Abstract

PATI, SWAMY. Effects of Subsurface Flows on Wetland Restoration at Juniper Bay and Surrounding Area. (Under the direction of Rodney L. Huffman.)

The North Carolina Department of Transportation purchased a 270-hectare, roughly elliptical tract of agricultural land, known as Juniper Bay (a Carolina Bay), to convert to wetlands as part of their wetlands mitigation program. Preliminary water balance work suggested that there are significant flows of groundwater entering and leaving the tract. This study was initiated to examine the subsurface potentials and determine the degree to which a ditch around the perimeter of the tract controls the lateral fluxes of groundwater in the surficial aquifer. Five nests of piezometers were installed along each of four 150-m transects crossing the perimeter ditch at approximately the major and minor axes of the tract, which correspond to the suspected maxima of influx and efflux. Deep soil cores (up to 13 m) were collected along each transect to guide placement of piezometers for monitoring hydraulic heads. Piezometer water levels were recorded at 15-minute intervals. Meteorological data were collected with an on-site weather station.

Models were developed for the four transects using Visual MODFLOW. Models were calibrated with observed groundwater pressure heads. Maximum absolute error in the calibration process was 0.5 m. The modeling results suggested that the ditch drained water from the surficial system from both sides. In the deeper sand layers, there was an indication of groundwater flowing into the bay at NW and NE transects. Groundwater flows in the SW transect indicated outflows. The SE transects showed water draining into the ditch from both sides. The models were extended to 800-m inside the bay to simulate

conditions after the interior ditch system was blocked. Simulation results showed groundwater inflows through the NW, NE, and SE transect, and groundwater outflows through SW transect. The lateral influence of the perimeter ditch had a maximum of approximately of 100 m, observed at the SW transect, and a minimum of 30 m, observed at the SE transect. The extent of influence of the perimeter ditch was also dependent on the weather conditions, showing more influence in summer months compared to winter months. Influence of the perimeter ditch was entirely in the upper sands at the NE and SE transects, but some influence was seen in the middle sand layers at the NW and SW transects. Groundwater flow estimates from the transects were extrapolated over the whole perimeter of Juniper Bay to obtain net groundwater inflow. Net groundwater inflow was approximately 125 mm for the time period of 1 January 2004 to 30 June 2004.

To develop recommendations for maintaining the perimeter ditch, the models were run for various scenarios focused on water levels in the perimeter ditch. Control levels were imposed on the ditch and options were investigated. A water level of 35.9 m MSL was identified as a critical point of control of the perimeter ditch. Controlling the water level in the perimeter ditch at 35.9 m will minimize offsite impacts and result in maximum wetland area.

Effects of Subsurface Flows on Wetland Restoration at Juniper Bay and Surrounding Area

by

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Dedication

I dedicate this work to my Loving Parents.

Biography

Swamy Pati was born in 1977 in Pitapuram, Andhra Pradesh in India. His father works with Indian Railways as Junior Engineer – Electrical, and mother is a house wife. His only brother was graduated with Masters of Computer Applications and working a software engineer in New Jersey, USA. Parents live in Kakinada, India.

He was bought up in Vijayawada, Andhra Pradesh in India where he did schooling in Railway Mixed High School and Nalanda Junior College. He graduated from High school in 1994. He graduated with a Bachelor of Technology in Agricultural Engineering in August 1999 from Acharya NG Ranga Agricultural University.

He started MS at Utah State University in Jan 2001 in Biological and Irrigation Engineering and graduated in August 2002. He worked with Dr. Wynn Walker in the project called IRRINET developing web-based course on Principles of Irrigation Engineer. After completing MS, with the quest for knowledge and interest he joined for PhD program in Biological and Agricultural Engineering at North Carolina State University. His concentration was in Environmental Engineering, he worked with Dr. Rodney L. Huffman in a project dealing with groundwater aspects at a wetland restoration site.

During his stay at NC State, he was awarded International Student Scholarship for 2004 by Rotary Club. He was initiated in Honor Society of Agriculture – Gamma Sigma Delta in 2006. He is a student member of professional societies American Society of Agricultural and Biological Engineers (ASABE) and National Groundwater Association (NGWA).

Apart from academics, he was active in social activities and served as Vice-President of MAITRI – Indian Graduate Student Association at NC State University for year 2004. He is also a member of charity organization – Two Cents of Hope, helps for educational needs of under privileged children in India. He likes playing cricket and volley ball. His other hobbies include spending time with friends, movies, music, and dance. He likes traveling and visited many parts of US in just 4 years. His mother tongue is Telugu and he can speak Hindi and English.

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Chapter 1

Introduction

The North Carolina Department of Transportation purchased a 270-hectare parcel of agricultural land, Juniper Bay (a drained Carolina Bay), to convert into wetland as part of their wetland mitigation program. The success rate for wetland conversion has been relatively low due to shortcomings in site assessment, identification of potential functions, methodologies to restore wetland functions, and effective assessment of progress of functional restoration, which are the factors that are set by the US Army Corps of Engineers. The Department of Soil Science at North Carolina State University, in collaboration with several other departments (Biological and Agricultural Engineering, Forestry, and Botany), started a research project to address those shortcomings in the study of restoration success in Juniper Bay. This research will help to define the characteristics of a site that affect the success of a project. The preliminary water balance work (Kreiser et al., 2003) on this project suggested that there is a significant amount of groundwater entering and leaving the bay. Water budget work showed a wide variation in estimates of groundwater inflows, which was mainly attributed to uncertainty in the estimation of evapotranspiration. When groundwater potentials were examined around the site and data suggested the possibility of significant lateral subsurface fluxes, it was decided to look into the groundwater situation in more detail. Due to the sparseness of the data being collected, any estimate of the subsurface flows based on those data would be crude. An assessment of the role of the groundwater flows in the hydrologic behavior of the Juniper Bay and its impacts on the surrounding area depends strongly on a reasonably accurate picture of what is happening at the perimeter of the bay. Therefore, a companion research project was initiated to examine the subsurface potentials and determine the degree to which a ditch around the perimeter of the tract controls the lateral fluxes of groundwater in the surficial aquifer.

Objectives:

1. Characterize the subsurface flows at the perimeter of the Bay.
2. Determine the degree and modes of interaction of the perimeter ditch of the Bay with the partially confined sand strata.
3. Model the subsurface flows in the Bay area and assess the impacts of these flows on the surrounding area.
4. Develop management recommendations for the perimeter ditch

Background

Carolina Bays are oval-shaped wet depressions with a northwest-southeast orientation (Howard, 1977). They are spread throughout the eastern coastal plain of the United States from Delaware to Florida. Some are filled with water and named as lakes. Many of them are in a vegetative wetland state. According to the theories of different hydrologists, the hydrology of Carolina Bays is influenced by the inputs from the subsurface flows and by the underlying fine-textured sediments that restrict vertical movement of water. Knight et al. (1989), Newman and Schalles (1990), Lide et al. (1995), and O'ney et al. (1999) have studied the complex hydrology of Carolina Bays and have shown the complex subsurface interactions with the surrounding area. Their studies also indicated there was local depressional hydrology superimposed on the regional subsurface hydraulic gradients of the landscape in which the bay occurred.

Juniper Bay is located in Robeson County, North Carolina. Figure 1 shows the location and elliptical shape of Juniper Bay, a common characteristic of Carolina Bays. Initially a wetland, Juniper Bay was drained for industrial purposes in the early 1960s and it was intensively drained for agriculture in the late 1970s. As of 2000, it had about 270 ha of drained and intensively managed agricultural land that was not jurisdictional wetland due to its status as prior converted agricultural land. Prior to ditching, surface runoff apparently left the bay through an area in the southern portion where the rim is very low or missing. The ditch system now conveys both surface and subsurface drainage to the outlet shown in Figure 1.1.

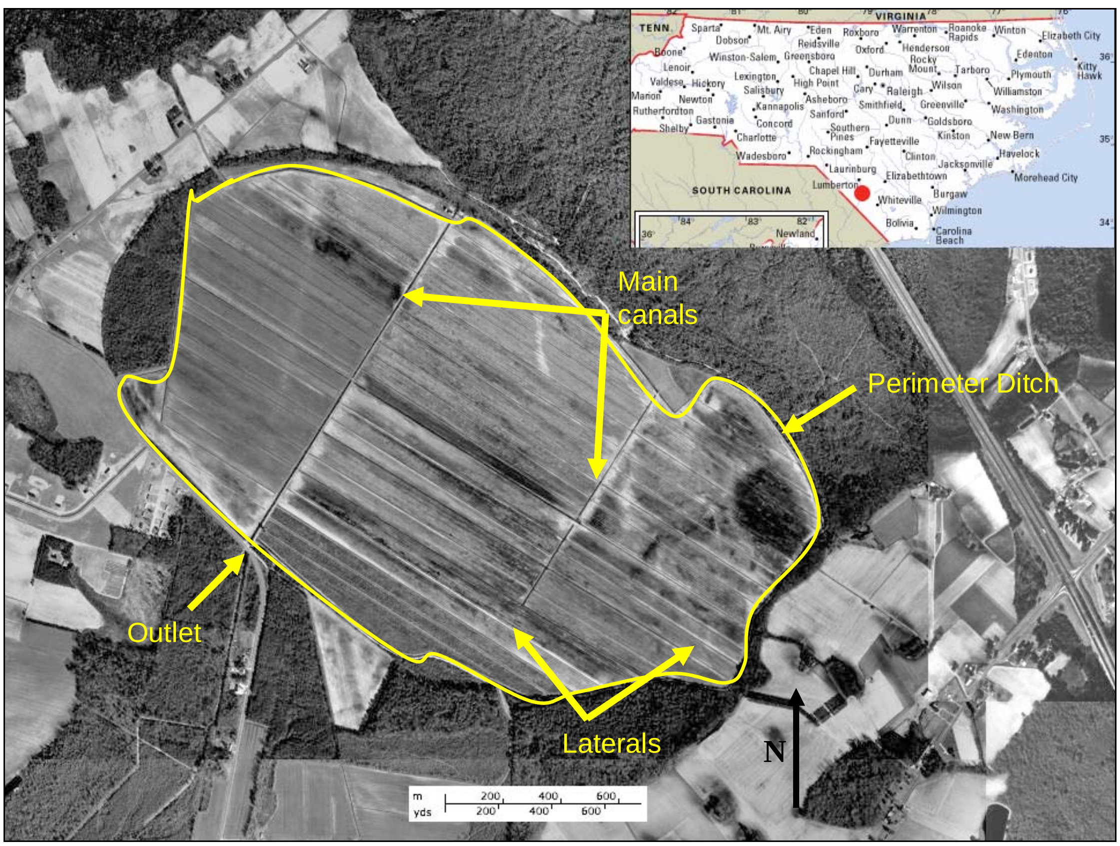

Figure 1.1: Aerial photo of Juniper Bay from 1993 (USDA-FSA). NW-SE extent is 2.5 km and SW-NE extent is 1.4 km.

A conceptual profile at Juniper Bay is shown in figure 2. This illustrates the expected types of formations at Juniper Bay. The stratigraphic work done to date identified the Black Creek Confining Unit (BCCU) at a depth of 6–10 m throughout the bay area. The BCCU is the fine-textured material underlying Juniper Bay. It restricts the water movement and can be considered an effective bottom of the system of interest. The overlying strata consist of discontinuous clay layers with unconfined and partially confined sands. Core work done to date suggests that there are typically one or two confined sand layers above the Black Creek Confining Unit. The property boundary was approximated by the perimeter ditch. The study area extends some distance outside the ditch, which was needed to assess interactions across the property/ditch boundary.

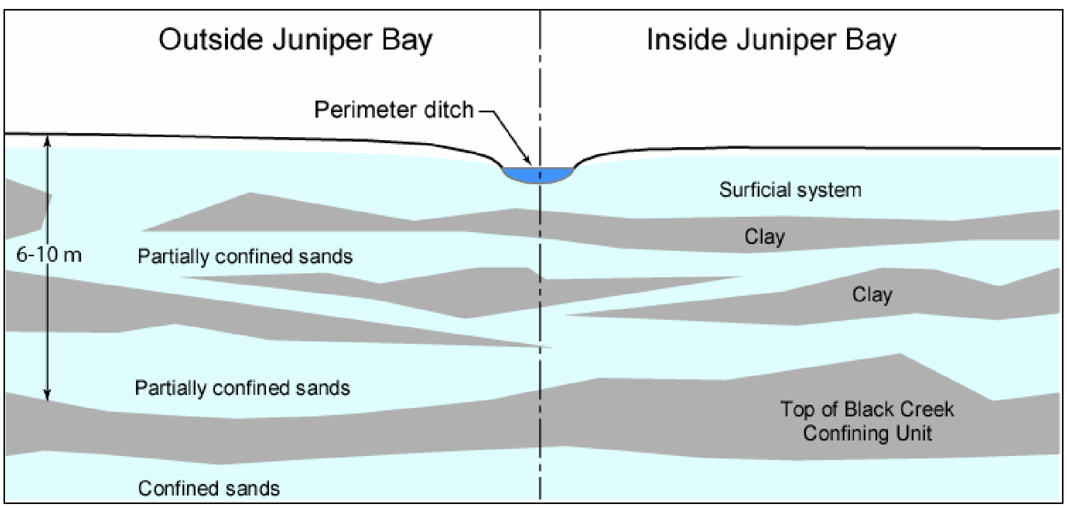

Figure 1.2: Conceptualization of stratigraphy at Juniper Bay

The perimeter ditch encircles the entire bay. It may have a significant influence on the hydrology of the bay. It could influence the flows in the surficial aquifer and intercept shallow flows between the interior and exterior of the bay. It can effectively drain approximately 30 m to either side. Lateral flows in the confined or partially confined sands may or may not be affected by the perimeter ditch. Determining its depth of influence is one of the main objectives of the project. This study will investigate whether the ditch could be eliminated, which could increase the converted wetland area by about 20 hectares.

To estimate the lateral ground water flows entering and leaving the bay, a groundwater potential monitoring system with good resolution was needed. Knowledge of the hydraulic heads across the perimeter section, along with hydraulic conductivities of the strata, would permit assessment of the impacts of the bay's drainage system on the surrounding area. Knowledge of the function of the perimeter ditch would provide a basis for recommendations on ditch management.

Groundwater modeling will be used in analyzing the subsurface flows for the collected data, and also applying extreme conditions for suggesting recommendations for future perimeter ditch management. The following chapters will discuss how these objectives are achieved, including data collection, modeling efforts and presentation of results and analysis.

Chapter 2

Literature Review

2.1 Carolina Bays

Juniper Bay is one of the typical isolated wetlands called Carolina Bays. Carolina Bays are oval shaped wet depressions with a northwest-southeast orientation (Howard, 1997). They are spread throughout the eastern Coastal Plain of the United States from Delaware to Florida. Figure 2.1.1 shows an Aerial photo, from 1903, of cluster of Carolina Bays near Myrtle Beach, South Carolina. Some are filled with water and named as lakes. These Bays are estimated to be at least 40,000 years old at deeper soils (2.3m) and atleast 5,750 years at shallow depths (1.05m). They have northwest to southeast orientation and they vary in size from few hundred feet to three of four miles in longest diameter. Many are bordered by rim of sands. Many of them are in a vegetative wetland state. There are several theories explaining their origin. Most important of them are which explain the origin from meteorites and wind action.

Origination of Carolina Bays

Johnson (1936) suggested that shape and orientation, as well as presence of sandy rims can be attributed to wind and wave action and depressions are attributed to the artesian process. Prouty (1952) attributed the origin of the Bays to the influence of comet or asteroidal body entering the earth atmosphere at an oblique angle from a relatively northwesterly direction. Thom (1970) explained the origin with the Humate that allows for a perched water table near the surface that would eventually evolve into shallow, wet depressions, orientated later by wind and wave action. Eyton & Parkhurst (1975) considered the theory stated by Prouty (1952) and then they stated finally that comets are the cause for the creation of Carolina Bays. Kaczorowski (1977) ruled out the extraterrestrial theory as a cause for Bay formation and supported Thom water table perching theory. He suggested that the only requirement for Bay existence is poor drainage leading to ponding mechanisms.

Figure 2.1.1: Arial Photo of Carolina Bays covering around five hundred middle near Myrtle Beach in Horry County, South Carolina.

Hydrology of Carolina bays

The hydroperiods of Carolina Bays range from permanently flooded to seasonally saturated. Due to the topographic gradient in bays, there is a soil drainage class gradient from excessively drained on the higher portions of the sand rims to poorly drained or very poorly drained in the lowest elevation portions. Most of the bays are jurisdictional wetlands. Some bays have surface runoff outlets, but the majority likely does not, some have dispersed overland flows as outlets and the others have stream channels.

According to the theories of different hydrologists, the hydrology of Carolina Bays is influenced by the inputs from the subsurface flows and by the underlying fine-textured sediments, which restrict the vertical movement of water. Sharitz and Gibbons (1982) showed that the hydroperiods were dominated by rainfall inputs and evaporation outputs. Knight et al. (1989), Newman and Schalles (1990), Lide et al. (1995), and O'ney et al. (1999) have studied the complex hydrology of Carolina Bays and have shown the complex subsurface interactions with the surrounding area. Their studies also indicated there was local depressional hydrology superimposed on the regional subsurface hydraulic gradients of the landscape in which the bay occurred. There was local depressional hydrology superimposed on the regional subsurface hydraulic gradients of the landscape in which the bay occurred. Lide etal. (1995) and O'ney et al. (1999) found that the topography of the subsurface was similar to the surface topography. Hydraulic gradient into the bay resulted in subsurface flows along sandy layers overlying fine-textured layers. Gradients are into the bay in the wet season. Lide et al. (1995) concluded that there is significant groundwater recharge in the dry periods of late spring/early summer at Thunder Bay, SC. Chapel bay was studied by O'ney et al. (1991), which provided some recharge, but drying was dominated by ET losses. Schalles et al. (1989) suggested that chemistry of water and soils in clay-based Carolina bays indicate a rainwater-dominated system characteristic of perched water settings. Landscape position, water table fluctuations, and impervious layers interact to produce differences in individual bay hydrology and response to rainwater. Bays are likely both recharge and discharge depending on bay water levels in relation to the regional water table (Schalles, 1979).

2.2 Juniper Bay

Juniper Bay is located in Robeson County, North Carolina. As a typical characteristic of Carolina bay, Juniper bay is elliptical in shape. Initially a wetland, Juniper Bay was drained for industrial purposes in the early 1960s and it was intensively drained for agricultural purposes in the late 1970s. As of 2000, it had about 270 ha of drained and intensively managed agricultural land that is not jurisdictional wetland due to its status as prior converted agricultural land.

Zanner (2003) concluded that Juniper Bay is formed in 5-8 m of Pliocene aged Duplin-Yorktown Formation sediments that are underlain by Cretaceous aged Donoho Creek and Bladen Formation of the Black Creek Group. Subsurface sediment topography is observed to be irregular with the newer sediment filling in erosional channels as it was deposited. Luginbuhl (2003) studied the groundwater hydrology at Juniper bay prior to restoration and her study suggested that groundwater flows may be entering from the northwest and southeast boundaries and leaving from the northeast and southwest boundaries. Kreiser (2003) studied water budget at Juniper bay and reported that there are significant amount of groundwater flows coming into the site. He estimated groundwater flows were in the range of 171 mm to 563 mm, though the estimates are very uncertain because of uncertainty in estimating evapotranspiration. Ewing (2003) studied the subsidence at Juniper bay from the time it was not drained and estimated that the soil surface is lowered about 1 m than it was before drained. These studies suggested that there were significant groundwater flows entering into the site. If the subsidence is taken into account with these groundwater inflows there is a possibility of formation of lake instead of a wetland.

2.3 Modeling

Groundwater models were approached typically for two main reasons (Fetter, 2001), 1) to understand why a flow system is behaving in a particular observed manner, and 2) to predict how a flow system will behave in the future. Initially analytical models were used for groundwater modeling and then numerical models were introduced. MODFLOW (McDonald and Harbaraugh, 1984) is one of the numerical models that use finite difference technique to solve the governing flow equation.

It was developed by USGS in 1998 and then updated with a new version in 2000. It was integrated with surface unsaturated flow models and developed MODFLOW-SURFACT by HydrGeoLogic Inc., in 2002. MODFLOW is widely used software for groundwater fate and transport modeling. It can be used for both two dimensional and three dimensional groundwater flow modeling.

McDonald and Harbaraugh (2000) explained concepts of groundwater flow concepts in MODFLOW. The partial-differential equation of groundwater flow used in MODFLOW is given in Equation 2.3.1. MODFLOW uses finite-difference method to solve this equation.

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)+W=S_s\frac{\partial h}{\partial t} \qquad (2.3.1)$$

K_{xx}, K_{yy}, and K_{zz} - Values of hydraulic conductivities along the x, y, and z coordinate axes (L/T)

h - Potentiometric head (L)

W - Volumetric flux per unit volume representing sources and/or sinks of water, with W<0.0 for flow out of the groundwater system, and W>0.0 for flow in (T^{-1})

S_s - Specific storage of the porous media material (L^{-1})

t - Time (T)

Sonenshein (2001) studied methods to quantify seepage beneath Levee 30, Miami-Dade County, Florida. His study used a 2-D finite difference groundwater model and simple application of Darcy’s Law to quantify these flows. Accuracy in estimating groundwater flows was less due to uncertainty in the horizontal conductivity in the main flow zone of the Biscayne aquifer. Simulated lateral groundwater flows were highest in the wet seasons.

Moreno et. al., (2003) compared the decision tree approach and automated parameter estimation approach to calibrate groundwater flow model. Their study concluded that the combination approach of trial and error calibration and automated parameter estimation would be ideal approach for calibration groundwater flow models.

Andre (2005) researched on using geochemical data and modeling to enhance understanding the groundwater flow in a regional deep aquifer, aquifer basin, south-west of France. They concluded that geochemical data can be used to identify deep groundwater flow patterns when geology and hydrogeology data is scarce to provide sufficient information.

Karahan (2005) proposed a transient groundwater modeling using spreadsheet. His study suggested that spreadsheet modeling for simple groundwater scenarios is in good agreement with MODFLOW results of hydraulic heads.

Chapter 3

Characterizing Subsurface flows

This chapter discusses methodology to accomplish the first objective, characterizing subsurface flows at the perimeter of Juniper Bay. It details the procedure followed in establishing transects, collecting cores and analyzing them for determining depths for the installation of piezometers. This chapter also explains development and deployment of water level monitoring systems at each piezometer nest. Furthermore, it presents preliminary analyses of water level data collected at each transect, focused on lateral and vertical fluxes along with influence of perimeter ditch.

3.1 Establishing Transects

From the topographic information shown in Figure 3.1.1, one can observe that the elevations to the northwest (NW) and southeast (SE) are higher than the elevations to the southwest (SW) and northeast (NE). A study of groundwater flows by Luginbuhl (2003) also suggests higher elevations on the SW and NE. The variation in the surface elevations at the interior of the bay is small, approximately 0.6 m over 2400 m, in comparison to the exterior of the bay which is approximately 1 m from NE transect to SE transect. At NW and SE transects the differences in surface elevation from interior 75 m to exterior 75 m of the bay are approximately 1m, exterior being on the higher elevation. Going further out to the NW and SE, the land surface rises even more, which suggests that subsurface flows might be entering through the major axis sides and leaving through the minor axis sides as shown in Figure 3.1.1. Thus four coring transects were selected on the perimeter of the bay at the intersection of the perimeter ditch with the major and minor axes. The four transects are designated as Northwest (NW), Southwest (SW), Southeast (SE), and Northeast (NE), as shown in Figure 3.2.1.

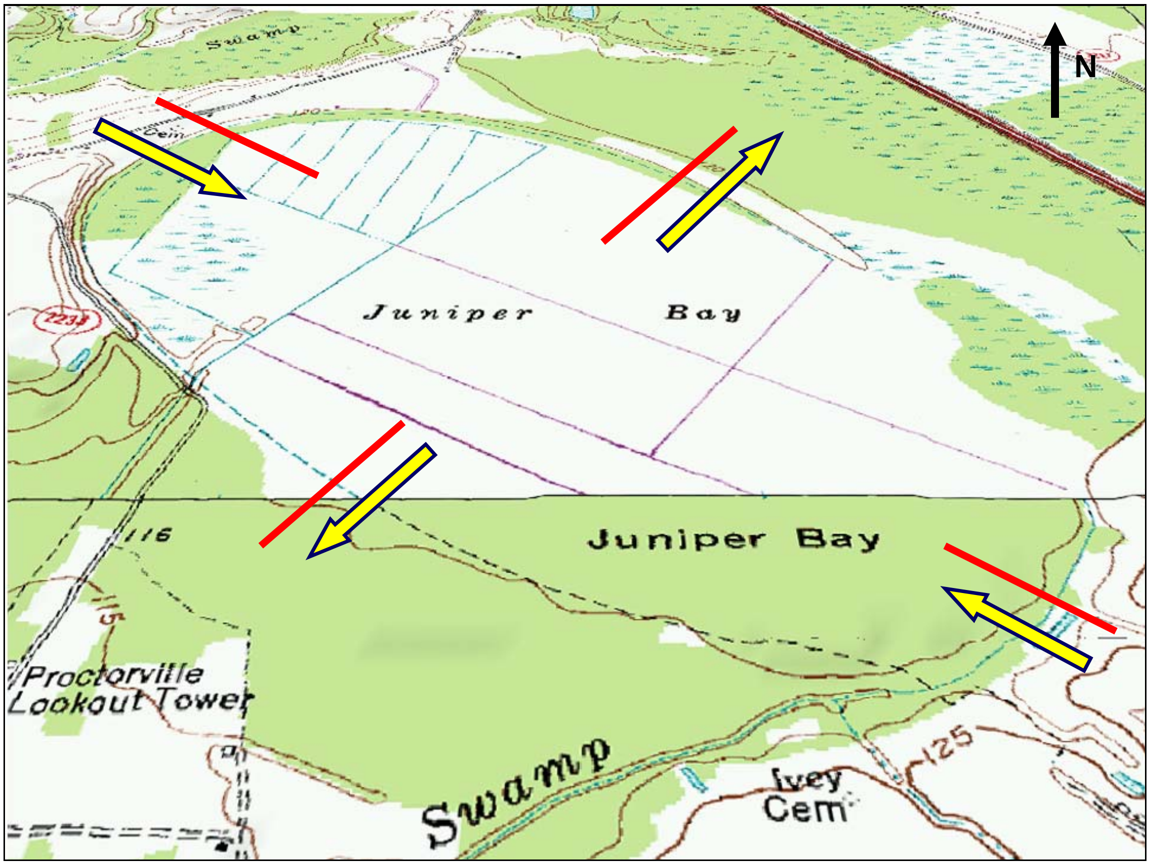

Figure 3.1.1: Elevation map of Juniper Bay (8x vertical exaggeration). Arrows indicate the proposed direction of subsurface flux.

3.2 Soil Coring

At each transect, sediment cores were collected at five different points on each transect as shown in Figure 4b. Three sediment cores were collected at the interior of the bay at 5, 25, and 75 m from the center of the ditch. Similarly, two sediment cores were collected at the exterior of the bay at 25 and 75 m from the center of the ditch. The drill rig from the Department of Biological & Agricultural Engineering, North Carolina State University, was used for the coring. Cores were collected using a 102-mm OD, 1.52-m long core barrel inside 108-mm ID hollow stem auger. Plastic (cellulose acetate butyrate) liners, 1.52 m x 87.8 mm OD x 0.79 mm wall thickness, facilitated handling and storage of the cores. Cores were collected at each location to depths of approximately 8 to 11 m, usually down to and penetrating the top of the Black Creek Confining Unit as shown in the Figure 3.2.2. Coring through the Black Creek Confining Unit was very difficult at most of the core locations.

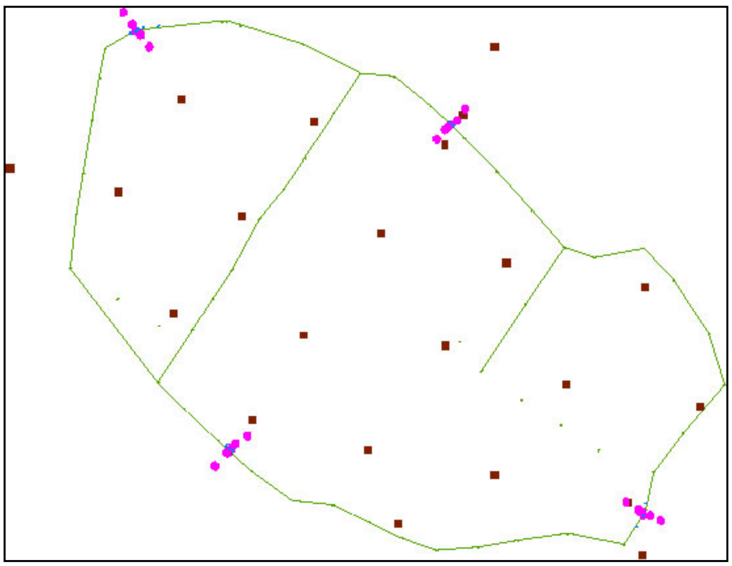

Figure 3.2.1: Schematic locations of each transect. Purple dots represent the location of piezometer nests. Brown squares represent location of preliminary cores collected for the initial project. Green lines represent the perimeter ditch and main canals.

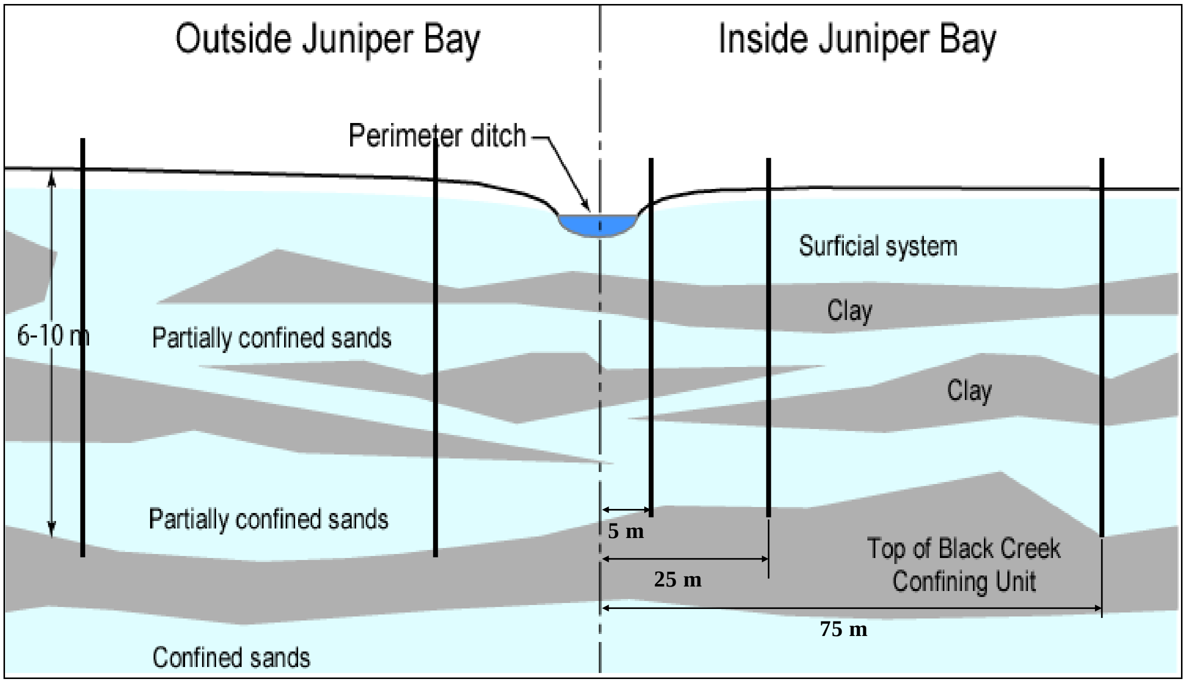

Figure 3.2.2: Core Locations on each transect

3.3 Soil Profiling

Soil cores were characterized in the laboratory. Figures 3.3.1, 3.3.2, 3.3.3, and 3.3.4 show the stratigraphy at the NW, NE, SE, and SW transects, respectively. Figure 3.3.5 gives the legend for description of soil profiles. Colors represent the texture of the sediments at each depth. Darker colors represent fine-textured sediments, like clayey material, and light colors represent coarse-textured sediments, like sandy material. The white sections indicate no recovery of sample. Those sections are assumed to be non-cohesive sands. Significant difference in layers could be observed which helped in the identifying sand layers that are the main water conducting layers. Horizontal distances in the Figures (3.3.1, 3.3.2, 3.3.3, and 3.3.4) are not to scale, but vertical distances are to scale. For the labels, EX represents exterior of the bay and IN represents interior of the bay, while 05, 25, 50, and 75 are the corresponding distances (in meters) of the core locations from the perimeter ditch. A survey was conducted to obtain the ground elevation at each of the core locations and perimeter ditch elevation and dimensions. Ground surface elevations in meters, obtained from survey, are presented in the Figures 3.3.1 to 3.3.4.

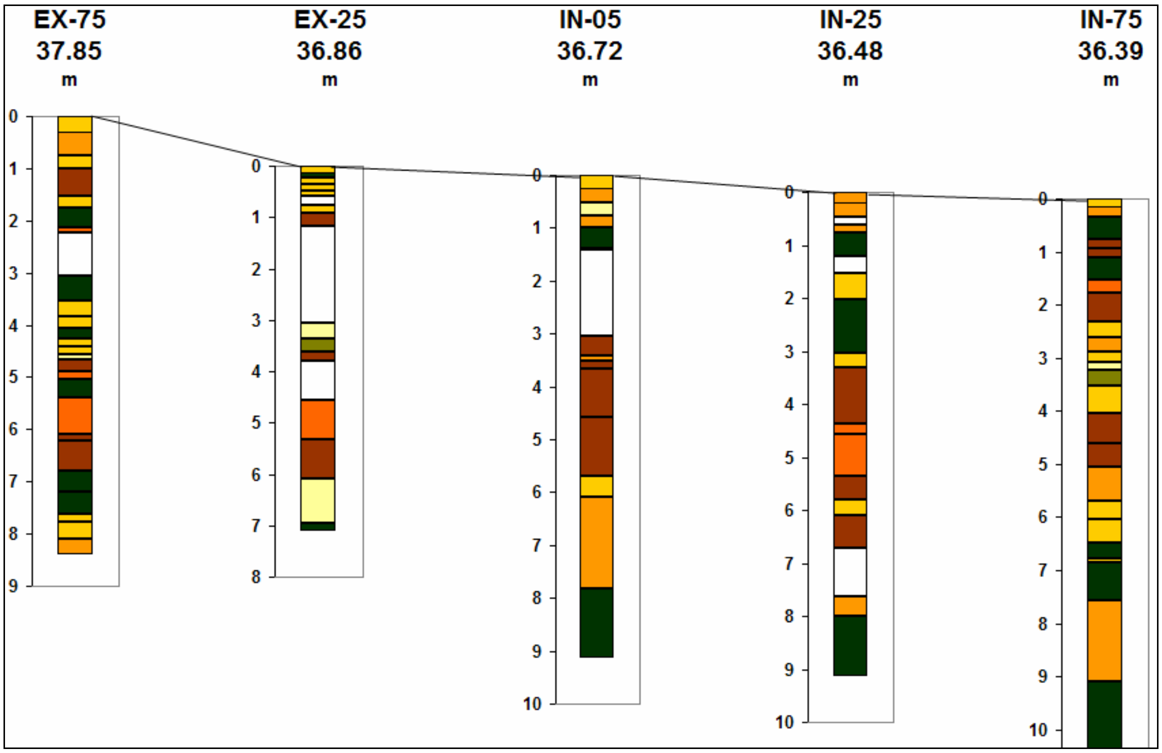

Figure 3.3.1: Soil profiles at NW transect, legend is given in Figure 3.3.5

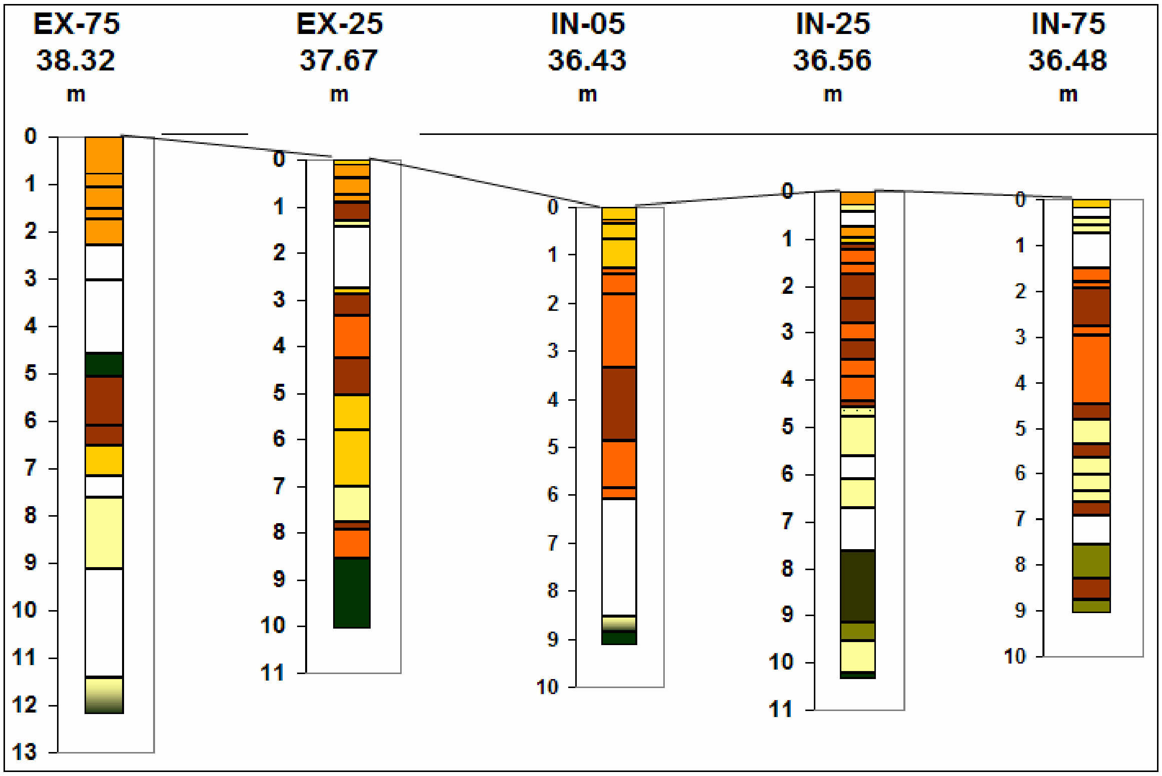

Figure 3.3.2: Soil profiles at NE transect, legend is given in Figure 3.3.5

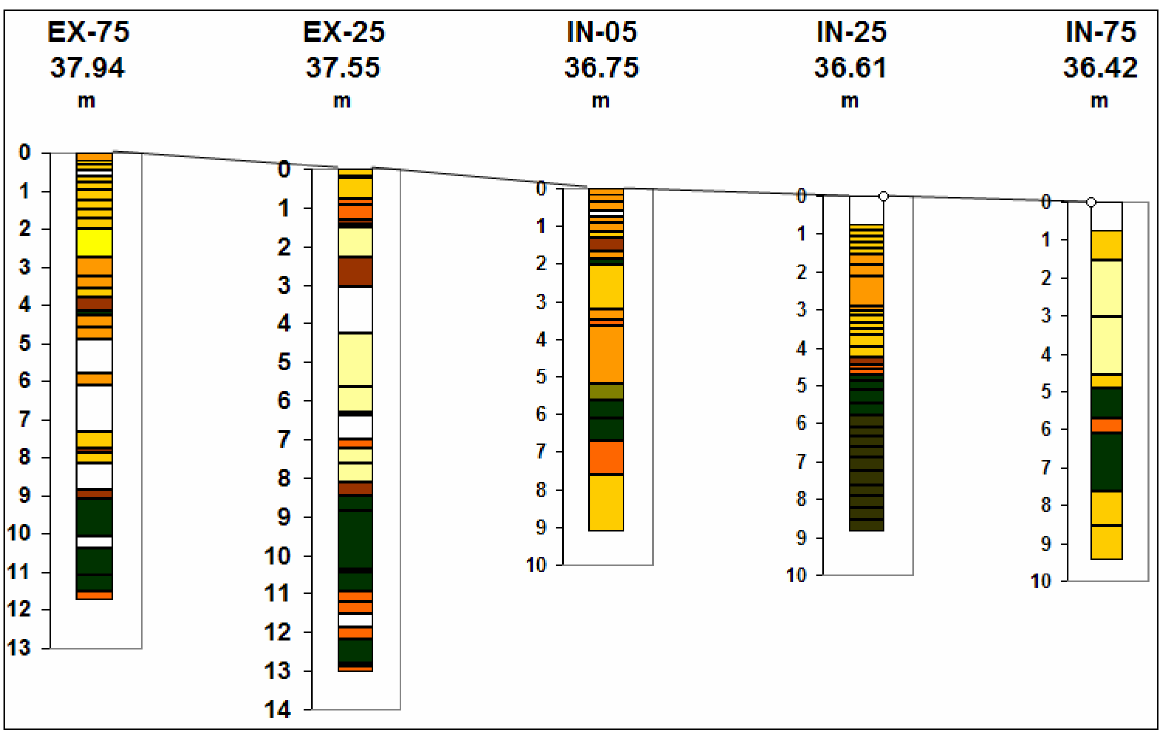

Figure 3.3.3: Soil profiles at SE Transect, legend is given in Figure 3.3.5

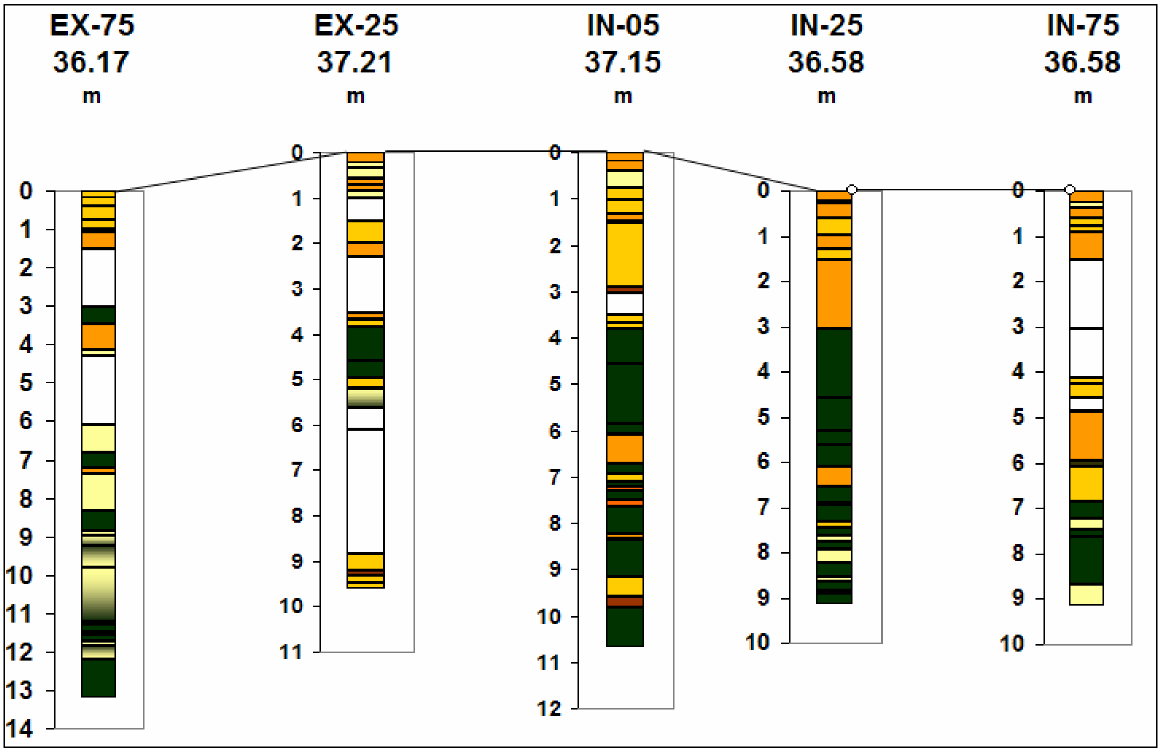

Figure 3.3.4: Soil Profiles at SW Transect, legend is given in Figure 3.3.5

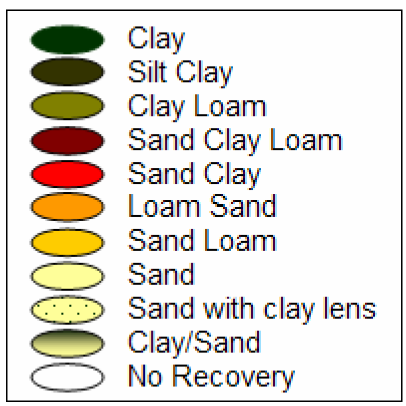

Figure 3.3.5: Legend for Figures 3.3.1-4

The NW transect (Figure 3.3.1) had three distinguishable sand and coarse textured layers. The top layer is considered to be surface layer to the depth of 2-4 m, and the deeper sandy layers were observed at the depths of 5-6 m and 8-10 m. Similarly, at the NE transect (Figure 3.3.2) deeper sandy layers were at the depths of 5-7 m and 7-9 m, varying with core locations. The SE transect had surficial sands to a depth of 3-5 m, and the deeper sands were found at the depths of 6-7 m and 8-10 m. The SW transect showed the surface layer to the depth of 3-4 m. Deeper sand layers were found at the depths of 6-7 m and 8-9 m. The clay layers were discontinuous at all transects. This stratigraphy agrees with the conceptual model of the subsurface.

3.4 Saturated Hydraulic Conductivity Tests

Samples from each significant stratum of the cores were inserted into 76 mm x 76 mm sleeves. Saturated hydraulic conductivity tests were conducted in the laboratory using a constant-head apparatus. To prepare the cores to run for saturated hydraulic conductivity (K_{sat}) tests, cores were saturated in water for 24 hours before setting up for test. The saturated soil core was placed on a permeable base, wire mesh, inside a Buchner funnel. Water from the constant head reservoir was allowed to flow through the sample and the outflow from the bottom of the core was collected and measured using a graduated cylinder, which has a measurement resolution of 1mL. Flow measurements were taken at intervals of 4 hours. Measurements were taken until constant flow was reached in two consecutive measurements. A schematic of the apparatus is shown in Figure 3.4.1. This flow rate was used to estimate K_{sat} of each core sample. K_{sat} was estimate using Darcy's Law (Equation 3.4.1).

$$K_{sat} = \frac{QL}{At\Delta H} \qquad (3.4.1)$$

K_{sat} – Saturated Hydraulic Conductivity
Q – Volume of the outflow during the time period t
A – Cross-sectional area of core
ΔH – Hydraulic head difference between the top and bottom of the core of length L

Table 3.4.1 gives the saturated conductivity values at different depths for the NW-EX-75 core location. Appendix A gives all other tables corresponding to the different core locations.

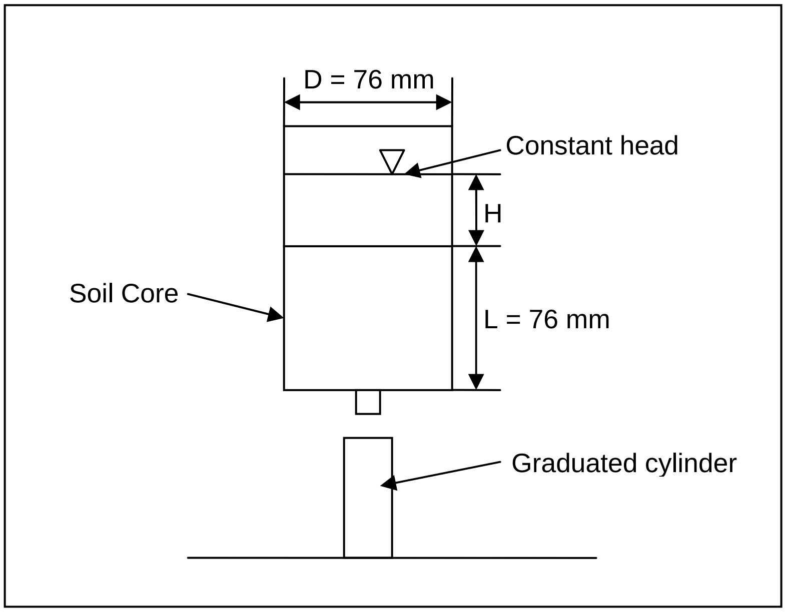

Figure 3.4.1: Schematic of K_{sat} Apparatus

Table 3.4.1: Example of K_{sat} table describing soil core color, texture and saturated sydraulic conductivity at NW-EX-75 core location

Location	Depth (ft)	Color	Texture	time (min)	Vol (ml)	Q (ml/min)	H (cm)	K (m/sec)
NW-EX-75	0 - 1	10YR3/2	SL	2	7	3.5	6	5.67E-06
NW-EX-75	1 - 2.5	2.5Y5/3	LS					
NW-EX-75	2.5 - 3.33	10YR3/1	SL				5.8	
NW-EX-75	3.33 - 5	10YR3/1 + 10YR5/1	SCL	7	5	0.72	5.6	1.11E-06
NW-EX-75				4	8	2	6	3.24E-06
NW-EX-75	5 - 5.75	2.5Y6/1	SL	0.5	5	10	5.5	1.54E-05
NW-EX-75	5.75 - 7	2.5Y7/1	C				5	
NW-EX-75	7 - 7.33	2.5Y5/2	SCL				5.5	
NW-EX-75	7.33 - 10							
NW-EX-75	10 - 11.583	2.5Y6/2	C				5.5	
NW-EX-75	11.583 - 12.583	2.5Y7/1 + 7.5YR6/8 concentration	SL	10	2	0.2	5.8	3.18E-07
NW-EX-75	12.583 - 13.33	2.5Y8/1	SL				5.8	
NW-EX-75	13.33 - 14	2.5Y7/1	C					
NW-EX-75	14 - 14.5	2.5Y8/1	SL				5.9	
NW-EX-75	14.5 - 15.0							
NW-EX-75	15.0 - 15.33	10YR7/1	S	1	5	5	5.2	7.46E-06
NW-EX-75	15.33 - 16.0	10YR5/8	SCL	0.167	100	598.8	4.7	0.00084
NW-EX-75	16.0 - 16.5	10YR6/2	SC	0.167	100	598.8	6.1	0.000979
NW-EX-75	16.5 - 17.66	4N	C				6	
NW-EX-75	17.66 - 20.0	3N	SC				5.9	
NW-EX-75	20.0 - 20.416	2.5Y3/1	SCL	0.267	70	262.1	5	0.000382
NW-EX-75	20.416 - 22.33	3N	SCL	2	5	2.5	6.2	4.12E-06
NW-EX-75	22.33 - 23.583	4N	C	1	6	6	5.7	9.44E-06
NW-EX-75	23.583 - 25.0	3N	C	1.5	6	4	5.5	6.17E-06
NW-EX-75	25.0 - 25.5	3.5GY	SL	0.2	50	250	4.8	0.000355
NW-EX-75	25.5 - 26.583	5.5GY	SL/C				5.9	
NW-EX-75	26.583 - 27.583	10YR4/1	LS				6	

3.5 Installation of Piezometers

Significant sand strata were identified at each location from the core descriptions and respective K_{sat} values. Piezometers were installed to the depths of significant sand layers at each location. Depending on the number of sand layers, two to four piezometers were installed in each piezometer nest to monitor hydraulic heads in the main sand strata. Table 3.5.1 gives the depths of significant sand layers at each core location, which corresponds to the depths of the piezometers installed at that location.

Piezometers were installed using 108-mm ID hollow stem augers. The 5-cm PVC screens and casings were assembled inside the auger once the desired depth was reached. The auger was filled with water and a wooden end plug was knocked out. Coarse sand was added to form a filter pack around the screen. A grout pump and a tremie pipe were used to inject a bentonite slurry grout into the borehole as the hollow stem auger was retracted.

Table 3.5.1: Screened depths of the piezometers

Transect	Piez. Nest	No. Piez.	Screened depths of piezometers (m)			
SE	SE-IN-75	3	3.7-4.3	5.8-7.9	8.1-10.2	
	SE-IN-25	3	3.0-3.7	4.3-4.9	8.5-9.1	
	SE-IN-5	2	2.1-3.4	7.6-9.1		
	SE-EX-25	3	5.5-6.1	7.6-8.2	10.7-12.2	
	SE-EX-75	4	3.0-3.7	4.6-5.2	6.7-8.2	9.4-11.0
SW	SW-IN-75	2	3.0-3.7	4.6-5.2		
	SW-IN-25	3	2.4-3.0	4.6-5.2	6.1-6.7	
	SW-IN-5	2	3.0-3.7	6.1-7.6		
	SW-EX-25	3	3.0-3.7	4.9-5.5	8.8-9.4	
	SW-EX-75	3	3.0-3.7	4.6-5.2	6.7-8.2	
NE	NE-IN-75	3	4.6-5.2	6.1-7.6	9.1-10.7	
	NE-IN-25	3	3.0-3.7	4.9-5.5	6.1-7.6	
	NE-IN-5	3	3.0-3.7	4.6-5.2	6.1-7.6	
	NE-EX-25	2	1.5-2.7	5.5-7.0		
	NE-EX-75	3	3.7-4.3	6.7-7.3	9.1-10.7	
NW	NW-IN-75	3	4.6-6.1	2.6-3.2	7.6-9.1	
	NW-IN-25	3	6.1-7.6	3.0-3.7	4.9-6.1	
	NW-IN-5	2	2.4-3.0	6.1-7.6		
	NW-EX-25	3	2.4-3.0	4.0-4.6	6.1-6.7	
	NW-EX-75	3	2.4-3.0	4.3-4.9	7.6-9.1	

3.6 Water Level Monitoring System

A water level sensing system was installed at each piezometer nest. Water level sensors were also installed in the perimeter ditch at each transect. This arrangement gives head data over a vertical cross-section that is 5-12 m deep and 150 m wide, centered on the perimeter ditch.

The water level monitoring systems use a pulsed gas bubbler system (Huffman et al., 1989). At each nest is a weatherproof enclosure containing a datalogger/controller unit (Onset Computer TFX11-v2), miniature air pump (Sensidyne 3A120CNSNF30PC1), solenoid valves (ASCO AL2112 & AL2312), pressure transducer (SenSym ASCX05DM), and a 7 amp-hour, 12V battery. A 2-watt solar panel kept the battery charged. Plastic 0.8-mm ID tubes connected the solenoid valves to each piezometer, where the open ends of the tubes are suspended at a depth of 2.74 m below the local average ground surface. Figure 3.6.1 shows a system with a nest of piezometers. The open ends of the air tubes within a nest are at the same elevation. The depth of 2.74 m was chosen because the preliminary data suggested the water levels would not go below that even in a drought period. Pressure transducers having a 35 kPa (5 psi) range, differential, were selected to accommodate the maximum likely variation in water levels, with a safety margin. Air vents in the caps of the piezometers allow the purging air pumped into the piezometers to escape. Use of a single, high quality pressure transducer at each nest makes all readings for the nest directly comparable. Piezometer elevations were determined by survey with a total station, using NCDOT markers (vertical accuracy approximately 0.03 m) as references. Vertical accuracy within a transect was about 5 mm. The ground surface elevations at each piezometer nest were calculated from the piezometer elevations and the relative heights of the piezometers in a nest as measured while installing the instrumentation.

Figure 3.6.1: Water level monitoring system

The monitoring units are programmed to take readings every 15 minutes. Figure 3.6.2 gives the schematic diagram of a monitoring unit. Switching transistors were used with each control line to switch the 12V supply to the air pump and solenoid valves. Figure 3.6.3 shows the inside of a weatherproof enclosure with the components in it. This monitoring system has a resolution of approximately 1 mm of water depth. The datalogger module has 2 MB of non-volatile memory.

At each sampling interval, air is pumped for several seconds into each piezometer in sequence to purge the tubes. After allowing a few seconds for equilibration, the pressure is read from each tube in sequence. Multiple pressure readings from each port are averaged and then stored in memory. The stored data were downloaded about every two weeks.

The monitoring units were calibrated before installing them in the field. A 3-m water column was set up in the lab and air tubes were suspended at depths of 600 mm, 1600 mm, and 2600 mm. Water was filled to a height of 2600 mm in the column. Using readings from each of the three depths and atmospheric pressure (as zero), calibration curves were developed for each of the units.

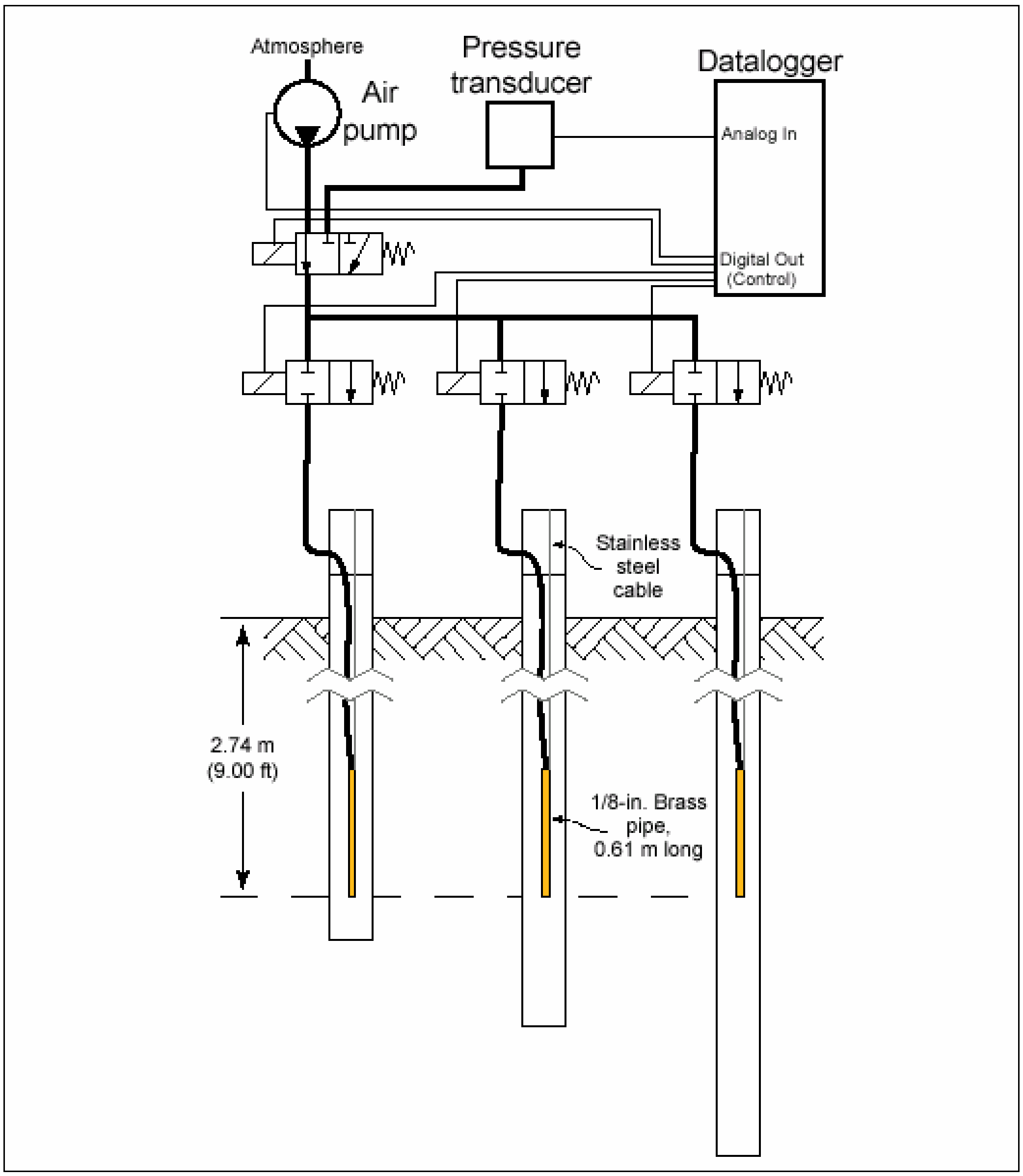

Figure 3.6.2: Schematic diagram of a monitoring unit assembly.

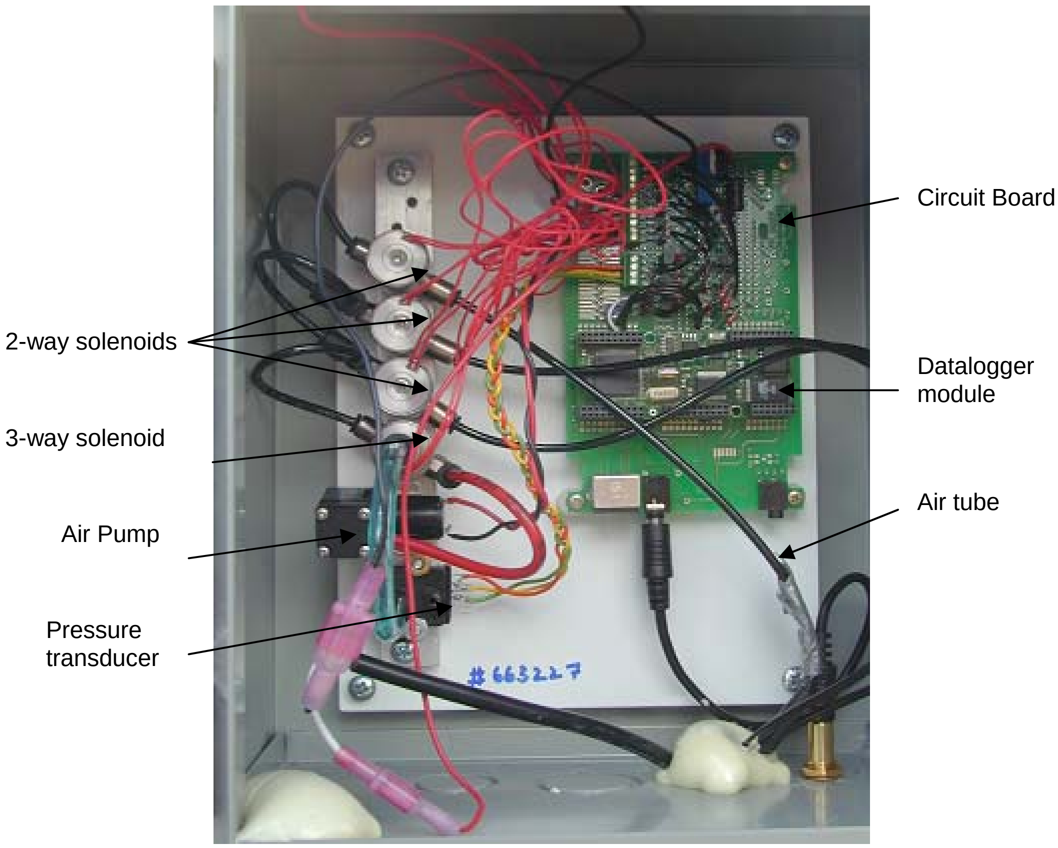

Figure 3.6.3: Monitoring unit in its enclosure.

3.7 In-situ Hydraulic Conductivity Tests

Slug tests were conducted to estimate in-situ hydraulic conductivity. The Hvorslev (1951) method was used for field tests to estimate K_{sat}. The piezometers that were installed to monitor heads were used for the slug tests. Water level in the well was raised by lowering the slug, a cylindrical mass, into the well and submerging it below the original water surface. The water level in the well was measured prior to the time the slug was lowered and also immediately after the slug was lowered. A level logger was dropped with the slug to measure the water level with time during the process of water falling back to the static water level. Data from the level logger was uploaded into a computer and used to estimate K_{sat} values using Equation 3.7.1.

$$K = \frac{r^2 \ln(L_e/R)}{2 L_e t_{37}} \qquad (3.7.1)$$

K – Hydraulic conductivity (cm/s)

r – radius of the wall casing (cm)

R – radius of the well screen (cm)

L_e – length of the well screen (cm)

t_{37} – time it takes for the water level to rise or fall for 37% of the initial change

Table 3.7.1: K_{sat} values from slug tests

	r (cm)	R(cm)	Le(cm)	ln(L/R)	t37(sec)	K(cm/sec)	K(cm/h)	K(m/sec)
Northeast								
NE-IN-5-D	2.5	5	152.4	3.417071	57	0.001229	4.42534	1.2E-05
NE-IN-5-M	2.5	5	61	2.501436	41	0.003126	11.252	3.1E-05
NE-IN-5-S	2.5	5	61	2.501436				
NE-IN-25-D	2.5	5	152.4	3.417071				
NE-IN-25-M	2.5	5	61	2.501436	70	0.001831	6.59043	1.8E-05
NE-IN-25-S	2.5	5	61	2.501436				
NE-IN-75-D	2.5	5	152.4	3.417071	9	0.007785	28.0272	7.8E-05
NE-IN-75-M	2.5	5	152.4	3.417071	58	0.001208	4.34904	1.2E-05
NE-IN-75-S	2.5	5	61	2.501436	24	0.005339	19.2221	5.3E-05
NE-EX-25-D	2.5	5	152.4	3.417071				
NE-EX-25-S	2.5	5	122	3.194583	97	0.000844	3.03693	8.4E-06
NE-EX-75-D	2.5	5	152.4	3.417071	233	0.000301	1.08259	3E-06
NE-EX-75-M	2.5	5	61	2.501436	267	0.00048	1.72783	4.8E-06
NE-EX-75-S	2.5	5	61	2.501436				
Northwest								
NW-IN-5-D	2.5	5	152.4	3.417071	72	0.000973	3.50339	9.7E-06
NW-IN-5-S	2.5	5	61	2.501436				
NW-IN-25-D	2.5	5	152.4	3.417071	260	0.000269	0.97017	2.7E-06
NW-IN-25-M	2.5	5	122	3.194583	113	0.000724	2.60692	7.2E-06
NW-IN-25-S	2.5	5	61	2.501436	230	0.000557	2.00578	5.6E-06
NW-IN-75-D	2.5	5	152.4	3.417071				
NW-IN-75-M	2.5	5	152.4	3.417071	213	0.000329	1.18425	3.3E-06
NW-IN-75-S	2.5	5	61	2.501436	480	0.000267	0.96111	2.7E-06
NW-EX-25-D	2.5	5	61	2.501436	49	0.002615	9.41491	2.6E-05
NW-EX-25-M	2.5	5	61	2.501436				
NW-EX-25-S	2.5	5	61	2.501436				
NW-EX-75-D	2.5	5	152.4	3.417071	6	0.011678	42.0407	0.00012
NW-EX-75-M	2.5	5	61	2.501436				
NW-EX-75-S	2.5	5	61	2.501436	600	0.000214	0.76888	2.1E-06

Table 3.3 (continuation): K_{sat} values from slug tests

Southwest								
SW-IN-5-D	2.5	5	152.4	3.417071	210	0.000334	1.20116	3.3E-06
SW-IN-5-S	2.5	5	61	2.501436				
SW-IN-25-D	2.5	5	61	2.501436	530	0.000242	0.87043	2.4E-06
SW-IN-25-M	2.5	5	61	2.501436				
SW-IN-25-S	2.5	5	61	2.501436				
SW-IN-75-D	2.5	5	61	2.501436	374	0.000343	1.2335	3.4E-06
SW-IN-75-S	2.5	5	61	2.501436				
SW-EX-25-D	2.5	5	61	2.501436	680	0.000188	0.67843	1.9E-06
SW-EX-25-M	2.5	5	61	2.501436	67	0.001913	6.88553	1.9E-05
SW-EX-25-S	2.5	5	61	2.501436				
SW-EX-75-D	2.5	5	152.4	3.417071				
SW-EX-75-M	2.5	5	61	2.501436	687	0.000187	0.67151	1.9E-06
SW-EX-75-S	2.5	5	61	2.501436	101	0.001269	4.56763	1.3E-05
Southeast								
SE-IN-5-D	2.5	5	152.4	3.417071				
SE-IN-5-S	2.5	5	122	3.194583	176	0.000465	1.67376	4.6E-06
SE-IN-25-D	2.5	5	61	2.501436	46	0.002786	10.0289	2.8E-05
SE-IN-25-M	2.5	5	61	2.501436	74	0.001732	6.23419	1.7E-05
SE-IN-25-S	2.5	5	61	2.501436				
SE-IN-75-D	2.5	5	61	2.501436	26	0.004929	17.7435	4.9E-05
SE-IN-75-S	2.5	5	61	2.501436	246	0.000521	1.87533	5.2E-06
SE-EX-25-D	2.5	5	61	2.501436	165	0.000777	2.79594	7.8E-06
SE-EX-25-M	2.5	5	61	2.501436	153	0.000838	3.01523	8.4E-06
SE-EX-25-S	2.5	5	61	2.501436	33	0.003883	13.9797	3.9E-05
SE-EX-75-D	2.5	5	152.4	3.417071				
SE-EX-75-MD	2.5	5	61	2.501436	91	0.001408	5.06956	1.4E-05
SE-EX-75-MS	2.5	5	61	2.501436	152	0.000843	3.03507	8.4E-06
SE-EX-75-S	2.5	5	61	2.501436	136	0.000942	3.39214	9.4E-06

At some of the piezometers the slug test could get the water back to the static water level position for a long time, which corresponds to the missing K values in the Table 3.7.1. These could be the piezometers which are installed in some fine textured layers or the well screen is clogged with soil material. Attempts to improve performance by surging were unsuccessful.

3.8 Data Collection

Water level data collection was started in December 2003. Collection was continued through the first quarter of 2005. A few problems arose with the performance of the monitoring systems. Trouble-shooting and repairs were conducted whenever necessary. Head data for the year 2004 are available for analysis, with a few gaps because of the unexpected problems with the monitoring modules. Preliminary data analysis was performed on the data for one point of time in April 2004. Figures 3.8.1, 3.8.2, 3.8.3, and 3.8.4 show the hydraulic heads at the NW, NE, SE, and SW transects, respectively. Figure 3.8.5 shows the legend for Figures 3.8.1, 3.8.2, 3.8.3, and 3.8.4. These head data were used in modeling the groundwater flows on each transect, which is discussed in detail in the chapter 4.

Water level depths collected from the monitoring units were converted to water level elevations using the survey data. This helped to see water levels relative to ground elevation. Head data for 4 April 2004 at the NW, NE, SE, and SW transects are presented in the Tables 3.4.1 to 3.4.4.

The head data for the NW transect, given in Table 3.8.1, shows the head gradients across the transect, which can be visualized in Figure 3.8.1. Flow in the surface layers indicate that the water drains into the perimeter ditch from both sides, because the head gradient was towards the perimeter ditch from both sides. In the middle sand layer the head gradient indicated flow from outside of the bay toward the inside, suggesting groundwater inflow, except for EX-25. But in the lower sands, the gradient suggests flow from the exterior to the interior of Juniper bay.

Table 3.8.1: NW transect water level data on 4 April 2004

4/1/2004	Shallow piezometer			Middle piezometer			Deep piezometer		
	Water Level depth m	Surface Elevation m MSL	Water Level Elevation m MSL	Water Level depth m	Surface Elevation m MSL	Water Level Elevation m MSL	Water Level depth m	Surface Elevation m MSL	Water Level Elevation m MSL
NW-EX-75	2.109	37.889	37.258	2.100	37.838	37.198	2.097	37.845	37.202
NW-EX-25	2.148	36.858	36.266	1.902	36.862	36.024	1.989	36.865	36.114
NW-IN-5	2.413	36.723	36.396				1.975	36.712	35.947
NW-IN-25	2.658	36.382	36.300	2.654	36.483	36.397	2.215	36.476	35.951
NW-IN-75	2.658	36.387	36.305	2.572	36.375	36.207	2.342	36.349	35.951

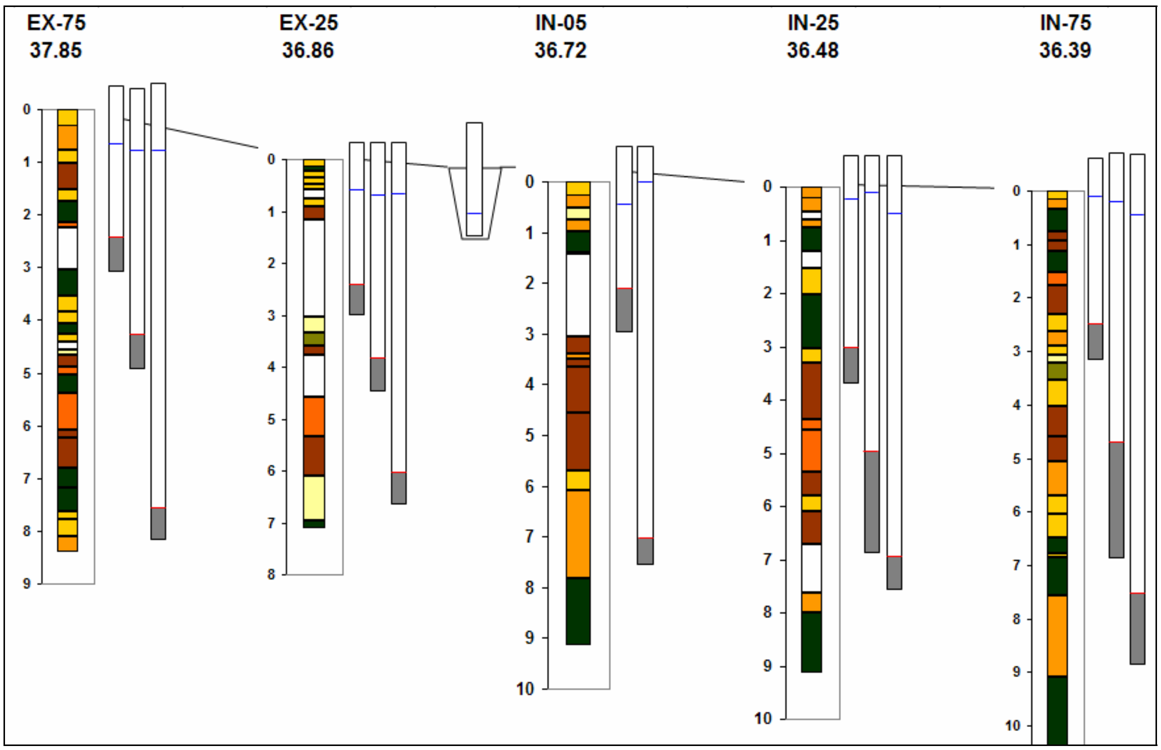

Figure 3.8.1: Hydraulic heads from the NW transect, 4 April 2004. Piezometers and water levels are shown at relative elevations. Cores at each nest are shown for reference.

Head data from the NE transect (Table 3.8.2) shows head gradients in the surface and middle sand layers suggesting water draining into the perimeter ditch. In the lower sand there was an indication of groundwater inflow. Figure 3.8.2 shows the same in graphical view relative to the ground elevation and soil profile.

Table 3.8.2: NE transect water level data on 4 April 2004

4/1/2004	Shallow piezometer			Middle piezometer			Deep piezometer		
	Water Level Depth m	Surface Elevation m MSL	Water Level Elevation m MSL	Water Level Depth m	Surface Elevation m MSL	Water Level Elevation m MSL	Water Level Depth m	Surface Elevation m MSL	Water Level Elevation m MSL
NE-EX-75	2.091	38.320	37.671	2.060	38.316	37.636	2.106	38.317	37.683
NE-EX-25	2.100	37.666	37.026				1.729	37.659	36.647
NE-IN-5	1.904	36.425	35.589	1.721	36.340	35.321	1.726	35.383	34.369
NE-IN-25	2.081	36.556	35.897	1.828	36.595	35.683	2.045	36.553	35.858
NE-IN-75	1.881	36.476	35.617	1.742	36.569	35.571	1.878	36.487	35.625

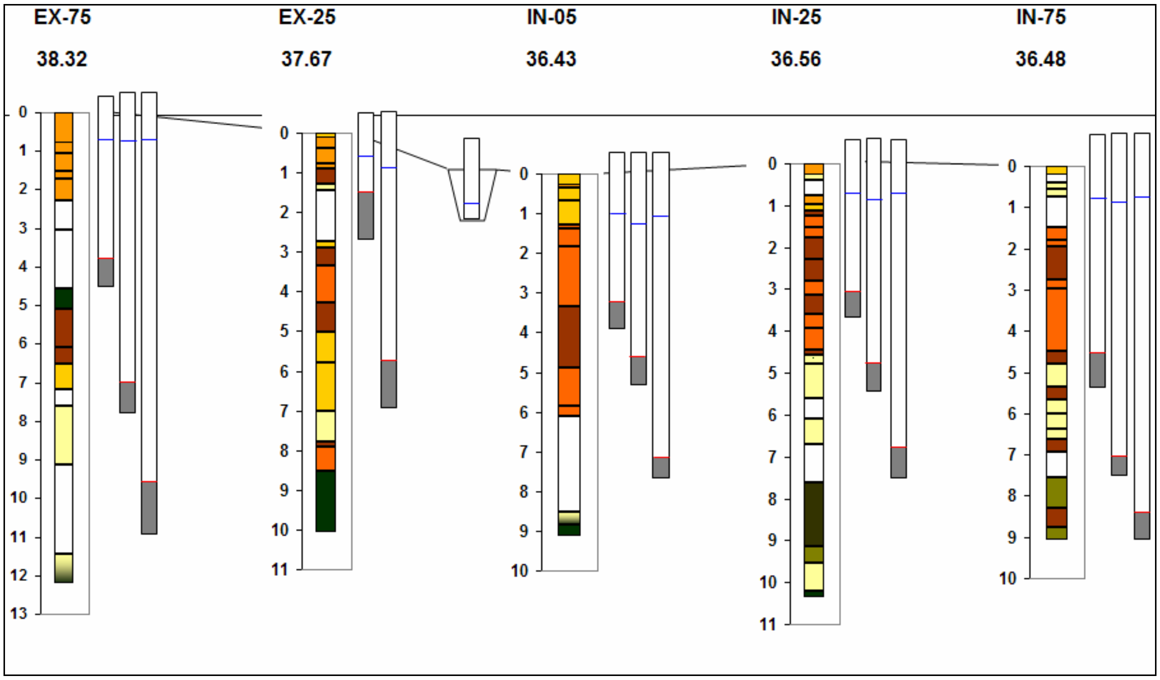

Figure 3.8.2: Hydraulic heads from the NE transect, 4 April 2004. Piezometers and water levels are shown at relative elevations. Cores at each nest are shown for reference.

The SE transect (Table 3.8.3) head data, which can be graphically viewed in Figure 3.8.3, showed that water drains into the perimeter ditch from both sides. Analyzing the flows in the middle sand layer, there was an indication of water moving from the exterior to the interior of the bay, but there was only one representative piezometer inside the bay in this layer. Modeling would help analyzing this part in detail. In the lower sands, the gradient was from exterior to interior indicating groundwater inflow.

Table 3.8.3: SE transect water level data on 4 April 2004

4/1/2004	Shallow piezometer			Middle/Shallow piezometer			Middle/Deep piezometer			Deep piezometer		
	Water Level Depth m	Surface Elevation m MSL	Water Level Elevation m MSL	Water Level Depth m	Surface Elevation m MSL	Water Level Elevation m MSL	Water Level Depth m	Surface Elevation m MSL	Water Level Elevation m MSL	Water Level Depth m	Surface Elevation m MSL	Water Level Elevation m MSL
SE-EX-75	1.975	37.938	37.173	1.974	37.680	36.914	2.044	37.520	36.824	1.989	37.350	36.599
SE-EX-25	1.425	37.930	36.615	1.670	37.550	36.480				1.678	37.160	36.098
SE-IN-5	2.167	36.740	36.167							2.040	36.700	36.000
SE-IN-25	2.185	36.610	36.055	2.186	36.612	36.058				2.080	36.611	35.951
SE-IN-75	2.312	36.423	35.996							2.116	36.430	35.806

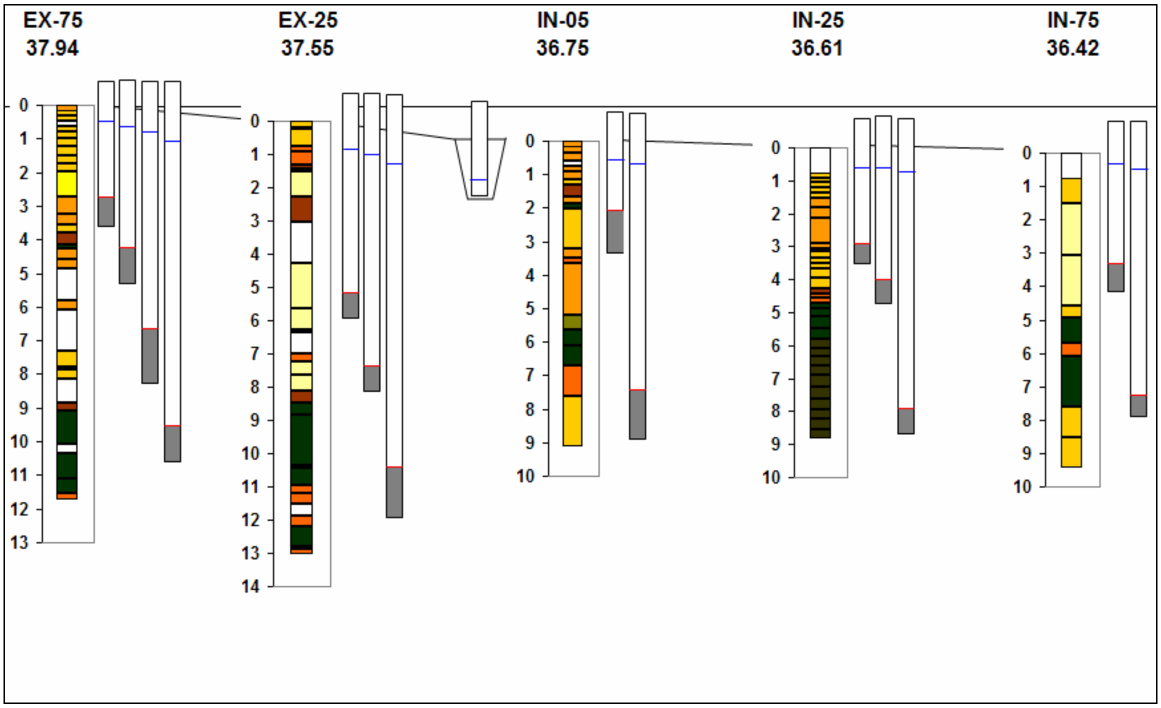

Figure 3.8.3: Hydraulic heads from the SE transect, 4 April 2004. Piezometers and water levels are shown at relative elevations. Cores at each nest are shown for reference

Head data at SW transect on 4 April 2004 (Table 3.8.4) was different in flow scenario analysis compared to the other transects. The graphical view relative to ground elevation and soil profile is presented in Figure 3.8.4. In the surface layer, water draining into the perimeter ditch, and in the middle and deeper layers head gradients suggested groundwater flows from interior to exterior.

Table 3.8.4: SW transect water level data on 4 April 2004

4/1/2004	Shallow piezometer			Middle piezometer			Deep piezometer		
	Water Level Depth m	Surface Elevation m MSL	Water Level Elevation m MSL	Water Level Depth m	Surface Elevation m MSL	Water Level Elevation m MSL	Water Level Depth m	Surface Elevation m MSL	Water Level Elevation m MSL
SW-EX-75	2.126	36.168	35.554	1.982	36.167	35.409	1.982	36.167	35.409
SW-EX-25	1.373	37.206	35.839	1.111	37.206	35.577	1.107	37.203	35.570
SW-IN-5	1.037	37.153	35.450				1.687	36.412	35.359
SW-IN-25	2.121	36.579	35.960				1.665	36.579	35.504
SW-IN-75	2.043	36.581	35.884				1.631	36.577	35.468

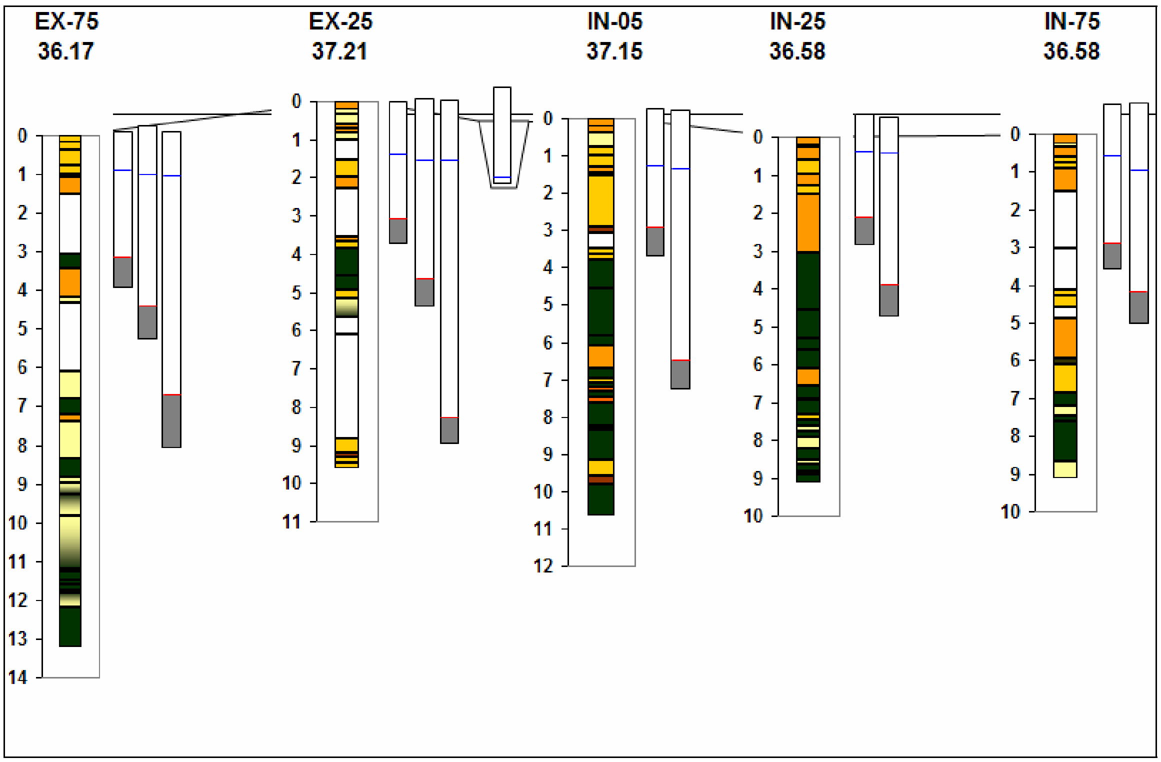

Figure 3.8.4: Hydraulic heads from the SW transect, 4 April 2004. Piezometers and water levels are shown at relative elevations. Cores at each nest are shown for reference

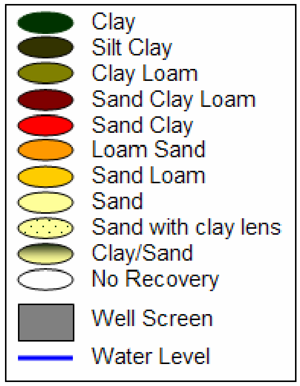

Figure 3.8.5: Legend for the Figures 3.8.1-4

3.9 Summary

Data obtained from the cores verified the conceptualization of Juniper Bay stratigraphy (Figure 3). Five nests of piezometers were installed at each transect with a water level monitoring system on each nest. Calibration runs for each of the monitoring units showed very good resolution (1 mm) from the system. Data collection began in late 2003. Installation was completed in early 2004. Over the course of several months, a number of problems, such as faulty solder joints, were found and corrected.

The preliminary data from this work suggests this resolution will give better representation of how groundwater is moving at the perimeter of the Bay than the previously existing hydrologic monitoring system. Figures 3.8.1 to 3.8.4 show the head data at all transects for the first week of April 2004. Since the resolution is close to millimeter level, the vertical gradients at the nests can be estimated precisely. This resolution will also help in precise estimation of hydraulic gradients across the transects. Preliminary flow analyses showed that the perimeter ditch influences water in the surface layers. Groundwater in the deeper sands was not greatly influenced by the perimeter ditch. Analysis also suggested groundwater inflow through the NW, NE, and SE transects and groundwater outflow through the SW transect. Groundwater models discussed in later chapters will explain more of the flow analyses.

Chapter 4

Modeling and Analysis of Subsurface Flows at the Four Transects

Stratigraphic information, head data and weather data collected onsite were used to model subsurface flows on all transects. This chapter discusses the development of the individual transect, including calibration and validation using Visual MODFLOW. Analysis of results from model output to determine the direction of flow and the degree of influence of the perimeter ditch is presented. This chapter addresses the second and third objectives of the project.

4.1 Model Development

The main objectives of subsurface flow modeling for this project were to:

- Determine the flow directions,
- Determine influence of the perimeter ditch,
- Quantify inflows/outflows, and
- Investigate management options for the ditch.

To achieve this, a two-dimensional, cross-sectional, finite difference groundwater flow model was developed using Visual MODFLOW, version 4.0 (McDonald and Harbaugh, 1988). This software has been extensively used for saturated conditions with both confined and unconfined aquifers.

Groundwater modeling required a thorough understanding of the hydrogeological characteristics of the site. Hydrogeological investigations at all four transects helped in defining a) the surface extent and thickness of aquifers and confining units, b) hydrogeologic boundaries which control rate and direction and movement of groundwater flow, c) hydraulic properties, d) head distribution, and e) groundwater recharge. The modeling process includes defining input parameters and boundary conditions. The following sections discuss input parameters and boundary conditions used in this groundwater modeling.

Input Parameters

The flow domain for each transect was divided into five layers based on the core descriptions and hydraulic conductivity estimates. These layers represent the surficial sand layer, first clay layer, a middle sand layer, second clay layer, and a deep sand layer. The top and bottom elevations of each layer were based on the ground surface elevations from the survey data. Table 4.1.1 presents top and bottom elevations of the five layers for the models for each transect. The five layers were assumed to be continuous between core locations. Although this represents an idealization, it was the best that could be done with the available field data. This configuration also reduced the complexity of the model. Effective hydraulic conductivity for each layer was estimated from corresponding values from five core points in the layer. Piezometric heads were used as inputs to describe the head distribution across each transect.

Table 4.1.1: Elevations of five layers for the four transect models, in meters MSL

Transect	EX-75	EX-25	IN-5	IN-25	IN-75
Northwest					
Ground surface	37.89	36.85	36.72	36.48	36.38
Bottom of layer 1 – Surface sand	34.79	33.81	33.67	32.82	33.34
Bottom of layer 2 – First clay	33.62	32.89	33.67	31.60	31.81
Bottom of layer 3 – Middle sand	33.01	32.28	30.62	30.38	30.29
Bottom of layer 4 – Second clay	30.27	30.76	30.62	30.38	28.76
Bottom of layer 5 – Deep sand	29.66	30.15	29.10	28.86	27.24
Northeast					
Ground surface	38.62	37.67	36.43	36.56	36.48
Bottom of layer 1 – Surface sand	33.80	34.70	33.40	32.80	31.50
Bottom of layer 2 – First clay	32.00	32.60	32.00	32.10	30.50
Bottom of layer 3 – Middle sand	29.00	31.00	30.80	30.50	29.00
Bottom of layer 4 – Second clay	29.00	30.50	30.00	30.00	28.50
Bottom of layer 5 – Deep sand	27.00	29.67	28.00	29.00	27.00
Southeast					
Ground surface	37.94	37.55	36.75	36.61	36.42
Bottom of layer 1 – Surface sand	34.40	32.00	33.25	33.10	32.42
Bottom of layer 2 – First clay	33.50	31.00	31.00	32.61	31.00
Bottom of layer 3 – Middle sand	29.00	29.50	29.50	31.61	30.42
Bottom of layer 4 – Second clay	28.00	26.50	29.25	28.61	29.00
Bottom of layer 5 – Deep sand	27.00	26.00	27.75	27.61	28.00
Southwest					
Ground surface	36.17	37.21	37.15	36.58	36.58
Bottom of layer 1 – Surface sand	32.30	33.70	33.50	33.70	32.50
Bottom of layer 2 – First clay	31.70	31.80	33.20	32.50	32.20
Bottom of layer 3 – Middle sand	30.00	31.80	32.70	31.50	30.50
Bottom of layer 4 – Second clay	29.00	31.20	31.00	30.50	30.20
Bottom of layer 5 – Deep sand	27.70	28.00	29.90	29.80	29.80

Boundary Conditions

Boundary conditions applied to these models are:

1) Known heads at the perimeter ditch at the center of each transect,

2) Known heads (hydrographs from the piezometers) at the EX-75 and IN-75 core locations to define left and right boundary conditions, respectively.

3) Surface conditions are defined by recharge and the evapotransipration (ET).

Recharge is the part of the precipitation that infiltrates into the saturated zone. The recharge fraction of the rainfall was estimated by subtracting runoff and ET from rainfall.

DRAINMOD (Skaggs, 2004), version 5.1, was run for 2004 data to obtain the percentage of rainfall that contributed towards runoff.

The weather parameters solar radiation, net radiation, wind speed, soil temperature, and relative humidity were measured at an on-site weather station. Those data were used to estimate the ET using the Penman-Monteith Equation. Ref-ET (Allen, 1990) was used to estimate ET. Appendix B provides tables with daily ET and daily precipitation data for the year 2004.

The grid model for the NW transect that was developed using MODFLOW is shown in Figure 4.1.1. The perimeter ditch is located at the lateral distance of 75 m in the flow domain. The flow domain on the left side of the ditch represents the exterior of the bay and the flow domain on the right side of the ditch represents the interior of the bay. This arrangement is used for all of the models. Given the availability of head data for only one year (2004), the observed heads from 01 January 2004 to 30 June 2004 were used for calibration, while the data from 01 July 2004 to 31 December 2004 were used for testing the model. The following section discusses the calibration process of the models.

Calibration

To calibrate a groundwater flow model, one needs well-defined calibration targets and parameters. The calibration targets refer to the observations that are compared with the calculated values, in this case, the piezometric heads. The calibration parameters are the parameters that are changed to obtain the best fit between the observed and calculated values. Saturated hydraulic conductivities (K_{sat}) of different layers and storage were used as the calibration parameters. Modeling efforts were initially focused on the NW transect, which is used as an example in the following discussion of calibration and testing.

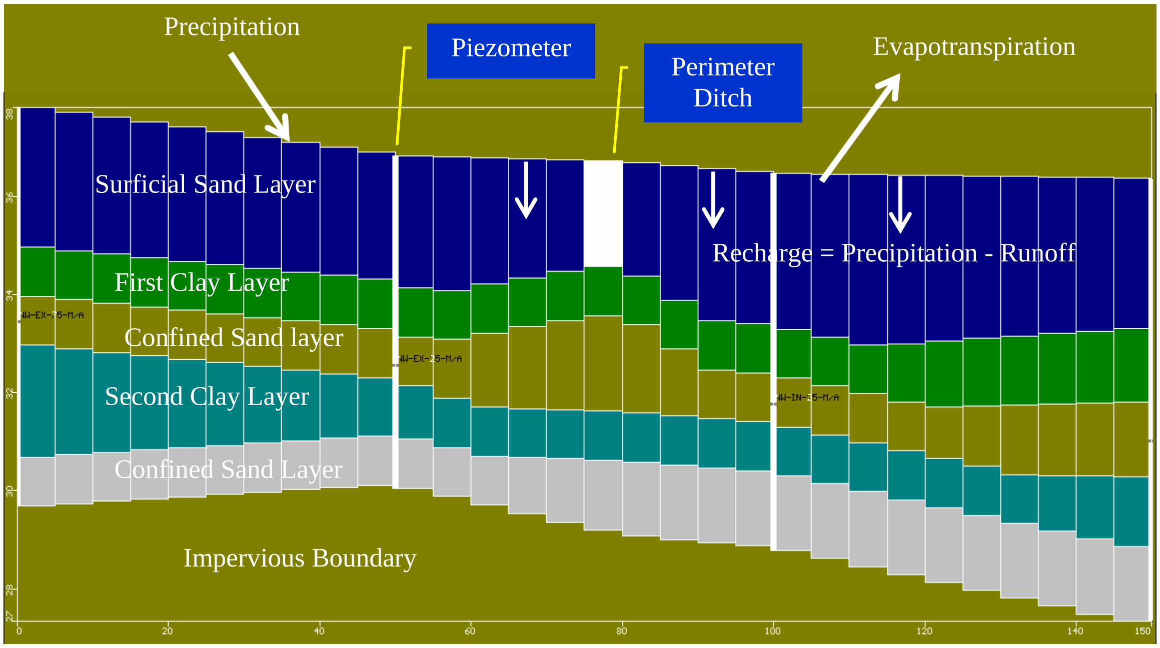

Figure 4.1.1: Model setup for NW Transect

Initially, the model was run for steady state conditions, and then extended to transient conditions. Hydraulic conductivity field estimates were available for different cores in each layer. An effective hydraulic conductivity (K_e) for a layer was calculated from the lab results as

$$K_e = \frac{K_x D_x}{\sum D_x} \qquad (4.1.1)$$

$K_x = K_{sat}$ of stratum x, and D_x = thickness of stratum x

Effective K_{sat} for each layer at the NW transect is given in Table 4.1.2. In the calibration phase, the conductivity values for each layer were varied within the range of +/- 1 standard deviation (SD) of K_{sat} values for each layer. The K_{sat} values were varied by the same relative amount in all layers at a time. Storage was handled differently for unconfined and confined layers. For confined layers, specific storage (S_s) was used to estimate storage volume. For unconfined sand, specific yield (S_y) was used to estimate storage volume. Specific storage for confined layers was varied from 1E-4 to 1E-9 (Fetter, 1994) and specific yield for the unconfined sand layer was varied from 0.1 to 0.3. The storage component does not have a significant effect on the model output. Therefore, the main soil parameter that was used as calibration parameter was hydraulic conductivity. The correlation coefficients were compared from different runs to find the parameter set that gave the highest correlation between observed and calculated head values. The observed correlation coefficient results are shown in Figure 4.1.2. K in the Figure 4.1.2 refers to set of K_{mean} values for all five layers.

Table 4.1.2: Effective Saturated Hydraulic Conductivity (m/sec) of different layers

Layer	EX-75	EX-25	IN-05	IN-25	IN-75	K_{mean}
1	3.36E-04	1.54E-05	1.58E-04	6.43E-06	1.11E-05	1.05E-04
2	3.18E-07	3.64E-06	1.47E-06	4.81E-06	1.91E-05	5.87E-06
3	3.96E-04	2.40E-04	2.45E-05	5.67E-05	2.85E-05	1.49E-04
4	2.08E-05	1.17E-07	9.34E-06	1.20E-05	2.02E-06	6.79E-06
5	3.55E-04	3.05E-04	6.29E-05	1.20E-04	7.95E-05	1.84E-04

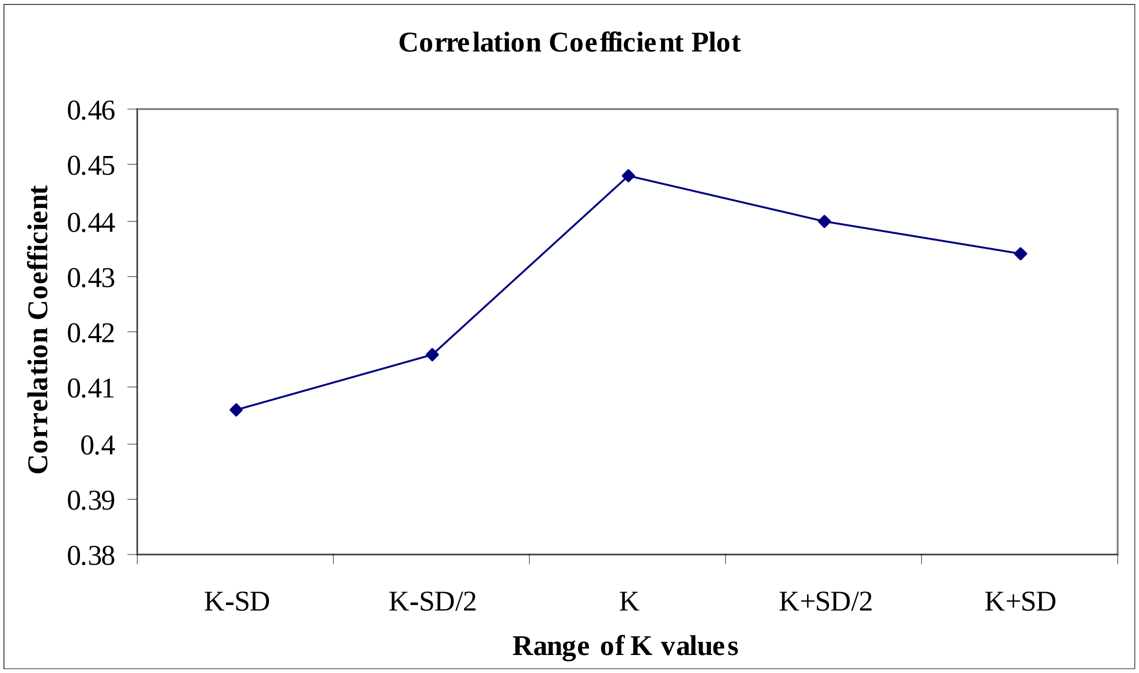

Figure 4.1.2: Correlation coefficient between observed and calculated for different sets of K values

Optimum parameters obtained from steady state conditions were used as a start for calibrating transient conditions. Then hydraulic conductivity values were varied for a range of values depending on the type of layers. Figure 4.1.3 shows an example of results from the calibration process between observed and calculated heads at the NW-EX-25-M piezometer. The absolute error between the calculated heads and observed heads was between 0.2 to 0.4 m.

In a similar manner, models for the NE, SE, and SW transects were also calibrated. The absolute error was in the range of 0 to 0.5 m at all transects. All four models were tested using the data from 1 July 2004 to 31 December 2004. Testing of the models showed absolute errors very similar to those of calibration.

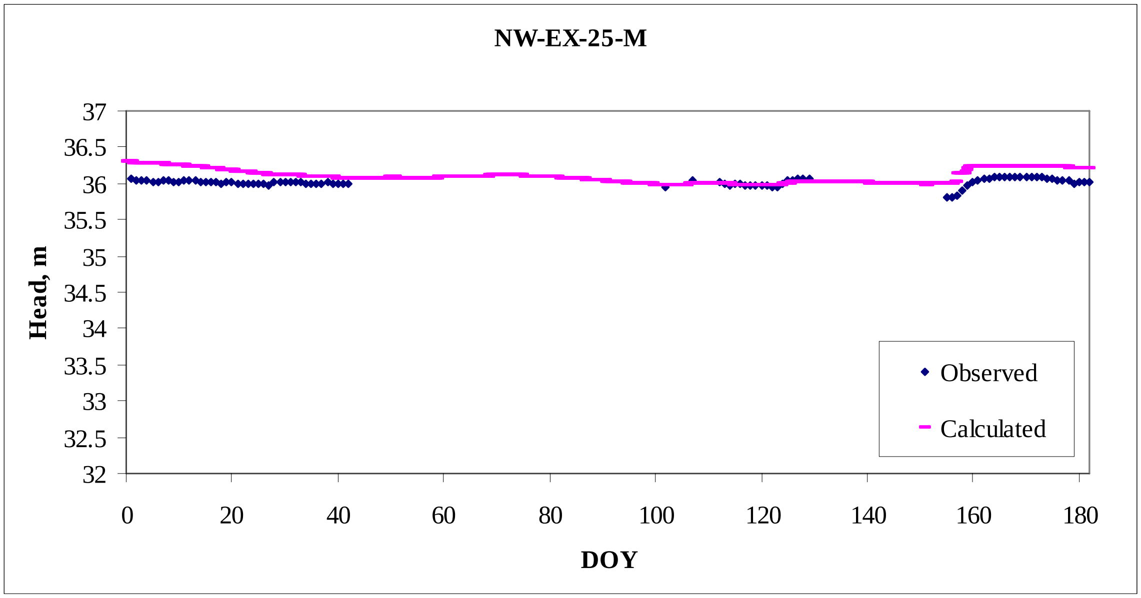

Figure 4.1.3: Comparison plot between observed and calculated

The following sections discuss the results from each of the four transect models in detail. Given the loss of certain piezometric head data in the second part of the year, the first part of the year that was used for calibration was also analyzed from model outputs. To analyze results in different climatic conditions, analysis was concentrated on 15 February 2004 and 13 May 2004. Results for 15 February 2004 reflect conditions for a winter month, which is usually relatively wet. Results for 13 May 2004 represent relatively dry conditions. Another reason for selecting 13 May for dry conditions was that there was no rain event for a few days leading to this day. 15 February 2004 is the 45th day of the year and 13 May 2004 is the 133rd day of the year 2004, so 45 and 133 have sometimes been used in place of 15 February 2004 and 13 May 2004 in this report.

4.2 Analysis of Modeling Results

This section presents the analysis of modeling results at each of the four transects. The first thrust of the modeling effort was to determine the hydraulic gradients and thereby the direction of movement of groundwater at each transect. The second thrust was to analyze the influence of the perimeter ditch on the groundwater flows. The figures presenting equipotential lines have the vertical dimension exaggerated for clearer visibility of flow velocities in the flow domain.

Northwest Transect

Analysis of the April 2004 data for observed heads at the NW (Chapter 3, Figure 3.8.1), demonstrated the fact that the perimeter ditch acts as a discharge point for the surficial and middle sand layers. Heads in the lower sands suggest flow moving from the exterior to the interior of the bay. Results from modeling also indicated groundwater flowing into the bay in the lower sands. Figures 4.2.1 and 4.2.2 show equipotential lines for the wet and dry periods, respectively, obtained from model outputs. The size of the arrow that is shown in these figures signifies the magnitude of flow velocity. These indicate the flow direction and the effect of the perimeter ditch on the lower sand layers.

The direction of the flow as shown by the arrows indicates that the perimeter ditch acts as a discharge point in the surficial sand layer. Flow velocity reduces as the lateral distance increases from the ditch. This signifies the zone of influence of the perimeter ditch, which is strong to a distance of approximately 50 m either side. Having more flow activity in the summer months could be due to the significant role of the ET and precipitation on the surface hydrology. The vertical gradient is more at the EX-75 location from upper sand layer to lower sand layers. For the wet condition, groundwater has a lateral gradient in the middle and deep sand layers from the outside to the inside of the bay, but then showed an upward gradient inside the bay. The thickness of the clay layer decreases from EX-75 to IN-75, which could be an explanation of this kind of groundwater movement. In the dry conditions, the ditch acts as a divide in the middle and deep sand layers. This shows an indication of the vertical influence of the ditch extending to the depth of the lower sand layers.

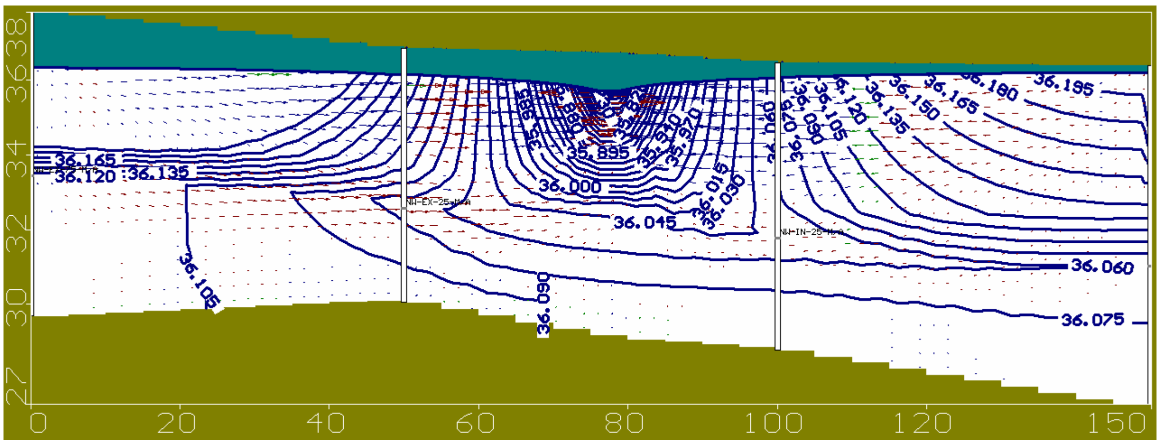

Figure 4.2.1: Equipotential Lines for 15 February 2004 at the NW transect

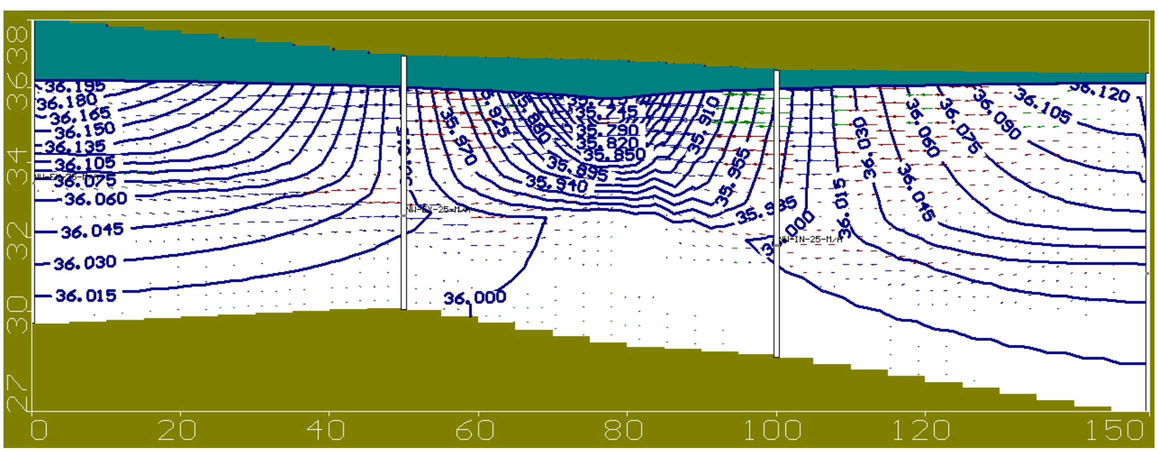

Figure 4.2.2: Equipotential Lines for 13 May 2004 at the NW transect

Northeast Transect

Equipotential lines from the output of the NE transect model are shown in Figures 4.2.3 and 4.2.4. Flow lines, which are perpendicular to equipotential lines and are shown as arrows, indicate drainage of water into the ditch from both sides in both wet (Figure 4.2.3) and dry conditions (Figure 4.2.4). The size of the arrows signifies the magnitude of the flow velocity. In the surficial sand layer, the flow lines diminish towards the inside of the bay. This indicates that the exterior of the bay is contributing more flow into the ditch than the interior of the bay. These flow velocity arrows also indicate that the influence of the ditch in the surface layer is higher in the summer months than the winter months.

The flow velocities in the middle sand layer are higher than in the surface and deep sand layers. One can observe that flow lines are passing under the ditch from the exterior to the interior of the bay, indicating that groundwater inflow occurs at the NE transect. However, the flow directions also indicate that the water is eventually draining into the ditch. Hydraulic connectivity between the layers could be one of the reasons for this kind of flow pattern.

In the deep sand layer, groundwater flow shows little influence of the perimeter ditch. In the winter months there is an indication of water flowing from the exterior of the bay, and then in the interior of the bay there is an upward gradient from the lower sands to the middle sand layer. This suggests that groundwater is entering into the bay, but eventually exiting through the perimeter ditch. In the summer months, groundwater movement is from the deep sand layer to the middle sand layer.

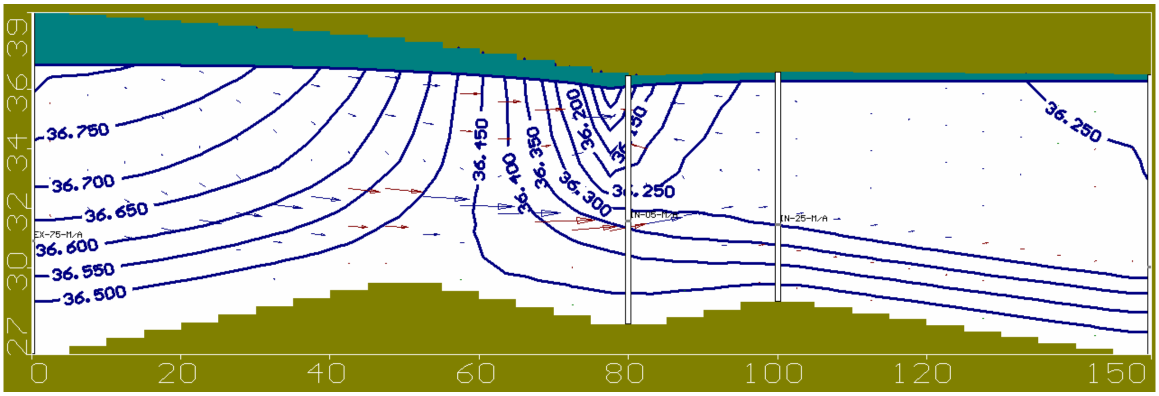

Figure 4.2.3: Equipotential Lines for 15 February 2004 at the NE transect

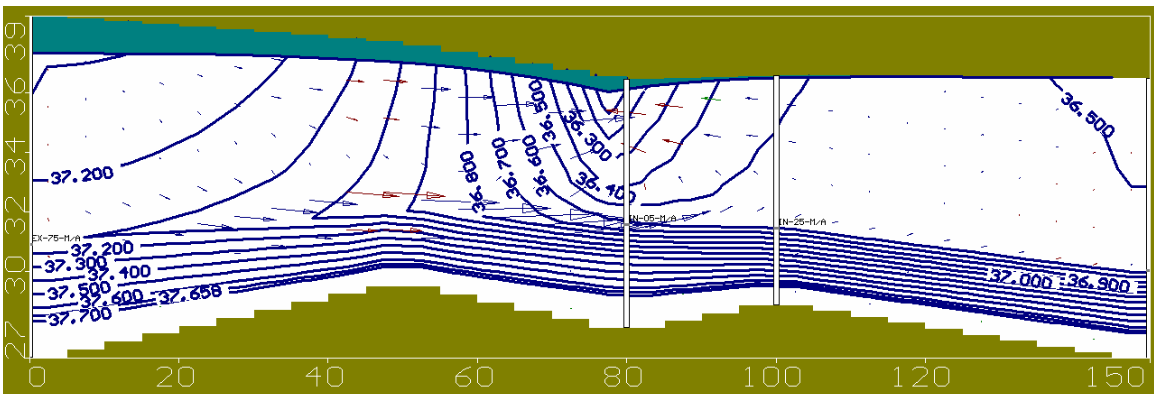

Figure 4.2.4: Equipotential Lines for 13 May 2004 at the NE transect

Southeast Transect

Figures 4.2.5 and 4.2.6 show equipotential lines and flow directions in the flow domain of the SE transect for the wet and dry conditions, respectively. These flows indicated water draining into the ditch from both sides in the surficial sand layer.

Groundwater movement is small at the SE transect. The hydrologic activity is mostly concentrated near the perimeter ditch in the surficial sand layer. As the lateral distance from the perimeter ditch increases, one can observe a low and no flow velocity. Both lateral and vertical flows are small in the middle and deep sand layers. The vertical gradient increases with increasing distance from the perimeter ditch. These vertical gradients are higher in the summer months than in the winter months. The influence of the ditch in the lower sands is relatively small. There is also an indication of groundwater flow from the outside to the inside of the bay. Equipotential lines also suggest that the lower sands are isolated from the upper and middle conducting layers. The thick clay layer between the middle and deep sand layers could be a reason for isolation.

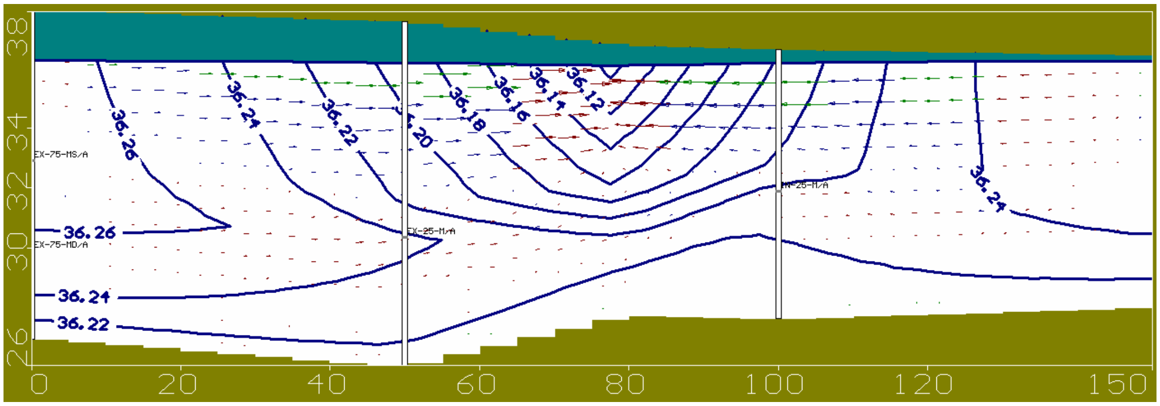

Figure 4.2.5: Equipotential Lines for 15 February 2004 at the SE transect

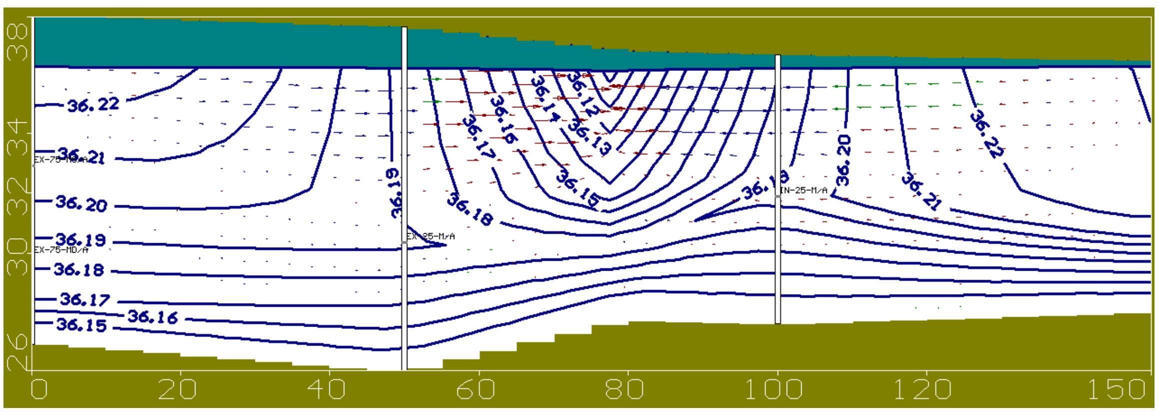

Figure 4.2.6: Equipotential Lines for 13 May 2004 at the SE transect

Southwest Transect

Equipotential lines and flow velocities in the flow domain are shown in Figures 4.2.7 and 4.2.8 for wet and dry conditions, respectively. The size of the arrow signifies magnitude of flow velocity. Flow direction indicated water draining into the ditch from both sides in the surface layer and also in the middle sand layer. The flow velocities are higher in the summer months than the winter months.

In the middle sand layer, flow velocity is very low and shows flow direction towards the perimeter ditch. In the deeper sand layer, flows are not much influenced by the perimeter ditch. Equipotential lines suggest that the deep sand layer is isolated from the upper sand layers. A thick clay layer between the middle and deep sand layers can be a reason for the vertical gradient that can be seen in Figures 4.2.7 and 4.2.8. There is no clear indication of water entering or leaving the bay.

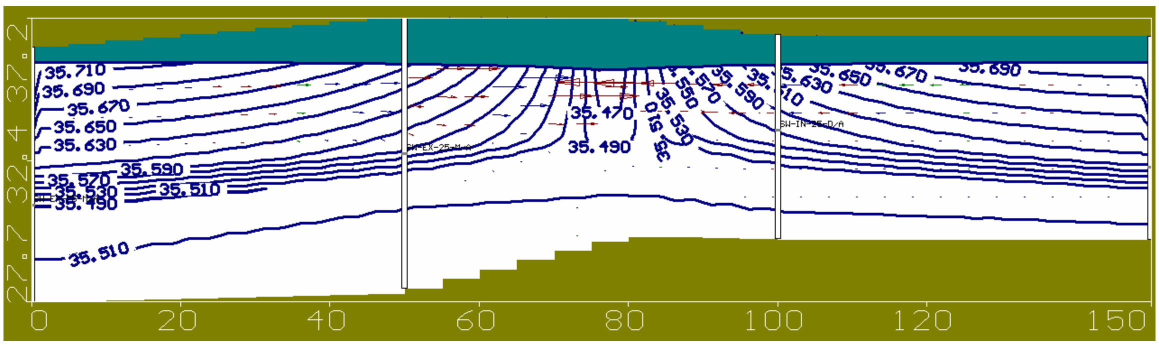

Figure 4.2.7: Equipotential Lines for 15 February 2004 at the SW transect

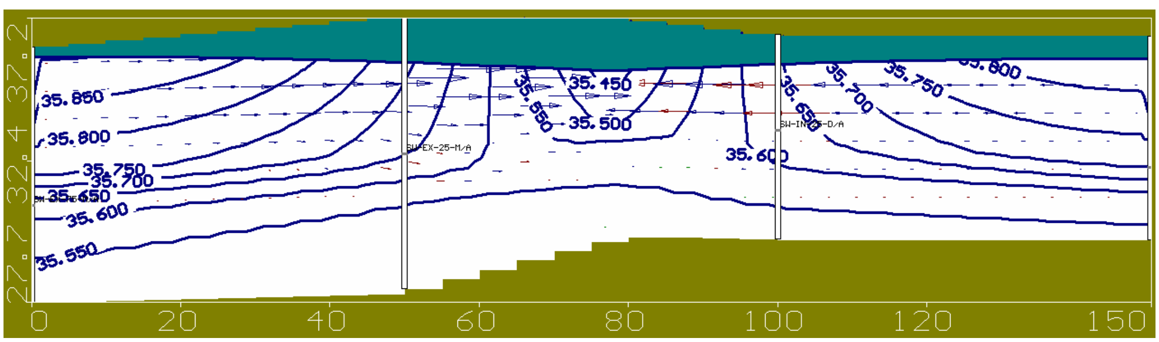

Figure 4.2.8: Equipotential Lines for 13 May 2004 at the SW transect

4.3 Extended Model

It could be that by imposing known heads as right and left boundary conditions, the model was forced to show flows into the perimeter ditch from the rest of the flow domain. Extending the models to an extent where a no-flow boundary condition could be safely assumed seemed like a good alternative. The model was extended through the inside of the bay approximately to the center of bay and a no-flow boundary condition was applied. The assumption was that the center of the site acts as the divide for the groundwater flow and that the influence of one side would not extend past the middle of the bay. The model domains were extended laterally to 800-m, which was approximately the center of the bay on the minor axis. The extended model also approximates the conditions after the interior ditch system is blocked.

An example of an extended model for the NW transect is shown in Figure 4.3.1. The perimeter ditch is located at the lateral distance of 75 m in the flow domain. The flow domain to the left side of the ditch represents the exterior of the bay and the flow domain to the right side of the ditch represents the interior of the bay. Each of the four transects was modeled separately. The extended models have similar input as was discussed earlier: 1) observed heads obtained from piezometers, 2) saturated hydraulic conductivities for each layer, and 3) top and bottom elevations of each layer. All five layers are configured as continuous layers because of the limited startigraphic data. This configuration reduces the complexity of the models. The boundary conditions applied were a) impervious boundary at the bottom, b) no-flow as right hand boundary at the center of the bay, c) known heads on EX-75 location and d) surface conditions defined by recharge and evapotranspiration.

Model convergence became a difficult task while calibrating the extended model. The WHS solver in MODFLOW (that uses Bi-conjugate Gradient Stabilized), which was used for the 150-m wide transect models, was unable to converge the extended model. The model kept terminating abnormally and hence could not run for the entire time period. For the portion that did run, the calibration results were not in an acceptable range and the calculated head values were very high compared to observed heads. Available data was sparse and the extended model was a little bit of astretch with this information. As an alternative, other solvers available with MODFLOW were tried, viz., 1) Preconditioned Conjugate-Gradient Package (PCG) and 2) Strongly Implicit Procedure Package (SIP), which can handle an ill-conditioned matrices in a better way. The SIP solver was found to be the best for this condition. This was confirmed by numerical experiments discussed in the following section.

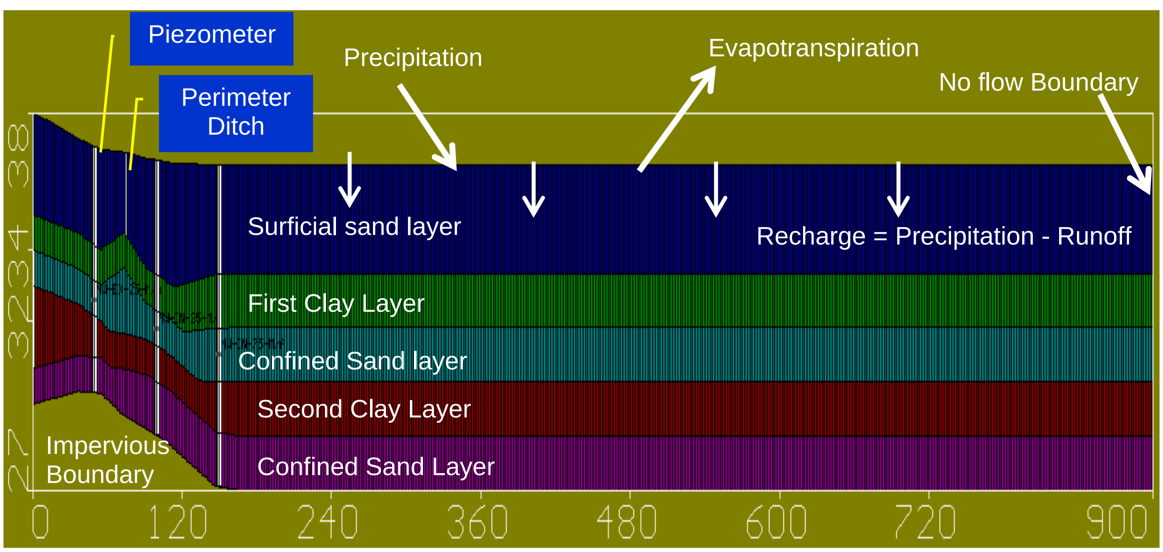

Figure 4.3.1: Extended Model shown for the NW Transect

Numerical Experiments

Numerical experiments were conducted to determine which factors were affecting model convergence. Factors considered were the soil properties of each layer, initial conditions of heads, distance to which the model extended. With a few trial and error combinations on these parameters within the range of values obtained from the field data, the results showed good calibration. The SIP and PCG solvers were used to run the model for numerical experiments. The SIP solver seemed to solve the matrix better than the PCG solver for the given situation. Therefore, the SIP solver is used for running the extended models. The calibrated model was found to have absolute maximum error of 0.3 to 0.5 m between the observed heads and the calibrated heads for most of the piezometers. An example at each transect for the calibration is shown in the Figures 4.3.2 (NW), 4.3.9 (NE), 4.3.14 (SE), and 4.3.20 (SW).

Northwest Transect

The Northwest transect model was calibrated using the piezometric heads. An example of the calibration plot is shown in Figure 4.3.2. There was a good calibration between days 100 and 130. The maximum absolute error of calibration was 0.3 m. The calibration error varied between 0m to 0.5m in all the piezometers. Equipotential lines obtained from the NW Transect model output are shown in Figures 4.3.3 and 4.3.5, representing 15 February 2004 (wet condition) and 13 May 2004 (dry condition) respectively.

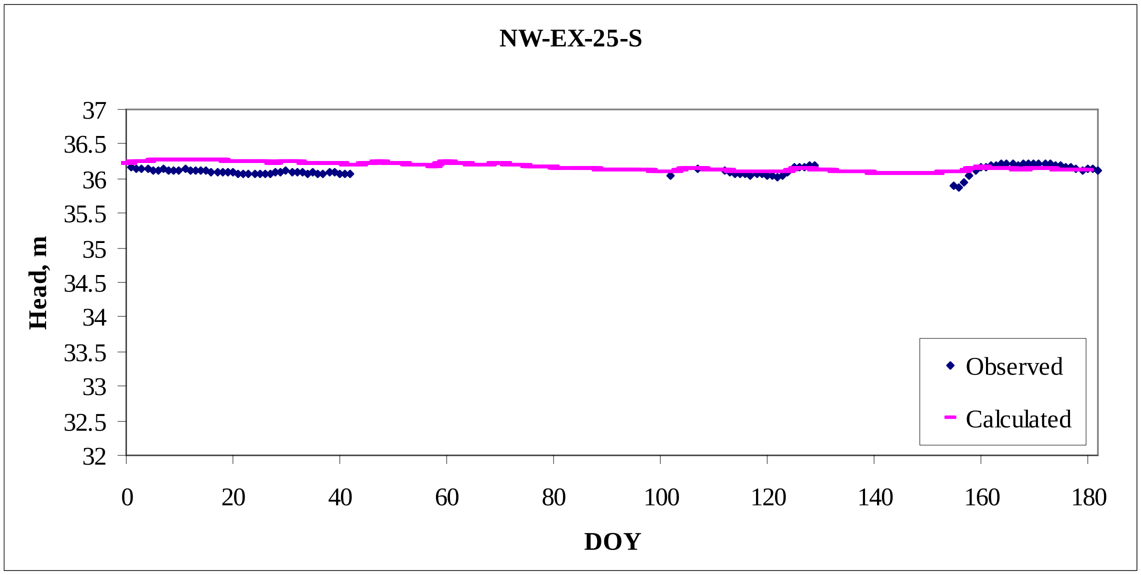

Figure 4.3.2: Calibration plot example (at exterior 25 m piezometer nest) at the NW transect

These equipotential lines indicated flow lines towards the perimeter ditch in the surface sand layer. The influence of the perimeter ditch in the surficial sand layer is to an extent of 75 m on either side. As shown in Figures 4.3.3 and 4.3.5, flows lines in the lower sands traverse from exterior to interior of the bay indicating a groundwater inflow at the NW transect. The gradients in the three water conducting sand layers are shown in Figures 4.3.4 and 4.3.6, which show spatial distributions of heads across the flow domain. These graphs clearly indicate that the perimeter ditch was draining the surficial sand layer. The influence of the perimeter ditch can be seen on the middle sand layer to an extent. In the deep sand layer, lateral gradients indicate that the groundwater flow from exterior to interior was not significantly influenced by the perimeter ditch. Influence of the perimeter ditch was greater in the dry conditions (Figure 4.3.6). The lateral gradient in the deeper layer was smaller in the dry conditions. Vertical gradient across the layers was higher in the dry condition compared to wet conditions. The vertical gradient indicates increasing potential for flow from the surficial sand layer to the deep sand layer, as the distance from the perimeter ditch increases. This could be due to the strong continuous clay layers between these sand layers. The model assumed continuous clays to 800 m inside the bay. The influence of the perimeter ditch extends to a distance of approximately 80 m to 100 m inside the bay and to the depth of 6–7 m from the surface.

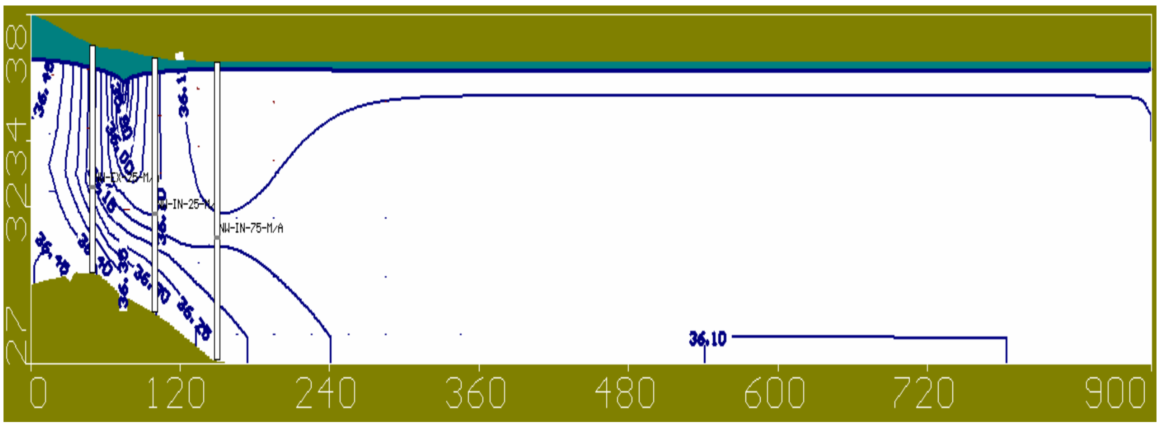

Figure 4.3.3: Equipotential Lines on 15 February 2004 at the NW transect extended model

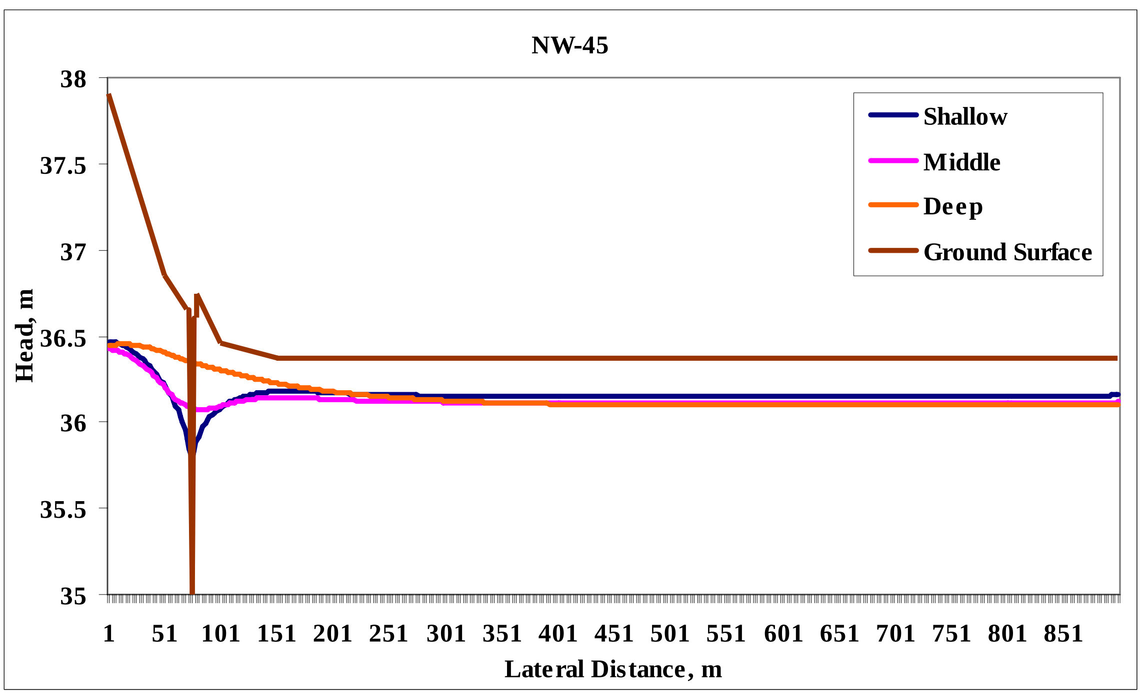

Figure 4.3.4: Heads in the three conducting layers at the NW transect on 15 February 2004

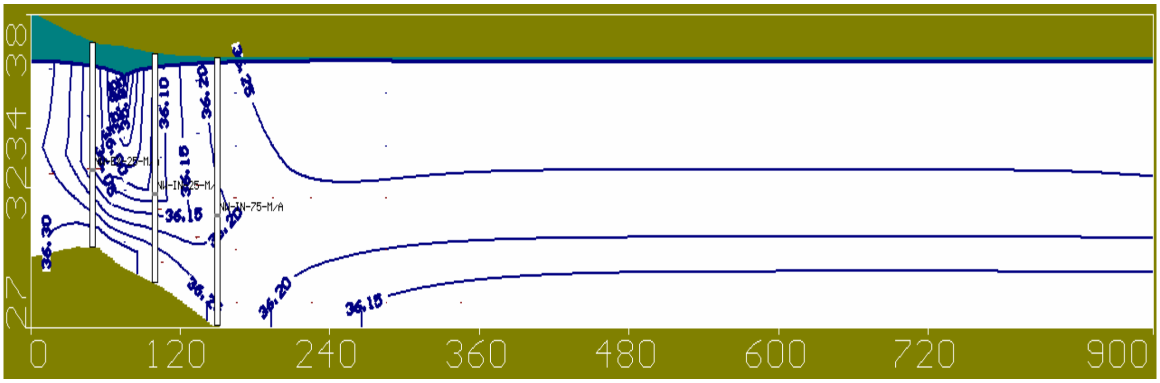

Figure 4.3.5: Equipotential Lines on 13 May 2004 at the NW transect extended model

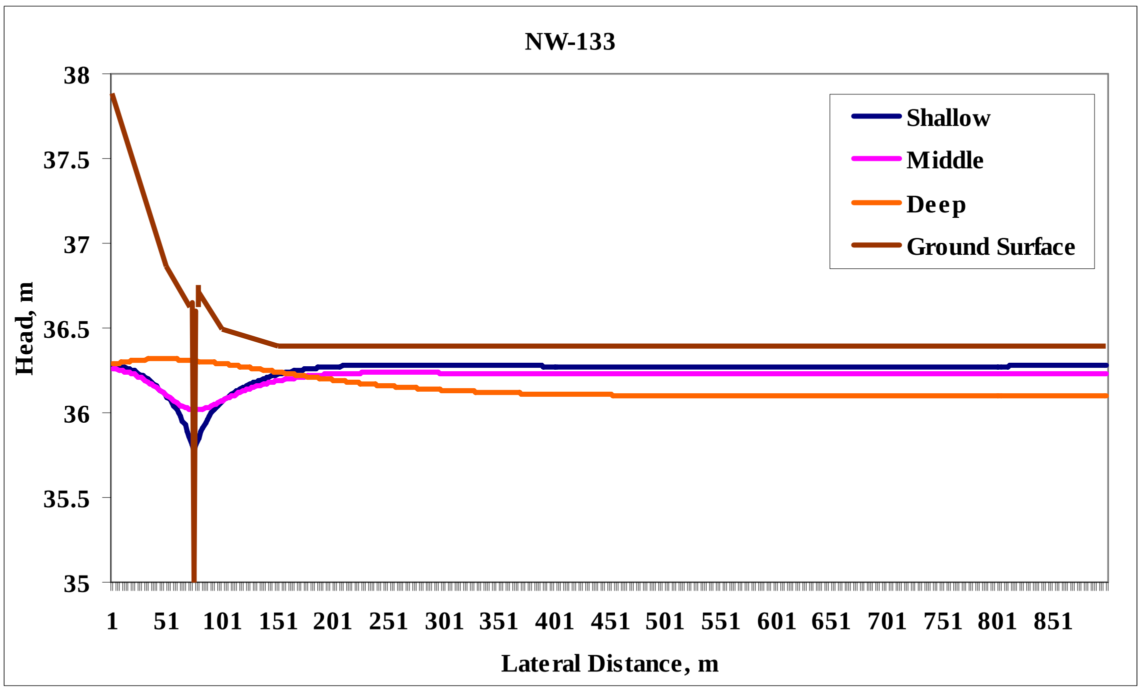

Figure 4.3.6: Heads in the three conducting layers at the NW on 13 May 2004

The groundwater flows are quantified to estimate the amount of groundwater coming into the site at the NW transect. The monthly inflows at the NW transect through both the middle and lower sands are shown in Figure 4.3.7. The inflows through the middle layer are larger than inflows through the deep layer. The inflow was highest in January and lowest in June 2004. Total inflow through the middle sand layer for the first half of year 2004 was approximately 7.09 m^3/m and the corresponding inflow through the lower sands was approximately 2.63 m^3/m. Furthermore, these inflows decreased as the season changed from winter to summer. The net groundwater inflow estimated at the NW transect is shown in Figure 4.3.7. The total inflow for the NW transect was approximately 9.72 m^3/m. Table 4.3.1 gives a summary of daily averages of groundwater inflows at the NW transect.

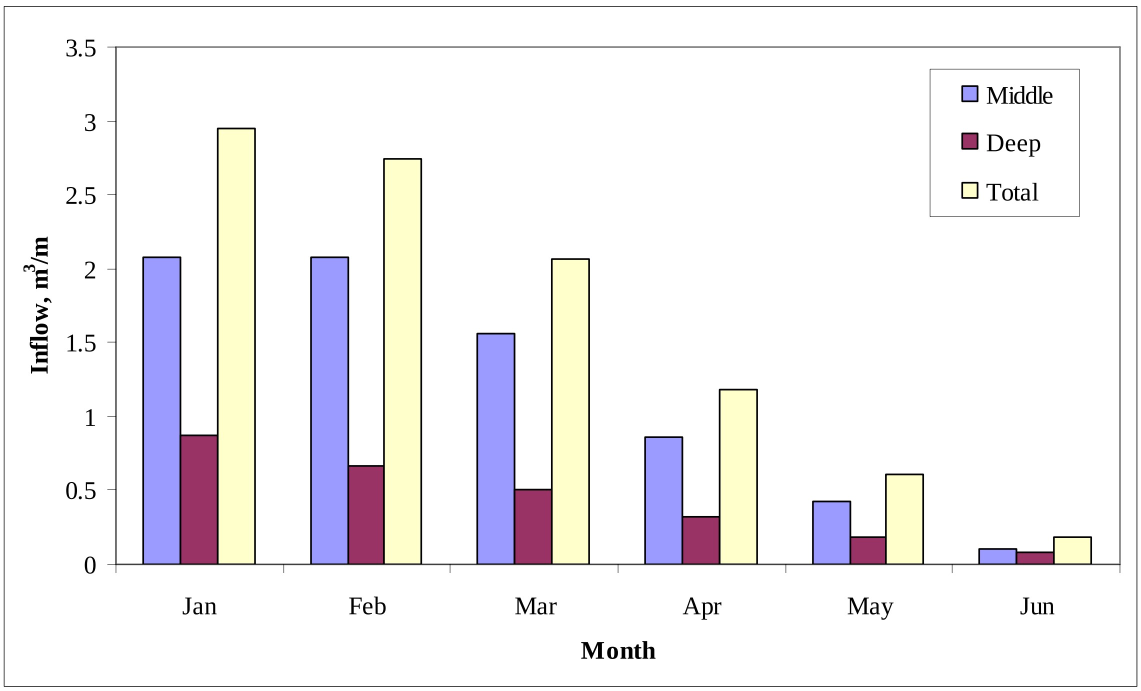

Figure 4.3.7: Inflow rates at the NW transect

Northeast Transect

The northeast transect extended model was calibrated using the piezometric heads. An example of the calibration plot is shown is Figure 4.3.8. The absolute error varied between 0 m and 0.5 m in all the piezometers. Figures 4.3.9 and 4.3.11 show the NE transect model outputs on 15 February 2004 and 13 May 2004, representing the wet and dry periods respectively. Flow lines, which are perpendicular to equipotential lines, indicate that the perimeter ditch draining water from both sides in the surface layer. The flow lines in the lower sands indicate groundwater inflow.

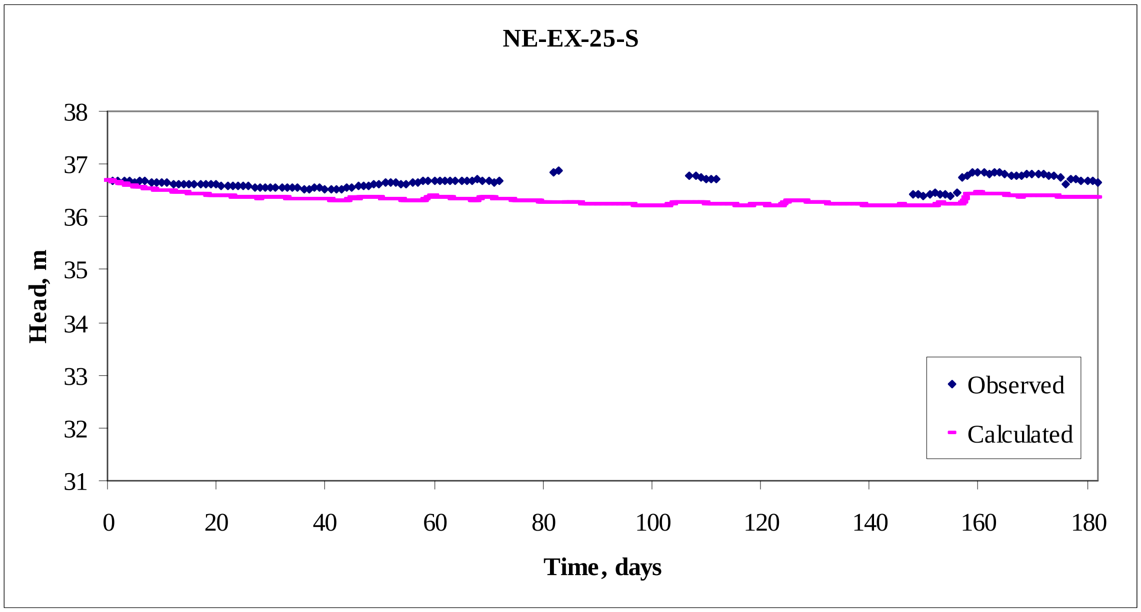

Figure 4.3.8: Calibration plot example (at exterior 25 m piezometer nest) at the NE transect

The head distribution can be viewed in a better manner in Figures 4.3.10 and 4.3.12, which show the spatial distributions of the heads in the three sand layers across the flow domain. One can observe the influence of the perimeter ditch on flows in the surface sand layer, but not on the flows in the middle and deep sands. Lateral gradients in middle and deep sand layers were from the exterior to the interior of the bay, indicating groundwater water inflow at the site through the NE boundary. The influence of the perimeter ditch was greater in dry conditions than in wet conditions in the surficial sand layer, as can be observed by the lateral gradients towards the ditch shown in Figures 4.3.10 and 4.3.12. Lateral gradients are lower in middle and deep sands for the dry conditions.

Spatial distributions of heads in the three sand layers, as shown in Figures 4.3.10 and 4.3.12, were used to estimate the zone of influence of the perimeter ditch. The perimeter ditch had an influence to the lateral distance of approximately 30 to 50 m and to a depth of 4 to 5 m from the surface. There was a vertical gradient from the surface layer to the deep sand layer and this gradient was greater in dry conditions than in wet conditions. This strong vertical gradient could be because of the thick continuous clay layers between the sand layers. In real conditions, the clay layers were not as continuous as represented in the model.

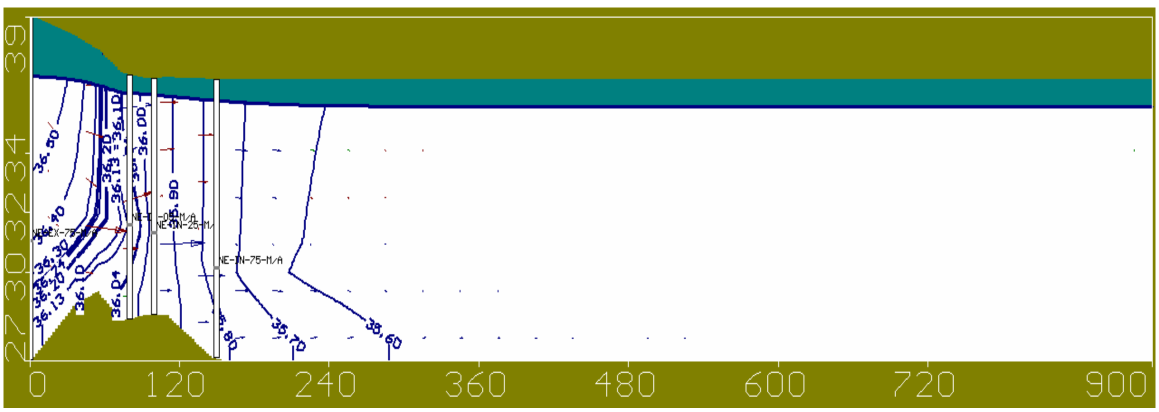

Figure 4.3.9: Equipotential Lines on 15 February 2004 at the NE transect extended model

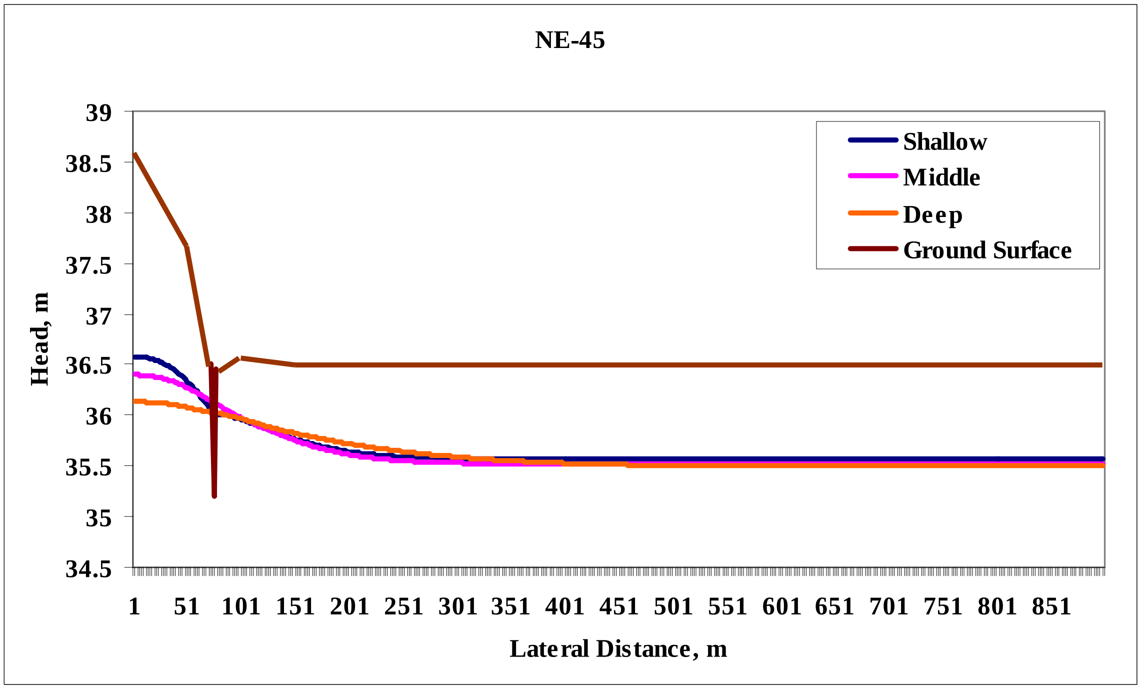

Figure 4.3.10: Heads in the three conducting layers at the NE transect on 15 February 2004

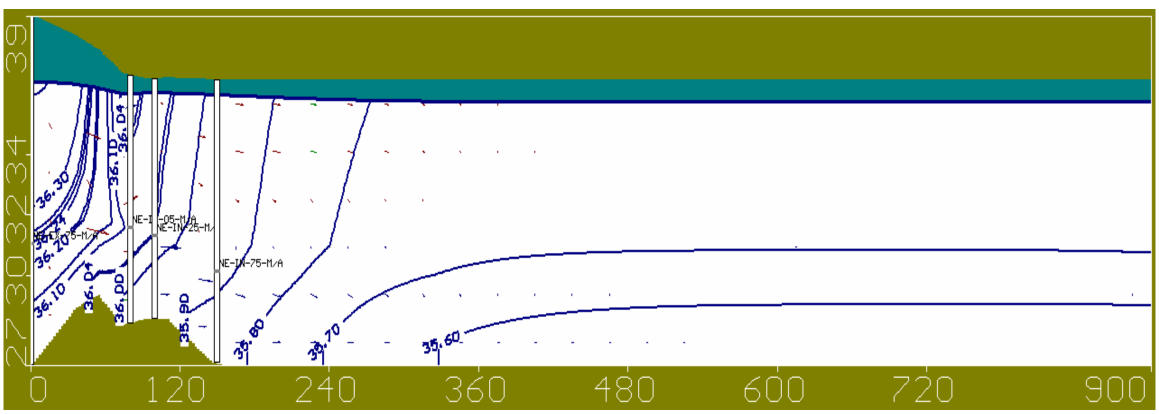

Figure 4.3.11: Equipotential Lines on 13 May 2004 at the NE transect extended model

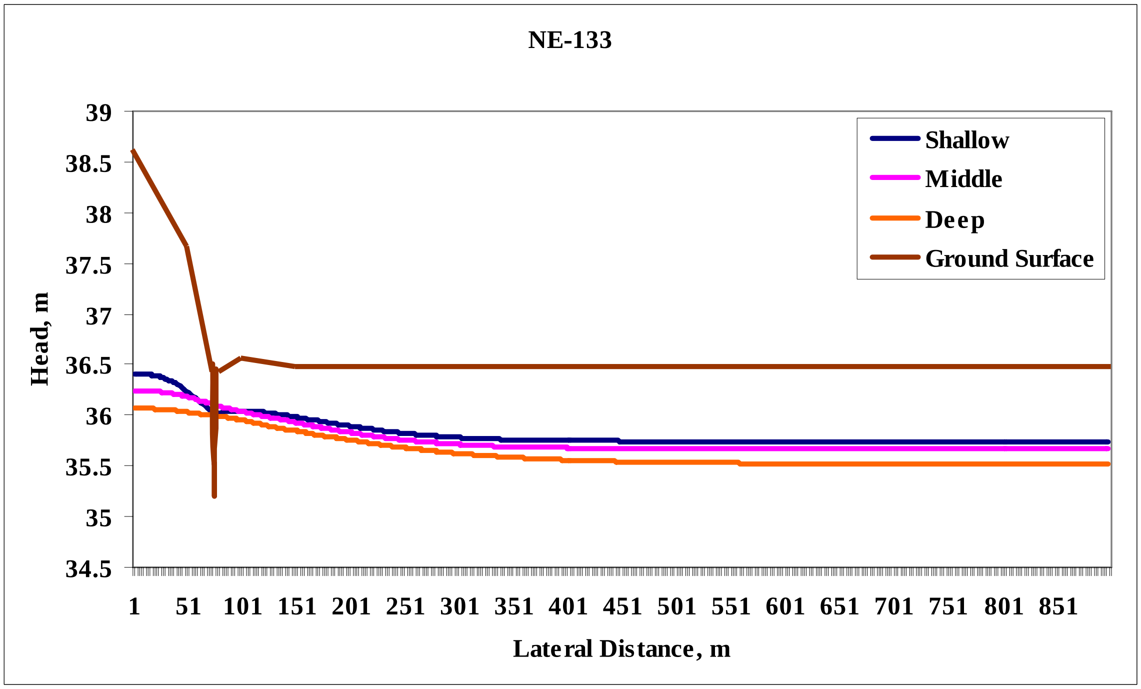

Figure 4.3.12: Heads in the three conducting layers at the NE transect on 13 May 2004

Figures 4.3.10 and 4.3.12 indicate that groundwater is clearly flowing into the bay through the middle and deep sand layers. The monthly inflows at the NE transect through both the middle and lower sands are shown in Figure 4.3.14. Inflows through the middle layer were found to be significantly larger than inflows through the deep layers. Flows were highest in January 2004 and lowest in June 2004. Inflows decreased as the season changed from winter to summer. Inflow through the middle sand layer for the first half of year 2004 was approximately 21.85 m^3/m and the corresponding inflow through the lower sands was approximately 4.00 m^3/m. The total amount of groundwater coming into the site at the NE transect is also shown in Figure 4.3.13. Total inflow contributed for the NE transect is approximately 25.86 m^3/m. The daily average flows from the middle and deep layers are shown in Table 4.3.1.

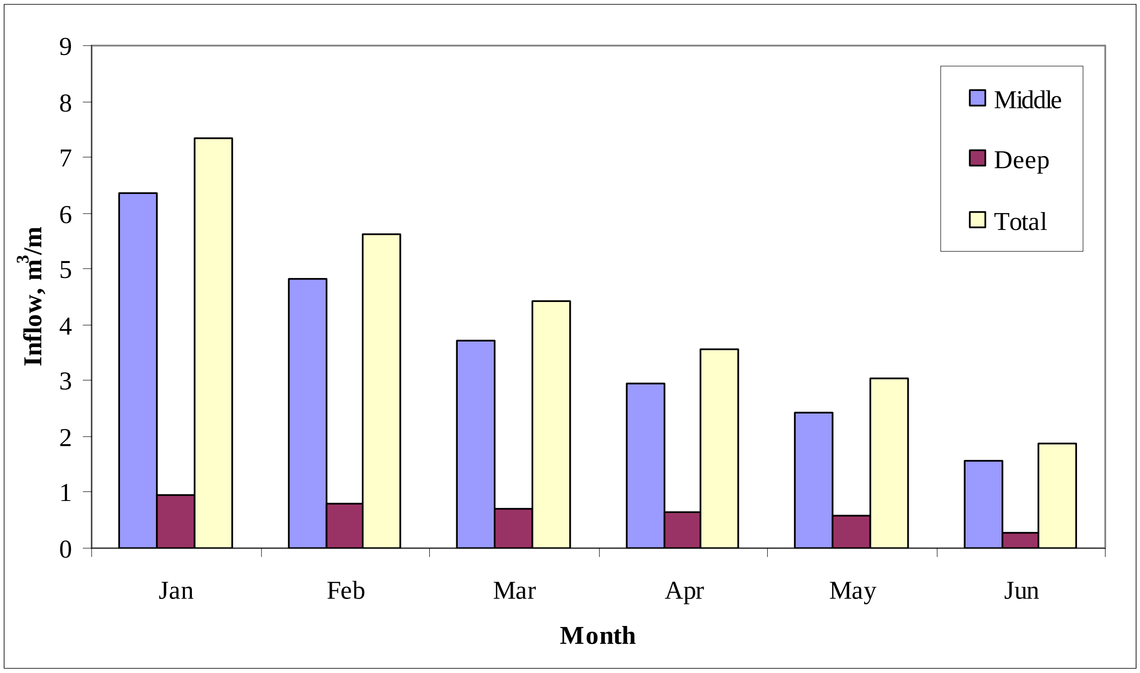

Figure 4.3.13: Inflow rates at the NE transect

Southeast Transect

The Southeast transect was modeled and calibrated using piezometer heads. An example of the calibration is shown in Figure 4.3.14. The absolute error was between 0 m to 0.5 m for all the piezometers. Figures 4.3.15 and 4.3.17 show equipotential lines from simulation results of the SE transect model on 15 February 2004 and 13 May 2004, representing wet and dry periods respectively. Results indicate that the perimeter ditch was very effective in draining water from the surface sand layer. In the lower sands, however, lateral gradients show an indication of groundwater inflow. The spatial distributions of heads in all three sand layers, as shown in Figures 4.3.16 and 4.3.18, would explain flow scenario more precisely. Surficial sand layer flows are influenced by the perimeter ditch, but the ditch had no appreciable effect on the middle and deeper sands. In the middle and deep layers, lateral gradients were greater in wet conditions (Figure 4.3.16) when compared to dry conditions (Figure 4.3.18). The vertical gradients across the layers could be because of the thick clay layers between sand layers. The perimeter ditch could be influencing approximately 50 m laterally and 5 m deep from the surface.

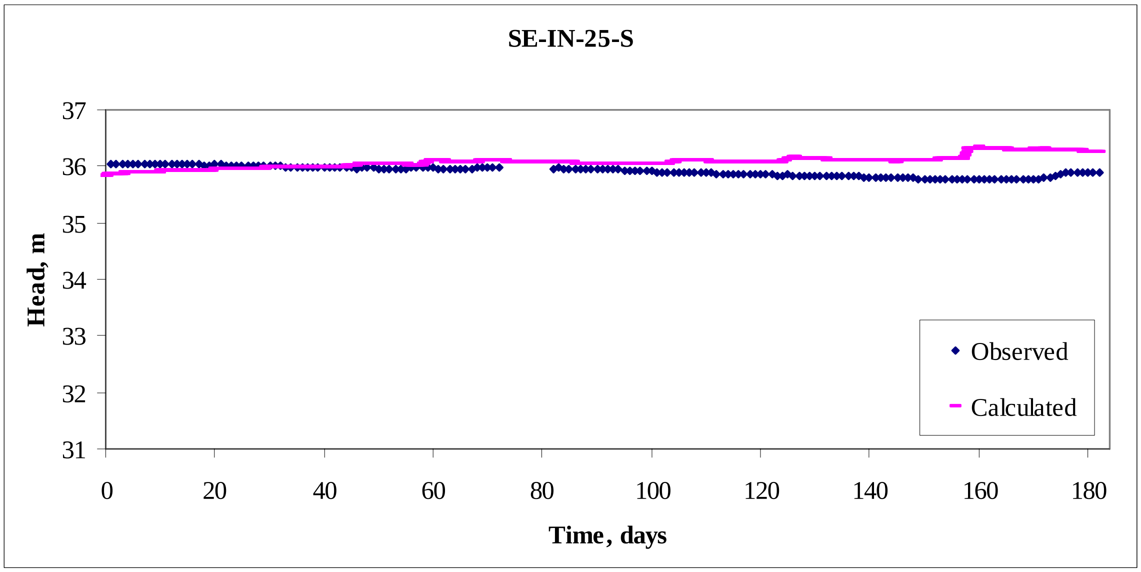

Figure 4.3.14: Calibration plot example (at interior 25m piezometer nest) at the SE transect

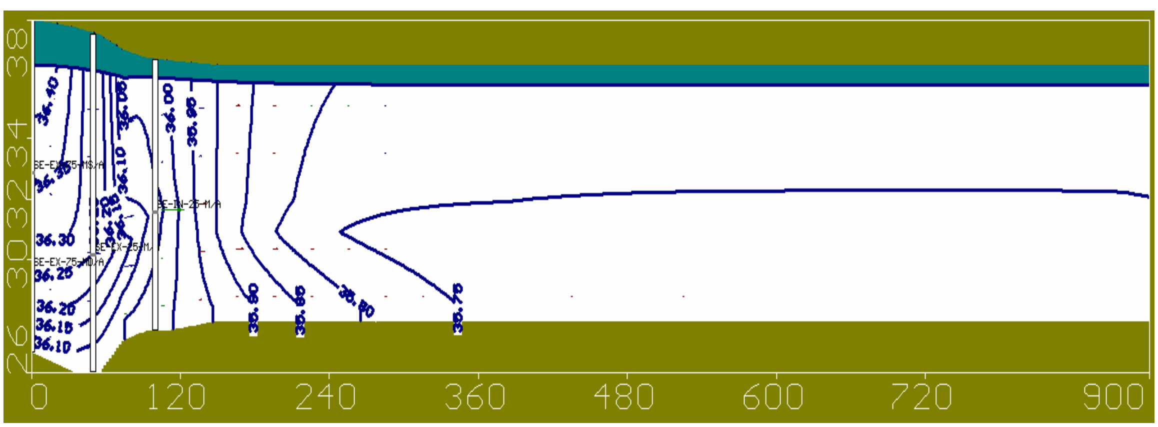

Figure 4.3.15: Equipotential Lines on 15 February 2004 at the SE transect extended model

Figures 4.3.16 and 4.3.18 indicate that groundwater is clearly flowing into the bay through the middle and deep sand layers at the SE transect. As shown in Figure 4.3.19, the monthly inflows at the SE transect through the middle sand layer are significantly larger than inflows through the deep sand layer. Flows were highest in January and lowest in

June 2004. Inflow decreased as the season changed from winter to summer. Inflow through the middle sand layer for the first half of 2004 was approximately 16.31 m^3/m and the corresponding inflow through the lower sands was approximately 1.56 m^3/m. The total amount of groundwater coming into the site at the SE transect is also shown in Figure 4.3.19. Total inflow for the SE transect was estimated as 17.87 m^3/m for the first half of the year 2004. The daily average flows from the middle and deep layers are presented in Table 4.3.1.

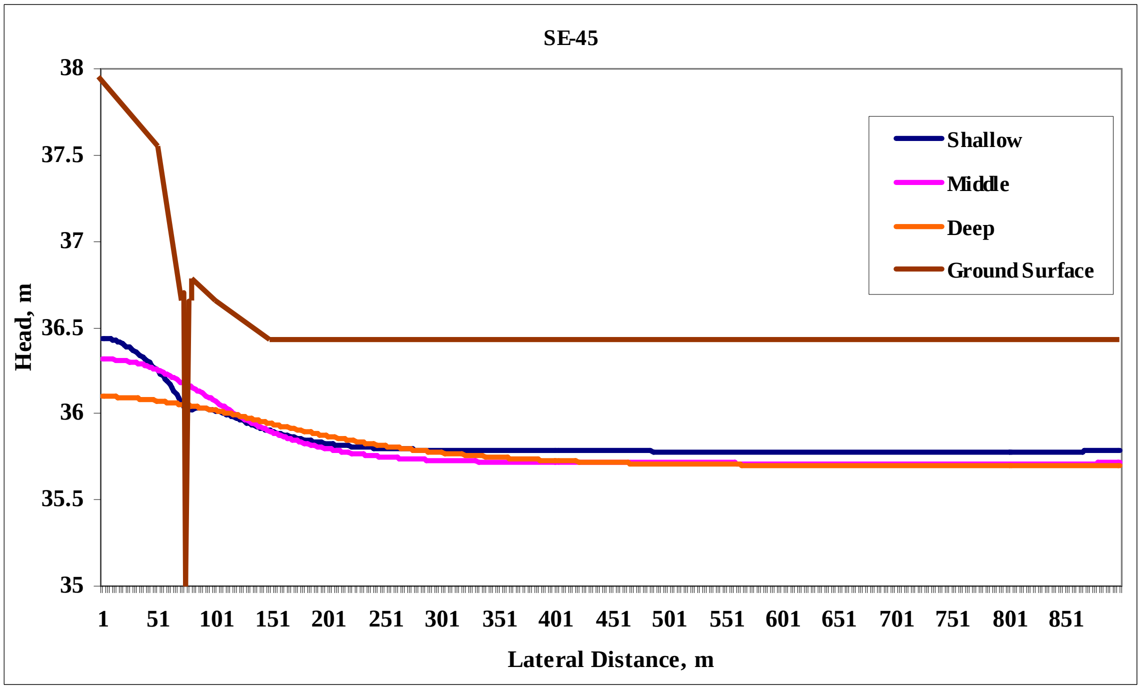

Figure 4.3.16: Heads in the three conducting layers at the SE transect on 15 February 2004

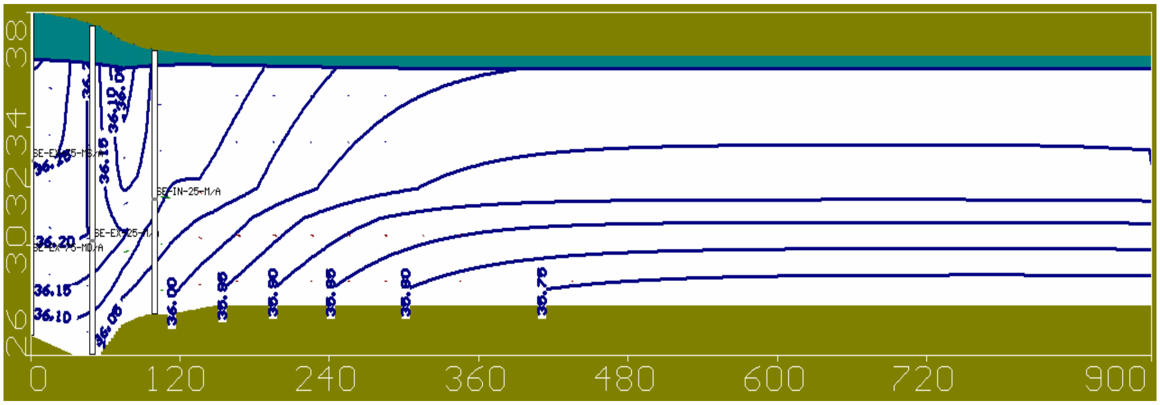

Figure 4.3.17: Equipotential Lines on 13 May 2004 at the SE transect extended model

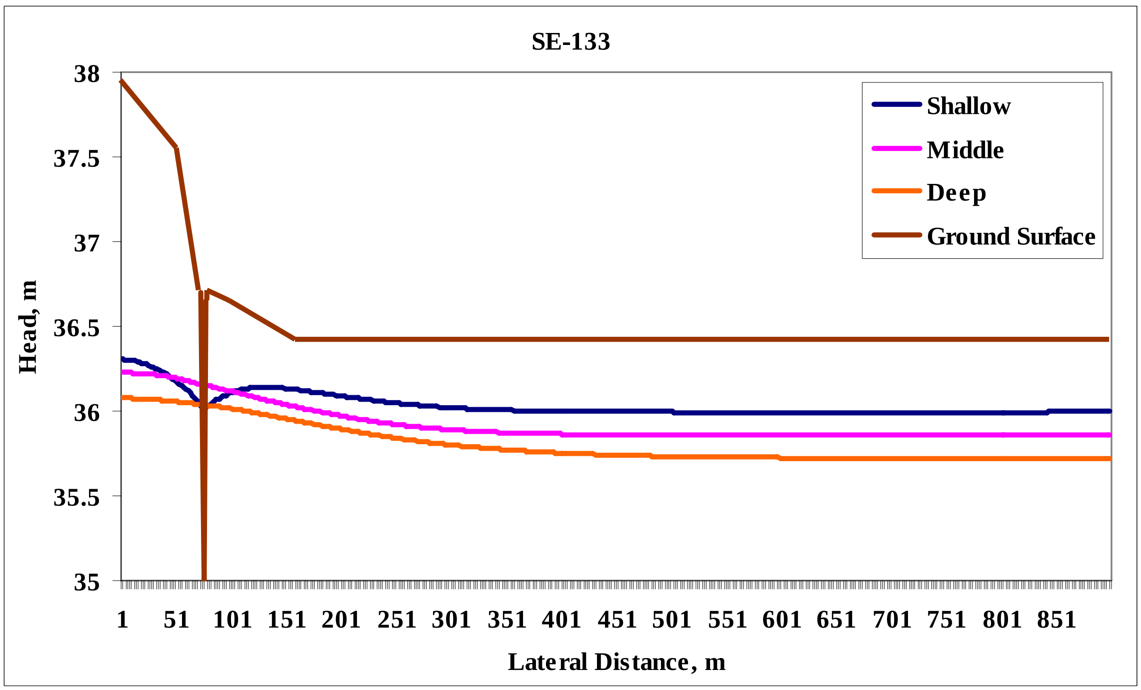

Figure 4.3.18: Heads in the three conducting layers at the SE transect on 13 May 2004

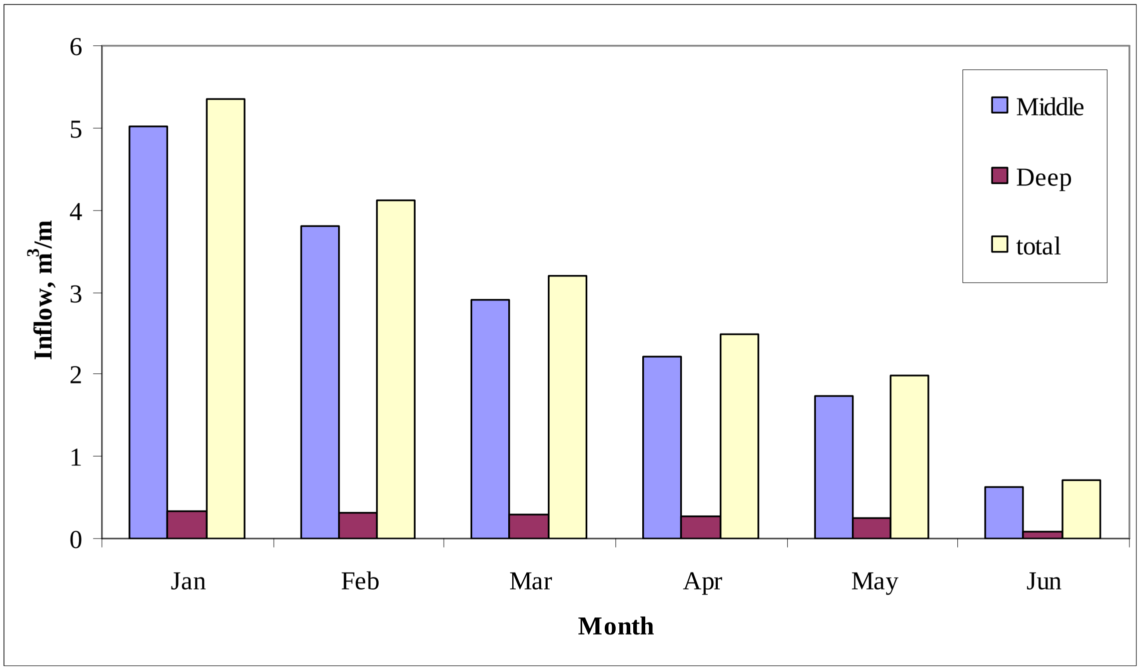

Figure 4.3.19: Inflow rates at the SE transect

Southwest Transect

The simulations results with equipotential lines in the flow domain of the SW transect are shown in the Figures 4.3.21 and 4.3.23 for 15 February 2004 and 13 May 2004, representing wet and dry periods, respectively. Flow lines indicated that the perimeter ditch can drain water effectively in the surface layer. In the lower sands the lateral gradient suggested groundwater outflow. Figures 4.3.22 and 4.3.24 show the spatial distributions of heads across the flow domain. The surface layer was influenced by the perimeter ditch and showed that water is draining into the ditch from both sides. The middle and deeper layers also showed some influence of the perimeter ditch. However, a greater influence can be observed in dry conditions than in wet conditions (Figures 4.3.22 and 4.3.24). In the deeper layers, there was a lateral gradient from the interior to the exterior of the bay indicating groundwater outflow from the southwest side of the bay.

The perimeter ditch influenced flows approximately 80 m to 100 m laterally and 6m deep from the surface.

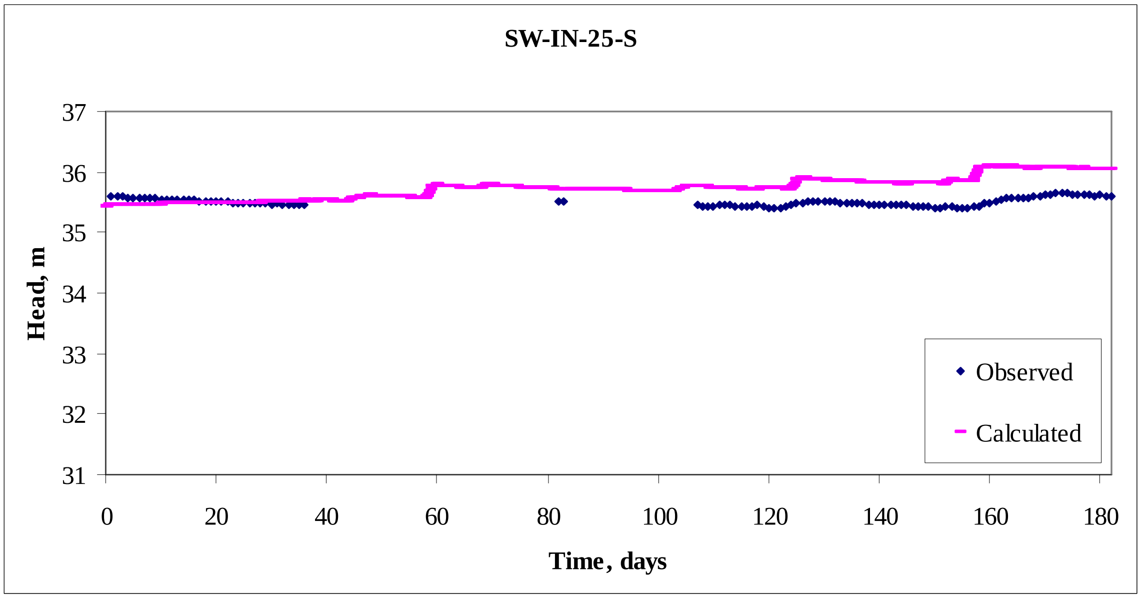

Figure 4.3.20: Calibration plot example (at interior 25m piezometer nest) at the SW transect

From the above analysis, it is clear that there is groundwater outflow through the southwest part of the site. Therefore, hydraulic trespass could occur along the southwest boundary of Juniper Bay.

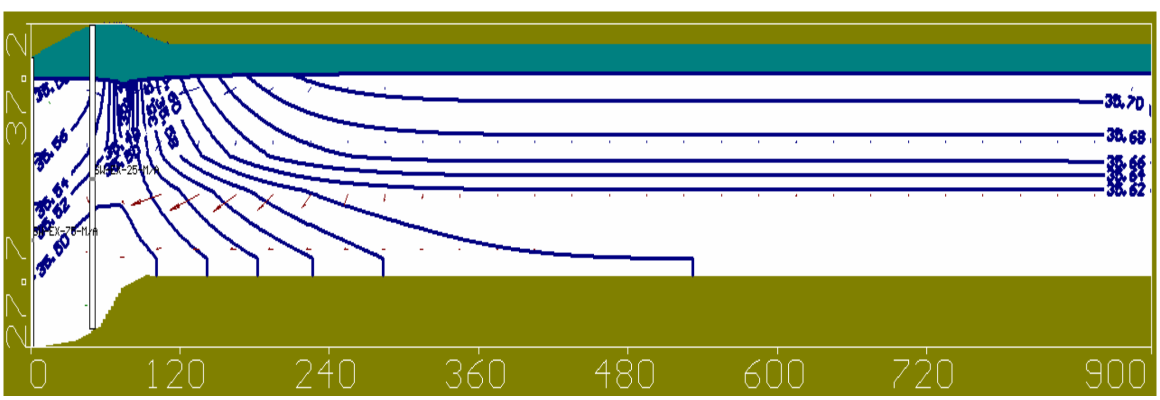

Figure 4.3.21: Equipotential Lines on 15 February 2004 at the SW transect extended model

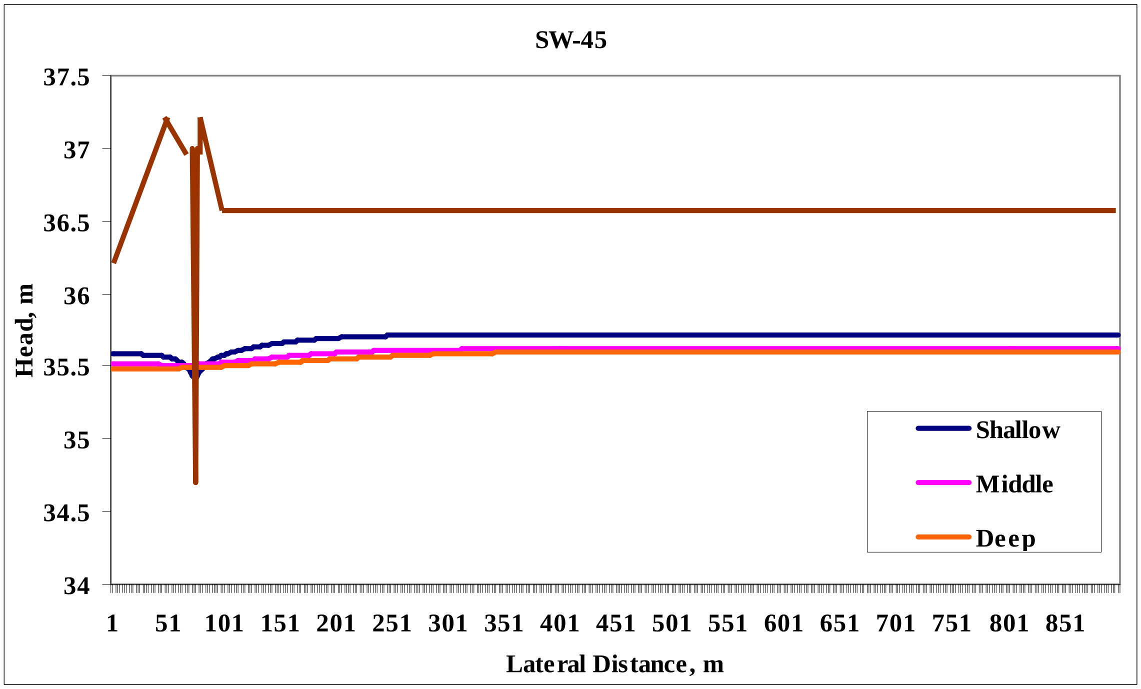

Figure 4.3.22: Heads in the three conducting layers at the SW transect corresponding to dry period (15 February 2004)

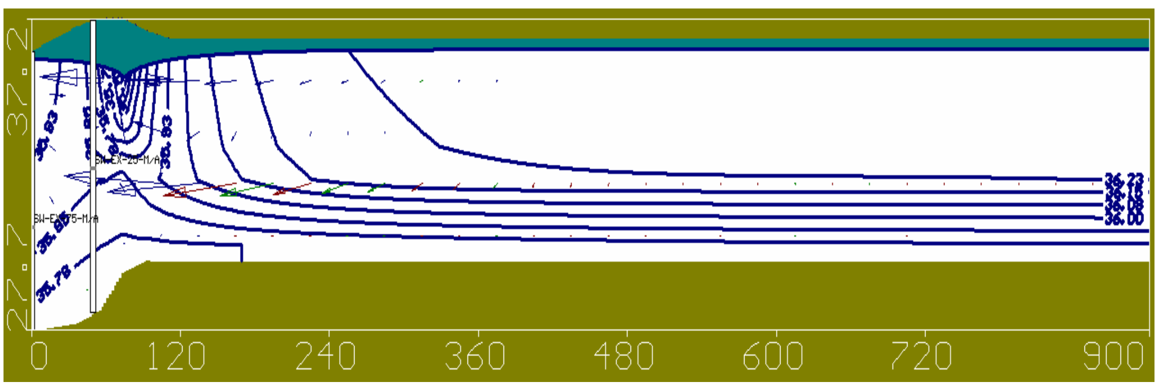

Figure 4.3.23: Equipotential lines on 13 May 2004 from the SW transect extended model

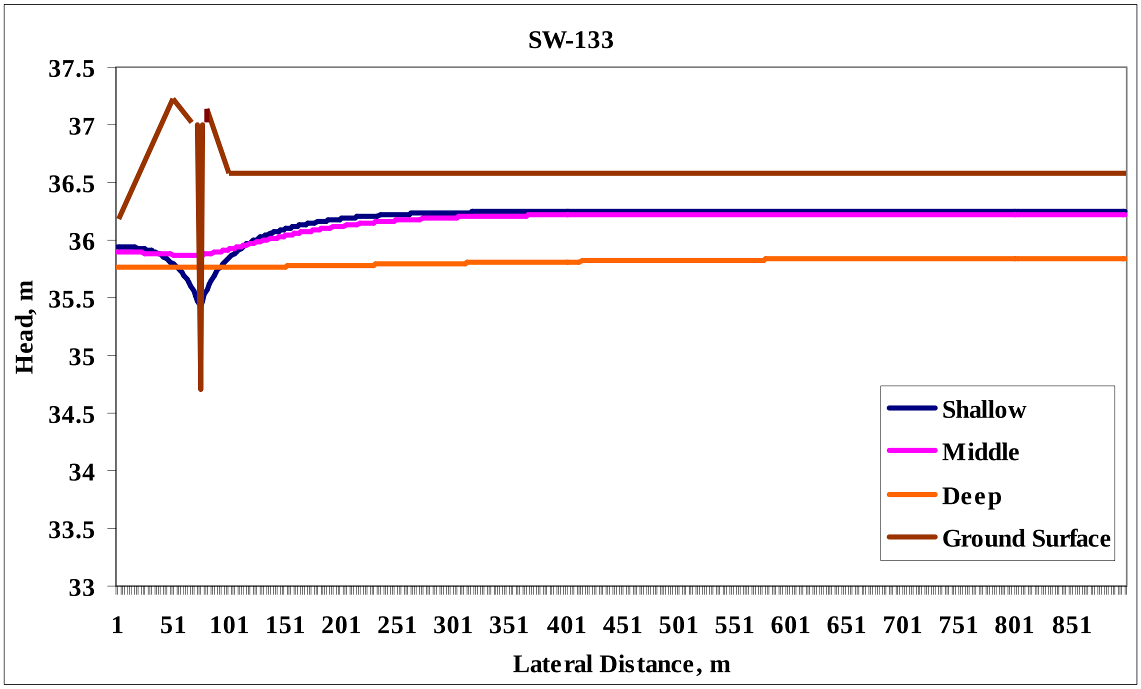

Figure 4.3.24: Heads in the three conducting layers at the SW transect corresponding to dry period (13 May 2004)

Flow analysis suggests outflows from the SW transect (Figures 4.3.22 and 4.3.24). Figure 4.3.25 shows the approximate quantity of groundwater flowing out of the site at the SW transect through the middle and deep sand layers. Figure 4.3.25 also shows total groundwater outflows at the SW transect. As shown in Figure 4.3.25, the amount of groundwater outflow increases as the season changes from winter to summer. The month of June contributes most for outflows and the outflows are least in January. Outflows were approximately 3.09 m^3/m and 0.27 m^3/m through the middle and deep sands. Total outflows through the SW transect were approximately 3.36 m^3/m. Table 4.3.1 gives the summary of daily average flows at the SW transect.

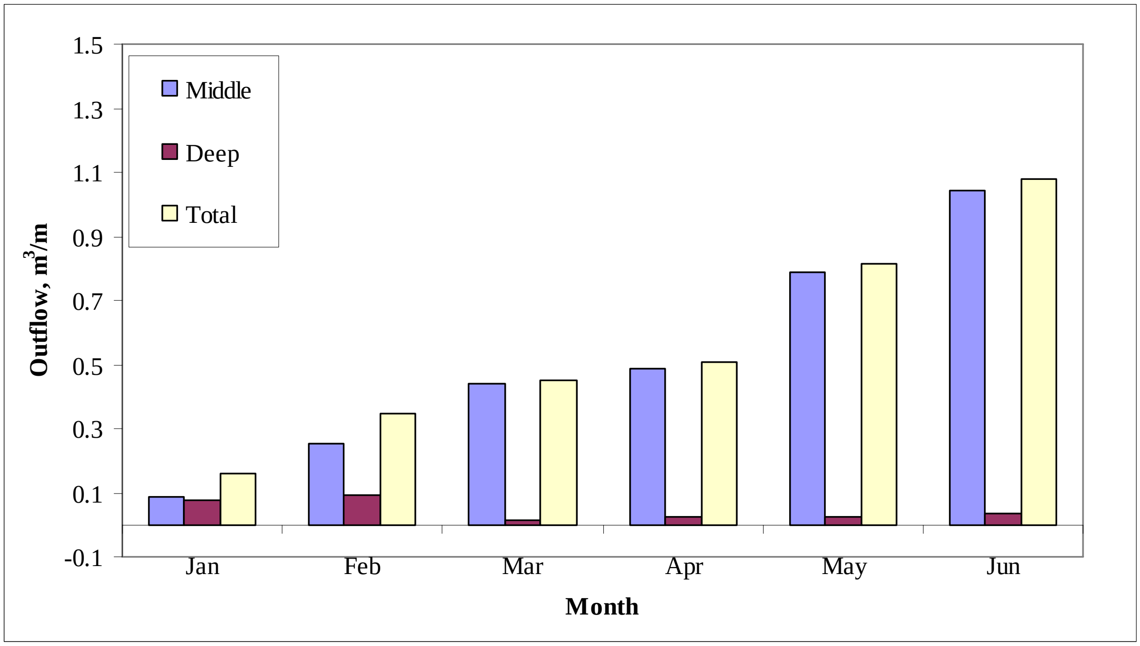

Figure 4.3.25: Outflow rates at the SW transect

Net Groundwater Flow at Juniper Bay

Analyses for the NW, NE, SE, and SW transects were extrapolated to estimate the groundwater flow for the entire Juniper Bay. Monthly flows for the four transects are shown in Figure 4.3.26. The amount of groundwater leaving the site (SW) is relatively small compared to the amount of groundwater entering the site (NW, NE, and SE). Table 4.3.1 gives the summary of groundwater flows at all four transects. Daily averages and totals for the first half of 2004 are presented in Table 4.3.1. The analysis shows that there is a significant amount of groundwater coming into the project site. When these flow values from each transect, are averaged over the full perimeter, total groundwater flows were estimated 0.022 m^3/m of perimeter. When the groundwater flows from individual transects are extrapolated to the entire perimeter, the total inflow for the first part of the year 2004 is estimated to be equivalent to a depth of 125 mm over the entire bay.

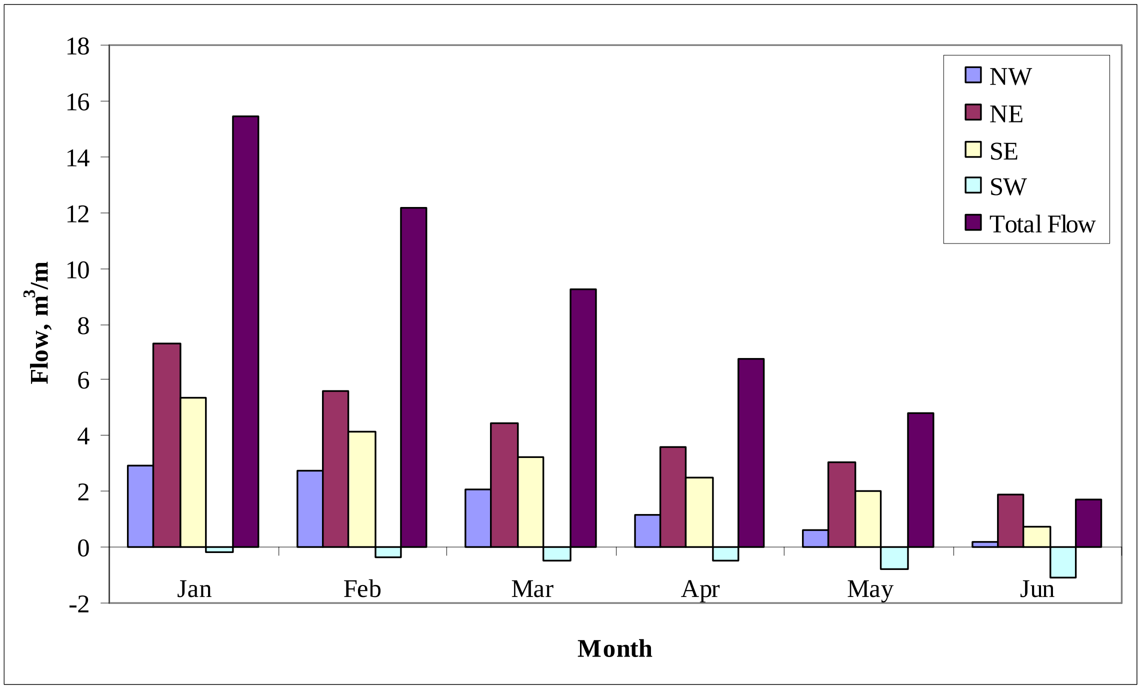

Figure 4.3.26: Comparison of Monthly Groundwater flows at all transects

Table 4.3.1: Summary of Groundwater flows for the first half of 2004

Transect	Sand Layer	Sum m^3/m	Daily Average m^3/m	Daily Max m^3/m	Daily Min m^3/m
	Middle	7.090	0.039	0.083	0.001
	Deep	2.634	0.014	0.028	0.002
NW (Inflow)	Total	9.724	0.053	0.111	0.003
	Middle	21.856	0.122	0.217	0.048
	Deep	4.005	0.022	0.033	0.008
NE (Inflow)	Total	25.862	0.144	0.250	0.056
	Middle	16.308	0.091	0.174	0.015
	Deep	1.559	0.009	0.011	0.002
SE (Inflow)	Total	17.867	0.100	0.185	0.016
	Middle	3.095	0.017	0.038	0.000
	Deep	0.266	0.001	0.003	0.000
SW (Outflow)	Total	3.360	0.019	0.041	0.000

4.4 Summary

The collection of hydraulic head data was started late 2003 and data collection continues to date. Data for the whole year of 2004 was used for modeling subsurface flows. Visual MODFLOW was used to model subsurface flows. Four different groundwater models were developed for the different transects. Models were calibrated using the observed piezometric heads. Absolute maximum error between observed heads and calibrated heads was 0.5 m.

Model results were analyzed separately for the four models for the data of 01 January 2004 to 30 June 2004. Groundwater flows were analyzed for each of the four transects individually, which indicated that the perimeter ditch drains groundwater from either side of it in the surficial and to an extent in the middle sand layers. Analysis indicated groundwater inflow from lower sands at the NW, NE, and SE transects. The SW transect has groundwater outflow in the lower sands. Lateral gradients were higher in the wet periods than in the dry periods.

The models were extended to the center of the bay (800 m) from the perimeter ditch. The center of the bay was modeled as a no-flow boundary. All transects had head gradients towards the perimeter ditch in the surface layer. In the middle layer, the ditch has influence at the NW, and SW transects. At the NE and SE transects, gradients indicate groundwater inflows. Flow in the lower sands at the NW, NE, and SE transects showed groundwater inflow with relatively higher gradients in wet conditions than in dry conditions. The SW transect showed groundwater outflow in the lower sands. Hydraulic trespass into the surrounding areas could be a problem in this area.

Figure 4.4.1 gives a summary of flow directions and the influence of the perimeter ditch. One can observe that the perimeter ditch is influencing flows in the surficial sand layer at all four transects. Influence also extended to middle layers in the NW and SW transects. Table 4.4.1 gives a summary of the lateral extent and depth of influence of the perimeter ditch. The perimeter ditch influences to a maximum extent of approximately 100 m and to a depth of 6–7 m corresponding to the middle sand layer at the NW transect. Influence is to a maximum extent of 75 m at the NE transect and to the depth of 4–5 m (surficial sand layer). The influence of the perimeter ditch is greater in wet periods than in dry periods and the influence is greater toward the outside of the bay. At the SE transect, influence is to the maximum extent of 75 m and to the depth of 4–5 m (surficial sand layer). The outside of the bay is more influenced than the inside of the bay. At the SW transect, the ditch influences to a maximum extent of 100 m inside the bay and 50 m outside the bay. Depth of influence was to the middle sand layer, which is 6–7 m deep from the ground surface.

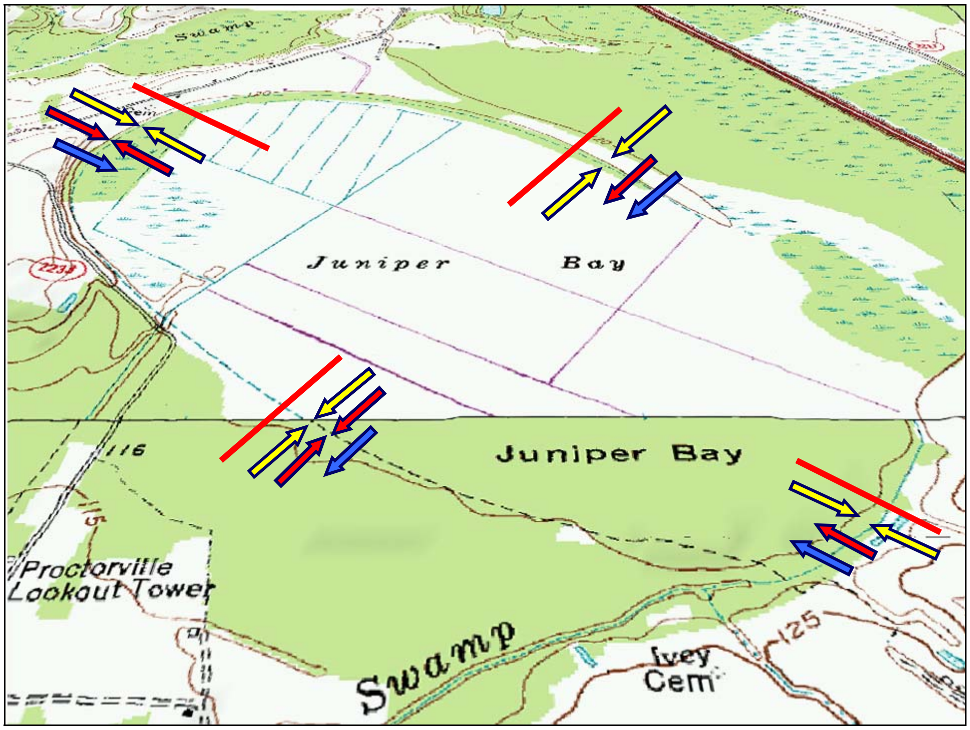

Figure 4.4.1: Summary of flow direction in significant sand layers

Table 4.4.1: Influence of the perimeter ditch

Transect	**Influence of the Perimeter Ditch, m**				
	Inside		**Outside**		**Depth**
	Wet Conditions	**Dry Conditions**	**Wet Conditions**	**Dry Conditions**	
Northwest	75	100	75	75	6 – 7
Northeast	30	50	75	75	4 – 5
Southeast	50	75	75	75	4 – 5
Southwest	100	120	50	50	6 – 8

Chapter 5

Recommendations for Perimeter Ditch Management

This chapter discusses the recommendations for the management of the perimeter ditch at Juniper Bay. It present simulations at the four transects for different scenarios examining options for controlled water levels in the perimeter ditch. It also presents analysis of the effects of various control levels on Juniper Bay and the immediately surrounding areas. Finally, it summarizes the possibilities in maintaining the perimeter ditch to get maximum credits for wetland restoration.

5.1 Control Levels on the Perimeter Ditch

Control levels refer to the water levels in the perimeter ditch that can be maintained by outflow control structures. Control levels were imposed on the perimeter ditch to determine the best options for its maintenance. The extended groundwater models developed for the four transects, which were discussed in chapter 4, were run for different scenarios focused on the perimeter ditch. Control levels in the ditch were input in the model as stage elevation in the ditch. Stage elevations were varied from the elevation of the ditch bottom to the elevation of the ditch top. The analysis of these scenarios will help in determining the critical control levels in the ditch to minimize offsite impacts. The analysis will also help in determining optimum control levels to avoid forming a pond in Juniper Bay instead of a wetland, which seems possible with significant groundwater inflows. The following sections discuss analysis of groundwater flow for different control levels in the ditch, individually for each transect. Control levels used for the analysis are 35.5, 35.7, 35.9, 36.1, 36.3, and 36.5 m MSL. Discussion of flow analysis for individual transects in the following sections have two phases. As a first phase, discussion is focused on analysis of the spatial distribution of heads in the flow domain at the four transects for 15 February 2004 and 13 May 2004, representing wet and dry conditions, respectively. In the second phase, discussion is focused on quantifying groundwater flows and analyzing the temporal distribution of groundwater flows. Later in the chapter, the results from individual transects are extrapolated to estimate approximate net groundwater flows at Juniper Bay relative to different ditch control levels. Positive numbers for net flow represent groundwater inflows to Juniper Bay and negative numbers represent groundwater outflows. From these analyses, critical control levels were obtained at the four transects. Critical control levels are defined as the water levels where the perimeter ditch changes its function from a drainage ditch (sink) to a water-contributing source.

5.2 Analysis of Control Levels at the Northwest (NW) Transect

Analysis of Spatial Distribution of heads at the NW Transect

The simulation results were analyzed to determine the effect of the perimeter ditch control levels on the flows in the surficial sand layer, middle sand layer, and deep sand layer. Figures 5.2.1 and 5.2.2 show head distributions in the flow domain from various scenarios on 15 February 2004 and 13 May 2004, respectively. The analysis showed that the ditch level above 36.3 m at NW transect would reverse the drainage function of the perimeter ditch. Water levels higher than 36.3 m would make the perimeter ditch function as a recharge point instead of a drainage ditch.

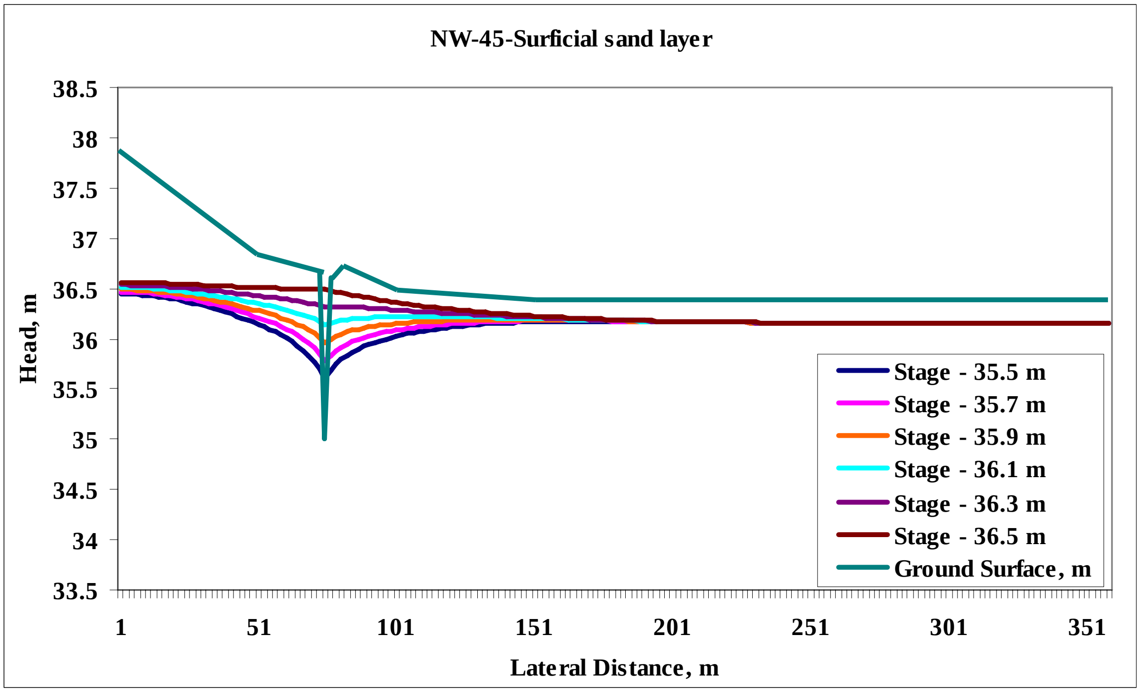

Figure 5.2.1: Spatial distribution of heads in surficial sand layer at the NW transect for different ditch control levels on 15 February 2004

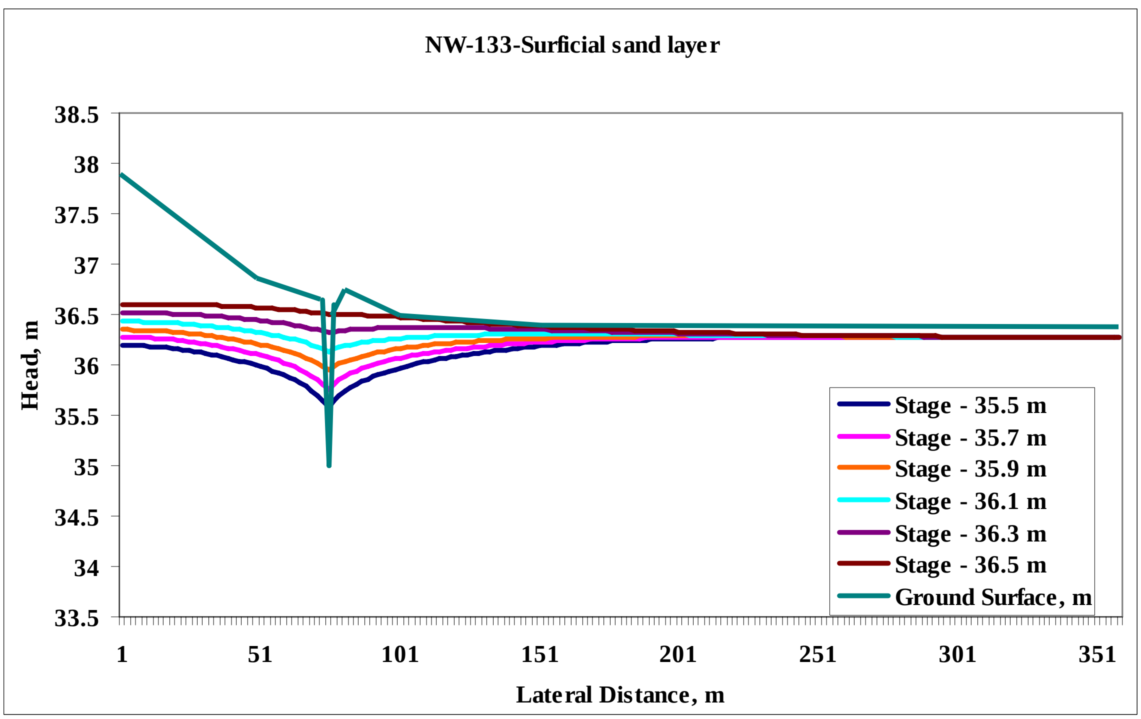

Figure 5.2.2: Spatial distribution of heads in surficial sand layer at the NW transect for different ditch control levels on 13 May 2004

In a similar manner, analysis from the middle sand layer, as shown in Figures 5.2.3 and 5.2.4, indicate that increases in the ditch control level increase the gradient from exterior to interior of the bay and decreases the influence of the perimeter ditch on groundwater flows. In the deep sand layers, as shown in Figures 5.2.5 and 5.2.6, control levels have very little effect on groundwater flows.

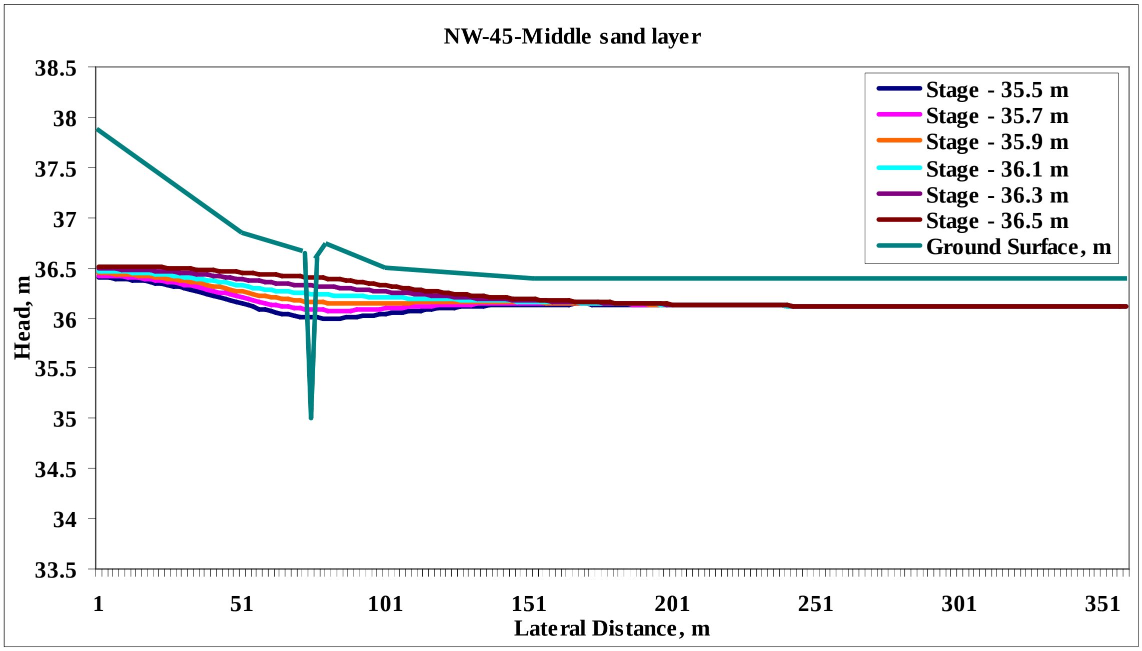

Figure 5.2.3: Spatial distribution of heads in middle sand layer at the NW transect for different ditch control levels on 15 February 2004

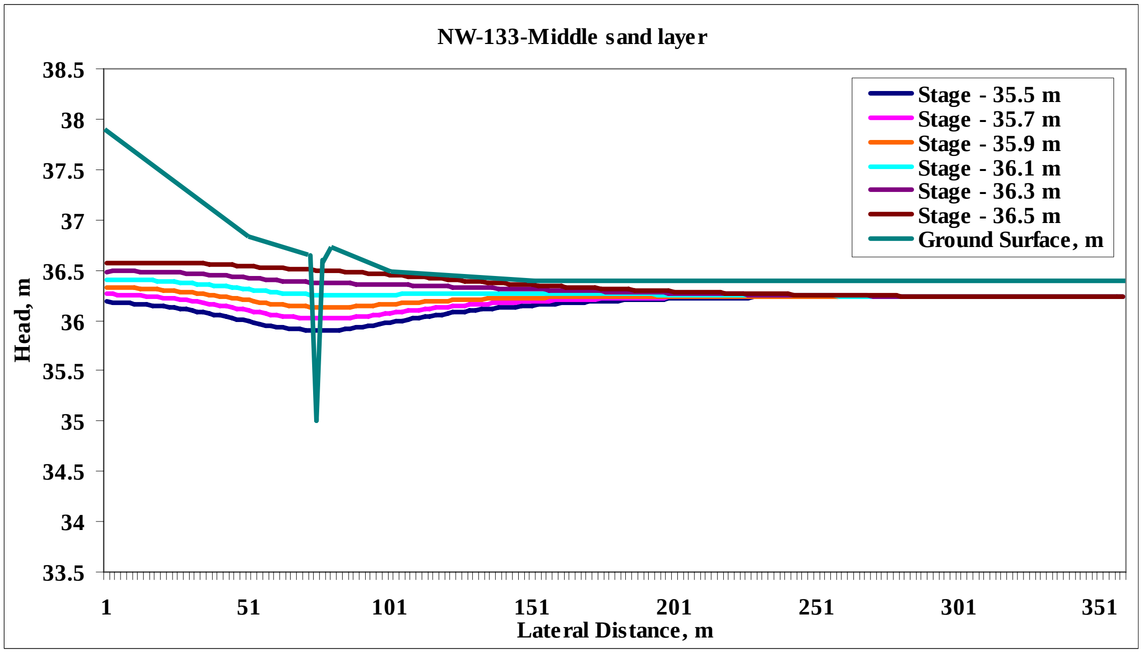

Figure 5.2.4: Spatial distribution of heads in middle sand layer at the NW transect for different ditch control levels on 13 May 2004

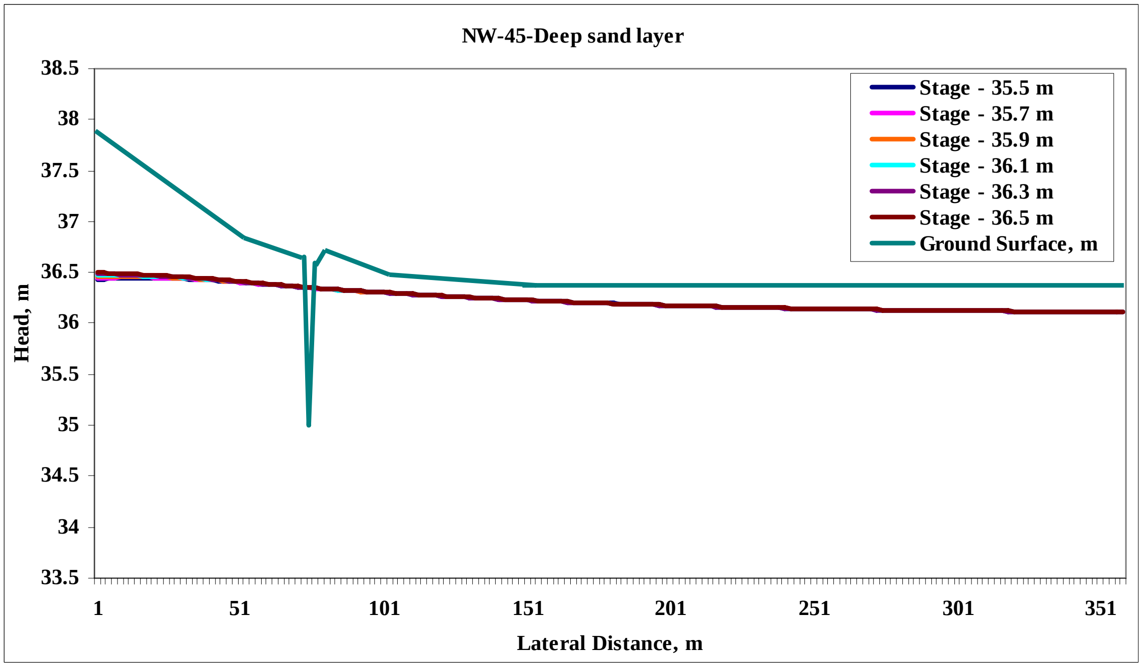

Figure 5.2.5: Spatial distribution of heads in deep sand layer at the NW transect for different ditch control levels on 15 February 2004

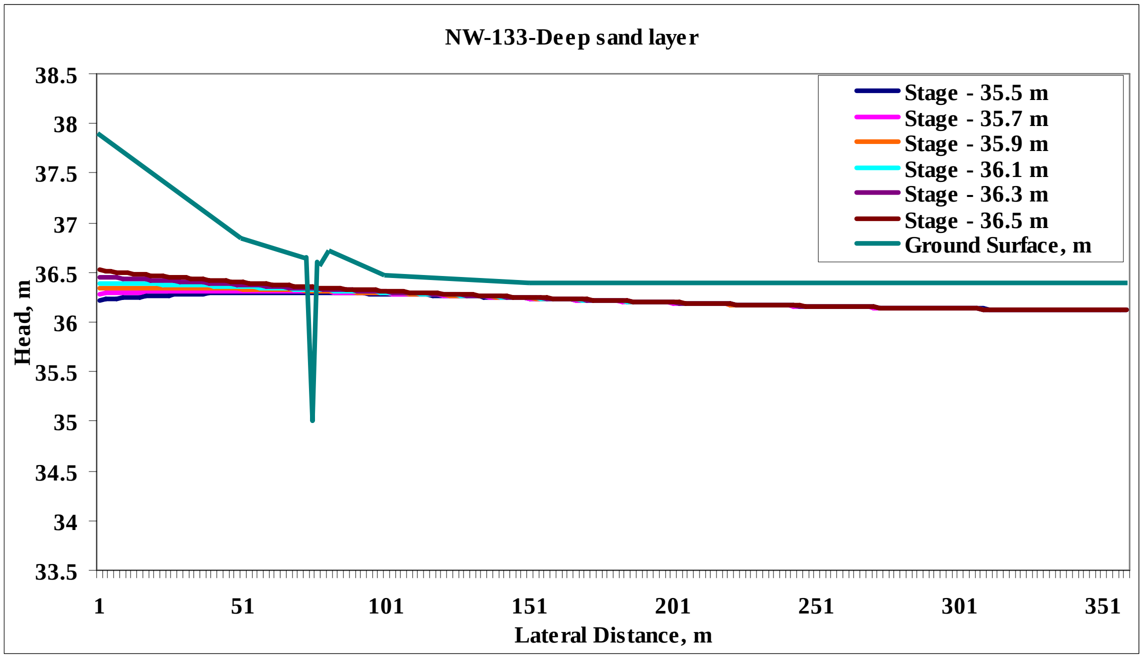

Figure 5.2.6: Spatial distribution of heads in deep sand layer at the NW transect for different ditch control levels on 13 May 2004

Net Groundwater Flows at the NW Transect

Net groundwater flows, as shown in Figure 5.2.7, suggest that increases in ditch water level increase inflows significantly in the middle sand and slightly in the deep sand layer. The monthly estimates of groundwater flows presented in Table 5.2.1, indicate the effect of water level elevations on groundwater flows in the middle and deep sand layers. The monthly distribution of groundwater flows suggest that the effect of the control level is less in winter months compared to summer months of year 2004. The percentage increase in flows relative to increase in water levels is highest in June 2004 and lowest in January 2004.

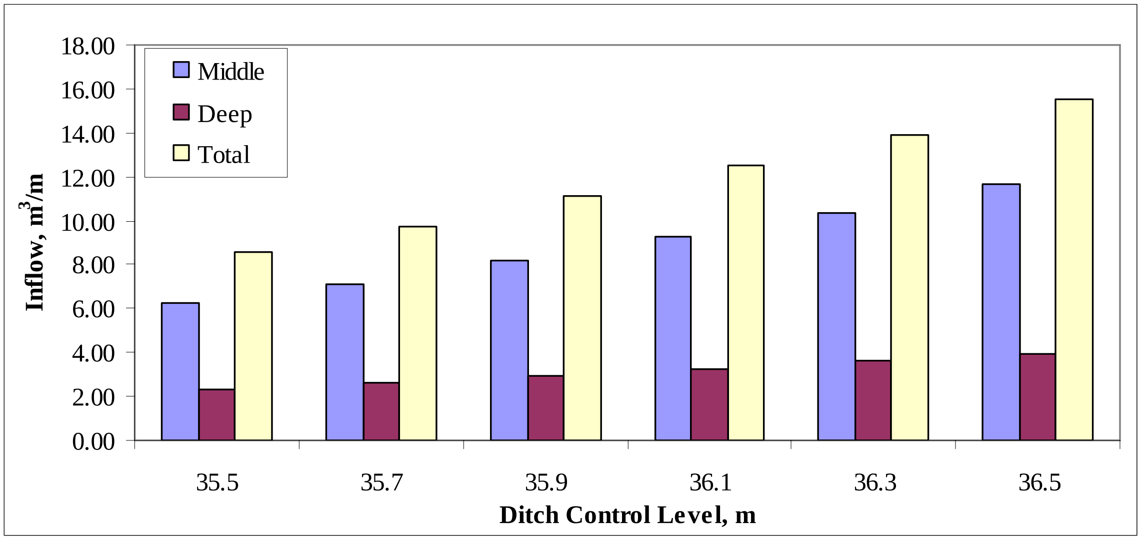

Figure 5.2.7: Net inflows at the NW transect from different control levels

Table 5.2.1: Net flow at the NW transect for different control levels

Ditch Control Level, m MSL	Month	Net Inflow, m^3/m		
		Middle	**Deep**	**Total**
35.5	Jan	2.05	0.86	2.91
	Feb	1.99	0.66	2.64
	Mar	1.40	0.47	1.87
	Apr	0.63	0.26	0.90
	May	0.15	0.09	0.24
	Jun	0.02	0.00	0.02
	Total	**6.24**	**2.35**	**8.58**
35.7	Jan	2.08	0.87	2.94
	Feb	2.07	0.67	2.74
	Mar	1.56	0.50	2.06
	Apr	0.86	0.32	1.18
	May	0.42	0.18	0.61
	Jun	0.10	0.08	0.18
	Total	**7.09**	**2.63**	**9.72**
35.9	Jan	2.12	0.87	2.99
	Feb	2.14	0.68	2.82
	Mar	1.71	0.53	2.24
	Apr	1.08	0.38	1.46
	May	0.71	0.28	0.98
	Jun	0.41	0.20	0.61
	Total	**8.16**	**2.94**	**11.10**
36.1	Jan	2.16	0.87	3.03
	Feb	2.21	0.69	2.90
	Mar	1.86	0.57	2.43
	Apr	1.30	0.45	1.74
	May	0.99	0.37	1.36
	Jun	0.72	0.32	1.04
	Total	**9.23**	**3.26**	**12.49**
36.3	Jan	2.19	0.87	3.06
	Feb	2.28	0.69	2.98
	Mar	2.01	0.60	2.61
	Apr	1.51	0.51	2.03
	May	1.27	0.48	1.75
	Jun	1.05	0.44	1.50
	Total	**10.32**	**3.59**	**13.91**
36.5	Jan	2.26	0.87	3.13
	Feb	2.35	0.70	3.05
	Mar	2.16	0.63	2.79
	Apr	1.73	0.58	2.31
	May	1.59	0.58	2.17
	Jun	1.53	0.57	2.11
	Total	**11.63**	**3.93**	**15.56**

5.3 Analysis of control levels at the Northeast (NE) Transect

Analysis of Spatial Distribution of Heads at the NE Transect

Figures 5.3.1 and 5.3.2 show spatial distributions of the heads in the surficial sand layer for various ditch water levels. One can observe that the influence of the perimeter ditch, located at lateral distance of 75 m in the flow domain, has changed its function for water surface elevations of 36.3 m or higher both on 15 February 2004 and 13 May 2004. Therefore, the ditch water level of 36.3 m would be critical, as the perimeter ditch converts into a water-contributing source instead of a drainage ditch.

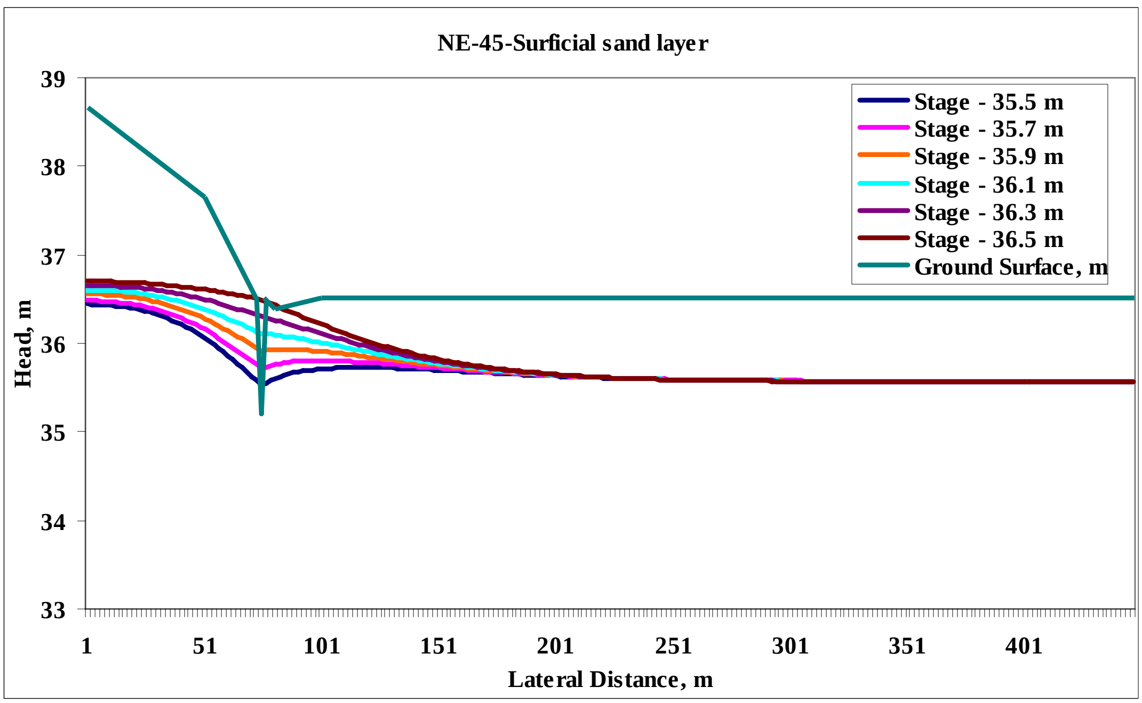

Figure 5.3.1: Spatial distribution of heads in surficial sand layer at the NE transect for different ditch control levels on 15 February 2004

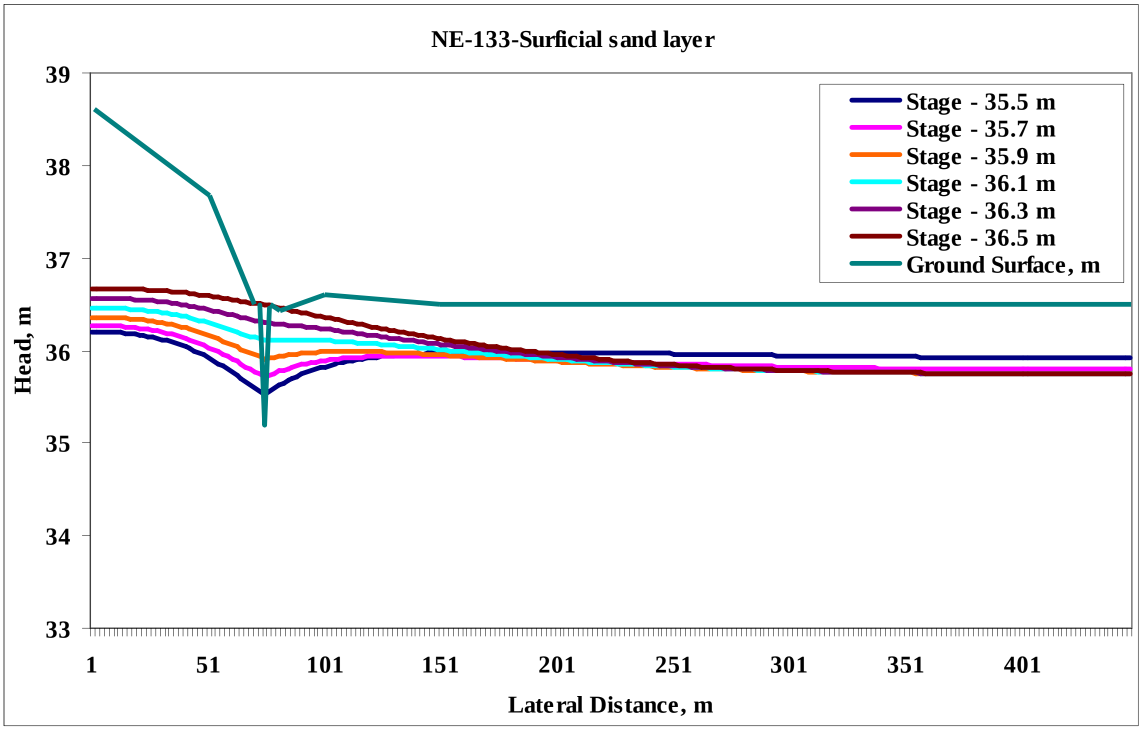

Figure 5.3.2: Spatial distribution of heads in surficial sand layer at the NE transect for different ditch control levels on 13 May 2004

Figures 5.3.3 and 5.3.4 show heads in the middle sand layer for 15 February 2004 and 13 May 2004 respectively. The influence of ditch water level is larger on 13 May 2004. Head gradient increases with increase in water level elevation. One can observe a similar pattern in the deep sand layer also, shown in Figures 5.3.5 and 5.3.6, except that the head gradients are smaller when compared to the middle sand layer.

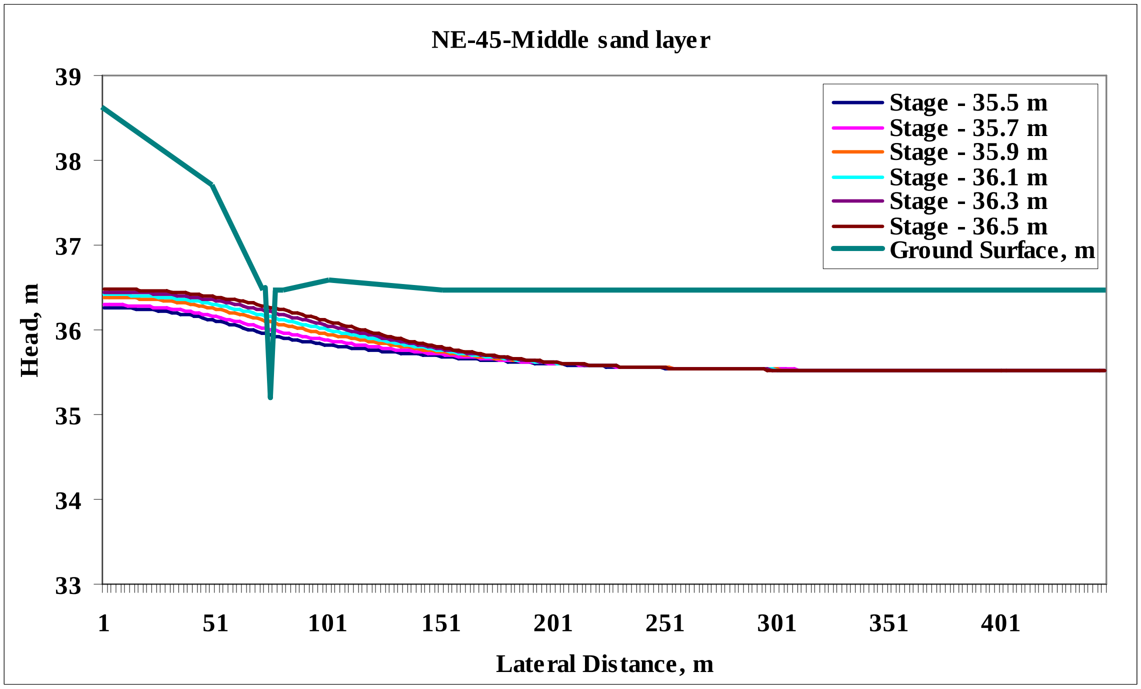

Figure 5.3.3: Spatial distribution of heads in middle sand layer at the NE transect for different ditch control levels on 15 February 2004

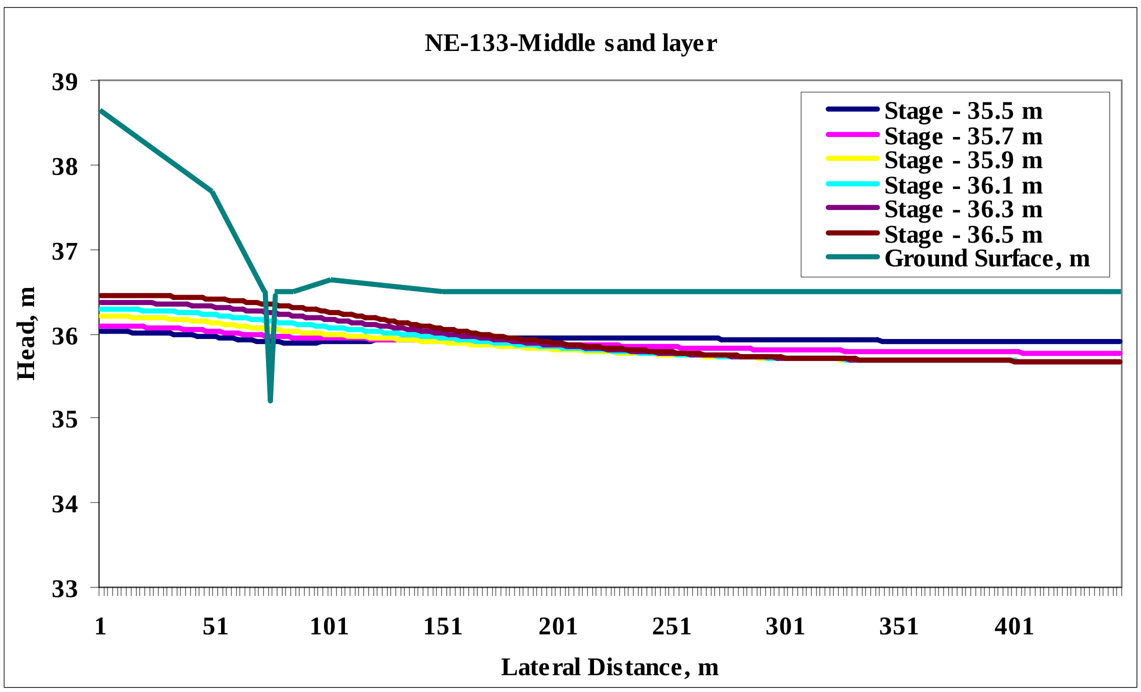

Figure 5.3.4: Spatial distribution of heads in middle sand layer at the NE transect for different ditch control levels on 13 May 2004

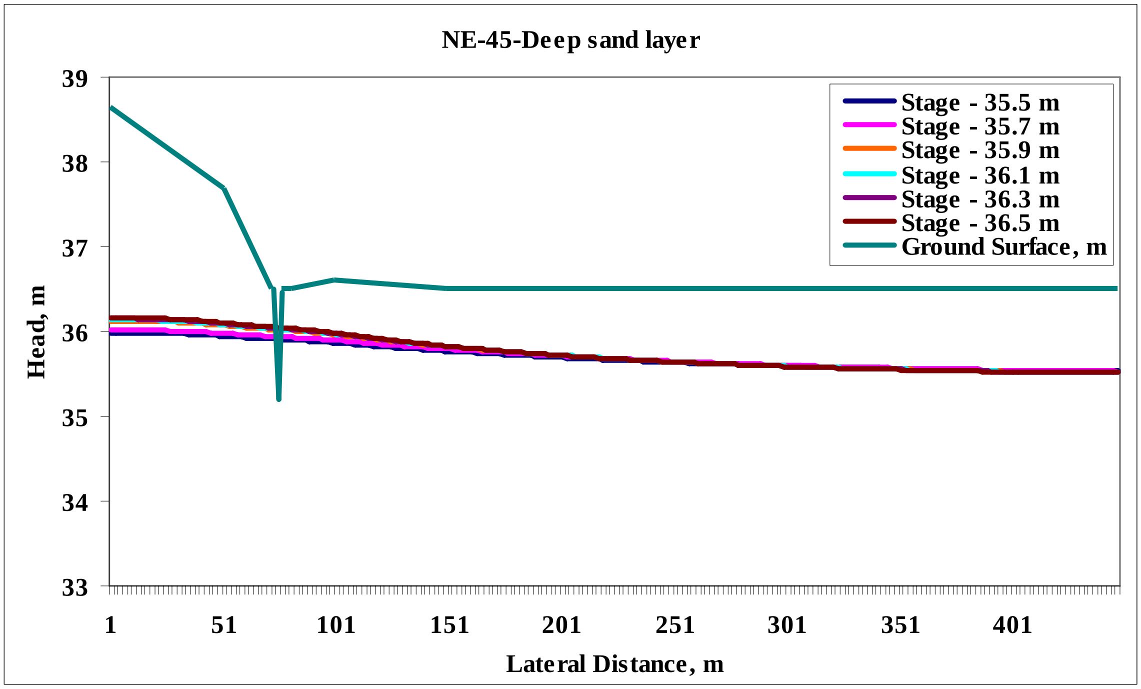

Figure 5.3.5: Spatial distribution of heads in deep sand layer at the NE transect for different ditch control levels on 15 February 2004

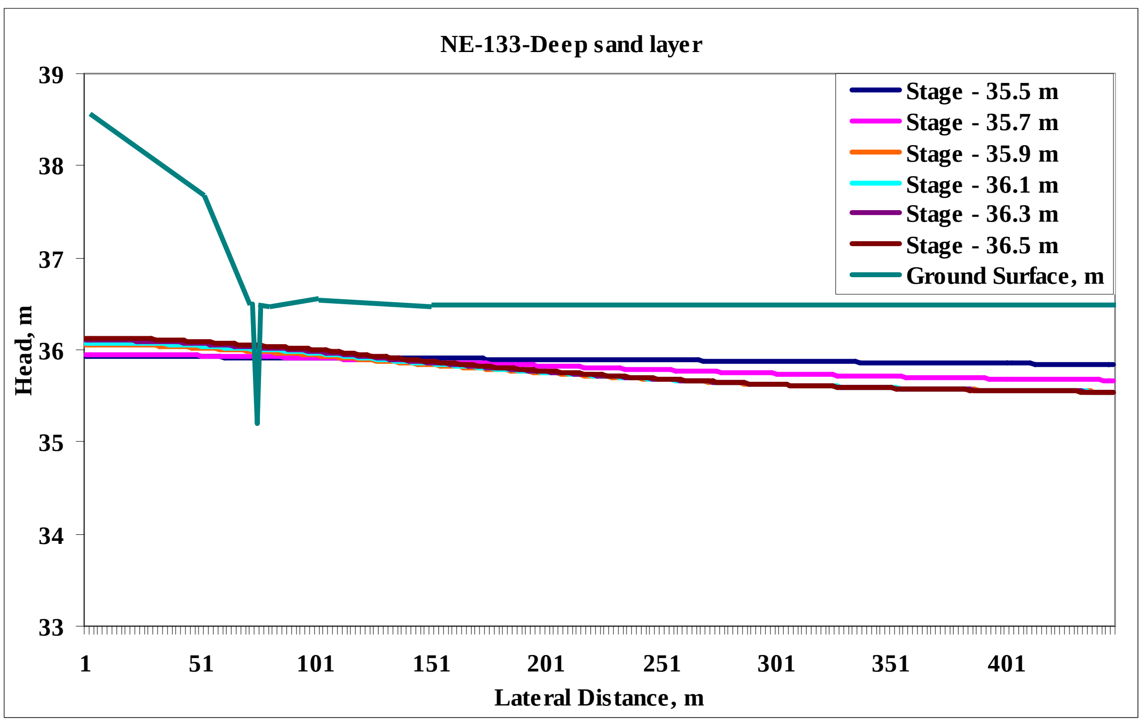

Figure 5.3.6: Spatial distribution of heads in deep sand layer at the NE transect for different ditch control levels on 13 May 2004

Net Groundwater Flows at the NE transect

Net flow estimates for each scenario are shown in Figure 5.3.7. One can observe that net groundwater inflows increase with increase in water level in the ditch. Monthly inflow estimates are given in Table 5.3.1. It can be observed that there is an increase in groundwater flows with an increase in water level in the ditch, and percentage increase is lower in winter months when compared to summer months. The lowest percentage of increase in inflows corresponds to January 2004, whereas the highest percentage of increase corresponds to June 2004.

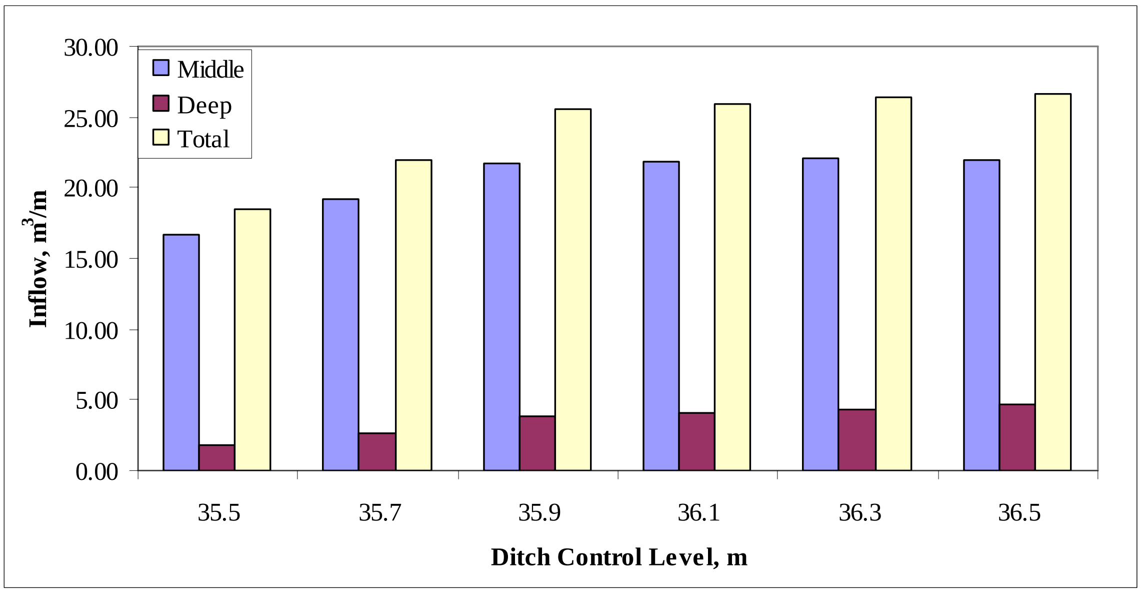

Figure 5.3.7: Net inflows at the NE transect from different control levels

Table 5.3.1: Net flow at the NE transect for different control levels

Ditch Control Levels, m MSL	**Month**	**Inflow, m^3/m**		
		Middle	**Deep**	**Total**
35.5	Jan	5.88	0.64	6.52
	Feb	4.58	0.56	5.14
	Mar	2.50	0.26	2.75
	Apr	2.10	0.25	2.35
	May	1.15	0.10	1.25
	Jun	0.51	0.01	0.52
	Total	**16.72**	**1.82**	**18.53**
35.7	Jan	5.83	0.65	6.48
	Feb	4.59	0.60	5.18
	Mar	3.54	0.56	4.10
	Apr	2.75	0.50	3.25
	May	1.58	0.23	1.81
	Jun	0.98	0.12	1.10
	Total	**19.26**	**2.65**	**21.91**
35.9	Jan	6.36	0.94	7.30
	Feb	4.85	0.80	5.65
	Mar	3.74	0.71	4.45
	Apr	2.94	0.63	3.56
	May	2.41	0.58	2.99
	Jun	1.42	0.24	1.66
	Total	**21.71**	**3.90**	**25.61**
36.1	Jan	6.37	0.98	7.35
	Feb	4.78	0.82	5.60
	Mar	3.69	0.73	4.42
	Apr	2.94	0.64	3.58
	May	2.46	0.61	3.06
	Jun	1.63	0.31	1.94
	Total	**21.86**	**4.09**	**25.95**
36.3	Jan	6.41	1.05	7.46
	Feb	4.71	0.85	5.57
	Mar	3.64	0.75	4.39
	Apr	2.93	0.67	3.60
	May	2.51	0.63	3.14
	Jun	1.84	0.40	2.24
	Total	**22.04**	**4.36**	**26.40**
36.5	Jan	6.39	1.12	7.51
	Feb	4.59	0.88	5.48
	Mar	3.55	0.77	4.32
	Apr	2.91	0.69	3.59
	May	2.55	0.66	3.20
	Jun	1.93	0.55	2.48
	Total	**21.92**	**4.66**	**26.59**

5.4 Analysis of Control Levels at the Southeast (SE) Transect

Analysis of Spatial Distribution of Heads at the SE Transect

Figures 5.4.1 and 5.4.2 show head distributions in the surficial sand layer at SE transect for 15 February 2004 and 13 May 2004, respectively. The analysis in the surficial sand layer suggest that 36.3 m will be the critical water level elevation in the perimeter ditch, above which the ditch acts as a recharge source rather than a drainage ditch. As the water level approached 36.5 m, head gradients indicate there will be flow coming into the site in the surficial sand layer.

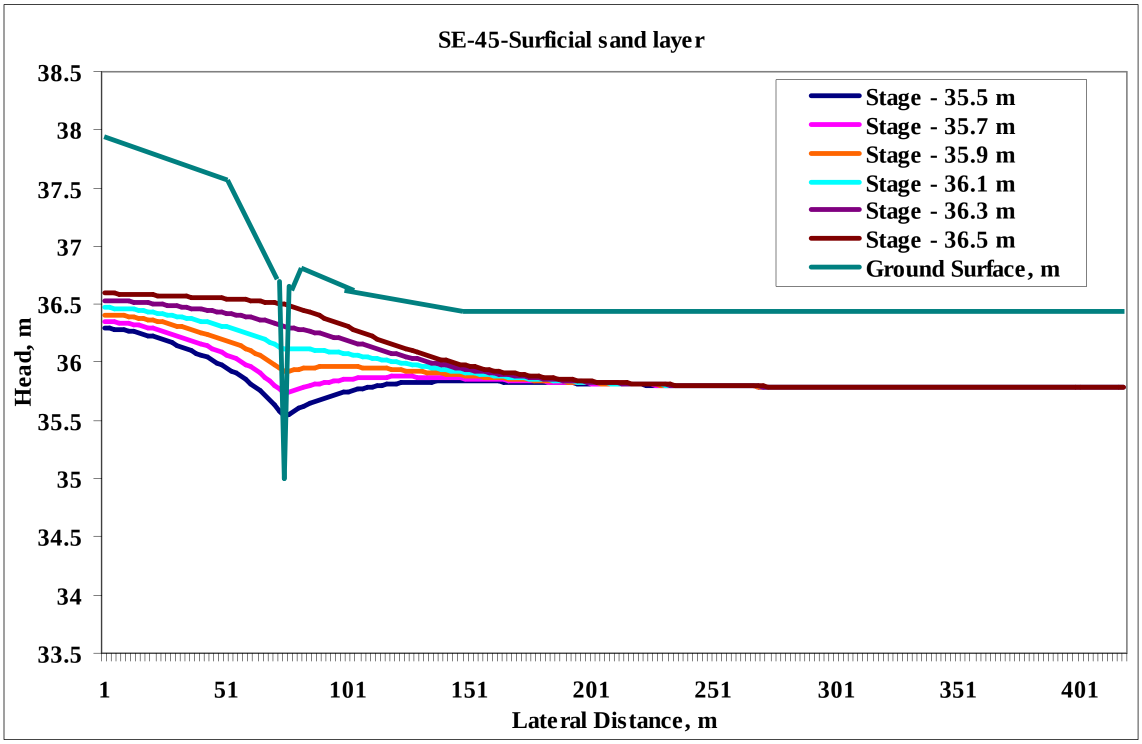

Figure 5.4.1: Spatial distribution of heads in surficial sand layer at the SE transect for different ditch control levels on 15 February 2004

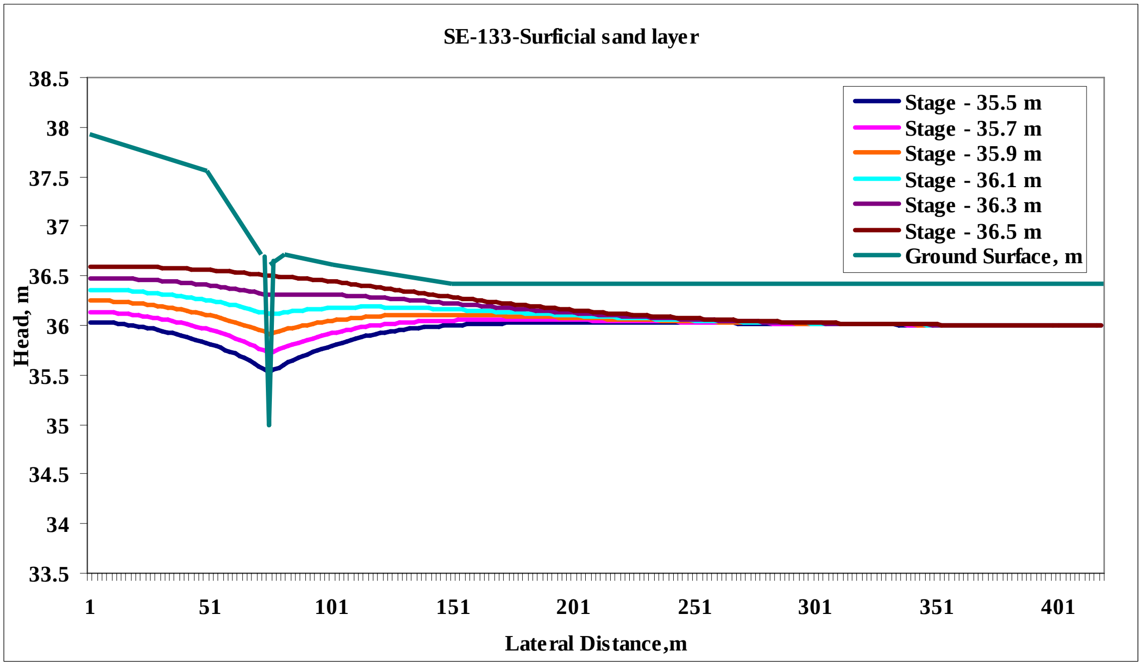

Figure 5.4.2: Spatial distribution of heads in surficial sand layer at the SE transect for different ditch control levels on 13 May 2004

The influence in the middle sand layer of water level elevation is larger in summer months (Figure 5.4.4) when compared to winter months (Figure 5.4.3). Hydraulic head gradients increase with the increase in water levels in the ditch. Figures 5.4.5 and 5.4.6 suggest that water levels in the perimeter ditch have no significant influence on the flows in deep sand layers.

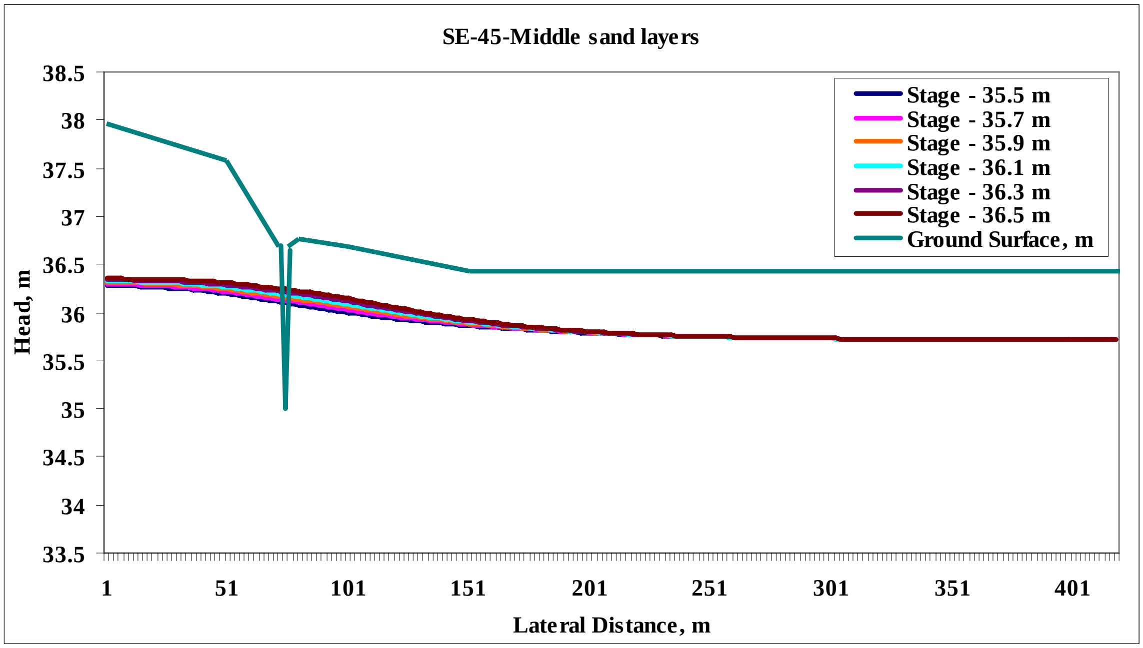

Figure 5.4.3: Spatial distribution of heads in middle sand layer at the SE transect for different ditch control levels on 15 February 2004

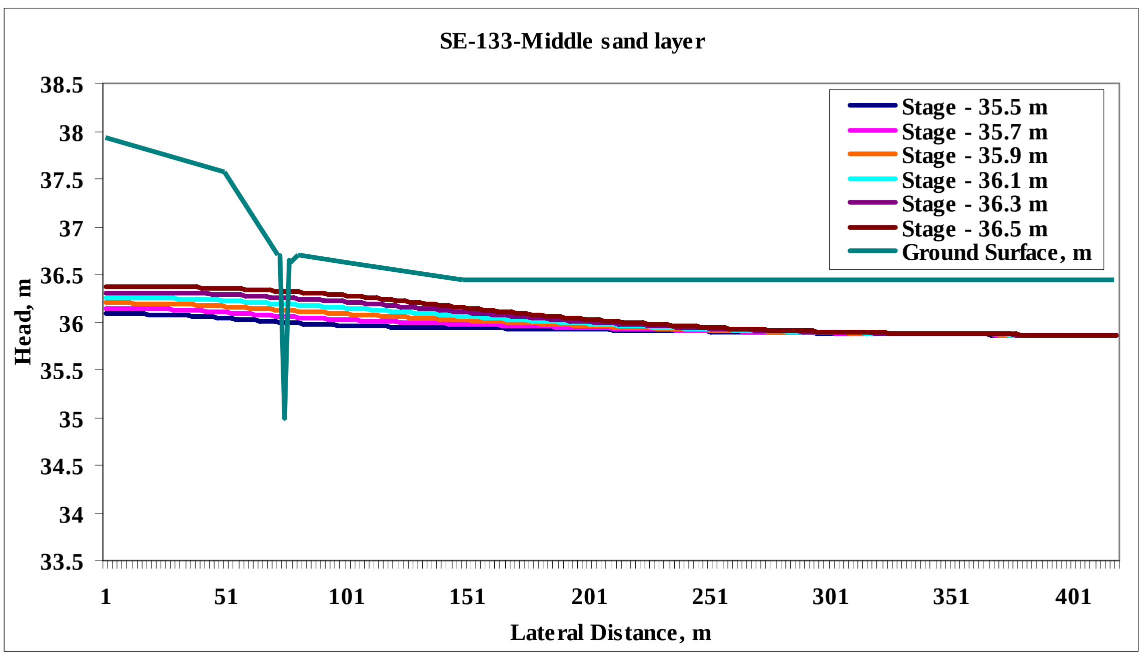

Figure 5.4.4: Spatial distribution of heads in middle sand layer at the SE transect for different ditch control levels on 13 May 2004

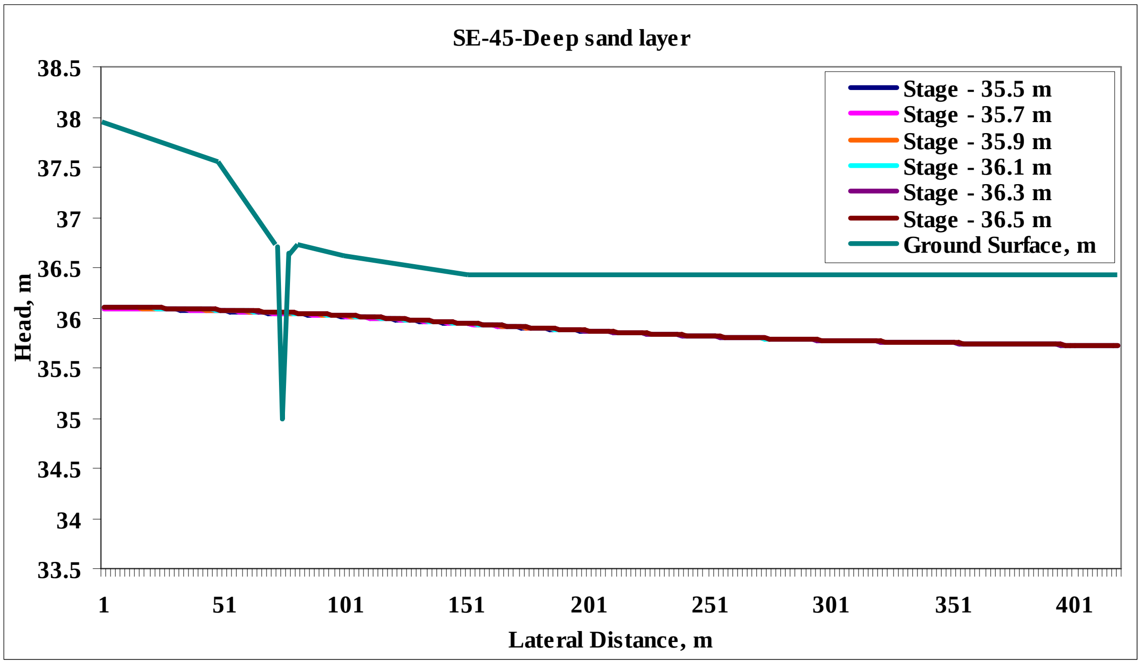

Figure 5.4.5: Spatial distribution of heads in deep sand layer at the SE transect for different ditch control levels on 15 February 2004

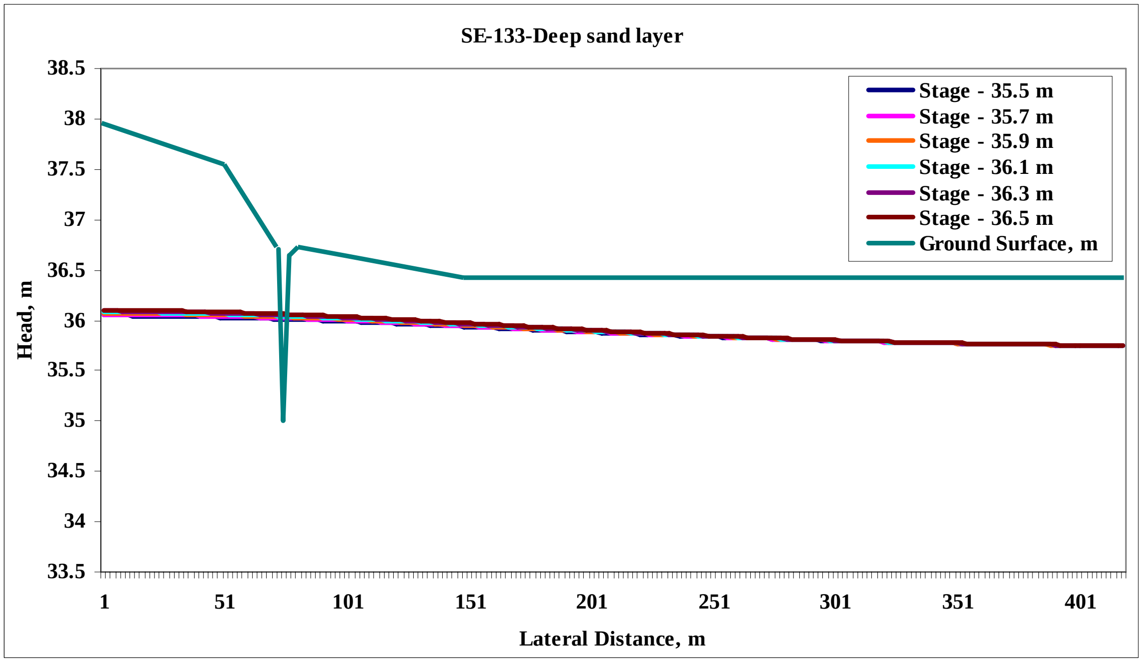

Figure 5.4.6: Spatial distribution of heads in deep sand layer at the SE transect for different ditch control levels on 13 May 2004

Net Groundwater Flows at the SE Transect

The net flows at the SE transect from various scenarios are shown in Figure 5.4.7. Figure 5.4.7 illustrates that the perimeter ditch water level elevation does not have a significant influence on net groundwater flows at the SE transect.

The flow estimates given in Table 5.4.1 indicate that flows in the middle sand layer decrease with increases in water level in the ditch whereas the flows in the deep sand layers increase with increases in water level in the ditch. Percentage changes of flows in the middle and deep sand layers are small.

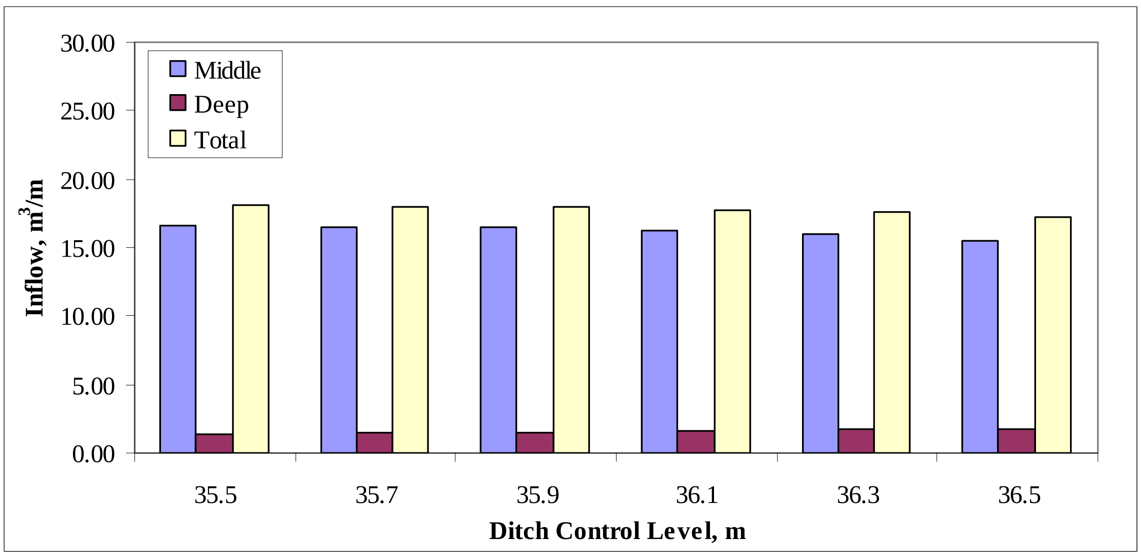

Figure 5.4.7: Net inflows at the SE transect from different control levels

Table 5.4.1: Net flow at the SE transect for different control levels

Ditch Control Level, m MSL	**Month**	**Net Inflow, m^3/m**		
		Middle	**Deep**	**total**
35.5	Jan	5.17	0.34	5.51
	Feb	4.12	0.31	4.43
	Mar	3.18	0.29	3.47
	Apr	2.40	0.25	2.65
	May	1.80	0.23	2.03
	Jun	-0.01	-0.01	-0.02
	Total	**16.66**	**1.41**	**18.07**
35.7	Jan	5.11	0.34	5.45
	Feb	4.00	0.31	4.31
	Mar	3.08	0.29	3.37
	Apr	2.33	0.26	2.59
	May	1.78	0.24	2.02
	Jun	0.24	0.03	0.27
	Total	**16.54**	**1.47**	**18.01**
35.9	Jan	5.06	0.34	5.39
	Feb	3.88	0.31	4.19
	Mar	2.97	0.29	3.26
	Apr	2.27	0.27	2.53
	May	1.76	0.25	2.01
	Jun	0.50	0.07	0.57
	Total	**16.43**	**1.53**	**17.96**
36.1	Jan	4.98	0.34	5.32
	Feb	3.73	0.31	4.04
	Mar	2.84	0.30	3.13
	Apr	2.18	0.27	2.45
	May	1.72	0.26	1.98
	Jun	0.75	0.12	0.87
	Total	**16.19**	**1.60**	**17.79**
36.3	Jan	4.91	0.34	5.24
	Feb	3.57	0.32	3.89
	Mar	2.70	0.30	3.00
	Apr	2.08	0.28	2.36
	May	1.67	0.27	1.94
	Jun	1.00	0.18	1.18
	Total	**15.93**	**1.68**	**17.61**
36.5	Jan	4.80	0.34	5.15
	Feb	3.40	0.32	3.72
	Mar	2.55	0.30	2.85
	Apr	1.98	0.28	2.26
	May	1.62	0.28	1.89
	Jun	1.13	0.24	1.37
	Total	**15.48**	**1.76**	**17.24**

5.5 Analysis of Control Levels at the Southwest (SW) Transect

Analysis of Spatial Distribution of Heads at the SW transect

Figures 5.5.1 and 5.5.2 show head distributions in the surficial sand layer at the SW transect for 15 February 2004 and 13 May 2004, respectively. The analysis of the surficial sand layer suggests that a water level above 35.7 m, in wet conditions, will be critical because the ditch will recharge surrounding areas. In dry conditions, 13 May, the critical level will be 36.1 m and water is above the ground surface towards the outside of the bay. This suggests that the ditch water level should be maintained at 35.9 m or lower to avoid causing an excessively high water table in the adjacent land.

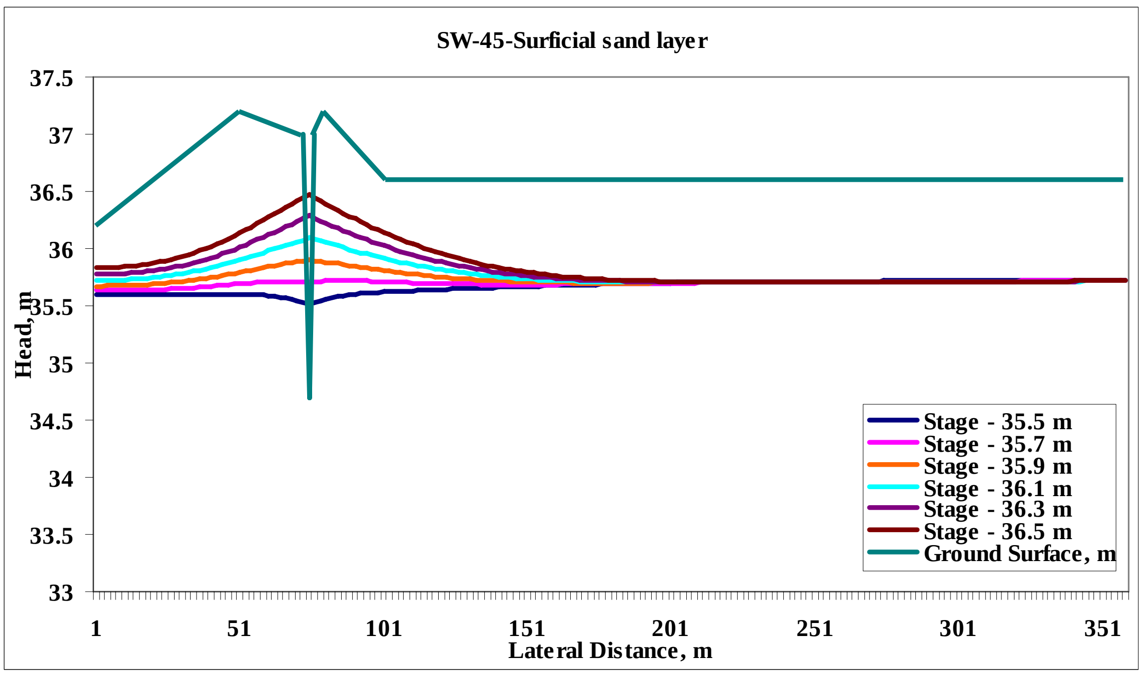

Figure 5.5.1: Spatial distribution of heads in surficial sand layer at the SW transect for different ditch control levels on 15 February 2004

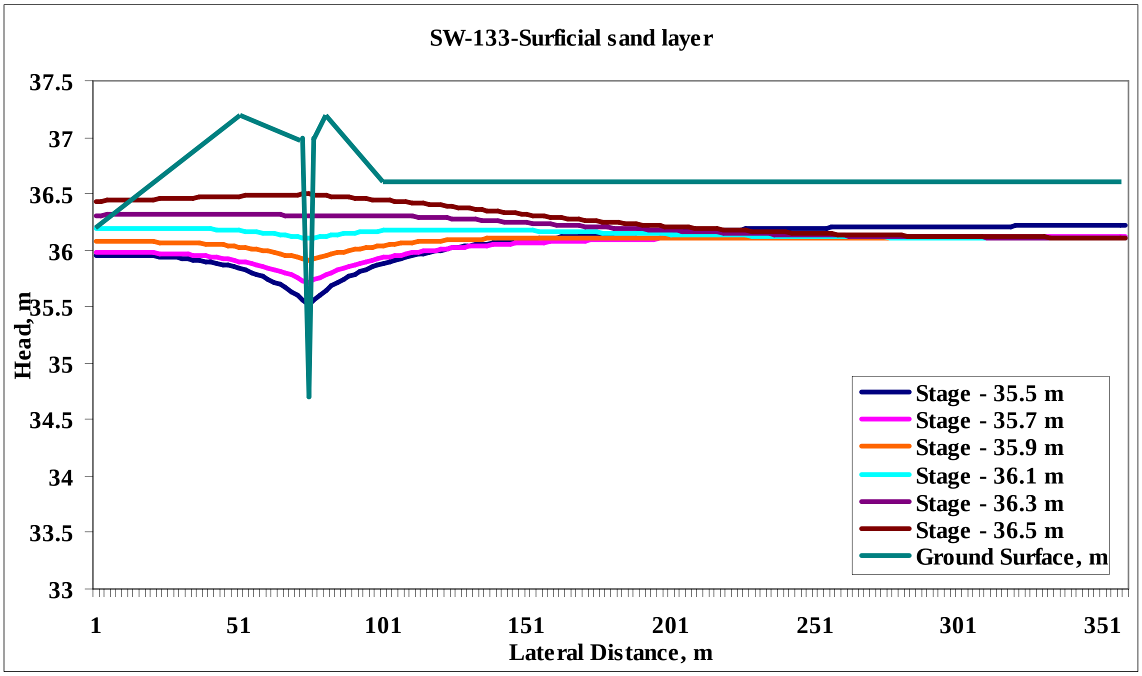

Figure 5.5.2: Spatial distribution of heads in surficial sand layer at the SW transect for different ditch control levels on 13 May 2004

Figures 5.5.3 and 5.5.4 show head distributions in the middle sand layers. One can observe that increasing the water level in the ditch is effective in changing the direction of flow at the SW transect. For dry conditions (13 May 2004), a ditch water level above 35.9 m suggests groundwater flows towards the interior of the bay, reversing the flow direction. Figures 5.5.5 and 5.5.6 indicate that the groundwater flows in the deep sand layers are not affected by the change in water levels in the perimeter ditch. As an interesting observation, the influence of the perimeter ditch in the middle layer is relatively higher at 35.5 m, as shown in Figure 5.5.4. This could be because of the deeper perimeter ditch at the SW transects and relatively low water level in the ditch.

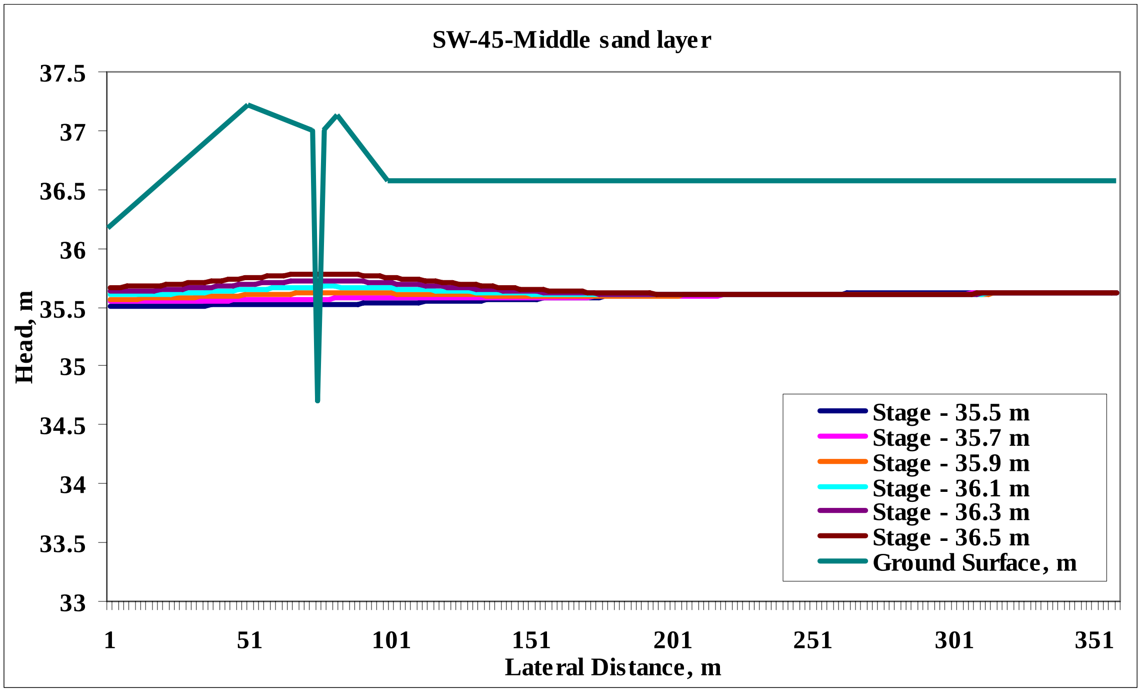

Figure 5.5.3: Spatial distribution of heads in middle sand layer at the SW transect for different ditch control levels on 15 February 2004

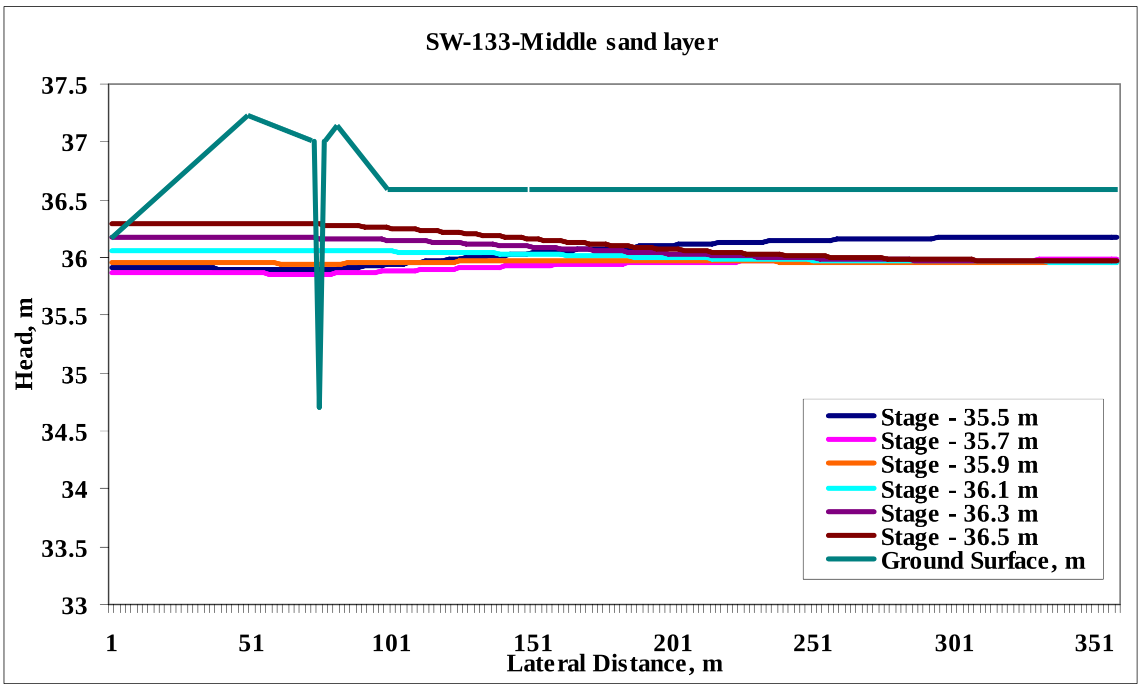

Figure 5.5.4: Spatial distribution of heads in middle sand layer at the SW transect for different ditch control levels on 13 May 2004

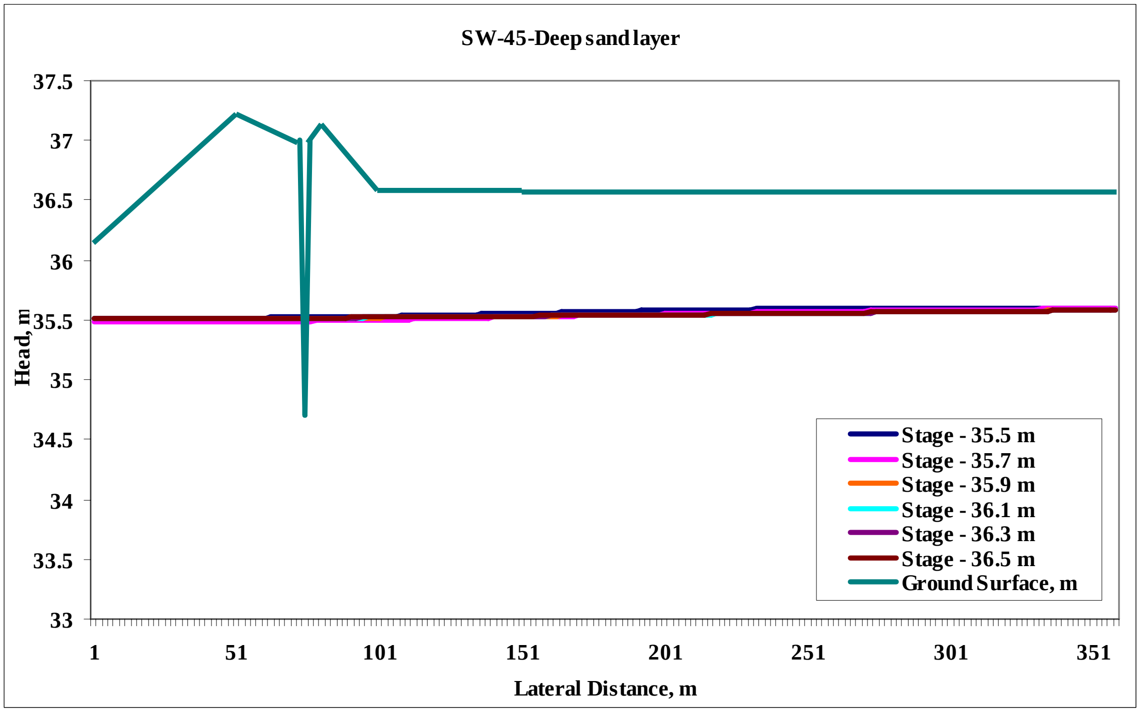

Figure 5.5.5: Spatial distribution of heads in deep sand layer at the SW transect for different ditch control levels on 15 February 2004

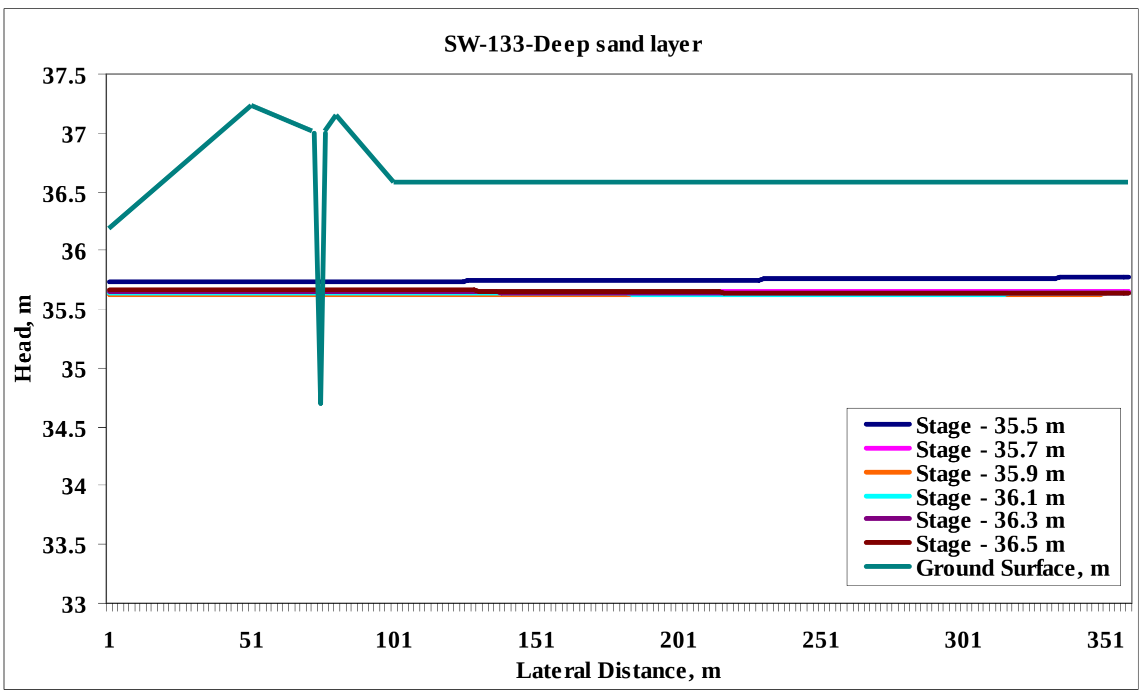

Figure 5.5.6: Spatial distribution of heads in deep sand layer at the SW transect for different ditch control levels on 13 May 2004

Net Groundwater Flows at the SW Transect

The net flow estimates at the SW transect, as shown in Figure 5.5.7, indicate that for any water level higher than 35.9 m there will be a net groundwater inflow into the site. Table 5.5.1 presents the net groundwater flows at the SW transect in the middle and deep sand layers. One can observe that the net groundwater flow increases with the increase in water level in the ditch. Control levels that are 35.9 m or lower will produce groundwater outflows at the SW transect. A control level of 36.1 m or above would produce groundwater inflows at the SW transect.

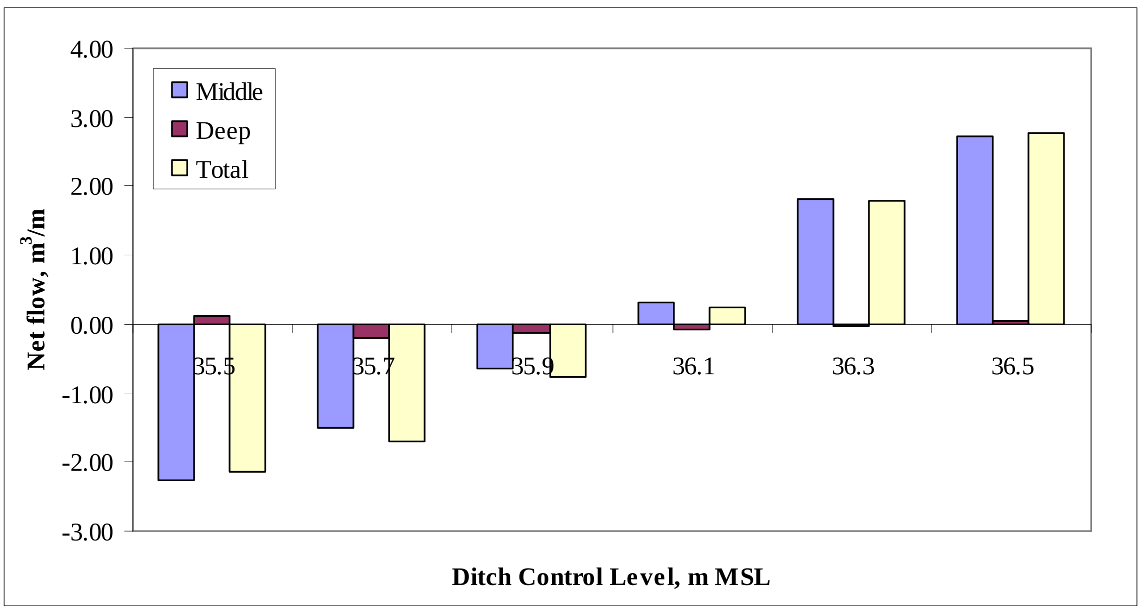

Figure 5.5.7: Net flows at the SW transect from different control levels

Table 5.5.1: Net flow at the SW transect for different control levels

Ditch Control Level, m MSL	Month	Net flow, m^3/m		
		Middle	**Deep**	**Total**
35.5	Jan	0.44	0.27	0.70
	Feb	-0.29	-0.08	-0.37
	Mar	-0.39	-0.01	-0.40
	Apr	-0.43	-0.02	-0.45
	May	-0.68	-0.02	-0.70
	Jun	-0.91	-0.03	-0.94
	Total	**-2.27**	**0.12**	**-2.15**
35.7	Jan	-0.01	-0.07	-0.09
	Feb	-0.20	-0.09	-0.29
	Mar	-0.21	0.00	-0.21
	Apr	-0.23	-0.01	-0.24
	May	-0.32	-0.02	-0.34
	Jun	-0.53	-0.01	-0.54
	Total	**-1.50**	**-0.21**	**-1.70**
35.9	Jan	-0.04	-0.05	-0.09
	Feb	-0.17	-0.04	-0.21
	Mar	-0.07	0.01	-0.07
	Apr	-0.05	-0.01	-0.06
	May	-0.09	-0.01	-0.10
	Jun	-0.23	-0.01	-0.25
	Total	**-0.65**	**-0.12**	**-0.77**
36.1	Jan	0.00	-0.05	-0.05
	Feb	-0.11	-0.04	-0.15
	Mar	0.10	0.01	0.12
	Apr	0.15	0.00	0.15
	May	0.16	-0.01	0.15
	Jun	0.00	0.01	0.01
	Total	**0.31**	**-0.08**	**0.23**
36.3	Jan	0.04	-0.05	-0.01
	Feb	-0.06	-0.04	-0.10
	Mar	0.29	0.02	0.31
	Apr	0.36	0.01	0.37
	May	0.40	0.00	0.41
	Jun	0.78	0.03	0.81
	Total	**1.82**	**-0.03**	**1.79**
36.5	Jan	0.10	-0.05	0.04
	Feb	0.01	-0.04	-0.03
	Mar	0.48	0.03	0.52
	Apr	0.58	0.02	0.60
	May	0.67	0.01	0.68
	Jun	0.89	0.07	0.96
	Total	**2.72**	**0.04**	**2.77**

5.6 Net Groundwater Flows in Juniper Bay

The analysis from individual transects, from the previous section, was extrapolated to estimate net groundwater flows for Juniper Bay. Each transect was assumed to represent one quarter of the perimeter. Flows estimated at each transect are projected over the corresponding quarter of the perimeter. Table 5.6.1 presents estimates of the net groundwater flows at each quarter, calculated as equivalent depths over the entire bay. These net flows were plotted in Figure 5.6.1. Net flow into the site was positive, indicating groundwater inflow at Juniper bay, varying from 107 mm to 155 mm. The net groundwater inflow increases with the increase in water level elevation in the perimeter ditch.

Table 5.6.1: Net Groundwater Flows for 01 January 2004 to 30 June of 2004

Ditch Control Level, m	**Net flows at different transects, mm**				**Total net flow, mm**
	NW	**NE**	**SE**	**SW**	
35.5	21.49	46.40	45.24	-5.39	107.73
35.7	24.35	54.86	45.10	-4.27	120.02
35.9	27.80	64.11	44.96	-1.94	134.90
36.1	31.28	64.98	44.53	0.58	141.35
36.3	34.83	66.09	44.09	4.49	149.49
36.5	38.97	66.56	43.16	6.92	155.59

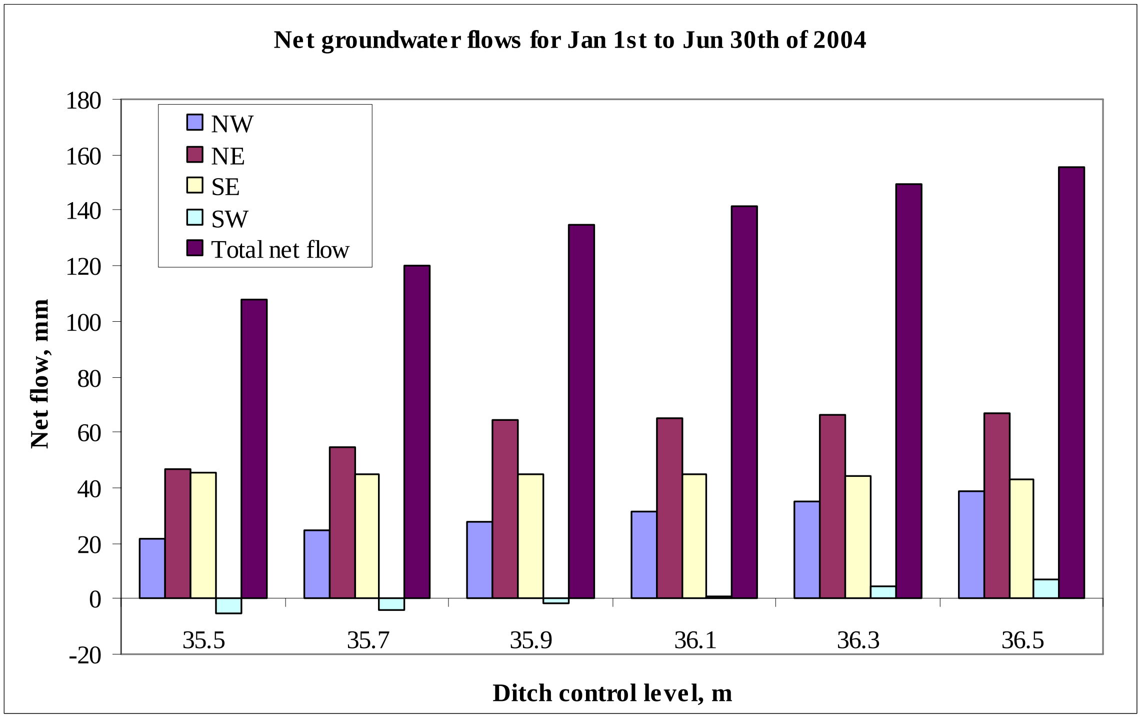

Figure 5.6.1: Net groundwater flows for 01 January 2004 to 30 June 2004

5.7 Summary

The analysis from various scenarios focused on control levels of the perimeter ditch revealed that offsite impacts are most likely at the southwest transect. Table 5.6 presents the summary of critical depths of water in the perimeter ditch at each transect. Critical control level is defined as the water level where the perimeter ditch will start behaving as a recharge source instead of a drainage ditch. From Table 5.7.1, one can observe that maintaining ditch water level at or below 35.9 m MSL will minimize any offsite impacts through the SW transect. Critical control levels at NW, NE and SE transects are 36.1 m, 36.3 m and 35.9 m MSL respectively. A helpful conclusion that can be drawn from this analysis is that maintaining the perimeter ditch at a control water level of 35.9 m MSL would help in reducing offsite impacts and also creating maximum wetland area in Juniper bay. Net groundwater inflow into Juniper Bay for a ditch level of 35.9 m is approximately 134.9 mm (total for the first six months of the year 2004).

Table 5.7.1: Summary of Critical Ditch Control Levels

Transect	**Critical Ditch Control Levels, m MSL**		**Ditch Top Elevation**
	Wet Conditions	**Dry Conditions**	
Northwest	36.10	36.30	36.65
Northeast	36.30	36.50	36.50
Southeast	35.90	36.30	36.70
Southwest	35.90	36.10	37.00

Chapter 6

Conclusions and Recommendations for Future Research

This research project was initiated to assess the groundwater flows affecting wetland restoration at Juniper bay. The three main thrusts of the project were to: 1) determine the hydraulic gradients of groundwater and quantify these groundwater flows, 2) determine the influence of the perimeter ditch, which would be the main drainage source after filling the internal main ditches for restoration, and 3) develop recommendations for maintenance of the perimeter ditch to reduce offsite impacts and restore maximum wetland area. The following conclusions were drawn from the results of this research project.

Conclusions

1. During the process of this research, the conceptual model of the subsurface at Juniper Bay was verified from the 20 soil cores collected at the four transects. The Black Creek Confining Unit, a fine textured impervious layer, was found at the depths of 8–11 m at all four transects. A distinct surficial sand layer and the two underlying sand layers were identified at most of these core locations. Clay layers were found in between these sand layers.

2. Hydraulic head data for the first six months of the year 2004 was used for analysis and modeling groundwater flows. Preliminary analysis of the head data showed that the perimeter ditch influences water in the surficial sand layer. Groundwater flows in the deep sand layers do not have significant influence of the perimeter ditch. The head

gradients suggested groundwater inflow through the NW, NE, and SE transects and groundwater outflow through the SW transect.

3. Groundwater flows were analyzed from the results of calibrated groundwater models at all the four transects, which indicated that the perimeter ditch drains water from either side of it in the surficial sand layer and to an extent in the middle sand layers. Analysis indicated groundwater inflow from lower sands at the NW, NE and SE transects. The SW transect had groundwater outflow in the lower sands. Lateral gradients were higher in the wet periods when compared to dry periods.

4. The models were extended to the center of the bay (800 m from perimeter ditch) to simulate the conditions when interior ditches will be blocked. This extended model had also helped for a better visualization of the gradients and the influence of the perimeter ditch towards the inside of the bay. All transects had head gradients towards the perimeter ditch in the surficial sand layer. The perimeter ditch influences groundwater flows in the middle sand layer at the NW, and SW transects. At the NE and SE transects, hydraulic gradients in the middle sand layer indicated groundwater inflow. Flow in lower sands at the NW, NE, and SE transects showed groundwater inflow with relatively higher gradients in wet conditions than in dry conditions. The SW transect showed groundwater outflow in the middle and lower sands. The SW transect is the location where hydraulic trespass into the surrounding area is likely.

5. Influence of the perimeter ditch was analyzed all four transects. This analysis showed that the lateral influence was extended approximately to maximum 100 m and vertical influence to a depth of 6-7 m, corresponds to the middle sand layer, at the NW transect. At the NE transect, lateral influence of the perimeter ditch extented to a maximum 75 m and vertical influence to a depth of 4-5 m (surficial sand layer). Also,

influence was higher in winter months than in summer months. The lateral influence of the perimeter ditch was more to outside of the bay. At the SE transect, influence of the perimeter ditch is to the maximum extent of 75 m and to the depth of 4-5 m (surficial sand layer). Outside of the bay was more influenced by the perimeter ditch than inside of the bay. At the SW transect, the ditch was influencing maximum to an extent of 100 m inside the bay and 50 m outside the bay. Depth of influence was to the depth of middle sand layer, which is 6-7 m deep.

6. These results from the individual transects were extrapolated to the entire lateral boundary of the project site for analyzing the net groundwater flows. Thus, with the present conditions at Juniper Bay, groundwater inflow can be expected through the three quarters of the boundary corresponding to the NW, NE, and SE transects. Groundwater outflow could be expected through the one quarter of the boundary corresponding to the SW transect. The net inflow to the bay was estimated as 125 mm for the first six months of year 2004.

7. Critical control levels for the perimeter ditch were identified at all the transects, and they were 36.1 m for the NW transect, 36.3 m for the NE transect, 35.9 m for the SE transect, and 35.9 m for the SW transect. To minimize the impact of the ditch on the surrounding area and restore the maximum wetland, the recommended control level would be 35.9 m. This analysis also suggested that the offsite impacts can be expected at the southwest transect. The net groundwater inflow of Juniper Bay for the perimeter ditch control level of 35.9 m was estimated as 134.9 mm for the first six months of the year 2004.

8. This study provides guidance for evaluating possible site conversions sites from groundwater perspective. The observations of general ground surface slopes in the entire site and its surrounding area would provide information regarding the expected locations of influx and efflux. In addition to this, soil coring helps determine fine textured layers and their depths, for example Black Creek Confining Unit at Juniper Bay indicates the capability of water holding in the surficial aquifer.

Recommendations for Future Research

The first recommendation for continuing this research is to modify the monitoring units and collect continuous data. Extending monitoring units along the perimeter would help describe the head distribution along the perimeter more precisely. The estimates of the groundwater flows would then be more accurate. If the study can be extended to surrounding areas, then the source of the significant groundwater inflows can be determined. If recommendations are followed for the further research, it would help to guide future restoration projects at drained Carolina Bays in terms of determining the sources of significant groundwater inflows.

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Appendices

Appendix A

Saturated Hydraulic Conductivity Tables for the Four Transects

Saturated hydraulic conductivity tests were conducted for the cores representing significant strata at each core location. The Tables A.1 to A.4 present K_{sat} for all the significant depths at all core locations. They also show texture and color of the cores, described by soil scientists. Missing values in the tables correspond to the cores that are from clayey strata. Strata that are not clayey and have missing data could correspond to the cores, which were disturbed during the preparation for K_{sat} tests.

Table A.1. K_{sat} Table for the Northwest (NW) Transect

Location	Top Depth (m)	Bottom Depth (m)	COLOR	TEXTURE	time (min)	Vol (ml)	Q (ml/min)	H20 ht (cm)	Ksat (cm/min)
NW-EX-75	0.00	0.30	10YR3/2	SL	2.00	7.0	3.50	6	0.034
	0.30	0.76	2.5Y5/3	LS					
	0.76	1.01	10YR3/1	SL				5.8	
	1.01	1.52	10YR3/1 + 10YR5/1	SCL	7.00	5.0	0.71	5.6	0.007
					4.00	8.0	2.00	6	0.019
	1.52	1.75	2.5Y6/1	SL	0.50	5.0	10.00	5.5	0.092
	1.75	2.13	2.5Y7/1	C				5	
	2.13	2.23	2.5Y5/2	SCL				5.5	
	2.23	3.05							
	3.05	3.53	2.5Y6/2	C				5.5	
	3.53	3.84	2.5Y7/1 + 7.5YR6/8 concentration	SL	10.00	2.0	0.20	5.8	0.002
	3.84	4.06	2.5Y8/1	SL				5.8	
	4.06	4.27	2.5Y7/1	C					
	4.27	4.42	2.5Y8/1	SL				5.9	
	4.42	4.57							
	4.57	4.67	10YR7/1	S	1.00	5.0	5.00	5.2	0.045
	4.67	4.88	10YR5/8	SCL	0.17	100.0	598.80	4.7	5.040
	4.88	5.03	10YR6/2	SC	0.17	100.0	598.80	6.1	5.873
	5.03	5.38	4N	C				6	
	5.38	6.10	3N	SC				5.9	
	6.10	6.22	2.5Y3/1	SCL	0.27	70.0	262.17	5	2.292
	6.22	6.81	3N	SCL	2.00	5.0	2.50	6.2	0.025
	6.81	7.19	4N	C	1.00	6.0	6.00	5.7	0.057
	7.19	7.62	3N	C	1.50	6.0	4.00	5.5	0.037
	7.62	7.77	3.5GY	SL	0.20	50.0	250.00	4.8	2.132

Table A.1 (continued). K_{sat} Table for the Northwest (NW) Transect

	7.77	8.10	5.5GY	SL/C				5.9	
	8.10	8.41	10YR4/1	LS				6	
NW-EX-25	0.00	0.13	10YR3/1	dark SL	10.00	14.0	1.40	5.5	0.013
	0.13	0.23	10YR6/4	light C	3.00	6.0	2.00	5.5	0.018
	0.23	0.36	10YR5/3	SL				5.5	
	0.36	0.48	10YR2/1	MSL	33.83	11.0	0.33	6	0.003
	0.48	0.59	10YR2/1	MSL					
	0.59	0.76							
	0.76	0.91	10YR5/4	SL					
	0.91	1.17	10YR5/4	SCL	2.00	29.0	14.50	6.3	0.145
	0.00	0.00			2.50	5.0	2.00	5.5	0.018
	1.17	3.05							
	3.05	3.35	2.5Y7/1	FS	2.00	5.0	2.50	5	0.022
	3.35	3.61	25% 2.5Y6/1 & 75% 2.5Y5/1	CL					
	3.61	3.79	2.5Y6/1	SCL					
	3.79	4.57							
	4.57	5.33	5BG4/1	SC				5.5	
	0.00	0.00						5.6	
	5.33	6.10	5BG4/1	SCL	14.40	1.2	0.08	4.5	0.001
					60.00	3.4	0.06	5.4	0.001
	6.10	6.96	2.5Y4/1	S	3.00	6.0	2.00	5.4	0.018
	6.96	7.11	2.5Y3/1	C	10.00	9.0	0.90	5	0.008
NW-IN-5	0.00	0.25	10YR3/1	SL	2.50	30.0	12.00	5.7	0.113
	0.25	0.51	10YR4/3	LS	3.00	5.0	1.67	5.4	0.015
	0.51	0.76	10YR7/1	S	0.50	90.0	180.00	5	1.573
	0.76	0.99	2.5Y5/3	LS					
	0.99	1.40	2.5Y6/4	C				5	
	1.40	1.40	2.5Y7/2	SL	2.00	6.0	3.00	5.3	0.027
	1.40	3.05							
	3.05	3.40	2.5Y6/2	SCL	1.00	100.0	100.00	5.1	0.885

Table A.1 (continued). K_{sat} Table for the Northwest (NW) Transect

					6.00	5.0	0.83	5.4	0.008
	3.40	3.51	2.5Y7/1	LS					
	3.51	3.66	2.5Y6/2	SCL				5	
	3.66	4.57	2.5Y6/2	SCL				5.5	
	0.00	0.00			2.00	35.0	17.50	5.5	0.162
	4.57	5.69	2.5Y5/1	SCL				5.5	
	0.00	0.00			7.00	5.0	0.71	5.5	0.007
	0.00	0.00						5	
	5.69	6.10	2G3/3/1	SL	1.50	5.0	3.33	5	0.029
	6.10	7.82	2G3/3/1	LS	1.00	6.0	6.00	5.6	0.056
					2.00	4.0	2.00	6	0.019
	7.82	9.14	N2.5/10Y	C(95%) & S(5%)	1.00	15.0	15.00	4.2	0.118
			10YR7/1					4.8	
NW-IN-25	0.00	0.20	10YR5/1	LS					
	0.20	0.46	10YR7/1	LS					
	0.46	0.61							
	0.61	0.76	10YR7/1	LS					
	0.76	1.22	2.5Y5/3	C	5.00	5.0	1.00	5.6	0.009
	1.22	1.52							
	1.52	2.03	2.5Y7/1	SL	1.50	4.0	2.67	5.5	0.025
					1.00	7.0	7.00	6	0.068
	2.03	3.05	2.5Y6/2	C				5.5	
	3.05	3.30	2.5Y6/1	SL	1.00	12.0	12.00	5.2	0.107
	3.30	4.37	2.5Y6/1	SCL	3.00	7.0	2.33	5.8	0.022
	4.37	4.57	N4/0	SC				5.8	
	4.57	5.36	N4/0	SC	1.00	5.0	5.00	5.1	0.044
					1.00	80.0	80.00	5.2	0.716
	5.36	5.79	N4/0	SCL	1.50	6.0	4.00	5.4	0.037
	5.79	6.10	N5/0	SL	1.00	20.0	20.00	5	0.175
	6.10	6.71	N4/0	SCL				6	

Table A.1 (continued). K_{sat} Table for the Northwest (NW) Transect

	6.71	7.62							
	7.62	8.00	N6/0	LS	1.00	60.0	60.00	5.2	0.537
					1.50	40.0	26.67	6	0.259
	8.00	9.14	N2.5/10Y	C	1.00	14.0	14.00	4.8	0.119
					1.00	45.0	45.00	4.7	0.379
					1.00	21.0	21.00	5.4	0.192
NW-IN-75	0.00	0.15	10YR2/1	SL					
	0.15	0.36	10YR6/1	S/SL	1.00	13.0	13.00	6.1	0.127
	0.36	0.76	10YR4/2	C	1.33	15.0	11.28	5.5	0.104
	0.76	0.94	10YR 4/3	SCL	1.50	5.0	3.33	5.8	0.032
	0.94	1.12	10YR5/2 & 10YR5/3	SCL				6.2	
	1.12	1.52	40% 10YR5/2 & 60% 10YR6/2	C w/ SCL	2.33	14.0	6.01	6	0.058
	1.52	1.78	90% 2.5Y6/2 & 10% 10YR2/1	SC				5.9	
	1.78	2.31	2.5Y6/2	SCL				5.8	
	2.31	2.62	2.5Y6/2	SL	14.40	0.2	0.01	5	0.000
	2.62	2.90	2.5Y7/2	LS	55.00	15.0	0.27	4.2	0.002
	2.90	3.08	2.5Y6/2	SL	9.66	9.0	0.93	5.4	0.009
	3.08	3.22	2.5Y8/1	S				5.5	
	3.22	3.53	2.5Y6/1	CL				5.5	
	3.53	4.04	2.5Y6/2	SL	2.10	50.0	23.81	6	0.231
	4.04	4.57	2.5Y4/1	SCL	33.83	11.0	0.33	4.5	0.003
	4.57	5.05	2.5Y3/1	SCL	1.67	60.0	35.93	5.5	0.332
	5.05	5.69	2.5Y3/2 & 6/2	LS/S	1.00	15.0	15.00	5	0.131
					2.58	35.0	13.57	4.4	0.110
	5.69	6.04	2.5Y3/1	SL	3.00	9.0	3.00	5.2	0.027
	6.04	6.48	2.5Y3/1	SL	1.00	24.0	24.00	4.7	0.202
	6.48	6.78	N4	C				4.9	
	6.78	6.86	2.5Y3/1	SL					
	6.86	7.57	2.5Y3/1	C	6.00	9.0	1.50	4.4	0.012

Table A.1 (continued). K_{sat} Table for the Northwest (NW) Transect

Location	Top Depth (m)	Bottom Depth (m)	COLOR	TEXTURE	time (min)	Vol, ml	Q, ml/min	H20 ht (cm)	Ksat (cm/min)
	7.57	9.09	2.5Y3/1	C	3.00	16.0	5.33	5.2	0.048
	9.09	10.62	2.5Y3/1	C				4	
	10.62	11.38	2.5Y3/1	C	60.00	1.0	0.02	5.8	0.000
	11.38	12.14	10YR3/1	C					
	12.14	12.90	10YR3/1	C					

Table A.2. K_{sat} Table for the Northeast (NE) Transect

Location	Top Depth (m)	Bottom Depth (m)	COLOR	TEXTURE	time (min)	Vol, ml	Q, ml/min	H20 ht (cm)	Ksat (cm/min)
NE-IN-5	0.00	0.25	N 2.5/0	SL					
	0.25	0.36	10YR 6/1	LS					
	0.36	0.66	10YR 2/1	SL					
	0.66	0.97	10YR 4/3	SL					
	0.97	1.09	10YR 3/1	SC					
	1.09	1.52	10YR 2/1	SC					
	1.52	3.05	10YR 3/1	SC					
	3.20	4.57	10YR 5/2-S	SCL					
			N 5/SGY-Clay						
	4.57	5.56	N4 10Y	coarse LS/SC					
	5.56	5.79	N4 10/Y sand	SC 70% LS 30%					
			N4 4/SG-clay						
	6.10	8.53		Sand?					
	8.53	8.84	Clay-N 3/SGY	Clay/Sand					
			Sand 2.5Y 6/2						
	8.84	9.14	N 3/SGY	Clay					
NE-EX-75	0.00	0.76	10YR 7/6	LS					0.017
	0.76	1.07	7.5YR 5/8	LS					0.009
	1.07	1.52	2.5Y 7/6	LS					0.015
	1.52	1.73	10YR 5/2	LS					0.012
	1.73	2.29	10YR 2/1	LS					0.012

Table A.2 (continued). K_{sat} Table for the Northeast (NE) Transect

	3.05	4.57							
	4.57	5.08	10YR 2/1	C					0.000
	5.08	6.10	10YR 4/2	SCL					0.007
	6.10	6.50	N 5/10GY	SCL					0.010
	6.50	7.16	25Y 6/2	SL					0.016
	7.62	9.14	2.5Y 6/2	coarse sand					0.036
	9.14	11.43							0.043
	11.43	12.19	N 2.5N-C 10YR 6/1-S	C/S					0.090
NE-EX-25	0.00	0.10	N2.5/6	MSL					
	0.10	0.38	10YR4/1	LS					
	0.38	1.07	10YR7/1	LS	0.5	40	80.000	6	0.7774
	0.76	0.91	10YR4/3	LS					
	0.91	1.30	10YR2/1	SCL				6	0.0000
	1.30	2.74							
	2.74	2.90	10YR2/1	SL				5.2	0.0000
	2.90	3.35	10YR4/1	SCL	1	8	8.000	5	0.0699
	3.35	4.27	N3/0	SC	5	5	1.000	5.4	0.0091
					1	72	72.000	5.5	0.6658
					1	9	9.000	6	0.0875
	4.27	5.03	2.5Y5/1	SCL	1	20	20.000	5	0.1748
								5.3	0.0000
	5.03	5.79	2.5Y5/1	SL	4	5	1.250	5.9	0.0120
								5.6	0.0000
	5.79	7.01	2.5Y5/1	SL	1	13	13.000	5.5	0.1202
					1.5	5	3.333	5.5	0.0308
					1	6	6.000	6	0.0583
	7.01	7.77	2.5Y5/1	S	1	10	10.000	6	0.0972
					1	18	18.000	6.5	0.1828
	7.77	7.92	N2.5/6	SCL	0.167	80	479.042	5.4	4.3830
	7.92	8.53	N2.5/6	SC	2	7	3.500	5	0.0306

Table A.2 (continued). K_{sat} Table for the Northeast (NE) Transect

					1	3	3.000	5.4	0.0274
	8.53	10.06	N4/10G	C	1	40	40.000	5.8	0.3814
					1	30	30.000	5.2	0.2684
NE-IN-25	0.00	0.25	10YR 2/1	LS	15	227	15.133	6.3	0.1511
	0.25	0.41	2.5Y 6/1	S	3	245	81.667	6.4	0.8223
	0.41	0.76		?					
	0.76	0.97	10YR 2/1	LS	60	37	0.617	5.7	0.0058
	0.97	1.12	10YR 2/2	SL	60	45	0.750	5.7	0.0071
	1.12	1.24	10YR 3/1	SCL	60	86	1.433	5.3	0.0130
	1.24	1.52	10YR 3/1	SC	60	0	0.000	5.5	0.0000
	1.52	1.75	10YR 3/1	SC	30	208	6.933	5.2	0.0620
	1.75	2.29	10YR 3/1	SCL	60	114	1.900	5.4	0.0174
	2.29	2.80	10YR 2/1	SCL	240	0	0.000	5.2	0.0000
	2.80	3.15	10YR 3/1	SC	240	0	0.000	5.3	0.0000
	3.15	3.58	10YR 3/1	SCL	240	0	0.000	5.4	0.0000
	3.58	3.94	10YR 2/2	SC	240	0	0.000	5	0.0000
	3.94	4.44	N 6/5GY	SC	90	163	1.811	5.4	0.0166
	4.44	4.57	N 5/5GY	SCL	120	0	0.000	5.2	0.0000
	4.57	4.77	N 4/5G	Sand with clay lenses	60	248	4.133	5.7	0.0390
	4.77	5.61	10YR 5/1	S	120	47	0.392	5.9	0.0038
					90	150	1.667	5.5	0.0154
	5.61	6.10		?					
	6.10	6.71	N 5/10GY	coarse sand	180	2	0.011	5.8	0.0001
					15	227	15.133	5.6	0.1414
	6.71	7.62		?					
	7.62	9.14	N 5/10GY	silty clay?	180	0	0.000	6	0.0000
					120	33	0.275	5.7	0.0026
					30	163	5.433	5.1	0.0481
					90	1	0.011	5.3	0.0001
					180	1	0.006	6	0.0001

Table A.2 (continued). K_{sat} Table for the Northeast (NE) Transect

	9.14	9.53	2.5Y2.5/1	CL	60	22	0.367	5.6	0.0034
	9.53	10.21	2.5Y4/1	S	15	224	14.933	5.8	0.1424
					75	198	2.640	5.9	0.0254
	10.21	10.36	4N	C	120	0	0.000	5.3	0.0000
NE-IN-75	0.00	0.18	10YR 2/1	SL	9	96	10.667	5.8	0.1017
	0.18	0.41		?					
	0.41	0.56	10YR 3/4	S	60	119	1.983	6.4	0.0200
	0.56	0.74	10YR 5/8	S	9	202	22.444	6	0.2181
	0.76	1.52		?					
	1.52	1.83	7.5YR 3/1	SC	120	1	0.008	5.7	0.0001
	1.83	1.98	10YR 2/1	SC	120	0	0.000	5.9	0.0000
	1.98	2.80	10YR 2/1	SCL	120	0.67	0.006	5.8	0.0001
	0.00	0.00			120	9	0.075	5.1	0.0007
	2.80	2.94	10YR 2/1	SC	120	9	0.075	5.9	0.0007
	3.05	4.57	N 5/10GY	SC	120	0	0.000	5.4	0.0000
					120	0	0.000	5.5	0.0000
					120	0	0.000	5.2	0.0000
					120	0.67	0.006	5.5	0.0001
	4.57	4.88	N 5/10GY	SCL					
	4.88	5.43	N 5/10GY	S	10	133	13.300	5.6	0.1243
					180	11	0.061	5.3	0.0006
	5.43	5.74	N 5/10GY	SCL	180	43	0.239	5.7	0.0023
	5.74	6.10	N 5/5GY	S					
	6.10	6.45	N 5/5GY	S	10	102	10.200	5.3	0.0923
	6.45	6.71	N 4 5/GY		180	1	0.006	5.1	0.0000
	6.71	7.01	N 4 5/GY	SCL	10	196	19.600	5.5	0.1813
	7.01	7.62		?					
	7.62	8.38	N 3/5GY	CL	120	0.5	0.004	5.2	0.0000
					120	5	0.042	5.5	0.0004
	8.38	8.84	N 2.5/N	SCL	60	11	0.183	4.9	0.0016
	8.84	9.14	2.5Y 2.5/1	CL	120	0	0.000	5.2	0.0000

Table A.3. K_{sat} Table for the Southeast (SE) Transect

Location	Top Depth (m)	Bottom Depth (m)	COLOR	TEXTURE	time (min)	Vol (ml)	Q (ml/min)	H20 ht (cm)	Ksat (cm/min)
SE-EX-75	0.00	0.18	10 YR 2/1	ML					
	0.18	0.33	10 YR 2/2	SL					
	0.33	0.76	10 YR 5/2	SL					
	0.76	0.91							
	0.91	1.07	10 YR 5/2	SL					
	1.07	1.27	10 YR 5/3	SL					
	1.27	1.52	10 YR 5/4	SL					
	1.52	1.52							
	1.52	1.78	10 YR 5/2	SL					
	1.78	2.01	10 YR 6/2	SL					
	2.01	2.26	10 YR 5/6	SL					
	2.26	3.05							
	3.05	3.56	10 YR 2/1	LS					
	3.56	3.86	10 YR 2/2	SL					
	3.86	4.11	10 YR 3/2	SL					
	4.11	4.44	10 YR 2/1	SCL					
	4.44	4.57	10 YR 2/1	C					
	4.57	4.88	2.5Y 6/4	LS					
	4.88	5.18	2.5Y 6/2	LS					
	5.18	6.10							
	6.10	6.40	5Y 8/1	LS					
	6.40	7.62							
	7.62	8.08	2.5Y 7/8	SL					
	8.08	8.18	G2 4/10B	SCL					
	8.18	9.14	2.5Y 7/8	SL					
	9.14	0.00							
	9.14	9.40	4N	SCL	2.00	0.0	0.00	5.70	0.000
	9.40	10.36	4N	C	2.00	0.0	0.00	5.60	0.000
					2.00	1.0	0.50	5.80	0.005

Table A.3 (continued). K_{sat} Table for the Southeast (SE) Transect

					2.00	0.5	0.25	5.30	0.002
	10.36	10.67							
	10.67	11.40	4N	C	2.00	1.0	0.50	5.50	0.005
	11.40	11.84	3N	C	0.25	50.0	200.00	4.30	1.592
	11.84	12.04	3 10/Y	SC	2.00	0.0	0.00	4.90	0.000
SE-EX-25	0.00	0.15	10YR3/1	FSL	1.00	11.0	11.00	5.40	0.101
	0.15	0.23	10YR5/1	LFS					
	0.23	0.76	10YR2/2	FSL	1.00	7.0	7.00	5.00	0.061
	0.76	0.94	2.5Y7/1	CS					
	0.94	1.32	10YR4/3+2	CS	1.00	18.0	18.00	5.20	0.161
	1.32	1.45	10YR2/1	SCL	1.00	23.0	23.00	5.50	0.213
	1.45	1.52							
	1.52	3.05	10YR4/2	S					
	0.00	0.00	10YR2/1	SCL					
	3.05	4.27							
	4.27	5.64	2.5Y7/3 (90%) + 2.5Y6/6 (10%)	FS	1.00	9.0	9.00	5.40	0.082
	5.64	5.79			1.00	17.0	17.00	6.00	0.165
	5.79	6.30	2.5Y7/4	S	2.00	25.0	12.50	6.00	0.121
	6.30	6.38	2.5Y8/1 & 2.5Y7/6(conc.)	LS					
	6.38	7.01							
	7.01	7.24	2.5Y7/2 & 2.5Y7/6(conc.)	SC	2.00	5.0	2.50	5.80	0.024
	7.24	7.62	2.5Y8/1	S	2.00	31.0	15.50	5.70	0.146
	7.62	8.13	2.5Y8/1 & 2.5Y7/6(conc.)	S	2.00	3.0	1.50	5.70	0.014
	8.13	8.48	7.5YR6/8 + depletions also 2.5Y7/1	SCL	1.00	10.0	10.00	5.90	0.096
	8.48	8.84	N4/	C	1.50	1.0	0.67	6.00	0.006

Table A.3 (continued). K_{sat} Table for the Southeast (SE) Transect

	8.84	10.36	N4/	C	2.00	2.0	1.00	6.40	0.010
					2.00	2.0	1.00	5.80	0.010
	10.36	10.44	2.5Y5/1	CS					
	10.44	10.95	N4/	C	1.50	4.0	2.67	5.50	0.025
	10.95	11.20	10YR6/8	SC				6.20	
	11.20	11.51	2.5Y8/1 & 10YR6/8(conc.)	CS				6.10	
	11.51	11.89							
	11.89	12.19	10YR6/8 + 2.5Y6/4	CS	4.00	5.0	1.25	6.20	0.012
	12.19	12.80	N4/	C				6.00	
	12.80	12.88	2.5Y4/1	CS					
	12.88	13.03	2.5Y4/1	SC				5.50	
SE-IN-5	0.00	0.15	10YR2/1	LS					
	0.15	0.36	10YR2/1	LS					
	0.36	0.76	10YR7/1	LS					
	0.76	0.91	N2.5/0	LS					
	0.91	1.17	N2.5/0	LS					
	1.17	1.30	10YR4/4	SL					
	1.30	1.68	N2.5/0	SCL					
	1.68	1.88	10YR3/3	LS					
	1.88	2.03	2.5Y6/2	C					
	2.03	3.20	10YR6/1	SL					
	3.20	3.51	10YR6/1	LS					
	3.51	3.66	10YR6/1	SC					
	3.66	5.18	10YR6/1	LS					
	5.18	5.64	7.5R6/8	CL					
	5.64	6.10	5B4/1	C					
	5.64	6.10	5B4/1	C					
SE-IN-25	0.76	0.91	N2.5/0	MSL					
	0.91	1.07	N2.5/0	ML					

Table A.3 (continued). K_{sat} Table for the Southeast (SE) Transect

	1.07	1.22	N2.5/0	MSL					
	1.22	1.37	10YR2/1	SL					
	1.37	1.52	10YR2/1	SL					
	1.52	1.83	10YR2/1	LS					
	1.83	2.13	10YR3/1	LS					
	2.13	2.90	10YR3/1	LS					
	2.90	3.05	10YR3/3	LS					
	3.05	3.15	10YR4/1	SL					
	3.15	3.35	10YR6/2	SL	28.00	59.0	2.11	4.70	0.018
	3.35	3.51	10YR6/2	SL	5.25	33.0	6.29	5.50	0.058
	3.51	3.66	10YR7/1	SL					
	3.66	3.96	10YR7/1	SL					
	3.96	4.27	10YR7/1	SL	305.00	74.0	0.24	4.90	0.002
	4.27	4.44	2.5Y7/2	SCL	6.33	11.0	1.74	5.00	0.015
	4.44	4.57	10YR6/4	SC					
	4.57	4.72	10YR6/4	SC					
	4.72	4.88	10YR6/4	C	16.35	23.5	1.44	4.70	0.012
	4.88	5.13	10YR6/6	C	71.00	9.5	0.13	4.90	0.001
	5.13	5.49	5BG5/1	C					
	5.49	5.79	5BG5/1	C	305.0	50.0	0.16	4.90	0.001
	5.79	6.10	5BG5/1	SiC					
	6.10	6.35	5G4/1	SiC					
	6.35	6.61	5BG4/1	SiC	305.0	6.0	0.02	5.00	0.000
	6.61	6.88	5BG4/1	SiC	305.0	20.0	0.07	5.20	0.001
	6.88	7.24	5BG4/1	SiC	305.0	6.0	0.02	4.70	0.000
	7.24	7.62	5G4/1	SiC	305.0	9.0	0.03	4.90	0.000
	7.62	7.92		SiC	102.0	25.0	0.25	4.80	0.002
	7.92	8.23		SiC	50.45	13.0	0.26	4.70	0.002
	8.23	8.53		SiC	15.25	28.0	1.84	5.20	0.016
	8.53	8.84		SiC	14.33	40.0	2.79	5.10	0.025
SE-IN-75	0.00	0.76	?	?					

Table A.3 (continued). K_{sat} Table for the Southeast (SE) Transect

	0.76	1.52	10 YR 2/1	SL					
	1.52	3.05	?	S?					
	3.05	4.57	?	S?					
	4.57	4.93	10YR 6/1	SL				4.90	0.000
								5.10	0.000
	4.93	5.72	G1 G/N	C	0.50	4.0	8.00	4.90	0.069
					1.00	5.0	5.00	5.00	0.044
	5.72	6.10	G1 4/5G	SC				5.00	
	6.10	7.62	G1 4/5G	C	0.50	26.0	52.00	5.30	0.471
					0.50	70.0	140.00	5.90	1.348
	7.62	8.53	10YR 5/1	SL?					

Table A.4. K_{sat} Table for the Southwest (SW) Transect

Location	Top Depth (m)	Bottom Depth (m)	COLOR	TEXTURE	time (min)	Vol (ml)	Q (ml/min)	H20 ht (cm)	Ksat (cm/min)
SW-EX-80	0.00	0.15	10YR2/1	SL	1.00	5.0	5.00	5.50	0.0462
	0.15	0.38	10YR4/3 + 5/3	SL	0.17	20.0	119.76	5.00	1.0468
	0.38	0.76	10YR5/1	SL	2.00	3.0	1.50	4.90	0.0130
	0.76	0.99	10YR5/1	SL	6.00	5.0	0.83	4.80	0.0071
	0.99	1.07	10YR8/1	S					
	1.07	1.52	10YR5/2	LS	5.00	6.0	1.20	4.80	0.0102
	1.52	3.05							
	3.05	3.45	10YR3/1	C	1.00	5.0	5.00	5.60	0.0467
	3.45	4.16	10YR3/2	LS	1.00	3.0	3.00	5.00	0.0262
	4.16	4.32	10YR8/1	S	0.17	12.0	71.86	5.00	0.6281
	4.57	6.10							
	6.10	6.81	2.5Y6/2	S					
	6.81	7.21	2.5Y3/1	C				5.50	

Table A.4 (continued). K_{sat} Table for the Southwest (SW) Transect

	7.21	7.39	Clay 2.5Y3/1 & Sand 5Y6/1	LS	1.00	6.0	6.00	5.40	0.0549
	7.62	7.72	Clay 2.5Y3/1	S	1.00	5.0	5.00	5.00	0.0437
	7.72	8.35	Sand 5Y6/1		1.00	8.0	8.00	4.90	0.0691
	8.35	8.45	Clay 2.5Y3/1	C				5.50	
	8.45	8.84	Sand 5Y6/1		1.50	4.0	2.67	5.20	0.0239
	8.84	8.99	2.5Y5/1	S	1.00	6.0	6.00	5.50	0.0555
	8.99	9.27	Clay 2.5Y3/1 & Sand 5Y6/1	S/C	4.00	5.0	1.25	5.40	0.0114
	9.27	9.83	Clay 2.5Y3/1	C/S				5.00	0.0000
	0.00	0.00	Sand 5Y6/1		5.00	5.0	1.00	5.50	0.0092
	10.36	11.20	Sand 2.5Y6/1	80% sand	1.00	9.0	9.00	5.50	0.0832
			Clay 2.5Y2.5/1	20% clay	1.00	16.0	16.00	5.60	0.1495
	11.20	11.28	2.5Y2.5/1	C					
	11.28	11.48	2.5Y2.5/1	C	1.00	5.0	5.00	5.20	0.0447
	11.48	11.58	Clay 2.5Y2.5/1	C/S	1.50	3.0	2.00	5.40	0.0183
			Sand 5Y6/1						
	11.58	11.73	2.5Y2.5/1	C				5.50	
	11.73	11.84	Clay 2.5Y2.5/1	C/S					
	0.00	0.00	Sand 2.5Y6/1						
	11.89	12.19	Clay 2.5Y2.5/1	C/S				5.50	
			Sand 2.5Y6/1						
	12.19	13.21	2.5Y2.5/1	C				5.00	
								4.50	
SW-EX-20	0.00	0.20	10YR 2/1	LS	30.00	181.0	6.03	5.80	0.0575
	0.20	0.33	2.5Y 3/2	S	4.00	153.0	38.25	5.50	0.3537
	0.33	0.59	2.5Y 4/2	S	4.00	194.0	48.50	4.90	0.4188
	0.59	0.71	10YR 4/2	LS					
	0.71	0.84	10YR2/2	LS	4.00	110.0	27.50	5.80	0.2622
	0.84	1.01	10YR 4/3	S					
	1.01	1.52		no sample					

Table A.4 (continued). K_{sat} Table for the Southwest (SW) Transect

	1.52	1.98	10YR 2/1	SL					
	1.98	2.29	10YR 2/2	LS	30.00	195.0	6.50	5.80	0.0620
	2.29	3.05							
	3.05	3.55							
	3.55	3.68	10YR 2/2	LS					
	3.68	3.86	N 2.5/0	ML (mucky loam?)					
	3.86	4.57	2.5Y 5/2	C	90.00	1.0	0.01	5.70	0.0001
	4.57	4.95	G1 4/10Y	C					
	4.95	5.18	2.5Y 6/2	SL	120.00		0.00	5.00	0.0000
	5.18	5.64	G1 2.5/0	S/C	20.00	195.0	9.75	5.00	0.0852
	5.64	6.10							
	6.10	8.84							
	8.84	9.20	10YR 4/2	SL	34.00	207.0	6.09	5.70	0.0575
	9.20	9.32	G1 3/N	SCL					
	9.32	9.47	G1 3/N	SL	90.00	65.0	0.72	5.40	0.0066
	9.47	9.60	SL-2.5Y 6/2, clay-10YR 2/1	80%SL, 20%SCL					
	9.60	10.36							
	10.36	10.52			0.25	10.0	40.00	6.10	0.3923
	10.52	10.97			0.17	10.0	59.88	6.10	0.5873
	10.97	11.28			1.00	8.0	8.00	5.40	0.0732
	11.28	11.58			2.00	2.0	1.00	4.40	0.0081
	11.58	11.89			4.00	3.0	0.75	4.00	0.0057
SW-IN-05	0.00	0.18	10YR5/1	LS					
	0.18	0.38	10YR3/3	LS	1.00	9.0	9.00	6.10	0.0883
	0.38	0.76	2.5Y8/1	S					
	0.76	1.01	10YR3/3	SL					
	1.01	1.32	10YR2/1	SL					
	1.32	1.47	2.5Y6/3	LS					
	1.47	1.52	2.5Y3/2	LS					

Table A.4 (continued). K_{sat} Table for the Southwest (SW) Transect

	1.52	2.90	2.5Y3/2	SL	3.00	7.0	2.33	6.20	0.0231
	2.90	3.05	10YR2/1	SCL					
	3.05	3.51							
	3.51	3.66	10YR4/2	SL	1.00	10.0	10.00	6.10	0.0981
	3.66	3.81	10RR2/1	SL	3.00	5.0	1.67	5.70	0.0157
	3.81	4.57	N2.5/0	C	1.00	10.0	10.00	6.00	0.0972
	4.57	5.84	N5/10GY	C					
	5.84	6.10	N5/10GY	C				5.90	0.0000
	6.10	6.71	10YR5/1	LS					
	6.71	6.96	N4/0	C					
	6.96	7.11	10YR5/1	SL					
	7.11	7.21	N4/0	C					
	7.21	7.32	10YR5/1	SC					
	7.32	7.49	N4/0	C					
	7.49	7.62	10YR5/1	SC					
	7.62	8.23		C 70% & S 30%					
	8.23	8.33		LS					
	8.33	8.36		Charcoal					
	8.36	9.14		C 70% & S 30%					
	9.14	9.60		SL					
	9.60	9.81		SCL					
	9.81	10.67		C 60% & S 40%					
SW-IN-25	0.00	0.20	10YR 2/1	LS					
	0.20	0.28	10YR 6/1	LS					
	0.28	0.61	10YR 6/3	LS					
	0.61	0.99	10YR 4/3	SL					
	0.99	1.30	10YR 2/1	LS					
	1.30	1.52	10YR 4/2	SL					

Table A.4 (continued). K_{sat} Table for the Southwest (SW) Transect

	1.52	3.05	10YR 4/2	LS
	3.05	4.57	Top- N2.5/0, bottom N5/10GY	C
	4.57	5.33	N 5/10GY	C
	5.33	5.61	N 5/10GY	C
	5.61	6.10	Clay-N 5/10GY, Sand 10YR 4/6	60% C & 40% CS
	6.10	6.55	2.5Y 7/1	LS
	6.55	6.91	10 YR 2/1	C
	6.91	6.96	2.5Y 6/2	SC
	6.96	7.32	10 YR 2/1	C
	7.32	7.47	2.5Y 6/1	SL
	7.47	7.62	10 YR 2/1	C
	7.62	9.14	Clay-N 3/5GY, Sand-2.5Y 6/1	
	9.14	7.77		S
	7.77	7.92		C
	7.92	8.23		S
	8.23	8.53		C
	8.53	8.63		S
	8.63	8.84		C
	8.84	8.92		S
	8.92	9.14		C
SW-IN-75	0.00	0.23	10YR 4/1	LS
	0.23	0.36	10YR 8/1	S
	0.36	0.61	10YR 5/3	LS
	0.61	0.76	10YR 2/1	SL
	0.76	0.91	10YR 3/2	SL
	0.91	1.52	10YR 3/4	LS
	1.52	3.05		No recovery
	3.05	4.11		No recovery

Table A.4 (continued). K_{sat} Table for the Southwest (SW) Transect

4.11	4.27	10YR 3/2	SL
4.27	4.57	N 5/10GY	SC
4.57	4.88		No recovery
4.88	5.94	Clay-N 5/10GY, 2.5Y 7/2	C 40% & LS 60%
5.94	6.10	N 5/10GY	C 40% & LS 60%
6.10	6.86	2.5Y 6/2	SL
6.86	7.21		90% C & 10% S
7.21	7.47	Clay- N 2.5/0, Sand 10YR 5/1	80% S & 20% C
7.47	7.62	Clay- N 2.5/0, Sand 10YR 5/1	90% C & 10% S
7.62	8.69	Clay- N 2.5/0, Sand 10YR 5/1	80% C & 20% S
8.69	9.14	Clay- N 2.5/0, Sand 10YR 5/1	80% S & 20% C

Appendix B: Input Parameters

Conductivities for different layers

Saturated hydraulic conductivity estimates are available from the K_{sat} tests. Each transect is configured as five layers in MODFLOW. The following shows an example of estimation of conductivities for each layer. This is shown for the Northwest (NW) transect.

The surface layer of the NW transect is to the depth of 3.1 m from the ground surface at EX-75 location. This layer in the model is comprised of a number of minor sediment layers having different conductivities. Effective K_{sat} was estimated using equation 4.1.

Table B.1. Example for estimating effective conductivity for NW-EX-75 in layer 1

Thickness (m)	K_{sat} (m/sec)	Effective K_{sat} (m/sec)
0.30	5.67E-06	
0.46		
0.25		
0.51	1.11E-06	
0.00		
0.23	1.54E-05	
0.38		
0.10		
0.81		5.6E-06

Effective conductivities were estimated in a similar manner for each layer at all five core locations. Table B.2 presents the estimates for the NW transect. For the missing data, estimates from slug tests and values from literature based on the soil texture were used.

Table B.2. Effective Saturated Hydraulic Conductivity for NW transect

NW	Effective hydraulic conductivity (m/sec)				
Layer	EX-75	EX-25	IN-05	IN-25	IN-75
1	5.6E-06	1.54E-05	1.58E-04	6.43E-04	1.11E-05
2	3.18E-07	3.64E-06	1.47E-06	4.81E-06	1.91E-05
3	0.000396	2.40E-04	2.45E-05	5.67E-05	2.85E-05
4	0.000208	1.17E-07	9.34E-06	1.20E-04	2.02E-06
5	0.000355	3.05E-04	6.29E-05	1.20E-04	7.95E-05

Weather Parameters

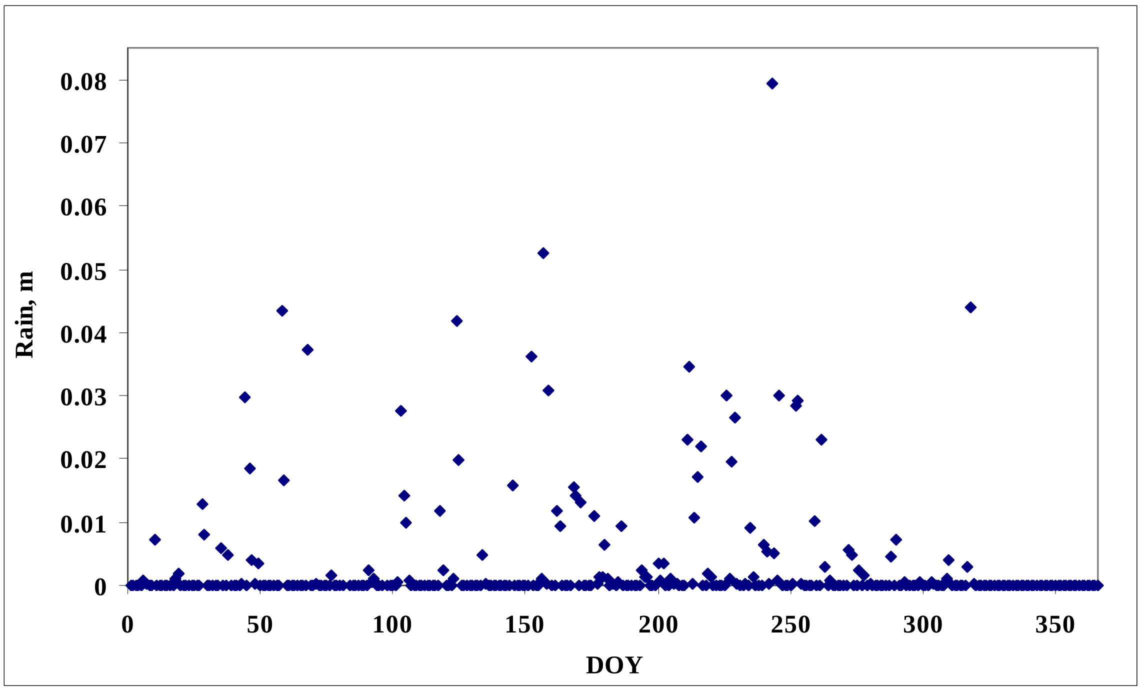

Figure B.1: Rainfall data for the year 2004

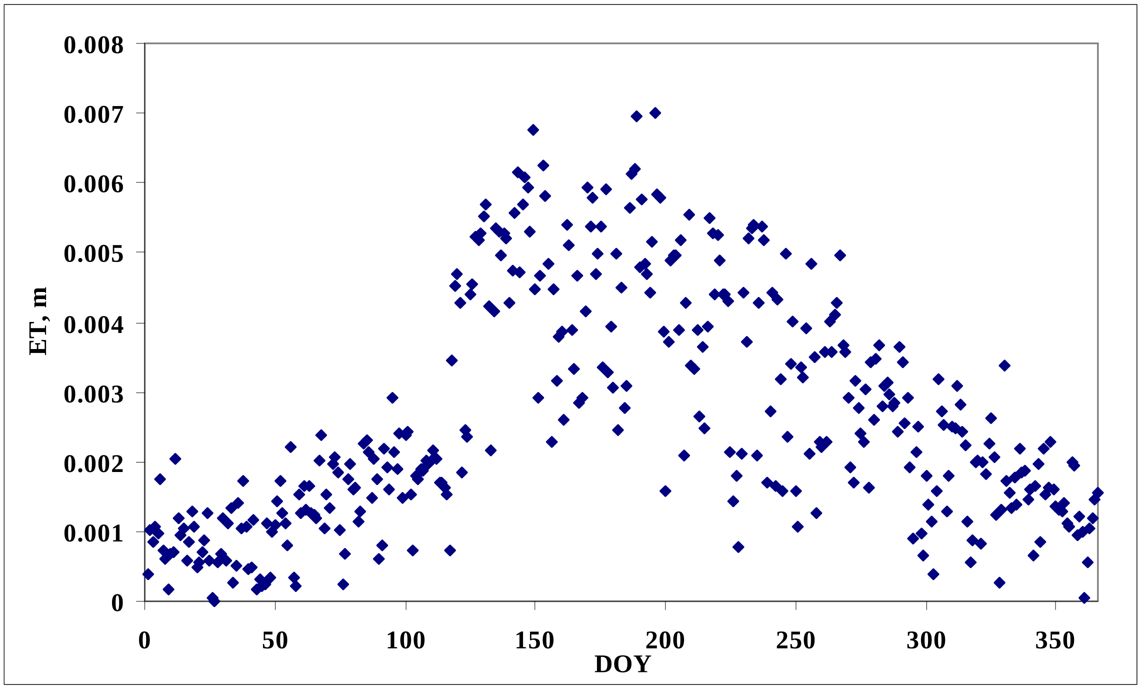

Figure B.2: Evapotranspiration estimates for the year 2004

Appendix C: Surveying Data

A total station (Topcon GTS-702) was used for surveying. Elevations of all piezometers and the ditch at all four transects were obtained. The ditch coordinate data (Table C.2) contains points from at least three cross-sections of the perimeter ditch centered on each of the transects. Each cross-section is approximated as a trapezoid by four points: top of bank interior, ditch bottom interior, ditch bottom exterior, top of bank exterior.

For the Northeast (NE), Southeast (SE), & Southwest (SW) transects, there are three cross-sections. The middle cross-section of each was taken at the transect, with the others at some distance on either side (15-50 m, depending on visibility). For the Northwest (NW) transect, there are four complete cross-sections. The middle two were taken at either end of the culvert under the power line right-of-way, with the exterior top of bank points taken in the bottom centers of the small ditches that feed into the perimeter ditch on either side of the right-of-way. Cross-sections 1 & 4 are SW and NE of those cross-sections. There is one point, NWDITCH-5, that is the interior top of bank NE of cross-section 4. The ditch changes direction at cross-section 4, so the NWDITCH-5 point was shot to provide an indicator of that bend.

All coordinates are given in State Plane (feet), referenced to the DOT stakes that were established around the time of the start of the project. Tables C.1 presents the survey data for all of the piezometers and Table C.2 presents survey data for the perimeter ditch at the four transects.

Table C.1: Survey data for the piezometers

Pt#	Northing	Easting	Elevation (ft)	Description	Elevation (m)
3001	273579.687	1991847.821	123.978	SWIN05E	37.788
3002	273582.051	1991844.527	122.774	SWIN05W	37.422
3005	273721.413	1992026.792	122.184	SWIN75E	37.242
3006	273725.949	1992025.775	122.399	SWIN75W	37.307
3007	273525.674	1991796.461	124.047	SWEX20E	37.810
3008	273528.879	1991791.802	124.464	SWEX20M	37.937
3009	273532.045	1991787.73	124.6	SWEX20W	37.978
3012	273384.219	1991654.546	120.805	SWEX75W	36.821
3011	273379.644	1991655.392	120.805	SWEX75M	36.821
3010	273375.37	1991656.298	121.516	SWEX75E	37.038
3004	273633.078	1991888.344	122.323	SWIN25W	37.284
3003	273631.181	1991890.638	122.386	SWIN25E	37.303
3019	273570.818	1991837.227	121.672	SWDITCH	37.086
3023	278156.712	1990912.793	120.944	NWIN75N	36.864
3024	278153.084	1990910.111	120.737	NWIN75M	36.801
3025	278148.218	1990908.173	122.058	NWIN75S	37.203
3026	278292.432	1990813.237	121.755	NWIN25N	37.111
3027	278287.447	1990809.811	121.175	NWIN25M	36.934
3028	278283.942	1990807.681	122.025	NWIN25S	37.193
3029	278331.208	1990767.35	122.882	NWIN05N	37.454
3030	278328.065	1990763.592	123.068	NWIN05S	37.511
3031	278338.686	1990745.011	121.04	NWDITCH	36.893
3032	278415.416	1990713.245	123.51	NWEX25N	37.646
3033	278412.77	1990711.168	123.646	NWEX25M	37.687
3034	278410.647	1990707.195	123.759	NWEX25S	37.722
3035	278549.254	1990613.573	126.311	NWEX75N	38.500
3036	278547.355	1990610.52	127.559	NWEX75M	38.880
3037	278545.194	1990607.831	127.143	NWEX75S	38.753
3050	277108.691	1994183.171	121.855	NEIN75W	37.141
3051	277104.34	1994188.18	121.478	NEIN75M	37.026
3052	277101.907	1994191.489	120.818	NEIN75E	36.825
3053	277211.396	1994275.388	121.999	NEIN25W	37.185
3054	277209.726	1994280.007	121.449	NEIN25M	37.018
3055	277207.005	1994283.419	121.248	NEIN25E	36.956
3056	277256.141	1994321.494	122.514	NEIN05W	37.342
3057	277253.415	1994324.641	122.02	NEIN05N	37.192
3058	277250.974	1994327.174	122.151	NEIN05E	37.232
3059	277277.941	1994351.428	122.976	NEDITCH	37.483
3060	277323.86	1994419.014	125.335	NEEX25W	38.202
3063	277277.994	1994351.476	122.958	NEDITCH	37.478
3064	277323.844	1994419.049	125.364	NEEX25W	38.211
3065	277321.923	1994422.763	125.566	NEEX25E	38.273
3066	277452.399	1994508.121	129.067	NEEX75W	39.340
3067	277451.009	1994510.972	127.523	NEEX75M	38.869
3068	277449.094	1994513.84	128.193	NEEX75E	39.073
3080	272970.675	1996346.435	118.358	SEIN75N	36.076

Table C.1 (continued): Survey data for the piezometers

3081	272970.677	1996346.43	123.114	SEIN75N	37.525
3082	272964.953	1996344.27	122.897	SEIN75S	37.459
3083	272884.764	1996486.245	121.833	SEIN25N	37.135
3084	272879.651	1996483.858	121.767	SEIN25M	37.115
3085	272874.905	1996480.919	122.184	SEIN25S	37.242
3086	272855	1996534.307	121.562	SEIN05N	37.052
3087	272843.81	1996530.314	123.327	SEIN05S	37.590
3088	272813.711	1996621.465	124.327	SEEX25N	37.895
3089	272810.953	1996620.814	124.437	SEEX25M	37.928
3090	272807.784	1996619.984	125.589	SEEX25S	38.280
3091	272755.104	1996742.306	124.936	SEEX75MS	38.080
3092	272752.019	1996744.834	125.969	SEEX75S	38.395

Table C.2: Survey data for the perimeter ditch

Point	Northing	Easting	Elevation (ft)	Descriptor	Elevation (m)
3102	277299.5422	1994321.654	119.625	NE-DITCH-1	36.462
3103	277305.4119	1994323.976	116.341	NE-DITCH-1	35.461
3104	277308.3524	1994326.679	116.601	NE-DITCH-1	35.540
3105	277311.3333	1994329.398	119.750	NE-DITCH-1	36.500
3106	277269.6605	1994351.687	119.948	NE-DITCH-2	36.560
3107	277273.1955	1994353.891	116.351	NE-DITCH-2	35.464
3108	277277.4735	1994357.277	116.126	NE-DITCH-2	35.395
3109	277280.3953	1994360.412	120.121	NE-DITCH-2	36.613
3110	277249.0029	1994374.532	120.309	NE-DITCH-3	36.670
3111	277253.1059	1994377.54	115.151	NE-DITCH-3	35.098
3112	277257.2418	1994380.323	115.637	NE-DITCH-3	35.246
3113	277259.866	1994385.501	119.955	NE-DITCH-3	36.562
3117	272957.5786	1996554.733	120.141	SE-DITCH-1	36.619
3118	272959.2714	1996562.717	114.516	SE-DITCH-1	34.905
3119	272958.6623	1996567.614	114.978	SE-DITCH-1	35.045
3120	272957.5373	1996572.294	120.554	SE-DITCH-1	36.745
3121	272820.3681	1996528.804	119.760	SE-DITCH-2	36.503
3122	272817.7661	1996535.72	115.237	SE-DITCH-2	35.124
3123	272815.9406	1996540.056	115.623	SE-DITCH-2	35.242
3124	272812.4011	1996545.732	121.033	SE-DITCH-2	36.891
3125	272683.8712	1996453.313	120.075	SE-DITCH-3	36.599
3126	272681.3526	1996461.668	114.713	SE-DITCH-3	34.965
3127	272679.3564	1996465.608	115.289	SE-DITCH-3	35.140
3128	272677.3565	1996473.64	121.277	SE-DITCH-3	36.965
3135	273557.3793	1991863.556	120.396	SW-DITCH-1	36.697
3136	273552.4397	1991857.311	114.104	SW-DITCH-1	34.779
3137	273549.2735	1991854.808	113.826	SW-DITCH-1	34.694
3138	273539.7866	1991850.712	121.573	SW-DITCH-1	37.055
3139	273570.1956	1991815.939	121.780	SW-DITCH-2	37.118
3140	273578.8994	1991821.711	114.097	SW-DITCH-2	34.777
3141	273582.0136	1991824.06	114.061	SW-DITCH-2	34.766

Table C.2 (continued): Survey data for the perimeter ditch

3142	273589.2178	1991831.652	120.588	SW-DITCH-2	36.755
3143	273617.552	1991793.51	120.486	SW-DITCH-3	36.724
3144	273613.2282	1991787.595	113.591	SW-DITCH-3	34.622
3145	273610.9204	1991784.568	113.582	SW-DITCH-3	34.620
3146	273603.1311	1991774.07	122.488	SW-DITCH-3	37.334
3153	278299.0526	1990693.545	119.817	NW-DITCH-1	36.520
3154	278306.474	1990689.509	115.960	NW-DITCH-1	35.345
3155	278309.7173	1990688.241	116.036	NW-DITCH-1	35.368
3156	278316.3547	1990687.515	119.351	NW-DITCH-1	36.378
3157	278331.1827	1990750.696	120.320	NW-DITCH-2	36.674
3158	278337.344	1990745.39	114.977	NW-DITCH-2	35.045
3159	278339.7024	1990743.466	115.086	NW-DITCH-2	35.078
3160	278344.0492	1990736.631	117.129	NW-DITCH-2	35.701
3161	278349.9161	1990783.465	120.382	NW-DITCH-3	36.692
3162	278359.2545	1990780.176	115.219	NW-DITCH-3	35.119
3163	278361.4981	1990779.148	115.626	NW-DITCH-3	35.243
3164	278366.9936	1990772.857	115.832	NW-DITCH-3	35.306
3165	278368.6504	1990837.723	120.241	NW-DITCH-4	36.649
3166	278376.5803	1990836.225	115.362	NW-DITCH-4	35.162
3167	278379.536	1990834.78	115.406	NW-DITCH-4	35.176
3168	278387.6903	1990831.933	119.364	NW-DITCH-4	36.382
3169	278398.1411	1991006.045	119.543	NW-DITCH-5	36.437