

Using the root zone water quality model (RZWQM) to predict water movement through a hydrocarbon contaminated soil
by Scott Michael Anderson

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering
Montana State University
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Abstract:
The quantification of hydrocarbon seepage into the groundwater is a regulatory concern for a refinery. Contaminant transport in the vadose (unsaturated soil) zone is highly dependent on the flow of soil-water. Vadose zone simulation models, such as the popular Root Zone Water Quality Model (RZWQM) can be used to predict seepage of infiltrated water to the groundwater. Basic soil properties, hydraulic parameters, hourly precipitation, and refinery groundwater data were used in the RZWQM. Soil properties were determined from soil samples obtained from five locations in a disturbed area. A representative composite soil profile, using data from the five sample locations, was used for most analyses. The Rosetta program was used to estimate the Brooks and Corey water retention and hydraulic conductivity parameters required by the RZWQM. The RZWQM predicted a nonzero quantity of seepage to groundwater for every year of simulation. Predicted mean annual seepage for the period of groundwater record (1995 thru 2002) was 11.9 cm, which increased to 21.2 cm for the comparatively wetter period of precipitation record (1949 thru 2002). Exceedence probabilities were calculated for each year based on the precipitation record. There was an 80 percent probability that 15 cm of annual seepage would be exceeded and a 20 percent probability that 26 cm of annual seepage would be exceeded. The soil profiles that had the most influence on seepage were bulk density and percent silt in the top soil layer. Monte Carlo simulations were used to determine predicted seepage confidence based on randomly generated, normally-distributed soil properties. The standard deviation of predicted seepage was relatively high (approximately 47 percent of the mean); therefore, variations in soil properties produced a large range of seepage estimates. RZWQM storage predictions were significantly over predicted, which effected annual seepage totals. Inaccuracies probably had less effect on large daily seepage events, which may be more appropriate for estimating contaminant seepage. The link between water seepage and hydrocarbon transport still needs to be evaluated.

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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Abstract

The quantification of hydrocarbon seepage into the groundwater is a regulatory concern for a refinery. Contaminant transport in the vadose (unsaturated soil) zone is highly dependent on the flow of soil-water. Vadose zone simulation models, such as the popular Root Zone Water Quality Model (RZWQM) can be used to predict seepage of infiltrated water to the groundwater. Basic soil properties, hydraulic parameters, hourly precipitation, and refinery groundwater data were used in the RZWQM. Soil properties were determined from soil samples obtained from five locations in a disturbed area. A representative composite soil profile, using data from the five sample locations, was used for most analyses. The Rosetta program was used to estimate the Brooks and Corey water retention and hydraulic conductivity parameters required by the RZWQM. The RZWQM predicted a nonzero quantity of seepage to groundwater for every year of simulation. Predicted mean annual seepage for the period of groundwater record (1995 thru 2002) was 11.9 cm, which increased to 21.2 cm for the comparatively wetter period of precipitation record (1949 thru 2002). Exceedence probabilities were calculated for each year based on the precipitation record. There was an 80 percent probability that 15 cm of annual seepage would be exceeded and a 20 percent probability that 26 cm of annual seepage would be exceeded. The soil profiles that had the most influence on seepage were bulk density and percent silt in the top soil layer. Monte Carlo simulations were used to determine predicted seepage confidence based on randomly generated, normally-distributed soil properties. The standard deviation of predicted seepage was relatively high (approximately 47 percent of the mean); therefore, variations in soil properties produced a large range of seepage estimates. RZWQM storage predictions were significantly over predicted, which effected annual seepage totals. Inaccuracies probably had less effect on large daily seepage events, which may be more appropriate for estimating contaminant seepage. The link between water seepage and hydrocarbon transport still needs to be evaluated.

INTRODUCTION

Due to unknown potential impacts to off-site locations, ConocoPhillips is concerned with the transport of petroleum hydrocarbons that exist in the vadose (unsaturated soil) zone within their Billings, Montana refinery. Contaminant transport is highly dependent on the flow of soil-water, thus a potential for a large precipitation event to transport contaminants to the relatively shallow groundwater and away from the refinery exists. A preliminary study by Kevin Germain (personal communication, 2001) used the Soil Conservation Service (SCS) curve number method in conjunction with the Thornthwaite water balance model to predict hydrologic processes at the refinery. These simplified lump-sum models are difficult to calibrate for site-specific conditions. Using average annual precipitation and crudely estimated coefficients near zero annual seepage was estimated, suggesting that hydrocarbon transport by infiltrated water was of little concern.

To better understand these hydrologic processes and enable ConocoPhillips to make more informed management decisions a robust hydrologic model, the Root Zone Water Quality Model (RZWQM), was used to model runoff, infiltration, evapotranspiration (ET), soil storage, and seepage to groundwater within the disturbed South 40 area of the Billings, Montana refinery. The RZWQM is an event-driven numerical model that utilizes site-specific soil properties and meteorological input data.

Of the hydraulic processes simulated with the RZWQM, seepage is of greatest concern here. The quantity of seepage is the result of many factors including the

characteristics of the soil profile, the volume of water initially in the soil, the depth to groundwater, and the intensity, duration, and frequency of precipitation events. Accurate estimates of soil-water transport are necessary before contaminant fate and transport can be predicted.

Mean annual and daily seepage quantities were determined from measured soil properties and historical precipitation data. Variations in mean annual seepage due to uncertainty in measured soil properties were also estimated. The confidence of mean annual seepage predictions were determined with the Monte Carlo method by randomly sampling the soil input parameters based on statistical distributions determined from the measured data and then determining the output seepage distribution.

Goals and Objectives

The primary goal of this research was to provide ConocoPhillips with a best estimate of the quantity of groundwater seepage (if any) using the RZWQM. The model incorporated measured site-specific soil properties obtained from five locations (sites A, B, C, D, and E) in the South 40 area and provided estimates for a larger composite area (composite site). The most permeable soil layers were identified, the sensitivity of seepage to the specific soil properties was determined, and the model confidence was estimated. This goal was accomplished by completing the following objectives:

1. On-site data collection. Necessary field data was collected from the South 40 area of the Billings, Montana ConocoPhillips Refinery site. Infiltration rates were measured using infiltrometers. Intact soil cores were used to measure texture (percent sand, silt, and clay), bulk density, saturated hydraulic conductivity, and other important soil properties. These and other related data provided the basis for developing a comprehensive assessment of seepage in the South 40 area.

2. Seepage estimation. The RZWQM was used to predict seepage to groundwater at the sample locations and the composite site based on mean soil properties and hourly precipitation data for the period of groundwater record (8/16/1994 thru 12/31/2002). Predicted seepage values are a necessary first step in estimating contaminant seepage.

3. Seepage probability. Long-term management decisions should not be entirely based on the relatively short period of groundwater record. Seepage was predicted for the composite site with the RZWQM using the full Billings hourly precipitation record (7/3/1948 thru 12/31/2002) and a constant groundwater elevation. Exceedence probabilities are calculated for annual and daily seepage events, which can be used in risk assessment.

4. Model sensitivity. A sensitivity analysis was performed to determine which soil properties had the greatest effect on RZWQM predicted seepage. The composite site's soil properties were varied plus or minus one standard deviation for the period of groundwater record. The variability of soil properties within each of the soil layers and between sites was used to determine seepage variation.

5. Model confidence. Confidence in predicted seepage, based on measured soil properties, was assessed using the Monte Carlo method. Simulations were run for the period of groundwater record using the composite site's physical and hydraulic inputs in the RZWQM. The probability that a specific quantity of seepage will be exceeded was determined based on soil property variability.

Monte Carlo Method

Rubinstein (1981) described the Monte Carlo method as the most commonly used and powerful complex problem analysis tool. Monte Carlo is not a computer model in itself, but can be used in conjunction with any numerical model. The Monte Carlo method uses statistical distributions of input parameters to estimate the range of possible outputs. The probability of an event can be determined from the statistical distributions of model outputs. Common applications for the Monte Carlo method are maintenance operations, wind tunnel analysis, river basin modeling, and military training (Rubinstein, 1981).

If there are a large number of model inputs, a sensitivity analysis may be performed to minimize inputs used in the Monte Carlo simulations (Rubinsein, 1981). Monte Carlo simulations are often executed only on the input parameters that have the greatest effect on model output. The statistical distributions for the sample population of each input parameter simulated must be known. Common statistical distributions are: uniform, normal, lognormal, exponential, gamma, etc. The chi-square goodness-of-fit test, described by Stephens (1998), can be used to determine which statistical distribution is most appropriate for each input parameter.

Using the Monte Carlo method, independent random (technically pseudorandom) numbers are generated from the statistical distributions of each input parameter (Rubinstein, 1981). Best results are obtained by generating as many sets of random numbers as practically possible. The generated values can be input into a numerical model, such as the RZWQM.

Root Zone Water Quality Model (RZWQM)

In 1992, the United States Department of Agriculture (USDA) developed the RZWQM to simulate soil-water, nutrient, and pesticide transport in the soil vadose zone (Ahuja et al., 1999a; RZWQM, 1992). The RZWQM is capable of simulating water quality and agricultural processes such as infiltration, runoff, evapotranspiration (ET), water distribution, chemical transport, macropore flow, heat transport, plant growth, organic matter cycling, and pesticide processes (Malone et al., 2002).

The RZWQM is a mass-conservative, mixed form iterative finite-difference numerical model (Ahuja et al., 1999a). Lateral heterogeneity is not considered because the RZWQM is a point-scale model (Malone et al., 2002). Vertical heterogeneity can be accurately modeled with up to twelve distinct soil layers to the maximum depth of three meters. The effects of varying input parameters can be easily analyzed by running multiple scenarios using the built-in batch mode. A maximum of 100 years of precipitation data can be simulated with the RZWQM (Ahuja et al., 1999a).

Minimum RZQWM inputs are precipitation and meteorological data, soil horizon depths, soil texture (percentage of sand, silt, and clay), bulk density, and bottom boundary condition. A unit gradient, constant flux, or constant pressure head boundary must be set at the bottom of the profile (Ahuja et al., 1999b). A unit gradient condition is used to simulate unsaturated soil below the bottom soil layer. The constant flux condition is used with a dynamic groundwater table. The third condition models a constant pressure head at the bottom boundary using the initial matric potential.

The RZWQM calculates a water balance between precipitation, runoff, infiltration, evapotranspiration (ET), seepage, and storage using sub-hourly time intervals (Ahuja et al., 1999a). Internal to the model are three numerical grids: the first grid is divided by the input layer depths used to describe the physical properties of the soil, the second is a non-uniform grid for water redistribution, and the third is a one centimeter grid for vertical infiltration (Ahuja et al., 1999b). The bottom soil profile depth occasionally needs to be adjusted by a few centimeters to accommodate the model's numerical schemes.

The Root Zone Water Quality Model uses a Modified Penman-Montieth model to simulate potential evapotranspiration (Malone et al., 2002). ET is the combined amount of evaporation and transpiration. Evaporation is the physical process of soil or surface water entering the atmosphere, and transpiration is an evaporative process facilitated by plant biological activity (Farahani and DeCoursey, 1999). The freezing and thawing of soils are not simulated with the current version of the RZWQM. Instead, the model uses the Precipitation Runoff Modeling System (PRMS) to determine snow accumulation and melt. The PRMS model simulates the water balance and heat transport to and from the snow. When snow has accumulated on the soil surface, the surface temperature is set to zero degrees Celsius. Otherwise, the soil surface temperature is set equal to the average air temperature for the day (Flerchinger et al., 1999).

Seepage is often the most difficult hydraulic process to measure or estimate. Precipitation, infiltration, runoff, ET, and soil storage measurements must be accurate for seepage to be accurately predicted. Singh et al. (1996) determined that effective porosity, initial water content, and lateral saturated hydraulic conductivity were the most important model parameters for quantifying seepage. Unfortunately, the lateral saturated hydraulic conductivity is difficult to measure because artificial drains are usually required.

Runoff and water content predictions using the RZWQM are usually reasonable though consistent biases have been documented. Ghidey et al. (1999) used the RZWQM to predict runoff and soil-water content at an agricultural site. Measured soil texture, bulk density, and 1/3-bar water content were used. The model tended to over predict runoff during dry periods and under predict during wet periods. However, the overall

predicted runoff varied by less than five percent of the measured runoff. Soil-water contents were slightly under predicted in most cases and seriously under predicted in high clay content soils. In a similar study, Malone et al. (2000) found that soil-water content predictions were generally adequate but sometimes under predicted.

A benchmark for estimating and calibrating ET is the Bowen Ratio Energy Balance (BREB). Jaynes and Miller (1999) found that ET predictions were somewhat under predicted using the RZWQM as compared to the BREB. However, the authors found that simulated annual seepage compared reasonably well to drainage from a closed subbasin. Farahani and DeCoursey (1999) found simulated seepage to be accurate when judged against measured seepage collected in metal troughs.

Ellerbroek et al. (1998) used the RZWQM and the Monte Carlo method to determine if metolachlor transport was more sensitive to irrigation rate or saturated hydraulic conductivity. The authors found that varying the water application rate had a greater affect on transport than the saturated hydraulic conductivity. In fact, conductivity was significant only at high application rates. Surprisingly, Malone et al. (2000) found that increasing the saturated hydraulic conductivity in the RZWQM decreased water and herbicide transport through relatively large cracks in the soil called macropores.

The model employs the popular Green-Ampt equation to simulate the downward flow of water through the soil profile during precipitation (Ahuja et al., 1999b). When water first enters the soil the infiltration rate is high, but gradually decreases until a constant final rate is attained (Or et al., 2002). The Green-Ampt equation is (Green and Ampt, 1911; Ahuja et al., 1999b):

$$V = K_{se} \cdot \frac{(\Psi_{wf} + H_o + Z_{wf})}{Z_{wf}}$$

where V is the infiltration rate (cm/hr), K_{se} is the effective average saturated hydraulic conductivity of the wetting zone (cm/hr), Ψ_{wf} is the matric potential (negative pressure head) at the wetting front (cm), H_o is the depth of surface ponding (cm), and Z_{wf} is the depth of the wetting front (cm). Basic assumptions of the equation are: a distinct wetting front exists in the soil where the water content is constant below and above it, the wetted soil has constant properties, and the matric potential is constant at the wetting front (Or et al., 2002).

The Richard's equation describes how soil-water is distributed in the vadose zone between precipitation events. The one-dimensional Richard's equation is built into the RZWQM (Ahuja et al., 1999b; Wu et al., 1996):

$$\frac{d\theta(\Psi)}{dt} = \frac{d}{dz}\left[K(\Psi)\left(\frac{d\Psi}{dz} - 1\right)\right]$$

where Ψ is the matric potential (cm), z is the height from a reference elevation (cm), $\theta(\Psi)$ is the soil-water content as a function of matric potential (cm^3/cm^3), and $K(\Psi)$ is the hydraulic conductivity as a function of matric potential (cm/hr). Water retention ($\theta(\Psi)$) and hydraulic conductivity ($K(\Psi)$) functions are required to determine the distribution of soil-water at any given time. Typical water retention and hydraulic conductivity curves are shown in Figures 1.1 and 1.2, respectively.

Figure 1.1. Water retention curves for three soil types (Or et al., 2002).

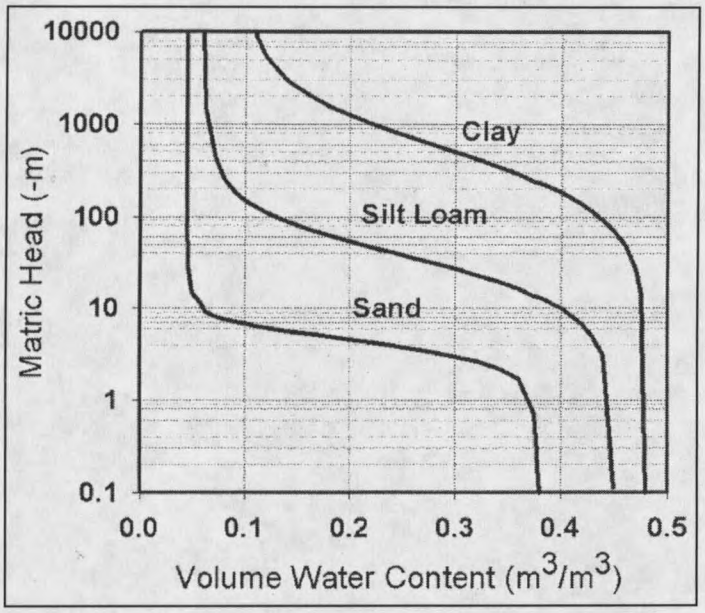
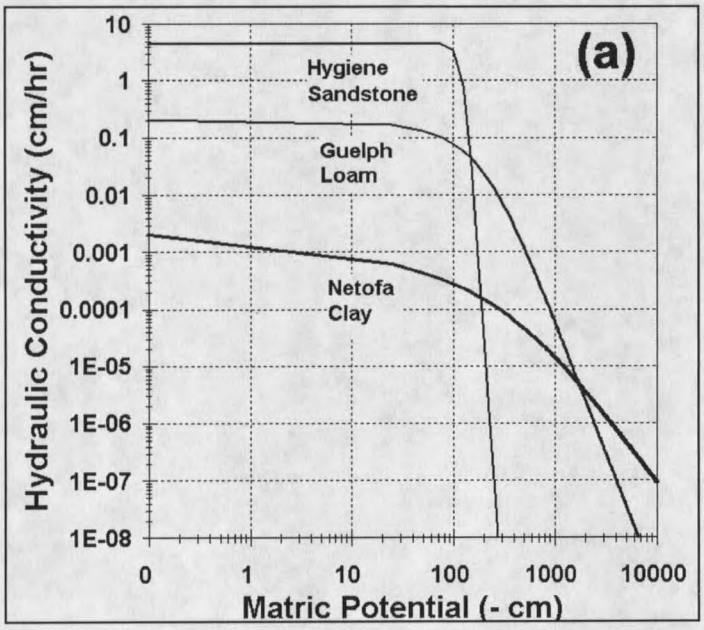


Figure 1.2. Hydraulic conductivity curves for three soil types (Or et al., 2002).



Water Retention and Hydraulic Conductivity Functions

Most numerical vadose zone models use either the Brooks and Corey (1964) or van Genuchten (1980) equations to approximate the water retention and hydraulic conductivity relationships necessary to describe the Richard's equation. The RZWQM uses the Brooks and Corey equations. An understanding of both sets of equations is useful because neither is universally accepted and there is often a need to convert between them. Figure 1.3 shows measured water retention data and calibrated Brooks and Corey and van Genuchten functions.

The Brooks and Corey equations are still widely used today, almost forty years after their development. Despite the popularity of these equations, a discontinuity exists at the bubbling pressure that makes them difficult to implement. Two separate matric potential ranges are required for the Brooks and Corey functions because of this discontinuity (Brooks and Corey, 1964; 1966):

For $\Psi > \Psi b$:

$$\frac{\theta(\Psi) - \theta_r}{\theta_s - \theta_r} = \left(\frac{\Psi_b}{\Psi}\right)^{\lambda} \qquad K(\Psi) = K_{sat}$$

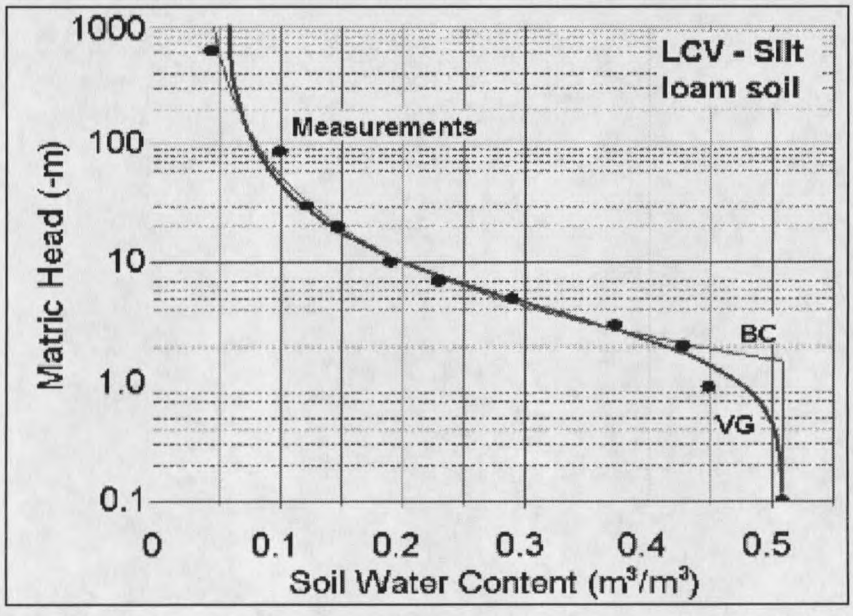
For $\Psi < \Psi b$:

$$\frac{\theta(\Psi) - \theta_r}{\theta_s - \theta_r} = 1.0 \qquad K(\Psi) = K_{sat}\left(\frac{\Psi_b}{\Psi}\right)^{2+3\cdot\lambda}$$

where θ_s is the saturated water content (cm^3/cm^3), θ_r is the residual water content (cm^3/cm^3), Ψ_b is the air-entry or bubbling pressure (cm), λ is the pore-size distribution index for the soil, and K_{sat} is the saturated hydraulic conductivity (cm/hr). θ_s is often

assumed equal to the soil porosity. θ_r is the amount of water in a volume of soil after the soil has thoroughly drained. Unfortunately, θ_r is difficult to measure accurately. van Genuchten (1980) suggested that a large matric potential (–15 bars) could be used as an approximation. Ψ_b is related to the largest pore diameter in a continuous network of flow pores and is approximated by the capillary pressure at which air first moves through the pores. λ is related to the size of the flow channels in the soil. Sands generally have a large λ, while clays usually have smaller values (Brooks and Corey, 1964; 1966). K_{sat} is a measure of how fast water is transported when the soil is completely saturated. It is important to note that K_{sat} is not equivalent to K_{se} in the Green-Ampt equation (Klute and Dirksen, 1986). Bouwer (1986) found that K_{se} was equal to approximately half K_{sat}.

Figure 1.3. Brooks and Corey and van Genuchten functions calibrated to measured water retention data (Or et al., 2002).



van Genuchten (1980) proposed a set of water retention and hydraulic conductivity equations that do not exhibit a discontinuity. The van Genuchten functions are:

$$\frac{\theta(\psi)-\theta_r}{\theta_s-\theta_r}=\left[1+(\alpha\cdot\Psi)^n\right]^{-m} \qquad K(\Psi)=K_{sat}\cdot\frac{\left[1-(\alpha\cdot\Psi)^{n-1}\cdot\left[1+(\alpha\cdot\Psi)^n\right]^{-m}\right]^2}{\left[1+(\alpha\cdot\Psi)^n\right]^{\frac{m}{2}}}$$

where α (1/cm), n, and m are fitting parameters and all other variables are as previously defined. As a simplification, the parameter m is usually defined equal to 1-1/n.

van Genuchten (1980) applied the proposed water retention and hydraulic conductivity functions to four types of soils: sandstone, two types of silt loams, and clay. For the sandstone and the silt loams, the model showed excellent agreement between observed and predicted hydraulic conductivities. However, the hydraulic conductivity was seriously under predicted with the clay (van Genuchten, 1980). van Genuchten et al. (1989) concluded that the unsaturated hydraulic conductivity models work reasonably well for coarse and medium-textured soils but give worse predictions for fine-textured (clay) soils.

Vereecken et al. (1989) compared five different forms of the van Genuchten water retention function ($\theta(\Psi)$) to measured water retention data. The only parameter that was varied was m. Best results were found when m was calibrated or set equal to unity. The standard form of the equation (m = 1-1/n) provided less accurate predictions for the 182 soil horizons analyzed. The parameter m was set equal to unity for a sensitivity analysis

of θ_s, θ_r, α, and n. The authors found that water retention was most sensitive to the saturated water content and least sensitive to the residual water content.

Vereecken et al. (1990) compared the accuracy of four different hydraulic conductivity equations ($K(\Psi)$) using data measured from 127 soil cores. The first model was an exponential function, the second was a power function, the third had the form of the Brooks and Corey equation with the residual water content set to zero, and the fourth model was the Gardner (1958) equation, which is very similar to the van Genuchten equation. The least amount of variance was found with the Gardner equation (0.16).

Regardless of which set of $\theta(\Psi)$ and $K(\Psi)$ functions are used, the fitting parameters (Ψ_b and λ or α and n (assuming m is fixed)) must be calibrated to a specific soil or estimated from known soil properties (van Genuchten, 1980). These parameters can be calibrated to measured water retention or hydraulic conductivity data. Because of the relative ease of measurement, the $\theta(\Psi)$ function is usually calibrated and the parameters used in the $K(\Psi)$ function.

Direct Measurements

The Brooks and Corey or van Genuchten functions can be calibrated from water retention data measured directly in the field or laboratory. Water retention data usually has the shape of the water retention curves shown in Figure 1.1 (Or et al., 2002). To obtain continuous functions, the Brooks and Corey parameters Ψ_b and λ or the van Genuchten parameters α and n (with m fixed) can be calibrated to the data by minimizing the sum of the squared errors (SSE) or maximizing the squared correlation coefficient

(R^2) using spreadsheet software (Wraith and Or, 1998). The calibrated parameters can be used in both the $\theta(\Psi)$ and $K(\Psi)$ functions.

Unfortunately, the cost and time involved in direct measurements often make these methods unfeasible. For example, water retention determination in the laboratory requires desorption of an initially saturated soil to a specific matric potential (soil suction head) while simultaneously measuring the water content. This procedure must be repeated for many matric potentials to obtain a smooth curve (Ayra and Paris, 1981). A popular field method for obtaining water retention curves consists of taking numerous measurements with a tensiometer for matric potential and time domain reflectometry (TDR) probe for water content (Or et al., 2002). Hydraulic conductivity measurements are even more arduous. It can take weeks to determine the conductivities of fine-textured or highly compact soils.

Estimation Techniques

Rather than calibrating the Brooks and Corey or van Genuchten parameters from measured data, the parameters can be directly estimated from easily measured soil properties. Most often these properties are soil texture, bulk density, organic carbon content, water contents measured at specific matric potentials (i.e. 1/3 or 1/10-bar), or any combination of these. The more soil properties included the better the results (Rawls et al., 1982; Wu et al, 1996). van Genuchten et al. (1989) stated some advantages of estimation techniques over direct measurement: the governing flow equations do not need

to be approximated, hydraulic conductivities can be predicted for the full range of water contents, and parameter uncertainty and model accuracy can be quantified.

The Brooks and Corey (1964) parameters must be input into the RZWQM directly or estimated by one of two methods built into the RZWQM. The first estimation method is used when only the soil texture (percent sand, silt, and clay) and bulk density are known (Ahuja et al., 1999b). The model determines the USDA Soil Conservation Service (SCS) texture class from these properties. Tabulated Brooks and Corey parameters are then assigned based on the bulk density and texture class alone.

The second RZWQM estimation method predicts the Brooks and Corey parameters using the soil scaling technique described by Warrick et al. (1977). This method can only be used if the measured saturated hydraulic conductivity and 1/3 or 1/10-bar water content are known in addition to soil texture and bulk density. The soil is first classified as it was in the previous method. Mean properties from this soil class are used as the "similar soil." The authors found that the matric potential of a soil sample could be related to the similar soil's scaled mean matric potential. The water retention curve of the similar soil is then shifted to coincide with the measured water content of the sample soil. The Brooks and Corey parameters are found by minimizing the sum of squares. Soil scaling was found to be most effective in coalescing large data sets, where it reduced the sum of squares by 34 to 90 percent (Ahuja et al., 1999b).

Cosby et al.'s (1984) method can be used to estimate the Brooks and Corey parameters directly. The authors found that soil texture was the only regression equation property of significance from a two-way analysis of variance (ANOVA). In fact, the

authors found that use of only one texture parameter gave an approximation nearly as good as using two texture components (three would be redundant). Linear regression equations were developed using only percent sand, silt, or clay. Correlation for all estimated parameters to 1448 measured water retentions and hydraulic conductivities was relatively high ($0.77 < R^2 < 0.97$).

Recently, neural networks have been used to improve the accuracy of empirical regression equations (Schaap, 1999). Neural networks get their name from their resemblance to biological neural systems. Neural networks use an iterative calibration procedure to link soil inputs to hydraulic outputs. Schaap et al. (1998) defined a common neural network as a nonlinear data transformation structure consisting of input and output nodes connected to a number of hidden nodes by adaptable coefficients. In this study, the authors compared four published water retention equations and six published hydraulic conductivity functions to the neural network predictions. A total of 1209 soil samples for water retention prediction and 620 for hydraulic conductivity were used.

Schaap et al. (1998) found the root mean square residuals (RMSR) of the neural network models to be approximately 0.01 to 0.02 m^3/m^3 lower than the published regression equations. These results, however, were comparable when water content data was unavailable or when uncertainty in the data was large. Of the published water retention equations, Vereecken et al.'s (1989) predictive equation had the least amount of error (average RMSR of 0.098). The comparable neural network model had an average RMSR of 0.087. Cosby et al.'s (1984) published hydraulic conductivity equation

performed best (average RMSR = 0.746 log(cm/day)). The neural network model with similar inputs (soil texture) had an average RMSR of 0.602.

Rosetta

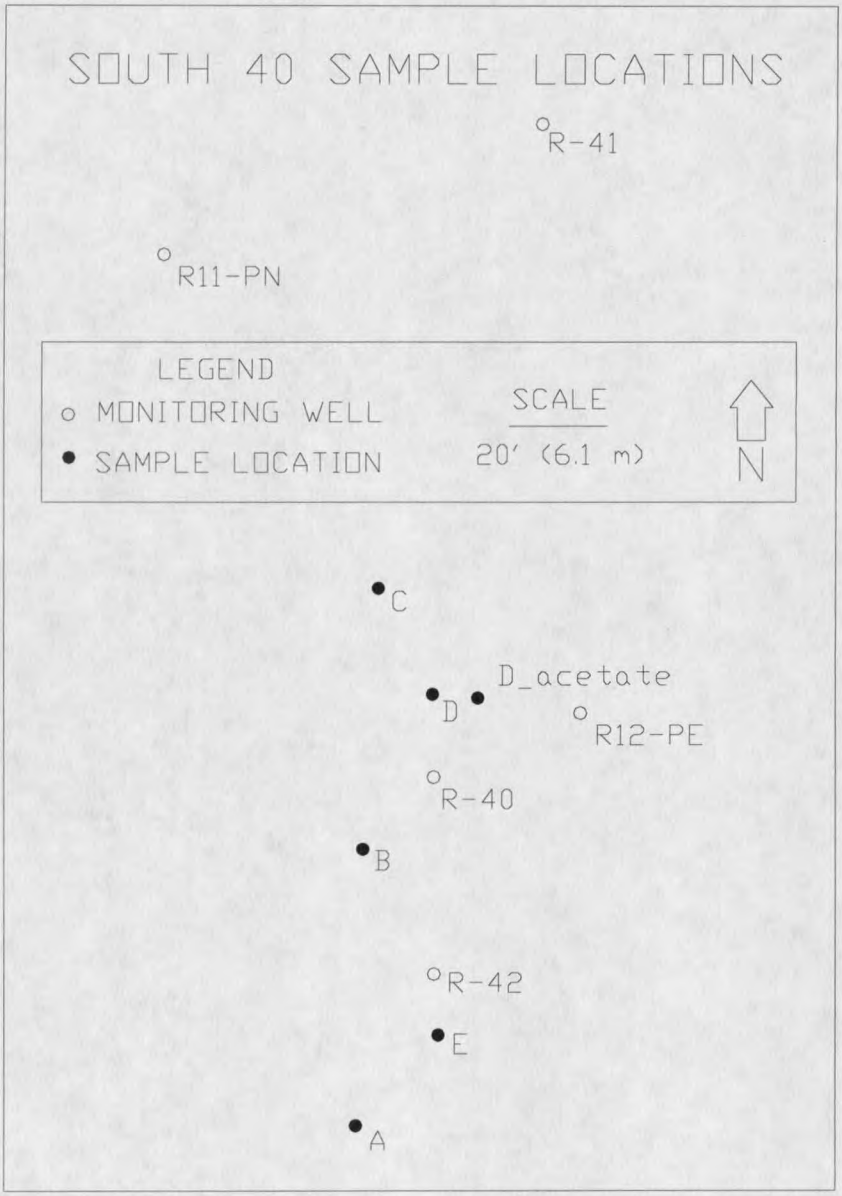
The Rosetta program was developed by Schaap (1999) to use neural networks to predict the van Genuchten function parameters. Rosetta uses soil texture, bulk density, and up to two measured water contents to estimate α, n, and K_{sat} (m=1-1/n). Feed-forward neural networks are used along with the bootstrap method to determine parameter uncertainties. Given calculated uncertainties are plus or minus one standard deviation. The theory behind the bootstrap method is "that multiple alternative realizations of the population can be simulated from the single data set that is available (Schaap, 1999)." The predicted van Genuchten parameters must be converted into Brooks and Corey parameters in order to be input into the RZWQM (described in Chapter 3).

METHODS AND MATERIALS

Field Tests

Fieldwork was performed during November 2002 at the Billings, MT ConocoPhillips refinery. A map of the refinery is provided in Appendix A. The disturbed South 40 area is located in the Southeast ¼ of the refinery. Groundwater flow is to the Northeast. Five sample locations were chosen within the "South 40 DNAPL" shaded area in the greater South 40 area. These sites were termed A, B, C, D, and E. At each of the sites, Shelby and acetate tubes were direct-pushed into the ground with a hollow stem auger. The acetate samples from site D were taken approximately three meters (ten feet) to the east of where the Shelby tube cores were obtained because deeper sampling was possible in that area due to less gravel at the surface. Otherwise, Shelby and acetate tube samples were within one meter of each other. The capability of the drill rig, the granularity and compaction of the soil, and the strength of the tubes limited the depth that samples could be obtained in some cases. The steel Shelby tubes were 7.6-cm (3-in) in diameter and 76.2-cm (2.5-ft) long. The acetate tubes were 3.5-cm (1.4-in) in diameter and 121.5-cm (4-ft) long. A South 40 location map with the five sample locations and nearby monitoring wells is included in Figure 2.1. The location D_acetate is where site D acetate tube samples were taken.

Figure 2.1. Soil sample and nearby well locations. Intact soil cores were obtained from all sites A, B, C, D, and E in the South 40 refinery area. Acetate tube samples were taken from each of these locations, except at site D they were taken approximately 3 meters (10 ft) east.



An approximately 152-cm (5-ft) deep trench was excavated with a backhoe at each of the five sample locations and the soil layer depths were measured. Three distinct soil layers were observed at each of the sites where the soil texture changed. Adjacent to each trench, the soil layers were individually excavated. One or two intact cores were obtained from each of the layers with Shelby tubes cut to a length of 15 cm (6 in). The backhoe pushed the cut Shelby tubes vertically into the soil and the intact cores were removed by hand excavation. For safety reasons, the deepest samples were obtained at 152 cm (5 ft) below the surface.

Blake and Hartage's (1986) sand-funnel method for determining surface bulk density was performed twice at each of the five South 40 sample locations. Bulk density is defined as the ratio of the mass of dry solids to the bulk volume of the soil. Mass-based soil properties can be converted to the more commonly used volume-based properties using the bulk density. The sand-funnel method required a sand-funnel apparatus, uniform sand, a template, a small shovel, plastic bags, and a scale. First, the sand-funnel was filled with sand and its mass was determined. The template was then placed over the soil of interest and a soil sample the diameter of the template (30.5-cm (12-in)) was carefully excavated and collected in a plastic bag and sealed. Next, the sand-funnel was inverted over the template and sand was dispensed into the excavated hole. When the hole and the funnel were completely filled, the sand-funnel apparatus was reweighed, the difference representing the soil sample volume. Bulk density calculations were made in the laboratory.

Infiltration rates were determined at each of the five locations using infiltrometers. Infiltration rate is the rate at which water soaks into the soil surface from a small head of water (Bouwer, 1986). Infiltrometers were made of 30.5-cm (12-in) diameter steel pipe cut into 30.5-cm lengths. The following field procedure was used: 1) the infiltrometers were pushed two to six inches into the highly compact soil with a backhoe, 2) the volume of water required to produce a 5.1 to 7.6 cm (2 to 3 in) ponding depth in the infiltrometer was measured in a graduated cylinder, 3) the ponding depth above the soil surface was marked on the inside of the infiltrometer, 4) water was carefully emptied into the infiltrometer, and 5) the depth of water from this mark was measured over time and recorded. Two replicate readings were taken at each site, one north and the other south of the soil sample locations. Infiltration rates (cm/hr) were calculated by dividing each decrease in water level by the corresponding time (Bouwer, 1986).

Laboratory Tests

Sealed soil samples from the sand-funnel method were taken to the laboratory for analysis. Samples were weighed, oven-dried at 75 degrees Celsius (105 degrees Fahrenheit) to preserve the organic matter, and then reweighed (Blake and Hartage, 1986). The volume of each excavation was calculated by dividing the mass of sand required to fill the excavation by its inherent bulk density (1.57 g/cm^3). Bulk density of the excavated soil was calculated by dividing the dried mass by the excavation volume. Porosity was calculated directly from the bulk density using an assumed particle density

of 2.65 g/cm^3. The bulk density of the intact soil cores was determined by dividing the dried soil mass by the sample volume (Or et al., 2002). Volumetric water content, the volume of water per bulk volume of soil, was calculated as the difference between wet and dry soil mass divided by the sample volume.

Sieving and sedimentation were used to determined soil texture (percent sand, silt, and clay) of all soil samples. Sieving the soil was used to separate the sand-sized (> 0.05 mm) particles (Or et al., 2002). Particles smaller than 0.05 millimeters were classified into silt and clay by the Modified Day hydrometer method. The soil particles separated by adding solution containing water and a dispersing agent (Sodium Hexametaphosphate) to the sample.

Additional soil properties were measured only on the relatively uncontaminated surface sand-funnel samples because of the lower cost of testing clean samples. The water content at 1/3-bar matric potential was measured with a pressure plate apparatus (Cassel and Nielsen, 1986). Nelson and Sommers (1982) method was used to determine the fraction of organic carbon in the surface samples. A LECO combustion analyzer was used to determine the total amount of carbon. Inorganic carbon was obtained from a gravimetric procedure that directly measures calcium carbonate. The fraction of organic carbon was equal to the total carbon minus the inorganic carbon.

Saturated hydraulic conductivity (K_{sat}) was measured using Bowles (1992) method. Measurements were possible only on 19 of the 33 Shelby tube samples. The remaining Shelby tube sections were partly crushed due to the large amount of gravel in the soil and could not fit into a permeameter for testing. All soil samples were gradually

saturated before testing. The falling-head method was used for all but one of the soil samples. Permeameters designed for 7.6-cm (3-in) diameter 15.2-cm (6-in) long Shelby tubes were used. Tubes that were not the precise diameter were not accommodated by the permeameter. The remaining sample had to be tested by the constant-head method due to its extreme compaction. Both methods use Darcy's law to determine K_{sat} (Bowles, 1992). A total of five tests were performed on each sample. K_{sat} tended to approach a steady value as more tests were run, probably due to the presence of air voids in the assumed "saturated" samples. Therefore, data from the first test was discarded and the four remaining tests were averaged to account for this phenomenon.

DATA COMPILATION RESULTS

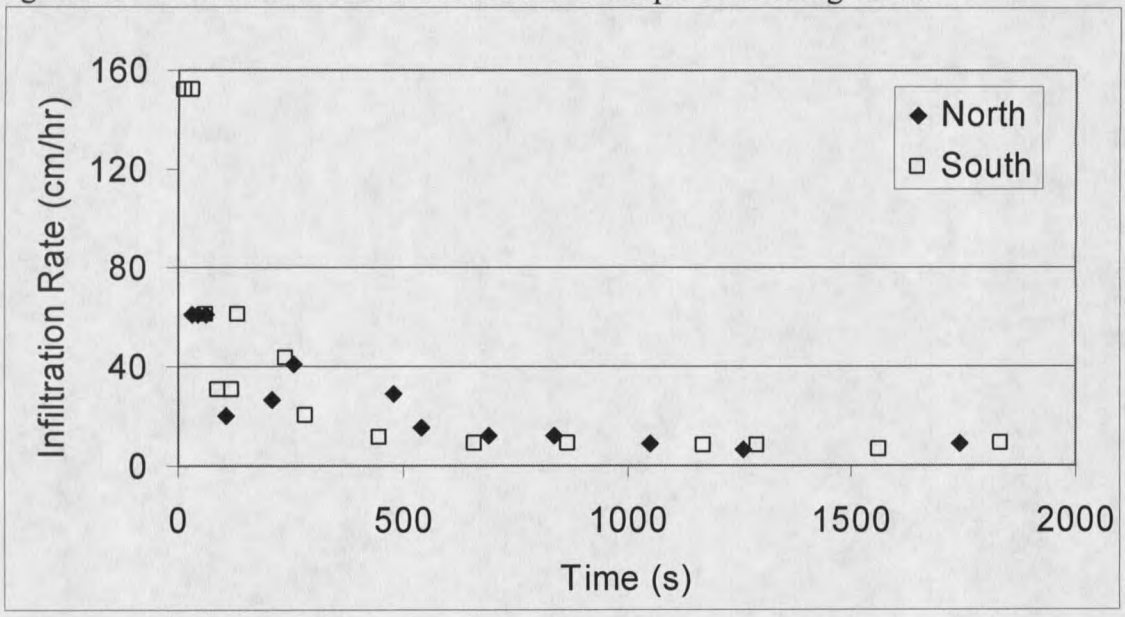
Measured soil properties had to be assigned to vertical soil layers to be input into the RZWQM. Brooks and Corey parameters were estimated from soil layer properties. In addition to these parameters, precipitation, meteorological, and groundwater data were required for RZWQM simulations.

Measured soil sample data were divided into the three layers observed at the five South 40 sites. Because the fraction of organic carbon was only measured on surface samples, the value from the top layer was also used for the bottom two layers. Measured saturated hydraulic conductivities were not represented in several of the soil layers and repeat samples within the soil layers often varied by orders of magnitude. Instead, K_{sat} was predicted with Rosetta from soil texture, bulk density, and the top layer's 1/3-bar water content (Schaap, 1999).

Field estimated infiltration rates were compared to predicted saturated hydraulic conductivities. Infiltration rates are shown in Figure 3.1 for a representative site (site C). Bouwer (1986) defined the final infiltration rate as the constant infiltration rate after long periods of testing. The final value was calculated by averaging the final three to five infiltration rates from each infiltrometer. Theoretically, the final infiltration rate is the effective average saturated hydraulic conductivity of the wetting zone or K_{se} from the Green-Ampt equation. K_{sat} was calculated from the infiltration rates using Bouwer's (1986) approximation: $K_{sat}=2*K_{se}$. This approximation does not take into account the initial water content. Average estimated K_{sat} from Rosetta (3.6 cm/hr) was more

conservative than the average calculated K_{sat} using the final infiltration rate (13.7 cm/hr). It is typical for saturated hydraulic conductivity measurements on the same soil to vary by an order of magnitude so the Rosetta predicted values seemed reasonable.

Figure 3.1. Infiltration rates calculated from two replicate readings at site C.



The close proximity of the five sample locations warranted the merging of data from all 62 soil samples into one "composite" site. Each of the composite site's three layers contained soil samples from each sample site's respective layers. Layer depths from the five sample locations were averaged. The USDA soil texture class was determined from the mean percent sand, silt, and clay for each layer. Visual profiles containing texture class, bulk density, porosity, and estimated K_{sat} are shown in Figure 3.2. The mean physical and hydraulic soil properties calculated for all sites are included

in Table 3.1. Standard deviations and number of samples used for mean and standard deviation calculations are included in Appendix A.

Figure 3.2. Observed soil profiles for the five sample locations and the composite site. The highest groundwater elevations are shown. All dimensions are in meters. BD = bulk density (g/cm^3), n = porosity (cm^3/cm^3), K = estimated saturated hydraulic conductivity (cm/hr).

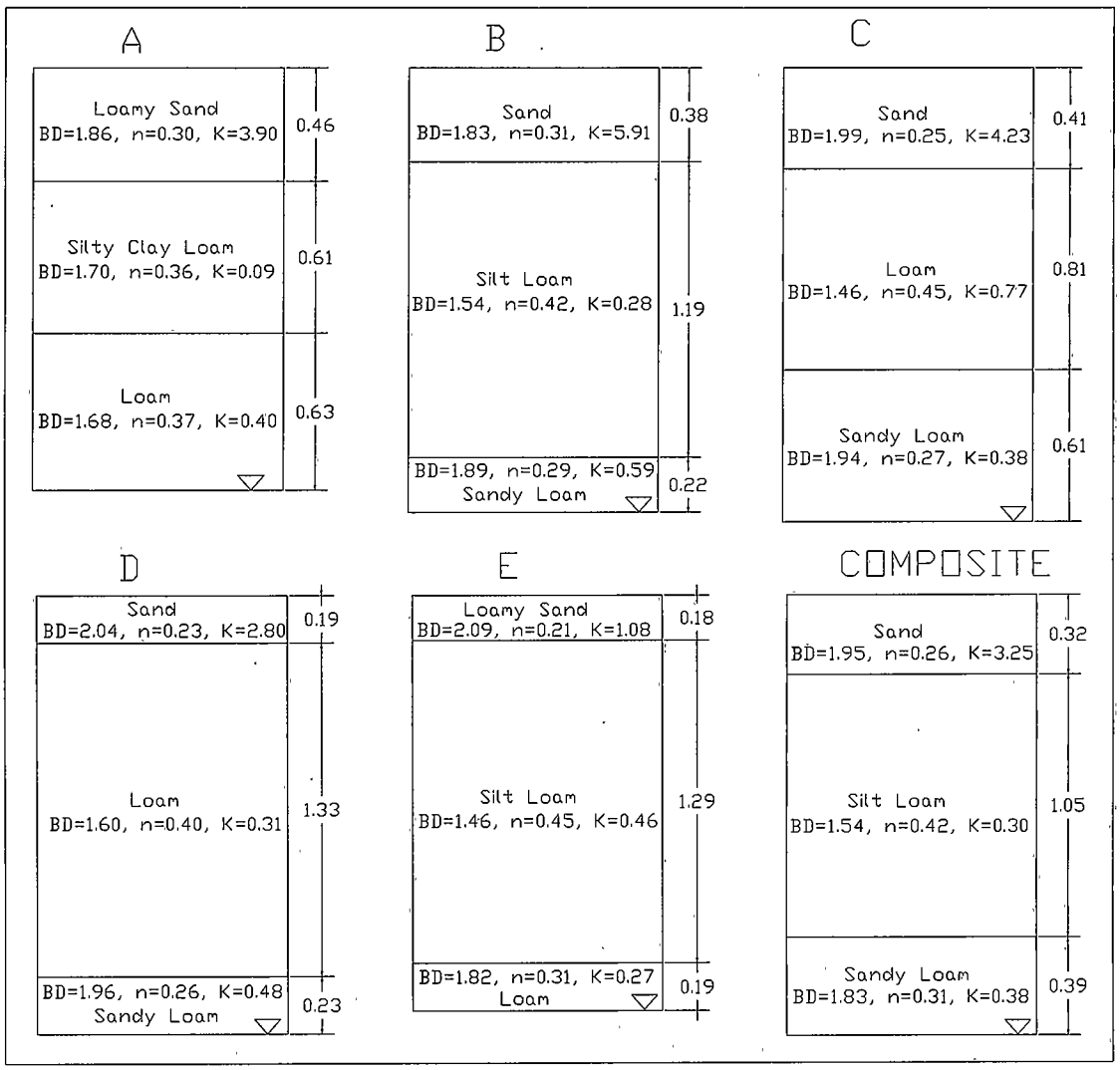


Table 3.1. Mean measured or estimated soil properties for all sites (CP = composite site, GW = groundwater depth, N/A = not applicable). Estimated values are shaded.

Site	Layer	USDA Texture Class	Layer Bottom Depth (cm)	Bulk Density (g/cm^3)	Por-osity	Sand (%)	Silt (%)	Clay (%)	Fraction Organic Carbon	Meas. K_{sat} (cm/ hr)	Est. K_{sat} (cm/ hr)	1/3 Bar Water Content (cm^3/ cm^3)	Initial Water Content (cm^3/ cm^3)
A	Top	Loamy sand	46	1.86	0.30	84.3	10.0	5.7	0.011	N/A	3.90	0.090	0.152
	Middle	Silty clay loam	107	1.70	0.36	13.8	55.8	30.4	0.011	0.732	0.09	0.259	0.089
	Bottom	Loam	GW	1.68	0.37	50.4	35.4	14.2	0.011	0.009	0.40	0.290	0.026
B	Top	Sand	38	1.83	0.31	92.0	6.0	2.0	0.011	N/A	5.91	0.079	0.096
	Middle	Silt loam	157	1.54	0.42	18.2	58.7	23.1	0.011	3.304	0.28	0.260	0.135
	Bottom	Sandy loam	GW	1.89	0.29	73.5	18.5	8.0	0.011	N/A	0.59	0.130	0.005
C	Top	Sand	41	1.99	0.25	92.5	5.6	1.9	0.015	N/A	4.23	0.075	0.136
	Middle	Loam	122	1.46	0.45	44.7	42.0	13.3	0.015	2.043	0.77	0.216	0.077
	Bottom	Sandy loam	GW	1.94	0.27	70.3	20.7	9.0	0.015	N/A	0.38	0.143	0.000
D	Top	Sand	19	2.04	0.23	89.4	7.3	3.3	0.013	N/A	2.80	0.083	0.120
	Middle	Loam	152	1.60	0.40	43.7	37.3	19.0	0.013	2.623	0.31	0.222	0.029
	Bottom	Sandy loam	GW	1.96	0.26	73.0	20.0	7.0	0.013	N/A	0.48	0.121	0.000
E	Top	Loamy sand	18	2.09	0.21	86.5	9.2	4.3	0.015	N/A	1.08	0.108	0.132
	Middle	Silt loam	147	1.46	0.45	16.9	61.2	21.9	0.015	8.515	0.46	0.273	0.097
	Bottom	Loam	GW	1.82	0.31	48.0	40.5	11.5	0.015	N/A	0.27	0.188	0.068
CP	Top	Sand	32	1.95	0.26	88.5	7.8	3.7	0.013	N/A	3.25	0.087	0.127
	Middle	Silt loam	137	1.54	0.42	25.7	53.1	21.3	0.013	4.292	0.30	0.248	0.098
	Bottom	Sandy loam	GW	1.83	0.31	60.9	28.4	10.8	0.013	0.009	0.38	0.178	0.019

Brooks and Corey Parameters

Once the basic soil properties were determined, it was possible to estimate the water retention and hydraulic conductivity parameters. Two of the most promising parameter estimation techniques, Cosby et al.'s (1984) method and neural networks, were used to obtain the Brooks and Corey parameters. Estimated 1/3-bar water contents for both methods were compared to the respective measured values from the five sample locations. Using Cosby et al.'s linear regression equations the average Mean Relative Absolute Error (MRAE) was 30 percent ($13 < MRAE < 47$ percent).

The second parameter estimation method employed the Rosetta program and its built-in neural networks to indirectly estimate the Brooks and Corey parameters. Rosetta

predictions were based on soil texture, bulk density, and 1/3-bar water content (for top layer only). The predicted van Genuchten parameters had to be transformed into Brooks and Corey parameters for the RZWQM. Rawls and Brakensiek (1985) suggested a simple conversion between the two sets of functions: $\lambda=n-1$ and $\Psi_b=1/\alpha$. The average MRAE (27 percent; 24 < MRAE < 31 percent) was only slightly improved from Cosby et al.'s method. Marcel Schaap (personal communication, 2003), the developer of Rosetta, found these conversions to work well only on very dry soils ($\alpha*\Psi >> 1$).

As an alternative to these conversions, the Brooks and Corey parameters were calibrated to the van Genuchten parameters. The van Genuchten parameters α and n, calculated from Rosetta, were used to calculate water contents for over thirty matric potentials between 1 and 100,000 centimeters. The Brooks and Corey parameters (λ and Ψ_b) were then calibrated to these water contents (average R^2 = 99.6 percent). These parameters produced the lowest average MRAE (16 percent; 11 < MRAE < 21 percent) and were used in the RZWQM. Brooks and Corey parameters are given in Table 3.2 for all sites.

Table 3.2. Brooks and Corey parameters for all sites. Layer 1, 2, and 3 correspond to the top, middle, and bottom soil layers, respectively.

Site	A			B			C			D			E			Composite		
Layer	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Ψ_b (cm)	-14.4	-53.8	-25.4	-16.5	-66.9	-13.9	-15.3	-46.0	-13.5	-9.7	-36.8	-13.4	-9.6	-75.5	-17.2	-14.7	-65.1	-14.4
λ	0.66	0.25	0.23	0.86	0.32	0.30	0.78	0.32	0.24	0.51	0.26	0.30	0.36	0.34	0.17	0.66	0.32	0.19

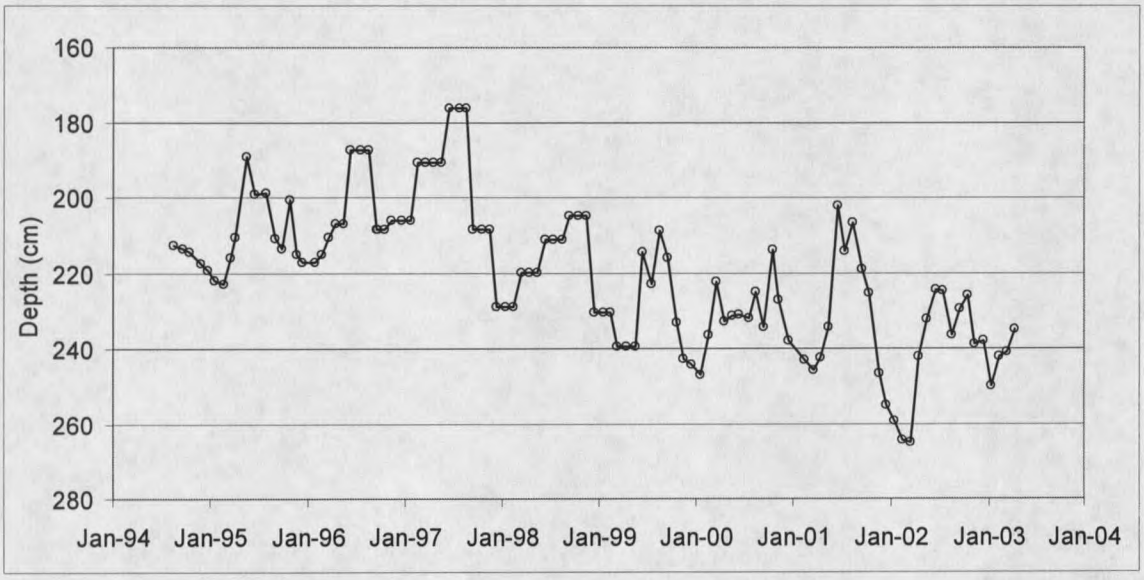
Climate

To accurately model soil-water it is essential to have an accurate precipitation and groundwater record. Billings/Logan Airport hourly precipitation data was obtained from the National Oceanic and Atmospheric Administration's (NOAA) National Climatic Data Center (NCDC). Precipitation data was available from July 3, 1948 thru December 31, 2002. All hourly precipitation was reported to a hundredth of an inch. Beginning in July 1996, trace amounts of precipitation were reported. Trace values were ignored because they cannot be quantified and are not represented over the entire period. Missing values were also ignored. Therefore, the annual precipitation based on hourly data is slightly less than the annual precipitation based on monthly data. Maximum and minimum air temperature, wind, solar radiation, and relative humidity were obtained from the RZWQM's built-in weather generator, CLIGEN, using Billings/Logan Airport recording station data. CLIGEN converts monthly station data into daily values by generating random numbers for each day, which are fit to normal distributions (RZWQM, 1992).

Monitoring well data were provided for the South 40 area wells. The four wells closest to the sample locations and with sufficient groundwater data were R-11PN, R-40, R-41, and R-42. All four wells have groundwater data starting August 16, 1994 or before. Refinery pumping wells began operation throughout 1994 but the groundwater elevations seem to have equilibrated by August. Depth to groundwater or floating product (if present) was determined for each of the wells. Depths were corrected for the known thickness of floating product (specific gravity of petroleum is approximately

0.85). The quadrant method described by McCuen (1998) was used to determine a distance-weighting factor for each of the wells. For each sample location the corrected depths were calculated. Corrected depths for the composite site were found by averaging depths from the five sample locations and are shown in Figure 3.3.

Figure 3.3. Corrected depth to groundwater or product for the composite site. Depths were corrected for floating product (if present).



SIMULATION RESULTS AND DISCUSSION

Infiltration, runoff, evaporation, soil storage, and seepage were predicted with the RZWQM. Seepage was of greatest concern to the refinery because of its relationship to contaminant transport. Four types of analyses were used to predict mean annual seepage to groundwater and determine the accuracy of these estimates. First, seepage was predicted at all sites based on mean soil properties and hourly precipitation data for the period of groundwater record (8/16/1994 thru 12/31/2002). Simulated groundwater elevations were varied over this period. Second, the full Billings hourly precipitation record (7/3/1948 thru 12/31/2002) and a constant groundwater table elevation were simulated to determine seepage for the composite site. Exceedence probabilities were calculated for annual and daily seepage events, which were used in risk assessment. Third, a sensitivity analysis was performed to determine which soil properties had the greatest effect on RZWQM predicted seepage. Mean soil properties within each soil layer were systematically varied plus or minus one standard deviation to determine the variability in mean annual seepage. The fourth and final analysis employed the Monte Carlo method to develop confidence intervals based on variability in soil properties. The latter two analyses utilized the composite site and precipitation data for the period of groundwater record.

Groundwater Record Analysis (GRA)

RZWQM seepage predictions were obtained by using mean soil properties for each of the three profile layers at the five sample sites and the composite site. RZWQM simulations were run from 11/1/1991 to 12/31/2002, which includes the period of groundwater record (8/16/1994 thru 12/31/2002). Initial soil moisture effects were minimized by using the measured water contents from soil samples obtained on 11/5/2002 and 11/13/2002. These initial conditions were input into the RZWQM beginning 11/1/1991.

Daily precipitation data, from the summation of NOAA hourly precipitation data, are shown in Figure 4.1 for 1/1/1995 thru 12/31/2002. Predicted infiltration and runoff are presented in Figure 4.2 for the composite site and in Appendix A for each individual sample site. Runoff is produced when precipitation continues after the water-holding capacity of the soil is reached (Or et al., 2002). The predicted runoff events were small and infrequent for all sites. Daily runoff greater than 0.5 cm was predicted only at sites D and E for one day of the eight-year period. On 7/20/1997, 0.9 and 2.4 cm of runoff were predicted at sites D and E, respectively. Typically, runoff was produced from frequent small and moderate storms instead of one large event. Mean annual runoff for the eight years was 0.6 cm for the composite site. As the summation of infiltration and runoff in the RZWQM is equal to precipitation, it is clear that the vast majority of precipitation infiltrates the soil (Ahuja et al., 1999a).

Figure 4.1. Billings/Logan International Airport daily precipitation from 1/1/1995 to 12/31/2002.

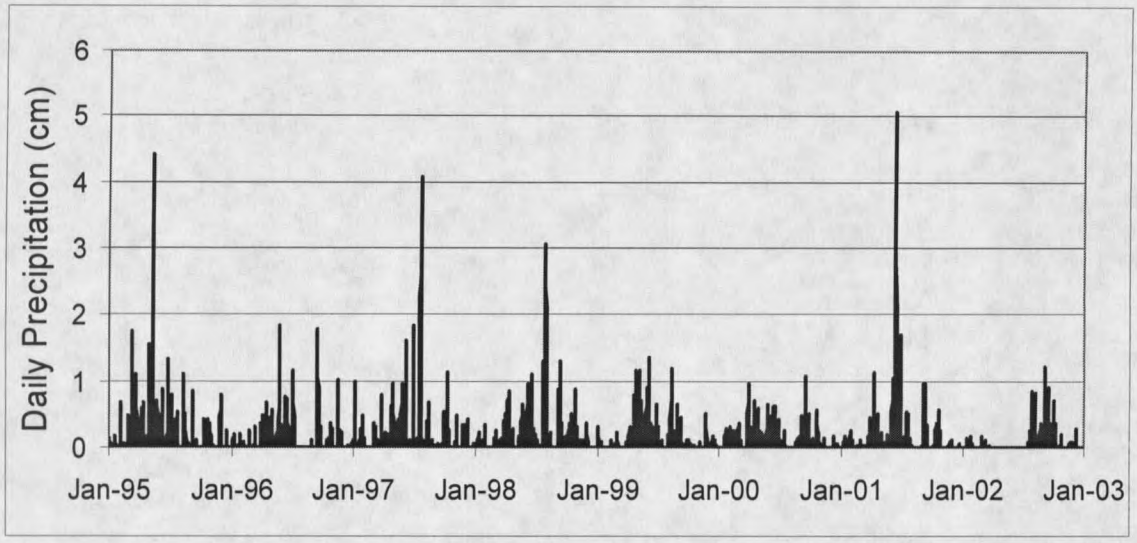
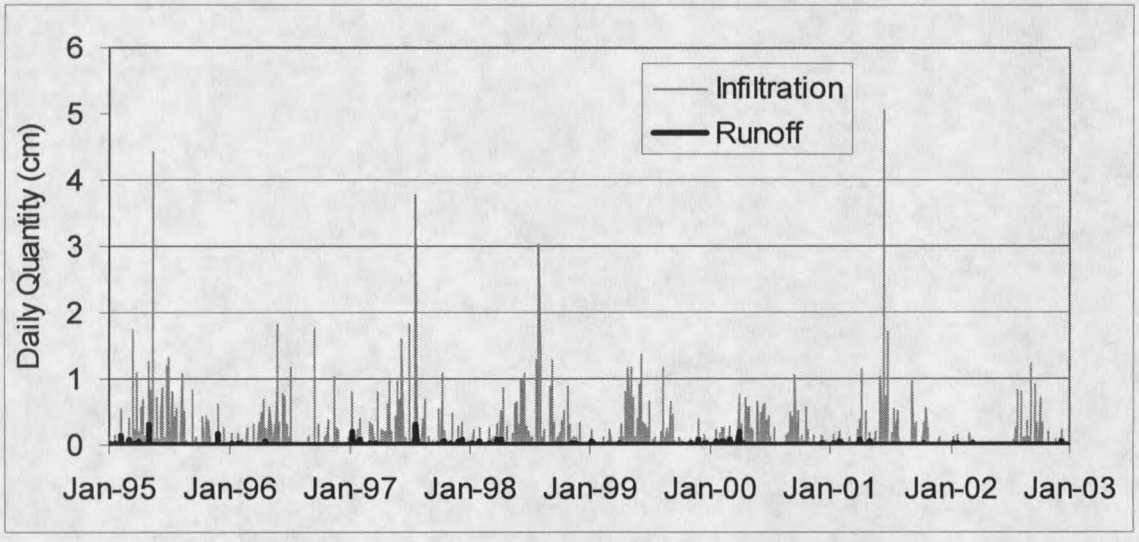


Figure 4.2. Predicted daily infiltration and runoff for the composite site over the period of groundwater record. Precipitation = Runoff + Infiltration.

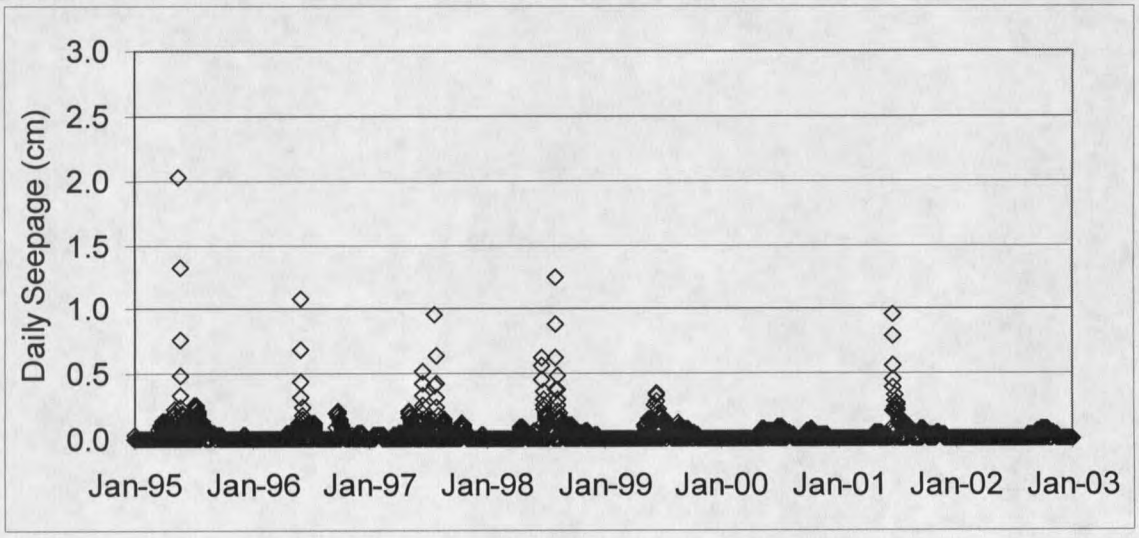


Infiltrated water is stored in the soil profile and may be available for either ET or seepage to deeper layers or groundwater. To approximate the groundwater influence on seepage, the constant pressure head boundary condition (described in Chapter 1) was used in the RZWQM. The dynamic constant flux boundary condition was inappropriate because the groundwater elevation was controlled by lateral migration and pumping, which could not be accounted for by the 1-D RZWQM. A constant head boundary allowed the groundwater table to be fixed at the bottom of the soil profile. Negative seepage values represent upward flow of water out of the water table. The RZWQM was unable to simulate a constant pressure head of zero at the bottom boundary. Laj Ahuja (personal communication, 2003), a member of the RZWQM design team, stated that setting the constant pressure head to the slightly negative Ψ_b would allow the model to run smoothly and essentially saturate the soil below the profile.

The constant pressure head boundary condition does not account for actual fluctuations in groundwater table depth, so multiple simulations, each with a unique profile depth, were required. Four to six simulations were run at each site, to cover the range of groundwater depths. For each simulation, the depth was varied by no more than 25-cm (9.8-in). For the composite site, bottom profile depths of 176, 198, 220, and 241 cm were simulated and seepage was predicted for each case. Daily seepage predictions were corrected by ignoring values less than the precision of the precipitation data (0.025 cm or 0.01 in). With this correction, predicted negative daily seepage values (values < 0.004 cm) did not adversely affect seepage totals.

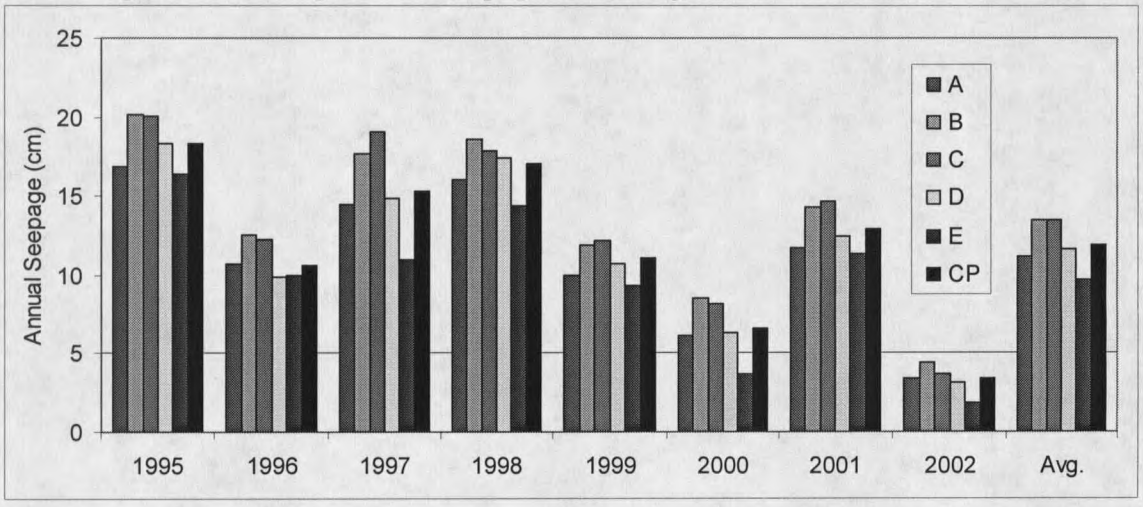
Corrected seepage between simulations were similar. Average corrected annual seepage for the eight years was 12.2, 12.0, 12.0, and 11.9 cm for the composite site profile depths of 176, 198, 220, and 241 cm, respectively. The lookup function built into Microsoft Excel™ was used to determine the amount of seepage that occurred on a given day based on the actual corrected groundwater elevation. For example, on 8/22/1997 the RZWQM predicted 0.12, 0.14, 0.15, and 0.16 cm of seepage for the bottom profile depths of 176, 198, 220, and 241 cm, respectively. The actual groundwater table elevation on that day was 180 cm, so the closest depth's (176 cm) seepage value (0.12 cm) was used. Corrected daily seepage predicted by the RZWQM are shown for the composite site in Figure 4.3 and for the five sample locations in Appendix A. Significant seepage events exceeding one centimeter occurred on four days over the eight-year period. These large daily events could potentially cause contaminant transport.

Figure 4.3. Daily seepage predictions for the composite site over the period of groundwater record. All values less than 0.025 cm were ignored.



Corrected annual seepage for years 1995 thru 2002 are presented in Figure 4.4 along with the eight-year average. Sites B and C had the highest average value (13.5 cm at both sites) and site E had the lowest (9.7 cm). The average value for the composite site was 11.9 cm. Annual seepage values closely correlate with total precipitation, 1995 had the highest values and 2002 had the lowest. For the eight-year period, average annual precipitation was 22.3 cm, of which 21.7 cm infiltrated and 0.6 cm was runoff using the composite site's soil profile. Assuming that soil storage was essentially constant over the eight years, infiltrated water that did not seep to groundwater was evaporated (9.8 cm).

Figure 4.4. Predicted annual seepage for the five sample sites and the composite ("CP") site. "Avg." is the average annual seepage for the eight years shown.



Hydrologic patterns are difficult to discern in the preceding daily figures due to the large time scale. Representative patterns can be seen in simulations from 9/10/1996 to 10/14/1996. The model was run using the composite site's average groundwater depth (220 cm). For clarity, a daily seepage cutoff was not used.

Precipitation, ET, and seepage are shown in Figure 4.5 (note the different vertical scales). Runoff was zero for the entire period, so total precipitation was distributed as ET, seepage, or a change in soil storage. There was no precipitation for 70 days preceding the 9/14 precipitation event (except for one minimal event on 8/28 (0.1 cm)), thus ET and seepage were near zero prior to this event. There was three days of relatively large precipitation on 9/14, 9/16, and 9/17 followed by a smaller event on 9/26 (precipitation was 1.8, 1.1, 0.7, and 0.3 cm, respectively). ET lagged precipitation by one to two days but followed a nearly identical pattern with a smaller magnitude (0.36, 0.15, 0.13, and 0.13 cm). Seepage was lagged by approximately five days as a result of the time required for water to percolate from the soil surface to the groundwater. Negligible seepage was predicted on days with precipitation, due to the RZWQM's calculation procedure. Neglecting these artificially low values, seepage peaked on 9/24 (0.12 cm), after which it gradually dropped off to 0.06 cm after 20 days. Annual seepage totals were the result of summing many days of minimal seepage from this and many other gradual seepage drops.

Using annual seepage to estimate contaminant seepage values may not be representative of real conditions because the majority of annual seepage was due to the summation of many minimal daily values. Low daily seepage values may not have the capacity to cause contaminant movement. Though just speculation, hydrocarbon transport may be more closely correlated to large daily seepage events than to annual seepage. The 0.025-cm seepage cutoff was very conservative but had the most physical significance. A larger cutoff may be more appropriate to actual conditions. Table 4.1

shows the effects of using different seepage cutoff values on mean annual seepage and the number of days that the cutoff was equaled or exceeded. The percentage of days was calculated from the number of days in the period (2922 days). With a 0.6 cm cutoff, the mean annual seepage was 1.6 cm and only 0.4 percent (13 days) of the days had seepage that equaled or exceeding the cutoff over the eight years.

Figure 4.5. Daily precipitation, ET, and seepage from 9/10/1996 to 10/14/1996. The average composite site groundwater depth (220 cm) was used. This period clearly shows patterns between hydrologic events. Runoff and infiltration were not included because there was no runoff over the entire period.

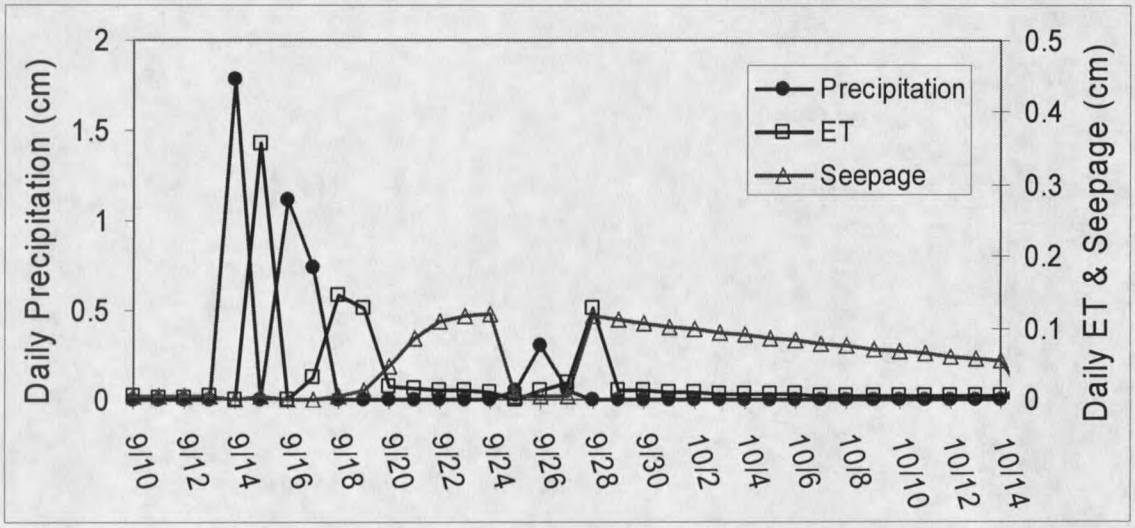


Table 4.1. Effects of using different seepage cutoff values on mean annual seepage and the number and percent of days seepage equaled or exceeded the specified cutoff from 1/1/1995 to 12/31/2002 (2922 days).

Daily Seepage Cutoff (cm)	0.025	0.1	0.2	0.4	0.6	0.8	1.0
Mean Annual Seepage (cm)	11.9	6.7	3.9	2.3	1.6	1.1	0.7
# Days Seepage >= Cutoff	1069	238	73	25	13	7	4
% Days Seepage >= Cutoff	36.6	8.1	2.5	0.9	0.4	0.2	0.1

Precipitation Record Analysis (PRA)

The influence of precipitation variability on seepage was estimated by the Weibull equation. Viessman and Lewis (2003) recommend using no less than ten years of data to determine risk calculated by the Weibull equation, so the precipitation record (7/3/1948 thru 12/31/2002) was used instead of the groundwater record (8/16/1994 thru 12/31/2002). The Weibull equation is a plotting formula that provides the probability that a specific value will be equaled or exceeded in any given year based on the number of years of record. To use the Weibull equation, seepage was sorted in descending order and the values were ranked. The Weibull equation is: $P_e=m/(n+1)$, where P_e is the exceedence probability, m is the rank, and n is the total number of ranked values. The recurrence interval (T) is the reciprocal of the exceedence probability and has units of years: $T=1/P_e$.

The RZWQM was run from 1/1/1947 to 12/31/2002, which included the entire Billings/Logan International Airport precipitation record. Because the depth of the groundwater table in the South 40 area was not known before 8/16/1994, the composite site's average groundwater depth (220 cm) was used. The GRA indicated that groundwater level had only a minor influence on predicted seepage.

Figure 4.6 shows predicted annual seepage for the composite site using 54 years (19,723 days) of precipitation data. Annual seepage ranged from 3.2 to 47.5 cm in 2002 and 1978, respectively (36.8 and 74.0 percent of precipitation). Averaged over 54 years, annual seepage was 21.2 cm. Average annual precipitation was 34.0 cm, of which 32.5

cm infiltrated and 1.5 cm was runoff. Overall, 62.4 percent of average annual precipitation reached the groundwater. Soil storage was assumed constant because its influence is diminished the longer the simulation period. Infiltrated water that did not seep to groundwater was evaporated (11.3 cm).

Figure 4.6. Predicted annual seepage for composite site. "Avg." is average seepage for all 54 years of precipitation record. A constant groundwater table elevation of 220 cm was used.

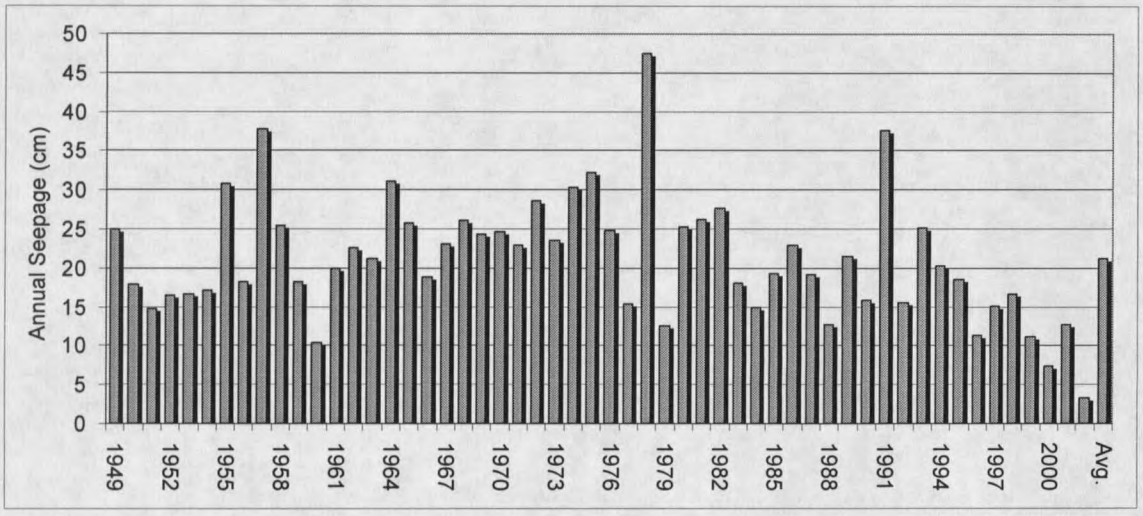


Table 4.2 is similar to Table 4.1 from the GRA, except a constant average groundwater level was used for the period of precipitation record. With a 0.6 cm cutoff the mean annual seepage was 2.0 cm and only 0.5 percent of the simulated days (105 days) had seepage that equaled or exceeding the cutoff over the 54 years. These values are about 25 percent higher than the GRA annual and daily estimates.

A plot of the cumulative probability that an annual seepage quantity will be exceeded in any given year is shown in Figure 4.7. There was an 80 percent probability that 15 cm of annual seepage would be exceeded and a 20 percent probability that 26 cm

of annual seepage would be exceeded. 80 percent and 20 percent exceedence probability events have recurrence intervals of 1.3 and 5 years, respectively. The probability of extreme events should be judged cautiously due to the lack of data in the outlying areas. A plot of the cumulative probability that the number of days of a specified amount of daily seepage is exceeded in a year is shown in Figure 4.8. There was a 40 percent probability that 0.4 cm of seepage will be exceeded for 5 days a year. Future work on the relation between water and contaminant transport in soil may determine which probability is most appropriate for hydrocarbon transport.

Table 4.2. Effects of using different seepage cutoff values on mean annual seepage and the number and percent of days seepage equaled or exceeded the specified cutoff from 1/1/1949 to 12/31/2002 (19,723 days).

Daily Seepage Cutoff (cm)	0.025	0.1	0.2	0.4	0.6	0.8	1.0
Mean Annual Seepage (cm)	21.2	12.5	6.9	3.3	2.0	1.4	1.0
# Days Seepage >= Cutoff	12033	3161	978	255	105	59	34
% Days Seepage >= Cutoff	61.0	16.0	5.0	1.3	0.5	0.3	0.2

Figure 4.7. Plot of the cumulative probability that an annual seepage quantity will be exceeded in any given year. The composite site was used with 54 years of precipitation data.

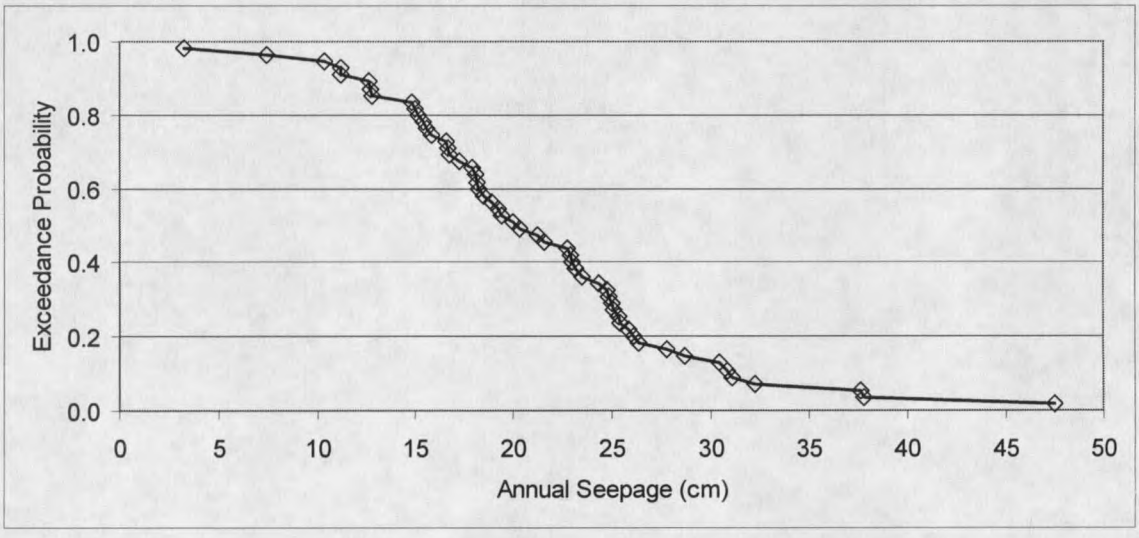
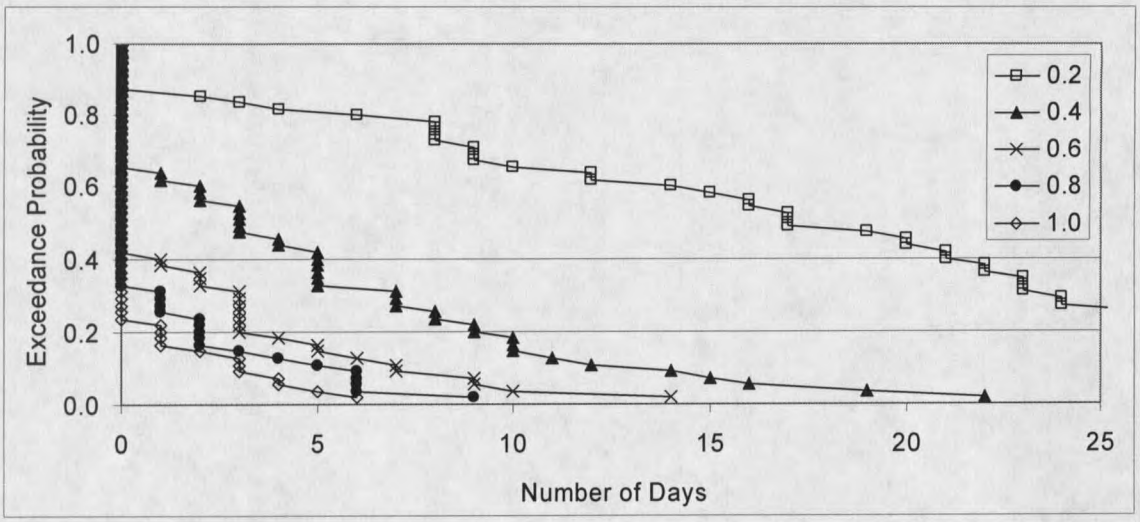


Figure 4.8. Plot of the cumulative probability that the number of days of a specified amount of daily seepage is exceeded in a year. The composite site was used with 54 years of precipitation data. Daily seepage (DS) exceedence quantities (cm) are given in the legend.



Sensitivity Analysis (SA)

Sensitivity analyses were performed to determine which soil properties have the greatest effect on seepage predicted with the RZWQM. The composite site's soil profile was used because it contains the most data and the effect of a variable layer depth could be analyzed. Simulations were run for the period of groundwater record to produce slightly more accurate seepage estimates by using a varying groundwater level. All measured soil properties with sufficient sample size to develop meaningful statistical distributions were varied plus or minus one standard deviation from the mean. Parameters varied were soil texture, bulk density, and depths to the divisions between soil layers.

To look at overall effects, an individual parameter was adjusted plus or minus one standard deviation in all layers simultaneously, while holding other parameters at mean measured values. Rosetta was run before each simulation because the RZWQM requires estimates of K_{sat} and the Brooks and Corey parameters, which are functions of soil texture and bulk density. Soil texture is composed of sand, silt, and clay; therefore, one parameter could not be changed without adjusting the others. To account for this, the other two texture properties were scaled proportionate to their original values so as not to exceed 100 percent. When sand was adjusted, scaled silt (%) was calculated by: $Silt_S=Silt_O-Silt_O/(Silt_O+Clay_O)*(Sand_A+Silt_O+Clay_O-100)$, where the subscripts S = scaled, O = original, and A = adjusted. A similar equation was used to determine the scaled clay percentage. The same procedure was used for adjusting silt and clay plus or minus one standard deviation. For example, when the top layer's sand content was increased by one standard deviation from 88.5 to 94.5 percent, the top layer's silt content was reduced from 7.8 to 3.7 percent and clay content from 3.7 to 1.8 percent.

The layer depths for the composite site were calculated by averaging the measured layer depths from the five sample locations. Depths of the divisions between soil layers were varied plus or minus one standard deviation to account for variability between sites. Percent variation in mean annual seepage due to variation in the three soil texture properties, bulk density, and the depths of the divisions between soil layers are shown in Table 4.3 along with the variability in the soil properties for all three layers. The mean seepage value of 11.9 cm from the GRA was used as a basis.

Table 4.3. Percent variation in mean annual seepage (11.9 cm) due to +/- 1 standard deviation (S.D.) variation in the three soil texture properties, bulk density, and the depths of the divisions between soil layers at the composite site. The percent variation corresponding to 1 S.D. variation in input properties are given for each layer in the last three rows.

Variation From Mean	Bulk Density		Sand		Silt		Clay		Top Division Depth		Bottom Division Depth	
%	-1 S.D.	+1 S.D.	-1 S.D.	+1 S.D.	-1 S.D.	+1 S.D.	-1 S.D.	+1 S.D.	-1 S.D.	+1 S.D.	-1 S.D.	+1 S.D.
Seepage	12.8	-14.6	-10.4	6.9	7.5	-19.6	-4.8	-7.8	9.7	-5.4	0.6	-0.8
Top Layer	11.1		6.8		40.3		79.2		40.2		85.8	
Middle Layer	10.3		66.6		24.0		32.4					
Bottom Layer	16.0		34.3		55.2		52.1					

The variability of seepage was most sensitive to variability in bulk density and percent silt. Seepage variability relative to the variability in bulk density was of the same magnitude. Relative variability for the other soil properties was much lower. Of the soil texture properties, seepage was most sensitive to relative variations in percent silt. Percent seepage variation due to variation in percent clay was negative in both cases and therefore seepage was relatively insensitive to clay variation. Variability between seepage and the top layer division (between the top and middle layers) was greater than the bottom layer division. Relative variability for both layer divisions was low. Therefore, it was justifiable to perform analysis on one composite site, calculated from a relatively large variation in layer depths between sites.

An additional analysis determined percent variation in mean annual seepage by adjusting bulk density plus or minus one standard deviation in each layer individually, while fixing values for the other layers at their mean values. Bulk density was used for this analysis because it was the most sensitive soil property and can be controlled in the field by compaction. As shown in Table 4.4, seepage was fairly sensitive to variation in top layer bulk density, while relatively insensitivity to variation in the lower layers (both

values were negative for the middle layer and positive for the bottom layer). These results, in addition to the layer division results, reveal that seepage was most sensitive to the top layer's soil properties.

Table 4.4. Percent variation in mean annual seepage (11.9 cm) due to +/- 1 standard deviation (S.D.) variation in bulk density on each layer individually.

Top Layer Bulk Density		Middle Layer Bulk Density		Bottom Layer Bulk Density	
-1 S.D.	+1 S.D.	-1 S.D.	+1 S.D.	-1 S.D.	+1 S.D.
13.7	-13.8	-0.5	-0.5	1.3	1.3

Monte Carlo Analysis (MCA)

Unlike a systematic sensitivity analysis, the confidence of RZWQM predicted seepage can be assessed for all soil properties simultaneously with the Monte Carlo method (described in Chapter 1). For this analysis, the composite site was used because it contained the most data. The chi-squared goodness-of-fit test was used to determine if specific soil sample properties were normally distributed. If the calculated chi-squared value was less than a specified significance value (5 percent is commonly used) then the assumed distribution was acceptable (Stephens, 1998). Only the composite site's middle layer had enough data for this test (38 samples). The chi-squared test indicated that bulk density and percent silt were normally distributed using a 5 percent significance value ($0.22 < 5.99$ significance value for bulk density and $3.37 < 3.84$ significance value for percent silt). A normal distribution was assumed for sand and clay because of their dependence on percent silt, and for the top and bottom layer's soil properties.

Random generations of bulk density and percent sand and silt were based on probabilities calculated from the means and standard deviations. The random number generator built into Microsoft Excel™ was used to determine each set of soil properties. Generated values for percent sand and silt were given upper and lower bounds of 98 and 2 percent, respectively to approximate realistic field conditions. To avoid summation of percent sand, silt, and clay exceeding 100 percent, the second most sensitive texture property, percent sand, often had to be adjusted. If the combined percentage of sand plus silt was greater than 98 percent, then percent sand was reduced until the summation was equal to 98 percent. The least sensitive parameter, clay, was assigned the remaining percentage (at least 2 percent). Layer depth was not analyzed because the RZWQM's numerical layering scheme would have forced the bottom profile depth to change by a few centimeters for each simulation. A total of 25 sets of normally distributed pseudorandom numbers were generated for each of the three soil layers.

Along with the randomly generated soil properties (soil texture and bulk density), the mean fraction of organic carbon, and Rosetta-estimated Brooks and Corey parameters and K_{sat} were input into the RZWQM. Rosetta was run before every simulation to account for the varying soil properties. Predicted annual seepage was averaged over the years 1995 thru 2002 for each Monte Carlo simulation. The mean and standard deviation of the average annual seepage was 10.3 and 4.8 cm, respectively. Average annual seepage predicted with the Monte Carlo method (10.3 cm) was slightly less than that predicted using the mean soil properties from the GRA (11.9 cm). Theoretically, the

Monte Carlo predicted seepage would be equal to the mean if an infinite number of simulations were run.

The chi-squared test was used to determine if the calculated mean annual seepage was normally distributed. The chi-squared test indicated that mean annual seepage was normally distributed using a 5 percent significance value ($1.84 < 3.84$ significance value). Based on the definition of the normal curve, the probability that mean annual seepage will be in exceedence of one standard deviation of the mean was 15.9 percent (Stephens, 1998). This corresponds to 15.1 cm of mean annual seepage. The probability that 20 cm of mean annual seepage will be exceeded in any given year was two percent. The percent of days that seepage exceeded a specified daily quantity was similarly analyzed. The probability that one percent of the days analyzed will have greater than 0.6 cm of seepage was only 0.1 percent. Exceedence probabilities for mean annual seepage and percent of days that seepage exceeds a specified quantity are shown in Table 4.5.

Table 4.5. Monte Carlo seepage confidence. Probabilities that mean annual seepage will be exceeded in any given year and the percent of days seepage is greater than a specified amount will be exceeded are shown. Variations in seepage were based on normally distributed soil properties. The years 1995 thru 2002 (2922 days) were used.

# of Standard Deviations Above Mean	0.0	0.5	1.0	1.5	2.0	2.5	3.0
Exceedence Probability (%)	50.0	30.9	15.9	6.7	2.3	0.6	0.1
Mean Annual Seepage (cm)	10.3	12.7	15.1	17.5	19.9	22.3	24.6
% Days Seepage > 0.025 cm	31.3	39.0	46.6	54.3	61.9	69.6	77.2
% Days Seepage > 0.1 cm	7.2	8.9	10.6	12.4	14.1	15.8	17.6
% Days Seepage > 0.2 cm	2.3	2.8	3.4	3.9	4.4	5.0	5.5
% Days Seepage > 0.4 cm	0.7	0.9	1.0	1.2	1.4	1.5	1.7
% Days Seepage > 0.6 cm	0.3	0.5	0.6	0.7	0.8	0.9	1.0
% Days Seepage > 0.8 cm	0.2	0.3	0.3	0.4	0.5	0.6	0.6
% Days Seepage > 1.0 cm	0.1	0.2	0.2	0.3	0.3	0.4	0.4

To account for higher mean annual precipitation over the longer PRA, the above results were scaled by the ratio of PRA to GRA predicted seepage (i.e. 21.2/11.9 = 1.78). The percent of days that seepage exceeded 0.025, 0.1, 0.2, 0.4, 0.6, 0.8, and 1.0 cm were scaled by 1.67, 1.97, 1.98, 1.51, 1.20, 1.25, and 1.26, respectively. Scaled MCA results are shown in Table 4.6.

Table 4.6. Monte Carlo scaled seepage confidence. All values were scaled from the period of groundwater record (Table 4.4) to the period of precipitation record.

# of Standard Deviations Above Mean	0.0	0.5	1.0	1.5	2.0	2.5	3.0
Exceedence Probability (%)	50.0	30.9	15.9	6.7	2.3	0.6	0.1
Mean Annual Seepage (cm)	18.4	22.6	26.9	31.1	35.4	39.6	43.9
% Days Seepage > 0.025 cm	52.3	76.7	92.6	82.0	74.1	86.9	97.2
% Days Seepage > 0.1 cm	12.0	17.5	21.1	18.7	16.9	19.8	22.1
% Days Seepage > 0.2 cm	3.8	5.6	6.7	5.9	5.3	6.2	6.9
% Days Seepage > 0.4 cm	1.2	1.7	2.1	1.8	1.6	1.9	2.2
% Days Seepage > 0.6 cm	0.6	0.9	1.1	1.0	0.9	1.1	1.2
% Days Seepage > 0.8 cm	0.3	0.5	0.7	0.6	0.6	0.7	0.8
% Days Seepage > 1.0 cm	0.2	0.3	0.4	0.4	0.4	0.4	0.5

Discussion

The RZWQM predicted a nonzero quantity of seepage to groundwater for every year of simulation. With the GRA, 53.4 percent of average annual precipitation (22.3 cm) reached the groundwater. PRA results revealed that 62.4 percent of the average annual precipitation (34.0 cm) seeped. Not only did the quantity of annual seepage increase with an increase in annual precipitation, but the fraction of precipitation also increased. Significant quantities of daily seepage occurred in almost every year. If 0.4 cm is considered a "significant daily seepage" quantity, then approximately five days a

year had significant seepage (from PRA). Even for the highest "significant daily seepage" value of 1.0 cm, approximately one event can be expected in any given year.

Other than the difference in precipitation, the only difference between the GRA and PRA was the simulated groundwater elevation. For the PRA, the constant groundwater elevation was assumed equal to the composite site's mean water table depth (220 cm), while variable elevations were incorporated into the GRA. Predicted average annual seepage between the two methods for years of common record, 1995 to 2002, were 11.9 and 12.0 cm for the GRA and PRA, respectively. This is consistent with the analysis within the GRA indicating that groundwater level had minimal influence on seepage.

Very little data is available to calculate the accuracy of the RZWQM results. However, a single data point is available for estimating the accuracy of soil moisture predictions from the RZWQM. Soil samples obtained on 11/5/2002 indicated was the soil profile was 8 percent saturated while the RZWQM simulation, using the constant average groundwater depth (220 cm), predicted an average of 71 percent during November 2002 (based on 78.1 cm of available storage). Similar results were found when the initial water content was used for a bottom boundary condition (instead of the bubbling pressure) and when a unit gradient boundary was imposed. Over predicted soil water is the probable cause for the long gradual decrease in seepage after a precipitation event as seen in Figure 4.5.

The reason for soil moisture over prediction is unknown, but may be the result of inaccuracies in the estimated Brooks and Corey water retention parameters, from not

including macropore flow, which would allow the soil to drain more rapidly and reduce soil saturation, or from under predicted ET. However, ET predictions are reasonable for bare soil conditions. In addition, the permeable surface layer may act as mulch, allowing infiltration, but drying relatively quickly and preventing the capillary rise necessary to supply surface evaporation.

Assuming ET estimates are accurate, the RZWQM probably under predicted annual seepage, as it is the only other flux capable of reducing the soil water content. Any error in seepage due to over prediction of soil water is likely manifested in annual values only. Large daily seepage values are a result of specific high precipitation patterns, which likely saturated or nearly saturated the soil profile. Thus, the analysis of the number of days over a specified value may be a more appropriate analysis of seepage risk.

The Monte Carlo simulation resulted in a large seepage standard deviation (value versus mean) due to uncertainty in measured and estimated input soil properties. Precise soil property estimates obtained from any measurement or estimation technique are difficult to obtain. To increase accuracy, the RZWQM could be calibrated to water contents and ET measured in the field over time. To reduce errors from the over predicted soil saturation, ET could be accurately measured using lysimeters. To better estimate the Brooks and Corey parameters, water retention and unsaturated hydraulic conductivity data could be obtained in the laboratory instead of estimated from basic soil properties.

A preliminary study by Kevin Germain (personal communication, 2001) estimated significantly less annual seepage using the SCS curve number method for runoff/infiltration partitioning in combination with the Thornthwaite ET model. For a period similar to the GRA, Germain's calculations distributed precipitation into runoff, ET, and seepage by 10, 89, and 1 percent, respectively (the RZWQM predicted 3, 44, and 53 percent, respectively). The SCS/Thornthwaite method is a relatively crude estimate requiring long term averaging of inputs and outputs. Germain used 24-hour precipitation values and did not have actual soil and groundwater data available, but rather lumped all soil influences into one of four possible SCS soil group categories. Soil was classified into groups B and C, while, in retrospect, group A was probably more appropriate because it approximates the well-drained sands and gravels found in the top soil layer. Using a type A soil group would have decreased runoff and increased infiltration. ET was most likely over predicted with the Thornthwaite evaporation model because the only meteorological inputs incorporated were mean monthly temperature and precipitation. Unlike the SCS/Thornthwaite model, the RZWQM used measured soil data, detailed climate data, a fluctuating groundwater table, and vastly superior computational algorithms.

Remedial Alternatives

Water seepage estimates are a necessary first step in the estimation of hydrocarbon seepage to groundwater. In addition to the flow of soil-water, contaminant

seepage is probably dependent on the contaminant's miscibility in water, adsorption to soil particles, the spatial distribution of contamination, and the groundwater flux.

If contaminant seepage is estimated to exceed EPA regulations, then the permeability of the soil can be reduced. Sensitivity analysis results suggest that replacing the sandy top layer with a less permeable layer would significantly reduce seepage. This layer may have prevented infiltrated water from evaporating and instead increased the amount stored in the lower layers, which percolated over time to the groundwater. The risk of hydrocarbon seepage from infiltrated water could be eliminated if the disturbed area was capped with an impermeable material, such as asphalt.

SUMMARY

The quantification of hydrocarbon seepage to groundwater is a regulatory concern for the Billings, Montana ConocoPhillips refinery. Contaminant transport in the vadose zone is highly dependent on the flow of soil-water. The Root Zone Water Quality Model (RZWQM) was used to predict runoff, infiltration, evapotranspiration (ET), soil storage, and seepage from precipitation and soil data. Soil samples were obtained from five locations in the disturbed South 40 refinery area and infiltration rates were measured. Soil texture (percent sand, silt, and clay), bulk density, and saturated hydraulic conductivity (K_{sat}) were determined for all samples. The fraction of organic carbon and the water content measured at 1/3-bar pressure were measured on the surface samples. The close proximity of the five sites warranted the creation of one composite site that contained all soil samples divided into three layers.

The Brooks and Corey (1964) water retention and hydraulic conductivity functions are used to estimate water distribution in the RZWQM. These parameters were estimated indirectly using the Rosetta program (Schaap, 1999). The saturated hydraulic conductivity was also estimated using Rosetta because the measured values were not representative of all layers. Rosetta estimated average K_{sat} was within one order of magnitude of average K_{sat} calculated from measured infiltration rates.

The RZWQM was simulated with Billings/Logan Airport hourly precipitation data from 1995 thru 2002. The bottom soil profile depth was varied to estimate actual groundwater elevations. The RZWQM predicted 11.9 cm of average annual seepage for

the composite site, while values for the five sample locations varied from 9.5 to 13.5 cm. The model was also run with 54 years of precipitation data and a constant average water table elevation and 21.2 cm of mean annual seepage was predicted. Exceedence probabilities were calculated for each year based on the precipitation record. There was an 80 percent probability that 15 cm of annual seepage would be exceeded and a 20 percent probability that 26 cm of annual seepage would be exceeded. The difference in predicted mean annual seepage is the result of the relatively dry period (1995 thru 2002) used in the first analysis.

A sensitivity analysis was performed on the composite site's soil texture and bulk density for the period of groundwater record. Seepage was determined to be most sensitive to variations in bulk density and percent silt. Of the three soil layers, seepage was most sensitive to variations in the top layer.

Monte Carlo simulations were used to determine predicted seepage confidence based on normally distributed random soil properties. The standard deviation of predicted seepage was relatively high (approximately 47 percent of the mean); therefore, variations in soil properties produced a large range of seepage estimates. The probability that 20 cm of mean annual seepage will be exceeded in any given year was two percent. The probability that one percent of the days analyzed will have greater than 0.6 cm of seepage was 0.1 percent. Results from the Monte Carlo analysis were scaled to the comparatively wetter 54 years of precipitation record. Using scaled values, the two percent exceedence probability corresponded to 35 cm of mean annual seepage and the

0.1 percent exceedence probability corresponded to 1.2 percent of the days analyzed having seepage greater than 0.6 cm.

The RZWQM predicted a nonzero quantity of seepage to groundwater for every year of simulation. RZWQM storage predictions were significantly over predicted compared to the water contents measured on 11/5/2002. The reason for this over prediction is unknown. Assuming ET estimates are accurate, the RZWQM probably under predicted annual seepage. The analysis of the number of days over a specified value may be more appropriate for determining seepage risk. Daily seepage events are probably most appropriate for estimating hydrocarbon seepage because of the momentum required to transport denser-than-water contaminants. The amount of hydrocarbons that the infiltrated water transports to the groundwater still needs to be determined.

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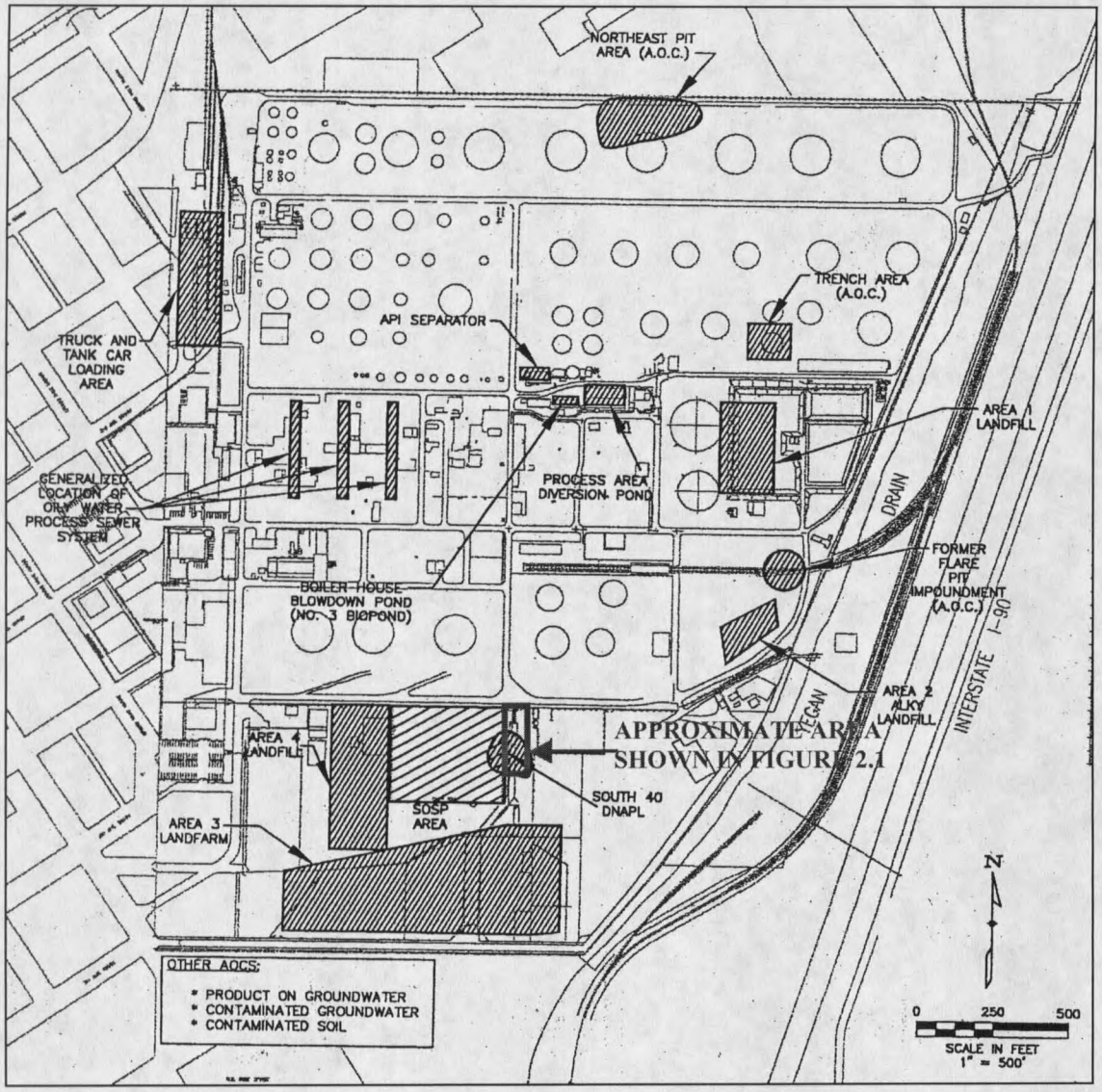
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APPENDIX A

REFINERY MAP, SOIL PROPERTIES, AND RZWQM DAILY ESTIMATES

Billings, MT ConocoPhillips refinery map. South 40 area is located in the SE ¼ of the refinery. Groundwater flow is to the NE.



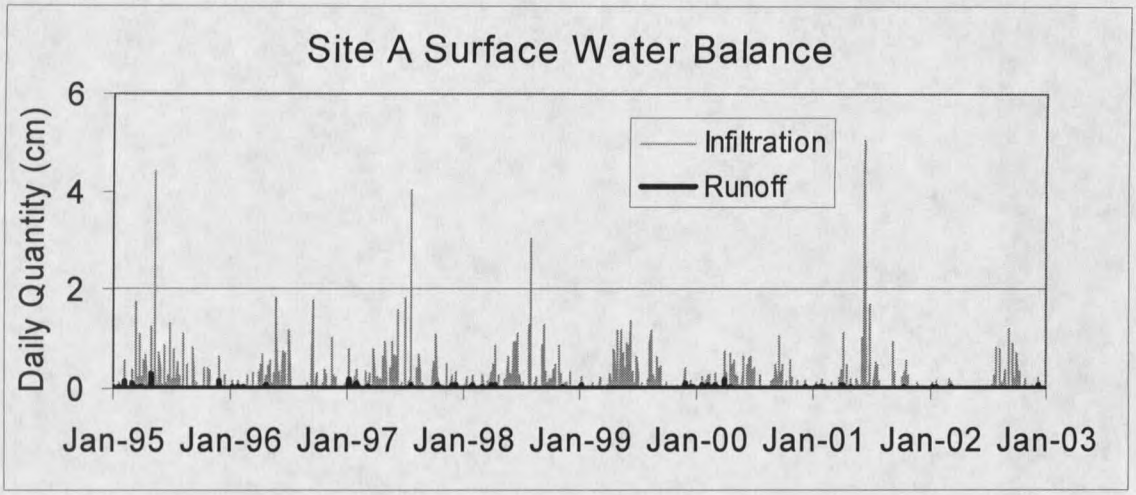
Standard Deviations of Mean Soil Properties for All Sites

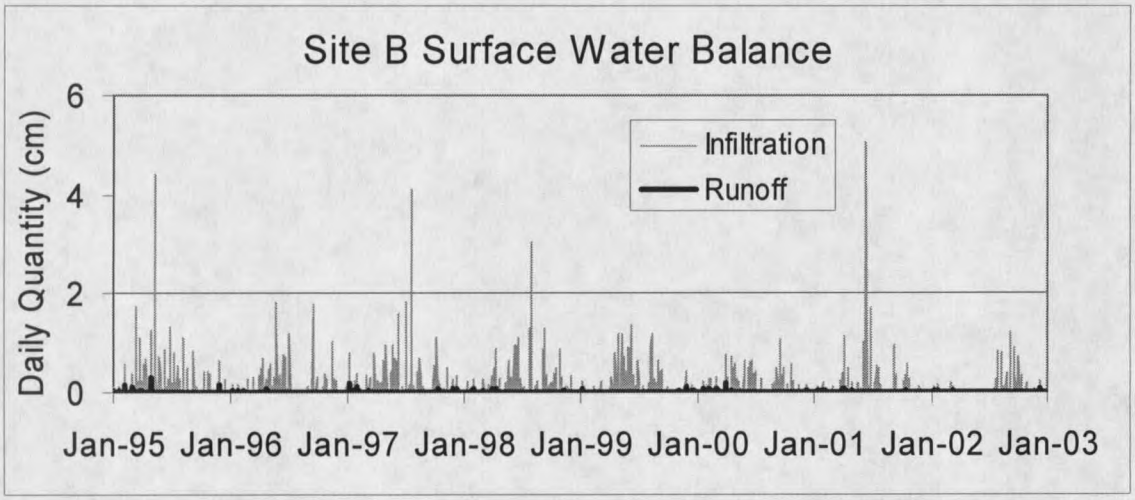
Site	Layer	USDA Texture Class	Layer Bottom Depth (cm)	Bulk Density (g/cm^3)	Porosity	Sand (%)	Silt (%)	Clay (%)	Fraction Organic Carbon	Meas. K_{sat} (cm/hr)	Est. K_{sat} (cm/hr)	1/3 Bar Water Content (cm^3/cm^3)	Initial Water Content (cm^3/cm^3)
A	Top	Loamy sand	N/A	0.11	0.04	10.7	5.3	5.4	0.001	N/A	N/A	0.004	0.056
	Middle	Silty clay loam	N/A	0.07	0.03	4.5	2.5	3.3	N/A	1.05	N/A	N/A	0.089
	Bottom	Loam	GW	0.39	0.15	23.1	16.7	7.1	N/A	N/A	N/A	N/A	0.029
B	Top	Sand	N/A	0.12	0.04	1.5	0.7	0.9	0.002	N/A	N/A	0.001	0.040
	Middle	Silt loam	N/A	0.14	0.05	13.3	10.3	4.2	N/A	3.41	N/A	N/A	0.096
	Bottom	Sandy loam	GW	0.00	0.00	2.1	2.1	0.0	N/A	N/A	N/A	N/A	0.007
C	Top	Sand	N/A	0.47	0.18	1.6	0.5	1.1	0.003	N/A	N/A	0.015	0.028
	Middle	Loam	N/A	0.25	0.10	16.4	14.6	4.1	N/A	0.77	N/A	N/A	0.109
	Bottom	Sandy loam	GW	0.17	0.06	5.0	2.5	2.6	N/A	N/A	N/A	N/A	0.000
D	Top	Sand	N/A	0.23	0.09	1.8	1.2	0.6	0.000	N/A	N/A	0.004	0.002
	Middle	Loam	N/A	0.06	0.02	11.1	7.6	4.4	N/A	N/A	N/A	N/A	N/A
	Bottom	Sandy loam	GW	0.10	0.04	2.8	1.4	1.4	N/A	N/A	N/A	N/A	0.000
E	Top	Loamy sand	N/A	0.22	0.08	1.3	2.2	1.0	0.008	N/A	N/A	0.012	0.042
	Middle	Silt loam	N/A	0.11	0.04	9.6	6.9	7.2	N/A	18.29	N/A	N/A	0.097
	Bottom	Loam	GW	0.50	0.19	41.0	31.8	9.2	N/A	N/A	N/A	N/A	0.096
CP	Top	Sand	13	0.22	0.08	6.0	3.1	3.0	0.003	N/A	N/A	0.014	0.035
	Middle	Silt loam	22	0.16	0.06	17.1	12.6	6.9	N/A	10.57	N/A	N/A	0.081
	Bottom	Sandy loam	GW	0.29	0.11	20.8	15.7	5.6	N/A	N/A	N/A	N/A	0.040

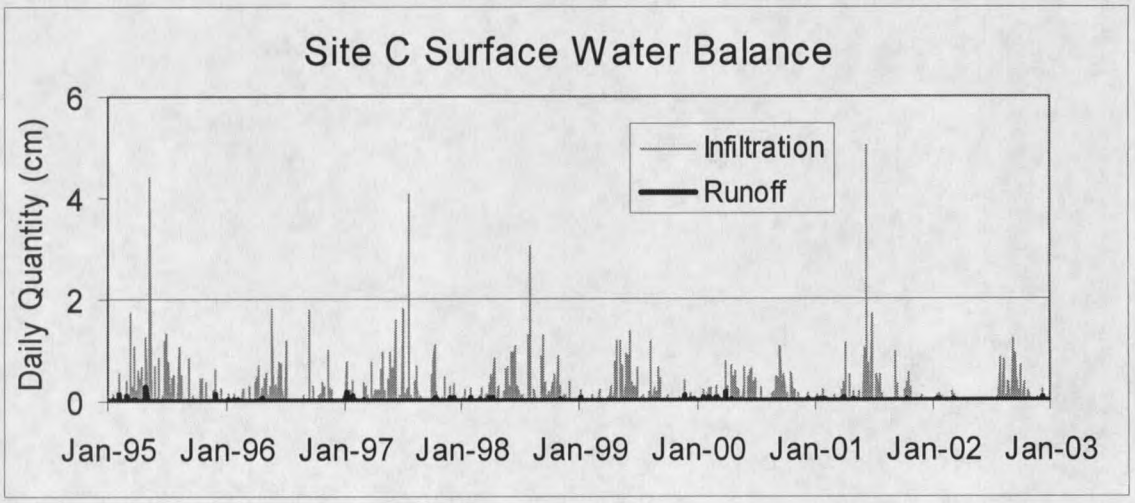
Number of Soil Samples for All Sites

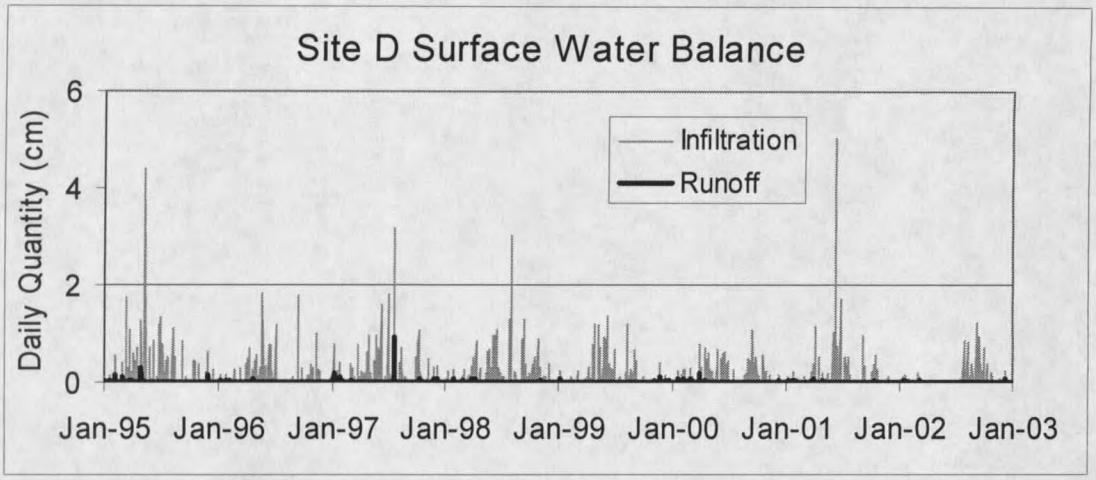
Site	Layer	USDA Texture Class	Layer Bottom Depth (cm)	Bulk Density (g/cm^3)	Porosity	Sand (%)	Silt (%)	Clay (%)	Fraction Organic Carbon	Meas. K_{sat} (cm/hr)	Est. K_{sat} (cm/hr)	1/3 Bar Water Content (cm^3/cm^3)	Initial Water Content (cm^3/cm^3)
A	Top	Loamy sand	N/A	3	3	3	3	3	2	N/A	N/A	2	2
	Middle	Silty clay loam	N/A	5	5	5	5	5	N/A	4	N/A	N/A	N/A
	Bottom	Loam	GW	5	5	5	5	5	N/A	1	N/A	N/A	4
B	Top	Sand	N/A	2	2	2	2	2	2	N/A	N/A	2	2
	Middle	Silt loam	N/A	11	11	11	11	11	N/A	5	N/A	N/A	3
	Bottom	Sandy loam	GW	2	2	2	2	2	N/A	N/A	N/A	N/A	2
C	Top	Sand	N/A	2	2	2	2	2	2	N/A	N/A	2	2
	Middle	Loam	N/A	6	6	6	6	6	N/A	2	N/A	N/A	2
	Bottom	Sandy loam	GW	3	3	3	3	3	N/A	N/A	N/A	N/A	3
D	Top	Sand	N/A	2	2	2	2	2	2	N/A	N/A	2	2
	Middle	Loam	N/A	5	5	6	6	6	N/A	1	N/A	N/A	1
	Bottom	Sandy loam	GW	2	2	2	2	2	N/A	N/A	N/A	N/A	2
E	Top	Loamy sand	N/A	2	2	2	2	2	2	N/A	N/A	2	2
	Middle	Silt loam	N/A	10	10	10	10	10	N/A	6	N/A	N/A	1
	Bottom	Loam	GW	2	2	2	2	2	N/A	N/A	N/A	N/A	2
CP	Top	Sand	5	11	11	11	11	11	10	N/A	N/A	10	10
	Middle	Silt loam	5	37	37	38	38	38	N/A	18	N/A	N/A	7
	Bottom	Sandy loam	GW	14	14	14	14	14	N/A	1	N/A	N/A	13

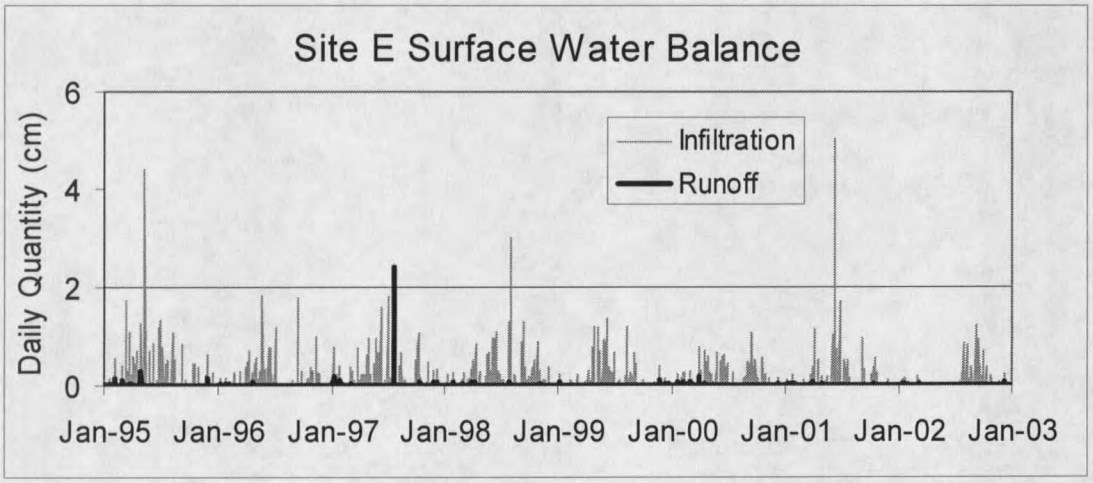
CP = composite site, GW = Bottom of profile is groundwater table depth. N/A = Not Applicable.
Estimated values are shaded.

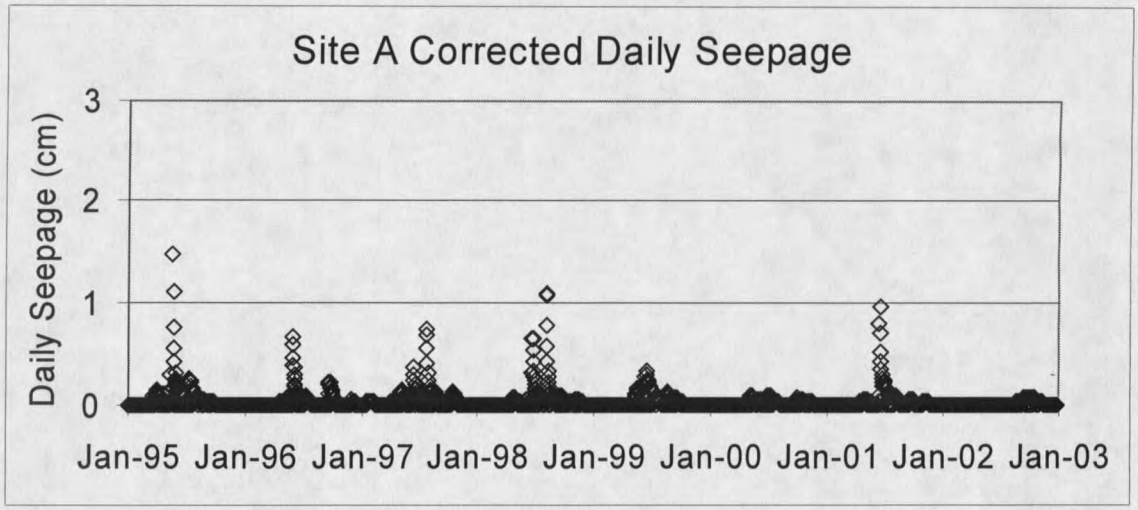

Site A Surface Water Balance
Daily Quantity (cm)
6
4
2
0
Infiltration
Runoff
Jan-95 Jan-96 Jan-97 Jan-98 Jan-99 Jan-00 Jan-01 Jan-02 Jan-03

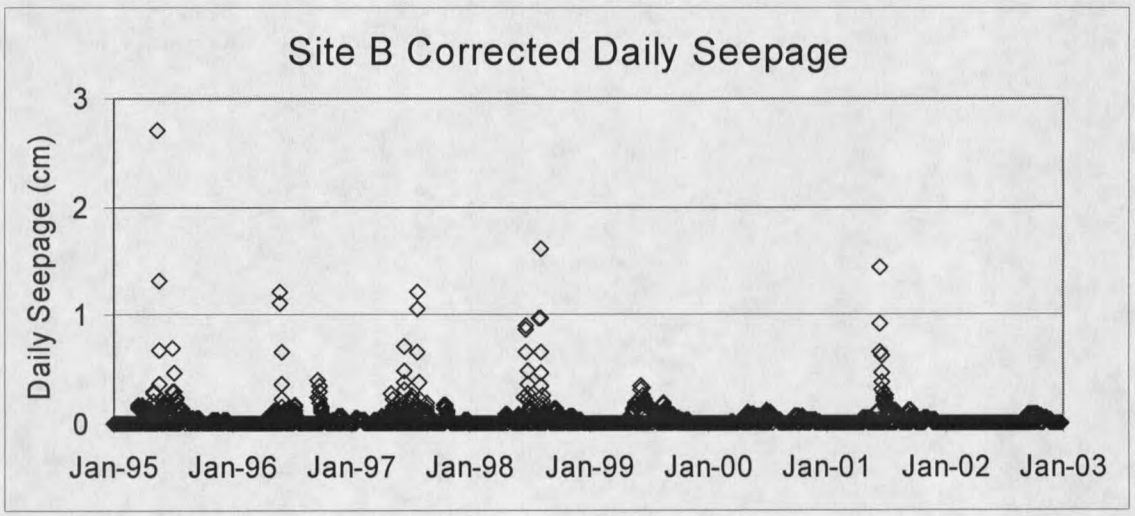

Site B Surface Water Balance
Daily Quantity (cm)
6
4
2
0
Infiltration
Runoff
Jan-95 Jan-96 Jan-97 Jan-98 Jan-99 Jan-00 Jan-01 Jan-02 Jan-03

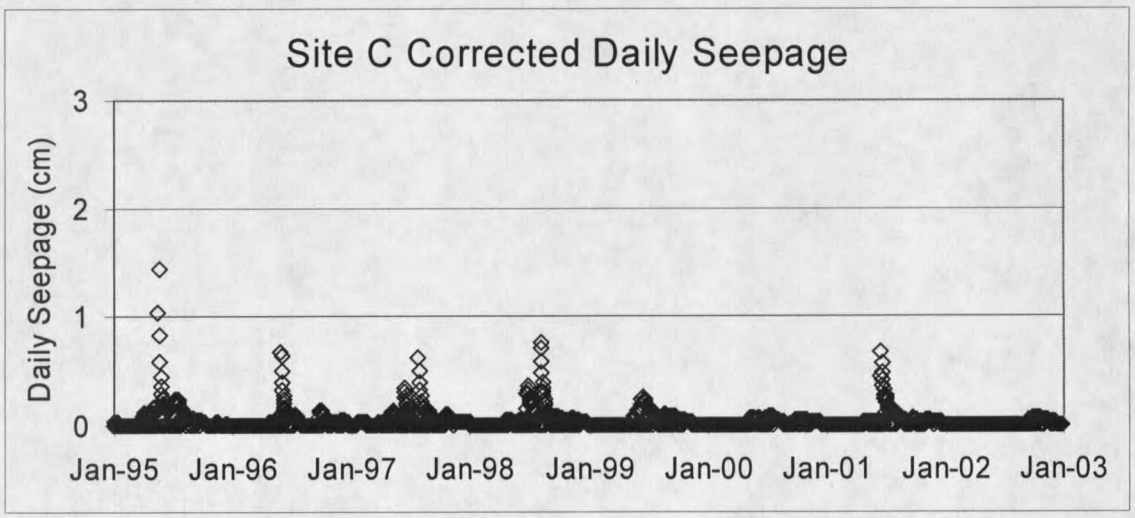

Site C Surface Water Balance
Daily Quantity (cm)
6
4
2
0
Infiltration
Runoff
Jan-95 Jan-96 Jan-97 Jan-98 Jan-99 Jan-00 Jan-01 Jan-02 Jan-03

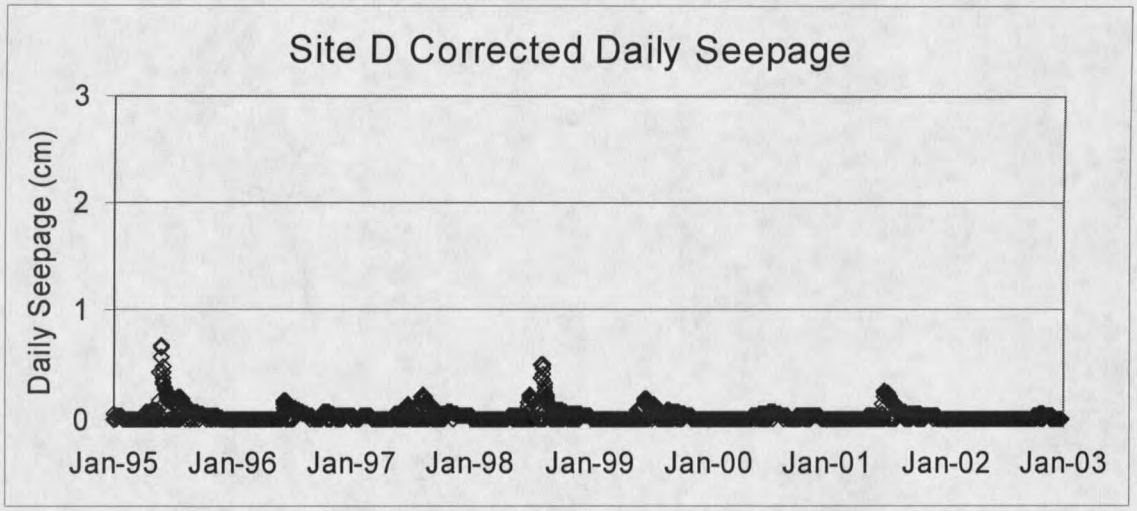

Site D Surface Water Balance
Daily Quantity (cm)
6
4
2
0
Infiltration
Runoff
Jan-95
Jan-96
Jan-97
Jan-98
Jan-99
Jan-00
Jan-01
Jan-02
Jan-03

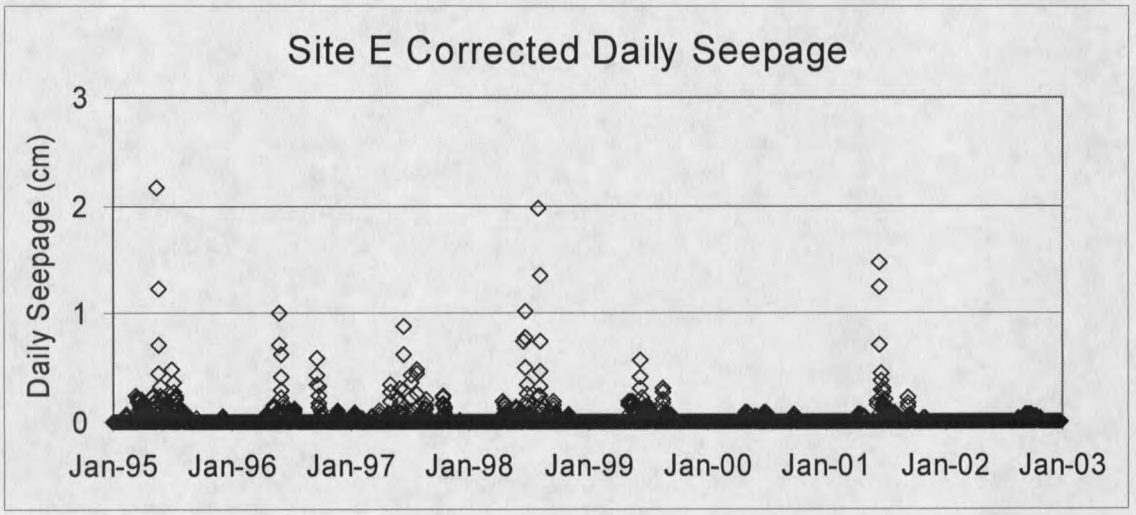

Site E Surface Water Balance
Daily Quantity (cm)
6
4
2
0
Infiltration
Runoff
Jan-95
Jan-96
Jan-97
Jan-98
Jan-99
Jan-00
Jan-01
Jan-02
Jan-03


Site A Corrected Daily Seepage
Daily Seepage (cm)
3
2
1
0
Jan-95 Jan-96 Jan-97 Jan-98 Jan-99 Jan-00 Jan-01 Jan-02 Jan-03


Site B Corrected Daily Seepage
Daily Seepage (cm)
3
2
1
0
Jan-95 Jan-96 Jan-97 Jan-98 Jan-99 Jan-00 Jan-01 Jan-02 Jan-03


Site C Corrected Daily Seepage
Daily Seepage (cm)
3
2
1
0
Jan-95 Jan-96 Jan-97 Jan-98 Jan-99 Jan-00 Jan-01 Jan-02 Jan-03


Site D Corrected Daily Seepage
Daily Seepage (cm)
3
2
1
0
Jan-95
Jan-96
Jan-97
Jan-98
Jan-99
Jan-00
Jan-01
Jan-02
Jan-03


Site E Corrected Daily Seepage
Daily Seepage (cm)
3
2
1
0
Jan-95
Jan-96
Jan-97
Jan-98
Jan-99
Jan-00
Jan-01
Jan-02
Jan-03

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