

DESIGN PARAMETERS FOR MULTI-PHASE EXTRACTION SYSTEMS USING UNSATURATED AND SATURATED SOIL PROPERTIES

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INTRODUCTION

In the environmental field, characterization and remediation of groundwater impact can be a challenging problem. The physical and chemical characteristics of the contaminants and the stratigraphic characteristics of the underlying media will determine the fate and transport of contaminants and ultimately the type of remedial action that can take place to effectively remove the contaminants in the most cost effective and timely manner.

Multi-phase Extraction (MPE) is an *in-situ* technology that uses various combinations of pumps for the remediation of volatile hydrocarbon-impacted soils and groundwater by removing impacted groundwater and vapours from the subsurface. There are several types of the MPEs that can be utilized for vapour and groundwater extraction such as Bioslurping, single pump, and double pump systems. The two pump configuration, or Dual-Phase Extraction (DPE) utilizes a submersible pump for groundwater removal and water table depression plus a separate vacuum applied to the wellhead for vapour extraction (USEPA 542-R-99-004). DPE maximizes the effectiveness of soil vapour extraction (SVE) by lowering the water table and increasing the air-phase permeabilities in the vadose zone (USEPA 510-B-95-007). Design of MPE systems (equipment and recovery well configurations) requires establishing an operating vacuum for effective recovery of vapours and anticipated groundwater recovery rates. These parameters are typically established from pilot tests.

On the basis of site characterization data, unsaturated soil properties can be used to establish an effective operating vacuum and saturated soil properties can be used in single well analysis for estimates of groundwater recovery and drawdown relationships. Determination of these parameters through representative grain size curves from a site and simple analytical solutions can provide additional levels of confidence in designing full-scale MPE remediation systems. This paper discusses the methodology for establishing relationships between soil properties and MPE remediation system design requirements and presents the results of a case study where this approach has been applied in a full-scale system design.

METHODS

In unsaturated soils, the pores are only partially filled with water and the fluid pressure is less than atmosphere, or negative. The moisture content and the hydraulic conductivity are functions of the pressure head (suction). The relationship between parameters during wetting and/or drying of the soils can produce characteristic curves (Freeze and Cherry, 1979). The unsaturated soil properties can be characterized by using the soil-water characteristic curve (SWCC). Determination of the SWCC establishes the moisture retention behaviour for a given soil. There are several laboratory and indirect methods

for determining the SWCC for a given soil type. SoilVision Systems Ltd. of Saskatoon, SK, who employs the SoilVision 3.15 software, provides an indirect method for determination of the SWCC. The software is a knowledge-based database system that uses two stages for the estimation of SWCC. The first stage involves the theoretical estimation of the soil-water characteristic curve based a representative grain size distribution curve and other general soil parameters. The second stage involves the comparison of the theoretical estimated curves to a database of 6000 laboratory measured soil-water characteristic curves.

Once a representative SWCC is established the air entry value (AEV) or minimum negative pressure required to initiate de-saturation of the soil can be determined. This parameter can be used in vapour extraction design as a minimum vacuum to initiate de saturation of the soil. The SWCC can also establish the corresponding negative pressure (vacuum) required to achieve a degree of saturation of 75% in the surrounding soil (typical value required for successful vapour extraction). Establishing the required vacuum to achieve 75% saturation in the surrounding soil is an important design parameter for vapour extraction system design. The SWCC curve can also assist in assessing the likelihood of saturated zones de-saturating under gravity drainage as a result of water table depression. One meter of water table drawdown would be equivalent to an applied suction of approximately 10 kPa at the top of the one-meter zone where the water table has been depressed.

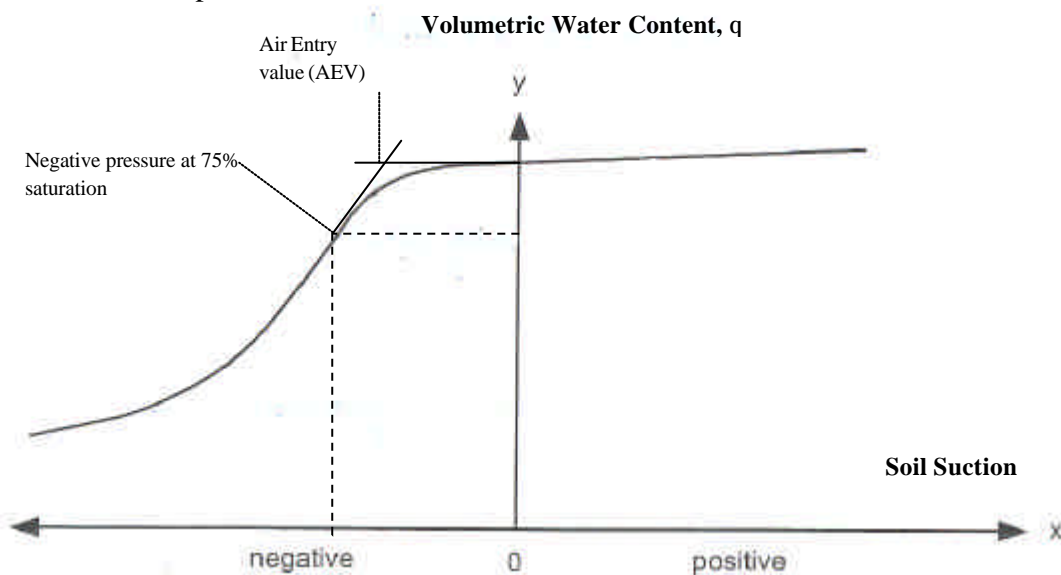


Figure 1. Typical Volumetric-Water Content versus Soil Suction Relationship

The saturated properties of the phreatic zone in an unconfined aquifer can be determined from several methods, such as multiple field rising head tests to determine the hydraulic conductivity, with the storage coefficient (or specific yield) derived from drawdown data collected during a pump test or estimated based on effective porosity. When pumping starts the effect on unconfined aquifers creates a drawdown cone of the water table as well as vertical components of flow (e.g. Gravity drainage). Water produced from a

pumping well arises from two mechanisms that are responsible for confined delivery (the expansion of water in the aquifer under reduced fluid pressures and compaction of the aquifer under increased effective stresses) and a third mechanism, actual dewatering of the pores in an unconfined aquifer (Freeze and Cherry, 1979). A qualitative analysis using the Theis single well hydraulic algorithms can establish approximate rates of drawdown versus time and drawdown versus distance relationships for a single pumping well based on Walton, 1984. For an unconfined well, the well function storativity becomes specific yield and transmissivity is defined as hydraulic conductivity multiplied by the initial saturated thickness.

CASE STUDY

The following case study presents how the above methods were applied in the design of a full-scale MPE system that is currently operating for a client at a site in Calgary, Alberta.

Site Description

The subject property is an existing retail service station that has been in operation for approximately 30 years. Approximately 100,000 litres of unleaded gasoline was released into the underlying stratigraphy and groundwater. Since 2001, multiple Phase II investigations have been conducted that have included the installation of approximately 90 groundwater monitor wells, 40 extraction wells, and the installation of two SVE systems.

Stratigraphy

Glacial lacustrine deposits underlie the study area with the stratigraphy consisting of less than 1 m of topsoil and silty clay fill, underlain by silty clay to a depth of 3 m below ground surface. Underlying the silty clay is approximately 12 m of silty sand (25 to 35% fines), with trace clay, and increasing silt with depth. Several discontinuous thin clay lenses (5 cm) situated at various depths are located throughout the study area. Cross-laminations are prevalent throughout the silty sand unit from 15 m to 20.5 m below ground surface. Interbedded clay and silt layers overlie a till like material to a depth of 22 m, the maximum depth investigated for this study. Figure 2 illustrates a generalized stratigraphic column for the study area.

Hydrogeology

Groundwater levels range from 6.2 to 7.3 m bgs with groundwater flow directed towards the southeast. The average hydraulic gradient was estimated to be 0.008 m/m, with the average hydraulic conductivity of the silty sand unit estimated to be 3×10^{-6} m/s. The average linear groundwater flow velocity was estimated to be approximately 2.5 metres per year. The vertical gradient was determined to be downwards indicating that the subject property is a recharge area. The aquifer is classified as an unconfined aquifer.

Hydrocarbon Impact

The extent of hydrocarbon-impacted soil has been estimated to cover approximately 36,200 m², with impacted groundwater covering an area of approximately 14,000 m². The smear zone ranges from 1.0 to 3.0 metres thick on average. Onsite the smear zone

can extend from surface down to 6.1 m bgs. Light Non Aqueous Phase Liquid (LNAPL) thicknesses measured in four onsite monitor wells has ranged from 5 mm to over 1 m.

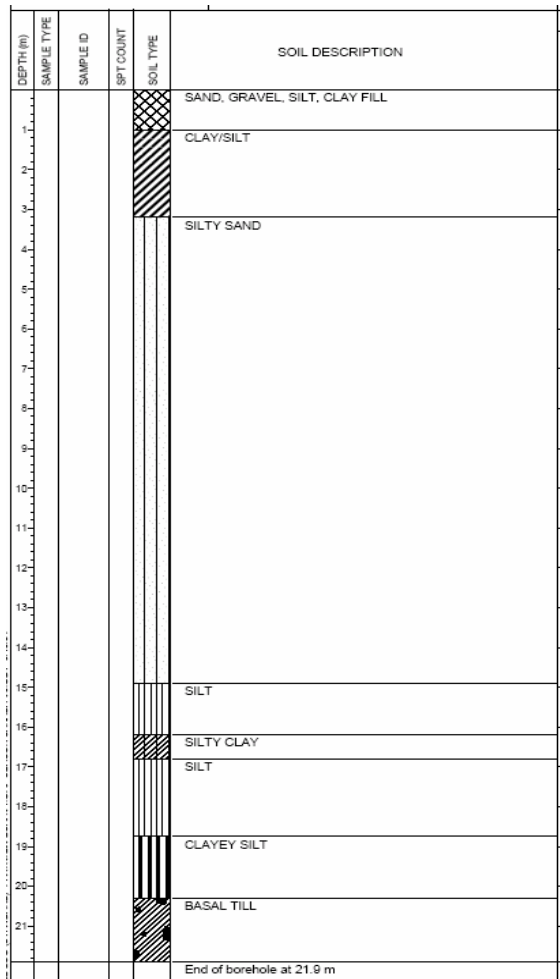


Figure 2. Generalized Stratigraphic Column

Pilot Test

A Pilot test was completed on the site to aid in the extraction system design. The pilot test involved a series of tests at various applied vacuums including 109 inches water column (inWC) (low), 170 inWC (medium), and 238 inWC (high) set at depths of 9.1 m (shallow) and 10.7 m (deep). Measured groundwater levels and vacuum readings at several observation wells in the vicinity of the extraction wells were used to determine the of radius of influence with respect to groundwater removal and vacuum extraction.

The radius of influence with respect to groundwater removal determined from the pilot test data ranged from 22 m to 29 m for shallow pumping and 30 m to 34 m for deep pumping.

The radius of influence with respect to vapour extraction determined from the pilot test data ranged from 9 m to 11 m for shallow vapour extraction at medium and high applied

vacuums, respectively, and 10 m to 11 m for deep vapour extraction at medium and high applied vacuums, respectively.

Key Design Issues

Although the pilot test provided insight into short-term performance several issues required further analysis and determination. These issues included;

- Establish the SWCC of the silty sand unit. The SWCC would assist in determining if the silty sand unit would de-saturate under gravity drainage as a result of water table depression.
- Determine the AEV and the vacuum corresponding to a degree of saturation of 75% for the silty sand unit. To provide another level of confidence on operating vacuum for effective hydrocarbon extraction the SWCC was used to establish the AEV and vacuum required to achieve 75% degree of saturation.
- Establish the drawdown versus time relationships for groundwater extraction. Estimates of the long term drawdown responses were required to establish if 3 m of drawdown were achievable and what time period would be required for this drawdown to occur.

To establish a representative SWCC representative grain size curves from soil samples collected at the site of the silty sand unit were provide to SoilVision. Figure 3 presents a representative grain size cure of the silty sand unit at the site. Based on the grain size curve the silty sand contains 75% fine sand, 20% silt and approximately 5% clay sizes.

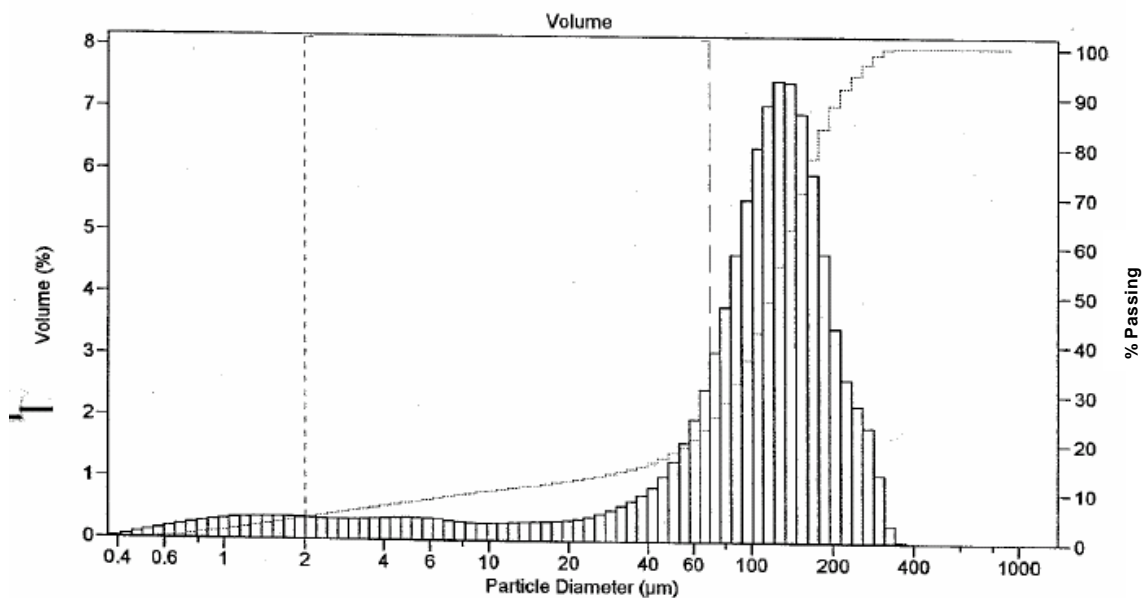


Figure 3. Representative grain size curve of silty sand unit.

Figure 4 presents four methods used by SoilVision to establish the silty sand SWCC based on the representative grain size curve. Results from three of the methods show

reasonable correlation. The recommended SWCC curve was based on the Fredlund and Wilson method, which was used for this project.

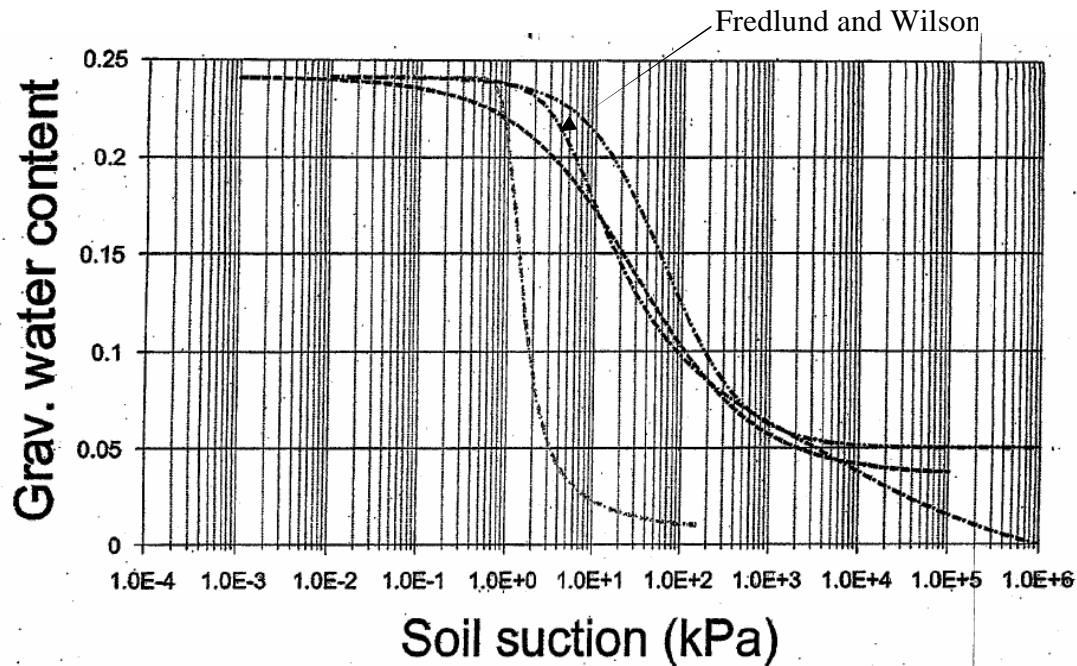


Figure 4. Soil-water characteristic curve as estimated by four different methods.

Based on the Fredlund and Wilson SWCC the AEV was calculated to be 2.5 kilopascals (kPa) (10 inWC), and to achieve a minimum degree of saturation of 75% (soil gravimetric water content of approximately 18%) an applied vacuum of 10 kPa (40 inWC) would be required. If a water table drawdown of 3 m is achieved, the upper 2 m of the dewatered zone would likely drain by gravity as the AEV value is 2.5 kPa, and a 3 m depression of the water table would impart a negative pressure on the upper 2 m of approximately 10 kPa to 20 kPa.

Figures 5 and 6 represent drawdown versus distance (radius from well) and drawdown versus time curves for a single well pumping at a rate of 3.0 cubic metres per day (m^3/d), (established from the pilot test) using the Theis single well analysis. The qualitative analysis suggests that it would take approximately 3 months to achieve a drawdown of 2.3 m at the extraction well and 0.75 m at a 10 m radius.

Based on the Theis analysis, at one month, drawdown at the extraction well was predicted to be approximately 1.8 m, and approximately 0.5 m at a 10 m radius.

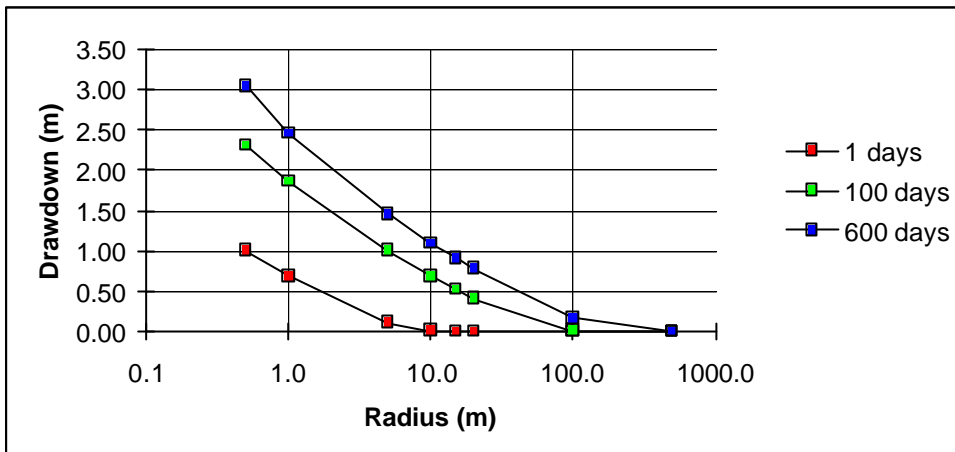


Figure 4. Predicted Drawdown (m) versus Radius (m)

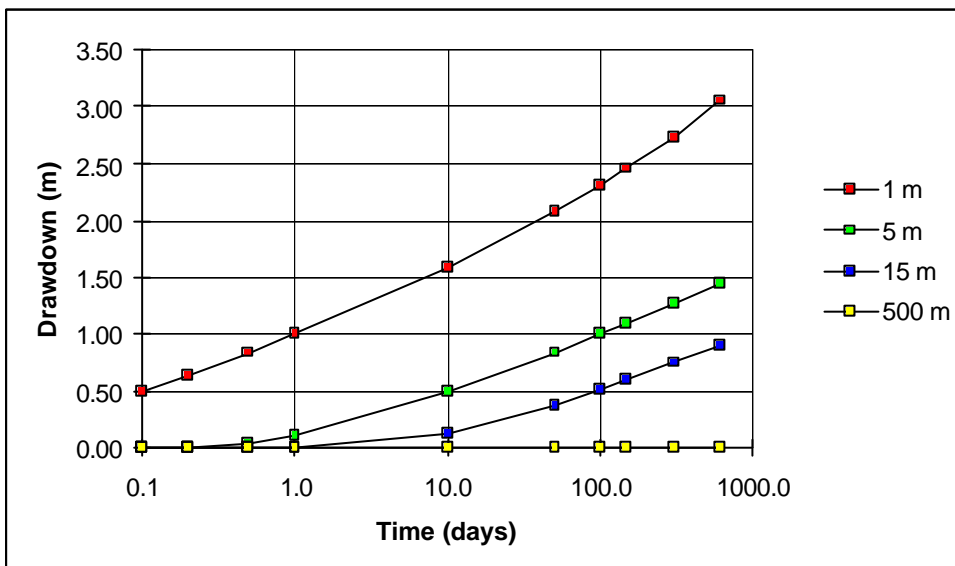


Figure 5. Predicted Drawdown (m) versus Time (days)

The remedial system design is based on the assumption that the water table drawdown will be approximately 3 m below static water levels and that induced vacuum will be applied to the vadose and exposed phreatic zones. Predicted drawdown versus time responses suggest that a drawdown of 3 m at a single pumping well would be accomplished between 2 and 3 years after pumping is initiated. However, the remedial system design incorporates several wells pumping simultaneously. It should be noted that the hydraulic head at any point in the aquifer with multiple pumping wells is equal to the sum of drawdown from each of the single wells (Freeze and Cherry, 1979). Therefore, drawdown within the radius of influence will be enhanced further from drawdown by neighbouring extraction wells. The influence as a result of application of a vacuum was not considered but would likely increase the groundwater recovery rates. The application of high vacuum increases the hydraulic gradient towards the extraction well, and thus increases the vapour and liquid recovery rates (EPA 510-B-95-007) and

will increase drawdown (Suthersan, 1997).

Remediation System Description

Extraction of hydrocarbon impacted soil vapour and groundwater/LNAPL for treatment and disposal has been selected as the remediation method for the site. Soil vapour is extracted by vacuum using a rotary lobed vacuum blower and groundwater/LNAPL is extracted using downhole submersible pneumatic pumps. The pumped groundwater/LNAPL is treated within a compartmentalized tank containing a sedimentation chamber, an aeration chamber, and a gravity separator. Vapours and groundwater from the extraction wells are collected through PVC piping.

The remediation system is connected to eight vapour extraction wells. Six of the eight vapour extraction wells contain down-hole pneumatic pumps for groundwater extraction. The design wellhead vacuum for the vapour extraction wells is 20 kPa (80 inWC) and the design groundwater extraction rate per extraction well was of 3 m³/day.

The extraction well screens were designed to straddle the static water table, for vapour extraction of impacted soil above the static water table, and to accommodate a 3 m drawdown. The screen length was determined to be 6.1 m in length installed from 4.6 to 10.7 m bgs. A screen slot size of 10 mm was used with a 10/20 filter sand pack. Extraction well spacing was determined using the radius of influence data collected from the pilot test. Extraction well spacing was established at 10 to 12 m. This spacing allows for overlap from every vapour extraction well and overlap of drawdown from every second groundwater extraction well.

RESULTS

Results from the determination of the unsaturated (SWCC, AEV and vacuum required for desaturation by to 75%) and saturated (Theis single well hydraulic drawdown calculations) properties and the pilot test results (applied vacuum rates, groundwater flow rates, ROI for vacuum and groundwater for well spacing) established the parameters for the design of the DPE remedial system.

The full-scale remediation system has been operating for over one month. Based on the initial results of system operation, the wellhead vacuum at the extraction wells was measured at 80 inWC (consistent with design value), and an average groundwater flow rate per extraction well of 1 m³/day based on six groundwater pumping wells (compared to the design value of 3 m³/day).

After one month of operation of the full-scale remediation system the radius of influence with respect to vacuum ranged from 24 m to 30 m compared to design values of 9 m to 11 m. The radius of influence with respect to groundwater pumping after one month of operation ranged from 30 m to 35 m compared to design values of 22 m to 30 m.

After one month of operation, average drawdown at the extraction wells ranged from 2.3 m to 3.0 m (compared to design estimates of 1.8 m) and average drawdown at a 10 m radius ranged from 0.4 m to 0.6 m (compared to design estimates of 0.5 m).

SUMMARY

Designing a remediation system to effectively remediate impacted soil and groundwater requires detailed understanding of the contaminants of concern as well as the unsaturated and saturated properties of the impacted stratigraphy.

A case study completed by SEACOR was presented where the SWCC was determined from representative grain size curves to establish unsaturated properties used in the design of a DPE remediation system. The SWCC provided determination of the AEV to initiate desaturation of the silty sand unit beneath the site and the required negative pressure to desaturate the pores to 75%. Drawdown versus time and distance were determined using the Theis single well hydraulic calculations to predict drawdown at a given flow rate over time and distance. The Theis analysis was conducted to determine the feasibility of a 3 m water table drawdown at the site. This data in combination with data accumulated during the pilot test aided in developing the design parameters for the DPE system in terms of required operating vacuum, groundwater flow rates, extraction well design and spacing to effectively remediate the impacted zones both vertically and horizontally.

Performance of the Multi-Phase extraction system in the first 30 days with respect to; recovery of hydrocarbons in the vapour phase, pneumatic radius of influence, groundwater recovery and water table drawdown have corresponded closely to predicted responses based on the SWCC data, Theis analysis and pilot test data.

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