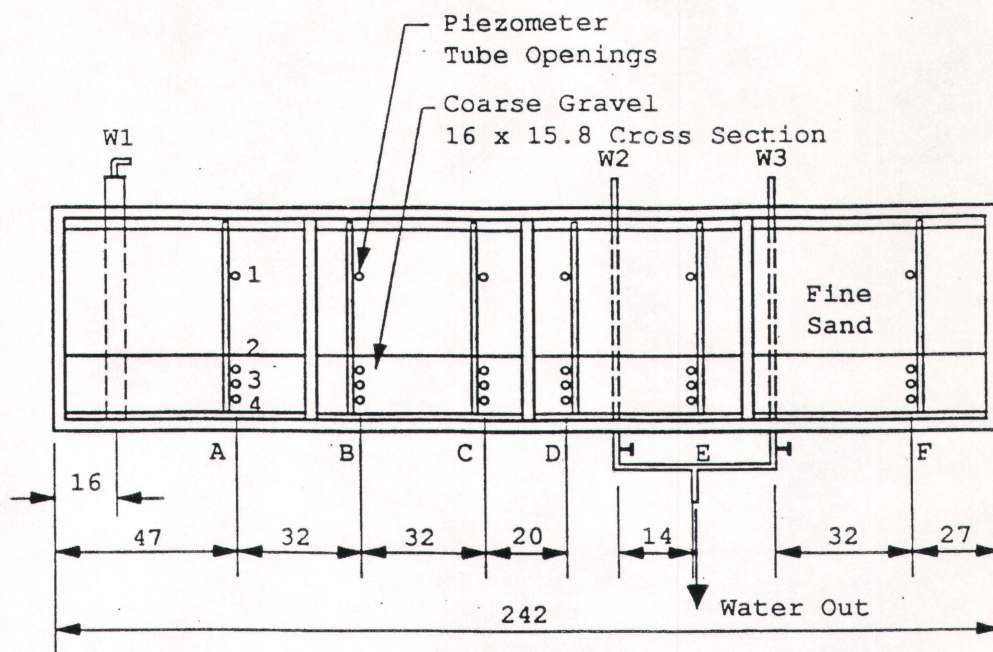


Figure 5.1: Laboratory model diagram. All dimensions in cm.

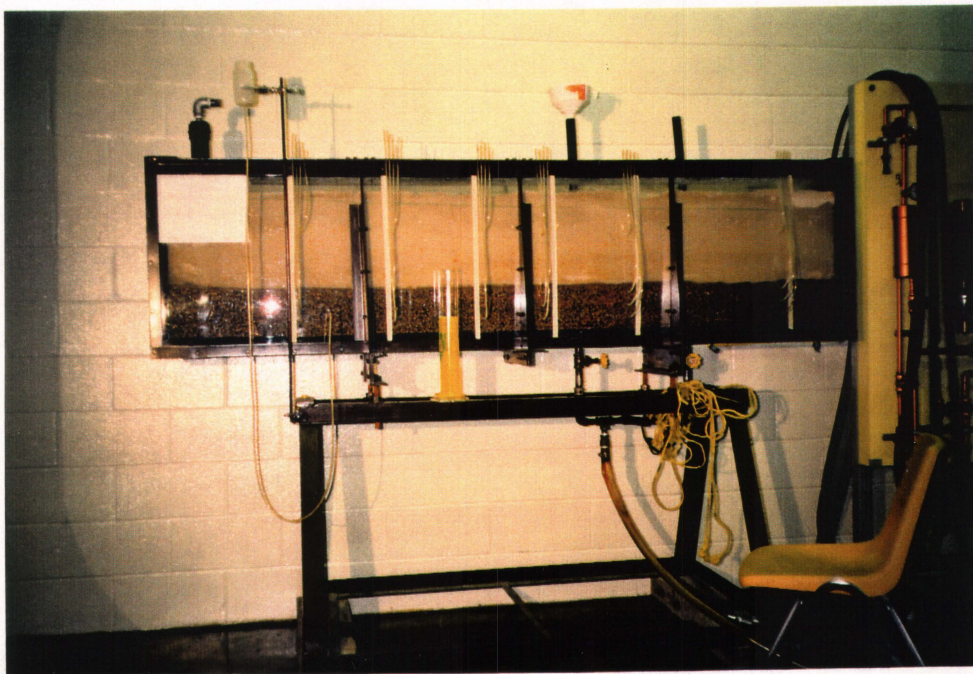


Figure 5.2: Laboratory model during testing

5.3 General Procedure

Initially, the model was gradually filled with a salt water solution through well W1. After water had ponded on the surface, the center foot valve was opened and the water level lowered to a set datum.

The experiments involved leveling the laboratory model, establishing the piezometric head of the salt water, waiting for the hydraulic equilibrium, then injecting fluorescein - dyed fresh water through well W2. The hydraulic head response and the tracer dye movement were then monitored over a 12 hour interval. After 12 hours, 1 of the valves was opened to begin drainage of the model and the dye was flushed from the sand and gravel.

The tracer dye front was described graphically by calculating the angle developed by the radial distance of front edges from the well versus the thickness of the sand layer. The angle developed over time was first described by Gardner et al. (1962).

5.3.1 Trial Procedures

Four experiments were conducted. In tests 1 and 2, 0.75 L and 1.3 L of fresh water were injected into the gravel, which had been saturated with a 2000 mg/L salt water solution to the height of piezometer tube No. 1. After 12 hours, the model was drained from W2.

In test 3, 0.75 L of fresh water was injected into the gravel which had been saturated with a 4000 mg/L salt water solution to the height of piezometer tube No. 1.

Test 4 was a replication of test 1, with an horizontal gradient of 0.02 m/m established across the length of the model.

6.0 GROUNDWATER FLOW MODEL

6.1 Introduction

During the field study, the volume of water injected and recovered from the aquifer and related changes in water quality were measured. The measurements were limited to data collected at the water well. A computer simulation of the groundwater flow into the aquifer was used to consider the significance of dispersion and density induced flow on the fresh water storage and recovery.

The software program to model artificial recharge is described in this section.

6.2 Description of Software

The mathematical demonstration model used in the study was developed by Cole (1985). The model had not been tested using field data because of the limited success of field artificial recharge trials conducted using a 0.9 m diameter cribbed well.

Parameters required to model groundwater movement into the aquifer during injection are presented in Table 6.1, with the corresponding input values from field trials 1, 2, 4 and 5.

The program was expanded to estimate recovery efficiency of the injected water, based on the volume estimation method developed by Gelhar and Collins (1971). The program calculated the volume of water recovered up to the design recovery volume or the acceptable water quality, assuming additional mixing would occur due to dispersion during recovery. The recovery calculations would cease when the calculated water quality exceeded the defined allowable water quality. Input parameters to calculate recovery efficiency are presented in Table 6.2.

Table 6.1: Input parameters: fresh water injection

Parameter	Units	Trial Number			
		1	2	4	5
ground elevation (assumed)	m A.S.L.	100.00	100.00	100.00	100.00
water level elevation	m A.S.L.	92.83	92.80	92.88	92.04
top of aquifer elevation	m A.S.L.	76.83	76.83	76.83	78.83
bottom of aquifer elevation	m A.S.L.	72.57	72.57	72.57	72.57
transmissivity	m ² /s	12.5 x10 ⁻⁶	12.5 x10 ⁻⁶	12.5 x10 ⁻⁶	11.4 x10 ⁻⁶
storativity	m ³ /m ³	0.0006	0.0006	0.0006	0.0007
well radius	m	0.0635	0.0635	0.0635	0.0635
porosity (assumed)	fraction	0.3	0.3	0.3	0.3
coefficient of dispersion	m	0.15	0.15	0.15	0.15
diffusion coefficient (assumed)	m ² /s	1 x10 ⁻¹¹	1 x10 ⁻¹¹	1 x10 ⁻¹¹	1 x10 ⁻¹¹
surface water temperature	°C	10	10	10	10
groundwater temperature	°C	10	10	5	10
surface water TDS	mg/L	155	155	155	415
groundwater TDS	mg/L	2635	2635	2635	2684
design pumping rate	L/s	0.45	0.45	0.45	0.45
injection rate	L/s	0.004	0.006	0.024	0.05
injection time	days	18	4	33	28

Table 6.2: Input parameters: stored water recovery

Parameter	Units	Trial Number			
		1	2	4	5
recovery rate	L/s	0.25	0.25	0.25	0.25
allowable water quality	mg/L	1500	1500	1500	1500

The computer program is presented in Appendix E.

The software program was unable to model field conditions observed during the first three trials, because of the small volumes and short time periods of the trials. The model scaling factor was not sensitive to the short steps required.

The program was able to estimate the volume of water injected during trials 4 and 5 after the field injection rate was increased to run the model and estimated the volume of water recovered at a preset quality.

7.0 GEOCHEMICAL MODEL

7.1 Introduction

One component of the research program involved measuring changes in water quality during storage and recovery. The field study was limited to monitoring water quality changes during recovery. A computer simulation of water mixing within the aquifer was used to consider the significance of geochemical changes to the recharge process.

This section describes the PHREEQE software program that was used in this study to model the geochemical reactions that would occur during artificial recharge of the water, assuming equilibrium.

7.2 PHREEQE Software

The pH - redox - equilibrium equations (PHREEQE) program simulates aqueous reactions that occur during mixing, addition of reactants, mixing and titration. The United States Geological Survey (USGS) developed and released this software into the public domain, and update and support the software on an ongoing basis.

The PHREEQE program is designed for IBM and compatible microcomputer systems.

The program calculates:

1. pH.
2. electrical potential (pE).
3. total concentration of elements.
4. amounts of minerals transferred into or out of the aqueous phase.
5. distribution of aqueous species.
6. saturation state of the aqueous phase with respect to specified mineral phase.

The problem was defined as follows:

1. Fresh water was equilibrated with calcite, present in intertill aquifers, as an open system (unlimited by carbon dioxide).
2. Fresh water was mixed with the aquifer water in a closed system (limited by carbon dioxide).
3. Mixture was equilibrated with calcite.

Step 1 simulated the initial injection water contact with the aquifer material. The system was considered open as the incoming fresh water would continue to replenish any carbon dioxide used in the chemical reactions.

Step 2 simulated the mixing that would occur between the injected water and the aquifer water, at the mixing zone. The mixing zone was assumed to be at a sufficient distance from the well that no additional carbon dioxide was available.

Once the mixture of fresh and brackish water was at equilibrium, the water mixture was equilibrated with the aquifer material, step 3.

Groundwater quality data for input into the program was obtained from the field test results in 1987 and from the regional aquifer study conducted by Fortin (1989). The results obtained were therefore a general indication of groundwater geochemical processes.

All data are presented in Appendix F.

8.0 RESULTS AND DISCUSSION

8.1 Site Selection

Farm wells within a 20 km radius of Saskatoon were evaluated in 1987 for the recharge project based on surface reservoir capacity, water well design, and aquifer characteristics. Owners of potentially suitable recharge sites were then approached for permission to conduct research using their facilities.

The research site selected was considered acceptable overall; the completed site selection form is presented in Appendix A. Limiting factors identified during the screening process included unacceptable well performance related to elevated dissolved iron concentration. It was decided to proceed with artificial recharge trials, with the understanding that well treatment may be necessary during the program.

8.2 Field Study

The field study involved injecting a total volume of 191.6 cubic meters of treated water into a confined aquifer, and recovering 191.5 cubic meters of water during five separate injection and recovery trials. Results are discussed in detail below.

8.2.1 Pump Testing

Pump tests were performed on the well 5 times during the field study and analyzed using the Theis curve matching technique and the modified Theis equation (Driscoll, 1986). Results of the pump testing are presented in Table 8.1. Pump test data are presented in Appendix C. Pump tests completed on 14 and 16 July 1987, prior to starting the artificial recharge program, indicated that the well efficiency had decreased since the 1975 installation.

The specific capacity of the well had decreased from $8.9 \text{ m}^3 \text{ day}^{-1} \text{ m}^{-1}$ in 1975 to $4.2 \text{ m}^3 \text{ day}^{-1} \text{ m}^{-1}$ in 1987. Shock chlorinating of the well between the 1987 and 1988 recharge periods resulted in an increase in the specific capacity to $5.4 \text{ m}^3 \text{ day}^{-1} \text{ m}^{-1}$ as calculated from the 16 June 1988 pump test, but over a period of three months this value

decreased to $1.7 \text{ m}^3 \text{ day}^{-1} \text{ m}^{-1}$. The change in calculated transmissivity and storativity indicate changes in aquifer properties. The artificial recharge project may have affected the aquifer, by introducing oxygen into the aquifer, creating an environment for bacterial growth, or transporting suspended matter into the aquifer (Huisman et al., 1983). However, the change in aquifer properties after shock chlorination of the well suggest that well performance was a contributing factor.

There were no nearby wells to measure drawdown in the aquifer beyond the pumped well.

Table 8.1: Variation in aquifer properties measured by pump tests

DATE	Pumping Interval	T	K	S	Specific Capacity
units	(minutes)	m^2/s	m/s	m^3/m^3	$\text{m}^3 \text{ day}^{-1} \text{ m}^{-1}$
1975	1440	no record	no record	no record	8.9
14/07/1987	215	12.8×10^{-6}	3.0×10^{-6}	0.0005	4.1
16/07/1987	120	12.5×10^{-6}	2.9×10^{-6}	0.0006	4.2
16/06/1988	450	11.0×10^{-6}	2.6×10^{-6}	0.0007	5.4
28/07/1988	120	11.4×10^{-6}	2.7×10^{-6}	0.0007	4.8
28/09/1988	1440	4.0×10^{-6}	1.0×10^{-6}	0.0004	1.7

8.2.2 Injection Trials

The injection volume was recorded frequently during all injection periods. Data collected during the injection trials are presented in Appendix D, Tables D.1 to D.5.

Injection trials were compared on the basis of injection volume, injection rate and injection capacity. Injection capacity is comparative to the specific capacity term commonly used for measuring well performance. The terms were calculated using the following equations:

Injection rate, Q'_i , (m^3/day) = volume of water injected per day:

$$Q'i = \frac{(V_{i\ n} - V_{i\ n-1})}{(t_{i\ n} - t_{i\ n-1}) \times 24} \quad (8.1)$$

where: $Q'i$ = stable injection rate (m^3/day)

V_i = volume of water injected into well at time n (m^3)

n = sequential time step

$t_{i\ n}$ = time at n (hours)

The injection rate was considered stable if the injection volume over time curve was linear over a 120 hour (5 day) period.

The specific capacity of the well during injection was defined as:

$$I = \frac{Q'i}{\left(\frac{s_{i\ max} + s_{i\ min}}{2}\right) + s_{i\ min}} \quad (8.2)$$

where: I = specific capacity during injection ($m^3/day/m$)

s_i = injection head, controlled by electronic sensors (m)

max = top sensor

min = bottom sensor

During trial 1, the injection rate stabilized at $0.29\ m^3/day$ for the given injection head interval of $0.93\ m$ to $3.93\ m$ above the initial well water level. Injection capacity was $0.009\ m^3\ day^{-1}\ m^{-1}$. The small injection capacity resulted in a small net volume of injection.

Trials 2 and 3 were characterized by frequent breakdown of the system due to a combination of human error and equipment failure, such that a consistent injection rate was not established. Injection volume over time curves for the three trials are presented in Figure 8.1.

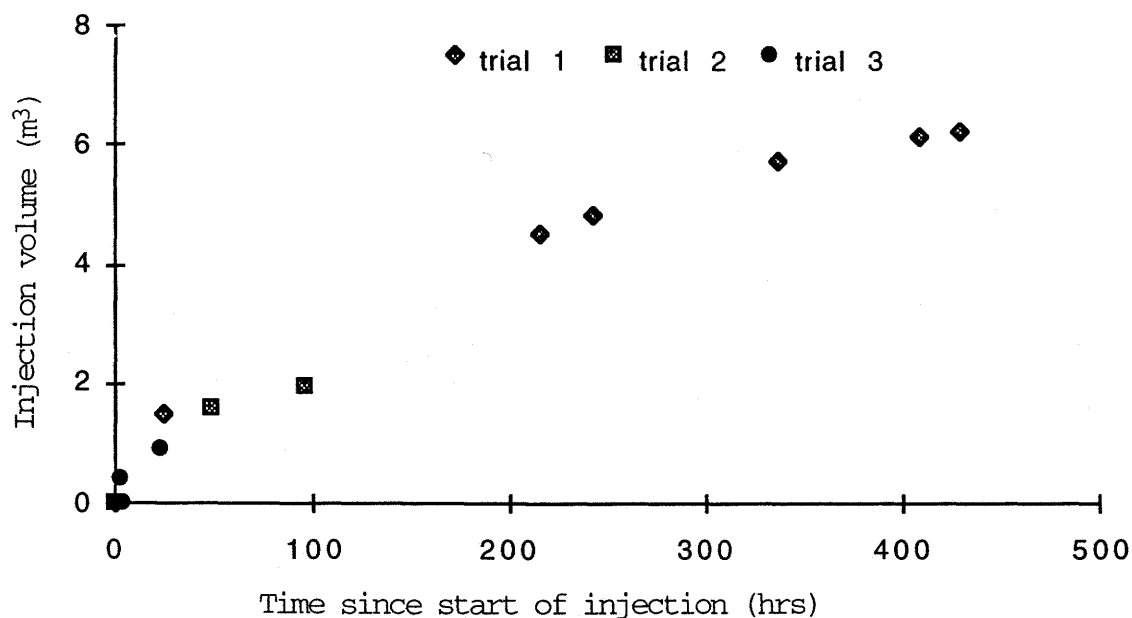


Figure 8.1: Injection volume curves, trials 1, 2 and 3.

Table 8.2: Record of injection trials

Parameter	Trial Number					
	1	2	3a	3b	4	5
t_i (hours)	429.5	96	2	20	792	675
t_r (hours)	200	96	2	20	1440	960
V_i (m ³)	6.26	1.94	0.77	2.73	67.11	112.75
s_i min (m)	0.93	1.25	1.25	1.05	1.72	0.96/1.96
s_i max (m)	3.93	3.25	3.25	3.05	3.42	2.96/3.96
Q'_i (m ³ /day)	0.29	n/a	n/a	n/a	1.99	2.16
I , (m ³ /day/m)	0.09	n/a	n/a	n/a	0.46	0.74

During trial 4, the sensor spacing and height were adjusted, as summarized in Table 8.2. The injection rate stabilized at 1.99 m³/day for the injection head interval of 1.72 m to 3.42 m above the initial water level. The injection capacity was 0.46 m³ day⁻¹ m⁻¹, with the exception of 2 equipment failures. In 792 hours, 67.11 m³ of water was injected.

Sensor height and spacing were adjusted again in trial 5, as presented in Table 8.2. Injection decreased from 5 m³/day to 2.16 m³/day within the first 200 hours of operation and to 1 m³/day after 450 hours. Sensors were raised to increase the injection head an additional meter, which increased the injection rate to 5 m³/day. The injection period was stopped after 675 hours of operation with over 100 m³ of water injected because the owner was requesting use of the well.

Injection volumes over time during trials 4 and 5 are presented in Figure 8.2.

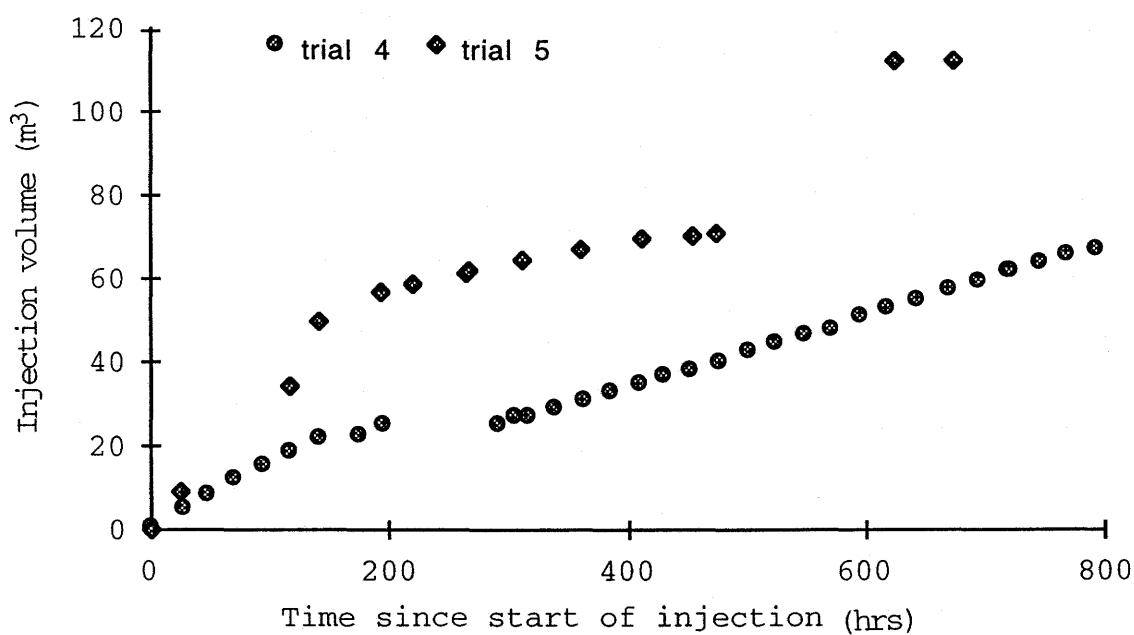


Figure 8.2: Injection volume curves, Trials 4 and 5. Trial 4 injection was stopped for repairs from 195 hours to 292 hours, and from 304 hours to 316 hours. Trial 5 injection was modified at 426 hours by raising the water level control sensors.

8.2.3 Recovery Trials

Water was recovered by continuous pumping of the well until the water quality, as indicated by the electrical conductivity, stabilized or approached initial groundwater quality.

It was intended to measure the electrical conductivity in the field and convert the value to total dissolved solids using either the USDA or Fortin equations, respectively. Electrical conductivity measurements during trial 1 recovery were taken relative to 10°C, rather than to standard temperature of 25°C.

Water quality is generally defined as fresh or brackish on the basis of concentration of total dissolved solids (Freeze and Cherry, 1979). Electrical conductivity values converted to total dissolved solids using the USDA conversion equation and the Fortin equation, and compared to the total dissolved solids concentration calculated from water quality analysis are presented in Table 8.3 and shown graphically in Figure 8.3. Neither conversion equation appears to estimate the total dissolved solids concentration calculated from ionic constituents. The fresh water and part of the recovered stored water may be approximated using the USDA equation, but as the stored water approaches groundwater concentration, the data is more closely estimated using the Fortin equation. Electrical conductivity measurements were used directly to generate the breakthrough curves for trials 1, 2, 4 and 5. The breakthrough curves represent the relative change in water quality from the fresh, injected water to the brackish initial groundwater.

Trial 3 was rejected for analysis of the breakthrough curve because of the small volume of water injected and the overlapping injection and recovery intervals from trial 2.

Table 8.3: Comparison of electrical conductivity to total dissolved solids

Electrical Conductivity $\mu\text{S}/\text{cm}$	Total Dissolved Solids (TDS) mg/L		
	field data	USDA ¹	Fortin ²
300 (25°C)	133 - 155*	192	5
370 (10°C)	149	265	85
390 (10°C)	142	250	108
420 (10°C)	153	269	142
550 (10°C)	256	352	291
750 (25°C)	415	480	521
1150 (10°C)	394	736	979
1750 (10°C)	991 ²	1120	1667
2000 (25°C)	2635	1280	1953
2300 (25°C)	2684	1472	2297
2600 (10°C)	1547 - 2015**	1664	2641

Notes:

$$^1 \text{ TDS} = \text{EC} \times 0.64 \quad (4.1)$$

$$^2 \text{ TDS} = -338.893 + 1.146 \times \text{EC} \quad (4.2)$$

* variation observed in four water samples

** estimated TDS, assuming manganese concentrations negligible

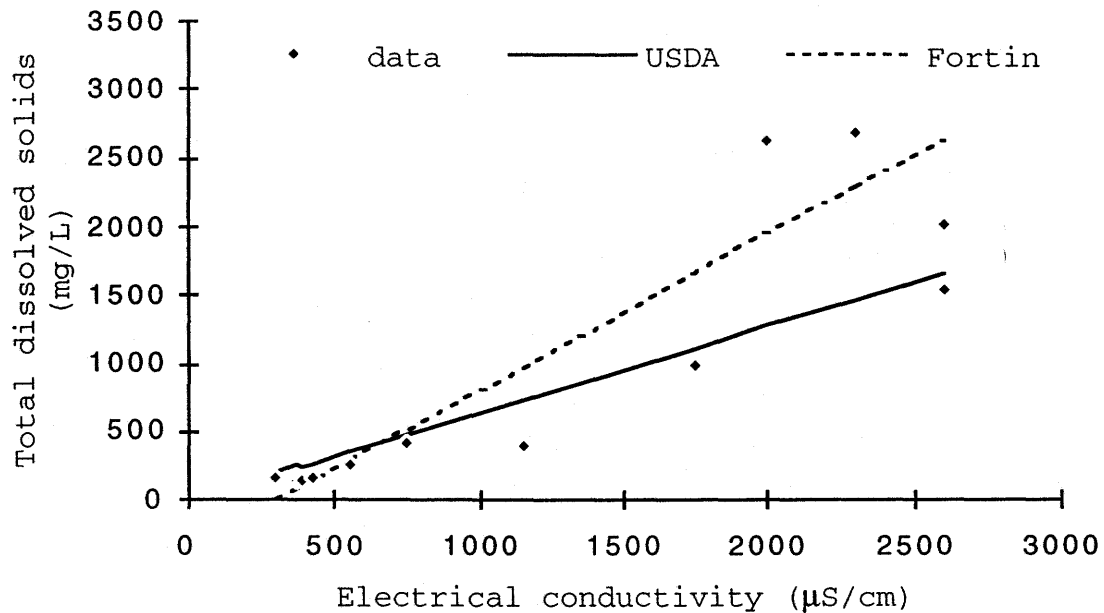


Figure 8.3: Comparison of electrical conductivity to total dissolved solids. Solid line indicates total dissolved solids concentration calculated from USDA (1954) equation; dashed line indicates total dissolved solids concentration calculated from Fortin (1989) equation.

Field results were summarized as unitless ratios of chemical concentrations and recovery volumes. The field results were then compared to theoretical results for mixing due to groundwater flow and dispersion.

Equations adapted from Gelhar and Collins (1971) to assess the field results were:

recovery ratio (from Equation 2.17):

$$\Psi = \frac{V_p}{V_i} \quad (8.3)$$

where: V_p = volume of pumped water (m^3)

V_i = volume of injected water (m^3)

concentration ratio:

$$C_r = \frac{C_p - C_{fw}}{C_{gw} - C_{fw}} \quad (8.4)$$

where: C_p = concentration of pumped water ($\mu\text{S}/\text{cm}$ or mg/L)

C_{fw} = concentration of fresh water ($\mu\text{S}/\text{cm}$ or mg/L)

C_{gw} = concentration of groundwater ($\mu\text{S}/\text{cm}$ or mg/L)

The input values to solve each equation are included in Appendix D, Tables D.6 to D.10.

The concentration ratio increased from 0 to 1. The steady state solution of the breakthrough curve is:

$$C_r = 1 - \frac{1}{2} \text{erfc}(B) \quad (8.5)$$

$$\text{where: } B = \frac{\Psi - 1}{\sqrt{\frac{16\alpha}{3R} [2 - |1 - \Psi|^{1/2} (1 - \Psi)]}} \quad (2.16)$$

$$\text{and: } R = \sqrt{\frac{Q_i t_i}{\alpha \eta b}} \quad (2.18)$$

Porosity, η was assumed to be 0.3. Porosity of unconsolidated sand and gravel deposits typically range from 0.25 to 0.40 (Freeze and Cherry, 1979). A change in the assumed porosity value from 0.25 to 0.40 did not change the shape of theoretical breakthrough curve, as shown in Figure 8.4.

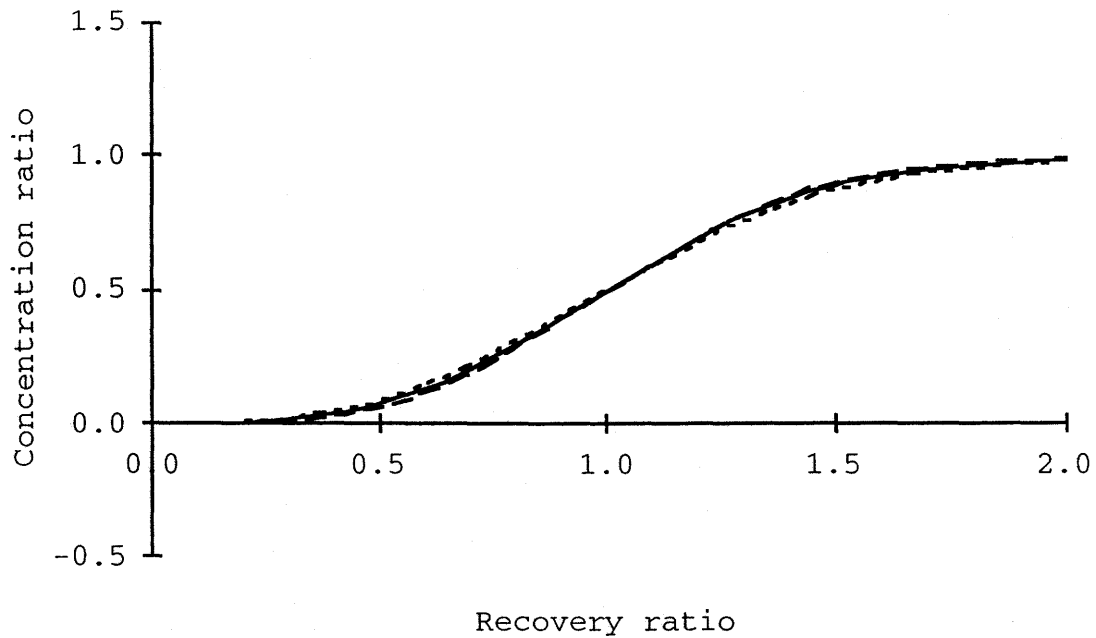


Figure 8.4: Theoretical breakthrough curves: $V_{in} = 6 \text{ m}^3$; $\eta = 0.25$, 0.30 and 0.40; $\alpha = 0.15 \text{ m}$.

An increase in the dispersivity, α , resulted in the theoretical breakthrough curve becoming flatter, with the concentration ratio increasing from 0 to 1 at a smaller volume ratio value. The theoretical curves presented in Figures 8.5 to 8.7 indicate that as injection volume increased, the assumed dispersivity values between 0.15 and 0.6 m represent increased mixing of the front.

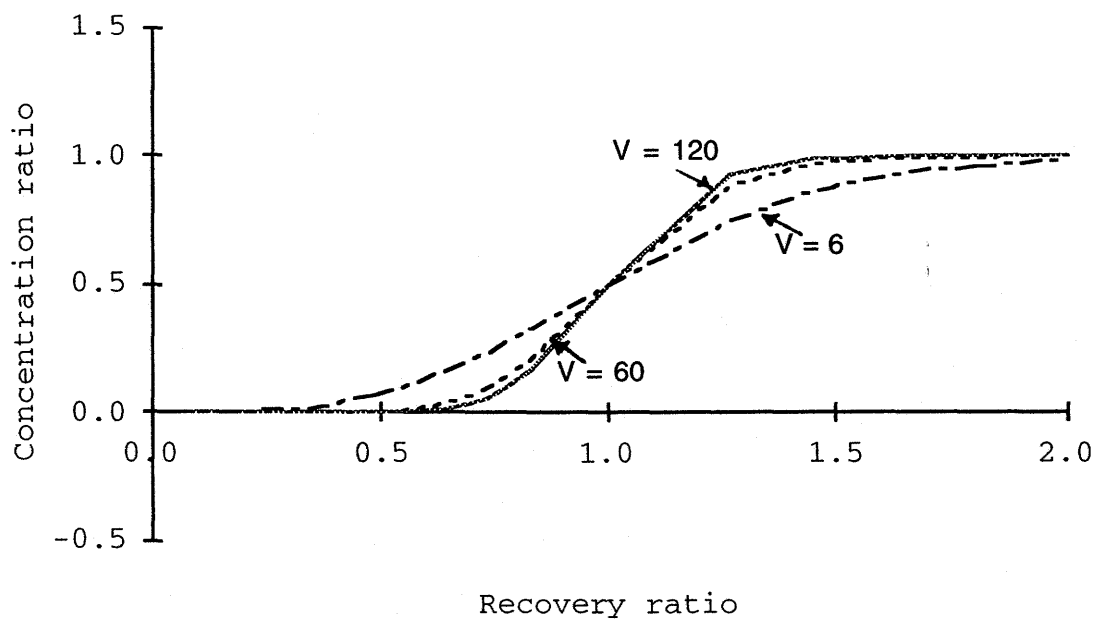


Figure 8.5: Theoretical breakthrough curves: $V_i = 6 \text{ m}^3$, 60 m^3 , 120 m^3 ; $\eta = 0.30$; $\alpha = 0.15 \text{ m}$

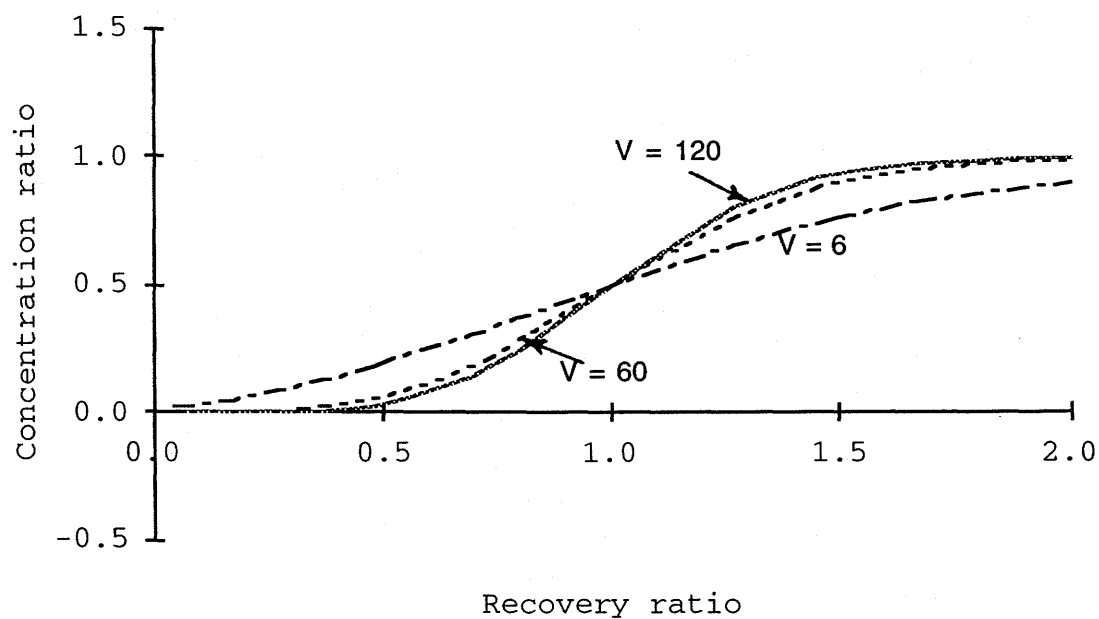


Figure 8.6: Theoretical breakthrough curves: $V_i = 6 \text{ m}^3$, 60 m^3 , 120 m^3 ; $\eta = 0.30$; $\alpha = 0.30 \text{ m}$

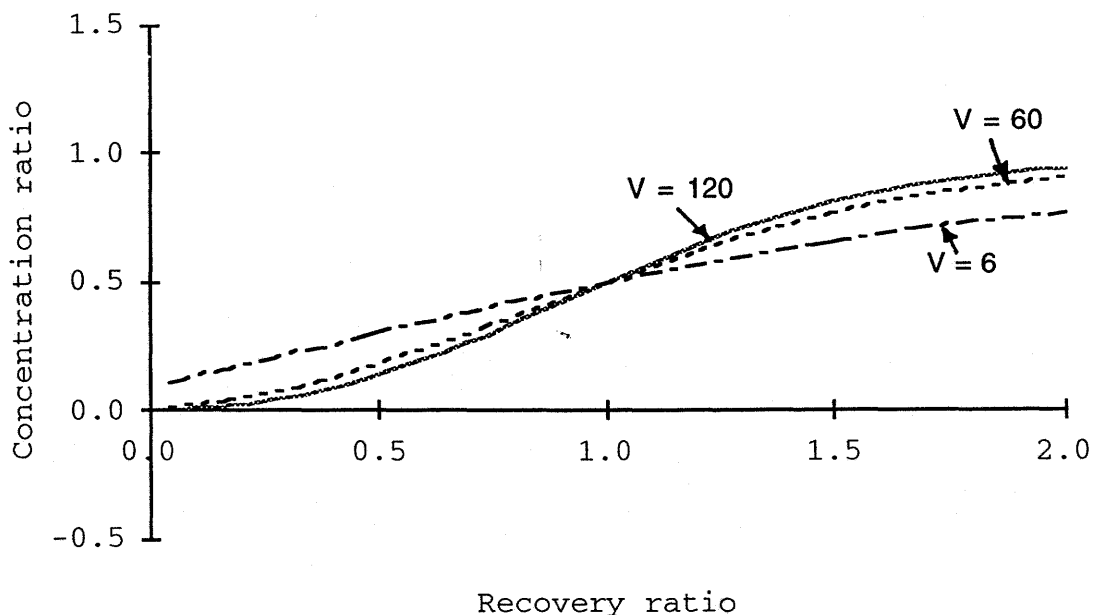


Figure 8.7: Theoretical breakthrough curves: $V_i = 6 \text{ m}^3$, 60 m^3 , 120 m^3 ; $\eta = 0.30$; $\alpha = 0.60 \text{ m}$

The assumed dispersivity, α , for all trials was calculated from the field recovery curve for Trial 1. Trials 4 and 5 were also compared with theoretical breakthrough curves assuming dispersivity increased to 0.6 m . The increased injection volume during trials 4 and 5 would require a greater soil volume to store fresh water, which has been related to an increase in dispersivity (Lam et. al., 1987). The theoretical curve for $\alpha = 0.60 \text{ m}$ corresponded with the field data in the initial stage of recovery in trial 4, but the trend did not continue during the entire recovery period in either trials 4 or 5.

A summary of the recovery trials is presented in Table 8.4. Recovery efficiency E_r , was calculated as the percent recovered in the field versus the recovery efficiency under ideal flow with dispersion when the concentration C_r was 0.5 .

Recovery efficiency, E_r :

$$E_r = \frac{V_{\text{measured}}}{V_{\text{ideal}}} \quad \text{at} \quad \frac{C_p - C_{fw}}{C_{gw} - C_{fw}} = 0.5 \quad (8.6)$$

Table 8.4: Record of recovery trials

Parameter	Trial Number			
	1	2	4	5
α	0.15	0.15	0.6	0.6
V_R (m ³) total recovery volume	6.26	1.94	67.11	112.75
R (m)	5.72	3.18	9.36	12.13
V_p (m ³) at $C_r = 0.5$ measured from field data	5.32	1.43	54.36	49.61
V_p (m ³) at $C_r = 0.5$ ideal dispersion	6.26	1.94	67.11	112.75
E_r recovery efficiency	85%	74%	81%	44%

Recovery trial data were plotted and compared to theoretical breakthrough curves assuming both slug flow and flow through porous media with losses due to dispersion. Sufficient information was obtained in recovery trials 1 and 5 to plot C_r for electrical conductivity, calcium and iron, as presented in Figures 8.8 to 8.10 for trial 1, and Figures 8.15 to 8.17 for trial 5. Trials 2 and 4 were limited to concentration ratio calculations based on electrical conductivity. Table 8.4 summarizes these results, using the electrical conductivity breakthrough curves, common to all trials.

Each figure includes:

1. Field measurements of the concentration ratio relative to the recovery ratio (Appendix D, Tables D.6 to D.10).
2. Breakthrough curve calculated using the Gelhar solution for mixing due to dispersion (Appendix H, Tables H.1 to H.6).
3. Breakthrough curve which would occur under slug flow.

Trial 1 closely matched the theoretical breakthrough curve, as indicated in Figure 8.8 to Figure 8.10, inclusive. The iron ratio curve presented in Figure 8.10 indicated less than 0.75 even after the recovery ratio exceeded 1.5. This may be due to oxidation and precipitation of iron during sampling, or under pumping conditions at the well screen.

Figure 8.11 presents the breakthrough curve for Trial 2. The recovery was stopped before complete recovery was achieved. The small volume of water to be recovered during Trial 2 may account for the pattern in the breakthrough curve, as the water volume would barely penetrate the aquifer material.

Figures 8.12 to 8.17 present breakthrough curves for trials 4 and 5. The curves indicate a general shift in the field data curve, away from the theoretical curve. The dispersivity was increased from 0.15 m to 0.6 m to observe if the shift may be partially attributed to increased mixing. Comparing Figure 8.12 to Figure 8.13, in Trial 4, it can be seen that increased mixing due to dispersion does bring the theoretical curve closer to the field data curve. The recovery ratio in Trial 4 did not continue to 2.0 to allow comparison of the curve to complete breakthrough.

Comparing Figure 8.14 to Figure 8.15, in Trial 5, it can be seen that increased mixing due to dispersion does not account for the variation between the theoretical curve and the field data curve. The field data in Figures 8.14 to 8.17 shows an increase in the concentration ratio from the start of recovery for electrical conductivity and calcium, and a rapid breakthrough approaching original groundwater concentration before the injected water volume is recovered. The iron ratio breakthrough curve is not as rapid. This may be contributed to oxidation.

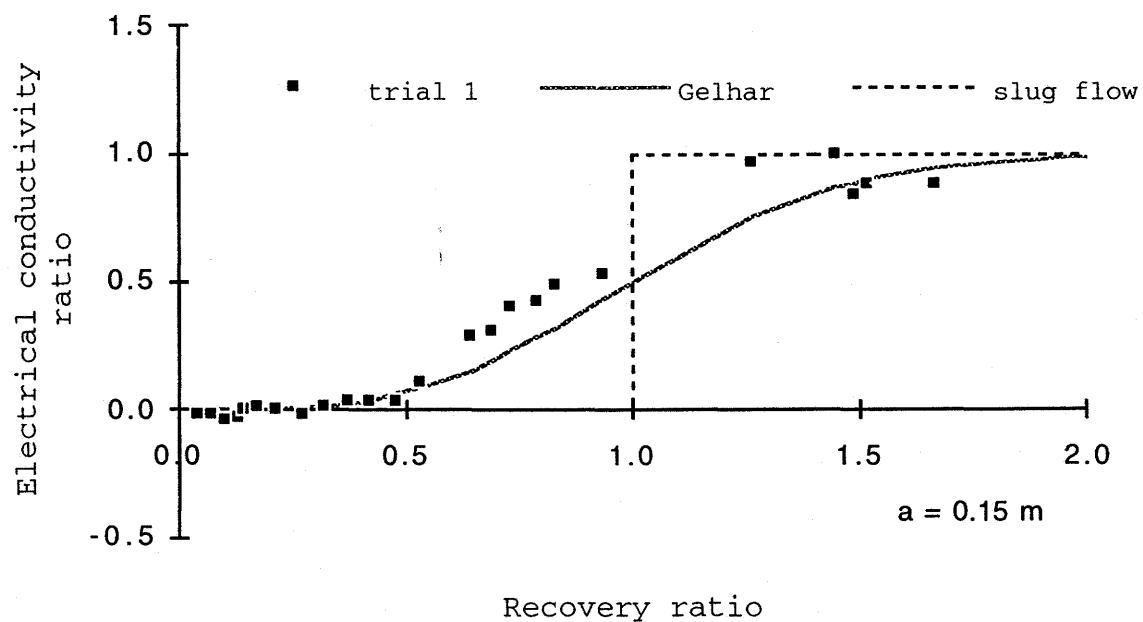


Figure 8.8: Recovery curve (electrical conductivity), trial 1
 $\alpha = 0.15 \text{ m}$.

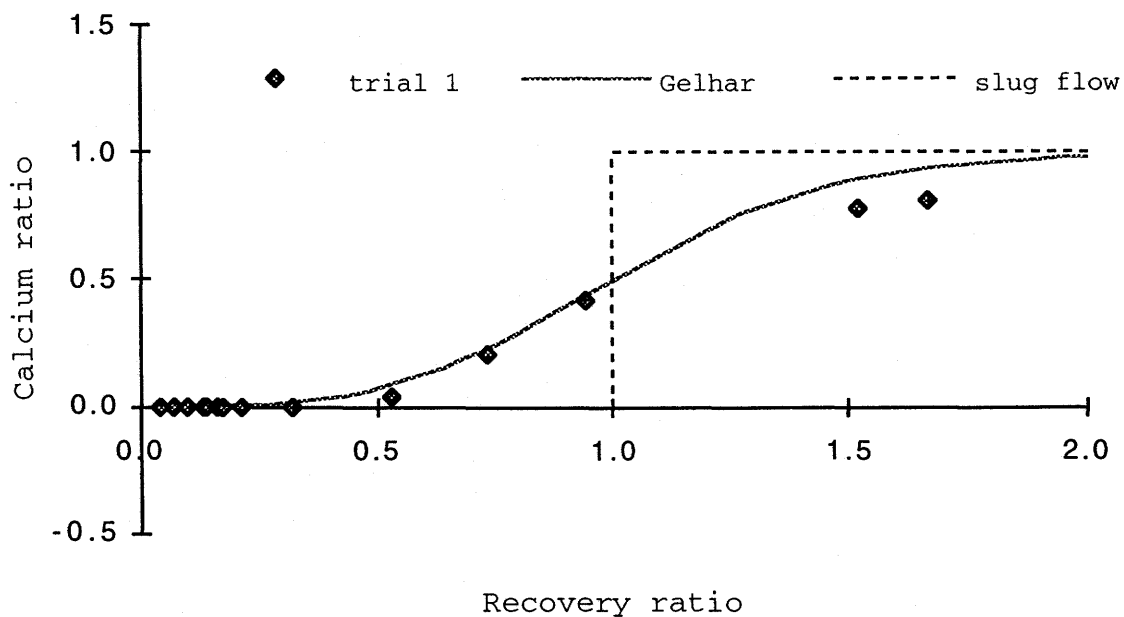


Figure 8.9: Recovery curve (calcium), trial 1. $\alpha = 0.15 \text{ m}$.

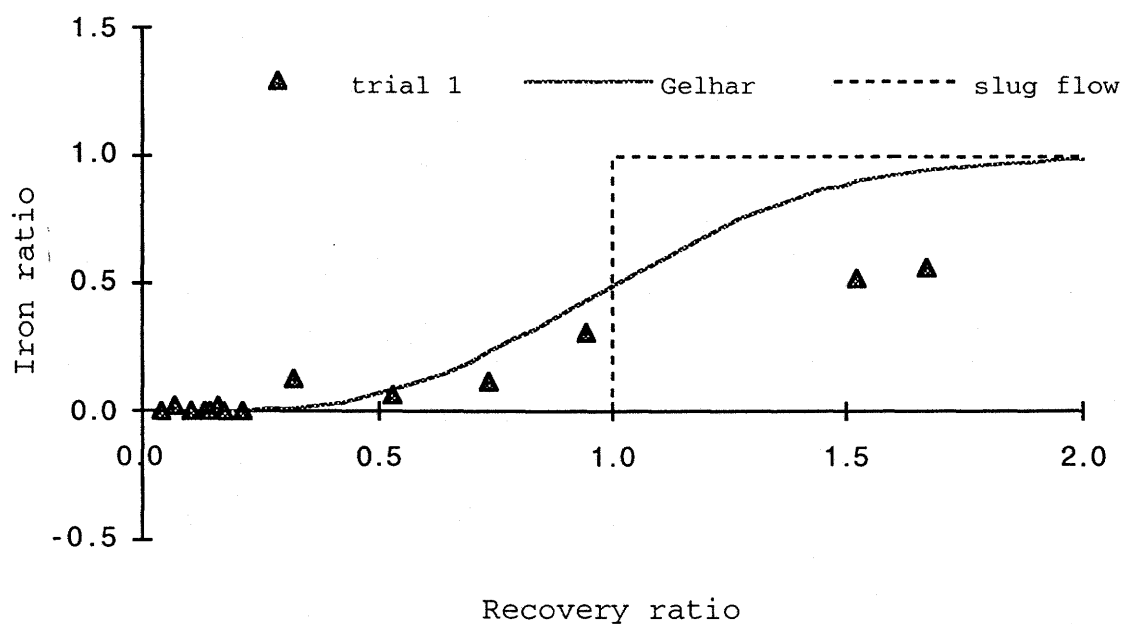


Figure 8.10: Recovery curve (iron), trial 1. $\alpha = 0.15$ m.

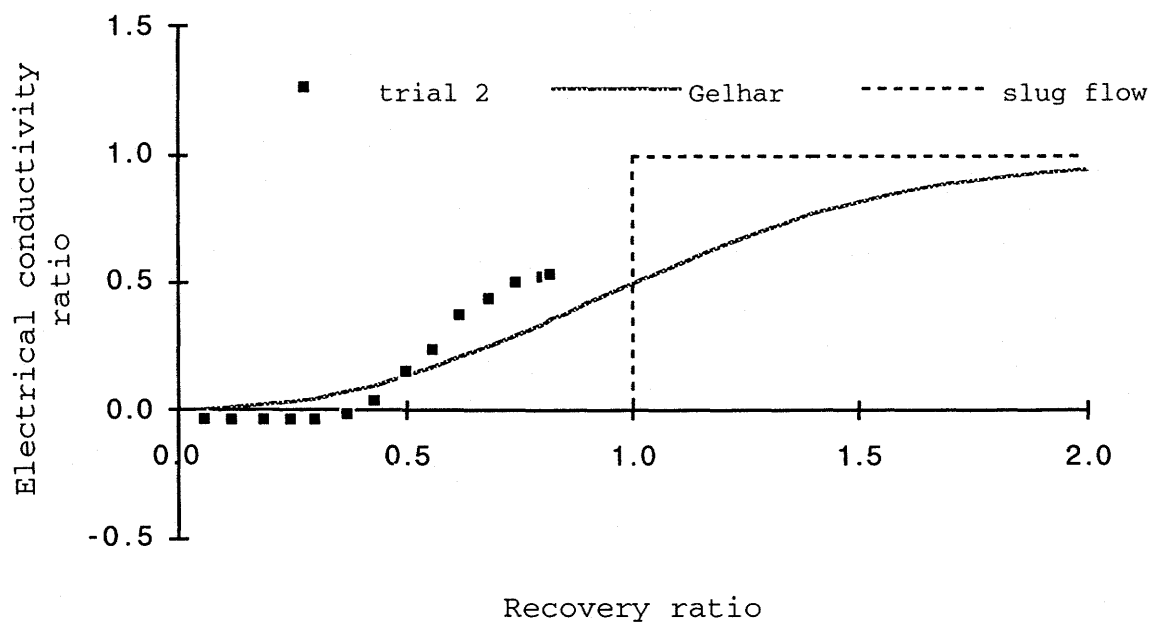


Figure 8.11: Recovery curve (electrical conductivity), trial 2
 $\alpha = 0.15$ m.

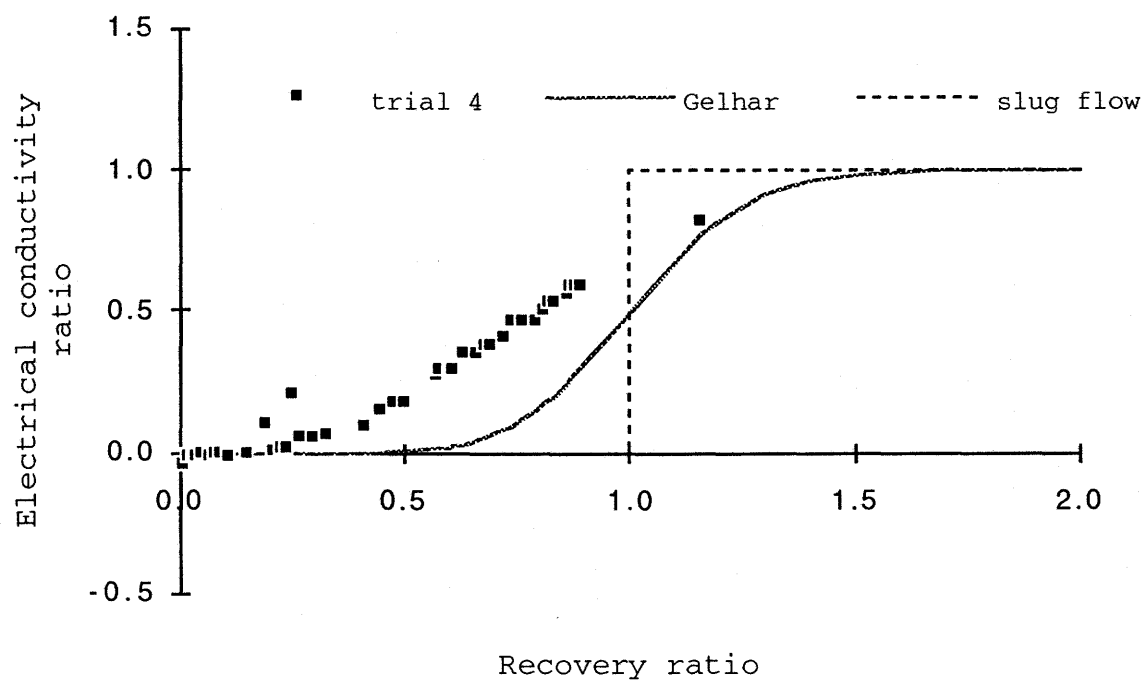


Figure 8.12: Recovery curve (electrical conductivity), trial 4.
 $\alpha = 0.15$ m.

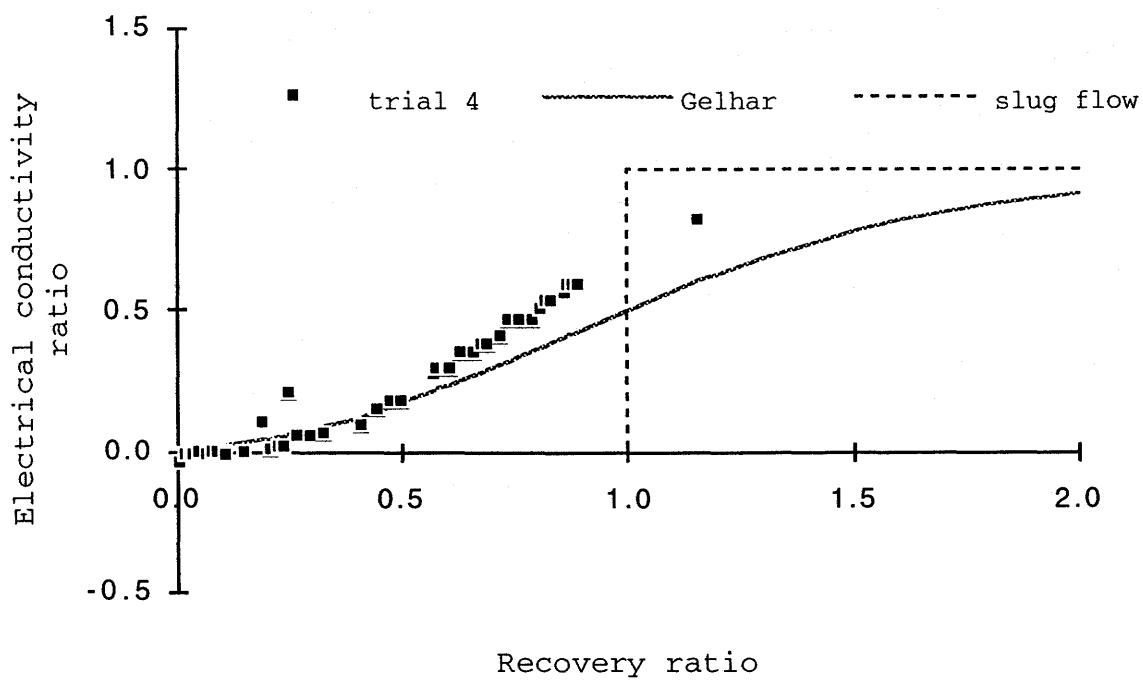


Figure 8.13: Recovery curve (electrical conductivity), trial 4.
 $\alpha = 0.6$ m.

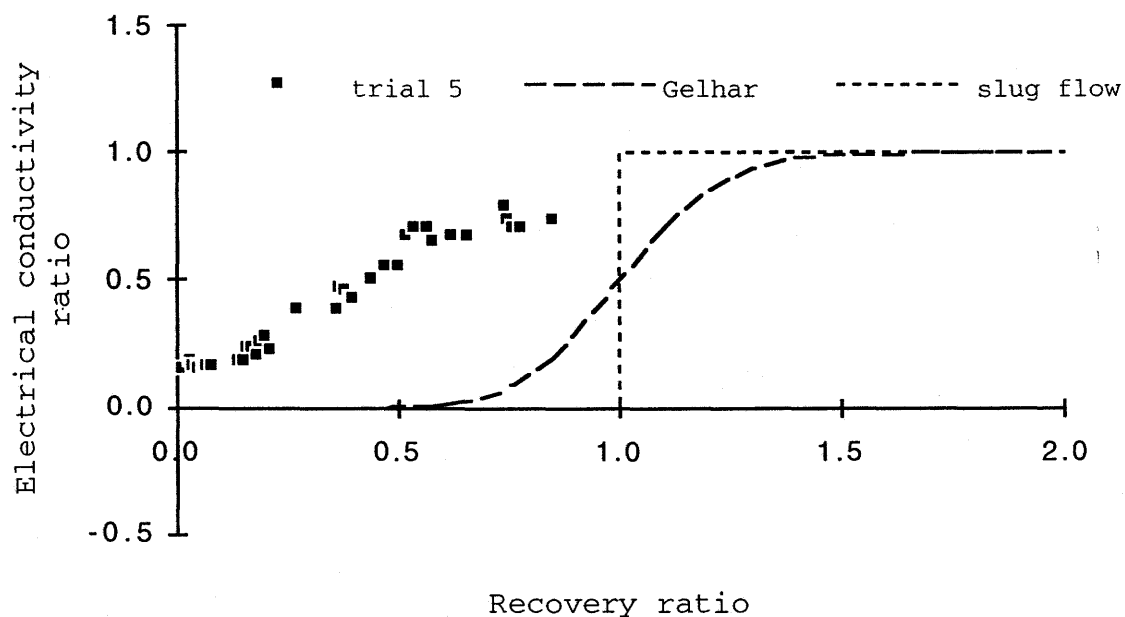


Figure 8.14: Recovery curve (electrical conductivity), trial 5.
 $\alpha = 0.15$ m.

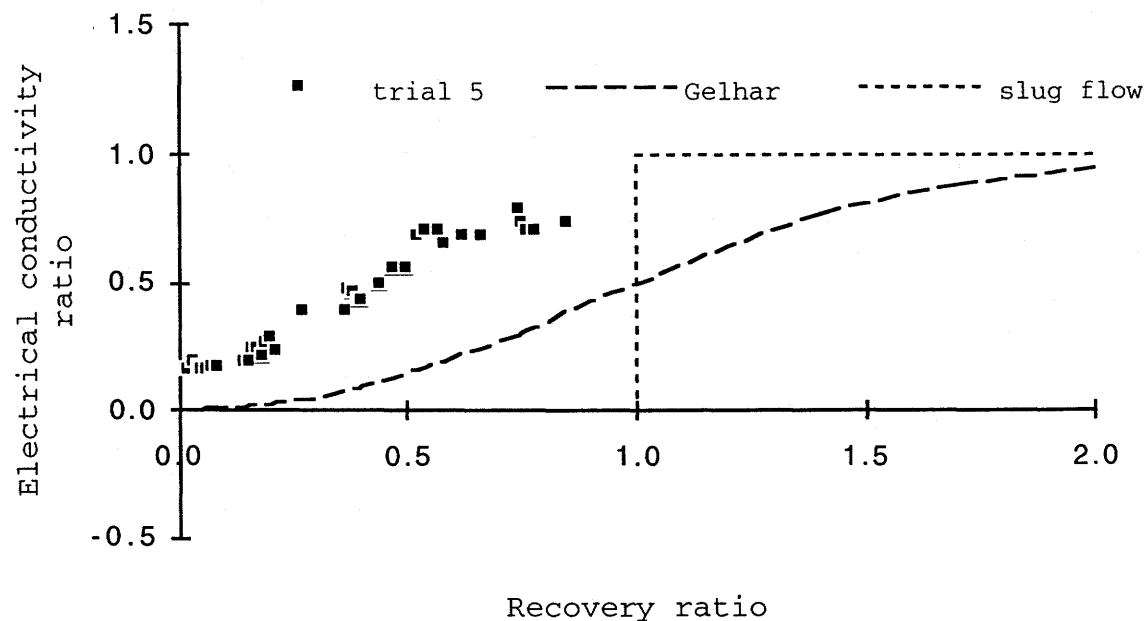


Figure 8.15: Recovery curve (electrical conductivity), trial 5.
 $\alpha = 0.6$ m.

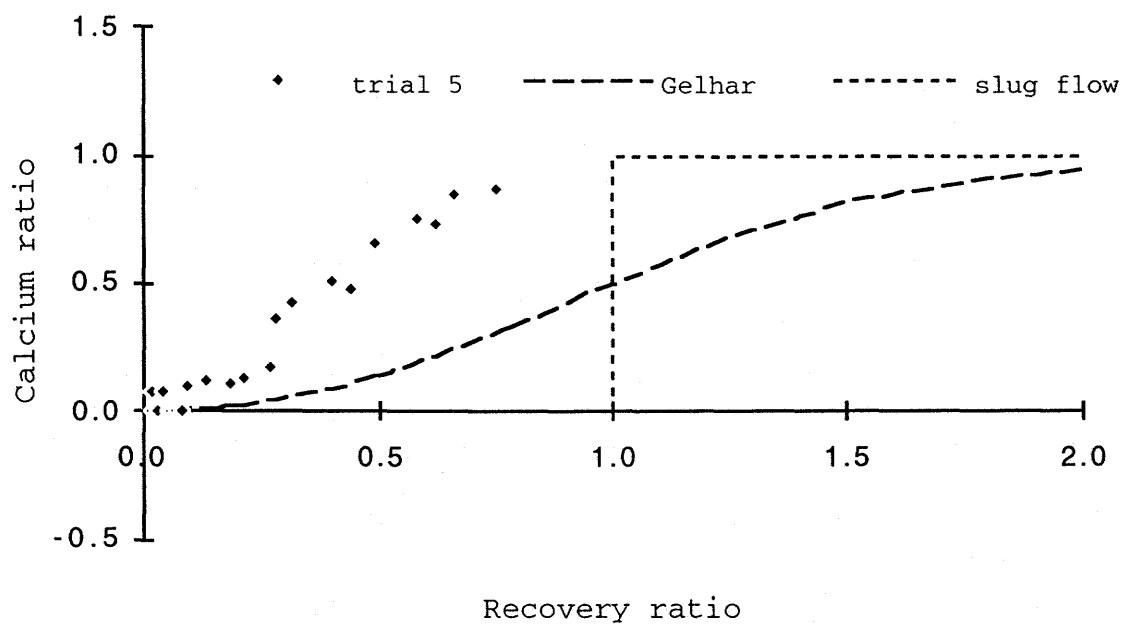


Figure 8.16: Recovery curve (calcium), trial 5. $\alpha = 0.6$ m.

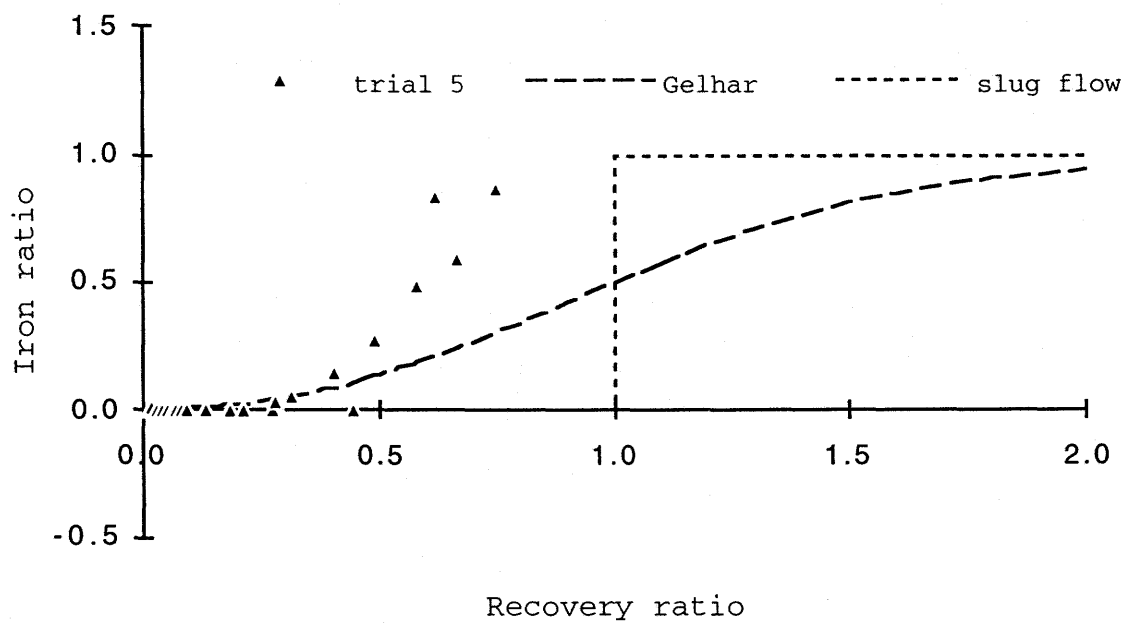


Figure 8.17: Recovery curve (iron), trial 5. $\alpha = 0.6$ m.

The recovery efficiency of the stored water decreased with increased retention time and with increased volume of water injected. Several factors may be affecting recovery:

1. Dispersivity may have increased with increased volume of the aquifer storing injected water (Lam et. al., 1987).
2. The regional velocity gradient is 4 m/yr to 7 m/yr (Fortin, 1989). The injection front radius was calculated to be a maximum 12.21 m for the 5 trials. Over a 1 to 2 month period, the regional gradient would be sufficient to increase mixing of stored and brackish water and induce flow of the injected water away from the well.
3. The reduced specific capacity, particularly during trial 5, would result in an increased required drawdown, which may result in more mixing during recovery and subsequently reduced efficiency (Driscoll, 1986).
4. The increased hydraulic head required during trial 5 may have been indicative of clogging problems, which would reduce efficiency (Huisman and Olsthoorn, 1983).
5. Over the storage period, the stored water may migrate to the upper zone of the aquifer by density induced flow (Cole, 1985).

The following equations were used to calculate the relative significance of each transport process, assuming the aquifer was homogeneous and isotropic:

groundwater velocity:

$$q = \frac{Q}{2 \pi \eta b} \quad (2.10)$$

dispersion:

$$D_m = \alpha \frac{q}{r} \quad (2.11, 2.12)$$

density induced flow:

$$q_{ds} = -K\phi C_r \quad (2.27)$$

Table 8.5: Summary of transport process parameters affecting recovery of stored water

Parameter	Units	Trial Number			
		1	2	4	5
groundwater flowrate:					
q	m ² /day	1.0	1.3	3.4	2.1
coefficient of dispersion:					
D _m	m ² /day	0.15	0.15	1.41	0.23
density induced flow:					
q _{ds} = -K _{oc} C _r	m ² /day	0.0006	0.0006	0.0006	0.0004

The calculated concentration gradient, q_{ds} , would not contribute significantly to groundwater flow over short retention periods, but may have greater impact during long term storage of fresh water.

8.3 Laboratory Tracer Study

The laboratory tracer study provided a visual observation of fresh water movement into a formation containing water high in dissolved solids. The fresh water profile was traced on the Plexiglas surface over time and the tilting angle of the fresh water front measured.

Water was injected into the center well and the movement of the fresh water into the saturated formation was observed over time. In all tests the fresh water moved to the upper half of the 16 cm thick gravel layer.

The tilting angle developed to 45° from vertical within 20 minutes in tests 1, 2 and 3, approaching 90° (perpendicular to the well) within 720 minutes. The 3 test curves are presented in Figure 8.18. Test 3 showed the most rapid change in the tilting angle; the dye front moved from 36° 10 minutes after starting the test, to 82° within 80 minutes.

Increasing the volume of fresh water did not impact on the tilting angle development, as noted in comparing test 1 and test 2. The 2 curves are parallel within 60 minutes. In tests 1, 2 and 3 the rate of change in the tilting angle decreased over time.

Test 4 was conducted with a 0.02 m/m horizontal hydraulic gradient across the model. The hydraulic gradient did influence the tilting angle development, as shown in Figure 8.19. The tilting angle was steeper than 45° from vertical for the first 60 minutes of the test. However, over the next 560 minutes, the tilting angle did approach 90°. However, up to 60 minutes of retention time, the angle was less than 45° from vertical. Only in test 4 did the rate of change in the tilting angle appear to increase with time.

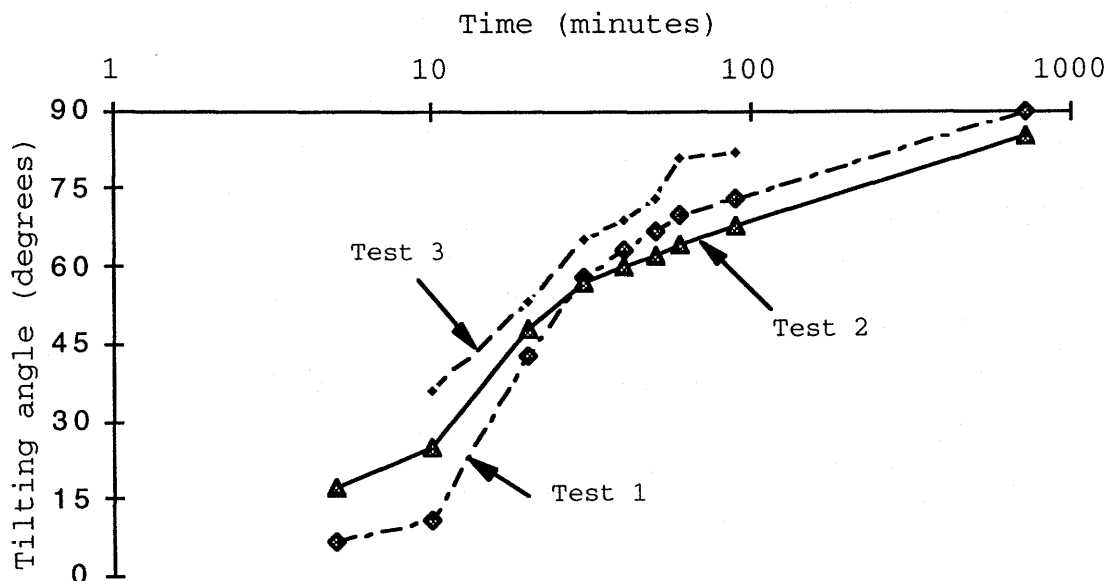


Figure 8.18: Development of tilting angles with time. Note tilting angle was more prone when salt concentration increased from 2000 mg/L (test 1) to 4000 mg/L (test 3).

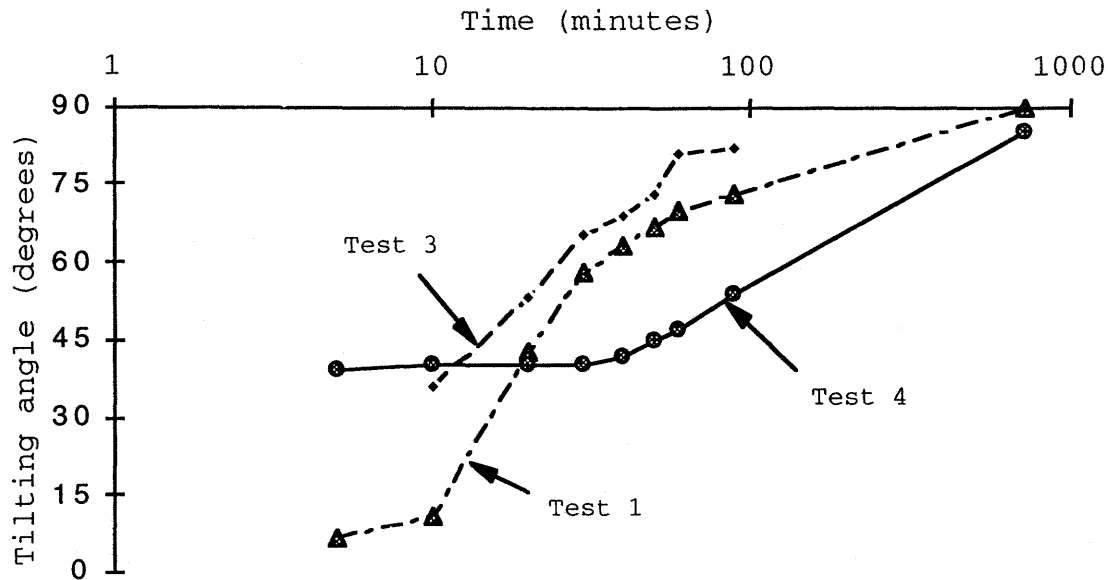


Figure 8.19: Development of tilting angles with time. Note gradual change in tilting angle when hydraulic gradient is present (test 4).

8.4 Groundwater Flow Model

The model developed by Cole (1985) was expanded and tested using the flow conditions measured during the field trials. A summary of the simulation results are presented in Table 8.6.

The model was not able to simulate trials 1 and 2 because of the small volume of water injected and the low rate of injection. The model was able to simulate trials 4 and 5, after the injection rate for trial 3 was increased from 0.024 L/s to 0.45 L/s. The position of the front indicates the front developed in the aquifer at an angle 64° from vertical during trial 3, and at 66° developed during trial 4. The model results indicate trial 4 had a higher recovery efficiency than trial 3, opposite of conditions observed during the field trials.

Table 8.6: Summary of simulated storage and recovery conditions

Parameter	Units	Trial Number			
		1	2	4	5
Injection	L/s	n/a	n/a	0.045 33 days	0.05 28 days
Injection front at base of aquifer:					
lagging edge	m	n/a	n/a	1.02	0.36
leading edge	m	n/a	n/a	1.53	0.67
Injection front at top of aquifer:					
lagging edge	m	n/a	n/a	9.98	10.08
leading edge	m	n/a	n/a	11.43	11.52
V_p at $C_r = 0.5$	(m^3)	n/a	n/a	85	100
Recovery efficiency		n/a	n/a	65%	80%

8.5 Geochemical Model

The computer program was used to investigate changes in the aquifer carbonate system due to the influx of injected water that may occur under artificial recharge (Huisman et al., 1983).

To assess changes in the aquifer carbonate system using PHREEQE model, the following steps were performed:

Part A: Simulation of fresh water equilibrating with calcareous porous medium. Fresh water was equilibrated with calcite at 10°C and ($P(CO_2)$ of 10^{-2}).

Part B: Water quality calculated in Part A was mixed with the brackish groundwater. The saturation index of calcite in a closed system mixture of 0.3 to 0.7, 0.5 to 0.5, and 0.7 to 0.3 freshwater to brackish water was calculated.

Part C: The final closed system mixture calculated in Part B was re-equilibrated with calcite.

The geochemical model PHREEQE was used to model possible changes in water quality due to the mixing between the injected and ground waters, and between the injected water and porous medium. The saturation index values of the waters shown in Table 8.7 indicate the potential for scaling of the well screen. If the treated water entering the aquifer reaches equilibrium with the aquifer material, assuming calcite is present in the aquifer, 0.001 mg/L of calcite would be dissolved. If the water in the mixed zone reached equilibrium with the aquifer material, 0.004 mg/L of calcite would precipitate out of solution in the mixed zone. The total change in water hardness due to the geochemical reactions are theoretically minimum.

TABLE 8.7 Summary of simulated changes in water quality during injection and storage

Stage of Mixing	Saturation Index of Calcite	mass transfer mg/L	pH	pE
injection: 100 % fw	0.0063	0.001 (dissolution)	7.36	13.94
injection front:				
70 % fw 30 % gw	0.4235	-	7.43	3.29
50 % fw 50 % gw	0.6090	-	7.46	3.02
30 % fw 70 % gw	0.7538	-	7.48	2.85
injection front reaction with aquifer:				
70 % fw 30 % gw	0.0063	-0.004 (precipitation)	7.12	3.29

8.6 General Discussion

Screening sites prior to beginning the artificial recharge program was useful in identifying potential problems prior to conducting the field test at the study site. The screening process did not indicate that decreased specific capacity of the well may occur.

The field, laboratory and groundwater flow model results suggest that over time the injected water migrates away from the well screen under the influence of density induced flow, although theoretically, density induced flow is a small component of the transport processes. The laboratory model did support the general field information that the injection front may have shifted from the well screen due to the regional groundwater flow. The groundwater flow model did not include regional groundwater flow.

9.0 CONCLUSIONS

Several conclusions may be drawn from the results of this study.

1. A water well developed into a confined aquifer was recharged with fresh water. The well was located north of Saskatoon, Saskatchewan in an area where similar wells are developed over an 800 km² area. The research indicated that artificial recharge would be a means to manage surface and groundwater resources within the Dalmeny aquifer area. Further work is required to determine if other confined aquifer systems in Saskatchewan would be suitable for a similar program.

Transport processes during injection, storage and recovery resulted in a percentage of the fresh water mixing with the groundwater in the aquifer. Recovery efficiency of the injected fresh water ranged from 44% to 85% in five trials.

2. The theoretical breakthrough curve for water recovery was suitable in determining the field breakthrough curve when a small volume of water was injected and immediately recovered. The theoretical curve did not match the field results when the storage volume and retention time of the fresh water in the aquifer increased. The decreased recovery efficiency indicates that dispersion was significant to the recovery process over a short period of time for a given volume, but did not account for the overall recovery efficiency.
3. The laboratory tracer study indicated that the decreased recovery efficiency observed in the field may be attributed to fresh water moving away from the well screen due to density induced flow. There was insufficient field data to determine if the injected water front moved above the existing groundwater during field trials.
4. The groundwater flow model developed by Cole (1985) was suitable to demonstrate the ideal storage conditions under artificial recharge when the injected water was less dense than the aquifer water. The model was able to estimate the recovery efficiency on the basis of the volume of water injected. The model was not

able to simulate the actual field conditions in which the hydraulic head in the water well was held constant and the flow rate was varied, nor was it able to model the injection at the small injection flow rate observed in the field during three of the five trials.

5. The stored water did not undergo geochemical transformation. Analysis of recovered water indicated a gradual change from fresh water to groundwater chemical composition. Geochemical equilibrium modeling using field and regional groundwater data indicated that the aquifer was not chemically altered due to the artificial recharge trials.
6. The site assessment procedure summarized hydrogeologic factors that may have influenced the study site. Additional field trials are required to allow prioritization of factors influencing site performance under artificial recharge.

10.0 RECOMMENDATIONS

This study determined that surface water may be stored in a confined aquifer and later recovered for domestic use. At the same time, the study identified several areas which should be more thoroughly addressed in further research.

1. The work conducted by the University of Saskatchewan has been supported by local farmers using water well installations 10 to 20 years old. Research efforts in the future should establish a permanent artificial recharge well field, allowing monitoring of the injection cycles, movement of the fresh water front within the aquifer through installation of monitoring wells and uninterrupted storage and recovery.
2. A dedicated water well field would allow sufficient data collection to use finite element or finite difference modeling techniques to estimate long term storage and transport processes. This development would broaden the scope of artificial recharge from individual water well users to municipal-scale groundwater conservation programs.
3. Additional laboratory testing should be conducted using the sand model. The tests would provide information regarding the movement of fresh water in storage at considerably less cost and time than field scale testing, and with no potential impact on a groundwater resource or water well.
4. The information developed in this thesis regarding assessing sites for artificial recharge on the basis of physical conditions, geochemical interaction and recovery efficiency should be made available to groundwater users potentially interested in conjunctive use of surface and subsurface water resource development.

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APPENDIX A

Site Selection Form - SE 18-38-05 W3

Appendix A: Site Selection Form SE 18-38-05 W3

Factor	Acceptable Parameter	Comments
Surface water storage capacity	> 50 % of annual domestic demand	surface storage = 4,000 m ³
Lift to pump water to well	lift < treatment pump capacity	sufficient lift capacity
Surface water quality	< 1500 mg/L total dissolved solids < 6.0 sodium adsorption ratio	acceptable water quality
Water well to aquifer connection	perforated casing OR machine slot, gravel packed annulus	machine slot, gravel packed
Water well performance	no maintenance problems OR performance problems that are controlled through treatment	iron problem, previously treated by shock chlorinating well screen
Groundwater quality	< 5000 mg/L total dissolved solids < 0.3 mg/L dissolved iron	acceptable TDS excessive iron in water
Regional groundwater flow		4 to 7 m/yr
Available recharge head		4 m

APPENDIX B
Water Analyses

Appendix B: Water Analyses

Table B.1: Surface reservoir water quality

Constituent (mg/L unless specified)	Sampling Date	
	16 July 1987	03 June 1988
total hardness	150	368
calcium Ca^{+2}	36.4	78.8
magnesium Mg^{+2}	14.3	41.5
sodium Na^{+}	0	0
potassium K^{+}	0	0
iron Fe^{+2}	0.25	0.16
manganese ⁺²	0	0
total alkalinity (as CaCO_3)	131	165
sulphate SO_4^{-2}	24.5	195
total dissolved solids	154.6	414.5
pH (units)	7.6	7.6
electrical conductivity ($\mu\text{S}/\text{cm}$)	300	750
sodium adsorption ratio	0	0

Appendix B: Water Analyses

Table B.2: Well water quality

Constituent (mg/L unless specified)	Sampling Date	
	16 July 1987	03 June 1988
total hardness	2109	1991
calcium Ca^{+2}	469.3	426.4
magnesium Mg^{+2}	226.1	218.7
sodium Na^{+}	15.2	15.0
potassium K^{+}	1.6	1.5
iron Fe^{+2}	20.1	16.0
manganese Mn^{+2}	3.4	3.6
total alkalinity (as CaCO_3)	550	540
sulphate SO_4^{-2}	1569.6	1465
total dissolved solids	2634.9	2684.3
pH (units)	6.7	6.8
electrical conductivity ($\mu\text{S}/\text{cm}$)	2000	2300
sodium adsorption ratio	0.25	0.26

Appendix B: Water Analyses

Table B.3: Treatment unit water quality 27 July 1987

Constituent (mg/L unless specified)	Water Treatment Process		
	permanganate filter	carbon filter	chlorinator
total hardness	158	145	132
calcium Ca^{+2}	29	28	26
magnesium Mg^{+2}	21	18	16
sodium Na^{+}	n/a	n/a	n/a
iron Fe^{+2}	0.3	0.2	0.2
manganese $^{+2}$	0	0.1	0
total alkalinity (as CaCO_3)	130	124	111
chloride Cl^{-}	0.04	0.05	0.02
nitrate NO_3^{-}	1.0	0.5	1.2
sulphate SO_4^{-2}	22	22	22
total dissolved solids	n/a	n/a	n/a
pH (units)	7.23	7.33	7.04
electrical conductivity ($\mu\text{S}/\text{cm}$)	300	300	300
sodium adsorption ratio	n/a	n/a	n/a

notes: n/a = not available

Appendix B Water Analyses

Table B.4: Water quality, trial 1 recovery

Constituent (mg/L unless specified)	Time since start of recovery (minutes)							
	30	90	150	210	270	330	540	600
total hardness	163	165	174	249	514	990	1590	1710
calcium Ca^{+2}	35	37	38	55	126	220	376	388
magnesium Mg^{+2}	19	18	19	27	49	107	158	180
sodium Na^{+}	0.8	0.8	0.9	1.7	3.6	7.4	11.0	11.5
potassium K^{+}	1.4	1.3	1.2	1.1	1.3	1.6	3.5	4.7
iron Fe^{+2}	0.5	0.5	2.8	1.5	2.6	6.3	10.5	11.3
manganese ⁺²	0.3	0.3	0.4	0.3	0.3	n/a	n/a	n/a
t. alkalinity (as CaCO_3)	143	148	150	179	257	270	372	564
nitrate NO_3^-	0.5	0.6	0.2	5.0	0	n/a	0	n/a
sulphate SO_4^{-2}	34	37	38	110	170	700	1110	1450
total dissolved solids	141.9	148.5	153.3	255.6	394.3	991 ¹	1547 ¹	2015 ¹
electrical conductivity ($\mu\text{S}/\text{cm}$) (10 C)	390	370	420	550	1150	1750	2600	2600
sodium adsorption ratio	0.05	0.04	0.05	0.08	0.12	0.18	0.14	0.21

Notes: ¹ assume manganese negligible

Appendix B: Water Analyses

Table B.5: Water quality, trial 5 recovery

Constituent (mg/L unless specified)	Time since start of recovery (minutes)							
	180	360	720	1080	1440	1680	2160	2340
total hardness	698	706	686	728	728	752	786	875
calcium Ca ⁺²	108	106	113	122	118	123	138	203
magnesium Mg ⁺²	104	107	98	103	105	108	107	89
iron Fe ⁺²	0.28	0.25	0.13	0.18	0.12	0.13	0.16	0.73
electrical conductivity (µS/cm)	1000	1020	1050	1050	1120	1180	1100	1480

Appendix B: Water Analyses

Table B.5 (cont'd): Water quality, trial 5 recovery

Constituent (mg/L unless specified)	Time since start of recovery (minutes)								
	2520	2880	3240	3600	3960	4680	5040	5400	6120
total hardness	975	1100	1275	1325	1500	1440	1490	1540	1570
calcium Ca ⁺²	228	240	256	244	308	338	334	374	380
magnesium Mg ⁺²	98	122	154	174	177	145	159	147	151
iron Fe ⁺²	1.08	1.80	2.6	3.5	4.6	8.0	13.5	9.5	13.9
electrical conductivity (µS/cm)	1420	1510	1620	1810	1750	1750	1800	1890	1900

APPENDIX C

Pump Tests

Appendix C: Pump Tests

Table C.1a: 14 July 1987 pump test: drawdown

$Q = 0.49 \text{ L/s}$		$r = 0.0635 \text{ m}$	
Time (t) Since Start of Pumping (minutes)	Depth to Water Surface (m)	Drawdown (s) (m)	
0	6.74	0	
0.33	7.64	0.9	
0.67	7.97	1.23	
0.83	8.37	1.63	
1	8.87	2.13	
1.5	10.34	3.60	
2	10.78	4.04	
2.5	10.83	4.09	
3	11.19	4.45	
3.5	11.38	4.64	
4	13.09	6.35	
4.5	13.21	6.47	
5	13.51	6.77	
6	14.03	7.29	
7	14.37	7.63	
8	14.90	8.16	
9	15.02	8.28	
10	15.07	8.33	
15	15.99	9.25	
22	16.18	9.44	
25	16.26	9.52	
30	16.68	9.94	
60	16.87	10.13	
120	17.01	10.27	
180	17.13	10.39	
215	17.14	10.40	

Appendix C: Pump Tests

Table C.1b: 14 July 1987 pump test: recovery

Time (t) Since Start of Pumping (minutes)	Time (t') Since Pump Stopped (minutes)	Ratio t/t' (unitless)	Depth to Water Surface (m)	Residual Drawdown s' (m)
215.00	0.00	∞	17.14	10.40
215.17	0.17	1291.00	16.88	10.14
215.33	0.33	646.00	16.19	9.45
215.50	0.50	431.00	16.07	9.33
215.67	0.67	323.50	15.56	8.82
215.83	0.83	259.00	15.07	8.33
216.00	1.0	216.0	14.73	7.99
216.50	1.5	144.3	13.59	6.85
217.00	2.0	108.5	12.73	5.99
217.50	2.5	87.0	11.87	5.13
218.00	3.0	72.7	11.21	4.47
218.50	3.5	62.4	10.50	3.76
219.00	4.0	54.8	10.07	3.33
219.50	4.5	48.8	9.61	2.87
220.00	5.0	44.0	9.22	2.48
221.00	6.0	36.8	8.64	1.90
222.00	7.0	31.7	8.23	1.49
223.00	8.0	27.9	7.93	1.19
224.00	9.0	24.9	7.70	0.96
225.00	10.0	22.5	7.54	0.80
226.00	11.0	20.6	7.43	0.69
227.00	12.0	18.9	7.35	0.61
228.00	13.0	17.5	7.29	0.55
229.00	14.0	16.4	7.24	0.50
230.00	15.0	15.3	7.20	0.46
245.00	30.0	8.2	7.04	0.30
275.00	60.0	4.6	6.97	0.23
335.00	120.0	2.8	6.92	0.18
455.00	240.0	1.9	6.82	0.08

Appendix C: Pump Tests

Table C.2a: 16 July 1987 pump test: drawdown

$Q = 0.49 \text{ L/s}$		$r = 0.0635 \text{ m}$
Time (t) Since Start of Pumping (minutes)	Depth to Water Surface (m)	Drawdown (s) (m)
0	6.85	0
0.17	7.43	0.58
0.33	7.90	1.05
0.50	8.35	1.50
0.67	8.76	1.91
0.83	9.22	2.37
1.00	9.64	2.79
1.50	10.62	3.77
2.00	11.32	4.47
2.50	12.09	5.24
3.00	12.64	5.79
3.50	13.15	6.30
4.00	13.61	6.76
4.50	13.97	7.12
5.00	14.31	7.46
6.00	14.82	7.97
7.00	15.23	8.38
8.00	15.54	8.69
9.00	15.78	8.93
10.00	15.95	9.10
15.00	16.40	9.55
20.00	16.57	9.72
25.00	16.64	9.79
30.00	16.68	9.83
35.00	16.72	9.87
40.00	16.75	9.90
45.00	16.76	9.91
50.00	16.79	9.94
55.00	16.80	9.95
60.00	16.82	9.97
120.00	16.94	10.09

Appendix C: Pump Tests

Table C.2b: 16 July 1987 pump test: recovery

Time (t) Since Start of Pumping (minutes)	Time (t') Since Pump Stopped (minutes)	Ratio t/t' (unitless)	Depth to Water Surface (m)	Residual Drawdown s' (m)
120.00	0.00	∞	16.94	10.09
120.17	0.17	721.00	16.70	9.85
120.33	0.33	361.00	16.21	9.36
120.66	0.66	181.00	15.15	8.30
121.00	1.00	121.00	14.48	7.63
121.50	1.50	81.00	13.58	6.73
122.00	2.00	61.00	12.48	5.63
122.50	2.50	49.00	11.40	4.55
123.00	3.00	41.00	11.13	4.28
123.50	3.50	35.29	10.42	3.57
124.00	4.00	31.00	9.95	3.10
124.50	4.50	27.67	9.58	2.73
125.00	5.00	25.00	9.19	2.34
126.00	6.00	21.00	8.37	1.52
127.00	7.00	18.14	8.24	1.39
128.00	8.00	16.00	7.74	0.89
129.00	9.00	14.33	7.71	0.86
130.00	10.00	13.00	7.56	0.71
135.00	15.00	9.00	7.22	0.37
140.00	20.00	7.00	7.11	0.26
145.00	25.00	5.80	7.12	0.25
150.00	30.00	5.00	7.08	0.23
155.00	35.00	4.43	7.05	0.20
160.00	40.00	4.00	7.04	0.19
165.00	45.00	3.67	7.03	0.18
170.00	50.00	3.40	7.02	0.17
175.00	55.00	3.18	7.01	0.16
180.00	60.00	3.00	7.00	0.15
215.00	95.00	2.26	6.97	0.12

Appendix C: Pump Tests

Table C.3a: 03 November 1987 pump test: drawdown

$Q = 0.49 \text{ L/s}$		$r = 0.0635 \text{ m}$	
Time (t) Since Start of Pumping (minutes)	Depth to Water Surface (m)	Drawdown (s) (m)	
0	6.80	0	
5	12.50	5.70	
10	17.31	10.51	
15	18.73	11.93	
20	19.62	12.82	
25	19.63	12.83	
30	19.61	12.81	
35	19.64	12.84	
40	19.65	12.85	
45	19.64	12.84	

Table C.3b: 03 November 1987 pump test: recovery

Time (t) Since Start of Pumping (minutes)	Time (t') Since Pump Stopped (minutes)	Ratio t/t' (unitless)	Depth to Water Surface (m)	Residual Drawdown s' (m)
45.00	0	∞	19.64	12.84
50.00	5.00	10.00	16.28	9.48
55.00	10.00	5.50	11.31	4.51
60.00	15.00	4.00	8.68	1.88
65.00	20.00	3.25	7.88	1.08
70.00	25.00	2.80	7.37	0.57

Appendix C: Pump Tests

Table C.4a: 16 June 1988 pump test: drawdown

$Q = 0.15 \text{ L/s}$		$r = 0.0635 \text{ m}$
Time (t) Since Start of Pumping (minutes)	Depth to Water Surface (m)	Drawdown (s) (m)
0	7.57	0
0.17	8.10	0.53
0.42	9.05	1.48
0.67	9.50	1.93
1.00	10.00	2.43
1.50	11.03	3.46
2.00	12.10	4.54
2.50	13.10	5.54
3.00	13.63	6.06
3.50	14.18	6.61
4.00	14.73	7.16
5.00	15.60	8.03
6.00	16.24	8.67
7.00	16.71	9.14
8.00	17.08	9.51
9.00	17.33	9.76
10.00	17.55	9.98
20.00	18.26	10.69
25.00	18.26	10.69
30.00	18.35	10.78
35.00	18.39	10.82
40.00	18.43	10.86
45.00	18.43	10.86
50.00	18.46	10.89
55.00	18.47	10.90
60.00	18.48	10.91
80.00	18.55	10.98
100.00	18.59	11.02
120.00	18.62	11.05
150.00	18.65	11.08
180.00	18.70	11.13
210.00	18.71	11.14
240.00	18.75	11.18
270.00	18.76	11.19
300.00	18.76	11.19
360.00	18.79	11.22
420.00	18.85	11.28
450.00	18.86	11.29

Appendix C: Pump Tests

Table C.4b: 16 June 1988 pump test: recovery

Time (t) Since Start of Pumping (minutes)	Time (t') Since Pump Stopped (minutes)	Ratio t/t' (unitless)	Depth to Water Surface (m)	Residual Drawdown s' (m)
450.00	0.00	∞	18.86	11.29
465.00	15.00	31.00	8.30	0.73
470.00	20.00	23.00	8.13	0.56
475.00	25.00	19.00	8.06	0.49
480.00	30.00	16.00	7.95	0.38
485.00	35.00	13.86	8.00	0.43
490.00	40.00	12.25	7.98	0.41
495.00	45.00	11.00	7.96	0.39
500.00	50.00	10.00	7.95	0.38
505.00	55.00	9.18	7.94	0.37
510.00	60.00	8.50	7.94	0.37

Appendix C: Pump Tests

Table C.5a: 28 July 1988 pump test: drawdown

$Q = 0.15 \text{ L/s}$		$r = 0.0635 \text{ m}$
Time (t) Since Start of Pumping (minutes)	Depth to Water Surface (m)	Drawdown(s) (m)
0	4.31	0
0.17	4.89	0.58
0.33	5.36	1.05
0.50	5.81	1.50
0.66	6.22	1.91
0.83	6.68	2.37
1.00	7.10	2.81
1.5	8.08	3.77
2.0	8.78	4.47
2.5	9.55	5.24
3.0	10.10	5.81
3.5	10.61	6.30
4.0	11.07	6.76
4.5	11.43	7.12
5.0	11.77	7.46
6.0	12.28	7.97
7.0	12.69	8.38
8.0	13.00	8.69
9.0	13.24	8.93
10.0	13.41	9.10
15.0	13.86	9.55
20.0	14.03	9.72
25.0	14.10	9.79
30.0	14.14	9.83
35.0	14.18	9.87
40.0	14.21	9.90
45.0	14.22	9.91
50.0	14.25	9.94
55.0	14.26	9.95
60.0	14.28	9.97
120.0	14.40	10.09

Appendix C: Pump Tests

Table C.5b: 28 July 1988 pump test: recovery

Time (t) Since Start of Pumping (minutes)	Time (t') Since Pump Stopped (minutes)	Ratio t/t' (unitless)	Depth to Water Surface (m)	Residual Drawdown s' (m)
120.0	0.00	∞	14.40	10.09
120.17	0.17	721.30	14.16	9.86
120.33	0.33	361.00	13.67	9.37
120.67	0.67	181.02	12.61	8.30
121.0	1.0	121.0	11.94	7.63
121.5	1.5	81.0	11.04	6.73
122.0	2.0	61.0	9.94	5.63
122.5	2.5	49.0	8.86	4.55
123.0	3.0	41.0	8.59	4.28
123.5	3.5	35.5	7.88	3.57
124.0	4.0	31.0	7.41	3.10
124.5	4.5	27.6	7.04	2.73
125.0	5.0	25.0	6.65	2.34
126.5	6.5	19.4	5.83	1.52
127.0	7.0	18.1	5.70	1.39
128.0	8.0	16.0	5.20	0.89
129.0	9.0	14.3	5.17	0.86
130.0	10.0	13.0	5.02	0.71
135.0	15.0	9.0	4.68	0.37
140.0	20.0	7.0	4.57	0.26
145.0	25.0	5.8	4.56	0.25
150.0	30.0	5.0	4.54	0.23
155.0	35.0	4.4	4.51	0.20
160.0	40.0	4.0	4.50	0.19
165.0	45.0	3.7	4.49	0.18
170.0	50.0	3.4	4.48	0.17
175.0	55.0	3.2	4.47	0.16
180.0	60.0	3.0	4.46	0.15
215.0	95.0	2.3	4.43	0.12

Appendix C: Pump Tests

Table C.6: 28 September 1988 pump test: drawdown

$Q = 0.22 \text{ L/s}$		$r = 0.0635 \text{ m}$
Time (t) Since Start of Pumping (minutes)	Depth to Water Surface (m)	Drawdown(s) (m)
0	7.95	0
1.00	10.40	2.45
1.50	11.00	3.05
2.00	11.72	3.77
2.50	12.47	4.52
3.00	13.50	5.55
3.50	13.70	5.75
4.00	14.28	6.33
4.50	14.75	6.80
5.00	15.24	7.29
6.00	16.08	8.13
7.00	16.69	8.74
8.00	17.25	9.30
9.00	17.70	9.75
10.00	18.05	10.10
15.00	18.98	11.03
20.00	19.26	11.31
25.00	19.33	11.38
30.00	19.32	11.37
35.00	19.28	11.33
40.00	19.24	11.29
45.00	19.21	11.26
50.00	19.19	11.24
55.00	19.15	11.20
60.00	19.15	11.20
80.00	19.11	11.16
120.00	19.07	11.12
210.00	19.00	11.05
240.00	19.00	11.05
300.00	18.95	11.00
360.00	18.98	11.03
1440.00	19.06	11.11

APPENDIX D

Injection and Recovery Volumes

Appendix D: Injection and Recovery Volumes

Table D.4: Trial 4: fresh water injection

Monitoring Time (D/M/Y)	(hour)	Time Since Start of Injection t_i (hours)	Flowmeter Reading (U.S. gallons)	Injection Volume V_i (m ³)	Injection Rate Q_i (m ³ /min)
04/09/87	1310	0	0063997.1	0	n/a
04/09/87	1325	0.25	0064176.9	0.68	0.0453
05/09/87	1600	26.83	0065317.0	5.00	0.0027
06/09/87	1245	47.58	0066276.3	8.63	0.0029
07/09/87	1140	70.50	0067250.0	12.31	0.0027
08/09/87	1020	93.16	0068128.9	15.64	0.0024
09/09/87	1010	117.00	0068978.6	18.86	0.0023
10/09/87	0955	140.75	0069771.5	21.86	0.0021
11/09/87	2000	174.83	0070002.0	22.73	0.0004
12/09/87	1545	194.58	0070726.4	25.47	0.0023
Breakdown, repaired and pump restarted 16/09/87					
16/09/87	1730	292.33	0070726.4	25.47	n/a
17/09/87	0520	304.16	0071103.0	26.90	0.0020
Breakdown, repaired and pump restarted 17/09/87					
17/09/87	1640	315.50	0071103.0	26.90	n/a
18/09/87	1500	337.83	0071653.8	28.98	0.0016
19/09/87	1610	363.00	0072263.0	31.29	0.0015
20/09/87	1350	384.67	0072738.2	33.09	0.0014
21/09/87	1510	410.00	0073271.2	35.11	0.0013
22/09/87	1017	429.11	0073672.6	36.63	0.0013
23/09/87	0940	452.49	0074171.6	38.51	0.0013
24/09/87	1000	476.83	0074677.6	40.43	0.0013
25/09/87	1102	501.86	0075233.9	42.54	0.0014
26/09/87	1015	525.08	0075787.8	44.63	0.0015
27/09/87	1000	548.83	0076382.5	46.88	0.0016
28/09/87	0905	571.91	0076650.1	47.92	0.0008
29/09/87	0915	596.08	0077522.0	51.20	0.0023
30/09/87	0815	619.08	0078037.6	53.15	0.0014
01/10/87	0810	643.00	0078572.0	55.17	0.0014
02/10/87	1150	670.66	0079192.7	57.52	0.0014
03/10/87	1142	694.53	0079747.0	59.62	0.0015
04/10/87	1235	719.41	0080335.1	61.87	0.0015
04/10/87	1520	722.16	0080400.4	62.09	0.0013
05/10/87	1445	745.59	0080930.4	64.10	0.0014
06/10/87	1335	768.42	0081441.9	66.04	0.0014
07/10/87	1300	791.83	0081717.0	67.08	0.0007

Appendix D: Injection and Recovery Volumes - (cont'd)

Start Up Conditions:

initial water depth = 7.12 m bottom sensor depth = 5.40 m
top sensor depth = 3.70 m

Treatment Process:

chlorine concentration = 0.20 mg/L
tank pressure = 276 kPa

Appendix D: Injection and Recovery Volumes

Table D.5: Trial 5: fresh water injection

Monitoring Time		Time Since Start of Injection	Flowmeter Reading	Injection Volume	Injection Rate
(D/M/Y)	(hour)	t_i (hours)	(U.S. gallons)	V_i (m ³)	Q_i (m ³ /min)
19/08/88	1400	0	0081717.3	0	
20/08/88	1345	23.75	0084074.9	8.92	0.0063
20/08/88	nr	nr	0084098.8	9.01	
24/08/88	1100	117.00	0090770.0	34.27	0.0045
25/08/88	1205	142.08	0094867.0	49.78	0.0103
27/08/88	1530	193.50	0096763.7	56.96	0.0023
28/08/88	1815	220.25	0097258.5	58.83	0.0012
30/08/88	1455	264.92	0097976.0	61.55	0.0010
30/08/88	1605	266.09	0098047.5	61.82	0.0038
01/09/88	1425	312.42	0098831.2	64.78	0.0011
03/09/88	1500	361.00	0099571.0	67.58	0.0010
05/09/88	1715	411.25	0100175.1	69.87	0.0008
07/09/88	1305	455.08	0100410.5	70.76	0.0003
08/09/88	0815	426.25	0100438.7	70.87	0.0001
08/09/88 Adjusted sensors: bottom sensor depth = 6.00 m top sensor depth = 4.00 m					
14/09/88	1430	624.50	0111401.5	112.37	0.9216
16/09/88	1705	675.08	0111502.0	112.75	0.0331

Start Up Conditions:

initial water depth = 7.96 m

bottom sensor depth = 7.00 m

top sensor depth = 5.00 m

Treatment Process:

chlorine concentration = 0.25 mg/L

storage tank pressure = 276 kPa

Appendix D: Injection and Recovery Volumes

Table D.6: Trial 1: fresh water recovery

Cumulative injection volume $V_i = 6.26 \text{ m}^3$ as of 17 August 1987

Electrical conductivity, injected water $EC_{fw} = 300 \text{ } \mu\text{S/cm}$ (25°C)
 $EC_{fw} = 450 \text{ } \mu\text{S/cm}$ (10°C)

Electrical conductivity, groundwater $EC_{gw} = 2000 \text{ } \mu\text{S/cm}$ (25°C)
 $EC_{gw} = 2900 \text{ } \mu\text{S/cm}$ (10°C)

Calcium concentration, injected water $Ca_{fw} = 36.4 \text{ mg/L}$

Calcium concentration, groundwater $Ca_{gw} = 470.0 \text{ mg/L}$

Iron concentration, injected water $Fe_{fw} = 0.16 \text{ mg/L}$

Iron concentration, groundwater $EC_{gw} = 20.1 \text{ mg/L}$

from Equation 2.19:
$$V = \frac{Q_p t_p}{Q_i t_i}$$

from Equation 8.1:
$$EC_R = \frac{C_p - C_{fw}}{C_{gw} - C_{fw}}$$

Appendix D: Injection and Recovery Volumes

Table D.6: Trial 1: fresh water recovery

Elapsed Time t_p (minutes)	Depth to Water Q_p (m)	Recovery Rate V_p (m ³ /min)	Recovery Volume EC_p (10°C) (m ³)	Electrical Conductivity Ca_p (μS/cm)	Calcium Fe_p (mg/L)	Iron (mg/L)	Temperature (°C)
0	7.15	0	0	390	nr	nr	nr
15	nr	0.015	0.23	390	nr	nr	10
30	nr	0.015	0.45	390	35	0.5	10
45	nr	0.013	0.64	340	nr	nr	10
60	nr	0.015	0.83	370	nr	nr	10
75	nr	0.005	0.90	440	nr	nr	10
90	nr	0.005	0.97	440	37	0.5	10
105	nr	0.005	1.03	480	nr	nr	10
120	nr	0.022	1.34	420	nr	nr	10
135	nr	0.022	1.68	400	nr	nr	10
150	nr	0.022	2.02	480	38	2.8	10
165	nr	0.022	2.33	520	nr	nr	10
180	nr	0.022	2.64	550	nr	nr	10
195	nr	0.022	2.98	550	nr	nr	10
210	nr	0.022	3.32	730	55	1.5	10
240	nr	0.022	4.00	1150	nr	nr	10
255	nr	0.022	4.29	1200	nr	nr	10
270	nr	0.022	4.60	1450	126	2.6	10
285	nr	0.022	4.92	1500	nr	nr	10
300	nr	0.022	5.21	1650	nr	nr	10
330	nr	0.022	5.89	1750	220	6.3	10
420	nr	0.022	7.94	2800	nr	nr	10
480	nr	0.022	9.07	2900	nr	nr	10
510	nr	0.008	9.30	2500	nr	nr	10
540	nr	0.008	9.53	2600	376	10.5	10
600	nr	0.016	10.47	2600	388	11.3	10

Appendix D: Injection and Recovery Volumes

Table D.6: Trial 1: fresh water recovery

Elapsed Time t_p (minutes)	Recovery Volume Ratio Ψ	Electrical Conductivity Ratio EC_R	Calcium Ratio Ca_R	Iron Ratio Fe_R
15	0.04	-0.02	nr	nr
30	0.07	-0.02	0.00	0.02
45	0.10	-0.04	nr	nr
60	0.13	-0.03	nr	nr
75	0.14	0.00	nr	nr
90	0.16	0.00	0.00	0.02
105	0.17	0.01	nr	nr
120	0.21	0.00	nr	nr
135	0.27	-0.02	nr	nr
150	0.32	0.01	0.00	0.13
165	0.37	0.03	nr	nr
180	0.42	0.04	nr	nr
195	0.48	0.04	nr	nr
210	0.53	0.11	0.04	0.07
240	0.64	0.29	nr	nr
255	0.69	0.31	nr	nr
270	0.73	0.41	0.21	0.12
285	0.79	0.43	nr	nr
300	0.83	0.49	nr	nr
330	0.94	0.53	0.42	0.31
420	1.27	0.96	nr	nr
480	1.45	1.00	nr	nr
510	1.49	0.84	nr	nr
540	1.52	0.88	0.78	0.52
600	1.67	0.88	0.81	0.56

Appendix D: Injection and Recovery Volumes

Table D.7: Trial 2: fresh water recovery

Cumulative injection volume $V_i = 1.94 \text{ m}^3$ as of 01 September 1987

Electrical conductivity, injected water $EC_{fw} = 300 \text{ } \mu\text{S/cm}$ (25°C)

Electrical conductivity, groundwater $EC_{gw} = 2000 \text{ } \mu\text{S/cm}$ (25°C)

from Equation 2.19:
$$v = \frac{Q_p t_p}{Q_i t_i}$$

from Equation 8.1:
$$EC_R = \frac{EC_p - EC_{fw}}{EC_{gw} - EC_{fw}}$$

Appendix D: Injection and Recovery Volumes

Table D.7: Trial 2: fresh water recovery (cont'd)

Elapsed Time t_p (minutes)	Depth to Water (m)	Recovery Rate Q_p (m ³ /min)	Recovery Volume V_p (m ³)	Recovery Volume Ratio Ψ	Electrical Conductivity EC_p (25°C) (μS/cm)	Electrical Conductivity Ratio EC_R	Temperature (°C)
0	7.06	0	0	0	nr	nr	nr
15	nr	0.008	0.12	0.062	260	-0.04	nr
30	nr	0.008	0.24	0.12	240	-0.04	nr
45	nr	0.008	0.36	0.19	240	-0.04	nr
60	nr	0.008	0.48	0.25	240	-0.04	nr
75	nr	0.008	0.60	0.30	240	-0.04	nr
90	nr	0.008	0.72	0.37	260	-0.02	nr
105	nr	0.008	0.84	0.43	375	0.04	nr
120	nr	0.008	0.96	0.50	550	0.15	nr
135	nr	0.008	1.08	0.56	700	0.24	nr
150	nr	0.008	1.20	0.62	920	0.37	nr
165	nr	0.008	1.32	0.68	1050	0.44	nr
180	nr	0.008	1.44	0.74	1150	0.50	nr
195	nr	0.008	1.56	0.80	1180	0.52	nr
210	nr	0.008	1.59	0.82	1200	0.53	nr

notes: nr = not recorded

Appendix D: Injection and Recovery Volumes

Table D.8: Trial 3: fresh water recovery

Cumulative injection volume $V_i = 0.77 \text{ m}^3$ as of 02 September 1987

Cumulative injection volume $V_i = 2.73 \text{ m}^3$ as of 03 September 1987

Electrical conductivity, injected water $EC_{fw} = 300 \text{ } \mu\text{S/cm}$ (25°C)

Electrical conductivity, groundwater $EC_{gw} = 2000 \text{ } \mu\text{S/cm}$ (25°C)

Parameters:

$$\text{from Equation 2.19: } v = \frac{Q_p t_p}{Q_i t_i}$$

$$\text{from Equation 8.1: } ECR = \frac{EC_p - EC_{fw}}{EC_{gw} - EC_{fw}}$$

Appendix D: Injection and Recovery Volumes

Table D.8: Trial 3: fresh water recovery (cont'd)

Elapsed Time t_p (minutes)	Depth to Water (m)	Recovery Rate Q_p (m ³ /min)	Recovery Volume V_p (m ³)	Recovery Volume Ratio \bar{V}	Electrical Conductivity EC_p (25°C) (μS/cm)	Electrical Conductivity Ratio EC_R	Temperature (°C)
02/09/87							
15	nr	0.023	0.34	0.44	375	0.04	nr
30	nr	0.023	0.68	0.88	350	0.03	nr
45	nr	0.023	1.02	1.32	1050	0.44	nr
60	nr	0.023	1.36	1.77	1700	0.82	nr
03/09/87							
30	nr	0.015	0.45	0.16	240	-0.04	nr
45	nr	0.015	0.68	0.23	240	-0.04	nr
60	nr	0.015	0.91	0.33	260	-0.02	nr
75	nr	0.015	1.14	0.42	325	0.02	nr
90	nr	0.015	1.36	0.50	510	0.12	nr
105	nr	0.015	1.59	0.58	1450	0.68	nr
135	nr	0.015	2.04	0.75	1680	0.81	nr
150	nr	0.015	2.27	0.83	1680	0.81	nr
165	nr	0.015	2.50	0.92	1680	0.81	nr
180	nr	0.015	2.73	1.00	1680	0.81	nr
04/09/87							
15	nr	0.015	2.96	1.08	1750	0.85	nr
30	nr	0.015	3.41	1.25	1800	0.88	nr
45	nr	0.015	4.09	1.50	1750	0.85	nr
60	nr	0.015	4.99	1.83	1700	0.82	nr

Appendix D: Injection and Recovery Volumes

Table D.9: Trial 4: fresh water recovery

Cumulative injection volume $V_i = 57.11 \text{ m}^3$ as of 03 November 1987

Electrical conductivity, injected water $EC_{fw} = 300 \text{ } \mu\text{S/cm}$ (25°C)

Electrical conductivity, groundwater $EC_{gw} = 2000 \text{ } \mu\text{S/cm}$ (25°C)

from Equation 2.19:
$$v = \frac{Q_p t_p}{Q_i t_i}$$

from Equation 8.1:
$$EC_R = \frac{EC_p - EC_{fw}}{EC_{gw} - EC_{fw}}$$

Appendix D: Injection and Recovery Volumes

Table D.9: Trial 4 fresh water recovery (cont'd)

Elapsed Time t_p (minutes)	Depth to Water (m)	Recovery Rate Q_p (m ³ /min)	Recovery Volume V_p (m ³)	Recovery Volume Ratio Ψ	Electrical Conductivity EC_p (25°C) (μS/cm)	Electrical Conductivity Ratio ECR	Temperature (°C)
0	nr	0	0	0	260	-0.04	5
60	nr	0.015	0.90	0.01	280	-0.01	5
90	nr	0.015	1.35	0.02	280	-0.01	5
120	nr	0.015	1.80	0.03	290	-0.01	6
180	nr	0.015	2.70	0.04	290	-0.01	6
240	nr	0.015	3.60	0.05	300	0.00	6
300	nr	0.015	4.50	0.07	280	-0.01	6
360	nr	0.015	5.40	0.08	300	0.00	7
420	nr	0.015	6.30	0.09	300	0.00	7
480	nr	0.015	7.20	0.11	300	0.00	6
pump shut down from 480 minutes to 900 minutes							
900	nr	0.011	7.20	0.11	280	-0.01	5
1140	nr	0.011	9.84	0.15	300	0.00	5
1380	nr	0.011	12.48	0.19	320	0.01	5
1500	nr	0.015	14.28	0.21	320	0.01	5
1560	nr	0.015	15.18	0.23	340	0.50	6
1620	nr	0.015	16.08	0.24	340	0.02	6
1680	nr	0.015	16.98	0.25	360	0.21	5
1740	nr	0.015	17.88	0.27	390	0.05	5
1890	nr	0.015	20.13	0.30	390	0.05	5
2040	nr	0.013	22.08	0.33	400	0.06	5
2460	nr	0.013	27.54	0.41	460	0.09	5
2640	nr	0.013	29.88	0.45	550	0.15	5
2820	nr	0.013	32.22	0.48	600	0.18	5
2940	nr	0.013	33.78	0.50	600	0.18	5

Appendix D: Injection and Recovery Volumes

Table D.9: Trial 4 fresh water recovery (cont'd)

Elapsed Time t_p (minutes)	Depth to Water (m)	Recovery Rate Q_p (m ³ /min)	Recovery Volume V_p (m ³)	Recovery Volume Ratio \forall	Electrical Conductivity EC_p (25°C) (μS/cm)	Electrical Conductivity Ratio EC_R	Temperature (°C)
3300	nr	0.013	38.46	0.57	750	0.27	5
3360	nr	0.013	39.24	0.58	800	0.29	5
3420	nr	0.013	40.02	0.60	800	0.29	5
3480	nr	0.013	40.80	0.61	800	0.29	5
3600	nr	0.013	42.36	0.63	900	0.35	5
3660	nr	0.013	44.14	0.66	900	0.35	5
3780	nr	0.013	45.70	0.68	950	0.38	5
3840	nr	0.013	46.48	0.69	950	0.38	5
3960	nr	0.013	48.04	0.72	1000	0.41	5
4080	nr	0.013	49.60	0.74	1100	0.47	5
4200	nr	0.013	51.16	0.76	1100	0.47	5
4320	nr	0.013	52.72	0.79	1100	0.47	5
4440	nr	0.013	54.28	0.81	1150	0.50	5
4500	nr	0.013	55.06	0.82	1200	0.53	5
4560	nr	0.013	55.84	0.83	1200	0.53	5
4680	nr	0.013	57.40	0.86	1250	0.56	5
4740	nr	0.013	58.18	0.87	1300	0.59	5
4800	nr	0.013	58.96	0.88	1300	0.59	5
4860	nr	0.013	59.74	0.89	1300	0.59	5
6240	nr	0.013	77.68	1.16	1700	0.82	5

Appendix D: Injection and Recovery Volumes

Table D.10: Trial 5: fresh water recovery

Cumulative injection volume = 112.75 m³ as of 02 September 1987

Electrical conductivity, injected water EC_{fw} = 750 μS/cm (25°C)

Electrical conductivity, groundwater EC_{gw} = 2300 μS/cm (25°C)

Calcium concentration, injected water Ca_{fw} = 36.4 mg/L

Calcium concentration, groundwater Ca_{gw} = 470.0 mg/L

Iron concentration, injected water Fe_{fw} = 0.2 mg/L

Iron concentration, groundwater EC_{gw} = 16.0 mg/L

from Equation 2.19:
$$V = \frac{Q_p t_p}{Q_i t_i}$$

from Equation 8.1:
$$ECR = \frac{C_p - C_{fw}}{C_{gw} - C_{fw}}$$

Appendix D: Injection and Recovery Volumes

Table D.10: Trial 5 fresh water recovery (cont'd)

Elapsed Time t_p (minutes)	Depth to Water (m)	Recovery Rate Q_p (m ³ /min)	Recovery Volume V_p (m ³)	Electrical Conductivity EC_p (10°C) (μS/cm)	Calcium Ca_p (mg/L)	Iron Fe_p (mg/L)	Temperature (°C)
120	19.07	0.015	1.81	1000	nr	nr	11
180	nr	0.013	2.59	nr	108	0.28	10
240	19.00	0.013	3.38	1050	nr	nr	10
360	18.98	0.013	4.99	1020	106	0.25	10
420	18.98	0.014	5.83	1000	nr	nr	10
480	nr	0.015	6.73	1000	nr	nr	10
600	nr	0.013	8.34	1020	nr	nr	10
660	nr	0.016	9.30	1020	nr	nr	10
720	nr	0.014	10.14	nr	113	0.13	10
1080	nr	0.014	15.18	nr	122	0.18	10
1095	nr	0.014	15.25	1050	nr	nr	10
1200	19.02	0.013	16.76	1040	nr	nr	10
1320	19.03	0.015	18.40	1120	nr	nr	10
1385	19.06	0.014	19.29	1120	nr	nr	10
1440	nr	0.014	20.07	1080	118	0.12	10
1500	nr	0.015	20.95	1160	nr	nr	10
1625	19.10	0.014	22.65	1180	nr	nr	10
1680	19.25	0.014	23.41	1100	123	0.13	10
2160	19.41	0.014	30.08	1350	138	0.16	10
2340	nr	0.014	32.60	nr	203	0.73	10
2520	nr	0.014	35.12	nr	228	1.08	10
2885	19.40	0.014	40.13	1360	nr	nr	10
3000	nr	0.014	41.72	1480	nr	nr	10
3060	19.43	0.015	42.60	1480	nr	nr	10
3120	nr	0.013	43.37	1460	nr	nr	10
3180	nr	0.014	44.20	1420	nr	nr	10
3240	nr	0.014	45.03	1420	256	2.6	10

Appendix D: Injection and Recovery Volumes

Table D.10: Trial 5 fresh water recovery (cont'd)

Elapsed Time t_p (minutes)	Depth to Water (m)	Recovery Rate Q_p (m ³ /min)	Recovery Volume V_p (m ³)	Electrical Conductivity EC_p (10°C) (μS/cm)	Calcium Ca_p (mg/L)	Iron Fe_p (mg/L)	Temperature (°C)
3545	nr	0.014	49.24	1510	nr	nr	10
3605	nr	0.014	50.09	1520	244	0.21	10
3790	nr	0.014	52.63	1620	nr	nr	10
3960	nr	0.014	55.01	nr	308	4.6	10
4080	nr	0.014	56.63	1620	nr	nr	10
4260	nr	0.014	59.10	1800	nr	nr	10
4380	nr	0.014	60.74	1850	nr	nr	10
4615	nr	0.014	63.96	1850	nr	nr	10
4680	nr	0.014	64.87	nr	338	8.0	10
4695	nr	0.014	65.04	1750	nr	nr	10
5040	nr	0.014	69.87	1800	334	13.5	10
5340	nr	0.014	74.07	1800	nr	nr	10
5400	nr	0.014	74.91	nr	374	9.5	10
6005	nr	0.014	83.38	1980	nr	nr	10
6120	nr	0.015	85.11	1890	380	13.9	10
6185	nr	0.014	86.02	1850	nr	nr	10
6285	nr	0.015	87.52	1850	nr	nr	10
6845	nr	0.014	95.36	1900	nr	nr	10

Appendix D: Injection and Recovery Volumes

Table D.10: Trial 5 fresh water recovery (con't)

Elapsed Time t_p (minutes)	Recovery Volume Ratio Ψ	Electrical Conductivity Ratio ECR	Calcium Ratio Ca_r	Iron Ratio Fe_r
120	0.016	0.16	nr	nr
180	0.02	nr	0.08	0.01
240	0.03	0.19	nr	nr
360	0.04	0.17	0.8	0.00
420	0.05	0.16	nr	nr
480	0.06	0.16	nr	nr
600	0.07	0.17	nr	nr
660	0.08	0.17	nr	nr
720	0.09	nr	0.10	0.00
1080	0.13	nr	0.12	0.00
1095	0.14	0.19	nr	nr
1200	0.15	0.19	nr	nr
1320	0.16	0.24	nr	nr
1385	0.17	0.24	nr	nr
1440	0.18	0.21	0.11	0.00
1500	0.19	0.26	nr	nr
1625	0.20	0.28	nr	nr
1680	0.21	0.23	0.13	0.00
2160	0.27	0.39	0.17	0.00
2340	0.28	nr	0.36	0.04
2520	0.31	nr	0.43	0.06
2885	0.36	0.39	nr	nr
3000	0.37	0.47	nr	nr
3060	0.38	0.47	nr	nr
3120	0.38	0.46	nr	nr
3180	0.39	0.43	nr	nr
3240	0.40	0.43	0.51	0.15

Appendix D: Injection and Recovery Volumes

Table D.10: Trial 5 fresh water recovery (con't)

Elapsed Time tp (minutes)	Recovery Volume Ratio V	Electrical Conductivity Ratio ECR	Calcium Ratio Car	Iron Ratio Fer
3545	0.44	0.49	nr	nr
3605	0.44	0.50	0.48	0.00
3790	0.47	0.56	nr	nr
3960	0.49	nr	0.66	0.0.28
4080	0.50	0.56	nr	nr
4260	0.52	0.68	nr	nr
4380	0.54	0.71	nr	nr
4615	0.57	0.71	nr	nr
4680	0.58	nr	0.75	0.49
4695	0.58	0.65	nr	nr
5040	0.62	0.68	0.73	0.84
5340	0.66	0.68	nr	nr
5400	0.66	nr	0.85	0.59
6005	0.74	0.79	nr	nr
6120	0.75	0.74	0.87	0.87
6185	0.76	0.71	nr	nr
6285	0.78	0.71	nr	nr
6845	0.85	0.74	nr	nr

APPENDIX E

Laboratory Tracer Study Data

Appendix E: Laboratory Tracer Study Data

Table E.1: Summary of Laboratory Tracer Study

Time (minutes)	Tilting Angle (degrees from vertical well screen)			
	Test 1	Test 2	Test 3	Test 4
5	7°	17°	n/a	39°
10	11°	25°	36°	40°
20	43°	48°	53°	n/a
30	58°	57°	65°	40°
40	n/a	n/a	69°	n/a
50	n/a	n/a	73°	n/a
60	70°	64°	81°	47°
90	73°	n/a	82°	n/a
720	90°	85°	n/a	85°

Notes: $V_i = 0.75 \text{ L}$ $V_i = 1.3 \text{ L}$ $V_i = 0.75 \text{ L}$ $V_i = 0.75 \text{ L}$
 $C_{gw} = 2000 \text{ mg/L}$ $C_{gw} = 2000 \text{ mg/L}$ $C_{gw} = 4000 \text{ mg/L}$ $C_{gw} = 2000 \text{ mg/L}$

APPENDIX F

Groundwater Flow Model

```
DECLARE SUB INFORMATION ()
DECLARE SUB FILEOUTPUT ()
```

```
COMMON SHARED GE, EL, TE, BO, TRANS, SC, RW, PR, ALF, DIFMOLM, TEMPS, TEMPF
COMMON SHARED TDSS, TDSF, QDESIGN, QR1GM, TS, VOLINJ, TLIFT, FILENAMES
COMMON SHARED J$, KK$, L$, NMS$, YMD$, FI$, LO$, PR$, RA(), RCFT(), TILIFT
COMMON SHARED VISCP1, VISCP2, VISCP, DENS1, DENS2, DSDf, NO(), VVV, WQ
COMMON SHARED LS$, NU$, SP$, HFT, N5U$, J12$, SPP$, SSP$, QREC, AWQ, VOUT
```

```
DEMO = FALSE: 'FOR DEMO ALTER THIS VARIABLE TO TRUE
```

```
'*****
'A program which calculates the freshwater/salt interface &
'piezometric head in a well which is being recharged artificial
'by injection.
'*****
```

```
10 SCREEN 0: CLS : SCREEN 0, 1: WIDTH 80: CLEAR
20 SCREEN 0: CLS : LOCATE 2, 4: PRINT "*****"
30 LOCATE 3, 4: PRINT " "
40 LOCATE 4, 4: PRINT " STEP 1 ESTIMATION OF FRESH WATER "
50 LOCATE 5, 4: PRINT " FRONT WHEN WATER IS INJECTED "
60 LOCATE 6, 4: PRINT " INTO A CONFINED AQUIFER AT A "
70 LOCATE 7, 4: PRINT " CONSTANT RATE "
80 LOCATE 8, 4: PRINT " "
90 LOCATE 9, 4: PRINT "*****"
100 '
110 'LOCATE 11,4:PRINT"press 'enter' to continue"
120 'R$=INKEY$: IF LEN(R$)=0 THEN 120 ELSE R%=ASC(R$)
130 'IF R%=13 THEN 150 ELSE 120
140 '
150 DIM RA(1000), RR(100), D(100), OL(100), T(100), H(100)
160 DIM A(100), B(100), C(100), E(100), U(100), V(100)
170 DIM X(100), Y(100), AA(100), RCFT(4), RE(100)
180 DIM R(300), YL(300), XL(300), XR(300), NO(3)
190 '
200 WL = 0: RJ = 0: INJ = 0: IN = 0: TI = 0: IC = 0: BOB = 0: PAT = 0
210 PAST = 0: PIEZ = 0: PEP = 0: SU = .1: RE = 0: JET = 0
214 PR = .4: 'POROSITY=0.4
215 DIFMOLM = 1E-10: 'coefficient of molecular diffusion ((m2)/s)
216 ALF = .01: ALFMM = 10: 'longitudinal dispersivity coefficient (mm)
217 TILIFT = .3: 'interval length for during injection (m)
220 LOCATE 15, 4: PRINT "*****"
230 LOCATE 16, 4: PRINT "YOU MAY INPUT PARAMETERS TO RUN THE PROGRAM"
240 LOCATE 17, 4: PRINT "OR ALLOW THE PROGRAM TO RUN ON DEFAULT VALUES"
260 LOCATE 18, 4: PRINT "*****"
270 LOCATE 21, 4: PRINT "press 'enter' to continue"
271 R$ = INKEY$: IF LEN(R$) = 0 THEN 271 ELSE R% = ASC(R$)
272 IF R% = 13 THEN 273 ELSE 271
273 'FIELD TEST DATA
274 CLS : NM$ = "SPECTRUM 1989": FI$ = "1989-01"
275 YMD$ = "1989-01-13": PR$ = "G/W RECHARGE": LO$ = "ENGINEERING BLDG"
276 QDESIGN = .5
277 TEMPS = 10: TEMPF = 5: TDSS = 400: TDSF = 2000
278 GE = 300: EL = 280: TE = 270: BO = 265
279 RW = .025: TS = 10: QR1GM = .2: TRANS = .00005: SC = .05
281 '*****
290 ' *
```

```

300 CALL INFORMATION: 'input subroutine  *
310 '*'
320 '*****
400 'TRANS = .00005: 'm/s
410 'SC = .005: 'STORATIVITY=0.005
420 CLS : SCREEN 0, 1: WIDTH 80
430 '
440 '
450 '
460 '
470 '
480 '
490 TP = EL - TE: BA = EL - BO: HFT = ABS(TE - BO)
500 'viscp= Pa.s :dens= mg/l
510 VISCP1 = (1.7762 - .054 * TEMPS + .0008 * TEMPS * TEMPS) * .001
520 VISCP2 = (1.7762 - .054 * TEMPF + .0008 * TEMPF * TEMPF) * .001
530 '
540 DENS1 = .9998753 + 1.211E-06 * TDSS - 1.409E-11 * TDSS * TDSS
550 DENS2 = .9998753 + 1.211E-06 * TDSF - 1.409E-11 * TDSF * TDSF
560 '
570 TSOLD = TS: 'remember old time
580 RMAX = 2 * SQR(QR1GM * 86.4 * TS / (3.142 * PR * HFT)): 'Meters
590 'RMAX = calculated radius for drawing front and horizontal scales
600 '
610 '*****
620 '*'
630 GOSUB 5710: 'calculate horizontal scale *
640 GOSUB 6080: 'calculate vertical scale *
650 '*'
660 '*****
670 '
680 IF RMAX > 2000 THEN RM = RMAX ELSE RM = 2000: 'max radius for piezometric h
690 FLING1 = QR1GM * 86.4 * TS: 'volume injected m3=(L/s)*86400(s/day)*1m3/1000
700 DENDF = DENS1 - DENS2: 'density difference
710 DSDF = ABS(DENS1 - DENS2): ' density difference
720 IF DSDF = 0 THEN DSDF = .00001: 'cannot have a divide by zero
730 VISCP = (VISCP1 + VISCP2) / 2: 'mean viscosity of injected and native fluid
740 TINCFT = TILIFT * .1: 'increment by which TILIFT is increased if mixed
750 'zone intersects well during calculations for first
760 'interval. (m).
770 RINCFT = TILIFT * .1: 'length of increment for mixed zone lengths. (m)

      OPEN "FRONT.DAT" FOR OUTPUT AS #1
      OPEN "PIEZO.DAT" FOR OUTPUT AS #2

800 '
810 'INITIALIZATION OF RADIUS VALUES
820 '-----
830 ' for estimating piezometric head values at selected radii

840 FOR N = 1 TO 100
850   AN = (1 / 6) * (N - 2): RA(N) = RW * 10 ^ AN
860   IF RM - RA(N) > 0 THEN RR(N) = RA(N) * RA(N): GOTO 880
870   RA(N) = RM: RR(N) = RM * RM: NM = N: NN = N - 1: GOTO 890
880 NEXT
890 DA = .383765: D2 = DA * DA
900 FOR N = 1 TO NM
910   Y(N) = 0: RE(N) = RE: D(N) = WL: OL(N) = WL
920 NEXT
930 DM = .9 * BA + .1 * TP

```

```

940 IF INJ = 100 OR INJ = 101 THEN 1030
950 NO(1) = 6: NO(2) = 12: NO(3) = 18: '3 radii values
960 IF PEP = 100 THEN 1030
970 '*****
980 '*'
990 'gosub 5480: 'pick three radius values
1000 '*'
1010 '*****
1020 '
1030 QP = -(QR1GM * 86.4): QA = .5 * QP / (3.142 * DA)
1040 '
1050 '*****
1060 '*'
1070 GOSUB 6290: 'draw diagram and scales
1080 '*'
1090 '*****
1100 GOTO 1160
1110 TILIFT = TILIFT + TINCFT
1120 GOTO 1350
1130 '
1140 'CONSTANTS AND CONVERSION FACTORS(FIELD UNITS TO C.G.S. UNITS)
1150 '-----
1160 VOLINJ = TS * QR1GM * 86.4: 'm3=days*1/s*((s/day)/(1/m3))
1170 ALF = ALFMM / 10: 'mm/cm
1180 DIFMOL = DIFMOLM * .0001: '(sq cm/sec)/(sq m/sec)
1190 PE = (TRANS / HFT) * 86400!: '((m2/sec)/m)*(sec/day)
1200 CFFTCM = 100: '(cm/m)
1210 CFMSCM = (VISCP2 / .001) / (DENS2 * .981 * 3600 * 24): '((sqcm/(m/day))
1220 CFGLCC = 1000000#: '(cm3/m3)
1230 CGMCCS = 1000: '((L/sec)*(1000)=cc/sec
1240 CFCPP = 10: '(poise/Pa.s)
1250 RINC = RINCFT * CFFTCM: '(cm)
1260 H = HFT * CFFTCM: '(cm)
1270 PPP = 3.1416 * PR * H: '(cm)
1280 PPP1 = 2 * PPP: '(cm)
1290 PLY = (PE * CFMSCM): '(cm2)
1300 FLINJ1 = FLING1 * CFGLCC: '(cc)
1310 QR1 = QR1GM * CGMCCS: '(cc/sec)
1320 VIS = VISCP * CFCPP: '(poise)
1330 DM1 = (PLY * 981 * DSDF) / (PR * VIS * H): '(dimensionless)
1340 DM2A = VIS ^ .6667 / (DSDF ^ 1.6667 * 981 ^ .3333): '(dimensionless)
1350 TILI = TILIFT * CFFTCM: '(cm)
1360 R4 = TILI / 2: '(cm)
1370 '
1380 'CALCULATIONS FOR INJECTION OF FLUID
1390 '-----
1400 '
1410 'CALCULATION OF MIXED ZONE DUE TO DIFFUSION AND DISPERSION
1420 '
1430 I = 1
1440 TRT = 0
1450 R(I) = TILI
1460 R5 = R(I) - R4
1470 R5SQ = R5 * R5
1480 R1 = R5 - RINC
1490 T1 = PPP * R5SQ / QR1
1500 DT = (PPP * R(I) * R(I) / QR1) / 86400!
1510 IF RJ = 7 THEN 1570 ELSE 1520: 'draw last cycle
1520 IF DT > TS THEN 1525 ELSE 1570
1525 CLS : SCREEN 0, 1: WIDTH 80

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1530 LOCATE 2, 4: PRINT "* NOTE - THE INJECTION PERIOD IS TOO SHORT"
1531 LOCATE 3, 4: PRINT "*"          FOR THE CONDITIONS YOU INPUT."
1532 LOCATE 4, 4: PRINT "*"          SORRY.  TRY AGAIN."
1540 CLOSE : CLS : INJ = 101: SCREEN 0, 1: WIDTH 80: GOTO 300
1550 '*****
1560 '*'
1570 GOSUB 4250: 'calculate the piezometric head '*'
1580 '*'
1590 '*****
1600 QI1 = QR1 / PPP1
1610 DNOMI1 = 2 * SQR(1.333 * ALF * (2 * QI1 * T1) ^ 1.5 + DIFMOL * (2 * QI1 * T1)
1620 XX = (R5SQ - R1 * R1) / DNOMI1
1630 '*****
1640 '*'
1650 GOSUB 3510: 'calculate erfc '*'
1660 '*'
1670 '*****
1680 '
1690 C11 = ERFCXX / 2
1700 IF (C11 - .5) > 0 THEN 1790
1710 IF (C11 - .03) > .0 THEN 1740
1720 R2 = R1
1730 GOTO 1770
1740 R1 = R1 - RINC
1750 IF (R1) > 0 THEN 1620
1760 IF (R1) <= 0 THEN 1110
1770 R1 = R5 + RINC
1780 GOTO 1620
1790 IF (C11 - .97) >= 0 THEN 1820
1800 R1 = R1 + RINC
1810 GOTO 1620
1820 R3 = R1 - R2
1830 '
1840 'CALCULATION OF INTERFACE PROJECTION DUE TO GRAVITY SEGREGATION
1850 '
1860 IF (I - 1) > 0 THEN 2000
1870 DG = DSDF / R3: DM2 = DM2A * DG
1880 T11 = PPP * R(I) ^ 2 / QR1
1890 TRT = TRT + T11
1900 X = DM1 * T11 * DM2 ^ .5
1910 IF (X - .1) > 0 THEN 1940
1920 YL(I) = 20 * X
1930 GOTO 1980
1940 IF (X - 1) >= 0 THEN 1970
1950 YL(I) = .7958 + 12.5238 * X - 4.8196 * X ^ 2
1960 GOTO 1980
1970 YL(I) = 6.5 + 2 * X
1980 XL(I) = YL(I) * H
1990 GOTO 2250
2000 DG = DSDF / R3: DM2 = DM2A * DG
2010 T11 = PPP * ABS(R(I) ^ 2 - R(I - 1) ^ 2) / QR1
2020 TRT = TRT + T11
2030 IF (YL(I - 1) - 2) > 0 THEN 2060
2040 X = YL(I - 1) / 20
2050 GOTO 2100
2060 IF (YL(I - 1) - 8.5) >= 0 THEN 2090
2070 X = 1.2993 - SQR(172.1873 - 19.2784 * YL(I - 1)) / 9.6392
2080 GOTO 2100
2090 X = (YL(I - 1) - 6.5) / 2
2100 TSP = X / (DM1 * DM2 ^ .5)

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2110 TT = T11 + TSP
2120 X = DM1 * TT * DM2 ^ .5
2130 IF (X - .1) > 0 THEN 2160
2140 YL(I) = 20 * X
2150 GOTO 2200
2160 IF (X - 1) >= 0 THEN 2190
2170 YL(I) = .7958 + 12.5238 * X - 4.8196 * X ^ 2
2180 GOTO 2200
2190 YL(I) = 6.5 + 2 * X
2200 XL(I) = YL(I) * H
2210 GOTO 2750
2220 '
2230 'APPROXIMATION TO RADIAL GEOMETRY
2240 '
2250 RU50 = R(I) + XL(I) / 2
2260 RL50 = R(I) - XL(I) / 2
2270 IF (RL50) >= 0 THEN 2790
2280 '
2290 LOCATE 24, 2: PRINT "INJECTION RATE TOO SMALL ";
2300 PEP = 100
2310 IF JET = 100 THEN 2630
2320 IF BOB = 100 THEN 2720
2330 CLOSE : JAM = 100: QROLD = QRIGM
2340 IF PAT = 100 THEN 2620 ELSE 2350
2350 LOCATE 25, 2: PRINT "PRESS ENTER TO CONTINUE ";
2360 K$ = INKEY$: IF LEN(K$) = 0 THEN 2360 ELSE K% = ASC(K$)
2370 IF K% = 13 THEN 2620 ELSE 2360
2380 LOCATE 25, 2: PRINT " ";
2390 IF PAT = 100 THEN 2620 ELSE 2400
2400 LOCATE 24, 2: PRINT "DO YOU WANT A PRINT OUT (Y/N)";
2410 R$ = INKEY$: IF LEN(R$) = 0 THEN 2410
2420 IF R$ = "y" OR R$ = "Y" THEN 2430 ELSE 2630
2430 LOCATE 25, 2: PRINT "PRESS ENTER TO CONTINUE ";
2440 R$ = INKEY$: IF LEN(R$) = 0 THEN 2440 ELSE R% = ASC(R$)
2450 IF R% = 13 THEN 2460 ELSE 2440
2460 LOCATE 25, 2: PRINT " ";
2470 LOCATE 24, 2: PRINT "IS THE PRINTER READY (Y/N) ";
2480 R$ = INKEY$: IF LEN(R$) = 0 THEN 2460
2490 IF R$ = "y" OR R$ = "Y" THEN 2500 ELSE 2470
2500 JAM = 100: GOSUB 7640: 'send output to printer
2510 'IF DAIS=2 THEN 2520 ELSE 2570
2520 'PAT=100:LPRINT :LPRINT TAB(12)"NOTE":LPRINT
2530 'LPRINT TAB(12)"INJECTION RATE TOO SMALL ";
2540 'LPRINT STRING$(2,CHR$(10))
2550 'LPRINT TAB(10)"UNIVERSITY OF SASKATCHEWAN"
2560 'LPRINT CHR$(12):GOTO 2620
2570 PAT = 100: LPRINT : LPRINT CHR$(27) + "G"; TAB(12); "NOTE"; CHR$(27) + "H"
2580 LPRINT : LPRINT CHR$(27) + "G"; TAB(12); "INJECTION RATE TOO SMALL ";
2590 LPRINT STRING$(4, CHR$(10))
2600 LPRINT CHR$(14) + CHR$(27) + "E"; TAB(7); "UNIVERSITY OF SASKATCHEWAN"; CH
2610 LPRINT CHR$(12)
2620 LOCATE 24, 2: PRINT " ";
2630 CLOSE : LOCATE 24, 2: PRINT "DO YOU WANT TO CONTINUE (Y/N)";
2640 R$ = INKEY$: IF LEN(R$) = 0 THEN 2640
2650 IF R$ = "y" OR R$ = "Y" THEN 2660 ELSE 30390
2660 LOCATE 25, 2: PRINT " ";
2670 LOCATE 24, 2: PRINT " INPUT A NEW INJECTION RATE (Y/N)";
2680 R$ = INKEY$: IF LEN(R$) = 0 THEN 2680
2690 IF R$ = "y" OR R$ = "Y" THEN 2700 ELSE 2720
2700 LOCATE 24, 2: INPUT ; "INPUT NEW INJECTION RATE (L/S) "; QRIGM

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2710 TS = TSOLD: GOTO 580
2720 CLOSE : PAT = 100: LOCATE 24, 2: PRINT "INJECTION RATE INCREASING ";
2730 QRIGM = QRIGM + .0012
2740 TS = TSOLD: BOB = 100: GOTO 580
2750 A1 = 3.142 * ((R(I - 1) + XR(I - 1) / 2) ^ 2 - R(I - 1) ^ 2)
2760 B1 = 3.142 * (R(I - 1) ^ 2 - (R(I - 1) - XR(I - 1) / 2) ^ 2)
2770 RU50 = SQR((3.142 * R(I) ^ 2 + A1) / 3.142) + (XL(I) - XL(I - 1)) / 2
2780 RL50 = SQR((3.142 * R(I) ^ 2 - B1) / 3.142) - (XL(I) - XL(I - 1)) / 2
2790 XR(I) = RU50 - RL50: '50% horizontal projection
2800 '*****
2810 '*'
2820 GOSUB 3850: 'draw front resulting from injection
2830 '*'
2840 '*****
2850 I = I + 1: LOCATE 24, 30: PRINT "I="; I - 1;
2860 R(I) = R(I - 1) + TILI
2870 IF RJ = 7 THEN 2900
2880 IF R(I) > SQR(FLINJ1 / PPP) THEN R(I) = SQR(FLINJ1 / PPP): RJ = 7
2890 GOTO 1460
2900 '
2910 'CALCULATION OF LEADING AND LAGGING EDGES OF MIXED ZONE
2920 '
2930 'POSITION OF FRONT AT END OF PUMPING"
2940 '
2950 ICOUNT = 0
2960 IF (DENDF) > 0 THEN 2990
2970 'RADII ON FLOOR OF AQUIFER
2980 GOTO 3060
2990 'RADII ON FLOOR OF AQUIFER
3000 GOTO 3090
3010 IF (DENDF) > 0 THEN 3040
3020 'RADII ON ROOF OF AQUIFER
3030 GOTO 3090
3040 'RADII ON ROOF OF AQUIFER
3050 GOTO 3060
3060 R50SQ = RL50 * RL50
3070 RCHECK = RL50
3080 GOTO 3110
3090 R50SQ = RU50 * RU50
3100 RCHECK = RU50
3110 QSI = R50SQ / (2! * TRT)
3120 SDENOM = 2! * SQR(1.33 * ALF * (R50SQ) ^ 1.5 + DIFMOL * (R50SQ) ^ 2 / QSI)
3130 RC = RCHECK - RINC
3140 XX = (R50SQ - RC * RC) / SDENOM
3150 '*****
3160 '*'
3170 GOSUB 3510: 'calculate erfc(xx)
3180 '*'
3190 '*****
3200 C11 = ERFCXX / 2!
3210 IF (C11 - .5) > 0 THEN 3330
3220 IF (C11 - .03) > 0 THEN 3270
3230 RCFT = RC / CFFTCM
3240 PRINT #1, USING "####.##"; RCFT
3250 'LAGGING EDGE OF MIXED ZONE
3260 GOTO 3310
3270 RC = RC - RINC
3280 IF (RC) > 0 THEN 3140
3290 RCFT = 0
3300 GOTO 3250

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3310 RC = RCHECK + RINC
3320 GOTO 3140
3330 IF (C11 - .97) >= 0 THEN 3360
3340 RC = RC + RINC
3350 GOTO 3140
3360 RCFT = RC / CFFTCM
3370 PRINT #1, USING "####.##"; RCFT
3380 'LEADING EDGE OF MIXED ZONE
3390 IF (ICOUNT - 1) >= 0 THEN 3420
3400 ICOUNT = ICOUNT + 1
3410 GOTO 3010
3420 CLOSE : 'close files before printout begins
3430 '*****
3440 '*'
3450 GOTO 7410: 'START PRINT OUT PORTION OF PROGRAM *
3460 '*'
3470 '*****
3480 '
3490 '*****
3500 '*'
3510 '* Gaussian error function *
3520 '* and complement *
3530 '*****
3540 X = XX: X1 = X: IF X1 = 0 THEN X1 = 1
3550 A = ABS(X) / X1: X = ABS(X)
3560 GOSUB 3590
3570 ERFCXX = C9: 'complementary function
3580 RETURN
3590 'Gaussian funtion by infinite series
3600 P8 = SQR(3.14159)
3610 T1 = .00001
3620 X2 = X * X
3630 IF (X > 1.5) THEN 3730
3640 S3 = X: T4 = X: I% = 0
3650 'REM begin loop
3660 IP% = IP% + 1: H3 = S3
3670 T4 = 2 * T4 * X2 / (1 + 2 * IP%): S3 = T4 + H3
3680 IF (T4 > T1 * S3) THEN 3660
3690 E9 = 2 * S3 * EXP(-X2) / P8
3700 C9 = 1 - E9
3710 IF A < 0 THEN C9 = 1 + E9
3720 RETURN
3730 REM complementary error function
3740 T5 = 12: V = .5 / X2: U = 1 + V * (T5 + 1)
3750 FOR J% = T5 TO 1 STEP -1
3760 S3 = 1 + J% * V / U: U = S3
3770 NEXT J%
3780 C9 = EXP(-X2) / (X * S3 * P8)
3790 E9 = 1 - (A * C9)
3800 IF A < 0 THEN C9 = 1 + E9
3810 RETURN
3820 END
3830 '*****
3840 '*'
3850 '* draw the front resulting from injection *
3860 '*'
3870 '*****
3880 DRU50 = INT(RU50 / RMAX): 'upper 50 % line
3890 DRL50 = INT(RL50 / RMAX): 'lower 50 % line
3900 IF DRU50 <= 0 THEN DRU50 = 0

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3910 IF DRL50 <= 0 THEN DRL50 = 0
3920 IF DRU50 = 0 THEN 3930 ELSE 3960
3930 LINE (183, Y2 + 1)-(183, Y3 - 1), 2
3940 LINE (171, Y2 + 1)-(171, Y3 - 1), 2
3950 GOTO 4210
3960 IF DRU50 <= 99 THEN 3970 ELSE 4080
3970 LINE (183, Y2 + 1)-(183, Y3 - 1), 2
3980 LINE (171, Y2 + 1)-(171, Y3 - 1), 2
3990 LINE (183, Y2 + 1)-(183 + DRU50, Y2 + 1), 2
4000 LINE (171, Y2 + 1)-(171 - DRU50, Y2 + 1), 2
4010 LINE (183 + DRU50, Y2 + 1)-(183 + DRL50, Y3 - 1), 2
4020 LINE (171 - DRU50, Y2 + 1)-(171 - DRL50, Y3 - 1), 2
4030 LINE (183 + DRL50, Y3 - 1)-(183, Y3 - 1), 2
4040 LINE (171 - DRL50, Y3 - 1)-(171, Y3 - 1), 2
4050 LINE (183, Y3 - 1)-(183, Y2 + 1), 2
4060 LINE (171, Y3 - 1)-(171, Y2 + 1), 2
4070 GOTO 4210: 'goto return
4080 AD = DRU50: DRU50 = 99
4090 CD = ABS(AD - 99): AE = ABS(Y3 - Y2)
4100 BD = ABS(AD - DRL50): CH = INT(AE * CD / BD)
4110 LINE (183, Y2 + 1)-(183 + 99, Y2 + 1), 2
4120 LINE (171, Y2 + 1)-(171 - 99, Y2 + 1), 2
4130 LINE (183 + 99, Y2 + 1)-(183 + 99, Y2 + CH), 2
4140 LINE (171 - 99, Y2 + 1)-(171 - 99, Y2 + CH), 2
4150 LINE (183 + 99, Y2 + CH)-(183 + DRL50, Y3 - 1), 2
4160 LINE (171 - 99, Y2 + CH)-(171 - DRL50, Y3 - 1), 2
4170 LINE (183 + DRL50, Y3 - 1)-(183, Y3 - 1), 2
4180 LINE (171 - DRL50, Y3 - 1)-(171, Y3 - 1), 2
4190 LINE (183, Y3 - 1)-(183, Y2 + 1), 2
4200 LINE (171, Y3 - 1)-(171, Y2 + 1), 2
4210 RETURN
4220 END
4230 '*****
4240 '*'
4250 '* SUBROUTINE TO CALCULATE THE PIEZOMETRIC HEAD AT A GIVEN TIME *
4260 '*'
4270 '*****
4280 IC = IC + 1
4290 TI = DT
4300 FOR N = 1 TO NM
4310 SD = BA - .5 * (D(N) + D(N + 1)): ST = SU
4320 IF SD < (BA - TP) THEN 4340
4330 SD = BA - TP: ST = SC
4340 H(N) = D2 / (SD * PE)
4350 T(N) = DT / (ST * RR(N))
4360 NEXT
4370 LOCATE 24, 2: PRINT USING "TIME ####.### DAYS"; DT;
4380 H(1) = .0001 * H(1)
4390 T(1) = 2 * DT * DA / RR(2): T(2) = 2 * T(2)
4400 H(NM - 1) = (LOG(RA(NM)) - LOG(RA(NM - 1))) * (LOG(RA(NM)) - LOG(RA(NM - 1)))
4410 H(NM) = 1E+10
4420 T(NN) = 2 * DT * DA / ((RA(NM) - RA(NN - 1)) * ST * RA(NN))
4430 T(NM) = DT * DA / ((RA(NM) - RA(NN)) * ST * RA(NM))
4440 IF JF = 1 THEN T(NM) = 1E-10 * T(NM)
4450 C(1) = 1 / H(1): B(1) = C(1) + 1 / T(1): E(1) = OL(1) / T(1) + QA
4460 FOR N = 2 TO NN
4470 A(N) = 1 / H(N - 1): C(N) = 1 / H(N)
4480 B(N) = A(N) + C(N) + 1 / T(N)
4490 E(N) = OL(N) / T(N) - RR(N) * RE(N)
4500 NEXT

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4510 A(NM) = 1 / H(NN): B(NM) = A(NM) + .5 / T(NM)
4520 E(NM) = .5 * OL(NM) / T(NM) - .5 * RR(NM) * RE(NM)
4530 U(1) = B(1): V(1) = E(1)
4540 FOR N = 2 TO NM
4550   U(N) = B(N) - (A(N) * C(N - 1)) / U(N - 1)
4560   V(N) = E(N) + (A(N) * V(N - 1)) / U(N - 1)
4570 NEXT
4580 D(NM) = V(NM) / U(NM)
4590 FOR N2 = 1 TO NN
4600   N = NN - N2 + 1
4610   D(N) = (V(N) + C(N) * D(N + 1)) / U(N)
4620 NEXT
4630 IF (ABS(D(1)) + EL) < (GE) THEN 4670
4640 LOCATE 2, 1: PRINT "EXCESSIVE INJECTION";
4650 '*****
4660 '*'
4670 GOSUB 7070: 'DRAW PIEZOMETRIC HEAD LEVELS
4680 '*'
4690 '*****
4700 LINE (62, 30)-(62, 40), 3: LINE -(168, 40), 3: LINE -(168, 30), 3
4710 LINE (212, 30)-(212, 40): LINE -(319, 40), 3
4720 'LOCATE 5,28:PRINT USING"RH=####.## m";ABS(D(1))
4730 LOCATE 5, 9: PRINT USING "Q=####^L/S"; QR1GM
4740 PRINT #2, USING "####^L/S"; TI; ABS(D(1)); ABS(D(NO(1))); ABS(D(NO(2)));
4750 FOR N = 1 TO NM: OL(N) = D(N): NEXT
4760 RETURN
4770 END
4780 '*****
4790 CALL INFORMATION
4800 '*****

5230 CLS : PRINT TAB(10); "OPERATING CONDITIONS": PRINT
5239 LOCATE 2, 37: PRINT TILIFT
5240 LOCATE 2, 4: INPUT "COMPUTATIONAL INTERVAL LENGTH (m)", A$
5245 IF A$ <> "" THEN TILIFT = VAL(A$): A$ = ""

5250 'check size of interval length
5260 'to estimate number of iterations (I=?)
5270 HFT = ABS(TE - BO)
5280 FLN = QR1GM * 86.4 * TS
5290 FLNJ1 = FLN * 1000000!
5300 PPPP = 3.1416 * PR * HFT * 100
5310 RNJ = SQR(FLNJ1 / PPPP)
5320 TIL = TILIFT * 100
5330 NTNT = (RNJ / TIL)
5340 IF NTNT > 175 THEN 5350 ELSE 5440
5350 LOCATE 10, 2: PRINT "INCREASE INTERVAL LENGTH": CLS : GOTO 5240
5360 '
5370 '
5380 '
5390 '
5400 '
5410 '
5420 '
5430 '
5440 RETURN
5450 END
5460 '*****
5470 '*'
5480 '* PICK NODE NUMBER AND RADIUS FOR PRINTOUT *

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5490 '*
5500 '*****
5510 CLS : SCREEN 0, 1: WIDTH 80
5520 FOR N = 1 TO NM STEP 2
5530 PRINT USING "NO. ### RA= #####.##"; N; RA(N);
5540 IF (N + 1) > NM THEN 5550 ELSE PRINT USING " NO. ### RA= #####.##"; N
5550 NEXT
5560 FOR J = 1 TO 3
5570 LOCATE 18 + J, 2: PRINT " OBS. WELL #"; J; : INPUT "... NODE NUMBER "; N
5580 NEXT
5590 LOCATE 24, 2: PRINT " IS EVERYTHING OKAY SO FAR (Y/N) ";
5600 R$ = INKEY$: IF LEN(R$) = 0 THEN 5600
5610 IF R$ = "Y" OR R$ = "y" THEN 5670 ELSE 5620
5620 FOR J = 1 TO 3
5630 LOCATE 18 + J, 2: PRINT " ";
5640 NEXT
5650 LOCATE 24, 2: PRINT " ";
5660 GOTO 5560
5670 RETURN
5680 END
5690 '*****
5700 '*
5710 '* subroutine to calculate horizontal scale factor *
5720 '*
5730 '*****
5740 LOCATE 2, 1: PRINT " ";
5750 LOCATE 3, 1: PRINT " ";
5760 VALUE = 0
5770 IF RMAX < 1 THEN RMAX = 1: GOTO 5950
5780 IF (RMAX) < 10 THEN RMAX = CINT(RMAX + .5): GOTO 5950
5790 VALUE = 5
5800 IF RMAX < 100 THEN 5810 ELSE 5830
5810 VALUE = VALUE + 5
5820 IF RMAX > VALUE THEN 5810 ELSE RMAX = VALUE: GOTO 5950
5830 VALUE = 0
5840 IF RMAX < 1000 THEN 5850 ELSE 5870: GOTO 5950
5850 VALUE = VALUE + 100
5860 IF RMAX > VALUE THEN 5850 ELSE RMAX = VALUE: GOTO 5950
5870 VALUE = 0
5880 IF RMAX < 10000 THEN 5890 ELSE 5910
5890 VALUE = VALUE + 1000
5900 IF RMAX > VALUE THEN 5890 ELSE RMAX = VALUE: GOTO 5950
5910 LOCATE 23, 2: PRINT "injection radius too large"; : BEEP
5920 LOCATE 24, 2: PRINT "DO YOU WANT TO START OVER (Y/N)";
5930 A$ = INKEY$: IF LEN(A$) = 0 THEN 5930
5940 IF A$ = "Y" OR A$ = "y" THEN 20 ELSE END
5950 IF RMAX < 10 THEN 5960 ELSE 5970
5960 VL = .01: VAF = .1: GOTO 6020
5970 IF RMAX < 100 THEN 5980 ELSE 5990
5980 VL = .1: VAF = 1: GOTO 6020
5990 IF RMAX < 1000 THEN 6000 ELSE 6010
6000 VL = 1: VAF = 10: GOTO 6020
6010 VL = 10: VAF = 100
6020 DX = RMAX / 50: 'horizontal scaling factor
6030 DPMH = 100 / RMAX: 'dots per meter horizontal
6040 RETURN
6050 END
6060 '*****
6070 '*
6080 '* VERTICAL SCALING SUBROUTINE *

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6090 '*
6100 '*****
6110 HV = 5
6120 IF HV < GE THEN 6130 ELSE 6150
6130 HV = HV + 5
6140 GOTO 6120
6150 GELV = HV
6160 HVALUE = 5: MAXV = GELV - BO
6170 IF (MAXV) > HVALUE THEN 6180 ELSE 6200
6180 HVALUE = HVALUE + 5
6190 GOTO 6170
6200 MAXV = HVALUE: DPMV = 100 / (MAXV): 'dots per meter vertical
6210 Y1 = CINT(DPMV * (GELV - EL)) + 16 + 32: 'water level in well
6220 Y2 = CINT(DPMV * (GELV - TE)) + 16 + 32: 'top of aquifer
6230 Y3 = CINT(DPMV * (GELV - BO)) + 16 + 32: 'bottom of aquifer
6240 Y4 = CINT(DPMV * (GELV - GE)) + 16 + 32: 'ground surface
6250 RETURN
6260 END
6270 '*****
6280 '*
6290 '* draw the aquifer diagram *
6300 '*
6310 '*****
6320 SCREEN 1, 1: KEY OFF: CLS
6330 LINE (0, 30)-(319, 178), 3, B
6340 LINE (66, Y4)-(172, Y4), 3: 'draw surface
6350 LINE (182, Y4)-(288, Y4), 3
6360 FOR X = 72 TO 162 STEP 10
6370   PSET (X, Y4 + 1), 3: DRAW "G2"
6380   PSET (X + 120, Y4 + 1): DRAW "F2"
6390 NEXT
6400 LINE (172, Y4 - 12)-(172, Y3), 3: 'draw casing
6410 LINE (182, Y4)-(182, Y3), 3
6420 LINE (172, Y4 - 12)-(208, Y4 - 12), 3
6430 LINE -(208, Y4), 3
6440 LINE (66, Y2)-(172, Y2), 3: 'top of aquifer
6450 LINE (182, Y2)-(288, Y2), 3
6460 LINE (66, Y3)-(288, Y3): 'bottom of aquifer
6470 FOR X = 170 TO 68 STEP -6: 'draw initial water level
6480   LINE (X, Y1)-(X - 3, Y1), 2
6490   LINE (X + 116, Y1)-(X + 119, Y1), 2
6500 NEXT
6510 LINE (62, 120 + 32)-(292, 120 + 32), 2
6520 FOR IT = 72 TO 172 STEP 20
6530   PSET (IT, 120 + 32), 2: DRAW "C2;U2"
6540   PSET (IT + 110, 120 + 32), 2: DRAW "C2;U2"
6550 NEXT
6560 'put on horizontal scale
6570 PLX = 44: PRX = 296
6580 FOR ID = 5 TO 1 STEP -1
6590   HOR = CINT(ID * (RMAX / 50) / VL)
6600   LOCATE 2, 2: PRINT HOR
6610   GET (15, 7)-(31, 15), AA
6620   PLX = PLX + 20: PRX = PRX - 20
6630   PUT (PLX, 122 + 32), AA, PSET
6640   PUT (PRX, 122 + 32), AA, PSET
6650 NEXT
6660 PUT (15, 7), AA
6670 LOCATE 2, 2: PRINT 0: 'zero marker
6680 GET (15, 7)-(23, 15), AA

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6690 PUT (174, 122 + 32), AA, PSET
6700 PUT (15, 7), AA
6710 LOCATE 22, 14: PRINT VAF; "* radius (m)"
6720 'vertical scale
6730 LINE (62, 16 + 32)-(62, 119 + 32), 2
6740 LINE (292, 16 + 32)-(292, 119 + 32), 2
6750 FOR YV = 16 TO 116 STEP 10: '20
6760   LINE (62, YV + 32)-(64, YV + 32), 2
6770   LINE (292, YV + 32)-(290, YV + 32), 2
6780 NEXT
6790 VI = 24
6800 FOR VS = 5 TO 0 STEP -1
6810   ELV = INT(GELV - (5 - VS) * MAXV / 5)
6820   LOCATE 23, 2: PRINT ELV
6830   GET (15, 175)-(47, 183), AA
6840   VI = VI + 20
6850   PUT (26, VI), AA, PSET
6860 NEXT
6870 PUT (15, 175), AA
6880 LINE (0, 178)-(50, 178), 3
6890 RESTORE
6900 FOR YM = 6 TO 1 STEP -1
6910   READ A$
6920   LOCATE YM + 5 + 4, 2: PRINT A$
6930 NEXT
6940 DATA S,R,E,T,E,M
6950 FOR PMP = 174 TO 198 STEP 8: 'put pump on the diagram
6960   READ A$
6970   LOCATE 2, 2: PRINT A$
6980   GET (7, 7)-(15, 15), AA
6990   PUT (PMP, Y4 - 10), AA, PSET
7000 NEXT
7010   PUT (7, 7), AA
7020 DATA P,U,M,P
7030 RETURN
7040 END
7050 '*****
7060 '*'
7070 '* routine to draw piezometric head *
7080 '*'
7090 '*****
7100 IF PIEZ = 100 THEN 7370
7110 DEPTH = INT((GELV - EL + D(1)) * DPMV) + 16 + 32
7120 IF DEPTH > Y4 THEN 7130 ELSE 7300
7130 IF IC <= 1 THEN DEPTH1 = DEPTH
7140 LINE (173, DEPTH1)-(181, DEPTH1), 0
7150 LINE (173, DEPTH)-(181, DEPTH), 3
7160 PAINT (177, DEPTH + 1), 1, 3
7170 XLD = 171: XRD = 183: YOLD = DEPTH
7180 FOR IH = 2 TO NM
7190   HSC = INT(RA(IH) * 100 / RMAX)
7200   IF HSC > 99 THEN HSC = 99: GOTO 7210
7210   XRR = 183 + HSC
7220   XLL = 171 - HSC
7230   YRL = INT((GELV - EL + D(IH)) * DPMV) + 16 + 32
7240   LINE (XRD, YOLD)-(XRR, YRL), 1
7250   LINE (XLD, YOLD)-(XLL, YRL), 1
7260   XRD = XRR: XLD = XLL: YOLD = YRL
7270 NEXT
7280 DEPTH1 = DEPTH

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7290 GOTO 7360
7300 LINE (173, Y4)-(181, Y4), 3
7310 LINE (173, Y4)-(173, DEPTH1), 3
7320 LINE (173, DEPTH1)-(181, DEPTH1), 0
7330 LINE (181, Y4)-(181, DEPTH1), 3
7340 PAINT (177, Y4 + 1), 1, 3
7350 PIEZ = 100: 'excessive injection water exceeds ground surface
7360 PSET (282, Y1): DRAW "C2;H7;R12;G7": 'water surface marker
7370 RETURN
7380 END
7390 '*****
7400 '** **
7410 '** output routine **
7420 '** **
7430 '*****

7440 JAM = 0: CLOSE
7450 '
7460 '*
7470 OPEN "front.dat" FOR INPUT AS #1
7480 '
7490 COUNT = 0
7500 IF EOF(1) THEN CLOSE : GOTO 7560
7510 COUNT = COUNT + 1
7520 INPUT #1, L
7530 RCFT(COUNT) = L
7540 IF RCFT(COUNT) <= 0 THEN PAST = 100
7550 GOTO 7500
7560 IF COUNT <> 4 THEN PAST = 100
7570 'ON ERROR GOTO 10190
7580 OPEN "piezo.dat" FOR INPUT AS #2
7590 '
7600 SFILE$ = "pic.drw"
7610 LOCATE 2, 1: PRINT "
7620 LOCATE 24, 2: PRINT "
7630 DEF SEG = &HB800: BSAVE SFILE$, 0, &H4000
7640 J$ = SPACE$(10): J12$ = SPACE$(12): KK$ = SPACE$(5)
7650 SP$ = "\
7660 SSP$ = "\
7670 NU$ = "#####.##": N5U$ = "#####.####"
7680 LS$ = "\
7690 SPP$ = "\
7700 '
7710 CLOSE : IF JAM = 100 THEN 8950 ELSE 7730
7720 '
7730 'OPEN "piezo.dat" FOR INPUT AS #2
7740 OPEN "front.dat" FOR INPUT AS #1
7750 '

GOSUB 20220: ' CALLING RECOVERY FILEOUTPUT

7760 LOCATE 25, 2: PRINT "DO YOU WANT A PRINT OUT (Y/N) ";
7770 A$ = INKEY$: IF LEN(A$) = 0 THEN 7770
7780 IF A$ = "Y" OR A$ = "y" THEN 8320
7790 '
7800 LOCATE 25, 2: PRINT "PUT OUTPUT ON SCREEN (Y/N) ";
7810 R$ = INKEY$: IF LEN(R$) = 0 THEN 7810
7820 IF R$ = "Y" OR R$ = "y" THEN 7830 ELSE 10090
7830 SCREEN 0, 1: WIDTH 80

```


CALL FILEOUTPUT

OPEN "PIEZO.DAT" FOR INPUT AS #2

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7850 LOCATE 25,2:PRINT"PRESS ENTER TO CONTINUE      ";
7860 K$=INKEY$:IF LEN(K$)=0 THEN 7860 ELSE K%=ASC(K$)
7870 IF K%=13 THEN 7880 ELSE 7860
7880 CLS:PRINT USING J$+"\"      \"+LS$ ;"NAME      : ",NM$;
7890 PRINT USING KK$+"\"      \"+\"      \"+\"      \"+\" ;"DATE : ",YMD$
7900 PRINT USING J$+"\"      \"+LS$;"FILE #      : ",FI$
7910 PRINT USING J$+"\"      \"+LS$;"LOCATION : ",LO$
7920 PRINT USING J$+"\"      \"+LS$;"PROJECT : ",PR$
7930 PRINT: PRINT USING J$+J$+J$+LS$;"DATA"
7940      PRINT USING J$+J$+J$+LS$;"-----"
7950 PRINT USING J$+SP$;"POROUS MEDIUM"
7960 PRINT: PRINT USING J$+SP$+NU$;"GROUND ELEVATION (m A.S.L.)";GE
7970 PRINT USING J$+SP$+NU$;"WATER LEVEL ELEVATION (m A.S.L.)";EL
7980 PRINT USING J$+SP$+NU$;"TOP OF AQUIFER ELEVATION (m A.S.L.)";TE
7990 PRINT USING J$+SP$+NU$;"BOTTOM OF AQUIFER ELEVATION (m A.S.L.)";BO
8000 PRINT USING J$+SP$+NU$;"THICKNESS OF THE MEDIUM (m)",HFT
8010 PRINT USING J$+SP$+SPACE$(4)+"#.###^";"TRANSMISSIVITY (m2/s)";TRANS
8020 PRINT USING J$+SP$+SPACE$(4)+"#.###^";"STORAGE COEFFICIENT (confined)";S
C
8030 PRINT USING J$+SP$+NU$;"WELL RADIUS (m)";RW
8040 PRINT USING J$+SP$+NU$;"POROSITY (fraction)";PR
8050 PRINT USING J$+SP$+NU$;"LONGITTUDINAL DISPERSIVITY OF THE MEDIUM (mm)",ALFM
M
8060 PRINT USING J$+SP$+SPACE$(4)+"#.###^";"COEFFICIENT OF MOLECULAR DIFFUSIO
N (m2/s)",DIFMOLM
8070 'PRINT USING J$+SP$+SPACE$(4)+"#.###^";"DESIGNED PUMPING RATE OF WELL (L
/s)";QDESIGN
8080 LOCATE 24,2:PRINT"PRESS ENTER TO CONTINUE      ";
8090 K$=INKEY$:IF LEN(K$)=0 THEN 8090 ELSE K%=ASC(K$)
8100 IF K%=13 THEN 8110 ELSE 8090
8110 CLS: PRINT: PRINT USING J$+J$+J$+LS$;"DATA"
8120 PRINT USING J$+J$+J$+LS$;"-----"
8130 PRINT USING J$+SP$;"FLUID PROPERTIES":PRINT
8140 PRINT USING J$+SP$+NU$;"TEMPERATURE OF NATIVE WATER (C)";TEMPF
8150 PRINT USING J$+SP$+NU$;"TEMPERATURE OF INJECTION WATER (C)";TEMPS
8160 PRINT: PRINT USING J$+SP$+NU$;"TOTAL DISSOLVED SOLIDS OF THE SURFACE WATER
(mg/L)";TDSS
8170 PRINT USING J$+SP$+NU$;"TOTAL DISSOLVED SOLIDS OF THE NATIVE WATER (mg/L)";
TDSF
8180 PRINT: PRINT USING J$+SP$;"VISCOSITY OF THE FLUIDS (Pa.s)"
8190 PRINT USING J12$+SSP$+N5U$;"VISCOSITY OF THE INJECTED FLUID",VISCP1
8200 PRINT USING J12$+SSP$+N5U$;"VISCOSITY OF THE NATIVE FLUID",VISCP2
8210 PRINT USING J12$+SSP$+N5U$;"MEAN VISCOSITY OF THE TWO FLUIDS",VISCP
8220 PRINT: PRINT USING J$+SP$;"DENSITY OF THE FLUIDS (kg/m3)"
8230 PRINT USING J12$+SSP$+N5U$;"DENSITY OF THE INJECTED FLUID",DENS1
8240 PRINT USING J12$+SSP$+N5U$;"DENSITY OF THE NATIVE FLUID",DENS2
8250 PRINT USING J12$+SSP$+N5U$;"DENSITY DIFFERENCE BETWEEN THE FLUIDS",DSDF
8270 LOCATE 24, 2: PRINT "PRESS ENTER TO CONTINUE      ";
8280 K$ = INKEY$: IF LEN(K$) = 0 THEN 8280 ELSE K% = ASC(K$)
8290 IF K% = 13 THEN 8300 ELSE 8280
8300 CLS : PRINT USING J$ + SP$; "OPERATING CONDITIONS"
8310 PRINT USING J$ + SP$; "-----"
8320 PRINT USING J$ + SP$ + NU$; "DESIGNED PUMPING RATE OF WELL (L/s)"; QDESIGN
8330 PRINT USING J$ + SP$ + NU$; "INJECTION RATE (L/s)"; QRIGM
8340 PRINT USING J$ + SP$ + NU$; "INJECTION TIME (days)"; TS
8350 PRINT USING J$ + SP$ + NU$; "VOLUME INJECTED(m3)"; VOLINJ
8360 PRINT : PRINT USING J$ + SP$; "RADIUS OF OBSERVATION WELLS"
8370 PRINT USING J$ + SP$; "-----"
8380 PRINT USING J$ + SP$ + NU$; "MINIMUM RADIUS (m)"; RA(1)
8390 PRINT USING J$ + SP$ + NU$; "WELL 1 (m)"; RA(NO(1))

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8400 PRINT USING J$+SP$+NU$;"WELL 2 (m)",RA(NO(2))
8410 PRINT USING J$+SP$+NU$;"WELL 3 (m)",RA(NO(3))
8420 PRINT USING J$+SP$+NU$;"MAXIMUM RADIUS (m)",RA(NM)
8430 PRINT: PRINT USING J$+SP$+NU$;"INTERVAL LENGTH FOR CALCULATIONS DURING INJE
CTION (m)";TILIFT
8440 LOCATE 24,2:PRINT"PRESS ENTER TO CONTINUE      ";
8450 K$=INKEY$:IF LEN(K$)=0 THEN 8450 ELSE K%=ASC(K$)
8460 IF K%=13 THEN 8470 ELSE 8450
8470 CLS: PRINT USING J$+SP$;"POSITION OF FRONT AT END OF INJECTION"
8480 PRINT USING J$+SP$;"-----" :PRINT
8490 IF PAST=100 THEN 8500 ELSE 8520
8500 PRINT:PRINT TAB(12);"FINAL POSITION OF FRONT NOT CALCULATED"
8510 GOTO 8580
8520 PRINT : PRINT USING J$ + SP$; "RADII ON FLOOR OF AQUIFER (m)": PRINT
8530 PRINT USING J12$ + SSP$ + NU$; "LAGGING EDGE OF MIXED ZONE"; RCFT(1)
8535 RFT1 = RCFT(1)
8540 PRINT USING J12$ + SSP$ + NU$; "LEADING EDGE OF MIXED ZONE"; RCFT(2)
8545 RFT2 = RCFT(2)
8550 PRINT : PRINT USING J$ + SP$; "RADII ON ROOF OF AQUIFER (m)": PRINT
8560 PRINT USING J12$ + SSP$ + NU$; "LAGGING EDGE OF MIXED ZONE"; RCFT(3)
8565 RFT3 = RCFT(3)
8570 PRINT USING J12$ + SSP$ + NU$; "LEADING EDGE OF MIXED ZONE"; RCFT(4)
8575 RFT4 = RCFT(4)
8580 ICC = 0: LOCATE 23, 2: PRINT "PRESS ENTER TO CONTINUE      ";
8590 K$ = INKEY$: IF LEN(K$) = 0 THEN 8590 ELSE K% = ASC(K$)
8600 IF K% = 13 THEN 8602 ELSE 8580

8602     CLS
        PRINT USING J$ + SP$; "RECOVERY CONDITIONS"
        PRINT USING J$ + SP$; "-----"
        PRINT USING J$ + SP$ + NU$; "RECOVERY RATE (L/s)"; QREC
        PRINT USING J$ + SP$ + NU$; "ALLOWABLE WATER QUALITY (TDS)"; WQ
        PRINT USING J$ + SP$ + NU$; "VOLUME RECOVERED (m^3)"; VOUT
        PRINT USING J$ + SP$ + NU$; "RECOVERY RATIO"; VV

8603     ICC = 0: LOCATE 23, 2: PRINT "PRESS ENTER TO CONTINUE      ";
8604     K$ = INKEY$: IF LEN(K$) = 0 THEN 8604 ELSE K% = ASC(K$)
        IF K% = 13 THEN 8610 ELSE 8603

8610 CLS : PRINT USING J$ + SP$; "CALCULATED PIEZOMETRIC LEVELS"
8620 PRINT USING J$ + SP$; "-----": PRINT
8630 PRINT USING J$ + SPP$; "TIME          MIN RADIUS    WELL 1      WELL 2      WELL
8640 PRINT USING J$ + SPP$; "(days)          (m)          (m)          (m)          (m)
8650 PRINT
8660 ICC = 0: 'setting counter to zero
8670 IF EOF(2) THEN CLOSE #2: GOTO 8740
8680 ON ERROR GOTO 8730
8690 LINE INPUT #2, L$
8700 PRINT TAB(8); L$
8710 ICC = ICC + 1
8720 IF ICC = 15 THEN 8580 ELSE 8670
8730 LOCATE 24, 2: PRINT "error in data file"; : END
8740 LOCATE 25, 2: PRINT "finished press ENTER TO CONTINUE";
8750 '
8760 K$ = INKEY$: IF LEN(K$) = 0 THEN 8760 ELSE K% = ASC(K$)
8770 IF K% = 13 THEN 8780 ELSE 8760
8780 GOTO 10090: 'LOCATE 25,2:PRINT"SEE WHAT WAS SAVED (Y/N) ";
8790 R$ = INKEY$: IF LEN(R$) = 0 THEN 8790
8800 IF R$ = "y" OR R$ = "Y" THEN 8810 ELSE 8830
8810 CLS : SCREEN 1: DEFSEG = &HB800: BLOAD "pic.drw"
8820 'GOTO 10080

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8830 LOCATE 25, 2: PRINT "DO YOU WANT A HARD COPY (Y/N) ";
8840 R$ = INKEY$: IF LEN(R$) = 0 THEN 8840
8850 IF R$ = "y" OR R$ = "Y" THEN 8870 ELSE 10000
8860 '
8870 LOCATE 25, 2: PRINT "IS THE PRINTER READY (Y/N) ";
8880 R$ = INKEY$: IF LEN(R$) = 0 THEN 8880
8890 IF R$ = "y" OR R$ = "Y" THEN 8900 ELSE 8870
8900 CLOSE : 'close files from screen output
8910 '
8920 OPEN "piezo.dat" FOR INPUT AS #2
8930 '*
8940 '
8950 LPRINT STRING$(8, CHR$(10));
8960 LPRINT USING J$ + "\"      \" + LS$; "NAME      : "; NM$;
8970 LPRINT USING KK$ + "\"      \" + \"      \"; "DATE : "; YMD$
8980 LPRINT CHR$(10);
8990 LPRINT USING J$ + "\"      \" + LS$; "FILE #      : "; FI$
9000 LPRINT USING J$ + "\"      \" + LS$; "LOCATION : "; LO$
9010 LPRINT USING J$ + "\"      \" + LS$; "PROJECT : "; PR$
9020 LPRINT STRING$(1, CHR$(10))
9030 LPRINT USING J$ + J$ + J$ + LS$; "DATA"
9040 LPRINT USING J$ + J$ + J$ + LS$; "-----": LPRINT
9050 LPRINT USING J$ + SP$; "POROUS MEDIUM": LPRINT
9060 LPRINT USING J$ + SP$ + NU$; "GROUND ELEVATION (m A.S.L.)"; GE
9070 LPRINT USING J$ + SP$ + NU$; "WATER LEVEL ELEVATION (m A.S.L.)"; EL
9080 LPRINT USING J$ + SP$ + NU$; "TOP OF AQUIFER ELEVATION (m A.S.L.)"; TE
9090 LPRINT USING J$ + SP$ + NU$; "BOTTOM OF AQUIFER ELEVATION (m A.S.L.)"; BO
9100 LPRINT USING J$ + SP$ + NU$; "THICKNESS OF THE MEDIUM (m)": HFT
9110 LPRINT USING J$+SP$+SPACE$(4)+"#.###^"; "TRANSMISSIVITY (m2/s)"; TRANS
9120 LPRINT USING J$+SP$+SPACE$(4)+"#.###^"; "STORAGE COEFFICIENT (confined)";
SC
9130 LPRINT USING J$+SP$+NU$; "WELL RADIUS (m)"; RW
9140 LPRINT USING J$+SP$+NU$; "POROSITY (fraction)"; PR
9150 LPRINT USING J$+SP$+NU$; "LONGITUDINAL DISPERSIVITY OF THE MEDIUM (mm)", ALFM
M
9160 LPRINT USING J$+SP$+SPACE$(4)+"#.###^"; "COEFFICIENT OF MOLECULAR DIFFUSI
ON (m2/s)", DIFMOLM
9170 LPRINT: LPRINT USING J$+SP$; "FLUID PROPERTIES" : LPRINT
9180 LPRINT USING J$+SP$+NU$; "TEMPERATURE OF NATIVE WATER (C)"; TEMPF
9190 LPRINT USING J$+SP$+NU$; "TEMPERATURE OF INJECTION WATER (C)"; TEMPS
9200 LPRINT
9210 LPRINT USING J$+SP$+NU$; "TOTAL DISSOLVED SOLIDS OF THE SURFACE WATER (mg/L)
"; TDSS
9220 LPRINT USING J$+SP$+NU$; "TOTAL DISSOLVED SOLIDS OF THE NATIVE WATER (mg/L)"
; TDSF
9230 LPRINT: LPRINT USING J$+SP$; "VISCOSITY OF THE FLUIDS (Pa.s)"
9240 LPRINT USING J12$+SSP$+N5U$; "VISCOSITY OF THE INJECTED FLUID", VISCP1
9250 LPRINT USING J12$+SSP$+N5U$; "VISCOSITY OF THE NATIVE FLUID", VISCP2
9260 LPRINT USING J12$+SSP$+N5U$; "MEAN VISCOSITY OF THE TWO FLUIDS", VISCP
9270 LPRINT: LPRINT USING J$+SP$; "DENSITY OF THE FLUIDS (kg/m3)"
9280 LPRINT USING J12$+SSP$+N5U$; "DENSITY OF THE INJECTED FLUID", DENS1
9290 LPRINT USING J12$+SSP$+N5U$; "DENSITY OF THE NATIVE FLUID", DENS2
9300 LPRINT USING J12$+SSP$+N5U$; "DENSITY DIFFERENCE BETWEEN THE FLUIDS", DSDF
9310 LPRINT STRING$(2, CHR$(10));
9320 '
9330 'IF DAIS=2 THEN 9340 ELSE 9350
9340 'LPRINT J$; "UNIVERSITY OF SASKATCHEWAN": GOTO 9360
9350 LPRINT J$+CHR$(14)+CHR$(27)+"E"; "UNIVERSITY OF SASKATCHEWAN": LPRINT CHR$(27
)+"F"
9360 LPRINT CHR$(12): LPRINT STRING$(8, CHR$(10));
9370 LPRINT USING J$+"\"      \"+LS$; "FILE #      : ", FI$ : LPRINT
9380 LPRINT USING J$+SP$; "OPERATING CONDITIONS"
9390 LPRINT USING J$+SP$; "-----": LPRINT
9400 LPRINT USING J$+SP$+SPACE$(4)+"#.###^"; "DESIGNED PUMPING RATE OF WELL (L
/s)"; QDESIGN
9410 LPRINT USING J$+SP$+SPACE$(4)+"#.###^"; "INJECTION RATE (L/s)"; QR1GM
9420 LPRINT USING J$+SP$+NU$; "INJECTION TIME (days)"; TS

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9430 LPRINT USING J$+SP$+SPACE$(4)+"###^";"VOLUME INJECTED (m3)";VOLINJ
9440 LPRINT: LPRINT USING J$+SP$+NU$;"INTERVAL LENGTH FOR CALCULATIONS DURING IN
JECTION (m)";TILIFT :LPRINT:LPRINT
9450 LPRINT USING J$+SP$;"RADIUS OF OBSERVATION WELLS"
9460 LPRINT USING J$+SP$;"-----"
9470 LPRINT USING J$+SP$+NU$;"MINIMUM RADIUS (m)",RA(1)
9480 LPRINT USING J$+SP$+NU$;"WELL 1 (m)",RA(NO(1))
9490 LPRINT USING J$+SP$+NU$;"WELL 2 (m)",RA(NO(2))
9500 LPRINT USING J$+SP$+NU$;"WELL 3 (m)",RA(NO(3))
9510 LPRINT USING J$+SP$+NU$;"MAXIMUM RADIUS (m)",RA(NM)
9520 LPRINT STRING$(3,CHR$(10));
9530 'LPRINT: LPRINT USING J$+SP$+NU$;"INTERVAL LENGTH FOR CALCULATIONS DURING I
NJECTION (m)";TILIFT :LPRINT:LPRINT
9540 IF JAM=100 THEN RETURN
9550 LPRINT USING J$+SP$;"POSITION OF FRONT AT END OF INJECTION"
9560 LPRINT USING J$+SP$;"-----":LPRINT
9570 '
9580 IF PAST = 100 THEN 9590 ELSE 9620
9590 LPRINT : LPRINT TAB(10); "POSITION OF INJECTION FONT NOT CALCULATED"
9600 GOTO 9690
9610 'ON ERROR GOTO 9940
9620 LPRINT USING J$ + SP$; "RADII ON FLOOR OF AQUIFER (m)": LPRINT
9630 LPRINT USING J12$ + SSP$ + NU$; "LAGGING EDGE OF MIXED ZONE"; RCFT(1)
9640 LPRINT USING J12$ + SSP$ + NU$; "LEADING EDGE OF MIXED ZONE"; RCFT(2)
9650 LPRINT : LPRINT USING J$ + SP$; "RADII ON ROOF OF AQUIFER (m)": LPRINT
9660 LPRINT USING J12$ + SSP$ + NU$; "LAGGING EDGE OF MIXED ZONE"; RCFT(3)
9670 LPRINT USING J12$ + SSP$ + NU$; "LEADING EDGE OF MIXED ZONE"; RCFT(4)
9680 'CLOSE #1
      LPRINT
      LPRINT USING J$ + SP$; "RECOVERY CONDITIONS"
      LPRINT USING J$ + SP$; "-----"
      LPRINT USING J$ + SP$ + NU$; "RECOVERY RATE (L/s)"; QREC
      LPRINT USING J$ + SP$ + NU$; "ALLOWABLE WATER QUALITY (TDS)"; WQ
      LPRINT USING J$ + SP$ + NU$; "VOLUME RECOVERED (m^3)"; VOUT
      LPRINT USING J$ + SP$ + NU$; "RECOVERY RATIO"; VVV
9690 LPRINT STRING$(4, CHR$(10))
9700 '
9710 'IF DAIS=2 THEN 9720 ELSE 9730
9720 'LPRINT J$;"UNIVERSITY OF SASKATCHEWAN" :GOTO 9750
9730 LPRINT J$+CHR$(14)+CHR$(27)+"E";"UNIVERSITY OF SASKATCHEWAN"
9740 LPRINT CHR$(27)+"F"
9750 IF RITE=100 THEN GOSUB 10220
9760 LPRINT CHR$(12):LPRINT STRING$(8,CHR$(10));
9770 LPRINT USING J$+"\\"+"LS$;"FILE # : ",FI$ :LPRINT
9780 LPRINT USING J$+SP$;"CALCULATED PIEZOMETRIC LEVELS"
9790 LPRINT USING J$+SP$;"-----":LPRINT
9800 LPRINT USING J$+SPP$;"TIME          MIN RADIUS    WELL 1      WELL 2      WELL 3
      MAX RADIUS"
9810 LPRINT USING J$+SPP$;"(days)      (m)          (m)          (m)          (m)
      (m)"
9820 LPRINT
9830 ICK = 0: 'setting counter to zero
9840 IF EOF(2) THEN CLOSE : GOTO 9910
9850 ON ERROR GOTO 9900
9860 LINE INPUT #2, L$
9870 LPRINT TAB(8); L$
9880 ICK = ICK + 1: RITE = 100
9890 IF ICK = 30 THEN 9750 ELSE 9840
9900 LOCATE 24, 2: PRINT "ERROR IN DATA FILE"; : BEEP: END
9910 GOSUB 10220
9920 LPRINT STRING$(4, CHR$(10));
9930 'LPRINT J$+CHR$(14)+CHR$(27)+"E";"UNIVERSITY OF SASKATCHEWAN"
9940 'LPRINT CHR$(27)+"F"

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9950 LOCATE 25, 2: PRINT " ";
9960 LPRINT CHR$(12): LOCATE 24, 2: PRINT "FINISHED PRESS ENTER TO CONTINUE";
9970 K$ = INKEY$: IF LEN(K$) = 0 THEN 9970 ELSE K% = ASC(K$)
9980 IF K% = 13 THEN 9990 ELSE 9970
9990 RITE = 0: GOTO 8830: 'see if another hard copy is wanted
10000 LOCATE 24, 2: PRINT "DO YOU WANT A HARD COPY OF ";
10010 LOCATE 25, 2: PRINT "THE PICTURE(Y/N) ";
10020 R$ = INKEY$: IF LEN(R$) = 0 THEN 10020
10030 IF R$ = "Y" OR R$ = "y" THEN GOSUB 40005 ELSE 10080
10035 GOTO 10080
10040 'LOCATE 24, 2: PRINT "PRESS ENTER TO EXIT PROGRAM ";
10050 'LOCATE 25, 2: PRINT "ENTER 'SCRNDMP' AT A> FOR HARD COPY";
10060 R$ = INKEY$: IF LEN(R$) = 0 THEN 10060 ELSE R% = ASC(R$)
10070 IF R% = 13 THEN CLS : PRINT : SYSTEM ELSE 10060
10080 CLS : SCREEN 0, 1: WIDTH 80
10090 LOCATE 25, 2: PRINT "DO YOU WANT TO REDO INJECTION STEP (Y/N) ";
10100 R$ = INKEY$: IF LEN(R$) = 0 THEN 10100
10110 IF R$ = "Y" OR R$ = "y" THEN 10 ELSE 30390
10140 LOCATE 24, 2: PRINT "press 'ENTER' to return to system ";
10150 LOCATE 25, 2: PRINT "at A> enter 'file name' to start ";
10160 R$ = INKEY$: IF LEN(R$) = 0 THEN 10160 ELSE R% = ASC(R$)
10170 IF R% = 13 THEN CLS : PRINT : SYSTEM ELSE 10160
10180 '
10190 IF ERR = 62 THEN MSG$ = "INPUT PAST END": GOTO 10210
10200 MSG$ = "ERROR " + STR$(ERR) + " in line " + STR$(ERL)
10205 'END
10210 LOCATE 25, 2: PRINT MSG$: : RESUME NEXT
10220 '*****
10230 '* *
10240 '* SUBROUTINE TO PRINT BOTTOM ON PAGE *
10250 '* *
10260 '*****

10270 '
10280 LPRINT STRING$(4,CHR$(10))
10290 'F DAIS=2 THEN 10300 ELSE 10320
10300 'LPRINT TAB(12)"UNIVERSITY OF SAKATCHEWAN":GOTO 10330
10310 '
10320 LPRINT J$+CHR$(14)+CHR$(27)+"E";"UNIVERSITY OF SASKATCHEWAN";CHR$(27)+"F"
10330 RETURN
10340 END

10400 'CLS : LOCATE 2, 4: PRINT "*****"
10410 'LOCATE 3, 4: PRINT "*"
10420 'LOCATE 4, 4: PRINT "*" STEP 2 ESTIMATION OF FRONTAL POSITION
10430 'LOCATE 5, 4: PRINT "*" WHEN WATER IS STORED IN CONFINED
10440 'LOCATE 6, 4: PRINT "*" AQUIFER OVER TIME
10450 'LOCATE 7, 4: PRINT "*"
10451 'LOCATE 8, 4: PRINT "*" IF THERE IS NO STORAGE, ENTER 0 DAYS
10452 'LOCATE 9, 4: PRINT "*" FOR STORAGE TIME
10460 'LOCATE 10, 4: PRINT "*****"
10470 'RESERVE = TS: A$ = "": LOCATE 12, 28: PRINT TS
10480 'LOCATE 12, 4: INPUT "INPUT STORAGE TIME (DAYS)", RESERV
10490 'IF A$ <> "" THEN RESERV = VAL(A$): A$ = "": IF RESERV < 1 THEN 19930
10500 'LOCATE 25, 4: PRINT "PRESS 'ENTER' TO CONTINUE"
10510 'R$ = INKEY$: IF LEN(R$) = 0 THEN 10510 ELSE R% = ASC(R$)
10520 'IF R% = 13 THEN 10525 ELSE 10500
10525 '*****
10527 '*
10528 GOSUB 6290: 'DRAW DIAGRAM AND SCALES
10529 '*
10530 '*****

```

```

10540 '*****
10550 TSP = X / (DM1 * DM2 ^ .5)
10560 T11 = T11 + RESERV: TT = T11 + TSP
10570 X = DM1 * TT * DM2 ^ .5
10580 IF (X - .1) > 0 THEN 10610
10590 YL(I) = 20 * X
10600 GOTO 10650
10610 IF (X - 1) > 0 THEN 10640
10620 YL(I) = .7958 + 12.5238 * X - 4.8196 * X ^ 2
10630 GOTO 10650
10640 YL(I) = 6.5 = 2 * X
10650 XL(I) = YL(I) * H
10660 '
10670 A1 = 3.142 * ((R(I - 1) + XR(I - 1) / 2) ^ 2 - R(I - 1) ^ 2)
10680 B1 = 3.142 * (R(I - 1) ^ 2 - (R(I - 1) - XR(I - 1) / 2) ^ 2)
10690 RU50 = SQR((3.142 * R(I) ^ 2 + A1) / 3.142) + (XL(I) - XL(I - 1)) / 2
10700 RL50 = SQR((3.142 * R(I) ^ 2 - B1) / 3.142) - (XL(I) - XL(I - 1)) / 2
10710 XR(I) = RU50 - RL50: '50%HORIZONTAL PROJECTION
10720 GOSUB 3850: 'DRAW FRONT RESULTING FROM STORAGE
10840 '*****
10850 '*'
10860 GOSUB 3850: 'DRAW FRONT RESULTING FROM STORAGE
10870 '*'
10880 '*****
10890 '
10900 '
10910 '
10920 '
10930 '
10950 '
12950 ICOUNT = 0
12960 IF (DENDF) > 0 THEN 12990
12970 'RADII ON FLOOR OF AQUIFER
12980 GOTO 13060
12990 'RADII ON FLOOR OF AQUIFER
13000 GOTO 13090
13010 IF (DENDF) > 0 THEN 13040
13020 'RADII ON ROOF OF AQUIFER
13030 GOTO 13090
13040 'RADII ON ROOF OF AQUIFER
13050 GOTO 13060
13060 R50SQ = RL50 * RL50
13070 RCHECK = RL50
13080 GOTO 13110
13090 R50SQ = RU50 * RU50
13100 RCHECK = RU50
13110 QSI = R50SQ / (2! * TRT)
13120 SDENOM = 2! * SQR(1.33 * ALF * (R50SQ) ^ 1.5 + DIFMOL * (R50SQ) ^ 2 / QSI)
13130 RC = RCHECK - RINC
13140 XX = (R50SQ - RC * RC) / SDENOM
13150 '*****
13160 '*'
13170 GOSUB 3510: 'calculate erfc(xx) *
13180 '*'
13190 '*****
13200 C11 = ERFCXX / 2!
13210 IF (C11 - .5) > 0 THEN 13330
13220 IF (C11 - .03) > 0 THEN 13270
13230 RCFT = RC / CFFTCM
13240 PRINT #1, USING "####.##"; RCFT

```

```

13250 'LAGGING EDGE OF MIXED ZONE
13260 GOTO 13310
13270 RC = RC - RINC
13280 IF (RC) > 0 THEN 13140
13290 RCFT = 0
13300 GOTO 13250
13310 RC = RCHECK + RINC
13320 GOTO 13140
13330 IF (C11 - .97) >= 0 THEN 13360
13340 RC = RC + RINC
13350 GOTO 13140
13360 RCFT = RC / CFFTCM
13370 PRINT #1, USING "#####.##"; RCFT
13380 'LEADING EDGE OF MIXED ZONE
13390 IF (ICOUNT - 1) >= 0 THEN 13420
13400 ICOUNT = ICOUNT + 1
13410 GOTO 13010
13420 CLOSE : 'close files before printout begins
19800 '
19810 '
19820 '
19870 'CLS : LOCATE 25, 2: PRINT "put output on screen (y/n) ";
19880 'R$ = INKEY$: IF LEN(R$) = 0 THEN 19880
19890 'IF R$ = "Y" OR R$ = "y" THEN 30070 ELSE 19900
19900 'LOCATE 25, 2: PRINT "DO YOU WANT TO REDO STORAGE STEP (Y/N)";
19910 'R$ = INKEY$: IF LEN(R$) = 0 THEN 19910
19920 'IF R$ = "Y" OR R$ = "y" THEN 10400 ELSE 30360

'
'
'

20220 '* RECOVERY VOLUME AND CONCENTRATION BASED ON
      '* PICKENS AND GRISAK
      '*****
      RSTEP = INT(FLING1 / 10 - 1) + 1
      R1 = ((RCFT(4) + RCFT(3)) / 2 + (RCFT(2) + RCFT(1)) / 2) / 2
      FOR VV = 0 TO VOUT STEP RSTEP
        VVV = VV / FLING1
        CC = (16 / 3) * (ALFMM / 1000) / R1
        DENOM = SQR(CC * (2 - SQR(ABS(1 - VVV)) * (1 - VVV)))
        XX = (VVV - 1) / DENOM
        GOSUB 3510: 'complementary error function
        BBB = ERFCXX / 2
        IF BBB<=BCB GOTO 20360
        WQ = BBB * (TDSS - TDSF) + TDSF
      NEXT
20360 RETURN
20365

'USED TO OUTPUT OF RECOVERY CONDITIONS

30360 LOCATE 24, 2: PRINT "DO YOU WANT TO START OVER? (Y/N)";
30370 R$ = INKEY$: IF LEN(R$) = 0 THEN 30370
30380 IF R$ = "Y" OR R$ = "y" THEN 10 ELSE 30390
30390 CLS : SCREEN 0, 1: WIDTH 80
30391 LOCATE 2, 4: PRINT "*****"
30400 LOCATE 3, 4: PRINT "*"
30410 LOCATE 4, 4: PRINT "          THANKYOU.  ENJOY THE REST OF THE SHOW"
30420 LOCATE 5, 4: PRINT "*"
30430 LOCATE 6, 4: PRINT "*****"

```

```

GOTO 40370
'***
'*** ASSEMBLER DUMP ROUTINE
'***
40590 DEF SEG = &HE00: SUBRT = 0: RESTORE 40600
40600 DATA &H55,&HCD,&H05,&H5D,&HCA,&H00,&H00
FOR I = 0 TO 6: READ J: POKE I, J: NEXT: RETURN
'***
40630 LOCATE X, 1: PRINT "DO YOU WANT TO CONTINUE (Y/N)";
40640 R$ = INKEY$: IF LEN(R$) = 0 THEN 40640
IF R$ = "Y" OR R$ = "y" THEN 40030 ELSE 10035
/
40670 CLS : PRINT "*****"
PRINT "*"
PRINT "*"          SCREENDUMP PROGRAM VERS 1.1          "*"
PRINT "*"
PRINT "*****": RETURN
END
'***
'*** TRAP COMMON ERRORS
'***
CLS : GOSUB 40670
IF ERR = 24 THEN MSG$ = "Printer not available": GOTO 40820
IF ERR = 70 THEN MSG$ = "Disk is write protected": GOTO 40820
IF ERR = 27 THEN MSG$ = "No paper in printer": GOTO 40820
IF ERR = 53 THEN MSG$ = "File not found": GOTO 40820
MSG$ = "Error " + STR$(ERR) + " in line " + STR$(ERL) + " - try again"
40820 PRINT : PRINT MSG$: RESUME 40140
RETURN

SUB FILEOUTPUT
'      PRINT RCFT(1), RCFT(2), RCFT(3), RCFT(4)

      FILENAME$ = FI$

      OPEN "PIEZO.DAT" FOR INPUT AS #2
      OPEN FILENAME$ + "D.DAT" FOR OUTPUT AS #3
      OPEN FILENAME$ + "P.DAT" FOR OUTPUT AS #4
PRINT #3, USING J$ + "\"          "\" + LS$: "NAME          : "; NM$;
PRINT #3, USING KK$ + "\"          "\" + "\"          \"; "DATE : "; YMD$
PRINT #3, USING J$ + "\"          "\" + LS$: "FILE #          : "; FI$
PRINT #3, USING J$ + "\"          "\" + LS$: "LOCATION : "; LO$
PRINT #3, USING J$ + "\"          "\" + LS$: "PROJECT : "; PR$
PRINT #3, USING J$ + J$ + J$ + LS$: "DATA"
PRINT #3, USING J$ + J$ + J$ + LS$: "----": PRINT #3,
PRINT #3, USING J$ + SP$: "POROUS MEDIUM": PRINT #3,
PRINT #3, USING J$ + SP$ + NU$: "GROUND ELEVATION (m A.S.L.)"; GE
PRINT #3, USING J$ + SP$ + NU$: "WATER LEVEL ELEVATION (m A.S.L.)"; EL
PRINT #3, USING J$ + SP$ + NU$: "TOP OF AQUIFER ELEVATION (m A.S.L.)"; TE
PRINT #3, USING J$ + SP$ + NU$: "BOTTOM OF AQUIFER ELEVATION (m A.S.L.)"; BO
PRINT #3, USING J$ + SP$ + NU$: "THICKNESS OF THE MEDIUM (m)"; HFT
PRINT #3, USING J$ + SP$ + SPACES(4) + "#.###^"; "TRANSMISSIVITY (m2/s)"; TF
PRINT #3, USING J$ + SP$ + SPACES(4) + "#.###^"; "STORAGE COEFFICIENT (confi
PRINT #3, USING J$ + SP$ + NU$: "WELL RADIUS (m)"; RW
PRINT #3, USING J$ + SP$ + NU$: "POROSITY (fraction)"; PR
PRINT #3, USING J$ + SP$ + NU$: "LONGITUDINAL DISPERSIVITY OF THE MEDIUM (mm)";
PRINT #3, USING J$ + SP$ + SPACES(4) + "#.###^"; "COEFFICIENT OF MOLECULAR I
PRINT #3, : PRINT #3, USING J$ + SP$: "FLUID PROPERTIES": PRINT #3,
PRINT #3, USING J$ + SP$ + NU$: "TEMPERATURE OF NATIVE WATER (C)"; TEMPF
PRINT #3, USING J$ + SP$ + NU$: "TEMPERATURE OF INJECTION WATER (C)"; TEMPS

```



```

30440 LOCATE 25, 2: PRINT "PRESS 'ENTER' TO START";
30450 K$ = INKEY$: IF LEN(K$) = 0 THEN 30450 ELSE K% = ASC(K$)
30460 IF K% = 13 THEN 30470 ELSE 30450
30470 LOCATE 24, 2: PRINT "'ENTER' returns you to the system ";
30480 LOCATE 25, 2: PRINT "at A> enter 'front' to start ";
30490 R$ = INKEY$: IF LEN(R$) = 0 THEN 30490 ELSE R% = ASC(R$)
30500 IF R% = 13 THEN CLS : PRINT : SYSTEM ELSE 30490

40005 LPRINT CHR$(27); CHR$(65); CHR$(8)
' THIS PROGRAM REQUIRES THE PRINTER TO BE SET TO THE IBM X24 MODE
' TO DO THIS ON THE KX-P1124 MUST BE SET WITH THE FIRST ROW LIGHT
' ON AND THE THIRD COLUMN LIGHT. FOR MORE INFORMATION CONSULT
' THE MANUAL. TROY LUCYSHYN
'* SCREENDUMP UTILITY IN BASIC 2.0 FOR IBM PC GRAPHICS PRINTER
40030 SCREEN 0, 1: WIDTH 80: CLS : KEY OFF
GOSUB 40670: 'put on the header message before starting
'*
CLS : GOSUB 40670
'LOCATE 16,2:PRINT" The picture cannot be drawn using a "
40140 'LOCATE 17,2:PRINT" Daisy wheel printer. ": X= 24 :GOTO 40630
,
40160 LOCATE 24, 2: PRINT " ";
LOCATE 16, 2: PRINT : INPUT ; "INPUT PROJECT NAME (maximum 20 letters)"; PR$
LOCATE 18, 2: PRINT : INPUT ; "INPUT FIGURE # (10 letters maximum)"; FI$
LOCATE 24, 2: PRINT "is everything o.k. (Y/N)";
40200 R$ = INKEY$: IF LEN(R$) = 0 THEN 40200
IF R$ = "y" OR R$ = "Y" THEN 40230 ELSE 40160
'*** Load graphics file onto screen
40230 CLS : SCREEN 2: DEF SEG = &HB800: BLOAD "pic.drw", 0
,
'add bottom to picture project and figure
LINE (0, 178)-(0, 194), 1: LINE (1, 178)-(1, 194), 1
LINE (0, 194)-(639, 194), 1
LINE (639, 194)-(639, 178), 1: LINE (638, 194)-(638, 178), 1
LOCATE 24, 2: PRINT "UNIVERSITY OF SASKATCHEWAN";
LINE (224, 178)-(224, 194), 1: LINE (225, 178)-(225, 194), 1
LOCATE 24, 30: PRINT USING "\ " + SPACE$(1) + "\ " "; "P
LINE (480, 178)-(480, 194), 1: LINE (479, 178)-(479, 194), 1
LOCATE 24, 62: PRINT USING "\ " + SPACE$(1) + "\ " "; "FIGURE"; FI$;
LOCATE 1, 1: PRINT "DO YOU WANT A HARD COPY (Y/N)";
40350 R$ = INKEY$: IF LEN(R$) = 0 THEN 40350
IF R$ = "y" OR R$ = "Y" THEN 40370 ELSE X = 1: GOTO 40630
40370 LOCATE 1, 1: PRINT "is the printer ready (y/n). ";
40380 R$ = INKEY$: IF LEN(R$) = 0 THEN 40380
IF R$ = "y" OR R$ = "Y" THEN 40400 ELSE 40380
40400 LOCATE 1, 1: PRINT " ";
CLEAR , &HE000: GOSUB 40590
'*** Dump to printer
DEF SEG = &HE00
CALL ABSOLUTE(0)
'*** Check for another else quit
LPRINT CHR$(12)
LOCATE 1, 1: PRINT "print another (y/n)";
40470 R$ = INKEY$: IF LEN(R$) = 0 THEN 40470
IF R$ = "y" OR R$ = "Y" THEN 40490 ELSE X = 1: GOTO 40630
40490 LOCATE 1, 1: PRINT "DO YOU WANT TO CHANGE THE INPUT PARAMETERS (Y/N)";
40500 R$ = INKEY$: IF LEN(R$) = 0 THEN 40500 ELSE 40510
40510 IF R$ = "y" OR R$ = "Y" THEN 40030 ELSE 40530
40530 LOCATE 1, 1: PRINT " ";

```

```

PRINT #3, USING J$ + SP$ + NU$; "TOTAL DISSOLVED SOLIDS OF THE SURFACE WATER (m
PRINT #3, USING J$ + SP$ + NU$; "TOTAL DISSOLVED SOLIDS OF THE NATIVE WATER (mq
PRINT #3, : PRINT #3, USING J$ + SP$; "VISCOSITY OF THE FLUIDS (Pa.s)"
PRINT #3, USING J12$ + SSP$ + N5U$; "VISCOSITY OF THE INJECTED FLUID"; VISCP1
PRINT #3, USING J12$ + SSP$ + N5U$; "VISCOSITY OF THE NATIVE FLUID"; VISCP2
PRINT #3, USING J12$ + SSP$ + N5U$; "MEAN VISCOSITY OF THE TWO FLUIDS"; VISCP
PRINT #3, : PRINT #3, USING J$ + SP$; "DENSITY OF THE FLUIDS (kg/m3)"
PRINT #3, USING J12$ + SSP$ + N5U$; "DENSITY OF THE INJECTED FLUID"; DENS1
PRINT #3, USING J12$ + SSP$ + N5U$; "DENSITY OF THE NATIVE FLUID"; DENS2
PRINT #3, USING J12$ + SSP$ + N5U$; "DENSITY DIFFERENCE BETWEEN THE FLUIDS"; DS
PRINT #3, STRING$(2, CHR$(10));
PRINT #3,
PRINT #3, USING J$ + SP$; "OPERATING CONDITIONS"
PRINT #3, USING J$ + SP$; "-----": PRINT #3,
PRINT #3, USING J$ + SP$ + NU$; "DESIGNED PUMPING RATE OF WELL (L/s)"; QDESIGN
PRINT #3, USING J$ + SP$ + NU$; "INJECTION RATE (L/s)"; QR1GM
PRINT #3, USING J$ + SP$ + NU$; "INJECTION TIME (days)"; TS
PRINT #3, USING J$ + SP$ + NU$; "VOLUME INJECTED (m3)"; VOLINJ
PRINT #3, : PRINT #3, USING J$ + SP$ + NU$; "INTERVAL LENGTH FOR CALCULATIONS D
PRINT #3, USING J$ + SP$; "RADIUS OF OBSERVATION WELLS"
PRINT #3, USING J$ + SP$; "-----"
PRINT #3, USING J$ + SP$ + NU$; "MINIMUM RADIUS (m)"; RA(1)
PRINT #3, USING J$ + SP$ + NU$; "WELL 1 (m)"; RA(NO(1))
PRINT #3, USING J$ + SP$ + NU$; "WELL 2 (m)"; RA(NO(2))
PRINT #3, USING J$ + SP$ + NU$; "WELL 3 (m)"; RA(NO(3))
PRINT #3, USING J$ + SP$ + NU$; "MAXIMUM RADIUS (m)"; RA(NM)
PRINT #3, USING J$ + SP$; "POSITION OF FRONT AT END OF INJECTION"
PRINT #3, USING J$ + SP$; "-----": PRINT #3,
,
PRINT #3, USING J$ + SP$; "RADII ON FLOOR OF AQUIFER (m)": PRINT #3,
PRINT #3, USING J12$ + SSP$ + NU$; "LAGGING EDGE OF MIXED ZONE"; RCFT(1)
PRINT #3, USING J12$ + SSP$ + NU$; "LEADING EDGE OF MIXED ZONE"; RCFT(2)
PRINT #3, : PRINT #3, USING J$ + SP$; "RADII ON ROOF OF AQUIFER (m)": PRINT #3,
PRINT #3, USING J12$ + SSP$ + NU$; "LAGGING EDGE OF MIXED ZONE"; RCFT(3)
PRINT #3, USING J12$ + SSP$ + NU$; "LEADING EDGE OF MIXED ZONE"; RCFT(4)
PRINT #3,

PRINT #3, USING J$ + SP$; "RECOVERY CONDITIONS"
PRINT #3, USING J$ + SP$; "-----"
PRINT #3, USING J$ + SP$ + NU$; "RECOVERY RATE (L/s)"; QREC
PRINT #3, USING J$ + SP$ + NU$; "ALLOWABLE WATER QUALITY (TDS)"; WQ
PRINT #3, USING J$ + SP$ + NU$; "VOLUME RECOVERED (m^3)"; VOUT
PRINT #3, USING J$ + SP$ + NU$; "RECOVERY RATIO"; VVV
PRINT #3,

PRINT #3, USING J$ + SP$; "CALCULATED PIEZOMETRIC LEVELS"
PRINT #3, USING J$ + SP$; "-----": PRINT #3,
PRINT #3, USING J$ + SPP$; "TIME          MIN RAOIUS    WELL 1          WELL 2          WELL
PRINT #3, USING J$ + SPP$; "(days)          (m)          (m)          (m)          (m)

```

```

'*****
WHILE ICM <> 1000
    ICM = 0: 'setting counter to zero
    IF EOF(2) THEN GOTO 99
    ON ERROR GOTO 98
    LINE INPUT #2, L$
    PRINT #3, TAB(8); L$

```

```

      ICM = ICM + 1
WEND

98  PRINT #3, "ERROR IN DATA FILE"

99  CLOSE #3: CLOSE #2

END SUB

SUB INFORMATION
  '*****
  '*
  '*  subroutine for the input of data
  '*
  '*****
4830 SCREEN 0: CLS : PRINT : PRINT TAB(10); "NUMERICAL INJECTION TEST": PRINT
4840 PRINT "NAME: "
4850 PRINT "FILE #: "
4860 PRINT "DATE Y/M/D: "
4870 PRINT "PROJECT: "
4880 PRINT "LOCATION: "
      LOCATE 4, 13: INPUT "", NMS$
      LOCATE 5, 13: INPUT "", FIS$
      LOCATE 6, 13: INPUT "", YMD$
      LOCATE 7, 13: INPUT "", PR$
      LOCATE 8, 13: INPUT "", LOS$

4890 LOCATE 24, 2: PRINT " IS EVERYTHING OKAY SO FAR (Y/N)";
4900 R$ = INKEY$: IF LEN(R$) = 0 THEN 4900
      IF R$ = "Y" OR R$ = "y" THEN 4920 ELSE 4830

4920  CLS : PRINT TAB(10); "PARAMETERS:": PRINT
      LOCATE 5, 4: PRINT "GROUND ELEVATION (m A.S.L.): "; GE
      LOCATE 6, 4: PRINT "WATER LEVEL ELEVATION (m A.S.L.): "; EL
      LOCATE 7, 4: PRINT "TOP OF AQUIFER ELEVATION (m A.S.L.): "; TE
      LOCATE 8, 4: PRINT "BOTTOM OF AQUIFER ELEVATION (m A.S.L.): "; BO
      LOCATE 9, 4: PRINT "TRANSMISSIVITY (m2/s): "; TRANS
      LOCATE 10, 4: PRINT "STORAGE COEFFICIENT (CONFINED): "; SC
      LOCATE 11, 4: PRINT "WELL RADIUS (m): "; RW
      LOCATE 12, 4: PRINT "POROSITY (fraction): "; PR
      LOCATE 13, 4: PRINT "LONGITUDINAL DISPERSIVITY COEFFICIENT (mm): "; ALF
      LOCATE 14, 4: PRINT "COEFFICIENT OF MOLECULAR DIFFUSION (m2/s): "; DIFMOLM

      LOCATE 5, 34: INPUT "", AS$
      IF AS$ <> "" THEN GE = VAL(AS$): AS$ = ""
      LOCATE 6, 39: INPUT "", AS$
      IF AS$ <> "" THEN EL = VAL(AS$): AS$ = ""
      LOCATE 7, 42: INPUT "", AS$
      IF AS$ <> "" THEN TE = VAL(AS$)
      LOCATE 8, 45: INPUT "", AS$
      IF AS$ <> "" THEN BO = VAL(AS$)
      LOCATE 9, 28: INPUT "", AS$
      IF AS$ <> "" THEN TRANS = VAL(AS$)
      LOCATE 10, 37: INPUT "", AS$
      IF AS$ <> "" THEN SC = VAL(AS$)
      LOCATE 11, 22: INPUT "", AS$
      IF AS$ <> "" THEN RW = VAL(AS$)
      LOCATE 12, 26: INPUT "", AS$
      IF AS$ <> "" THEN PR = VAL(AS$)

```

APPENDIX G

PHREEQE Data Entry

TOTAL MOLALITIES OF ELEMENTS

ELEMENT	MOLALITY	LOG MOLALITY
Ca	8.185321D-04	-3.0870
Mg	5.102883D-04	-3.2922
Na	8.701304D-05	-4.0604
K	2.558183D-04	-3.5921
Cl	5.642435D-05	-4.2485
TOT ALK	2.555033D-03	-1.5926
S	1.978338D-04	-3.7037

----PHASE BOUNDARIES----

PHASE	DELTA PHASE*	LOG IAP	LOG KT	LOG IAP/KT
FIX PCO2	1.587260D-03	-3.2694	-1.2694	-2.0000
CALCITE	1.057864D-03	-8.4042	-8.4042	.0000

* NEGATIVE DELTA PHASE INDICATES PRECIPITATION
AND POSITIVE DELTA PHASE INDICATES DISSOLUTION.

---- LOOK MIN IAP ----

PHASE	LOG IAP	LOG KT	LOG IAP/KT
CALCITE	-8.4042	-8.4105	.0063
ARAGONIT	-8.4042	-8.2553	-.1489
DOLOMITE	-17.3733	-16.7236	-.6497
GYPSUM	-6.8302	-4.6192	-2.2110
ANHYDRIT	-6.8301	-4.2170	-2.6131
PCO2	-3.2694	-1.2694	-2.0001
O2 GAS	-6.1145	-2.8884	-3.2261
H2 GAS	-45.6815	-3.0817	-42.5999

----DESCRIPTION OF SOLUTION----

PH = 7.3565
 PE = 13.9435
 ACTIVITY H2O = .9999
 IONIC STRENGTH = .0074
 TEMPERATURE = 10.0000
 ELECTRICAL BALANCE = -9.8605D-06
 THOR = 2.1991D-02
 TOTAL ALKALINITY = 4.6740D-03
 ITERATIONS = 24

---- LOOK MIN IAP ----

PHASE	LOG IAP	LOG KT	LOG IAP/KT
CALCITE	-7.9870	-8.4105	.4235
ARAGONIT	-7.9870	-8.2553	.2684
DOLOMITE	-16.1786	-16.7236	.5450
SIDERITE	-10.0644	-10.3316	.2672
RHODOCHR	-11.9160	-10.3293	-1.5867
GYP SUM	-5.4925	-4.6192	-.8733
ANHYDRIT	-5.4922	-4.2170	-1.2752
HEMATITE	14.7557	-2.8102	17.5660
GOETHITE	7.3778	1.0483	6.3295
FE OH3A	7.3777	4.8910	2.4867
PYRITE	-104.8658	-18.9188	-85.9470
FES PPT	-58.1126	-3.9150	-54.1976
PCO2	-3.1922	-1.2694	-1.9228
O2 GAS	-48.4373	-2.8884	-45.5489
H2 GAS	-24.5202	-3.0817	-21.4385

TOTAL MOLALITIES OF ELEMENTS

ELEMENT	MOLALITY	LOG MOLALITY
Ca	4.095636D-03	-2.3877
Mg	2.501439D-03	-2.6018
Na	1.081213D-03	-2.9661
K	2.636795D-04	-3.5789
Fe	3.553972D-05	-4.4493
Mn	4.926513D-07	-6.3075
Cl	2.383079D-04	-3.6229
C	7.653857D-03	-2.1161
S	3.666668D-03	-2.4357

----DESCRIPTION OF SOLUTION----

PH = 7.4284
 PE = 3.2909
 ACTIVITY H2O = .9997
 IONIC STRENGTH = .0208
 TEMPERATURE = 10.0000
 ELECTRICAL BALANCE = -6.9023D-06
 THOR = 5.2690D-02
 TOTAL ALKALINITY = 7.0434D-03
 ITERATIONS = 22

----- LOOK MIN IAP -----

PHASE	LOG IAP	LOG KT	LOG IAP/KT
CALCITE	-7.4875	-8.4105	.9230
ARAGONIT	-7.4875	-8.2553	.7679
DOLOMITE	-15.0709	-16.7236	1.6527
SIDERITE	-9.3584	-10.3316	.9732
RHODOCHR	-11.2485	-10.3293	-.9192
GYP SUM	-4.9121	-4.6192	-.2928
ANHYDRIT	-4.9114	-4.2170	-.6944
HEMATITE	14.7797	-2.8102	17.5899
GOETHITE	7.3897	1.0483	6.3414
FeOH3A	7.3894	4.8910	2.4984
PYRITE	-96.1615	-18.9188	-77.2427
FES PPT	-52.9304	-3.9150	-49.0154
PCO2	-3.0475	-1.2694	-1.7781
O2 GAS	-50.6347	-2.8884	-47.7463
H2 GAS	-23.4217	-3.0817	-20.3400

=====

.300 = FRACTION OF SOLUTION 1.

.700 = FRACTION OF SOLUTION 2.

TOTAL MOLALITIES OF ELEMENTS

ELEMENT	MOLALITY	LOG MOLALITY
Ca	7.054623D-03	-2.1515
Mg	5.156307D-03	-2.2877
Na	2.406812D-03	-2.6186
K	2.741611D-04	-3.5620
Fe	8.292602D-05	-4.0813
Mn	1.149520D-06	-5.9395
Cl	4.808192D-04	-3.3180
TOT ALK	1.092546D-02	-1.9616
S	8.291781D-03	-2.0814

---- LOOK MIN IAP ----

PHASE	LOG IAP	LOG KT	LOG IAP/KT
CALCITE	-7.6567	-8.4105	.7538
ARAGONIT	-7.6567	-8.2553	.5986
DOLOMITE	-15.4349	-16.7236	1.2887
SIDERITE	-9.5724	-10.3316	.7592
RHODOCHR	-11.4535	-10.3293	-1.1242
GYP SUM	-5.0877	-4.6192	-.4685
ANHYDRIT	-5.0873	-4.2170	-.8702
HEMATITE	14.7758	-2.8102	17.5861
GOETHITE	7.3878	1.0483	6.3395
FE OH3A	7.3876	4.8910	2.4966
PYRITE	-98.6090	-18.9188	-79.6902
FES PPT	-54.3869	-3.9150	-50.4719
PCO2	-3.1051	-1.2694	-1.8357
O2 GAS	-50.0168	-2.8884	-47.1284
H2 GAS	-23.7306	-3.0817	-20.6489

TOTAL MOLALITIES OF ELEMENTS

ELEMENT	MOLALITY	LOG MOLALITY
Ca	7.054623D-03	-2.1515
Mg	5.156307D-03	-2.2877
Na	2.406812D-03	-2.6186
K	2.741611D-04	-3.5620
Fe	8.292602D-05	-4.0813
Mn	1.149520D-06	-5.9395
Cl	4.808192D-04	-3.3180
C	1.092546D-02	-1.9616
S	8.291781D-03	-2.0814

-----DESCRIPTION OF SOLUTION-----

PH = 7.4796
 PE = 2.8448
 ACTIVITY H2O = .9995
 IONIC STRENGTH = .0370
 TEMPERATURE = 10.0000
 ELECTRICAL BALANCE = -2.9581D-06
 THOR = 9.3623D-02
 TOTAL ALKALINITY = 1.0207D-02
 ITERATIONS = 20

=====

.500 = FRACTION OF SOLUTION 1. .500 = FRACTION OF SOLUTION 2.

TOTAL MOLALITIES OF ELEMENTS

ELEMENT	MOLALITY	LOG MOLALITY
Ca	5.575130D-03	-2.2537
Mg	3.828873D-03	-2.4169
Na	1.744012D-03	-2.7585
K	2.689203D-04	-3.5704
Fe	5.923287D-05	-4.2274
Mn	8.210855D-07	-6.0856
Cl	3.595635D-04	-3.4442
C	9.289658D-03	-2.0320
S	5.979224D-03	-2.2234

---- LOOK MIN IAP ----

PHASE	LOG IAP	LOG KT	LOG IAP/KT
CALCITE	-7.8015	-8.4105	.6090
ARAGONIT	-7.8015	-8.2553	.4539
DOLOMITE	-15.7537	-16.7236	.9699
SIDERITE	-9.7709	-10.3316	.5607
RHODOCHR	-11.6422	-10.3293	-1.3129
GYPSUM	-5.2512	-4.6192	-.6319
ANHYDRIT	-5.2508	-4.2170	-1.0338
HEMATITE	14.7693	-2.8102	17.5796
GOETHITE	7.3846	1.0483	6.3363
FEOH3A	7.3844	4.8910	2.4934
PYRITE	-101.0328	-18.9188	-82.1140
FES PPT	-55.8303	-3.9150	-51.9153
PCO2	-3.1471	-1.2694	-1.8777
O2 GAS	-49.4037	-2.8884	-46.5153
H2 GAS	-24.0371	-3.0817	-20.9554

TOTAL MOLALITIES OF ELEMENTS

ELEMENT	MOLALITY	LOG MOLALITY
Ca	5.575130D-03	-2.2537
Mg	3.828873D-03	-2.4169
Na	1.744012D-03	-2.7585
K	2.689203D-04	-3.5704
Fe	5.923287D-05	-4.2274
Mn	8.210855D-07	-6.0856
Cl	3.595635D-04	-3.4442
C	9.289658D-03	-2.0320
S	5.979224D-03	-2.2234

----DESCRIPTION OF SOLUTION----

PH = 7.4587
 PE = 3.0190
 ACTIVITY H2O = .9996
 IONIC STRENGTH = .0291
 TEMPERATURE = 10.0000
 ELECTRICAL BALANCE = -4.9302D-06
 THOR = 7.3157D-02
 TOTAL ALKALINITY = 8.6251D-03
 ITERATIONS = 22

=====

.700 = FRACTION OF SOLUTION 1.

.300 = FRACTION OF SOLUTION 2.

TOTAL MOLALITIES OF ELEMENTS

ELEMENT	MOLALITY	LOG MOLALITY
Ca	4.095636D-03	-2.3877
Mg	2.501439D-03	-2.6018
Na	1.081213D-03	-2.9661
K	2.636795D-04	-3.5789
Fe	3.553972D-05	-4.4493
Mn	4.926513D-07	-6.3075
Cl	2.383079D-04	-3.6229
C	7.653857D-03	-2.1161
S	3.666668D-03	-2.4357

APPENDIX H

Breakthrough Curve Calculations

Appendix H: Breakthrough Curve Calculations

Table H.1: Trial 1: theoretical breakthrough curve data
($\alpha = 0.15$)

dispersivity $\alpha = 0.15$ m
 volume injected $V_i = 6.26$ m³
 porosity $\eta = 0.30$
 aquifer thickness $b = 4.26$ m
 radial distance of front $R = 5.72$ m

Recovery ratio	B function	erfc(B) solution	C _r
0.04	-2.492787	1.9993	0.0002
0.07	-2.366522	1.9989	0.0006
0.10	-2.246768	1.9981	0.0009
0.13	-2.132846	1.9970	0.0015
0.14	-2.096064	1.9953	0.0015
0.16	-2.024172	1.9952	0.0023
0.17	-1.989024	1.9948	0.0025
0.21	-1.853364	1.9909	0.0045
0.27	-1.663073	1.9808	0.0096
0.32	-1.514896	1.9671	0.0159
0.37	-1.374817	1.9468	0.0266
0.42	-1.241788	1.9198	0.0401
0.48	-1.090226	1.8765	0.0618
0.53	-0.969779	1.8253	0.0852
0.64	-0.720358	1.6911	0.1544
0.69	-0.612898	1.6115	0.1943
0.73	-0.529157	1.5376	0.2269
0.79	-0.406776	1.4284	0.2858
0.83	-0.327057	1.3489	0.3255
0.94	-0.113810	1.1236	0.4382
1.27	0.493253	0.4885	0.7557
1.45	0.792712	0.2641	0.8680
1.49	0.855565	0.2293	0.8853
1.52	0.901813	0.2031	0.8985
1.67	1.121715	0.1138	0.9431
1.80	1.297492	0.0684	0.9670
1.90	1.423878	0.0450	0.9775
1.95	1.484341	0.0367	0.9817
2.00	1.543059	0.0298	0.9851

Appendix H: Breakthrough Curve Calculations

Table H.2: Trial 2: theoretical breakthrough curve data

dispersivity $\alpha = 0.15 \text{ m}$
 volume injected $V_i = 1.94 \text{ m}^3$
 porosity $\eta = 0.30$
 aquifer thickness $b = 4.26 \text{ m}$
 radial distance of front $R = 3.18 \text{ m}$

Recovery ratio	B function	erfc(B) solution	C_r
0.06	-1.790327	1.9886	0.0057
0.12	-1.619230	1.9771	0.0115
0.19	-1.432723	1.9564	0.0218
0.25	-1.286966	1.9293	0.0354
0.30	-1.173738	1.9013	0.0494
0.37	-1.025774	1.8502	0.0749
0.43	-0.907240	1.7969	0.1015
0.50	-0.777045	1.7235	0.1382
0.56	-0.678233	1.6563	0.1718
0.62	-0.570254	1.5795	0.2102
0.68	-0.473136	1.4935	0.2533
0.74	-0.379404	1.3990	0.3005
0.80	-0.288536	1.3077	0.3461
0.82	-0.258798	1.2763	0.3618
0.85	-0.214648	1.2334	0.3833
0.90	-0.142133	1.1569	0.4216
1.00	0.000000	1.0000	0.5000
1.10	0.139903	0.8542	0.5729
1.20	0.275908	0.7028	0.6486
1.30	0.406641	0.5716	0.7142
1.40	0.531412	0.4538	0.7731
1.50	0.649917	0.3656	0.8172
1.60	0.762104	0.2827	0.8587
1.70	0.868085	0.2241	0.8880
1.80	0.968081	0.1747	0.9126
1.90	1.062379	0.1348	0.9326
2.00	1.151302	0.1047	0.9476

Appendix H: Breakthrough Curve Calculations

Table H.3: Trial 4: theoretical breakthrough curve data

dispersivity $\alpha = 0.15 \text{ m}$
 volume injected $V_i = 67.11 \text{ m}^3$
 porosity $\eta = 0.30$
 aquifer thickness $b = 4.26 \text{ m}$
 radial distance of front $R = 18.71 \text{ m}$

Recovery ratio	B function	erfc(B) solution	C_r
0.01	-4.752329	1.9999	0.0001
0.02	-4.670200	1.9999	0.0001
0.03	-4.589659	1.9999	0.0001
0.04	-4.510642	1.9999	0.0001
0.05	-4.433092	1.9999	0.0001
0.07	-4.282169	1.9999	0.0001
0.08	-4.208694	1.9999	0.0001
0.09	-4.136478	1.9999	0.0001
0.11	-3.995646	1.9999	0.0001
0.11	-3.995646	1.9999	0.0001
0.15	-3.727245	1.9999	0.0001
0.19	-3.474630	1.9999	0.0001
0.21	-3.353621	1.9999	0.0001
0.23	-3.235857	1.9999	0.0001
0.24	-3.178129	1.9999	0.0001
0.25	-3.121141	1.9999	0.0001
0.27	-3.009293	1.9999	0.0001
0.30	-2.846543	1.9999	0.0001
0.33	-2.689369	1.9998	0.0001
0.41	-2.294190	1.9981	0.0009
0.45	-2.108010	1.9970	0.0015
0.48	-1.972740	1.9946	0.0027
0.50	-1.884484	1.9921	0.0040
0.57	-1.586534	1.9743	0.0129
0.58	-1.545246	1.9702	0.0149
0.60	-1.463550	1.9606	0.0197
0.61	-1.423127	1.9550	0.0225
0.63	-1.343094	1.9413	0.0293
0.66	-1.224978	1.9151	0.0425
0.68	-1.147446	1.8922	0.0539
0.69	-1.109025	1.8802	0.0599
0.72	-0.995068	1.8383	0.0808
0.74	-0.920127	1.8065	0.0967
0.76	-0.845958	1.7650	0.1175

Appendix H: Breakthrough Curve Calculations

Table H.3: Trial 4: theoretical breakthrough curve data (cont'd)

Recovery ratio	B function	erfc(B) solution	C _r
0.79	-0.736053	1.6978	0.1511
0.81	-0.663618	1.6492	0.1754
0.82	-0.627636	1.6191	0.1904
0.83	-0.591803	1.5957	0.2021
0.86	-0.485146	1.5025	0.2488
0.87	-0.449857	1.4661	0.2670
0.88	-0.414690	1.4378	0.2811
0.89	-0.379640	1.3990	0.3005
1.16	0.538594	0.4538	0.7731
1.20	0.669131	0.3508	0.8246
1.30	0.986182	0.1660	0.9170
1.40	1.288776	0.0707	0.9646
1.50	1.576174	0.0267	0.9866
1.60	1.848249	0.0094	0.9953
1.70	2.105273	0.0030	0.9985
1.80	2.347783	0.0011	0.9994
1.90	2.576475	0.0004	0.9998
2.00	2.792130	0.0001	0.9999

Appendix H: Breakthrough Curve Calculations

Table H.4: Trial 4: theoretical breakthrough curve data
($\alpha = 0.60$)

dispersivity $\alpha = 0.60$ m
 volume injected $V_i = 67.11$ m³
 porosity $\eta = 0.30$
 aquifer thickness $b = 4.26$ m
 radial distance of front $R = 9.36$ m

Recovery ratio	B function	erfc(B) solution	C _r
0.01	-1.680202	1.9823	0.0088
0.02	-1.651165	1.9801	0.0100
0.03	-1.622689	1.9778	0.0111
0.04	-1.594753	1.9753	0.0123
0.05	-1.567335	1.9723	0.0139
0.07	-1.513975	1.9671	0.0164
0.08	-1.487998	1.9633	0.0183
0.09	-1.462466	1.9606	0.0197
0.11	-1.412674	1.9537	0.0232
0.11	-1.412674	1.9537	0.0232
0.15	-1.317780	1.9358	0.0321
0.19	-1.228467	1.9151	0.0425
0.21	-1.185684	1.9043	0.0479
0.23	-1.144048	1.8922	0.0539
0.24	-1.123638	1.8862	0.0569
0.25	-1.103490	1.8802	0.0599
0.27	-1.063946	1.8652	0.0674
0.30	-1.006405	1.8427	0.0786
0.33	-0.950836	1.8209	0.0896
0.41	-0.811119	1.7478	0.1261
0.45	-0.745294	1.7045	0.1478
0.48	-0.697469	1.6706	0.1647
0.50	-0.666266	1.6492	0.1754
0.57	-0.560924	1.5714	0.2143
0.58	-0.546327	1.5548	0.2226
0.60	-0.517443	1.5291	0.2355
0.61	-0.503151	1.5205	0.2398
0.63	-0.474855	1.4935	0.2533
0.66	-0.433095	1.4566	0.2717
0.68	-0.405683	1.4284	0.2858
0.69	-0.392099	1.4186	0.2907
0.72	-0.351810	1.3794	0.3103
0.74	-0.325314	1.3489	0.3255
0.76	-0.299091	1.3182	0.3409

Appendix H: Breakthrough Curve Calculations

Table H.4: Trial 4: theoretical breakthrough curve data
($\eta = 0.60$) (cont'd)

Recovery ratio	B function	erfc(B) solution	C _r
0.79	-0.260234	1.2868	0.3566
0.81	-0.234624	1.2549	0.3726
0.82	-0.221903	1.2442	0.3779
0.83	-0.209234	1.2227	0.3886
0.86	-0.171525	1.1899	0.4051
0.87	-0.159048	1.1680	0.4160
0.88	-0.146615	1.1569	0.4216
0.89	-0.134223	1.1458	0.4271
1.16	0.190422	0.7882	0.6059
1.20	0.236573	0.7451	0.6274
1.30	0.348668	0.6308	0.6846
1.40	0.455651	0.5245	0.7377
1.50	0.557262	0.4367	0.7817
1.60	0.653455	0.3580	0.8210
1.70	0.744326	0.2955	0.8522
1.80	0.830067	0.2408	0.8796
1.90	0.910921	0.1983	0.9009
2.00	0.987167	0.1660	0.9170

Appendix H: Breakthrough Curve Calculations

Table H.5: Trial 5: theoretical breakthrough curve data

dispersivity $\alpha = 0.15 \text{ m}$
 volume injected $V_i = 112.75 \text{ m}^3$
 porosity $\eta = 0.30$
 aquifer thickness $b = 4.26 \text{ m}$
 radial distance of front $R = 24.25 \text{ m}$

Recovery ratio	B function	erfc(B) solution	C _r
0.02	-5.354195	2.0000	0.0000
0.02	-5.317014	2.0000	0.0000
0.03	-5.225318	2.0000	0.0000
0.04	-5.135358	2.0000	0.0000
0.05	-5.047067	2.0000	0.0000
0.06	-4.960382	2.0000	0.0000
0.07	-4.875242	2.0000	0.0000
0.08	-4.791590	2.0000	0.0000
0.09	-4.709372	2.0000	0.0000
0.13	-4.393848	2.0000	0.0000
0.14	-4.318075	2.0000	0.0000
0.15	-4.243462	2.0000	0.0000
0.16	-4.169969	2.0000	0.0000
0.17	-4.097562	2.0000	0.0000
0.18	-4.026203	2.0000	0.0000
0.19	-3.955860	2.0000	0.0000
0.20	-3.886499	2.0000	0.0000
0.21	-3.818092	2.0000	0.0000
0.27	-3.426075	2.0000	0.0000
0.28	-3.363571	2.0000	0.0000
0.31	-3.180458	2.0000	0.0000
0.36	-2.888731	1.9999	0.0000
0.37	-2.832242	1.9999	0.0000
0.38	-2.776333	1.9999	0.0001
0.38	-2.776333	1.9999	0.0001
0.39	-2.720988	1.9999	0.0001
0.40	-2.666192	1.9998	0.0001
0.44	-2.452222	1.9993	0.0003
0.44	-2.452222	1.9993	0.0003
0.47	-2.296847	1.9981	0.0009
0.49	-2.195510	1.9970	0.0015
0.50	-2.145482	1.9970	0.0015
0.52	-2.046652	1.9953	0.0023

Appendix H: Breakthrough Curve Calculations

Table H.5: Trial 5: theoretical breakthrough curve data (cont'd)

Recovery ratio	B function	erfc(B) solution	C _r
0.54	-1.949389	1.9938	0.0031
0.57	-1.806266	1.9891	0.0055
0.58	-1.759260	1.9864	0.0068
0.62	-1.574517	1.9733	0.0134
0.66	-1.394635	1.9505	0.0248
0.66	-1.394635	1.9505	0.0248
0.74	-1.047563	1.8577	0.0711
0.75	-1.005236	1.8427	0.0786
0.76	-0.963121	1.8253	0.0874
0.78	-0.879507	1.7812	0.1094
0.85	-0.592660	1.5957	0.2021
0.90	-0.392441	1.4186	0.2907
0.95	-0.195209	1.2118	0.3941
1.00	0.000000	1.0000	0.5000
1.10	0.386284	0.5912	0.7044
1.20	0.761804	0.2827	0.8587
1.30	1.122767	0.1138	0.9431
1.40	1.467269	0.0394	0.9803
1.50	1.794471	0.0114	0.9943
1.60	2.104227	0.0030	0.9985
1.70	2.396849	0.0011	0.9994
1.80	2.672947	0.0002	0.9999
1.90	2.933311	0.0000	1.0000
2.00	3.178835	0.0000	1.0000

Appendix H: Breakthrough Curve Calculations

Table H.6: Trial 6: theoretical breakthrough curve data
($\alpha = 0.60$)

dispersivity $\alpha = 0.60$ m
 volume injected $V_i = 112.75$ m³
 porosity $\eta = 0.30$
 aquifer thickness $b = 4.26$ m
 radial distance of front $R = 12.13$ m

Recovery ratio	B function	erfc(B) solution	C _r
0.02	-1.892994	1.9924	0.0038
0.02	-1.879848	1.9917	0.0042
0.03	-1.847429	1.9906	0.0047
0.04	-1.815623	1.9895	0.0053
0.05	-1.784408	1.9880	0.0060
0.06	-1.753760	1.9864	0.0068
0.07	-1.723658	1.9849	0.0076
0.08	-1.694083	1.9830	0.0085
0.09	-1.665015	1.9808	0.0096
0.13	-1.553460	1.9712	0.0144
0.14	-1.526670	1.9682	0.0159
0.15	-1.500290	1.9661	0.0169
0.16	-1.474307	1.9620	0.0190
0.17	-1.448707	1.9578	0.0211
0.18	-1.423478	1.9550	0.0225
0.19	-1.398608	1.9505	0.0248
0.20	-1.374085	1.9468	0.0266
0.21	-1.349899	1.9413	0.0293
0.27	-1.211300	1.9127	0.0437
0.28	-1.189202	1.9043	0.0479
0.31	-1.124462	1.8862	0.0569
0.36	-1.021321	1.8502	0.0749
0.37	-1.001349	1.8427	0.0786
0.38	-0.981582	1.8340	0.0830
0.38	-0.981582	1.8340	0.0830
0.39	-0.962014	1.8253	0.0874
0.40	-0.942641	1.8161	0.0920
0.44	-0.866991	1.7759	0.1120
0.44	-0.866991	1.7759	0.1120
0.47	-0.812058	1.7478	0.1261
0.49	-0.776230	1.7235	0.1382
0.50	-0.758542	1.7112	0.1444
0.52	-0.723601	1.6911	0.1544

Appendix H: Breakthrough Curve Calculations

Table H.6: Trial 6: theoretical breakthrough curve data
($\alpha = 0.60$) (cont'd)

Recovery ratio	B function	erfc(B) solution	C _r
0.54	-0.689213	1.6635	0.1683
0.57	-0.638611	1.6268	0.1866
0.58	-0.621992	1.6191	0.1904
0.62	-0.556676	1.5633	0.2183
0.66	-0.493078	1.5115	0.2443
0.66	-0.493078	1.5115	0.2443
0.74	-0.370370	1.3990	0.3005
0.75	-0.355405	1.3794	0.3103
0.76	-0.340515	1.3692	0.3154
0.78	-0.310953	1.3388	0.3306
0.85	-0.209537	1.2227	0.3886
0.90	-0.138749	1.1458	0.4271
0.95	-0.069017	1.0676	0.4662
1.00	0.000000	1.0000	0.5000
1.10	0.136572	0.8542	0.5729
1.20	0.269338	0.7132	0.6434
1.30	0.396958	0.5814	0.7093
1.40	0.518758	0.4709	0.7645
1.50	0.634441	0.3732	0.8134
1.60	0.743956	0.2955	0.8522
1.70	0.847414	0.2350	0.8825
1.80	0.945029	0.1839	0.9080
1.90	1.037082	0.1460	0.9270
2.00	1.123887	0.1138	0.9431