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An Analysis of Groundwater Flow Patterns in a Constructed Treatment Wetland Cell

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AN ANALYSIS OF GROUNDWATER FLOW PATTERNS IN A CONSTRUCTED TREATMENT WETLAND CELL

THESIS

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Abstract

This research effort analyzed groundwater flow paths within a treatment wetland constructed to degrade tetrachloroethylene (PCE) in groundwater. The treatment cell is a vertical flow wetland that allows the water to flow from the bottom to the surface breaking down PCE and daughter products. The method of conducting this research included collecting field data of hydraulic head contours nested piezometers and collecting data from sampling wells to determine hydraulic conductivities in the wetland. The field data was used to create a numerical computer model to determine groundwater flow patterns. The field data and the model demonstrate that there are areas in the wetland with flow velocities as low as 0.0019 m/day and as high as 2.779 m/day. The computer model also shows residence times of water particles traveling from the bottom of the wetland cell to the surface water varying from < 1 day, to over 1000 days. Groundwater flow patterns occurring in the wetland today were compared to a study five years ago. The hydraulic head contours and hydraulic parameters measured in the field were similar in both studies. The results of both studies show the residence times and the desired uniform flow across the wetland is being short circuited.

Acknowledgments

I would like to thank my wonderful thesis advisor for the opportunity to take on the topic at hand and for the gentle guidance that kept me on track but allowed for a chance to grow and test my own academic capabilities. Also I would like to extend thanks to my thesis committee who ensured my research would be of quality and contribute to the greater goal of this overall research stream. I wish the department and all the members continued support from students who tackle this subject and further the understanding of this great subject.

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- Rebecca S. Corbin

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AN ANALYSIS OF GROUNDWATER FLOW PATTERNS IN A CONSTRUCTED TREATMENT WETLAND CELL

I. Introduction

Purpose

Contaminated groundwater is a major concern in the United States. Some contaminants are easier to detect, capture and clean up than others. Contaminants that are more dense than water and not in an aqueous phase are commonly referred to as DNAPLs (Dense Non-Aqueous Phase Liquids). These types of contaminants are of particular concern in groundwater remediation because they tend to pool at the bottom of an aquifer allowing groundwater to flow past the contaminating substance and transport it along the groundwater path. Water that has passed through this type of contaminants is not easy to track, capture, or treat completely. Common degreasing solvents used by industry and the United States Air Force (USAF) are such DNAPL contaminants. To clean the leaks or contamination from the past, the USAF is researching ways to treat contaminated groundwater in the most efficient and cost effective way possible. The USAF is looking for ways to reduce clean up costs following the guidelines set forth by the Environmental Protection Agency's (EPA) regulations. One treatment option that could save millions for the USAF and the Department of Defense (DOD) is the use of natural attenuation, a process that naturally breaks down contaminants in the groundwater. Current research is focusing on the feasibility of constructing wetland areas to naturally decontaminate groundwater containing DNAPLs. This thesis research concentrated on one particular aspect of that process characterization of the flow of groundwater through a constructed treatment wetland cell. Understanding the groundwater flow paths is a critical link to determining the treatment efficiency of the cell. This information will aid other research on constructed wetland studies that focus on microbial activity, chemical breakdown, and plant contributions to a most efficient natural groundwater decontamination processes.

Background

The treatment cell examined in this study was constructed in 2000 at Wright Patterson Air Force Base (WPAFB) in Dayton, OH. The wetland cell is treating groundwater from an aquifer that is contaminated by a plume of tetrachloroethylene (PCE). The treatment site has been identified and documented with the Ohio Environmental Protection Agency and there exists no current requirement for remediation. The location and the low priority on the EPA clean up list make this location ideal for groundbreaking remediation research.

In a joint effort with Wright State University students and staff, the Air Force Institute of Technology (AFIT) continues to study the ability of constructed wetlands to naturally degrade PCE. PCE is among the most frequently detected and problematic groundwater contaminants nationwide. PCE is a potential carcinogen and a contaminant regulated by the EPA for any water that may be used for drinking with assigned maximum contaminant level of five parts per billion (Environmental, 2006). The concentration of

PCE in the aqueous phase when the cell was constructed was approximately fifty parts per billion (ppb), the concentration at the outflow is currently measured at one ppb. PCE and degradation products are classified as volatile organic compounds (VOC) which usually involve complex treatment systems. Currently the most common way of treating groundwater contaminated with VOCs is to pump the water above ground and treat it through an energy intensive cleaning process. The EPA estimated budget for pump and treat systems around the US for the year 2002 was approximately $32.5M in operation and maintenance fees for ongoing projects (Environmental, 2002). This is the largest amount ever required in the budget with no completion date anticipated for the majority of these clean-up projects. Another option for cleaning VOCs is to aerate contaminated groundwater to encourage vaporization of the contaminant. Aeration is achieved by exposing the contaminated water to a fresh air supply. When the air and water mix, the volatile compounds are driven into a vapor state. The key to these types of systems is the air and water contact. There are many ways to achieve this goal; however the packed tower aeration (PTA) is the most commonly applied for VOC removal. The EPA has acknowledged this type of aeration technology as a best available technology based on the degree of treatment that can be achieved for both potable water purification and remedial work. In this system air and water are run counter-current through a randomly-dumped or structured media that will enhance the air/liquid contact by exposing a large surface area of the water. The larger surface area exposed, the greater the opportunity for transfer of VOCs out of the water and into the passing air. This option is also costly and involves mechanical systems that require maintenance and energy for continuous operation over very long periods of time. PTA is also limited in the specific situations where it can be used. For example this practice is not recommended for small flows (less than 25 gallons per minute) or for areas with high iron content (Nyer, 1992:61).

Constructed treatment wetlands have been shown to be a more energy efficient method with lower operating costs and little to no required maintenance. A study done by Luederitz et al. (2001) compared semi-centralized constructed treatment wetlands to central technical systems in place for treating wastewater from small communities in Europe. The results showed the constructed treatment wetland method required 83% less energy for their function compared to the central technical system and 72% less energy than the discharge to a central treatment plant 20 km away. The study included an estimation of total material and energy requirement for the different possibilities of sewage treatment. For the construction material inputs the constructed wetlands required 76% less than a centralized system and 63% less energy than the discharge to the central treatment plant. The conclusion of the study was that in rural areas and small towns the advantages of the semi-centralized solution of using constructed wetland cells for treatment are dominant over other types of the more common centralized treatment (Luederitz, 2001:170). This study is just one example of many studies that have been completed to show the benefits of constructed wetlands since the process was introduced in the 1960s. The constructed wetland option of cleaning contaminated water is becoming more and more acceptable around the world. In a segment in the Water Encyclopedia written by Langergraber (2005) on constructed wetlands, the definition touts that constructed wetlands provide the optimal treatment conditions found in natural wetlands but have the flexibility of being constructed. This can lead to a specialized concentration on specific contamination degradation requirements or land size issues for placement. If implemented where feasible this method of decontaminating water could save millions of dollars in cleanup costs.

In a constructed wetland cell, the water to be treated is pumped into the wetland area at a controlled rate through specially selected media. The water then travels horizontally or vertically through the layers of wetland substrate and vegetation until it reaches the outlet weir. The effluent is discharged into open water, an adjacent aquifer, or a next level treatment stage, in an acceptably decontaminated state. In a constructed treatment wetland cell, the resident microorganisms and vegetation are nature's tools that clean the contamination from the inflow. If designed correctly, the levels of contamination remaining in the water effluent will meet or exceed EPA standards.

The constructed wetland cell located at Wright Patterson AFB, is 18 m wide, 36 m long and approximately 1.7 m deep. The contaminated water is pumped from a known plume in the aquifer just beneath the cell. The water is distributed through three parallel, three inch diameter, PVC pipes in the bottom layer of the constructed cell. The pipes are perforated along the sides and run lengthwise through a 23 cm layer of gravel. Just beneath the gravel and on the sides of the cells is an impermeable geomembrane layer that prevents the contaminated water from flowing into the surrounding soil. The water (ideally) travels vertically in this wetland cell, through 1.1 m of hydric (historically saturated) soil relocated from a former natural wetland site in the local area. The water then flows across the top of the surface to the outlet weir at one end. Figure 1-1 depicts a cross- section view of the constructed wetland.

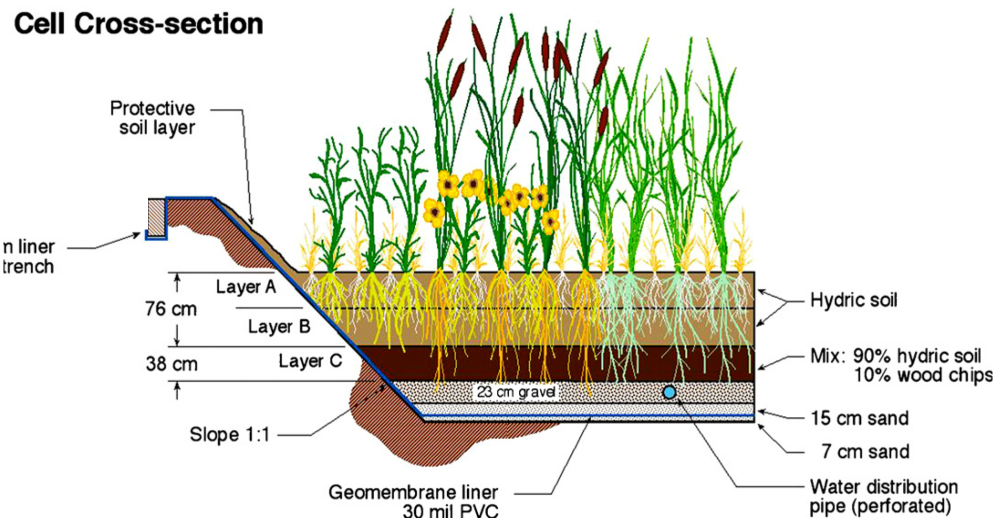

Fig 1-1. Cross-section of the wetland cell at WPAFB (adapted from Amon et al., 2007).

Plots of different emergent wetland plant species were planted in each cell. The soil composition in the cell of interest is composed of three layers of the hydric soil that was placed in the cell 38 cm in thickness each. The bottom soil layer was originally placed with a 10% woodchip amendment added to provide initial concentrated levels of carbon for beginning anaerobic microbial actions. Over time it is assumed that that carbon has since been broken down and helped to create a very active anaerobic zone of activity deep in the soil.

Problem Statement

The design and understanding of constructed treatment cells is still a relatively new field of study. The more patterns of flow that can be researched, documented, and understood, the more we can determine the required residence time in different sediment zones of different chemical and biochemical conditions, and the more this option of natural water treatment can be correctly designed and applied to accommodate various contaminants and situations. The hydrology in constructed treatment cells can lead to effective treatment or wasted effort thus it must be studied and understood. Long term characteristic changes must be determined to predict lifecycle performance and to improve future construction techniques.

Research Questions

1) What are the water flow paths throughout the wetland?
2) What are the hydraulic residence times of the water in the various depths of the wetland cell?
3) How does this behavior compare to what was detected in the first study completed just after construction?

Method

The method for characterization and analysis of groundwater flow patterns was first to measure hydraulic conductivity and hydraulic head from a three-dimensional grid of piezometers located in the constructed wetland cell. From this information a simulation model was built in DOD groundwater modeling software to show flow paths occurring in the treatment cell. Applying Darcy's Law for groundwater flow, it was possible to determine the groundwater flow direction and speed using only these parameters. By understanding the hydraulic characterization of the wetland cell at the current time, a comparison can be made to the results found in a similar study conducted five years ago.

II. Literature Review

Chapter Overview

Natural attenuation and biodegradation are processes that are now being studied and used for water treatment and remediation. One specific example of these processes is the design and use of manmade wetland cells for cleaning contamination from groundwater. Environmental scientists are now beginning to gain insight into how manmade wetland areas can efficiently emulate natural purification processes. The implementation of this technology provides a more aesthetic, more energy efficient and more cost effective way to treat contaminated groundwater. The use of treatment wetlands began in the early 1960s with some small and inefficient applications. After nearly 30 years of being used on a case by case basis, mostly for tertiary cleaning of wastewater, the technology is now beginning to be regulated and accepted worldwide for various uses. Wetlands are now constructed to treat water from a variety of sources such as mine waters heavy in metallic compounds, animal waste runoff from farm operations, storm water runoff, secondary wastewater treatment, and groundwater contaminated with nitrates or chlorinated ethenes. As of 1998, treatment wetlands in the US numbered nearly 600 and another 500 were in use in Europe. The advancement in the understanding of how wetland systems work and long term studies proving the theoretical background make constructed treatment cells now considered as a regular treatment option (Cole, 1998).

The first research identifying that wetland treatment may be suitable for treating groundwater contaminated with chlorinated ethenes, beginning with a study of volatile organic compounds, was introduced in 1999 by researchers Michelle M. Lorah and Lisa D. Olsen. These researchers determined that chlorinated ethenes had entered a natural wetland area and had broken down into daughter products of dichloroethylene (DCE) and vinyl chloride (VC) by the natural microbial activity in the wetland ecosystem (Lorah and Olsen, 1999). Lorah and Olsen's research effort motivated the research stream at AFIT supported by this study. With the knowledge that naturally occurring mechanisms in a wetland ecosystem can break down chlorinated ethenes that pose threats to groundwater supplies across the country, studies of how to most effectively construct a wetland to treat these contaminants is a pressing topic in bioremediation today. This chapter provides the background of the hydrogeological research occurring in the field of constructed wetland cell remediation. The topics discussed include a focused look at artificial wetland design and functionality, groundwater flow theory including Darcy's Law, a common numerical modeling technique that will be used in this study and the results of a previous study conducted on the same wetland cell in Dayton, OH in 2002.

Constructed Wetland Design and Function

The two most common types of manmade treatment wetlands being designed and used today include surface flow (SF) and subsurface flow (SSF) wetlands. SF wetlands have water flowing across the surface of a soil field with algae, cattails and reeds growing plentifully in the treatment area. This type of wetland is fairly deep (0.6 meters -2 meters), built with hydric (natural wetland) soils, high organic content soils, carefully selected vegetation, and specially designed inflow and outflow controls.

SSF wetland cells, on the other hand, are built so the water flows and is treated beneath the surface. The water is never seen on the surface; rather it flows through the gravel media at a depth of 0.5 meters. SSF wetlands are most commonly used due to smaller space requirements, concealed water preventing the introduction of insects, pests and odors, and aesthetic appeal. These types of wetlands can usually be integrated into the landscape with decorative rock or small plants (National, 1998:3).

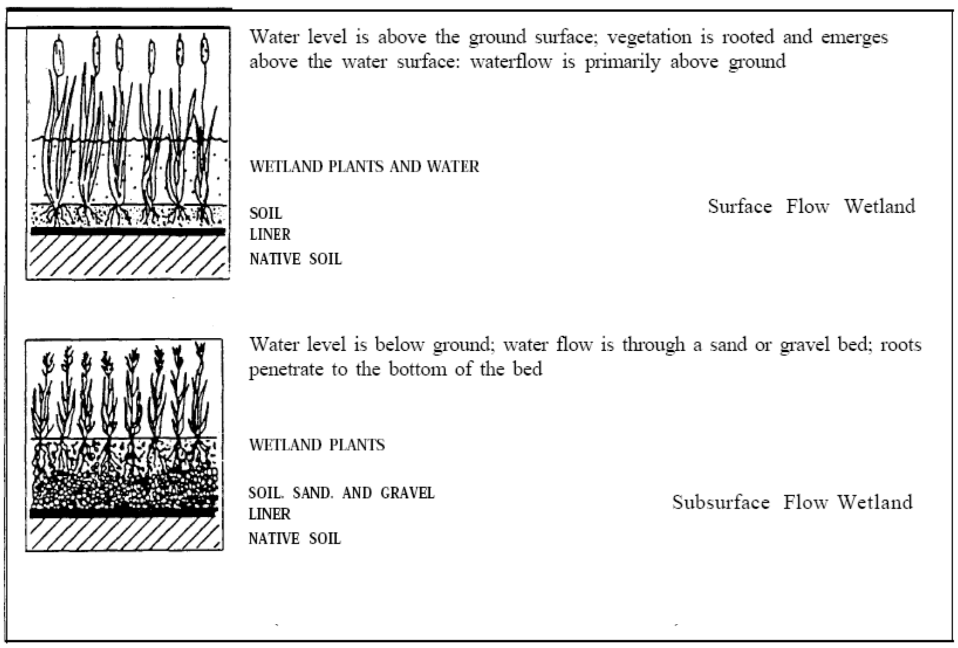

Fig 2-1. Cross-sectional description of SF and SSF wetland designs (adapted from EPA, 2000)

The contaminated groundwater for treatment is introduced into the wetland treatment area by perforated pipes, gated pipes, or a series of weirs. As soon as it is introduced, natural processes start biodegrading the contaminants. In SF wetlands the vegetation plays multiple roles in treatment effectiveness. One of the basic roles is that roots, stems, and deteriorating plant debris acting as a filter for any suspended materials. These sections of the vegetation also create millions of small spaces for bacteria to attach and feed on contaminant elements. Bacteria are the crucial part of the treatment process working both in the aerobic and in the anaerobic zones of the cell. As the bacteria consume the waste, the water continues to flow toward the outlet and becomes cleaner with every bacteria colony that is in the flow path. The bacteria also create substances that help plants to continue providing habitats for insects and other microorganisms that live in the wetland ecosystem.

SSF wetland cells are built with a treatment medium of large rock or gravel. Similar to the plants chosen for SF cells, the medium selected for SSF cells is chosen to provide a multitude of small pore spaces where bacteria can thrive and consume waste products. Because the flow of water will remain at least 0.05 m below the finished ground surface, the vegetation that does grow in SSF cells helps treatment by taking up nutrients that are generated from the waste or the bacteria; however they do not play as important a role as in the SF cells. As mentioned earlier, a SSF treatment cell is more desirable on a site of households or businesses that can incorporate it into their landscape design, thereby saving money from treatment and gaining low maintenance landscaping.

The design of treatment wetlands is a combination of few known factors, assumptions based on the performance of existing systems, and the limited knowledge of natural systems. A constructed system can be designed to provide what is believed to be optimal treatment, but it is still a natural process. Deviations from designed flow paths and residency times are likely to occur after construction. A conservative design can help alleviate some of these issues; however flow rates and patterns of groundwater through the wetland cell are vital research topics. In natural wetlands, water flows through relatively narrow and well established channels. In contrast, the goal of a constructed cell is to uniformly distribute flow across the width of each cell as the water travels lengthwise from the inlet to an outlet. Hydrology is the most important design factor in constructed wetlands; it often determines success or failure (Environmental, 2000:7). When the size, shape, and medium of a cell is selected, the most important factor driving those choices is the required hydraulic residence time, or the amount of time (usually days or weeks) that the water must spend in the cell to meet effluent standards at the outlet.

In the study conducted by Luederitz et al. (2001) the advantages and disadvantages between horizontal and vertical flow wetlands was also researched. Table 2-1 below shows these advantages and disadvantages.

Table 2-1 Comparison of advantages and disadvantages between horizontal and vertical flow wetlands (Luederitz, 2001).

	Advantages	Disadvantages
Vertical Flow Wetlands	Smaller area demand	Shorter flow distances
	Good oxygen supply	Higher technical demands
	Simple hydraulics	
	High purification performance from the beginning	
Horizontal Flow Wetlands	Long flowing distances possible; nutrient gradients can be established	Higher area demand
	Longer life cycle	Careful calculation of hydraulics necessary for optimal O2 supply
		Equal waste water supply is complicated

The results showed that each type favored separate types of contaminants that it could effectively treat. Horizontal flows degraded phosphorus much more effectively than vertical flow wetlands while the latter type was much better at denitrification of ammonium and nitrate than the horizontal flow. In the Luederitz study, as in other design and remediation guides the vertical flow type of wetlands receive the contaminated water at the top of the substrate and water flows assisted by gravity down through the media chosen and exits the cell via pipe or pump located on the bottom of the cell. This is essentially the reverse direction of the flow induced in the wetland cell at WPAFB.

The design for the treatment wetland cell in this study is a vertically imposed flow pattern. The theory that vertical flows can effectively degrade certain DNAPL groundwater contaminants is the most current research in this field. The design was originally conducted with much the same objectives used in horizontal flow construction.

Proper construction would create paths and hydraulic residence times to effectively clean the contaminated water without creating unnecessary distance for the water to travel. The vertical flow design ensures that the breakdown of the chlorinated ethenes will take place by introducing the original contaminant PCE into the substrate with no oxygen present (anaerobic) zone, the only place with suitable conditions for contaminant degradation. Continuing the flow upward the daughter products, TCE, DCE and VC enter an oxygen rich (aerobic) zone where they in turn can be broken down further into non volatile compounds.

Groundwater Flow Theory

Darcy's Law. Groundwater flow has been studied for centuries. Laws, equations and theories have been developed and tested, and today we have a good understanding of movement patterns. Success in predicting underground water movement depends on how accurately pertinent hydraulic parameters (such as hydraulic conductivity, K) can be evaluated. Variables for every piece of land are different and complex. In this research the flow of groundwater through the treatment cell at WPAFB is studied using proven equations, models and assumptions from a hydrogeology perspective.

The definitive framework for studying groundwater flow was developed by Henry Darcy through his experiments in 1856. The equation Darcy developed is considered a law of groundwater flow. A set-up of this experiment is illustrated in Fig 2-2.

$$q = Q/A \qquad (1)$$

$$q = -K\,((h_1-h_2)/L) \qquad (2)$$

Where: Q = volumetric flow rate

q = Darcy velocity (theoretical velocity)

A = cross-sectional area where flow is passing through

K = hydraulic conductivity

h_1, h_2 = measurements of water elevations (hydraulic head)

L = the distance between two head measurements

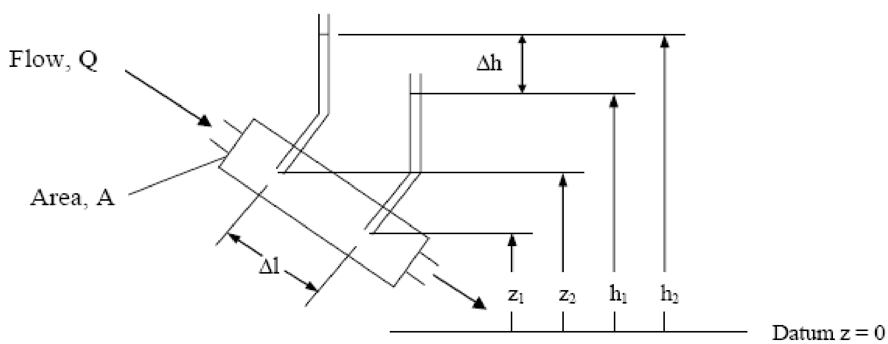

Fig 2-2. Experimental Apparatus for Darcy's Law (Freeze and Cherry, 1979:15)

With a known volumetric rate of flow, Q, in units of volume per time (L^3/T), the elevations in two separate manometers, h1 and h2, are measured relative to a local datum. Often a negative sign is included in the equation to show the characteristic of flow moving from areas of higher head to lower head. The parameters of this experiment will yield three key variables for understanding groundwater movement: specific discharge, hydraulic gradient and hydraulic conductivity.

Specific discharge. The symbol q (L/T) is often called Darcy's velocity, and represents the volumetric flow rate per unit cross-sectional area of the cylinder. This is not an accurate measure, as volumetric area is constituted by both the solid soil particles and the voids between them. This measure ignores the fact that water cannot flow through space occupied by a solid particle. A more accurate measure of the void space is the pore velocity, v, which can be calculated using the same Q and A values and a parameter called porosity, n.

$$v = Q/(A*n) \qquad (3)$$

This velocity is a closer approximation of actual velocity in soil or aquifer materials that has been proven accurate on both small scale studies (cm/min) done by Bouwer and Rice and very large scale studies (km/thousands of years), performed by Pearson and White (Bouwer, 1978:39). The variable of porosity provides a clearer understanding of how much water a soil can hold in the space between soil particles. The measure of porosity itself is the ratio of volume of voids in a sample of soil to the total sample volume:

$$n = V_v/V_t \qquad (4)$$

The amount of voids in soil is important because it dictates the spaces that could transport water or air. In a wetland condition, the soil is considered saturated. Voids in this kind of soil would contain nearly 100% water and very little air. Porosity varies depending on the characteristics of the media. Clay materials have a much higher porosity than sand and gravels, where the grain size is larger and takes up more space in the overall sample volume. Porosity for generally porous soils is usually around 0.3. Porosity for peat soils, commonly found in wetlands, is near 0.5.

Hydraulic gradient. The term (h1-h2)/L, is the second key variable. This variable is the change in hydraulic head measurements between two manometers, piezometers, or wells open to atmospheric pressure a known distance apart. For small distances, this parameter is designated as dh/dl and is the slope of the water table or piezometric surface at that point. The hydraulic gradient is measured from the field in either a horizontal direction, using piezometers with screens set to the same depth, or in the vertical direction, by using piezometers in close proximity to each other in an x-y plane, but with screens located at varying depths. This grouping is referred to as a piezometer nest. The basic hydrogeologic framework for a given locality is based on spatial variation of hydraulic head values measured in the field. The hydraulic head or water level information is visually integrated into potentiometric surface maps and potentiometric profiles. Construction of potentiometric maps and profiles provides fundamental information needed to determine groundwater flow directions, flow velocities and travel times (Bair and Lahm 2006:1-13). The piezometers installed in the treatment cell are set in nests of three each to monitor the vertical component of flow. With the piezometers set at known depths, elevation differences can be measured and compared both with piezometers at the same depth across the wetland and with the piezometers in the same nest. The piezometric head measured above ground is a sum of the elevation at which the piezometer screen is located, the pressure present at that depth of soil, and the velocity at which the groundwater is flowing. The equation calculates the hydraulic head which can be measured in each piezometer. The piezometric head is another name for the hydraulic head that can be measured in the piezometers that are open to atmospheric pressure.

$$h = z + (P/p_w)*g + v^2/2 \qquad (5)$$

Due to the relatively slow velocity of groundwater the v term of the equation is usually neglected and the simplified version then becomes

$$h = z + (P/p_w)*g \qquad (6)$$

z = elevation to bottom of piezometer from datum

P = pressure at a given depth

p_w = density of water

v = pore velocity

g = gravitational acceleration (9.81 m/s^2)

After measurements of the piezometric head are taken in the field, the same elevations measured at a given depth can be connected with a contour line. The direction of the groundwater flow will always be perpendicular to the lines connecting the points of identical elevation. Elevation measurements can be compared within a nest of piezometers to determine a vertical flow profile. This profile will give a clear indication of the vertical gradient found in the wetland cell and aid in the focus of this research. The spacing between these contour lines leads to an estimation of the groundwater velocity. Groundwater always flows from a point of higher head to lower head regardless of space or time. The proximity of the contours to each other will represent the velocity of the groundwater flow through a volume of soil. The closer the contour lines are together, the faster the velocity will be.

Hydraulic conductivity. The variable, K (L/T), is proportionality constant in the Darcy equation of groundwater flow. Hydraulic conductivity describes the property of both the fluid and the media to allow groundwater to flow through the pores of that particular media in response to the hydraulic gradient. This parameter is one of the most important variables in characterizing groundwater flow. This parameter will show to a close degree the conditions of the soils in the field. If a material is said to be heterogeneous the value of K varies spatially. Materials that demonstrate a directional dependency in conductivity are said to be anisotrophic (Domenico, 1998:39). In a groundwater study, the term anisotropy means that the value of K at a given location depends on direction x, y, and z that is traveled from a given point in that material. In a homogeneous material, K is independent of location. The term isotropy implies that the K value of the soil is the same regardless of the direction traveled from a particular location. Although real geologic materials are never perfectly homogeneous or isotropic, it is reasonable to assume that they are for calculations covering small distances (Fitts, 2002:49).

Hydraulic conductivity can be determined using several methods including lab work and empirical relationships; however, the truest and most accurate way to obtain this critical parameter for a specific study site is to test it in-situ. To obtain field conditions of hydraulic conductivity many tests have been developed over the years. Two of the most widely used field scale approaches to measure hydraulic conductivity are pumping tests and slug tests. These types of field tests involve manipulation of a potentiometric surface to determine the properties of the soil in which a piezometer is placed. These are methods for collecting field data that can be interpreted to give an approximation of the naturally occurring hydraulic conductivity. Table 2-2 shows some common values of K in various types of soils.

Table 2-2 Values of Hydraulic Conductivity of common soils (Freeze and Cherry, 1979:29)

Soil Type	min value of K, (m/s)	max value of K, (m/s)
gravel	10^{-1}	1.0
clean sand	10^{-4}	10^{-2}
silty sand	10^{-7}	10^{-3}
shale	10^{-13}	10^{-9}

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The slug test method will be used for this study and is outlined below. A slug test is a localized test of the media, and can show subtle changes in conductivity over a smaller area. Common ways to conduct slug tests include either adding a known volume of water or removing a known volume of water from a piezometer or well to instantaneously change the elevation of water in the piezometer. This new elevation is recorded and the change in water level is noted over time as the slug dissipates and the water returns to its pre-test level.

With the data obtained from these tests it is possible to determine the hydraulic conductivity of the soil for use in flow calculations. The most common ways to calculate K values are with equations derived from years of studying the results of the field tests mentioned above. The groundwater wells used in this study represent data gathered at single point observations (or single borehole tests); therefore applicable equations to determine K include both the Hvorslev (1951) and the Bouwer and Rice (1976) methods.

The Hvorslev equation requires the use of some simplifying assumptions: homogeneous, isotropic soil characteristics near the test site, uniform thickness of a confined aquifer, a fully penetrating well, a potentiometric surface that is nearly horizontal throughout, negligible specific storage, and a finite effective radius (Bair and Lahm, 2006: 5-2). The Hvorslev estimate depends on information about well construction and includes many derived constants for differing well configurations and geometries.

$$K = \frac{r2 * \ln (L_e/R)}{2 * L_e * T_o} \qquad (7)$$

r = radius of piezometer

L_e = effective length of screen

R = effective radius of the screen (to include any gravel pack)

T_o = time lag from the potential surface to rise or fall to 37% initial water-level change

The Bouwer and Rice equation for analysis is similar, but allows for application in both fully and partially penetrating wells, and in unconfined aquifers with water levels above the screened interval. This method also assumes homogeneous, isotropic, a uniform thickness of the aquifer and a saturated thickness that is assumed not to change during the test. In this equation the radial distance that the hydraulic conductivity effects (Re) is usually unknown in field conditions and must be derived from empirical measures for which Bouwer and Rice present a methodology containing well geometry and empirically derived parameters as the constants A, B and C (Bair and Lahm, 2006: 5-16).

$$K = \frac{r^2 * \ln (R_e/R)}{2 * L_e} \frac{1}{t} \ln \frac{Ho}{H_t} \qquad (8)$$

For fully penetrating wells:

$$\ln (R_e/R) = \frac{1}{\frac{1.1}{\ln (L_w/R)} + \frac{C}{(L_e/R)}} \qquad (9)$$

For partially penetrating wells:

$$\ln (R_e/R) = \frac{1}{\frac{1.1}{\ln (L_w/R)} + \frac{A + B \ln [(h-L_w)/R]}{(L_e/R)}} \qquad (10)$$

r = radius of piezometer

R_e = effective radial distance where conductivity is measured

R = effective radius of screen (to include any gravel pack)

L_e = effective length of the well screen

H_o = hydraulic head at initial time (t = 0)

H_t = hydraulic head measured in piezometer (t = t)

t = time since injection or withdrawal of slug

h = saturated thickness

L_w = length from water table to bottom of screen

A,B,C = constants from Bouwer and Rice (1976)

Numerical Modeling

The techniques for modeling groundwater flows have developed rapidly as the use and programmability of computers has improved in the last couple of decades. There are now many choices in programs that can be used to simulate the flow of groundwater. One of the earliest and now the industry standard in groundwater modeling software packages is the Modular Three-Dimensional Finite-Difference Ground-Water Flow Model, more commonly referred to as MODFLOW. It was developed in the early 1980's by the U.S. Geological Survey to consolidate the commonly used groundwater simulation capabilities into a single code that was easy to understand, use, and modify (Harbaugh, 2006). MODFLOW has been upgraded many times since then and in 1990s MODFLOW became the most widely used groundwater flow modeling suite. In MODFLOW 2000, the software used in this study, the modular design of previous versions was expanded to incorporate related equations for transport or parameter estimation. The portion of the code that solves major ground water equations or sets of related equations became the

Ground-Water Flow (GWF) process. Within this process there are many independent subroutines that are made up of "packages" that each deal with a specific feature of a hydraulic system to be simulated (Harbaugh, 2006). MODFLOW is a deterministic and numeric type of modeling suite using the finite differences method to solve equations. MODFLOW is the most widely used, tested and verified software packages for modeling groundwater flow on the market. It is praised for versatility and the independent modular packages that are user friendly enough to allow a modeler at any level to create comprehensive and easy to understand model outputs (Kresic, 2007:500). The software is based on the partial differential equation for the three-dimensional movement of groundwater. Using partial derivatives the computer system can solve for the flow rates in each dimension with the equation below.

$$Ss\frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left(Kxx\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(Kyy\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(Kzz\frac{\partial h}{\partial z}\right) + W \qquad (11)$$

Kxx, Kyy, Kzz = hydraulic conductivity along the x, y and z axis (L/T)

H = potentiometric head (L)

W = volumetric flux per unit volume for sources or sinks (1/T)

Ss = specific storage of the material (1/L)

t = time

The software package MODPATH has a similar set-up to MODFLOW and allows for particle tracking and analysis of water particles in a simulated environment. This package is imperative for collecting particle movement. From that data a probability distribution function can be created to estimate the residence time in the various depths of the wetland cell.

The modeling platform used in this study to create and manipulate the MODFLOW software is a DOD created modeling environment called Groundwater Modeling System (GMS). It is the most sophisticated groundwater modeling environment available today. The DOD with the Department of Energy, the U.S. EPA, the U.S Nuclear Regulatory commission, and 20 academic partners created this environment to allow a more practical application for groundwater modeling. GMS integrates and simplifies groundwater flow modeling by bringing together a collection of the tools needed to successfully simulate and analyze realistic conditions. GMS provides an interface for the codes of MODFLOW 2000, MODPATH and many other groundwater and transport tools (Coastal, 2007).

Previous study results

In a study of the hydrogeologic characteristics of the constructed wetland cell located at Wright Patterson AFB, Dayton, OH conducted in 2002; results on the various attributes that will be studied in this research were also studied. Entingh conducted a study using a similar methodology to the one that will be used in this study. The methods to collect head measurements and measure hydraulic conductivities were well documented and provided great insight for this research effort. The results of Entingh's work provided a baseline of how the wetland was operating after construction was complete. The results of his work will be compared with the results of this thesis to determine what changes have occurred in the groundwater flow patterns after five years of operation. The results of the piezometric surface measurements from the 2002 study indicated there were areas of preferential flows in the wetland. The contour plots from that thesis indicated a fairly uniform distribution of hydraulic head in the bottom soil layer but depicted regions of higher head and preferential flows towards the north side and weir end of the wetland cell in the middle and top soil layers (Entingh, 2002: 4-8). Entingh reported that the magnitude of variation in the head measurements would not be significant if it occurred gradually over the full length of the wetland, however there were measured differences of 12 to 18 inches between piezometers located in nests near each other in the top two layers. This finding further indicated preferential short circuiting flow paths for groundwater in the wetland as opposed to the desired uniform vertical flow paths. Entingh (2002, 4-10) also reported a very visible amount of soil heaving where water could be seen coming up from beneath the soil in the area of piezometer nest number 29. This indicated an anomaly in groundwater flow and substantiated his belief that the center of the wetland had higher head values than other locations, again demonstrating a non uniform flow field was present.

The results for hydraulic conductivity measured in the wetland in 2002 ranged over values representing soil types of silts, sandy silts, clayey sands and tills to silty sands. The magnitude of standard deviations relative to the means found in each layer indicated variation within each layer of soil, while the reported means showed variations existed between the soil layers as well. The impact of developing the piezometers was also reported by Entingh because the magnitudes of hydraulic conductivities changed an order of magnitude or more after the development of the piezometer was completed. Entingh (2002: 4-13) reported that before the piezometers were developed there was an apparent increase in hydraulic conductivity as depth increased, however after the piezometers were developed the same type of slug test showed a nearly equal conductivity between the top and middle layers. Entingh believed the development of the piezometers may have altered the hydrogeologic properties surrounding the screened intake areas, leading to altered soil properties based on the elastic properties of soil. Comparisons of slug tests before and after piezometer development showed an order of magnitude increase in 9 of 19 piezometers and an increase in two orders of magnitude in 7 of 19 piezometers (Entingh, 2002: 4-5).

Entingh had an initial concern of the choice of method used to determine hydraulic conductivity; he chose to use the Bower and Rice method (1976). As he completed his study he determined the shape factor for the piezometers in the field and was able to calculate hydraulic conductivities using the Hvorslev method (1951). The results from both methods were well within the order of magnitude precision possible for hydraulic conductivities showing that both methods are applicable for the slug testing done in the wetland cell.

Entingh reported the average porosity of the soil to be 0.53, a range typical of silts and clays. Also, the effective porosity 0.05 and specific yield of 0.022 were reported for the soils in the wetland cell.

In the numerical modeling portion of his results Entingh found that there was a tendency for water to flow towards the sides of the wetland in the more permeable layers. Flow from the bottom soil layer and gravel layer was predominantly horizontal, while the flow in the top two soil layers was predominately straight up. The model indicated that the sediments along the sides of the wetland have a greater transmissivity and facilitate greater flows relative to the central sections of the wetland. He reported that the model output showed a greater amount of water moves towards the north side of the wetland cell. Entingh was able to determine an average hydraulic residence time of three days using visual MODFLOW’s particle tracking feature. The results showed minimum residence times of 16.5 hours near multiple piezometer nests across the wetland area and a maximum residence time of 15 days. Entingh reports that 64% of the tracked particles had a residence time less than the average (2002: 4-15).

III. Methodology

Chapter Overview

The purpose of this chapter is to explain the steps used to study the hydraulic flows occurring or suspected to be occurring in the wetland cell. The steps described begin with the field measurements and analysis, and continue with the steps used to model the wetland. The modeling steps include defining a conceptual model, adjusting and analyzing the data and finally evaluating the model itself. Aquifer test modeling is a stepwise process to search for aquifer test domain conceptual and numerical models that closely reproduce measured values (Walton, 2007). The goal of modeling the wetland is to find a numerical model that will produce results close to the measurements taken in the field while displaying the groundwater movements that cannot be determined by field work.

Piezometer Set-up

The wetland is mapped out with piezometers located systematically throughout the cell to allow for complete analysis on a small scale. The piezometers are located in nests of three to allow for specific measurements at various depths at each location. The distance between piezometers located at the same depth is only every 3-4 m in the wetland which presents closely gridded points for greater study accuracy. The nest arrangement also allows for comparison measures between piezometers at various depths to indicate the presence of vertical flow. The nests are equally spaced six across the width of the cell (18 m) by eleven nests down the length of the cell (36 m) for a total of 196 piezometers, 66 piezometer nests throughout. Fig 3-1 shows this layout. The weir is located between nests 63 and 64. Piezometers labeled A are positioned in the top portion of the wetland at depth of 0.37 meters from the top, B are positioned at mid depth in the soil 0.75meters, and C are positioned approximately 1.13 meters from the top of the wetland soil.

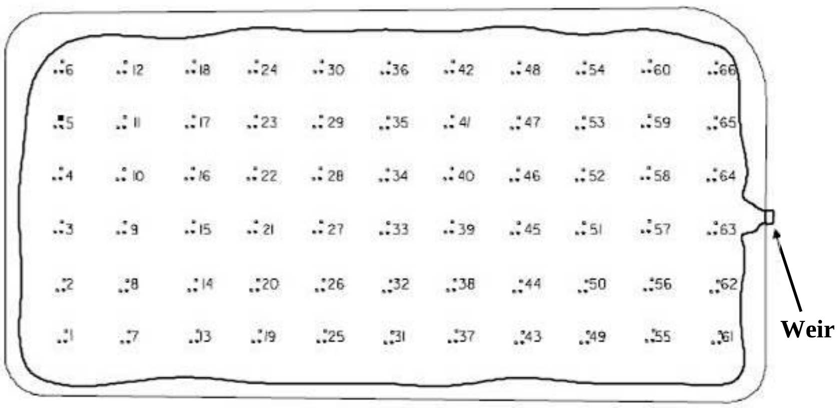

Fig 3-1, layout of wetland piezometer nests 6 rows x 11 columns.

Each individual piezometer is 2.5 cm in diameter, circular steel tube construction, with 10 small circular screens 1 cm in diameter creating a screened opening of approximately 15% of the surface area. The screens were installed to be located at the three desired depths of the wetland soil mentioned above. The piezometers were installed by a post driver to a depth 6" past their desired depth and then retracted to remove a shield that covered the screen as it was driven through the substrate. The Entingh study contains a stepwise explanation of the piezometer installation process.

The piezometers rise above the datum (defined as the horizontal plane at the depth of the bottom of the wetland cell) 1.7 m to 2.3 m to allow observations of hydraulic head measurements inside a clear ½ inch Teflon lined tube housed inside each piezometer. After installation each piezometer was developed using a peristaltic pump and either injecting or drawing water through the Teflon tube to ensure clear screens for water filtration. This was the process that led to Entingh's discrepancy in hydraulic conductivities.

Each piezometer is assumed to be allowing enough unobstructed flow today after five years of steady use to believe the measurements of hydraulic head are representative of the soil elevation where the screen is located. The head measurements for the piezometers are made with a Solinist water level sensor. Further steps in conducting the hydraulic measurements are outlined below.

Piezometric Measurements (Hydraulic Head)

These measurements are used to determine direction and velocities of groundwater flow, and the contours of hydraulic head. The measured hydraulic head is the head level present at the midpoint elevation of the piezometer screens. The elevations are derived from the elevations of the top of the risers and the length of the piezometers for each soil depth being tested. By adding the height that the nylon tube protrudes from each piezometer to the surveyed elevation of the riser, the elevation of head is then measured from the top of the nylon tube down to the detected level of the water. All water levels were measured with a Solinst Model 101M water level sensor to ensure each measurement was obtained using identical means and with the same level of accuracy, to the nearest 1/100th of a foot. Where the water level was visible in the nylon tube, a second measurement was taken with a tape measure to validate the water level detection.

All of these measurements are then adjusted to a common datum or a horizontal X-Y plane at a known elevation. In this study the datum is located at a depth of 1.7m below the riser of piezometer 1a and 2.4 m below the top of the weir outlet box. By using a common datum, measured values can be compared and areas of higher head and lower head can be determined thus detecting head contours and flow patterns in the cell. The elevations of the risers were gathered in an elevation survey conducted with a category three degree of accuracy (single measurements, done with relation to a reference point not a USGS benchmark and a survey accurate enough only for small scale project use) by the GEM 08M section in spring of 2007 to ¼ inch. Water levels were measured in March 2007. The flow rate in the cell during the study measurements was 5.5 gallons per minute (gpm).

Parameter Estimation (Hydraulic Conductivity)

The in-situ method used to test field conditions for hydraulic conductivity was the slug test. The slug test has two variations that involve instantaneously changing the head elevation of the water, then measuring time and water level changes until the well reaches its steady state once more. The slug test variation used in this study is the rising head test. In this test a known volume of water is extracted from the well, the head is displaced instantaneously the downward and starts to rise as water from the surrounding medium enters the well (Kresic, 2007). This field test was chosen for multiple reasons, which include the current field set-up and the desire to have a comparison with previous studies. The 2 inch test wells inserted into the wetland for various data collection reasons provided a randomly placed opportunity to conduct the slug tests. With a grab sampling device already in place within the wells, removing a known volume of water from the well was very simple and straightforward. The ability to accurately measure and record the recovery of the water in the wells was a major motivating factor in using the larger test wells rather than the narrower piezometers. The use of the test wells allowed for various soil and plant areas of the wetland to be sampled. This data was then used in creating the wetland computer model.

The steps used in conducting the slug tests in the field are found in many texts and papers describing hydraulic testing. The description presented in Kresic (2007) is used in this study. The specific steps begin with measuring the pre-slug depth of water in the testing well. Once that is done, the clock starts as the known volume, 141 cubic cm of water, is removed from the well. The recovery rate of water into the well from the surrounding soil medium was measured and recorded at various time checks until the water level returned to 90% of its initial pre-slug level. A sample of the recorded measurements from the field is shown in table 3-1 below.

Table 3-1 Sample record of time and water level measurements during slug testing

Well #	6
Layer	C
Pre-slug depth	1.50 ft
t (min)	**Depth to water (ft)**
0.08	1.88
0.13	1.85
0.4	1.71
0.6	1.66
0.8	1.61
1.0	1.58
1.3	1.56
1.5	1.55
1.7	1.54
2.0	1.53
2.3	1.52
2.5	1.52
2.8	1.51
3.1	1.51
3.4	1.50

The slug tests resulted in data sets demonstrating the changing water levels measured at given time intervals until equilibrium between the soil and the test well was reached. The recorded numbers were then graphed comparing normalized head change (the difference between the pre slug elevation and the changes in head elevation as the water recovered to the original elevation) on the y-axis and the time in minutes on the x-axis. To use either of the analysis methods that can determine the horizontal conductivity from the drawdown data, the results had to be altered to a straight line relating head values and time. This was done by changing the axis of the previous graphs to the log of head recovery vs. time. Examples of both graphical representations are shown below in figure 3-2.

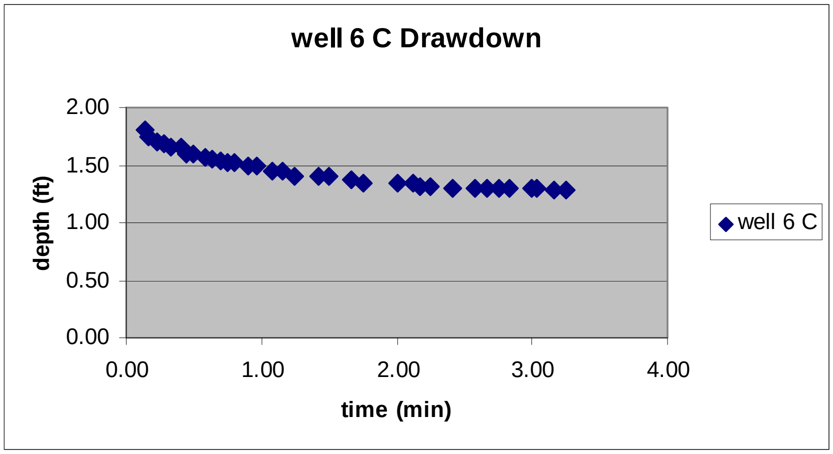

Fig 3-2a Exponential recovery curve from field data of slug test

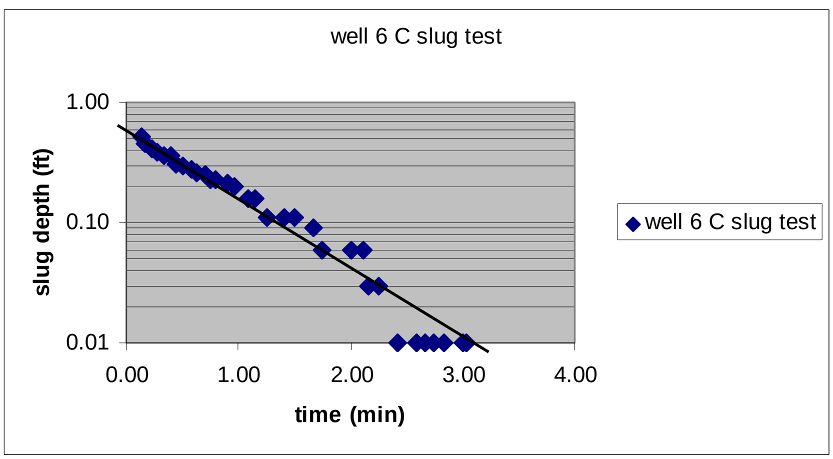

Fig 3-2b Example of slug test results graphed on a log axis for use in the hydraulic conductivity equations

To analyze the recovery results and calculate a hydraulic conductivity for each area and each layer of the wetland there are two common approaches to be considered. These included the method set forth by Hvorslev in 1951 and a method introduced in the work by Bouwer and Rice in 1967. Properties of both are described in table 3-2 below.

Table 3-2 Comparison of methods for determining hydraulic conductivity values (Entingh 2002)

Bouwer & Rice method	**Hvorslev method**
- for unconfined, leaky confined	- confined aquifers
- measures rate of recovery relative to initial water table elevation	- rate of recovery relative to initial potentiometric surface
- uses wells to measure hyd. Conduct.	- normally associated w/ piezometers
- used for Entingh's test, geometry of piezometers intakes mimicked B&R test	- shape factor for use is available in literature

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In previous work, both methods have been used. The Bouwer and Rice method was originally used by Entingh, although admittedly information found later in his research would have allowed for the Hvorslev method to be used. Entingh did use the Hvorslev equation in his data results to check the accuracy of his field data. In Blalock's (2003) study, the Hvorslev method was determined to be most adequate in creating estimates of hydraulic conductivity necessary to input into the computer modeling software to create a realistic representation of the actual wetland. In this study it was concluded that the Hvorslev method was the more appropriate choice for analyzing the slug test results due to the reasons included in table 3-2 above and the results of the previous studies done on the wetland cells. The Hvorslev method measures the water change relative to the potentiometric surface rather than the water table surface. This was the case in the test wells as the potentiometric surface was in most cases located above the actual water table in the wetland. Also, the Hvorslev method is accurate when a shape factor for the well can be determined. In the case of the test wells in the wetland the shape and size of the intake screens were known, therefore an accurate shape factor could be calculated. The shape factor calculation and Hvorslev equation for determining hydraulic conductivity are shown below in equations 11 and 12 respectively.

$$F = \frac{2 * \pi * L}{\ln \frac{L}{r}} \qquad (11)$$

$$K = \frac{A}{F * (t_1 + t_2)} * \ln \frac{h_1}{h_2} \qquad (12)$$

Previous research recommended taking measurements until the water has recovered to 90%. In other literature, a goal of 50% recovery is reported to suffice in low conductivity sediments. The recovery rate in this study was found to vary greatly from the top soil layers and the bottom soil layers. The results are discussed further in the next chapter.

In Entingh's work, pump tests were used for the bottom layer due to high levels of conductivity. He stated the reason for this change in test method was due to the appearance of drawdown data collected, showing characteristics of a confined leaky aquifer with influence from a source bed, citing Dawson and Istok (1991). The source bed in this case would be the gravel layer that contains three perforated pipes introducing the water into the wetland cell. Entingh had two-fold evidence for this assumption; 1) bottom layer slug tests showed instantaneous recoveries, and 2) pump tests measured decline of potentiometric surface rather than water table. In this study the instantaneous recovery of the well was only seen in 1 of 5 wells in the bottom layer. Each of the others allowed for measured recovery; therefore, assumptions similar to Entingh's were not made and a consistent method of hydraulic testing was applied to all the wells.

The method for obtaining the head and time values to use in the Hvorslev equations came from utilizing a line of best fit through the data points on the straight line logarithmic graph. Two points that fell on the line of fit were used as t1, t2, h1 and h2 values in the equation. A fit called the double straight-line fit application is required when the results plotted on the semi logarithmic graph demonstrate a much quicker recovery during the initial first few time segments of recovery. This fitting technique takes into account the appearance of two joined line segments rather than just a single line of field data points. This technique was used in a couple of cases where the log scale graphs showed a period of steeper slope indicating a faster recovery period during the first few seconds of the test. This can be a result of a highly permeable zone around the well as is common with a gravel pack or a developed zone. The second line segment that suggests a slower recovery segment is then more indicative of the flow from the undisturbed aquifer into the well (Kresic, 2007). The head and time values used for the Hvorslev equation came from the second segment to avoid any effects of the highly permeable zone that commonly lead to a quicker recovery than the soil actually contributes. An example of this occurrence is shown in the logarithmic graph of the slug test results from well 2 A shown in figure 3-3 below.

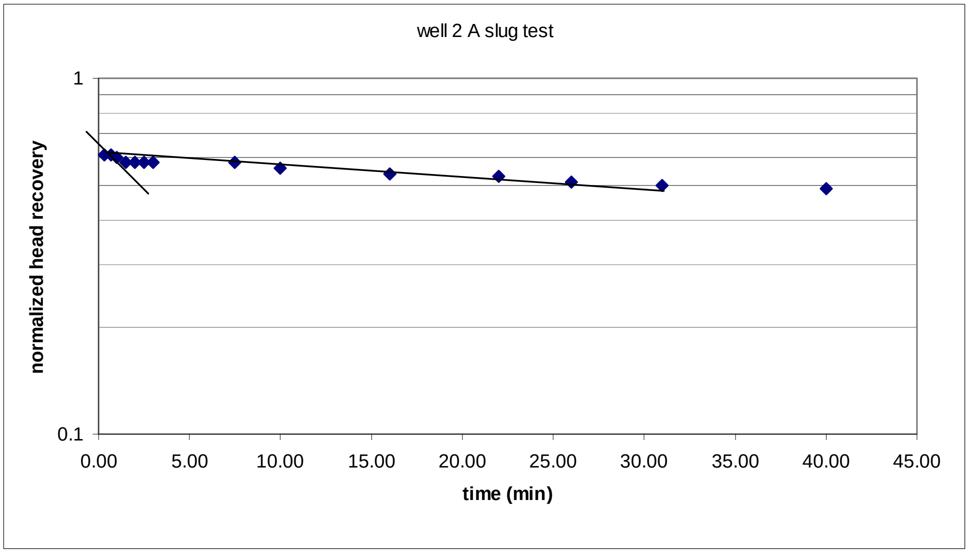

Fig 3-3 Demonstration of the double straight line application for determining t and h values for conductivity equations

Conceptual Modeling

The field data collected was not enough to create an accurate interpretation of the groundwater flow beneath the wetland surface. The hydraulic head and hydraulic conductivity measurements from the field were used to build and verify a computer simulation model of the wetland environment. The initial step in building the wetland cell model was to create a conceptual model and determine the most effective way of designing and solving that model's parameters in the available software package. A conceptual model is a space and time representation and approximation of groundwater flow system within an aquifer test domain that captures the essence of a groundwater system (Walton, 2007). The conceptual model consists of listing assumptions and ruling out the small level details that are not necessary in creating a simulation of the real wetland area. The conceptual model helps to organize, simplify and idealize the wetland area. The five steps in creating a conceptual model from Walton, 2007 are: first, define the hydrostatic framework, next, characterize the hydrostratigraphic units, third, determine the slugged observation well characteristics, fourth, determine the time dimension that will be used, and finally, include any groundwater or surface water budgets and any temporal changes on the flow system.

The first determinations that had to be made on how the wetland would be modeled included the distinction of the boundary layers. In the real wetland cell, the side and bottom boundaries are an impermeable geo-membrane. This was held true for the conceptual model and computer model as well; the side and bottom are input as no-flow boundaries. The top surface of the wetland was a different type of boundary layer. It represented a free flow boundary where the water could flow out of the soil or into the soil (dependent upon the pressure gradient). A real world observation showed that the water collecting on the top would flow to the outlet weir eventually. In numerical models the soil and water interaction layer was represented two different ways. In one model, the water surface was modeled as a constant water boundary similar to a stream or body of water on top of the wetland. In a second version of the wetland model this layer was modeled as a general boundary where the water was free to move in or out of the layer dependent on the pressures and conductivities encountered.

The next step in creating the conceptual model is to define the hydrostratigraphic units by the types, thicknesses, and heterogeneities of the soil using K values (hydraulic conductivity values). This includes using the field data collected on hydraulic conductivities to characterize the hydraulic properties of the wetland soils. The field data will show the current conditions and variations in soil properties. The known factors about the soil, such as porosity, come from the paper published by a team of researchers working on the wetland characteristics led by Amon *et al*. 2007. This paper discusses the original condition of the soils as hydric soils collected from the local wetland areas in OH, containing silts, clays and one layer of the soil being amended 10% with high carbon content (woodchips). This information helps in determining the characteristics that can be expected in the wetland soil.

To accurately determine the slugged observation well characteristics, the following details of the well should be included when possible: casing radius, effective radius, well-bore storage and well-bore skin. In this study, the casing radius is known. The effective radius is not of significant contribution to the results of the tests as there is no gravel pack. Therefore, the conductivity measured in the well is representative of the soil surrounding the well 360 degrees. To account for any effect of the aforementioned well characteristics, the double straight line method for determining hydraulic conductivities, as discussed earlier in the chapter, is used in choosing the head and corresponding time values.

The time dimension for this study will be a single time step equal to one day in the wetland cell. Due to the assumption that the cell is operating under steady state conditions, the results would not change if the time step were lengthened or repeated. The groundwater budget is only accounted for in the current study in calibration of the numerical model output. In this study the main source of groundwater inputs are through the perforated pipes and outputs are through the weir, both are assumed to be known and controlled. The evapotranspiration of the wetland system could be considered a small percentage of the overall output is accounted for in this study in the small margin of difference in the balance of the water budget output of the numerical model calculations. Flow system temporal changes were negligible for this closed controlled system. The atmospheric pressure was recorded at the time of head measurements and the measurements were taken in a small enough time span (3-4 hours) the pressure didn't change during measurements.

Computer Model Construction

The computer model was created in the Groundwater Modeling Software environment created by the DOD for groundwater studies. The software interface creates a computer environment where multiple groundwater modeling packages can be brought into a 3-D space and integrated to create the most realistic picture of the groundwater flow.

The steps used to create the model are described in the following paragraphs. The first way of turning the conceptual model into a computer model is to create the wetland cell in three dimensions by creating the grid that will represent the wetland. This is accomplished by knowing how long and wide the area is and determining the interval at which the intervals of the cells will provide an accurate picture of the groundwater activity. In this model the wetland dimensions are 18 m by 36 m represented in a grid of cells ½ m long by ½ m wide. The next step is to determine the number of layers that will accurately represent the hydrographic characteristics of the aquifer in question. In the wetland model the depth is a total of 1.7 m deep measured to the datum at the bottom of the wetland cell. This depth is divided into nine layers to represent the variety of hydrographic layers present in the constructed wetland. From the top down, the first layer represents a simulated layer of open water on the surface of the wetland cell. The next layer is a representation of the interface between the water and the soil in the wetland. The third through eighth layers represent the hydric soils that were used in the construction of the cell. The ninth (bottom) layer is representative of the gravel layer where the perforated pipes are located. The properties of each layer are specific to the media, water, soil, or gravel. These are represented by the hydraulic conductivities, vertical conductivity and anisotropy characteristics which are introduced in a following step in the model building process. Fig 3-4 below is an elevation view of the layers and gridded layout of the 3-D model.

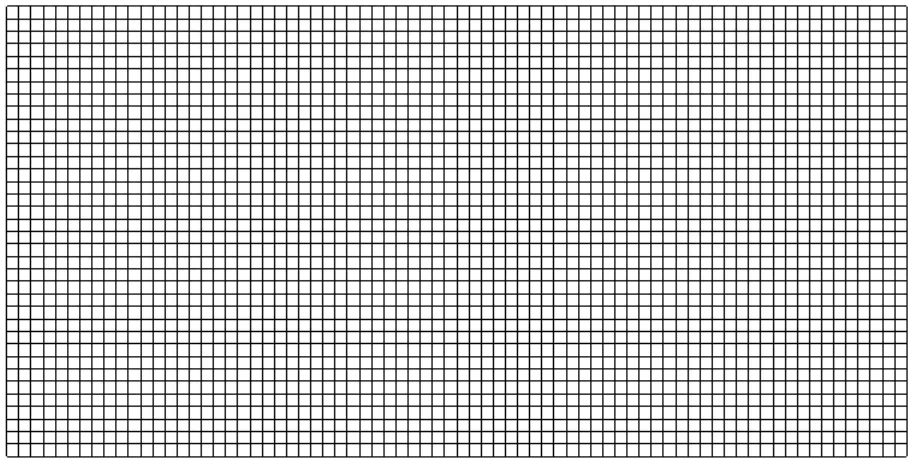

Fig 3-4a. plan view of gridded wetland cell for computer modeling

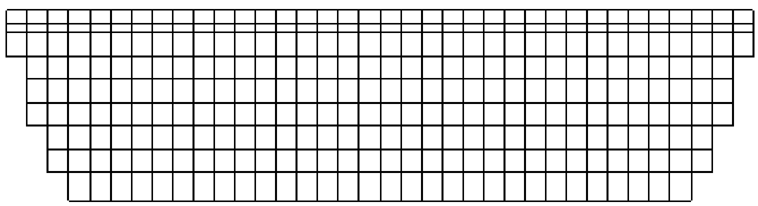

Fig 3-4b. cross sectional view of the layers in the wetland model

The next step in creating the 3-D model is to ensure each layer has a specific top and bottom layer elevation input into the model to determine the layer thickness. In this model the top layer representing the water is 0.1 m thick, while the layer representing the interface between the soil and water, the upper boundary, is only 0.08 m thick. The layers representing the soil, layers three to eight, are of equal thickness at 0.19 m each. Finally the gravel layer at the bottom of the computer model has a bottom elevation of 0.15 m above the datum and a top elevation of 0.38 m giving a thickness of 0.23 m. Each layer is bounded by the top and bottom elevations evenly across the entire layer and remain unchanged during the model runs.

Once the model space is set-up and the shell is intact, the characteristics of the different layers can be added. This includes setting the boundary types discussed in the conceptual model section. In order to test two different types of boundary conditions representing the interface between the wetland soil and the surface water, two computer models were created. The layer representing the interface between the soil and the water is represented by a specific head layer in one model and a general head layer in the second. The constant head layer in the first model acts as a control layer that maintains the balance of flow into and out of the wetland. This layer is considered an inactive layer that will be balanced, and each cell in the layer will be held to a constant level for mass balance of the overall model. In the second model, the interface layer is designated as a source/sink package called general head. This type of boundary layer is considered active and allows free flow into and out of the wetland through this layer. Also at this point in building the model, the simulation of the perforated pipes that introduce water into the system is inserted. In this study the piping is simulated by a series of injection wells that each introduces an equal amount of water, (0.19161 m^3/d), into the wetland. The total water entering the system is 5.5 gpm, which is the measured amount of water being released into the wetland cell. The injection wells are placed in the three rows in a similar layout of the piping within the gravel layer at the bottom of the wetland. The wells are in cells 15-65 in rows 9, 19, and 29.

Once the main characteristics of the wetland cell are input, the soil properties are next to be added in the wetland simulation. The porosity for all of the soil layers is set at 0.5 as was reported in the Amon *et al*. paper published on this wetland cell. The horizontal anisotropy is set at 1.0 for the entire wetland cell because the same type of soil was used throughout the cell therefore it is assumed that the soil has no directional dependency. Also the equations used in calculating the conductivity require the assumption of homogeneous and isotropic soil conditions. This was also an assumption made by Entingh in the study conducted in 2002. The relationship between horizontal conductivity and vertical conductivity (K_h/K_v) is set at 1.5 for the soil layers, and 1.0 for the water layer on the top. This parameter is used in place of vertical conductivity since that parameter alone was not tested for in the wetland. The hydraulic testing done in this wetland study used the Hvorslev tests taking into account the shape factor of the well screens. The flows measured by these well screen orientations are assumed a radial flow and is thus counted in all equations and models as the K_h parameter. A separate K_v parameter can be calculated as a portion of the measured K_h values in the hydraulic testing. Equation 13 can be used to distribute the horizontal and vertical components.

$$Kv = 1/z1 + 1/z2 + 1/z3 \qquad (13)$$

The value of the K_h/K_v parameter is set at this value to show that the relationship between the flow in the vertical direction and the horizontal direction are nearly the same because again the soil is of a similar make-up throughout the wetland. Also, the vertical flow is the primary flow direction; horizontal flow is a more difficult direction for the water to travel. It was found through various model runs that the model output was not sensitive to this parameter. For values between 1.0 and 3.0, a common default value, the output for the model did not change. The larger piece of the conductivity puzzle is the input of the horizontal conductivity. This leads into the next step of building the model, input and interpolation of measured variables.

The horizontal conductivities were determined from the slug tests in the field. These values along with their x, y, and z coordinates can be documented in a text document that is then imported and interpolated throughout the wetland model space. In this study the method of inverse distance weighted interpolation was used. This method, with a gradient plane nodal function option as well as all points being used to compute the nodal function coefficients and interpolation weights, was selected for this model. The interpolation methods of nearest neighbor and Kriging were also attempted during the model calibration phase and resulted in the same output of horizontal conductivity contours. A second file that is inserted and interpolated across the wetland cell is the initial setting of the head. This piece of the model is important and will influence the probable paths of the groundwater flow. The initial head setting is a starting point for the computer to calculate head as the model is run. These values are compared against the observation points of measured head that are also imported into the model. The initial head settings were the variable factor when the model calibration was underway.

The calibration of the model was done by trying a myriad of initial head settings while the other parameters of soil and model characteristics were held constant. The best fit of the parameters in the computer models is determined by the sum of the weighted residuals created when the model is run. The lower the sum of the residuals between the calculated and the actual head values, the more accurate the model will be in reproducing real world results. The initial head setting that was the closest fit was a value that changed from 1.7 m head at the surface of the water to a head value of 2.9 m at the bottom of the wetland model. There was also a built in gradient across the top two layers. The head started at 1.7 m at the end opposite the weir and lowers to a value of 1.6 m at the weir. An interesting observation was made in the process of calibrating the models. There was a close relationship between the initial head settings and the total sum of residuals as expected. The process of finding the closest fit between calculated and measured head values showed some initial head values that produced closer fit results (lower total residuals) to the measured head values in the field than the final combination; however the model demonstrated non-realistic behavior. The final fit for a realistic version of the simulation summed the residuals to only 20.5. This is a very close fit compared to the sum of $3.67x10^4$ which was the original difference before the calibration process was started. The sum of residuals was brought down to 12.0 with some initial head settings, but the model was demonstrating unrealistic velocities and water discharge that did not show what was actually happening in the wetland cell. Therefore, the best fit was the sum of residuals between calculated and measured which was 20.5.

It was also during the calibration step in the modeling process that the second of the two models, the test of general head boundary layer for the soil/water interface layer, was shown to not be a viable option for modeling the wetland cell. The second model was built with all the same soil parameters and interpolated data as the first. However, when the initial head variations were attempted during the calibration phase, the model consistently showed results of very high head contours rising above the surface of the wetland almost a full meter, and very high velocities of the surface water that were unrealistic in our cell. The lowest achieved sum of residuals for this model version was 146.0. This did not provide a close representation of the real world measurements, so the model was determined not to be the appropriate choice for boundary conditions. The results section of this body of work does not include the unrealistic results of the second attempted model.

Conclusion

The method for conducting the field experiments and then bringing that information into the numerical model comes together to create a picture of what is happening with water flows underground. By using the common hydraulic testing technique of slug testing and then determining the conductivity value of the soil, the parameters for building a model come into place. When all of the parts of the model have been identified and created in the computer modeling environment a picture is created that predicts the characteristics of the groundwater flow. The input files of field data are vital in creating the model, using K_h values then calibrating the model with the measured head values. The model is deemed accurate when the sum of the residual difference between the computed and measured head values is minimized.

IV. Results

Field work results (hydraulic head)

Only one measurement of the hydraulic head values was needed for the purpose of this study. The results of measuring the hydraulic head elevations, or piezometric surface of the wetland, provided an initial idea of the flow patterns occurring in the wetland. In May of 2007 the hydraulic head elevation was measured in each of 192 piezometers using the steps detailed in the previous chapter. There were 3 piezometers that did not have a water level present and one piezometer was missing (nest 35 has no piezometer for the top layer). The comparison of the head values, within each piezometer nest and across each of the measured depths, gave very good insight into the direction that the flow was expected to take. The nested piezometers in most cases, 47/63 or 75% of the nests where all three levels were measured, demonstrated flow in the upward direction. This direction of flow was shown because hydraulic head values decreased in elevation from the bottom level piezometer elevations to the top level piezometers. This change demonstrated the water would tend to flow from the bottom to the top of the wetland. An example of this is nest number 2 where the values from the bottom level up were: 2.483, 1.903 and 1.806 m at the top level piezometer elevation. This showed that the designed vertical flow which was created in the wetland by placement of the perforated piping at the bottom of the cell is occurring. Of the 16 nests that did not show the vertical flow, the only discrepancies were in very close measurements between the top and mid level piezometer readings. For example in nest number 17, the middle level piezometer measured at 1.825 m while the top, rather than being a smaller value was measured at 1.902 m. The difference is only 7.7 cm in head which may change the path for the water to travel. In all of the nests where this kind of closeness of measurement took place there was still an increase in head values from the bottom layer to the middle layer indicating the water traveled upward to the central depth of the cell and then may have routed to a lower head value horizontally rather than straight up to the surface. Again the example of nest number 17 shows a value at the bottom of the wetland as 2.416 m, much higher than that of the middle and top layers. The listing of all the hydraulic head elevations is included in Appendix A. An example of the change in head measurements from the top layer to the middle layer and then the bottom layer is shown in fig 4-1 below. Ideally the hydraulic head measurements get higher as the depth increases.

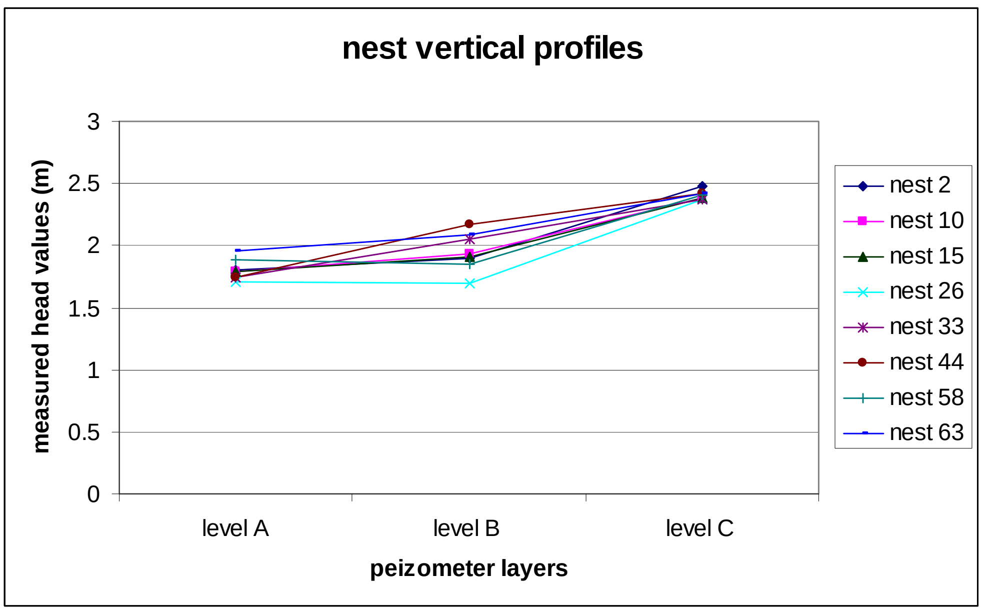

Fig 4-1 profiles of hydraulic head for various nests across the wetland

Across each layer of the wetland the head measurements varied by 29 to 63 centimeters. The statistics indicating the variation of head measurements in each layer are shown in table 4-1 below.

Table 4-1 Statistical description of measured head values per layer of wetland soil

Layer of wetland	Mean h value (m)	St Dev	Range of h Values	Min	Max
Top, A	1.799	0.082	0.384	1.640	2.024
Middle, B	1.896	0.147	0.632	1.654	2.286
Bottom, C	2.408	0.038	0.291	2.192	2.483

The layers have very little change; however the changes are in varied locations in each layer. There is no overall gradient or gradual change across the length or width of any layer. The points of higher head values are scattered in their locations across the wetland. For example the highest points of layer A occur near nests numbered 16, 23, 40 and 63. These nests are scattered across the wetland from row 3 to row 11. The lowest values of hydraulic head occur in areas not far from the higher points; these values do not create a general direction or an area in which lower values are grouped together. The lowest points in layer A for example occur in nests 6, 26, 43, 50, 54 and 56. The 3-D maps demonstrate the smaller amount of variations that occur across the bottom and top layers. They also show the higher points and lowest points of head are scattered throughout the wetland cell. This characteristic is most obviously seen in the middle soil layer head values.

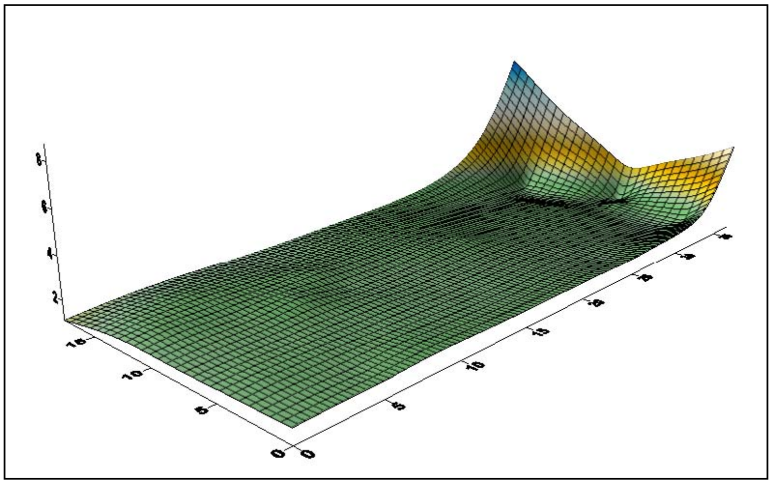

Fig 4-2a. 3-D contours of hydraulic head values in the top soil layer

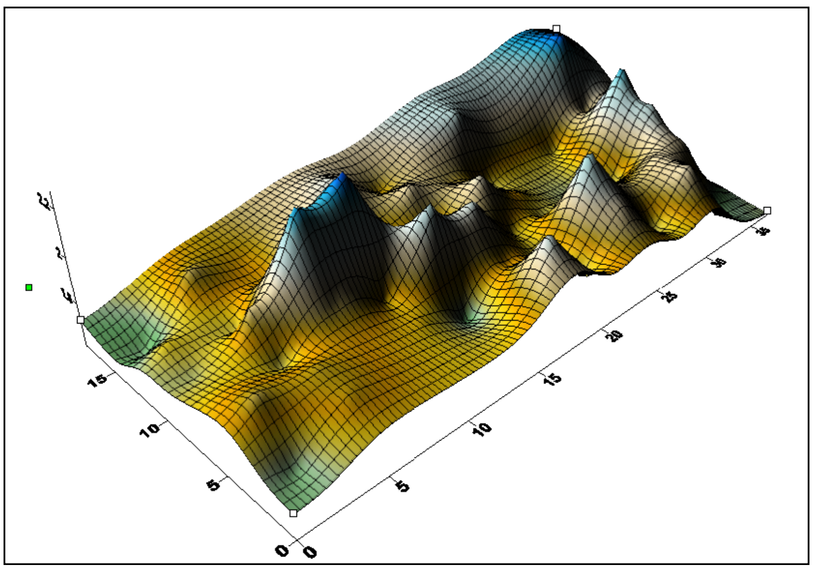

Fig 4-2b. 3-D contours of hydraulic head values in the middle soil layer

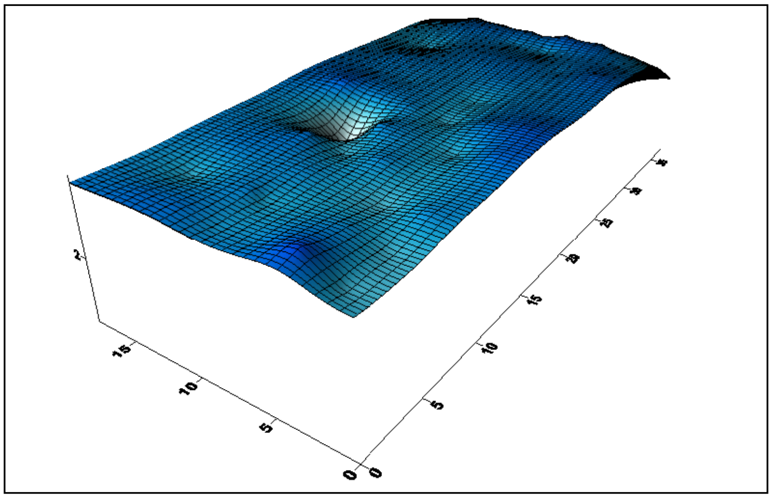

Fig 4-2c. 3-D contours of hydraulic head values in the bottom soil layer

The 3-D maps were created using a program for contouring in 2-D and 3-D called Surfer to compare findings in a visual representation between this study and Entingh's study from 2002. Contour maps of the measured head values can show where head values rise up to these higher points and where the measured heads are at their lowest values. The comparison of layer A from Entingh's work and the findings of this study are found in the fig 4-3a and 4-3b. The actual head measurements from Entingh's work give mean hydraulic head averages in the top, middle and lower layer as 6.2 feet, 6.61 feet and 8.04 feet respectively. In Entingh's work the standard deviations across each layer are also similar to those found in this study: they are 0.335 ft for the top layer, 0.469 ft for the middle layer and 0.093 ft for the bottom layer. This shows that the overall variations in head measurements have not changed dramatically in the last five years of wetland operation.

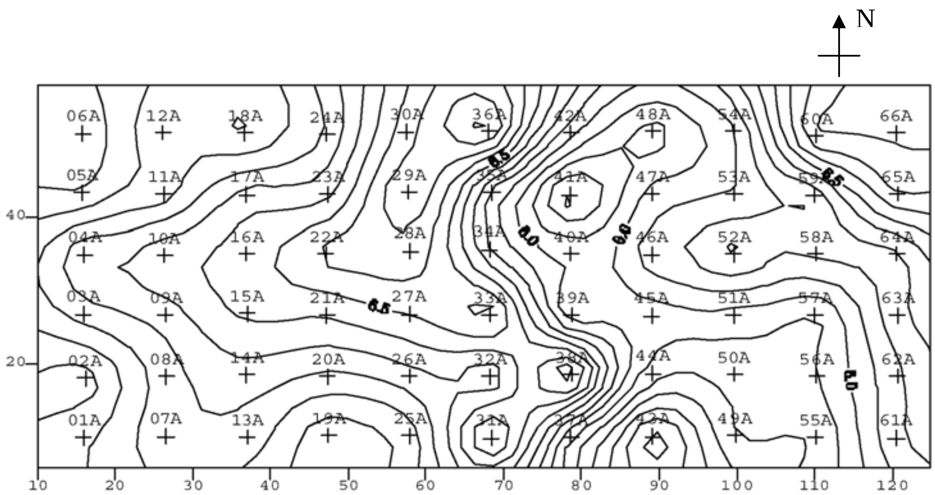

Fig 4-3a. Entingh head contours for top layer of soil (contours labeled in ft)

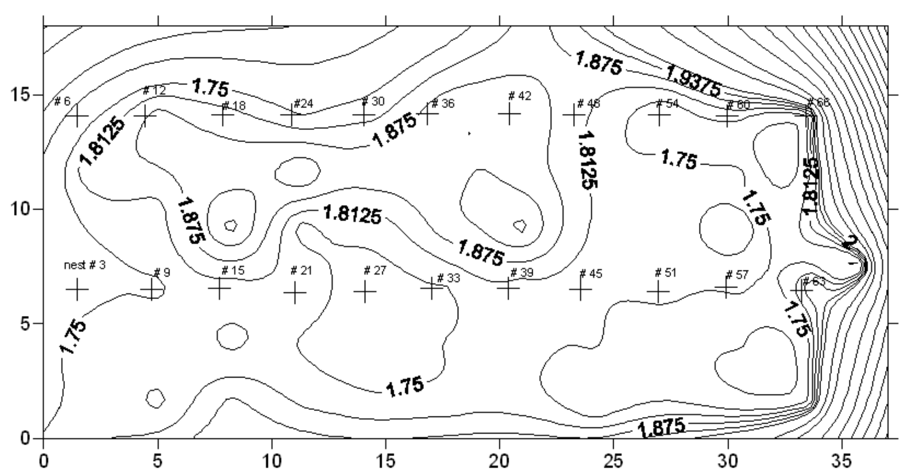

Fig 4-3b head contours for top layer of soil for the current study (contours labeled in m)

The contours for the middle and lower layers are illustrated in appendix B. These contour maps can help predict where the groundwater preferential flow paths will form. The hydraulic gradient determined by the distance between contours of measured head will show where the water will flow. The water will cross the head contour lines at right angles, from higher values to lower ones. Also an area with a greater gradient or faster change in head should correlate with areas of higher groundwater flow magnitudes in the computer model. In the section on the results of the computer modeling it will be described how these areas do align.

Field work results (hydrologic conductivity)

The results of the slug tests performed, as outlined in the methodology chapter, describe the heterogeneity in horizontal conductivity found throughout the wetland. These values were determined by the Hvorslev equation and then interpolated throughout three dimensions of the wetland computer model. The results came from sixteen 2" diameter sampling wells located throughout the wetland cell, again in nests of three representing the three measured depths in each nest. The horizontal conductivities differ greatly with depth as the head values do. The differences through the depth of the wetland vary by an average of 2 orders of magnitude. The differences between the top two layers are very small; however the differences between the middle layer and the bottom layer of soil is very large. The higher values in the bottom layer indicate there may be influence from the gravel layer beneath the soil at the bottom of the cell. With the highest values nearer the bottom of the wetland and the much smaller conductivities near the top, the difference creates areas of lower flow velocities near the top soil layer. Table 4-2 shows the ranges and averages of the horizontal conductivities through the depth of the wetland.

Table 4.2 Horizontal Conductivity measurements

Layer	Low value K_h, m/d	High value K_h, m/d	Average Value K_h, m/d
Top Layer	0.020	0.463	0.129
Mid Layer	0.020	0.823	0.242
Bottom Layer	3.155	51.200	24.976

The top soil layer represented conductivities similar to those found in silts and clays. The hydric soil brought in to construct the wetland was reported to contain high volumes of these soil types (Amon *et al*. 2007). The lower conductivities are characteristic of the organic materials that have built up over the last five years of wetland operation. The areas in the middle depths of the wetland showed a more varied but similar conductivity pattern as the top layer. This is attributed again to the high amounts of silts and clays originally contained in the native soils. The bottom layer represented a large range of conductivities. Areas of very high values indicate the presence of the gravel layer that was originally placed below the wetland soils. In these cases it is concluded that either the piezometer has sunk down into the gravel layer, or the gravel has gradually worked its way up into the bottom of the soil layers following the imposed vertical gradient. Another possible explanation for the very high conductivities measured in the bottom layer is a situation where the depth of the installed piezometers is actually located in the bottom layer rather than in the soil as was intended during installation. Although the measured conductivities were not as high as anticipated in a gravel pack, some soils mixed into the gravel layer may contribute to slower velocities. The distribution of the hydraulic conductivity contours in Fig 4-3 show the values of horizontal hydraulic conductivities interpolated throughout the three dimensions of the computer model. The X's within the cell boundaries show the locations of the wells where hydraulic conductivities were calculated and entered as points in a 3-D scatter plot for the software.

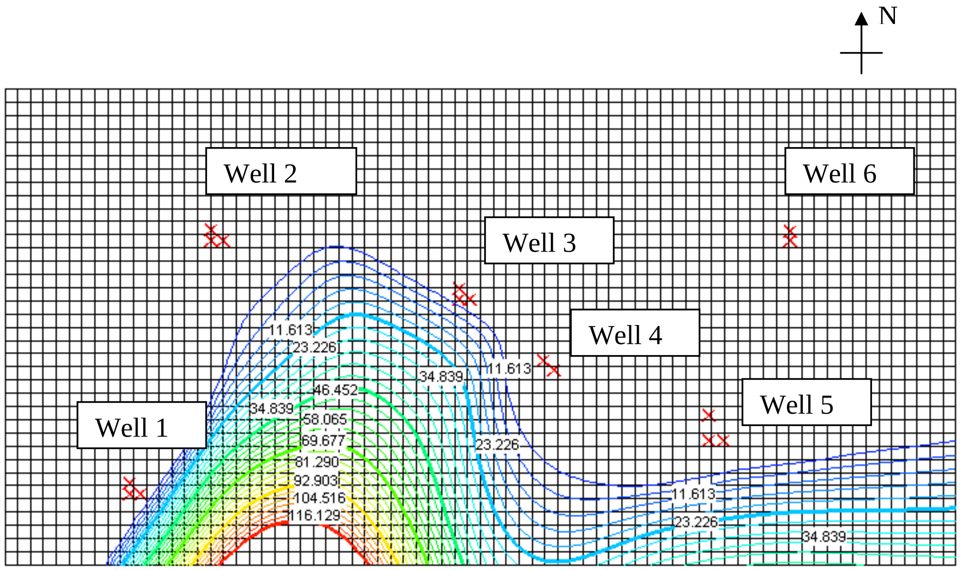

Fig 4-4a. top layer plan view of hydraulic conductivity contours

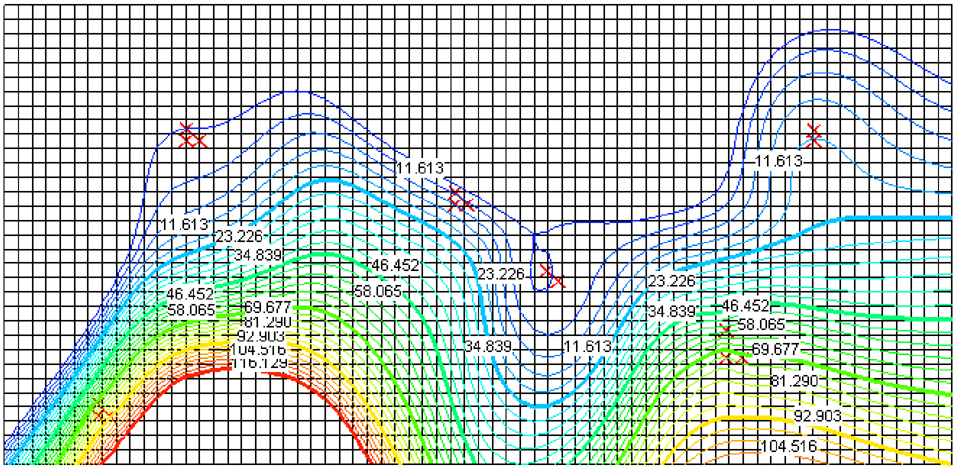

Fig 4-4b. bottom layer plan view of hydraulic conductivity contours

In the top section of the wetland soils the conductivities measured ranged from 0.0004 m/d to .001 m/d. The higher conductivities were found in the center area of the top layer near wells 3 and 4. The interpolated values range from 0.001 to 120.0 with no wells included inside the contour line for 0.1 m/d. The horizontal conductivities measured in the middle section of the wetland depth ranged from 4 m/d to 12 m/d. Slicing through the contours generated by the computer program, the values in the middle layer are similar to the top layer. When looking only at the in the middle layer section of the soil wells 1, 3, 5 are inside the contours of 0.1 m/d. In the bottom section of the wetland soils, nearest the gravel layer the conductivities are higher than in each of the other layers. In this layer the conductivities range from 3 m/d to 51 m/d. The contouring seen in the bottom layer section includes all the sampling wells between the contours of 5 m/d and 51 m/d with other areas of the lower soil layer having interpolated values up to 120 m/d. Similar to the top layer both the middle and bottom layers demonstrate their highest conductivities near the center area of their respective soil layers and near the west side of the wetland cell. These values are similar to those found by Entingh's work previously as shown in table 4-3 below.

Table 4-3 Comparison between average layer conductivities measured in the two studies of the wetland cell (in ft/s)

Study	Top layer	Middle layer	Bottom Layer
Entingh ('02)	0.0210	0.0147	1.7885
Corbin ('07)	0.0099	0.0225	2.3584

These are interesting results because the soil was of similar kind throughout the entire cell with the only minor difference being the addition of some carbon rich materials as 10% of the volume of the bottom soil layer. The soil was added in three lifts of approximately 38 cm depth as mentioned in the introduction chapter. These three layers of soils lead to the depths of the piezometer placement to measure changes in vertical head and conductivity for this research effort. The soil being the same makeup leads to assumptions of uniform porosity and isotropy properties throughout the wetland for the modeling effort as discussed in chapter covering methodology. Further, in checking the sensitivity of the anisotropy parameter in the computer model it was determined that the computer generated flow patterns are not sensitive to this particular parameter. Although the horizontal conductivities are heterogeneous, the vertical conductivities are assumed to be similar throughout the wetland cell at a ratio of K_h/K_v of 1.5. Changing the ratio in a range from a default value of 3.0 which is commonly assumed for the horizontally flowing aquifers, to 0.5 which would indicate a ratio much more conducive to the induced vertical flow in the cell, the model demonstrated very little change in the overall flow paths and velocities showing very small sensitivity to this parameter.

To test the reliability of the slug test measurements and try to determine if the well screens were clear and allowing enough unobstructed flow from the surrounding soils, the wells were developed using a technique of flushing the wells with clean water. A comparison of slug test results from before and after the development determined if the wells achieved any difference after sediment was flushed from the well and screens cleared of obstruction. The development procedure included creating a low pressure spray from the end of a garden hose, lowering the hose down to the bottom of the well to below the screens, and letting the well fill and overflow for five minutes, flushing the well of any dirt or debris inside the well. This procedure was conceived to try a clearing of the well and well screen without changing the soil properties surrounding the well. The process was repeated for all three levels of each nest of 2" sampling wells in the wetland cell. To avoid changing the soil properties during development, as was reported in Entingh's work when the wells were developed in 2002, the spray from the hose was kept small with a span of spray only 6" wide and very low pressure. The hose was twisted as it was lowered, as it rested on the bottom of the well, and when it was raised to prevent single direction spray for the entire five minutes. A slug test was done before the clearing process was begun, and again after the water reached equilibrium once the clearing process was over. The comparisons of conductivities before and after the clearing process are shown in table 4-4. Unlike the results reported in Entingh's work where the conductivities of 16 of 19 tested wells changed by an order of magnitude or more after the development of the wells, the results from the clearing procedure in this study did not show a change in hydraulic conductivities that dramatically. In this study 3 of the 16 tested wells did not recover after the initial slug test nor did they recover after being flushed and filled with water. It was the hope that after the initial slug tests did not recover, the clearing procedure would clear the screens and the slug tests after the clearing of the screens would recover appropriately. After the post clearing slug tests still did not recover, it was concluded that the well screens were obstructing flow from the flowing out of the well into the surrounding soil, preventing the well from reaching the static head level until several hours later. In two wells, the conductivity changed by a little over one magnitude, and in another case the conductivity decreased by one order of magnitude. These differences actually created more reasonable conductivity values in all three cases. This leads to a determination that the clearing of the well created a more accurate measure of the conductivity of the soil at that depth than the measure of the conductivity before the clearing procedure.

Table 4-4 the pre and post clear conductivity values

	Pre clear Kh (m/d)	Post clear Kh (m/d)
Well # 1 a	0.039	0.061
# 1 b	0.164	0.615
# 1 c	21.180	58.838
Well # 2 a	0.171	0.494
# 2 c	6.680	38.134
Well # 3 b	0.121	0.373
# 3 c	171.290	53.315
Well # 4 a	0.132	0.149
# 4 b	0.275	0.269
# 4 c	32.300	26.980
Well # 5 a	1.410	2.185
# 5 c	21.110	62.171
Well # 6 c	10.330	159.388
* wells 3a, 5b, and 6b had no recovery after the slug test		
* wells 2b, and 6a have no string for conducting the slug tests		

The small change in conductivity measured before and after the clearing procedure in all except the previously mentioned wells leads to one of two conclusions. Either the screens were allowing enough flow to measure the soil properties before the clearing procedure so that the procedure did not change the conductivity values; or that, despite the development procedure used, the wells maintained the same level of obstructed flow as before the clearing to give similar results. Either way the slug test results were similar and, in using the same procedure for the tests before and after the clearing process, proved the process was repeatable in the field to provide accurate slug test results.

Computer Modeling

The computer model of groundwater flow verifies and follows the flow patterns demonstrated by both the contours of head values across the wetland and the interpolated conductivities. As the head values indicated with contours and higher measured head values, the flow along the north side of the wetland is much slower than the flows seen along the south side of the wetland cell. As the hydraulic conductivity contours indicated, there are distinct areas of very low flow where the conductivity is low and areas of very high velocity of flow along the south side where the conductivities are highest. In the areas of the wetland with very low vertical flow rates shown in the computer model, and very low hydraulic conductivities in the soils, horizontal flow is present in the layer representing the gravel bed where the perforated pipes introduce the water into the wetland. In the gravel layer across the wetland the water flows horizontally until it comes to a high conductivity region of the wetland. An example of this horizontal flow in areas where the conductivity in the soil is low is a cross section of the wetland near the west end, shown in Fig 4-5.

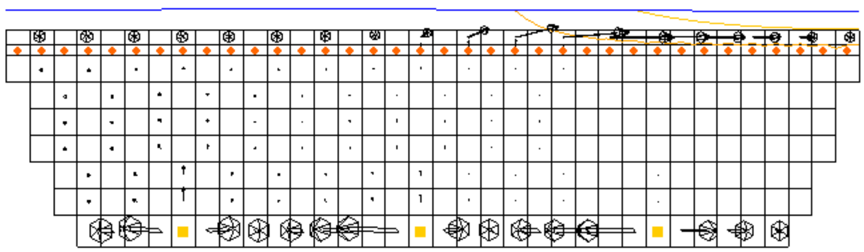

Fig 4-5. A cross section of the width of the wetland near the west end, row number 10; depicting the horizontal flow preferred by the groundwater in the gravel layer

Overall in the top and bottom layers of the computer model the water flows horizontally from the west end to the weir. These flow vectors are shown in fig 4-6 below. The magnitude of the flow is shown in the different sizes of the arrows demonstrating the direction of the water flow.

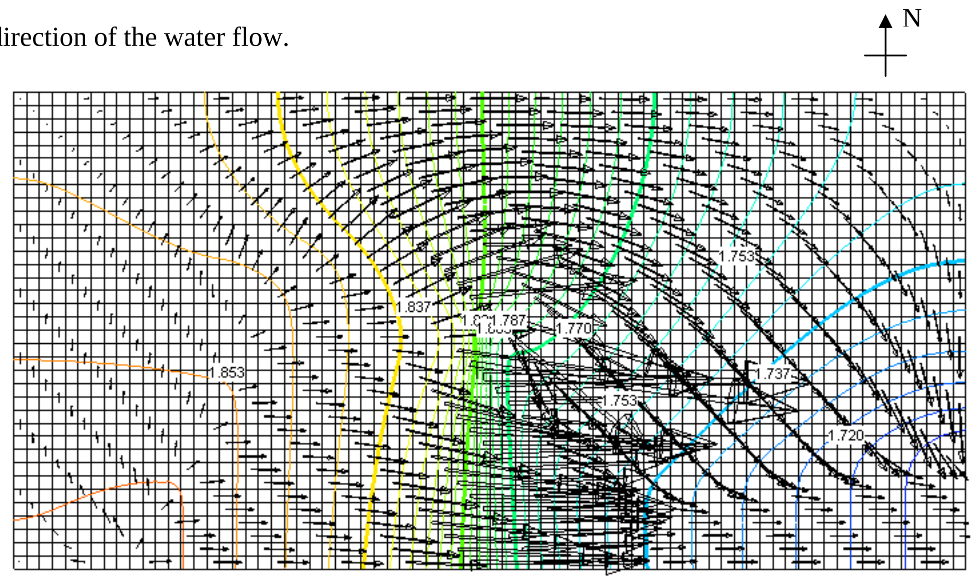

Fig 4-6. the top most layer of the computer model, surface water, demonstrating water flowing from the west end towards the weir on the east.

In the soil layers of the model the groundwater flows in vertical direction as is consistent with the decrease in head values between the bottom layers and the top of the soil. In the center areas of the wetland and the areas nearer the weir end, there is mostly vertical movement with some horizontal inclination towards areas of lower head values in the southeast corner of the wetland. Cross-sections of the wetland showing how the vectors flow vertically throughout the soil layers are shown in fig 4-7and 4-8.

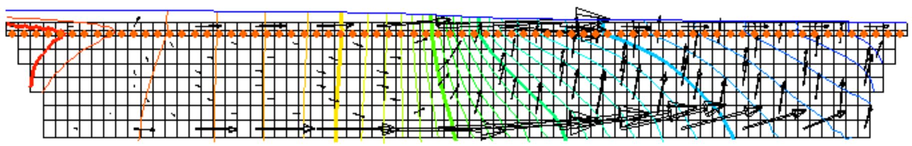

Fig 4-7. cross section the length of the wetland cell, demonstrating horizontal flows in the top and bottom layers, and the vertical flows present in the soil layers between.

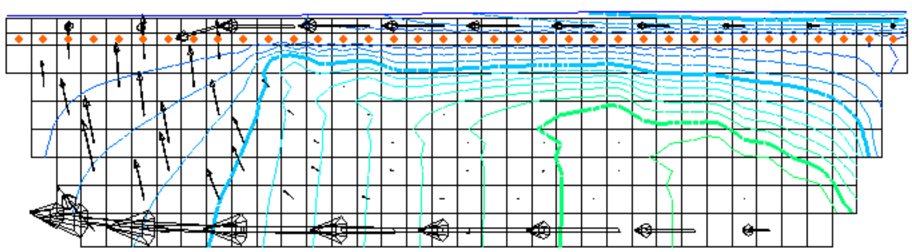

Fig 4-8. section of the width of the wetland cell demonstrating the vertical flow present in the areas of greater conductivity along the south side of the wetland cell

The results of the computer model demonstrate what was suspected in both the results of the hydraulic head measurements and the hydraulic conductivity testing. As the field data supports, the model shows the water flows from areas from higher to lower head values (from the bottom of the wetland to the surface) and from areas of lower conductivity to higher conductivity regions.

It is interesting to note that, while Entingh (2002) found similar flow characteristics and areas where there were higher flow velocities and lower flow velocities, he reported the water generally flowing towards the north side of the wetland cell. This research showed the preference of the groundwater to flow towards the south side of the wetland cell and then to the surface. Also, Entingh reported that there was vertical flow throughout the wetland cell even though there was some short circuiting of the water. Again this is a bit contradictory to the areas with very little to no visible vertical flow components near the northwest corner of the cell that were realized in this study of the wetland. With the similarity in methodology, almost to a point of replication between the two studies, it is apparent that the water has changed or shifted to more distinct areas of higher flow rates and very low flow rates since the study conducted in 2002.

Residence Time Calculations

The water flows vertically through the areas of low conductivity; however it is at a very slow pace. The ideal flows intended for the constructed wetland cell was a direct vertical path for a particle of water flowing from the gravel layer to the top of the soil and into the weir outlet. This occurs most closely in the area near the weir end. The residence time for a particle of water from the gravel layer at the bottom of the cell to the top of the soil generated by the computer model in this study is only 1.25 days. To track the particles flowing in the wetland a package in the MODFLOW suite of programs called MODPATH was used. Particles of water generated at the cells that simulated the gravel layer were tracked to determine an average time that the particle will spend in the wetland soil before reaching the surface where the water flows in a sheet flow manner towards the weir outlet. While tracking the particles from the gravel layer an average for each of the 3 soil layers was computed individually and the probability function distribution of residence times in each layer were graphed. The three graphs below show the histogram representation of each distribution of water particles traveling through the top, middle and bottom soil layers respectively. The graphs show there is very small difference between the time water particles spend traveling through the separate soil layers. The most common time in each of the layers was 0.4 and 0.5 days.

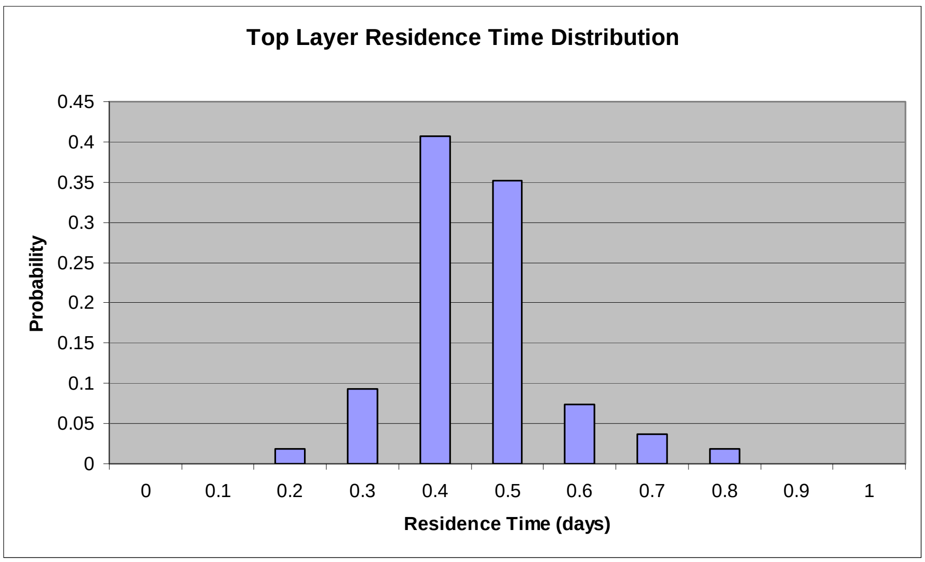

Fig 4-9a. Residence time distribution for particles in the top soil layer

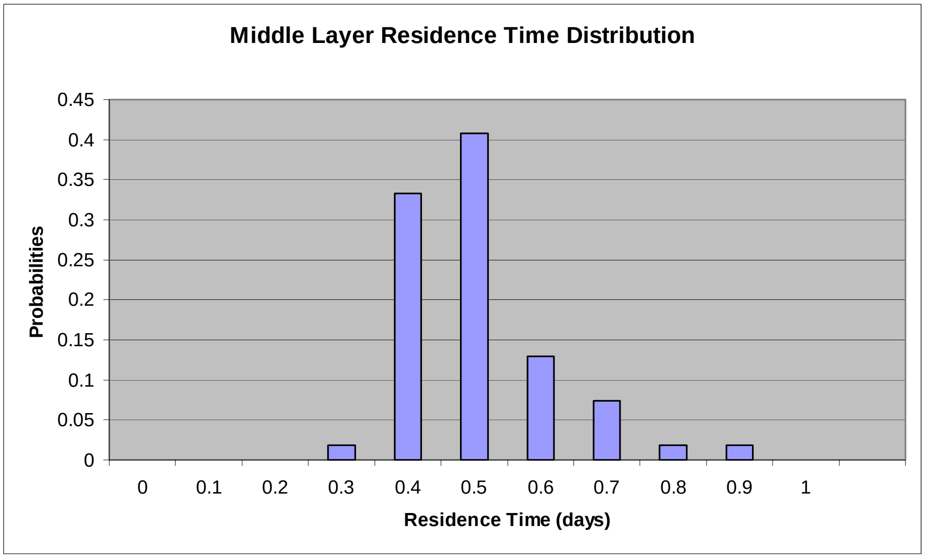

Fig 4-9b. Residence time distribution for particles in the middle soil layer

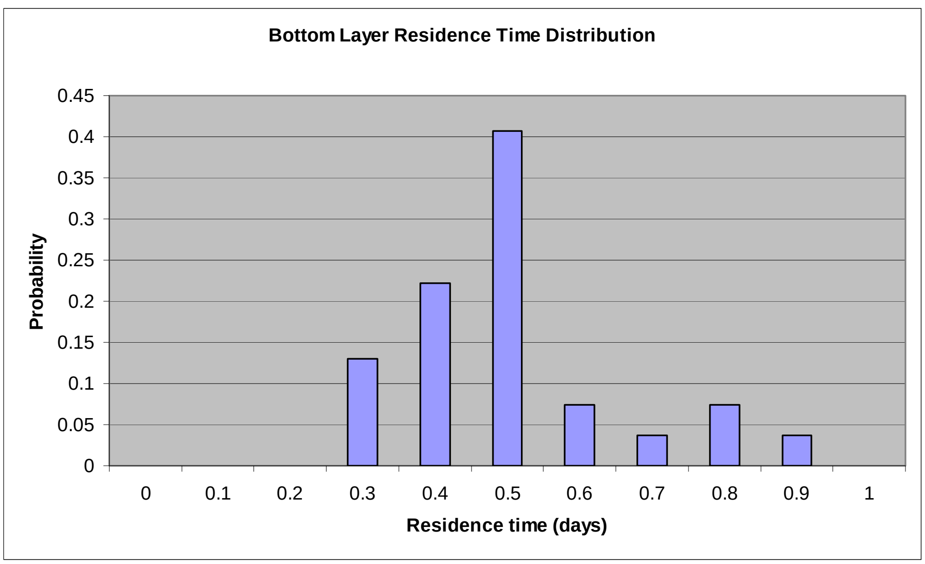

Fig 4-9c. Residence time distribution for particles in the bottom soil layer

As is apparent in the distributions shown in Fig 4-9, the average time for water particles generated in the gravel layer and traveling through the top, middle and bottom layers of the wetland soil are 0.43, 0.48 and 0.47 days respectively. The groundwater from all of the randomly selected cells in the gravel layer traveled horizontally from the north side of the wetland cell to the south side and then vertically to the surface. This was a trend for the entire length of the wetland cell. Fig 4-10 shows a representation of the water particles being tracked using MODPATH with a scale of 0.5 days per arrow.

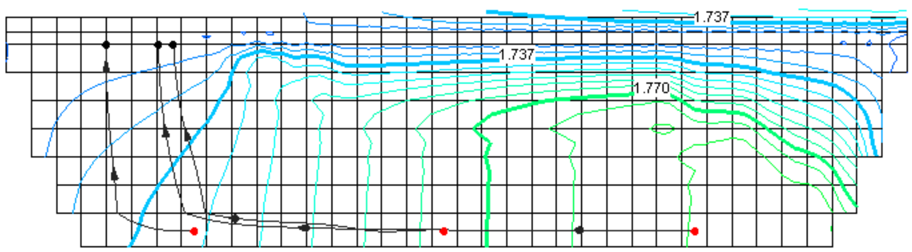

Fig 4-10. cross-section of wetland cell near the weir end, row 46, showing the flow paths tracked by water particles generated at the injection wells

For particles of water traveling in the lower conductivity areas, K less than 0.1 m/d, the average residence time in each layer of the wetland cell is much larger than the particles that are tracked beginning at the gravel layer. The averages are 436,000 days for the top layer, 439,000 for the middle layer and 425,000 days for the bottom soil layer. This is largely found in the areas of the wetland cell where the flows have very low velocities near the north side and west end. Conversely in the areas of higher conductivity, along the south side of the wetland cell, the residence time is between 1 day and 10 days through all three soil layers for particles being tracked in areas above the gravel layer which is more in line with the residence time reported in Entingh's work five years ago.

He reported an average residence time of 3.6 days using the MODPATH package in visual MODFLOW. With a simple equation that correlates volume of water in the wetland with the average flow rate of water a simple overall residence time can be calculated.

$$t = V/Q \qquad (14)$$

Where t = mean residence time (days)

V = volume of water (cubic meters)

Q = flow of water through the system (cubic meters per day)

The overall theoretical residence time for the water traveling through the volume of the wetland cell and exiting the weir would be 5.5 gpm traveling through 522.87 cubic meters of soil. Using the measured porosity of 0.5 for the wetland soils, the volume of water is 261.44 cubic meters. The average residence time works out to 8.75 days for the water flowing uniformly through the wetland cell. A more accurate residence time would take into account only the areas where water is actively flowing (with a residence time less than 5 days for the depth) and not including the areas of nearly stagnant flow in the overall volume of the wetland cell. This leads to a better understanding of the amount of water being handled by the small area where the vertical flow is occurring most significantly (with a residence time less than 5 days from bottom to top of the soil). Fig 4-11 on the next page illustrates a series of randomly placed particles along the gravel layer and the volume of soil that captures the majority of the vertical flow.

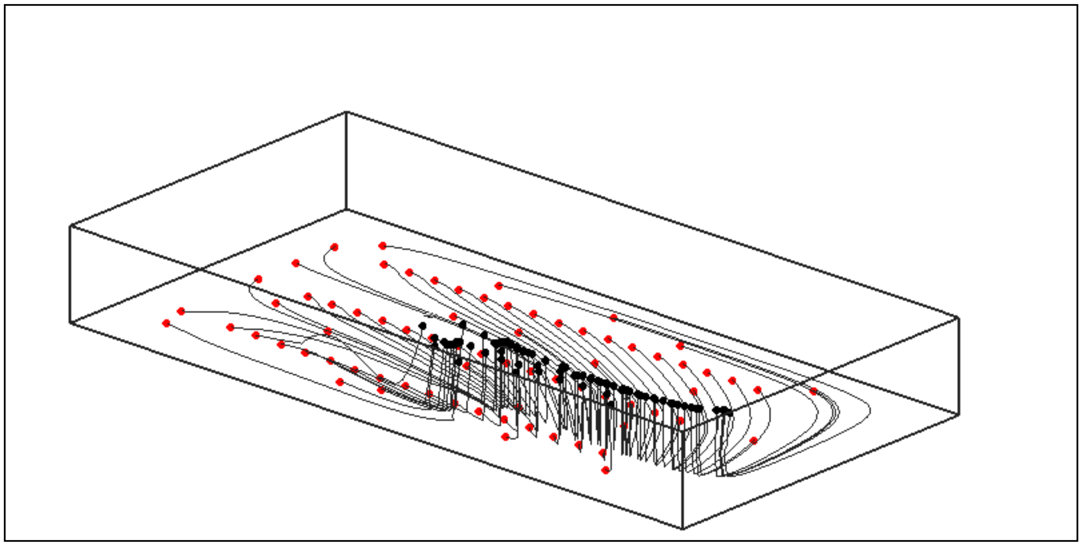

Fig 4-11. an illustration of particles tracked from the gravel layer to the top of the wetland soil

This active area at the surface is approximately 18 m long (from x = 18.6m to x = 36m) and 3.7 m wide (from y = 0.51m to y = 4.24m) through the depth of the wetland 1.7m. Which yields a soil volume of 113.22 cubic meters, add to that the volume of the gravel layer (111.72 cubic meters) and the total actual wetland volume that handles all of the 5.5 gpm flow is only 224.94 cubic meters. This reveals a more accurate residence time of 3.75 days for the water to travel from the gravel layer to the surface of the soil.

Using the MODPATH package in combination with the flow velocity profiles that were calculated at the surface of the wetland cell a particle can be tracked from a random starting point in the gravel layer, where the water enters the wetland cell, to the surface and then tracked to the weir. With this additional information it can be determined that the water particles at the surface in the south east corner of the wetland cell where the velocities range from 1.7 m/day near the center of the cell, to 0.25 m/day near the weir, take between 18 and 24 days to travel across the surface to the outlet weir. The total residence time for particles from the gravel layer to the outlet weir is actually calculated as a range from 25.46 days to 51.96 days. The majority of that time is spent as slow flow across the surface, the second largest amount of that time is spent traveling horizontally the length of the wetland cell in the gravel layer and the smallest portion of that time is the vertical component in the south east corner of the wetland cell.

Conclusion

Overall the wetland cell demonstrates the vertical flow that it was designed to provide. Once the water reaches the surface it flows to the outflow weir. There are regions where the magnitude of the groundwater flow greatly increases and sharply changes direction in the center of the cell. There are areas where the flow is very slow and there are areas where the water flows rapidly in a horizontal direction. By including the field data and the soil parameter assumptions into a computer generated model, a full picture of the preferential paths of groundwater flow in the constructed wetland cell can be studied. The model itself is believed to be reliable as it was calibrated until the difference between the measured head values in the wetland and the head values calculated by the model itself were within only a weighted residual sum of 20.496 at a 95% confidence level. This level of calibration was achieved and determined adequate during the calibration step of the computer model which is outlined more clearly in chapter three. A summary of the closeness of the measured and calculated values table is included in table 4-5 below.

Table 4-5. residual between the observation head values (measured) and the calculated head values

Deleted: caluculated

Obs pt	Obs H	calculated H	residual	Obs pt	Obs H	calculated H	residual
1	1.715	1.869175	0.154175	23	2.435	1.810427	-0.62457
2	1.819	1.867655	0.048655	24	1.936	1.757029	-0.17897
3	2.413	1.861871	-0.55113	25	1.973	1.790838	-0.18216
4	1.703	1.869497	0.166497	26	2.42	1.801052	-0.61895
5	1.654	1.868071	0.214071	27	1.799	1.742571	-0.05643
6	1.8	1.859991	0.059991	28	1.764	1.774346	0.010346
7	1.882	1.860104	-0.0219	29	2.423	1.784	-0.639
8	2.415	1.860039	-0.55496	30	1.793	1.735055	-0.05795
9	1.79	1.86288	0.07288	31	1.762	1.759554	-0.00245
10	1.777	1.862392	0.085392	32	2.43	1.778257	-0.65174
11	2.42	1.861279	-0.55872	33	1.688	1.720747	0.032747
12	1.832	1.854934	0.022934	34	1.992	1.727387	-0.26461
13	1.89	1.856368	-0.03363	35	2.417	1.729619	-0.68738
14	2.427	1.857327	-0.56967	36	1.784	1.735456	-0.04854
15	1.805	1.84595	0.04095	37	1.784	1.776001	-0.008
16	1.812	1.846764	0.034764	38	2.425	1.775199	-0.6498
17	2.42	1.846593	-0.57341	39	1.787	1.715339	-0.07166
18	1.79	1.834737	0.044737	40	1.956	1.726956	-0.22904
19	2.03	1.836693	-0.19331	41	2.42	1.730548	-0.68945
20	2.361	1.840883	-0.52012	42	1.777	1.735178	-0.04182
21	1.757	1.798318	0.041318	43	2.267	1.766507	-0.50049
22	1.832	1.807777	-0.02422	44	2.418	1.774413	-0.64359

V. Conclusions and Recommendations

Conclusions

The goal of this research effort was to determine the current flow patterns in the constructed treatment wetland cell at Wright Patterson Air Force Base, OH. The results of this study show that there exists varying levels of hydraulic head gradients across three separate depths of the wetland soils indicating areas of much higher groundwater flows as well as large areas of very low flow rates. Measured horizontal hydraulic conductivities also show a wide variation of contours from 0.001 m/day to 51 m/day, also indicating areas of very high velocities and areas of very low velocities. The wetland cell was constructed to induce uniformly vertical flow to create the most efficient decomposition of the PCE through the wetland substrate. As was shown in Entingh's study of the groundwater flow patterns in the cell in 2002, this study also verifies that the groundwater flow patterns are not always uniformly vertical. There are preferential flow patterns occurring such as those shown in the residence time section.

The residence time of each soil layer was determined to demonstrate the differences that exist from the bottom soil depths and the soil near the top of the wetland. It was shown that the calculated residence time of particles of water starting in the gravel layer in the bottom of the wetland cell are similar to the residence time that was envisioned during the design of the cell. However particles tracked from the soil layers of the wetland cell took much longer average times to reach the surface in areas where the measured conductivities were very small. These areas represent stagnant sections of the wetland, mostly along the north side and west end of the wetland.

Each section of this study was compared to a study done on this same wetland cell when it was first constructed in 2002. The head measurements in this study showed similar variations as were found in Entingh's work five years ago. The head measurements in both studies showed areas of higher head and lower head located very close to each other and showed gradients where the preferential paths of groundwater would tend to flow. The patterns of head gradient and hydraulic contours lead to regions of higher and lower magnitude groundwater flows across the wetland. These patterns are similar to what Entingh had found in the original study. The conductivities found in the current study were similar to the conductivities determined by Entingh. Overall however, it appears that after five years of continuous operation the wetland has developed distinct areas where the water flow velocities are very slow and other areas that are much faster.

Areas for Future Study

A suggested follow on to this study would be to use a physical test of flow in the wetland cell with a conservative tracer or dye. This would lead to measurements of where the tracer or dye appears over time to determine if the groundwater flow velocities and residence times are similar to those determined in this study. Expected time for measuring a tracer or dye would be found in the nests located along the southern side of the wetland cell, the areas of most vertical flow. Table 5-1 below suggests the time to measurable tracer or dye being located in the nest piezometer.

Table 5-1. estimated time for detectable measurements of a tracer or dye test

Nest #	Level of Screen	Estimated time to measurements (days)
37	A	1.5
37	B	1.0
37	C	0.4
43	A	1.2
43	B	1.0
43	C	0.4
49	A	1.5
49	B	1.0
49	C	0.5
55	A	1.6
55	B	1.0
55	C	0.5
61	A	1.4
61	B	1.0
61	C	0.5

Another suggested area for future study would be to do a replicated study with the same field work and allow time for formal training and more in depth use of the MODFLOW computer program to generate a model more closely aligned with the data collected in the field.   A suggested method of creating a model with more closely calibrated calculated and field measured data would be to explore the use of various fitting algorithms with the MODFLOW output.

Finally a study conducted with similar methodology to this research and including more wells for testing could detect the heterogeneities that are occurring in the wetland cell could lead to a more accurate understanding of the groundwater flow patterns. It is suggested that to achieve a more accurate study the addition of 4-6 sampling wells would be necessary. The area of most need of the additional wells is along the northern side of the wetland cell where the conductivities were measured at very low values. More exploration in this area of the wetland cell could provide a clearer picture of the hydraulics of the decontamination process.

Study Strengths

This study gathered a good bit of field data that helped describe the possible flow paths of the groundwater. The amount of head data from the closely spaced piezometer grid allowed for a good characterization of the direction of preferred groundwater flow. The horizontal conductivities collected by commonly used slug test methodology provided a contour definition of the conductivities found in the wetland cell. This study used the field data collected to create and calibrate the computer model using Groundwater Modeling System and the MODFLOW package of software. These programs are considered user friendly and an industry standard in the case of MODFLOW. They create clear output pictures that help to define the movement of groundwater given a combination of soil and pressure characteristics that are easily defined and changed. A follow up to this study using the same numerical modeling package would be relatively easy to begin and created a model that more closely represents the actual wetland cell.

Appendix A

This appendix shows the measured head values for the piezometers in the wetland. The measurements were taken May 11, 2007 with a wetland flow of 5.5 gallons per minute.

piezometer #	Soil layer	H20 depth measured (ft)	elev piez surface (ft)	elev piez surface (m)
1	a	0.8	5.805	1.769
1	b	2.55	5.636	1.718
1	c	1.45	7.76	2.365
2	a	0.62	5.925	1.806
2	b	1.13	6.242	1.903
2	c	0.9	8.145	2.483
3	a	0.71	5.626	1.715
3	b	1.33	5.969	1.819
3	c	1.05	7.916	2.413
4	a	0.75	5.745	1.751
4	b	1.15	5.769	1.758
4	c	1.09	7.874	2.400
5	a	0.49	6.03	1.838
5	b	1.6	5.927	1.807
5	c	1.05	7.998	2.438
6	a	0.61	5.588	1.703
6	b	1.63	5.426	1.654
6	c	dry		
7	a	0.8	5.69	1.734
7	b	1.4	6.133	1.869
7	c	1.22	7.754	2.363
8	a	0.61	5.907	1.800
8	b	1.41	6.175	1.882
8	c	1.01	7.924	2.415
9	a	0.79	5.706	1.739
9	b	1.74	5.806	1.770
9	c	1.22	7.861	2.396
10	a	0.83	5.869	1.789
10	b	1.45	6.344	1.934
10	c	1.36	7.823	2.384
11	a	0.88	5.872	1.790
11	b	1.91	5.831	1.777
11	c	1.25	7.944	2.421
12	a	0.46	6.218	1.895
12	b	1.21	6.266	1.910

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piezometer #	Soil layer	H20 depth measured (ft)	elev piez surface (ft)	elev piez surface (m)
12	c	1.25	7.78	2.371
13	a	0.58	6.21	1.893
13	b	2.25	5.993	1.827
13	c	1.36	7.931	2.417
14	a	0.86	5.699	1.737
14	b	2.14	6.032	1.839
14	c	1.42	7.736	2.358
15	a	0.72	5.878	1.792
15	b	2.07	6.275	1.913
15	c	1.44	7.834	2.388
16	a	0.05	6.641	2.024
16	b	0.16	7.336	2.236
16	c	1.1	7.925	2.416
17	a	0.5	6.239	1.902
17	b	1.69	5.988	1.825
17	c	1.22	7.928	2.416
18	a	0.7	6.01	1.832
18	b	1.46	6.084	1.854
18	c	1.15	7.961	2.427
19	a	0.8	5.902	1.799
19	b	1.8	5.908	1.801
19	c	1.31	7.905	2.409
20	a	0.96	5.727	1.746
20	b	1.68	5.977	1.822
20	c	1.33	7.823	2.384
21	a	0.58	5.922	1.805
21	b	1.6	5.944	1.812
21	c	1	7.94	2.420
22	a	1.07	5.65	1.722
22	b	0.05	7.5	2.286
22	c	1.36	7.763	2.366
23	a	0.31	6.548	1.996
23	b	0.73	6.81	2.076
23	c	1.2	8	2.438
24	a	0.95	5.713	1.741
24	b	0.98	6.38	1.945
24	c	1.04	7.923	2.415
25	a	0.85	5.788	1.764
25	b	2.35	5.878	1.792
25	c	1.23	8.025	2.446
26	a	1.11	5.603	1.708
26	b	2.65	5.558	1.694

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piezometer #	Soil layer	H20 depth measured (ft)	elev piez surface (ft)	elev piez surface (m)
26	c	1.57	7.781	2.372
27	a	0.97	5.639	1.719
27	b	0.52	7.002	2.134
27	c	1.3	7.895	2.406
28	a	0.76	5.828	1.776
28	b	1.33	6.048	1.843
28	c	1.1	7.956	2.425
29	a	0.65	6.286	1.916
29	b	1.5	6.15	1.875
29	c	1.97	7.19	2.192
30	a	0.89	5.873	1.790
30	b	1.44	6.661	2.030
30	c	1.33	7.745	2.361
31	a	0.82	5.835	1.779
31	b	1.39	6.79	2.070
31	c	1.21	8.07	2.460
32	a	1.03	5.763	1.757
32	b	2.1	6.011	1.832
32	c	1.47	7.99	2.435
33	a	1.1	5.738	1.749
33	b	1.43	6.729	2.051
33	c	1.73	7.775	2.370
34	a	0.3	6.308	1.923
34	b	1.59	5.929	1.807
34	c	1.07	7.94	2.420
35	a	x		
35	b	0.98	6.491	1.978
35	c	dry		
36	a	0.38	6.344	1.934
36	b	1.49	6.086	1.855
36	c	1.12	8.067	2.459
37	a	0.85	5.851	1.783
37	b	2.57	5.778	1.761
37	c	1.37	7.969	2.429
38	a	0.88	5.873	1.790
38	b	2.51	5.772	1.759
38	c	1.58	7.936	2.419
39	a	0.88	5.868	1.789
39	b	2.5	5.879	1.792
39	c	1.44	7.812	2.381
40	a	0.03	6.628	2.020
40	b	0.57	6.588	2.008

piezometer #	Soil layer	H20 depth measured (ft)	elev piez surface (ft)	elev piez surface (m)
40	c	1.13	7.919	2.414
41	a	0.44	6.253	1.906
41	b	1.3	6.207	1.892
41	c	1.21	7.906	2.410
42	a	0.03	6.363	1.939
42	b	1.06	6.473	1.973
42	c	1.13	7.939	2.420
43	a	1.13	5.5	1.676
43	b	dry		
43	c	1.34	7.969	2.429
44	a	0.82	5.787	1.764
44	b	1.19	7.119	2.170
44	c	1.49	7.923	2.415
45	a	0.89	5.783	1.763
45	b	2.51	5.785	1.763
45	c	1.35	7.954	2.424
46	a	0.83	5.918	1.804
46	b	1.64	6.03	1.838
46	c	1.24	7.918	2.413
47	a	0.97	5.902	1.799
47	b	1.71	5.787	1.764
47	c	1.34	7.948	2.423
48	a	0.38	5.93	1.807
48	b	0.8	6.832	2.082
48	c	1.08	7.969	2.429
49	a	0.81	5.745	1.751
49	b	2.55	5.771	1.759
49	c	1.35	8.037	2.450
50	a	1.11	5.588	1.703
50	b	1.32	6.32	1.926
50	c	1.52	7.925	2.416
51	a	0.92	5.864	1.787
51	b	2.04	5.748	1.752
51	c	1.46	7.988	2.435
52	a	0.85	5.881	1.793
52	b	2.04	5.78	1.762
52	c	1.42	7.973	2.430
53	a	0.64	5.898	1.798
53	b	1.7	5.943	1.811
53	c	1.32	7.942	2.421
54	a	0.65	5.589	1.704
54	b	1.21	6.436	1.962

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piezometer #	Soil layer	H20 depth measured (ft)	elev piez surface (ft)	elev piez surface (m)
54	c	1.33	7.789	2.374
55	a	0.96	5.537	1.688
55	b	1.3	6.535	1.992
55	c	1.39	7.93	2.417
56	a	1.1	5.38	1.640
56	b	1.33	6.438	1.962
56	c	1.42	7.961	2.427
57	a	0.71	5.83	1.777
57	b	1.86	5.809	1.771
57	c	1.65	7.847	2.392
58	a	0.35	6.193	1.888
58	b	1.59	6.082	1.854
58	c	1.32	7.889	2.405
59	a	0.8	5.853	1.784
59	b	1.83	5.854	1.784
59	c	1.39	7.955	2.425
60	a	0.69	5.82	1.774
60	b	0.95	6.632	2.021
60	c	1.23	7.959	2.426
61	a	0.5	5.859	1.786
61	b	2.19	5.461	1.665
61	c	1.49	7.806	2.379
62	a	0.89	5.862	1.787
62	b	1.35	6.418	1.956
62	c	1.37	7.939	2.420
63	a	0.19	6.428	1.959
63	b	0.84	6.835	2.083
63	c	1.47	7.953	2.424
64	a	0.78	5.997	1.828
64	b	0.39	7.29	2.222
64	c	1.27	7.866	2.398
65	a	0.75	5.852	1.784
65	b	1.33	6.24	1.902
65	c	1.38	7.891	2.405
66	a	0.54	5.831	1.777
66	b	0.12	7.439	2.267
66	c	1.39	7.934	2.418

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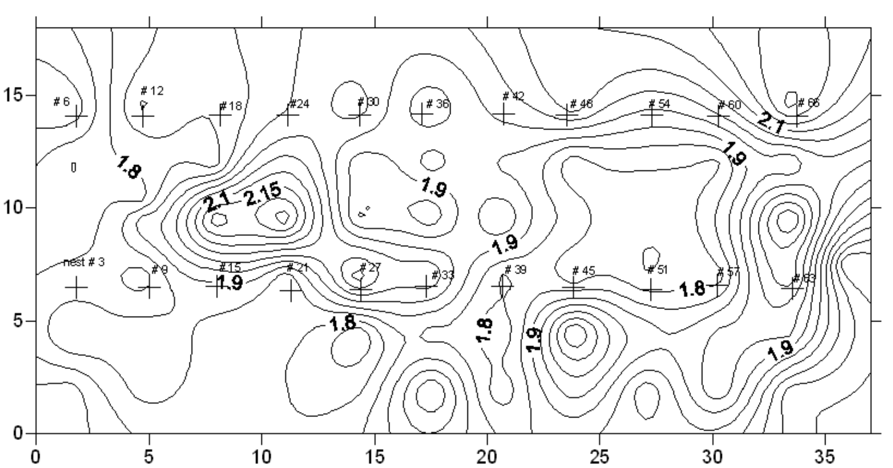
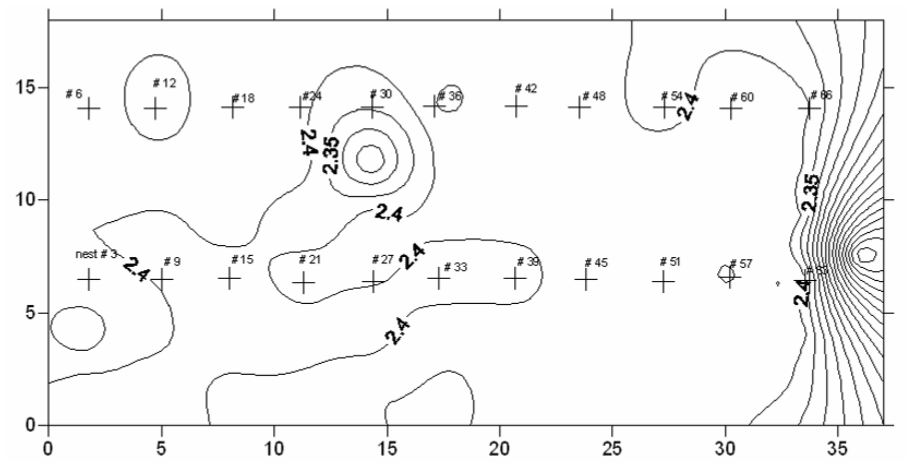
Appendix B

This appendix contains 2-D illustrations of the hydraulic head gradients in the measured depths of the wetland soil. The top layer is at a depth of 1.33 m above the horizontal datum represented by the geo-membrane beneath the soil, gravel and sand layers at the bottom of the wetland cell. The middle layer is represented by a depth of 0.95 m above the datum and the bottom layer is represented at a depth of 0.57 m above the datum. These illustrations can be compared to those created during the Entingh study conducted on the same wetland cell in 2002.

The 2-D illustration of the top layer of head values can be found in chapter 4, pg. 59.



Mid level head contours (m) of the current study



Bottom level contours (m) of the current study

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14. ABSTRACT This research effort analyzed groundwater flow paths within a treatment wetland constructed to degrade tetrachloroethylene (PCE) in groundwater. The treatment cell is a vertical flow wetland that allows the water to flow from the bottom to the surface breaking down PCE and daughter products. The method of conducting this research included collecting field data of hydraulic head contours nested piezometers and collecting data from sampling wells to determine hydraulic conductivities in the wetland. The field data was used to create a numerical computer model to determine groundwater flow patterns. The field data and the model demonstrate that there are areas in the wetland with flow velocities as low as 0.0019 m/day and as high as 2.779 m/day. The computer model also shows residence times of water particles traveling from the bottom of the wetland cell to the surface water varying from < 1 day, to over 1000 days. Groundwater flow patterns occurring in the wetland today were compared to a study five years ago. The hydraulic head contours and hydraulic parameters measured in the field were similar in both studies. The results of both studies show the residence times and the desired uniform flow across the wetland is being short circuited.						
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