Assessment of Groundwater Flows at Juniper Bay and their Impacts on the Surrounding Area

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16. Abstract

The North Carolina Department of Transportation purchased a 750-acre, 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 492-ft (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 42 ft) were collected along the transects to guide placement of piezometers for monitoring hydraulic heads. Water levels in the piezometers were recorded at 15-minute intervals. Meteorological data were collected with a weather station near the middle of the bay.

Models were developed for the four transects using Visual MODFLOW. The models were calibrated with observed hydraulic heads. The maximum absolute error in the calibration process was 1.6 ft (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 the Northwest (NW) and Northeast (NE) transects. Modeling of the Southwest (SW) transect indicated outflows. The Southeast (SE) transect showed water draining into the ditch from both sides. The models were extended to 2600 ft (800 m) inside the bay to simulate conditions after the interior ditch system was blocked. Simulation results showed groundwater inflows at the NW, NE, and SE transects, and groundwater outflow at the SW transect. The lateral influence of the perimeter ditch had a maximum of approximately of 330 ft (100 m), observed at the SW transect, and a minimum of 100 ft (30 m), observed at the SE transect. The extent of influence of the perimeter ditch also dependeD on the weather conditions, showing more influence in summer months than in 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 transect models were extrapolated over the entire perimeter of Juniper Bay to obtain an estimate of net groundwater inflow. Net groundwater inflow was approximately 0.41 ft (125 mm) for the period of 1 January 2004 to 30 June 2004.

To develop recommendations for maintenance and operation of 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 117.8 ft (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 that level would, according to the model, minimize offsite impacts and result in maximum wetland area.

17. Key Words
Groundwater, wetland, modeling, MODFLOW

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This project was built upon the prior work of several of graduate students under the direction of Drs. M. Vepraskas and J. Gregory. Technical support was provided by many, most notably Alex Adams and Pete Caldwell. Alex Adams also contributed many hours to data collection and provided his soils expertise for sediment profiling.

Executive Summary

The North Carolina Department of Transportation purchased a 750-acre, 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 492-ft (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 42 ft) were collected along the transects to guide placement of piezometers for monitoring hydraulic heads. Water levels in the piezometers were recorded at 15-minute intervals. Meteorological data were collected with a weather station near the middle of the bay.

Models were developed for the four transects using Visual MODFLOW. The models were calibrated with observed hydraulic heads. The maximum absolute error in the calibration process was 1.6 ft (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 the Northwest (NW) and Northeast (NE) transects. Modeling of the Southwest (SW) transect indicated outflows. The Southeast (SE) transect showed water draining into the ditch from both sides. The models were extended to 2600 ft (800 m) inside the bay to simulate conditions after the interior ditch system was blocked. Simulation results showed groundwater inflows at the NW, NE, and SE transects, and groundwater outflow at the SW transect. The lateral influence of the perimeter ditch had a maximum of approximately of 330 ft (100 m), observed at the SW transect, and a minimum of 100 ft (30 m), observed at the SE transect. The extent of influence of the perimeter ditch also dependeD on the weather conditions, showing more influence in summer months than in 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 transect models were extrapolated over the entire perimeter of Juniper Bay to obtain an estimate of net groundwater inflow. Net groundwater inflow was approximately 0.41 ft (125 mm) for the period of 1 January 2004 to 30 June 2004.

To develop recommendations for maintenance and operation of 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 117.8 ft (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 that level would, according to the model, minimize offsite impacts and result in maximum wetland area.

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1. Introduction

The North Carolina Department of Transportation purchased a 750-acre parcel of agricultural land, Juniper Bay (a drained Carolina Bay), to convert into wetland for wetland mitigation credit. 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, this 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 shallow sand layers.

Objectives

Characterize the subsurface flows at the perimeter of the Bay.
Determine the degree and modes of interaction of the perimeter ditch of the Bay with the partially confined sand strata.
Model the subsurface flows in the Bay area and assess the impacts of these flows on the surrounding area.
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 1.1 shows the 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.

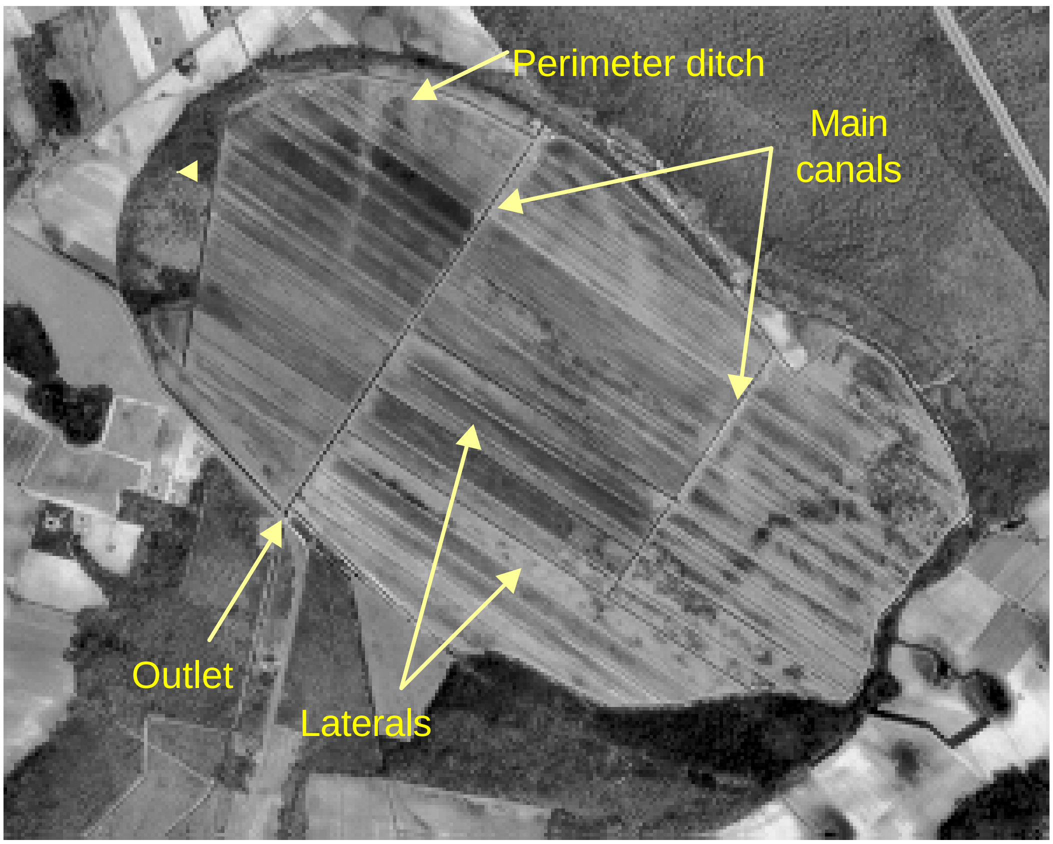

Figure 1.1 Aerial photo of Juniper Bay from 1993 (USDA-FSA). NW-SE and SW-NE extents are approximately 1.6 mi and 0.9 mi, respectively.

A conceptual profile at Juniper Bay is shown in Figure 1.2. 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.

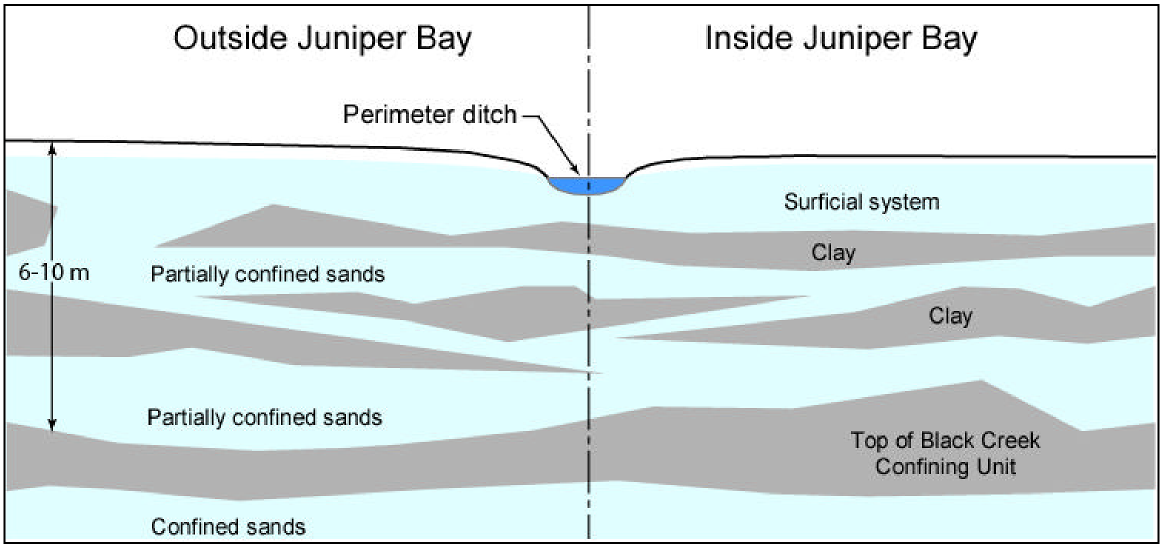

Figure 1.2 Conceptualization of stratigraphy at Juniper Bay

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 50 acres.

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.

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 shows an aerial photo, from 1903, 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 at least 5,750 years at shallow depths (1.05m). They have northwest to southeast orientation and vary in size from a few hundred feet to three or four miles on the major axis. Many are bordered by a rim of sands. Many are in a vegetative wetland state. There are several theories explaining their origin. The most popular are those which postulate origins from meteorites or wind action.

Origin of Carolina Bays

Johnson (1936) suggested that the 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 comets or asteroids entering the 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 the Thom water table perching theory. He suggested that the only requirement for Bay existence is poor drainage leading to ponding.

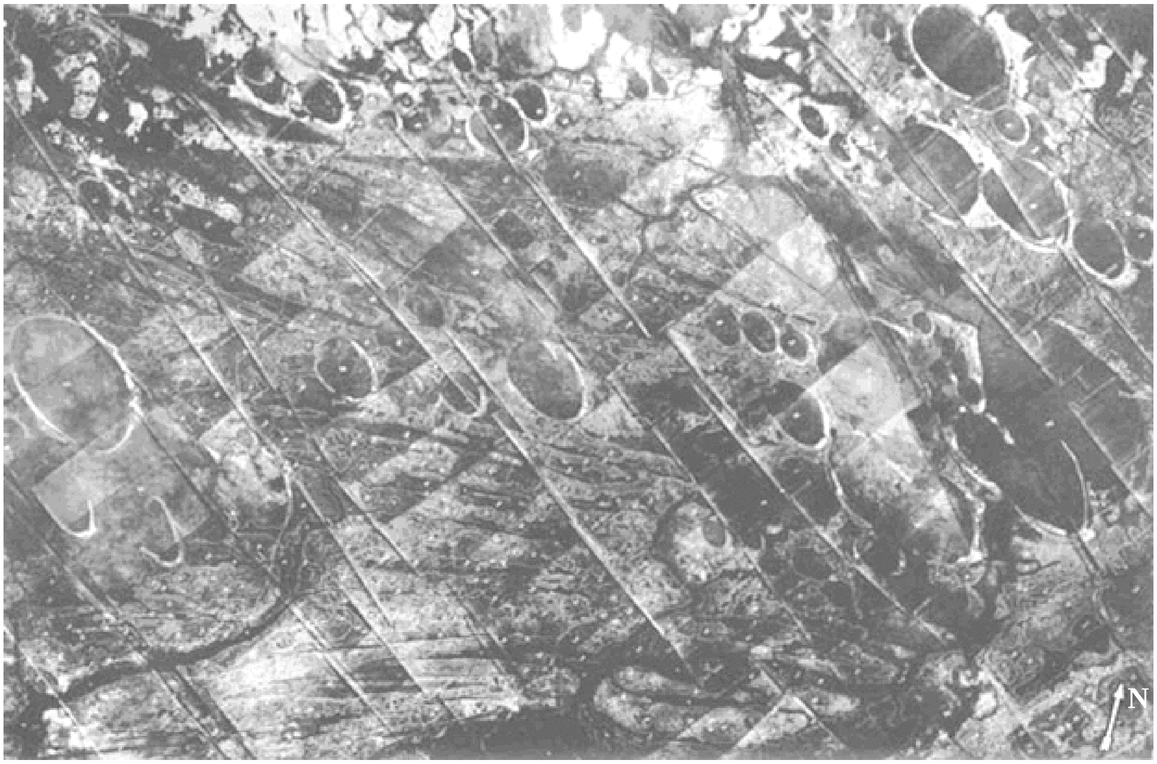

Figure 2.1 Arial Photo of Carolina Bays near Myrtle Beach in Horry County, South Carolina.

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 6.7 to 22.2 in., 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 uses finite difference techniques to solve the governing flow equations.

MODFLOW 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 HydroGeoLogic 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 Harbaugh (2000) explained concepts of groundwater flow concepts in MODFLOW. The partial-differential equation of groundwater flow used in MODFLOW is given in Equation 2.1. MODFLOW uses finite-difference methods to solve this equation.

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)+W=S_s\frac{\partial h}{\partial t} \qquad (2.1)$$

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.

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

The topographic map shown in Figure 3.1, shows 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. 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), Northeast (NE), Southeast (SE), and Southwest (SW).

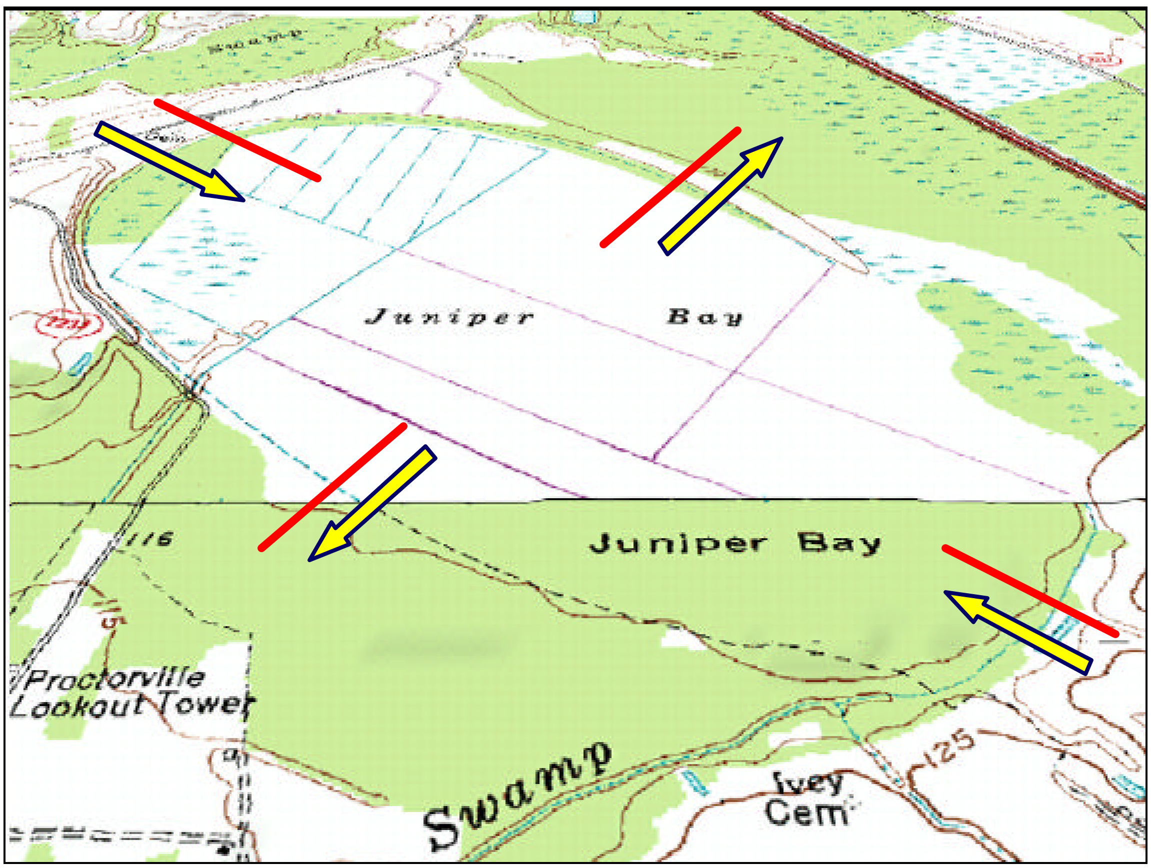

Figure 3.1 Perspective view of Juniper Bay topography. Arrows indicate the expected directions of subsurface flux.

3.2. Soil Coring

At each transect, sediment cores were collected at five different points on each transect as shown in Figure 3.2. Three sediment cores were collected from the interior of the bay at 16, 82, and 246 ft (5, 25, and 75 m) from the center of the ditch. Similarly, two sediment cores were collected from the exterior of the bay at 82 and 246 ft (25 and 75 m) from the center of the ditch. A drill rig from the North Carolina State University Department of Biological and Agricultural Engineering was used for the coring. Cores were collected using a 4-in. OD, 5-ft long core barrel inside a 4¼-in. ID hollow stem auger. Plastic (cellulose acetate butyrate) liners, 5 ft × 3.46 in. OD × 1/32 in. wall thickness, facilitated handling and storage of the cores. Cores were collected at each location typically to 25–35 ft, usually penetrating the top of the Black Creek Confining Unit. The interior of the SE transect was an exception because consolidated shells were encountered at about 30 ft. No cores were deep enough to reach the Black Creek Aquifer.

Figure 3.3 shows the locations of the individual cores and nests of piezometers on each of the transects.

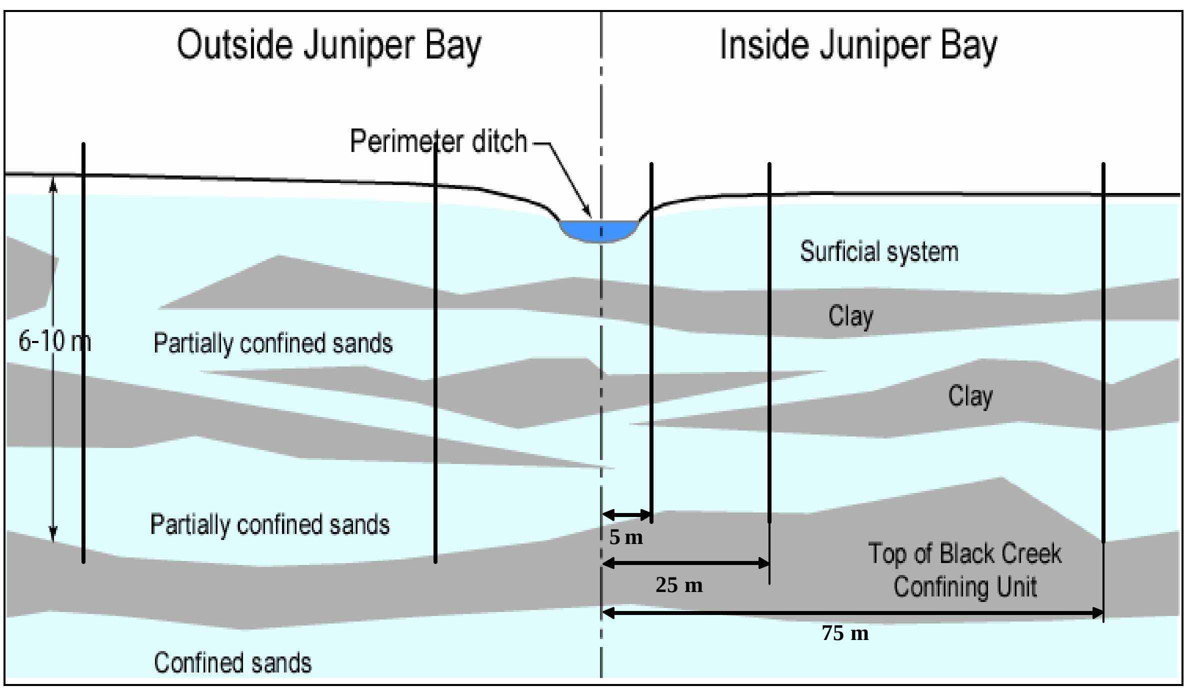

Figure 3.2 Core locations on each transect.

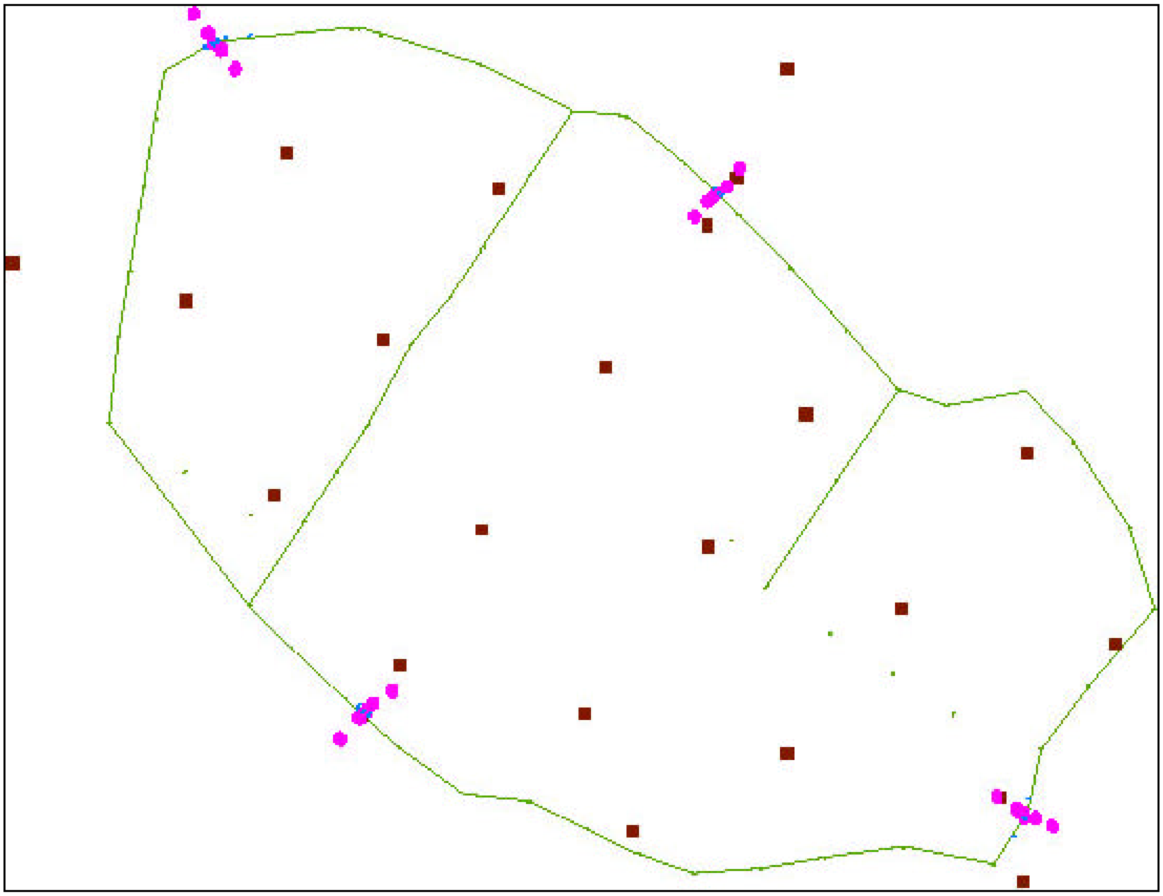

Figure 3.3 Locations of transects. Dots represent the location of piezometer nests. Squares represent locations of preliminary cores collected for the initial project. Solid lines represent the perimeter ditch and main canals.

3.3. Soil Profiling

Soil cores were characterized in the laboratory. Figures Figure 1.1Figure 3.4, Figure 3.5, Figure 3.6, and Figure 3.7 show the stratigraphy at the NW, NE, SE, and SW transects, respectively. Figure 3.8 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 noncohesive sands. Significant differences in layers could be observed which helped in identifying sand layers that are the main water conducting layers. Horizontal distances in the profile figures 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 the perimeter ditch elevation and dimensions. Ground surface elevations, in meters, are presented in the figures.

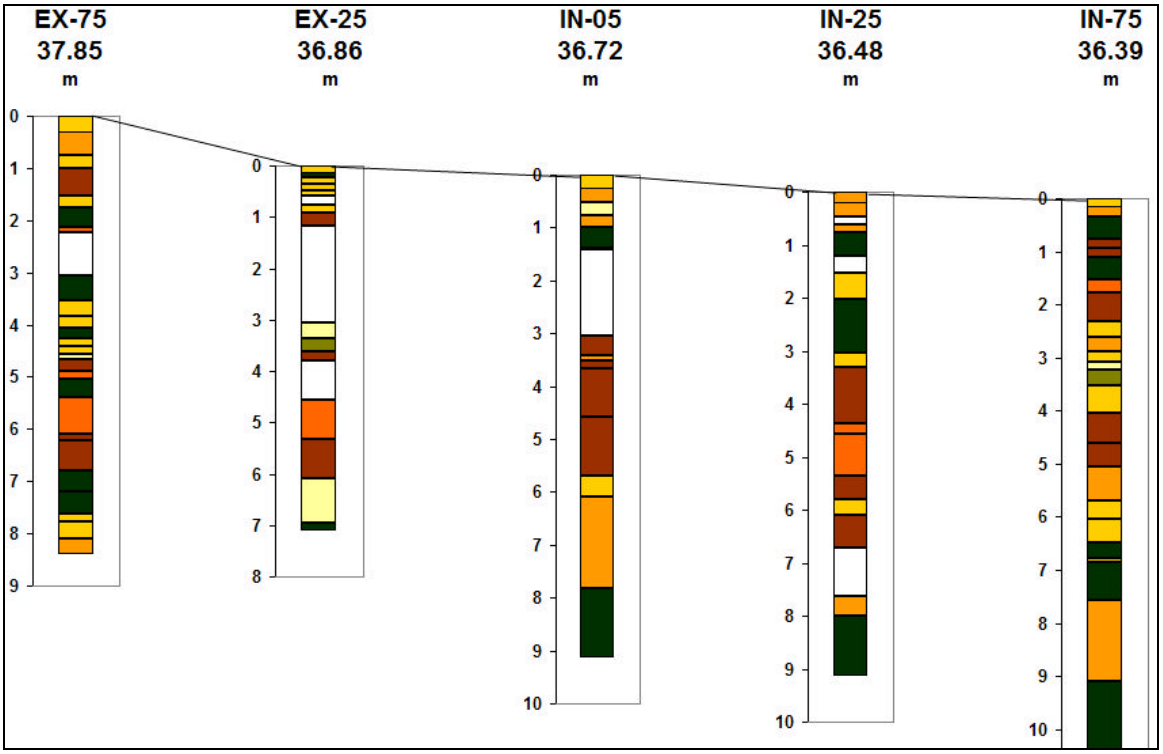

Figure 3.4 Soil profiles at NW transect. Legend is given in Figure 3.8.

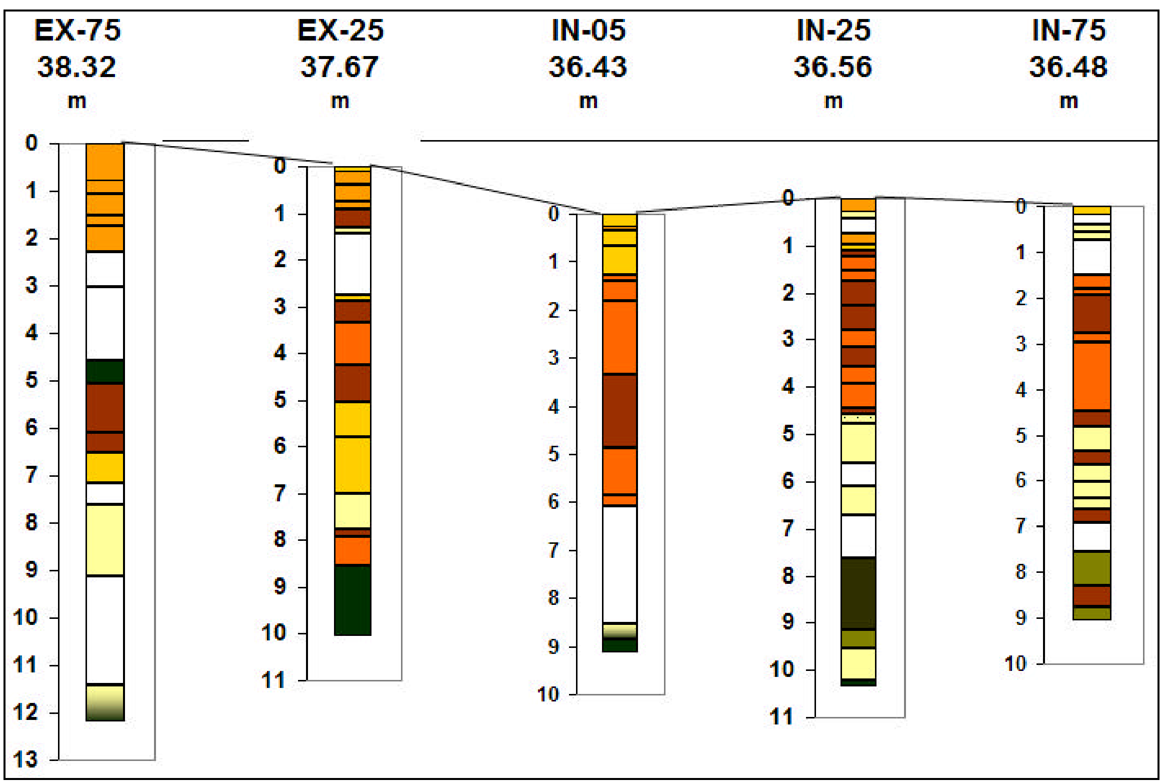

Figure 3.5 Soil profiles at NE transect. Legend is given in Figure 3.8.

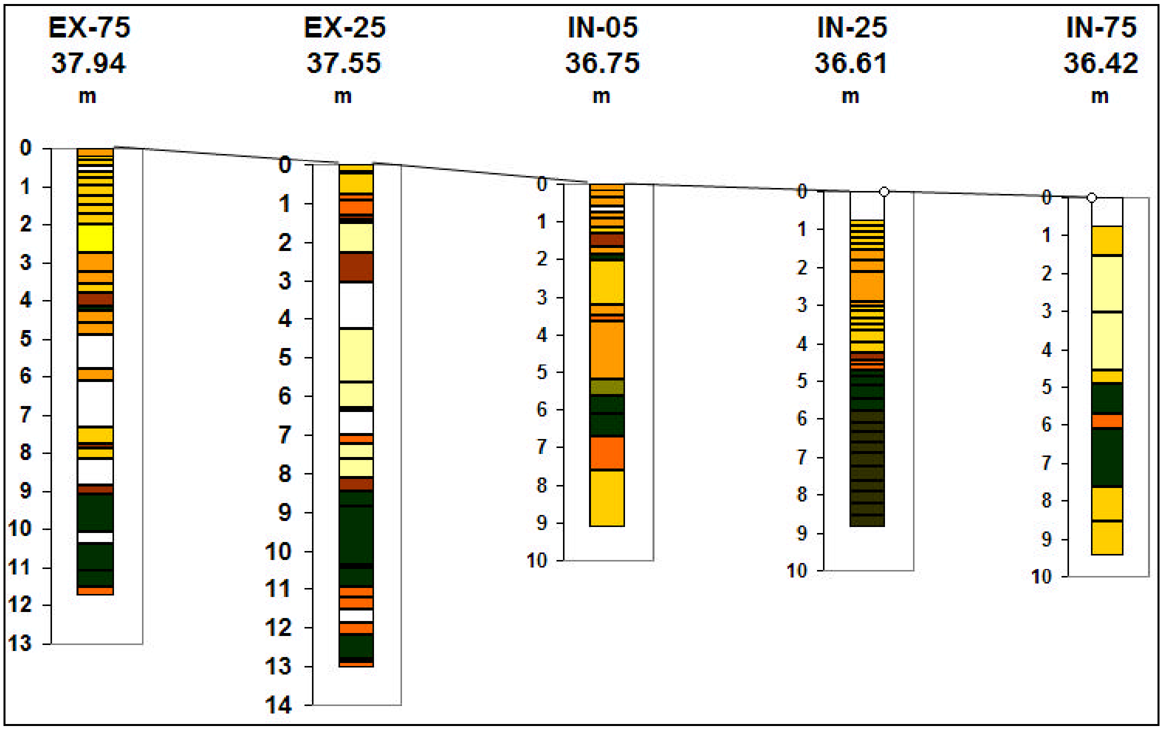

Figure 3.6 Soil profiles at SE transect. Legend is given in Figure 3.8.

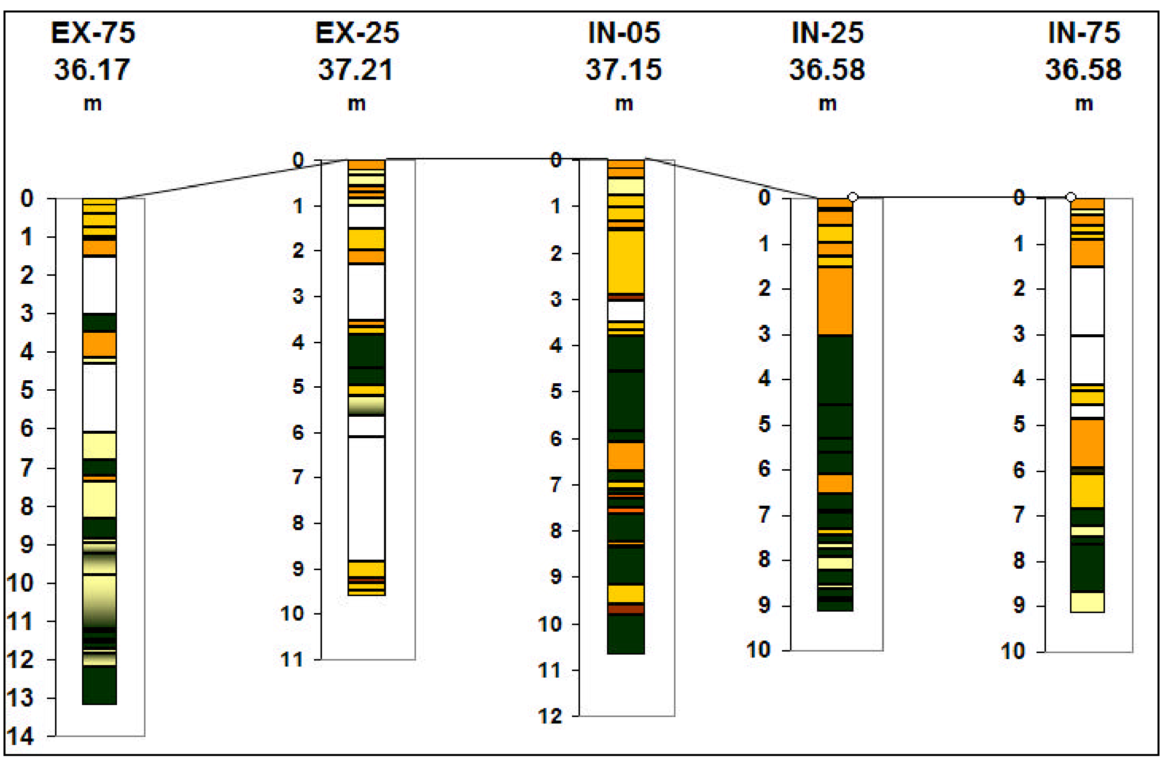

Figure 3.7 Soil profiles at SW transect. Legend is given in Figure 3.8.

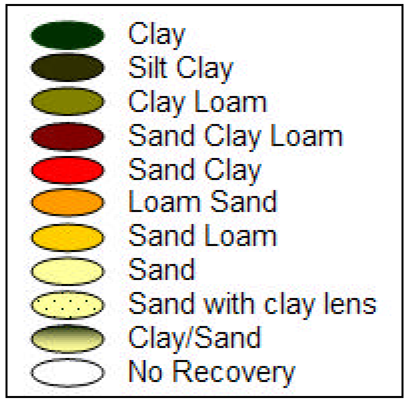

Figure 3.8 Legend for Figure 3.4 toFigure 3.7

The NW transect (Figure 3.4) had three distinguishable sand and coarse-textured layers. The top layer is considered to be surface layer to the depth of 6.5-10 ft, and the deeper sandy layers were observed at the depths of 16-20 ft and 26-33 ft. Similarly, at the NE transect (Figure 3.5) deeper sandy layers were at the depths of 16-23 ft and 23-30 ft, varying with core location. The SE transect had surficial sands to a depth of 10-16 ft, and the deeper sands were found at the depths of 20-23 ft and 26-33 ft. The SW transect showed the surface layer to the depth of 10-13 ft. Deeper sand layers were found at the depths of 20-23 ft and 26-30 ft. 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 3 in.×3 in. cylindrical 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 a test. The saturated soil core was placed on a 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 with a resolution of 1 mL. 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 3.9. This flow rate was used to estimate K_{sat} of each core sample. K_{sat} was estimate using Darcy's Law (Equation 3.1).

$$K_{sat} = \frac{V}{At\frac{\Delta h}{L}} \tag{3.1}$$

K_{sat} = saturated Hydraulic Conductivity
V = volume of outflow during the time period t
A = cross-sectional area of core
?h = hydraulic head difference between the top and bottom of core
L = length of core

Table 3.1 gives an example of the calculation of the saturated conductivity values the various strata for the NW-EX-75 core. Samples that had extremely low flow rates do not have K_{sat} values in the table.

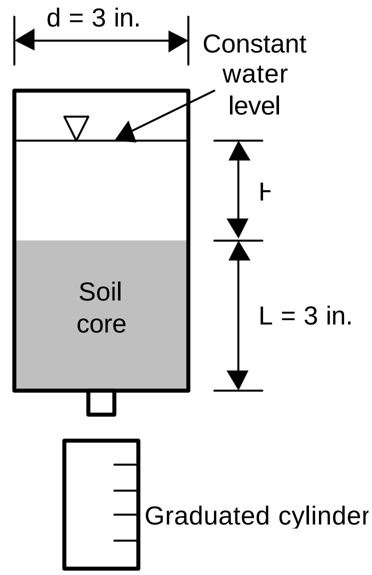

Figure 3.9 Schematic of K_{sat} apparatus.

Table 3.1 K_{sat} Calculations for the NW-EX-75 Core Strata

Top (in.)	*Bottom (in.)*	*Color*	*Texture*	*t (s)*	*V (ml)*	*H (in.)*	K_{sat} *(ft/d)*
0	12	10YR3/2	SL	120	7	2.36	2.0E+00
12	30	2.5Y5/3	LS				
30	40	10YR3/1	SL			2.28	
40	60	10YR3/1 + 10YR5/1	SCL	420	5	2.20	4.3E-01
40	60			240	8	2.36	1.2E+00
60	69	2.5Y6/1	SL	30	5	2.17	6.0E+00
69	84	2.5Y7/1	C			1.97	
84	88	2.5Y5/2	SCL			2.17	
88	120						
120	139	2.5Y6/2	C			2.17	
139	151	2.5Y7/1 + 7.5YR6/8 conc.	SL	600	2	2.28	1.2E-01
151	160	2.5Y8/1	SL			2.28	
160	168	2.5Y7/1	C				
168	174	2.5Y8/1	SL			2.32	
174	180						
180	184	10YR7/1	S	60	5	2.05	3.1E+00

Top (in.)	*Bottom (in.)*	*Color*	*Texture*	*t (s)*	*V (ml)*	*H (in.)*	K_{sat} *(ft/d)*
184	192	10YR5/8	SCL	10	100	1.85	3.8E+02
192	198	10YR6/2	SC	10	100	2.40	3.5E+02
198	212	4N	C			2.36	
212	240	3N	SC			2.32	
240	245	2.5Y3/1	SCL	16	70	1.97	1.6E+02
245	269	3N	SCL	120	5	2.44	1.4E+00
269	283	4N	C	60	6	2.24	3.6E+00
283	300	3N	C	90	6	2.17	2.4E+00
300	306	3.5GY	SL	12	50	1.89	1.6E+02
306	319	5.5GY	SL/C			2.32	
319	331	10YR4/1	LS			2.36	

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 3.2 gives the depths of significant sand layers at each core location, which corresponds to the screened depths of the piezometers installed at those locations.

Piezometers were installed using 4¼ in. ID hollow stem augers. The 2-in. 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 at the lower end was knocked out. Coarse sand was added to form a filter pack around the screen. A grout pump with a tremie pipe were used to inject bentonite grout into the borehole as the hollow stem auger was retracted.

Table 3.2 Screened depths of the piezometers

Transect	Piezometer Nest	Number of Piez.	Screened depths of piezometers (ft)			
SE	SE-IN-75	3	12-14	19-26	26.5-33.5	
	SE-IN-25	3	10-12	14-16	28-30	
	SE-IN-5	2	7-11	25-30		
	SE-EX-25	3	18-20	25-27	35-40	
	SE-EX-75	4	10-12	15-17	22-27	31-36
SW	SW-IN-75	2	10-12	15-17		
	SW-IN-25	3	8-10	15-17	20-22	
	SW-IN-5	2	10-12	20-25		
	SW-EX-25	3	10-12	16-18	29-31	
	SW-EX-75	3	10-12	15-17	22-27	
NE	NE-IN-75	3	15-17	20-25	30-35	
	NE-IN-25	3	10-12	16-18	20-25	
	NE-IN-5	3	10-12	15-17	20-25	
	NE-EX-25	2	5-9	18-20		
	NE-EX-75	3	12-14	22-24	30-35	
NW	NW-IN-75	3	15-20	8.5-10.5	25-30	
	NW-IN-25	3	20-25	10-12	16-20	
	NW-IN-5	2	8-10	20-25		
	NW-EX-25	3	8-10	13-15	20-22	
	NW-EX-75	3	8-10	14-16	25-30	

3.6. Water Level Monitoring System

An independent water level monitoring system was installed at each piezometer nest. Water level in the perimeter ditch at each transect were also monitored. This arrangement gives head data over a vertical cross-section that is 16-40 ft deep and 492 ft (150 m) wide, centered on the perimeter ditch.

The water level monitoring systems used 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 1/32-in. ID tubes connected the solenoid valves to each piezometer, where the open ends of the tubes were suspended at a depth of 9.00 ft 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 9.00 ft was chosen because the preliminary data suggested the water levels would not go below that even in a drought period. Differential pressure transducers having a 5 psi range 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 made all readings for the nest directly comparable. Piezometer elevations were determined by survey with a total station, using NCDOT markers (vertical accuracy approximately 0.1 ft) as references. Vertical accuracy within a transect was about 0.02 ft. 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 3.10 Nest of three piezometers with water level monitoring system.

The monitoring units were programmed to take readings every 15 minutes. Figure 3.11 shows a 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 3.12 shows the inside of a weatherproof enclosure with the components in it. This monitoring system has a resolution of approximately 0.003 ft (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 10-ft water column was set up in the laboratory and air tubes were suspended at depths of 1.97, 5.25, and 8.53 ft (600, 1600, and 2600 mm). Water was filled to a height of 8.53 ft in the column. Voltage outputs were used to develop calibration curves for each of the units.

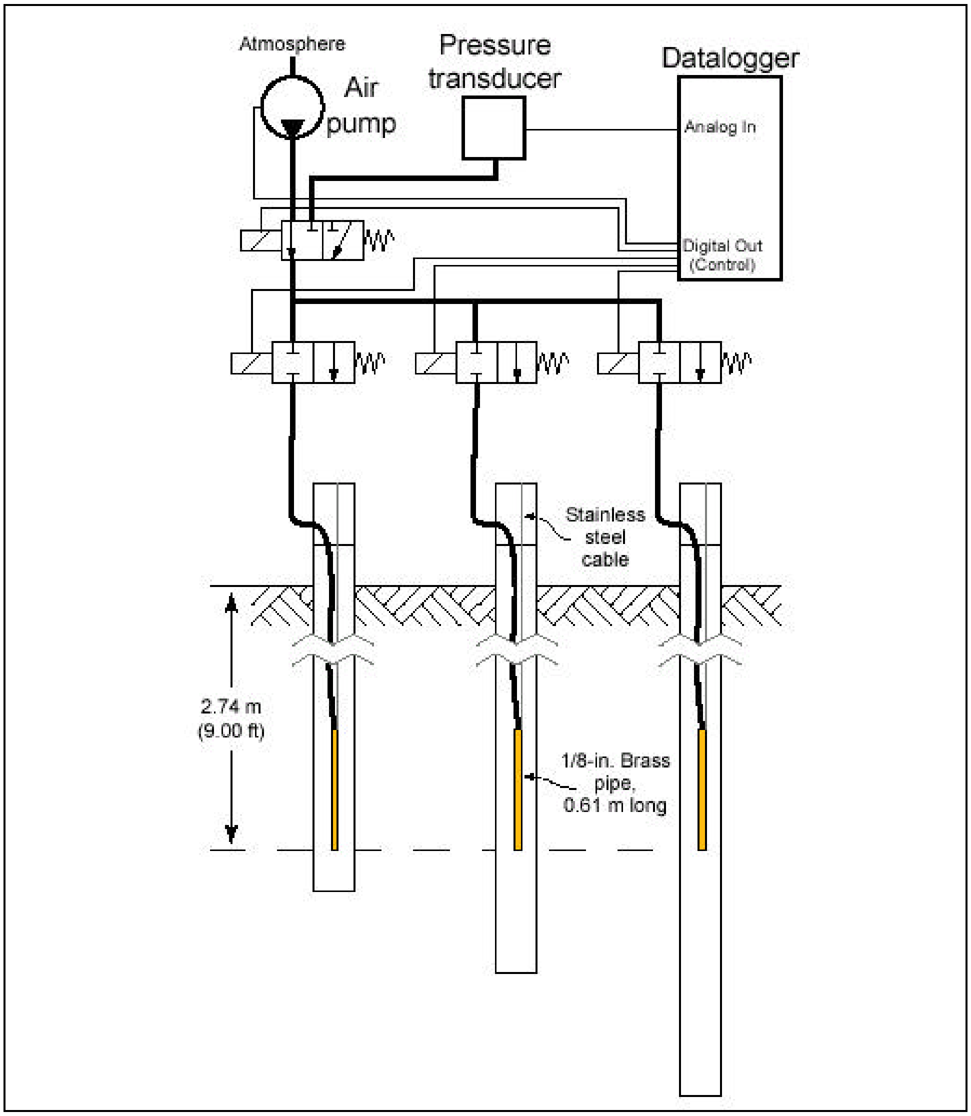

Figure 3.11 Schematic diagram of a monitoring unit assembly

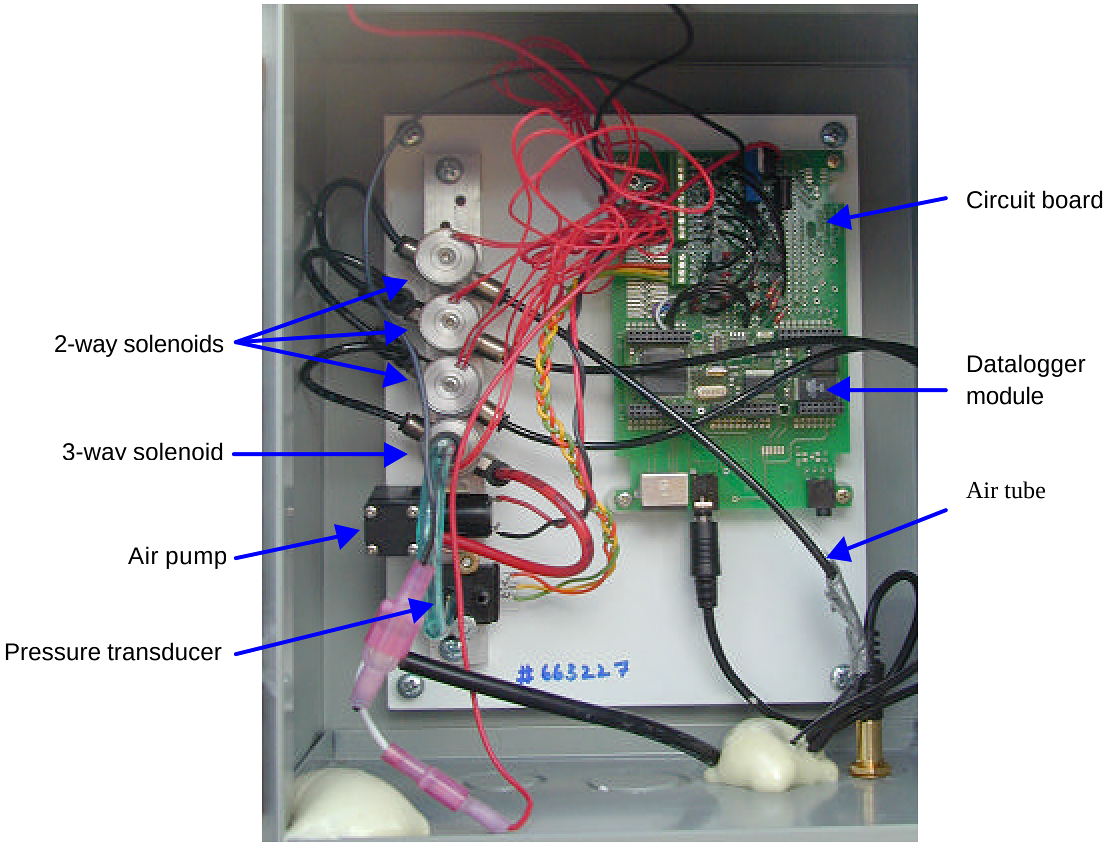

Figure 3.12 Monitoring unit in its enclosure.

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 3.2.

$$K = \frac{r^2 \ln(L_e / R)}{2 L_e t_{37}} \qquad (3.2)$$

where 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 for the water level to rise or fall 37% of the initial change

Table 3.3 K_{sat} values from slug tests

	r, in.	*R, in.*	L_e*, in.*	t_{37}*, s*	*K, in./s*	*K, ft/d*
Northeast						
NE-IN-5-D	1.0	1.0	60	57	6.0E-04	4.3E+00
NE-IN-5-M	1.0	1.0	24	41	1.6E-03	1.2E+01
NE-IN-5-S	1.0	1.0	24			
NE-IN-25-D	1.0	1.0	60			
NE-IN-25-M	1.0	1.0	24	70	9.5E-04	6.8E+00
NE-IN-25-S	1.0	1.0	24			
NE-IN-75-D	1.0	1.0	60	9	3.8E-03	2.7E+01
NE-IN-75-M	1.0	1.0	60	58	5.9E-04	4.2E+00
NE-IN-75-S	1.0	1.0	24	24	2.8E-03	2.0E+01
NE-EX-25-D	1.0	1.0	60			
NE-EX-25-S	1.0	1.0	48	97	4.2E-04	3.0E+00
NE-EX-75-D	1.0	1.0	60	233	1.5E-04	1.1E+00
NE-EX-75-M	1.0	1.0	24	267	2.5E-04	1.8E+00
NE-EX-75-S	1.0	1.0	24			
Northwest						
NW-IN-5-D	1.0	1.0	60	72	4.7E-04	3.4E+00
NW-IN-5-S	1.0	1.0	24			
NW-IN-25-D	1.0	1.0	60	260	1.3E-04	9.4E-01
NW-IN-25-M	1.0	1.0	48	113	3.6E-04	2.6E+00
NW-IN-25-S	1.0	1.0	24	230	2.9E-04	2.1E+00
NW-IN-75-D	1.0	1.0	60			
NW-IN-75-M	1.0	1.0	60	213	1.6E-04	1.2E+00
NW-IN-75-S	1.0	1.0	24	480	1.4E-04	9.9E-01
NW-EX-25-D	1.0	1.0	24	49	1.4E-03	9.7E+00
NW-EX-25-M	1.0	1.0	24			
NW-EX-25-S	1.0	1.0	24			
NW-EX-75-D	1.0	1.0	60	6	5.7E-03	4.1E+01
NW-EX-75-M	1.0	1.0	24			
NW-EX-75-S	1.0	1.0	24	600	1.1E-04	7.9E-01
Southwest						
SW-IN-5-D	1.0	1.0	60	210	1.6E-04	1.2E+00
SW-IN-5-S	1.0	1.0	24			
SW-IN-25-D	1.0	1.0	24	530	1.2E-04	9.0E-01
SW-IN-25-M	1.0	1.0	24			
SW-IN-25-S	1.0	1.0	24			
SW-IN-75-D	1.0	1.0	24	374	1.8E-04	1.3E+00
SW-IN-75-S	1.0	1.0	24			
SW-EX-25-D	1.0	1.0	24	680	9.7E-05	7.0E-01
SW-EX-25-M	1.0	1.0	24	67	9.9E-04	7.1E+00
SW-EX-25-S	1.0	1.0	24			
SW-EX-75-D	1.0	1.0	60			
SW-EX-75-M	1.0	1.0	24	687	9.6E-05	6.9E-01
SW-EX-75-S	1.0	1.0	24	101	6.6E-04	4.7E+00

	r, in.	R, in.	L_e, in.	t_{37}, s	K, in./s	K, ft/d
Southeast						
SE-IN-5-D	1.0	1.0	60			
SE-IN-5-S	1.0	1.0	48	176	2.3E-04	1.6E+00
SE-IN-25-D	1.0	1.0	24	46	1.4E-03	1.0E+01
SE-IN-25-M	1.0	1.0	24	74	8.9E-04	6.4E+00
SE-IN-25-S	1.0	1.0	24			
SE-IN-75-D	1.0	1.0	24	26	2.5E-03	1.8E+01
SE-IN-75-S	1.0	1.0	24	246	2.7E-04	1.9E+00
SE-EX-25-D	1.0	1.0	24	165	4.0E-04	2.9E+00
SE-EX-25-M	1.0	1.0	24	153	4.3E-04	3.1E+00
SE-EX-25-S	1.0	1.0	24	33	2.0E-03	1.4E+01
SE-EX-75-D	1.0	1.0	60			
SE-EX-75-MD	1.0	1.0	24	91	7.3E-04	5.2E+00
SE-EX-75-MS	1.0	1.0	24	152	4.4E-04	3.1E+00
SE-EX-75-S	1.0	1.0	24	136	4.9E-04	3.5E+00

Slug test water level responses for a number of the piezometers were extremely slow. Those correspond to the missing K values in Table 3.3. It could be that the piezometers were installed in some fine-textured layers or the well screen was 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. Troubleshooting and repairs were conducted whenever necessary. Head data for the year 2004 are available for analysis, with a few gaps because of the problems with the monitoring modules. Preliminary data analysis was performed on the data for one point of time in April 2004. Figure 3.13Figure 3.14Figure 3.15Figure 3.16 show the hydraulic heads at the NW, NE, SE, and SW transects, respectively. Figure 3.17shows the legend for Figure 3.13-Figure 1.1Figure 3.16. These head data were used in modeling the groundwater flows on each transect, which is discussed in detail in 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 Table 3.4 to Table 3.7.

The head data for the NW transect, given in Table 3.4, show the gradients across the transect, which can be visualized in Figure 3.13. Heads in the surface layers indicate that the water drains into the perimeter ditch from both sides, because the gradient was towards the perimeter ditch from both sides. In the middle sand layer the gradient indicated flow from outside of the bay toward the inside, suggesting groundwater inflow, except for EX-25. In the lower sands, the gradient suggests flow from the exterior to the interior of Juniper bay, bypassing the perimeter ditch.

Table 3.4 NW Transect Water Level Data on 4 April 2004. Values are feet, MSL.

Piezometer Nest	*Shallow*	*Middle*	*Deep*
EX-75	122.24	122.04	122.05
EX-25	118.98	118.19	118.48
IN-5	119.41		117.94
IN-25	119.09	119.41	117.95
IN-75	119.11	118.79	117.95

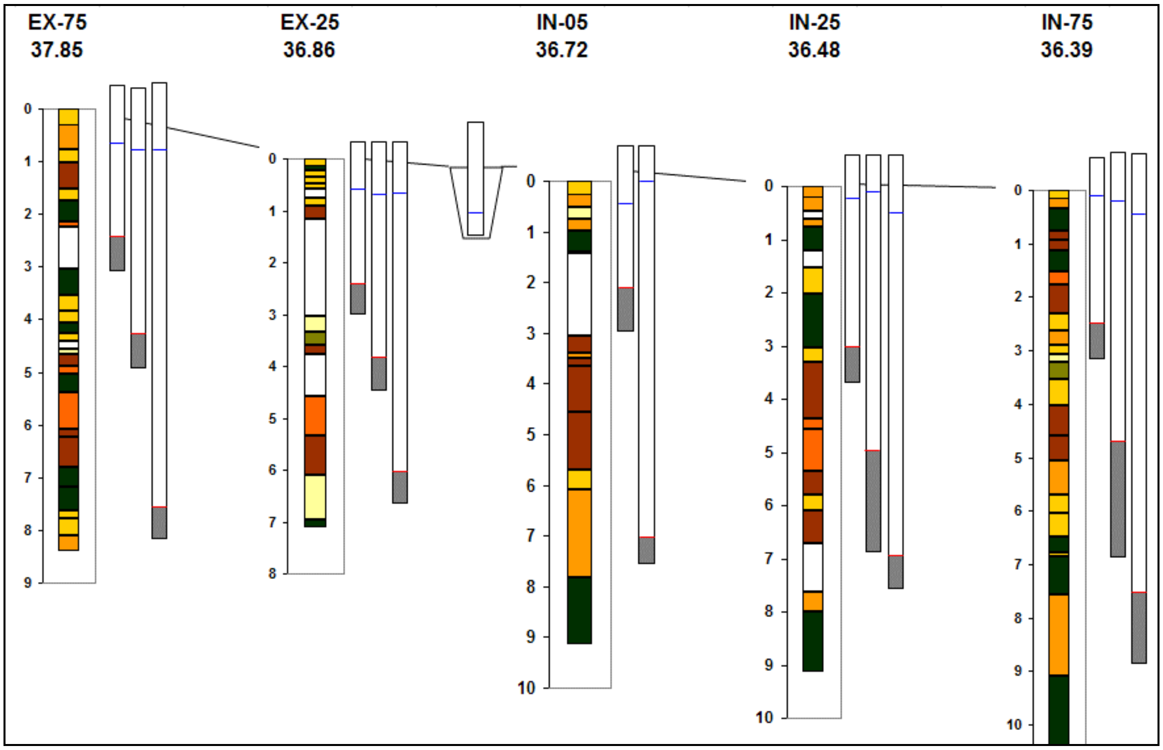

Figure 3.13 Hydraulic heads from the NW transect, 4 April 2004.

Head data from the NE transect (Table 3.4) show 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 3.14 shows the same data in a graphical view relative to the ground elevation and soil profile. Piezometers and water levels are shown at relative elevations. Cores at each nest are shown for reference.

Table 3.5 NE Transect Water Level Data on 4 April 2004. Values are feet, MSL

Piezometer Nest	*Shallow*	*Middle*	*Deep*
EX-75	123.59	123.48	123.63
EX-25	121.48		120.23
IN-5	116.76	115.88	112.76
IN-25	117.77	117.07	117.64
IN-75	116.85	116.70	116.88

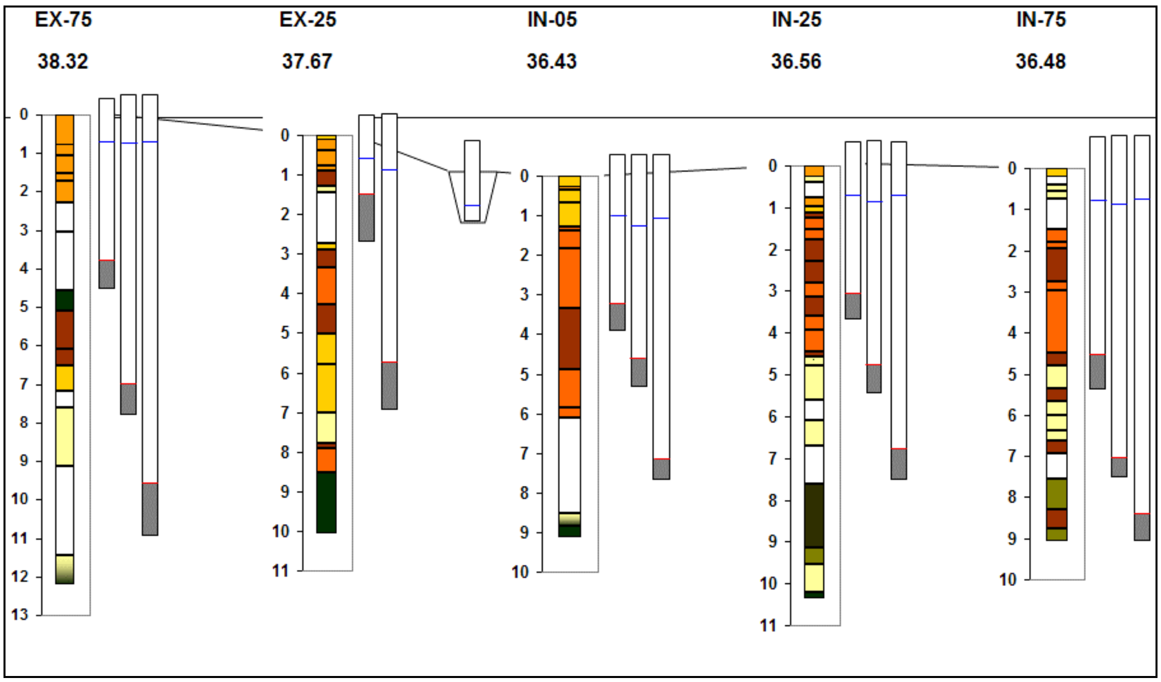

Figure 3.14 Hydraulic heads from the NE transect, 4 April 2004.

The SE transect (Table 3.6) head data, which can be graphically viewed in Figure 3.15, 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 3.6 SE Transect Water Level Data on 4 April 2004. Values are feet, MSL

Piezometer Nest	*Shallow*	*Middle*	*Middle-Deep*	*Deep*
EX-75	121.96	121.11	120.81	120.08
EX-25	120.13	119.69		118.43
IN-5	118.66			118.11
IN-25	118.29	118.30		117.95
IN-75	118.10			117.47

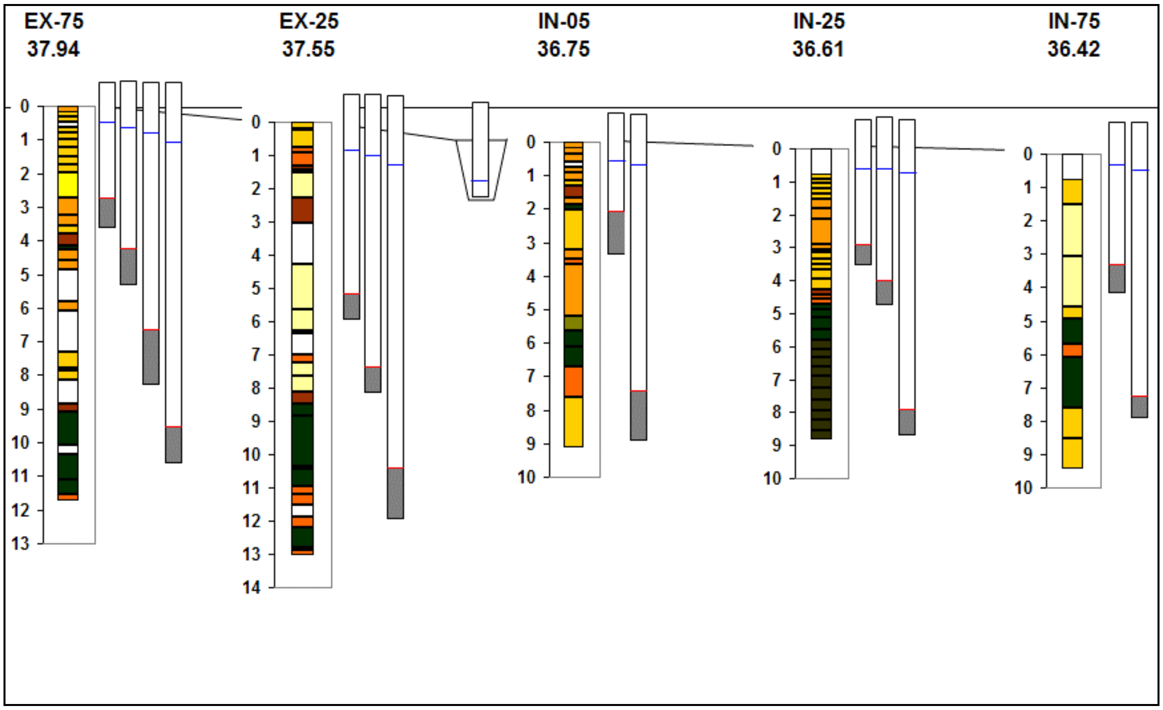

Figure 3.15 Hydraulic heads from the SE transect, 4 April 2004.

Head data at SW transect on 4 April 2004 (Table 3.7) 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 3.16. In the surface layer, water draining into the perimeter ditch, and in the middle and deeper layers gradients suggested groundwater flows from interior to exterior.

Table 3.7 SW Transect Water Level Data on 4 April 2004. Values are feet, MSL

Piezometer Nest	*Shallow*	*Middle*	*Deep*
EX-75	116.65	116.17	116.17
EX-25	117.58	115.93	116.70
IN-5	116.31	0.00	116.01
IN-25	117.98	0.00	116.48
IN-75	117.73	0.00	116.36

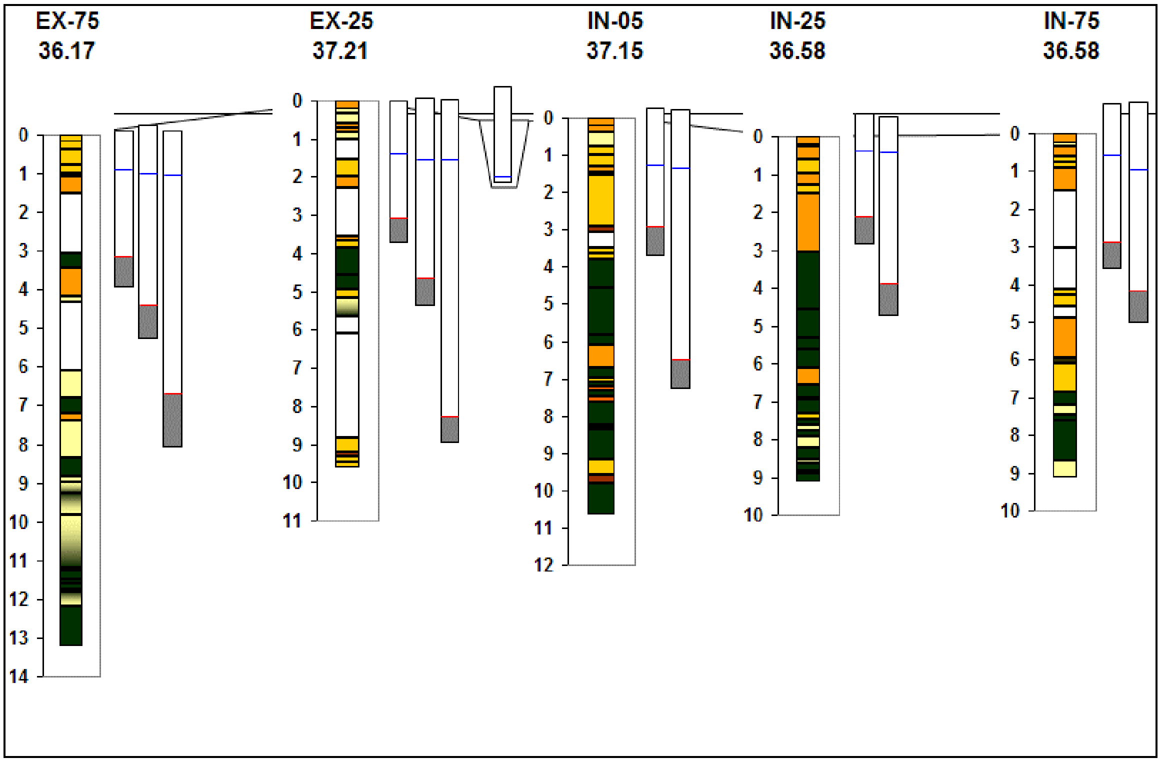

Figure 3.16 Hydraulic heads from the SW transect, 4 April 2004.

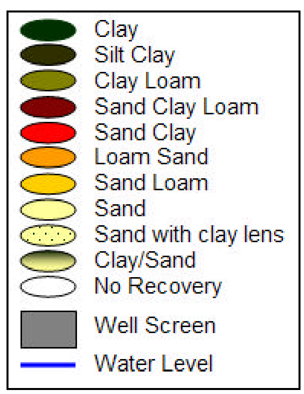

Figure 3.17 Legend for Figure 3.13 Hydraulic heads from the NW transect, 4 April 2004.Figure 3.16.

3.9. Summary

Data obtained from the cores verified the conceptualization of Juniper Bay stratigraphy (Figure 1.2). 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 (0.04 in.) 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 suggested this resolution will give a better representation of how groundwater is moving at the perimeter of the Bay than the previously existing hydrologic monitoring system. Figure 3.13 to Figure 3.16 show the head data at all transects for the first week of April 2004. Since the field resolution is approximately 0.1 in., the vertical gradients at the nests can be estimated precisely. This resolution also permits precise estimation of hydraulic gradients along 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. Analyses also suggested groundwater inflow at the NW, NE, and SE transects and groundwater outflow through the SW transect. The groundwater models and the flow analyses are discussed in greater detail in the following chapters.

4. Modeling and Analysis of Flows at Each Transect

Stratigraphic information, head data, and weather data collected on-site 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.
- Estimate the quantities of subsurface inflows and/or outflows.
- Investigate management options for the ditch.

To achieve these, 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 requires a thorough understanding of the hydrogeologic characteristics of the site. Hydrogeologic 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 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 Elevations of five layers for the four transect models, in feet MSL

Transect & Layer	EX-75	EX-25	IN-5	IN-25	IN-75
Northwest					
Ground surface	124.3	120.9	120.5	119.7	119.4
Bottom of layer 1 – Surface sand	114.1	110.9	110.5	107.7	109.4
Bottom of layer 2 – First clay	110.3	107.9	110.5	103.7	104.4
Bottom of layer 3 – Middle sand	108.3	105.9	100.7	99.7	99.4
Bottom of layer 4 – Second clay	99.3	100.9	100.7	99.7	94.4
Bottom of layer 5 – Deep sand	97.3	98.9	95.5	94.7	89.4
Northeast					
Ground surface	126.7	123.6	119.5	120.0	119.7
Bottom of layer 1 – Surface sand	110.9	113.9	109.6	107.6	103.4
Bottom of layer 2 – First clay	105.0	107.0	105.0	105.3	100.1
Bottom of layer 3 – Middle sand	95.1	101.7	101.1	100.1	95.1
Bottom of layer 4 – Second clay	95.1	100.1	98.4	98.4	93.5
Bottom of layer 5 – Deep sand	88.6	97.3	91.9	95.1	88.6
Southeast					
Ground surface	124.5	123.2	120.6	120.1	119.5
Bottom of layer 1 – Surface sand	112.9	105.0	109.1	108.6	106.4
Bottom of layer 2 – First clay	109.9	101.7	101.7	107.0	101.7
Bottom of layer 3 – Middle sand	95.1	96.8	96.8	103.7	99.8
Bottom of layer 4 – Second clay	91.9	86.9	96.0	93.9	95.1
Bottom of layer 5 – Deep sand	88.6	85.3	91.0	90.6	91.9
Southwest					
Ground surface	118.7	122.1	121.9	120.0	120.0
Bottom of layer 1 – Surface sand	106.0	110.6	109.9	110.6	106.6
Bottom of layer 2 – First clay	104.0	104.3	108.9	106.6	105.6
Bottom of layer 3 – Middle sand	98.4	104.3	107.3	103.4	100.1
Bottom of layer 4 – Second clay	95.1	102.4	101.7	100.1	99.1
Bottom of layer 5 – Deep sand	90.9	91.9	98.1	97.8	97.8

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 (from the piezometers) at the EX-75 and IN-75 locations to define left and right boundary conditions, respectively.
3. Surface conditions 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.

The grid model for the NW transect that was developed using MODFLOW is shown in Figure 4.1. 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.

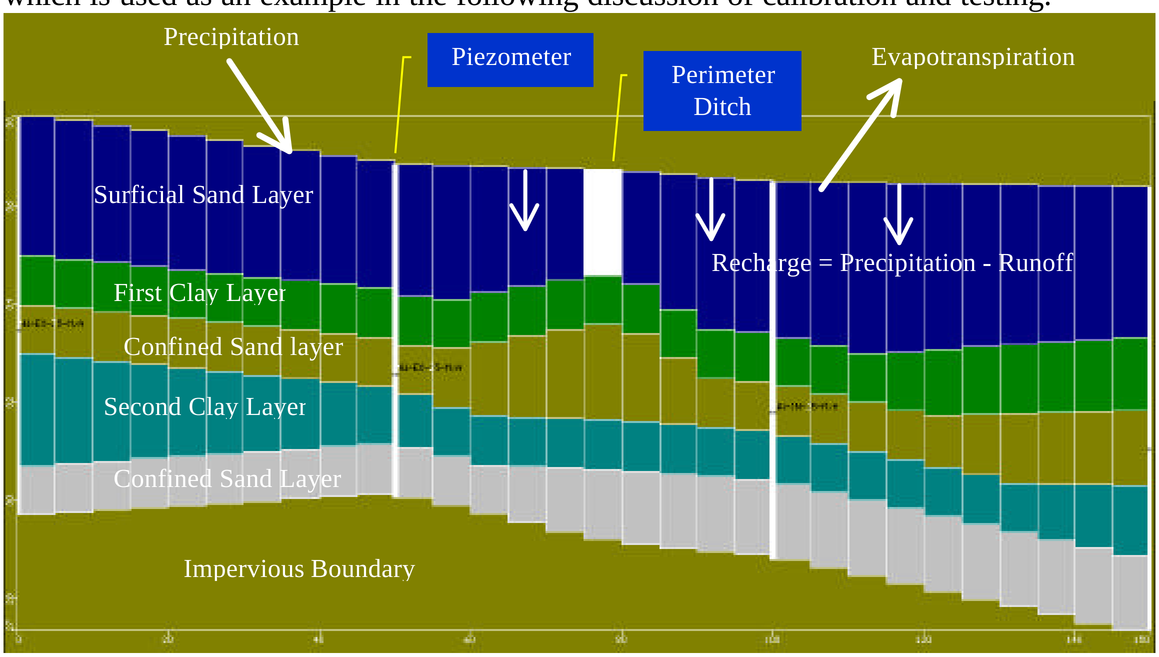

Figure 4.1 Model setup for the NW transect.

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

$$K_e = \frac{K_x D_x}{\sum D_x} \tag{4.1}$$

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

Effective K_{sat} for each layer at the NW transect is given in

Table 4.2. 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 4.2. *K* in Figure 4.2

Table 4.2 Effective Saturated Hydraulic Conductivity (ft/d) of Layers, NW

Layer	*EX-75*	*EX-25*	*IN-05*	*IN-25*	*IN-75*	K_{mean}
1	9.5E+01	4.4E+00	4.5E+01	1.8E+00	3.1E+00	3.0E+01
2	9.0E-02	1.0E+00	4.2E-01	1.4E+00	5.4E+00	1.7E+00
3	1.1E+02	6.8E+01	6.9E+00	1.6E+01	8.1E+00	4.2E+01
4	5.9E+00	3.3E-02	2.6E+00	3.4E+00	5.7E-01	1.9E+00
5	1.0E+02	8.6E+01	1.8E+01	3.4E+01	2.3E+01	5.2E+01

refers to set of K_{mean} values for all five layers

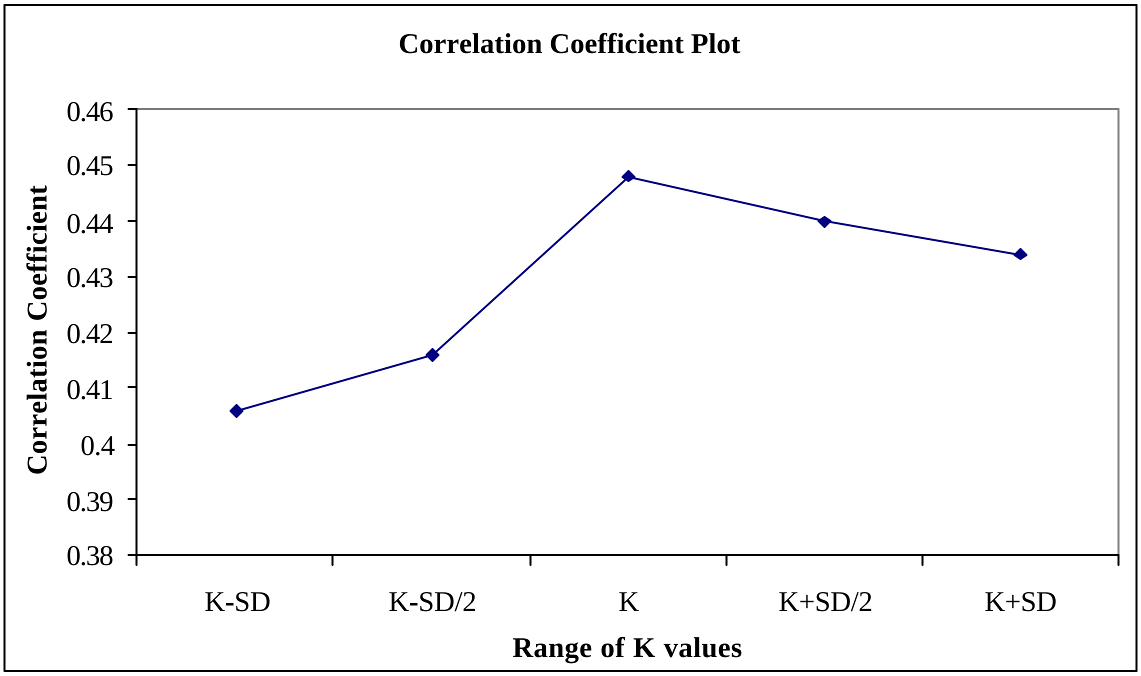

Figure 4.2 Correlation coefficient between observed and calculated for different sets of K values.

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 4.3 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 0.7 and 1.3 ft.

Models for the NE, SE, and SW transects were calibrated in a similar manner. The absolute error was in the range of 0 to 1.6 ft 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.

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 prior 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.

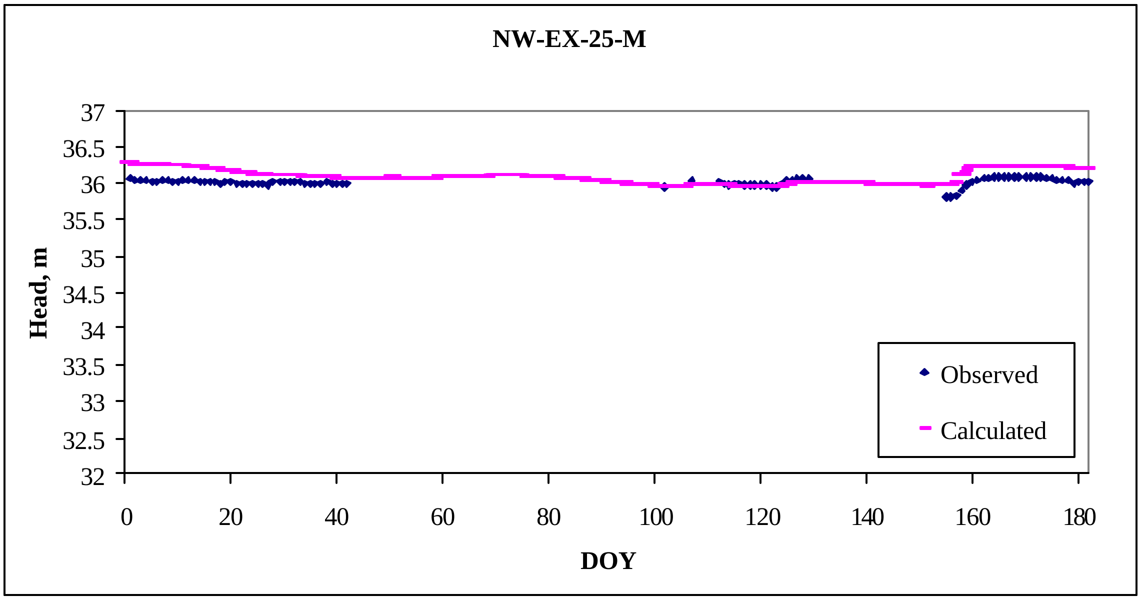

Figure 4.3 Comparison plot between observed and calculated

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 3.13 Hydraulic heads from the NW transect, 4 April 2004.), 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. Figure 4.4 and Figure 4.5 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 165 ft on 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 from the upper sand layer to lower sand layers is greatest at the EX-75 location. 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.

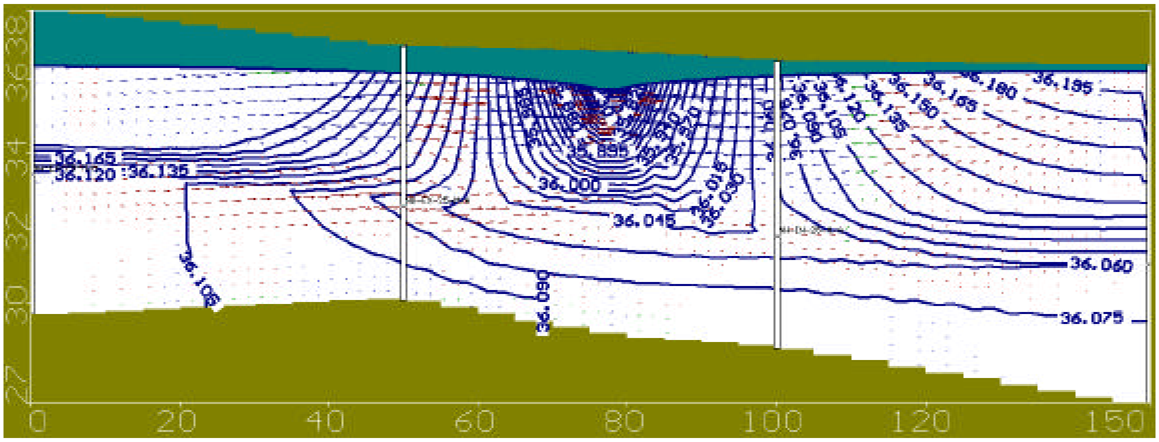

Figure 4.4 Equipotential Lines for 15 February 2004 at the NW transect.

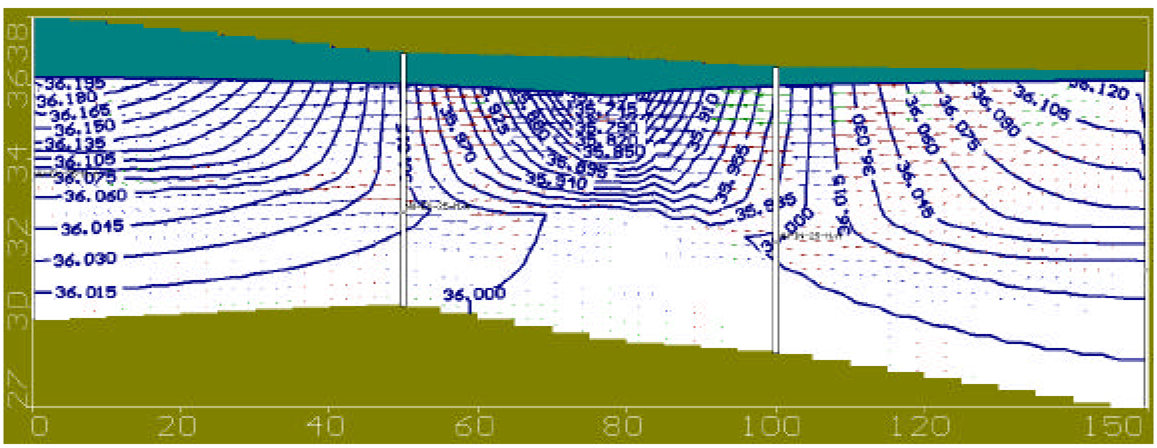

Figure 4.5 Equipotential Lines for 13 May 2004 at the NW transect.

Northeast Transect

Equipotential lines from the output of the NE transect model are shown in Figure 4.6 and Figure 4.7. 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 4.6) and dry conditions (Figure 4.7). 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.

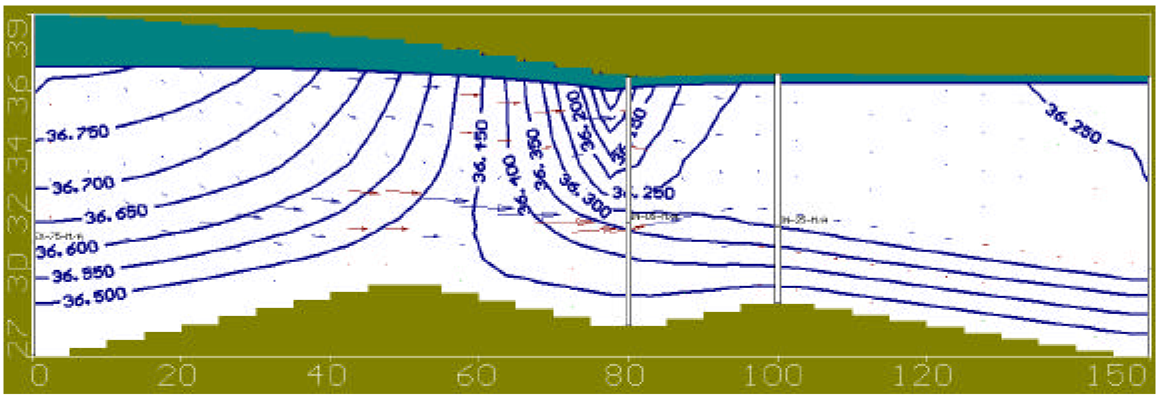

Figure 4.6 Equipotential Lines for 15 February 2004 at the NE transect.

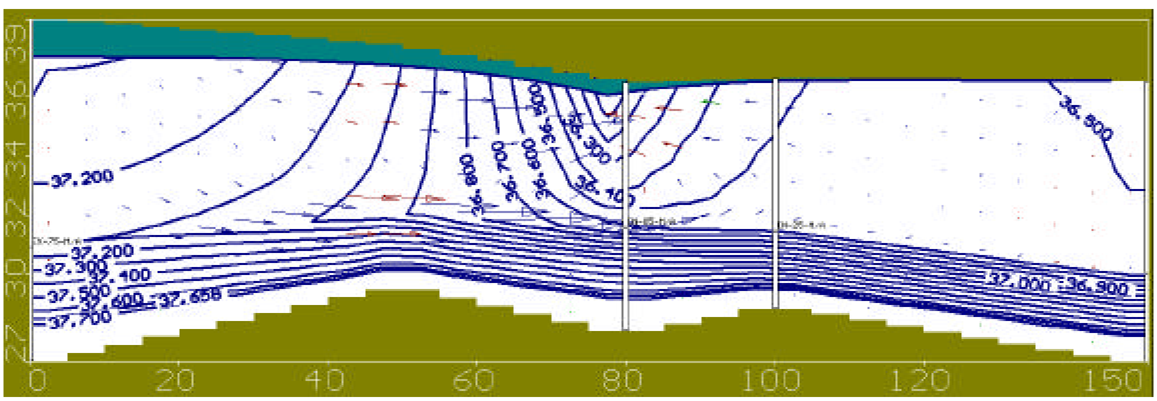

Figure 4.7 Equipotential Lines for 13 May 2004 at the NE transect.

Southeast Transect

Figure 4.8 and Figure 4.9 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.

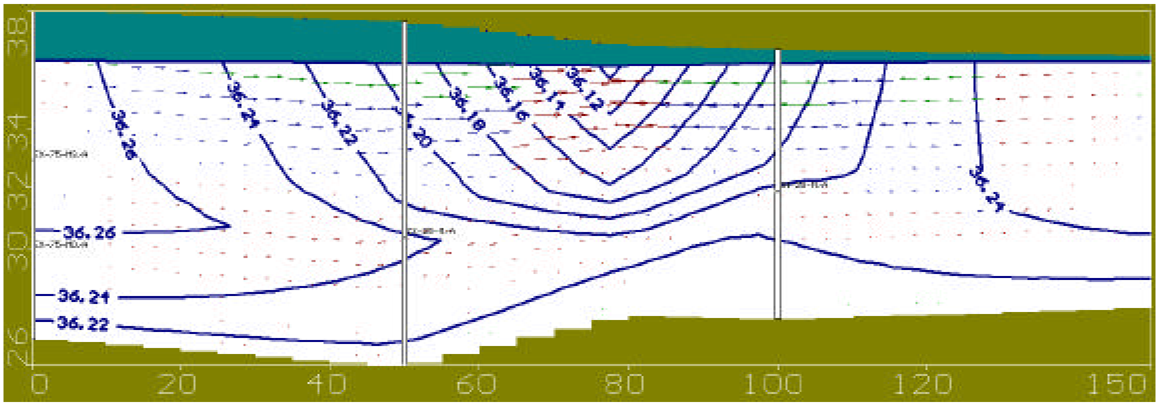

Figure 4.8 Equipotential Lines for 15 February 2004 at the SE transect.

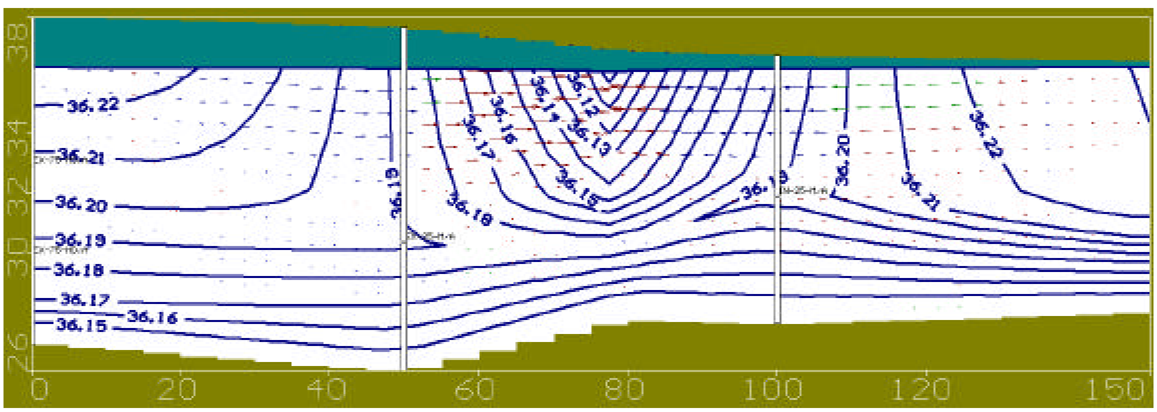

Figure 4.9 Equipotential Lines for 13 May 2004 at the SE transect.

Southwest Transect

Equipotential lines and flow velocities in the flow domain are shown in Figure 4.10 and Figure 4.11 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 Figure 4.10 and Figure 4.11. There is no clear indication of water entering or leaving the bay.

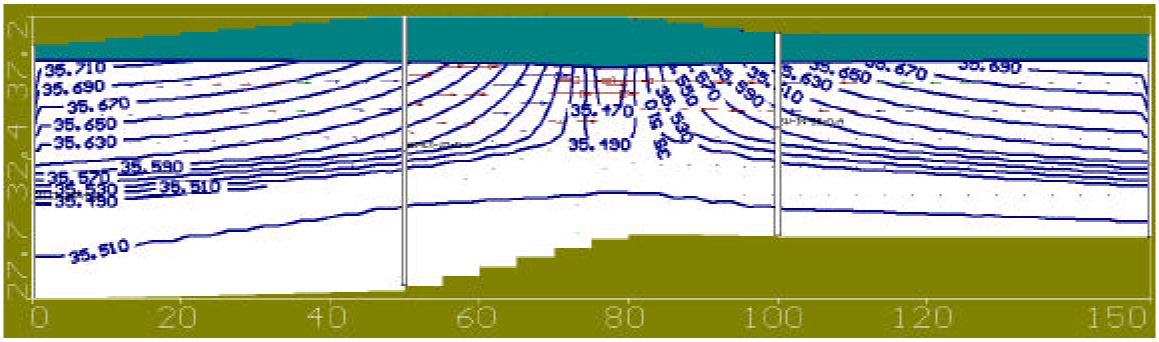

Figure 4.10 Equipotential Lines for 15 February 2004 at the SW transect.

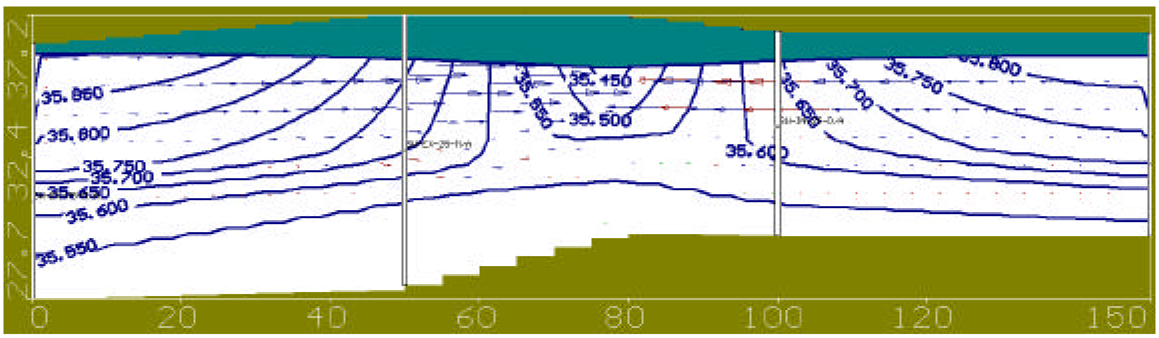

Figure 4.11 Equipotential Lines for 13 May 2004 at the SW transect.

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 2625 ft (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 4.12. The perimeter ditch is located at the lateral distance of 246 ft (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 inputs for extended models were similar to those 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 492-ft (150-m) wide transect models, was unable to converge the extended model. The model would terminate 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 an extrapolation 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 better handle ill-conditioned matrices. The SIP solver was found to be the best for this condition. This was confirmed by numerical experiments discussed in the following section.

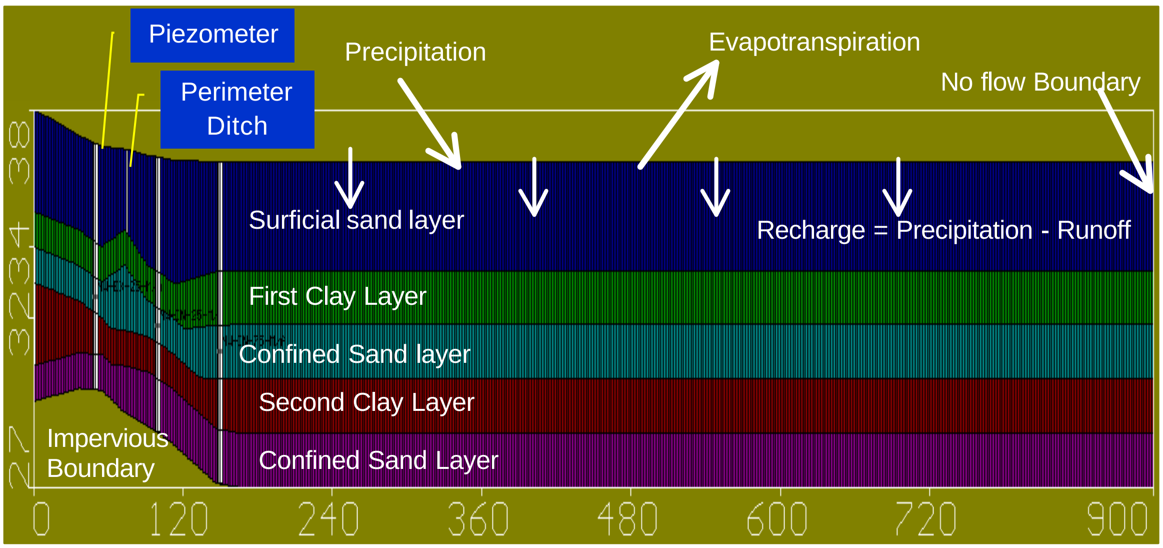

Figure 4.12 Extended model shown for the NW Transect.

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 1.0 to 1.6 ft (0.3 to 0.5 m) between the observed heads and the calibrated heads for most of the piezometers. Example for the calibration at each transect are shown in Figure 4.13 (NW), Figure 4.20 (NE), Figure 4.14 (SE), and Figure 4.31 (SW).

Northwest Transect

The Northwest transect model was calibrated using the piezometric heads. An example of the calibration plot is shown in Figure 4.13. There was a good calibration between days 100 and 130. The maximum absolute error of calibration was 1.0 ft (0.3 m). The calibration error varied between 0 and 1.6 ft (0 and 0.5 m) in all the piezometers. Equipotential lines obtained from the NW Transect model output are shown in Figure 4.14 and Figure 4.16, representing 15 February 2004 (wet condition) and 13 May 2004 (dry condition) respectively.

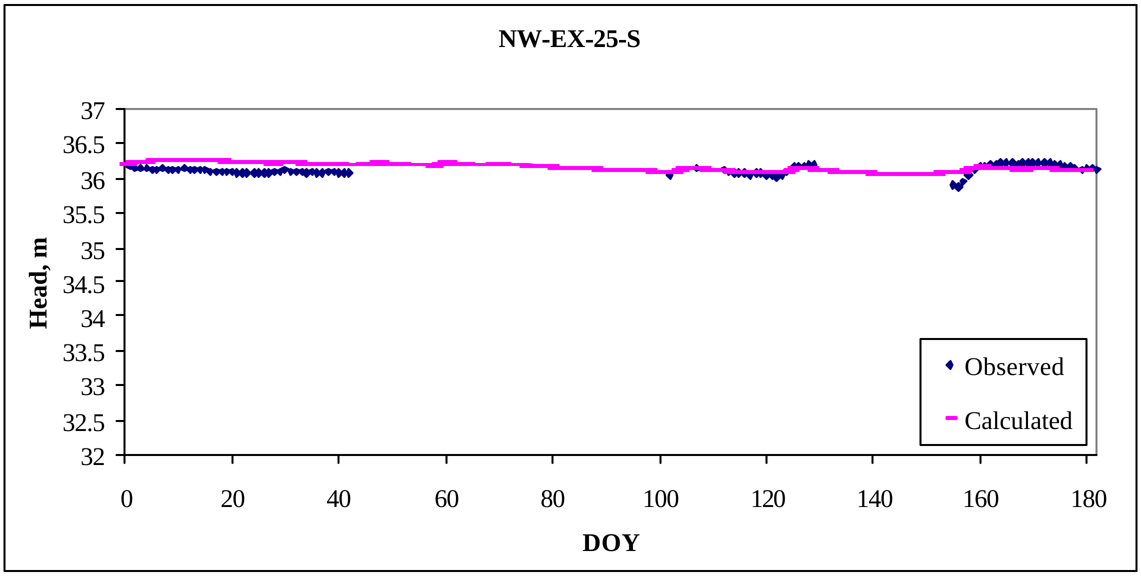

Figure 4.13 Calibration plot example (at exterior 25 m piezometer nest) at the NW transect.

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 Figure 4.14 and Figure 4.16, 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 Figure 4.15 and Figure 4.17, 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 4.17). 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 2600 ft (800 m) inside the bay. The influence of the perimeter ditch extends to a distance of approximately 260 to 330 ft (80 to 100 m) inside the bay and to the depth of 20 to 23 ft (6 to 7 m) from the surface.

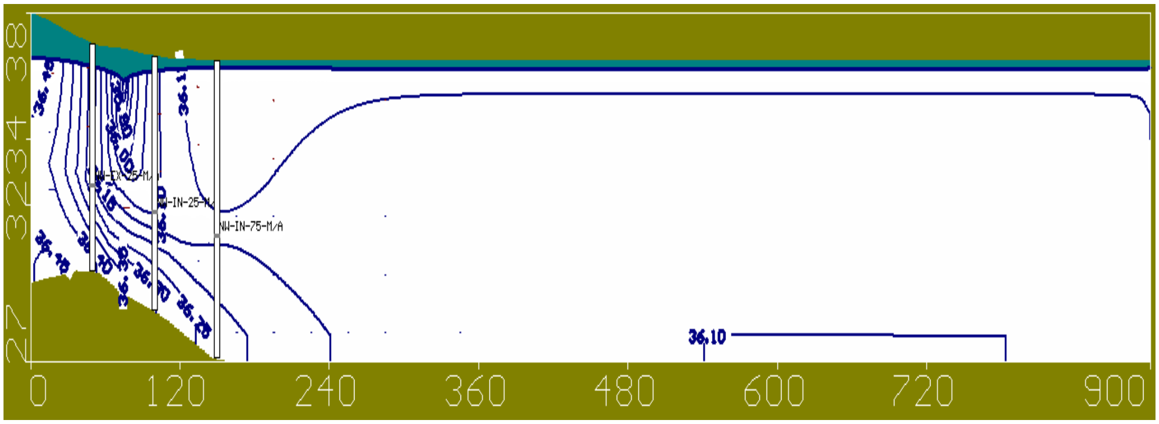

Figure 4.14 Equipotential Lines on 15 February 2004 at the NW transect extended model.

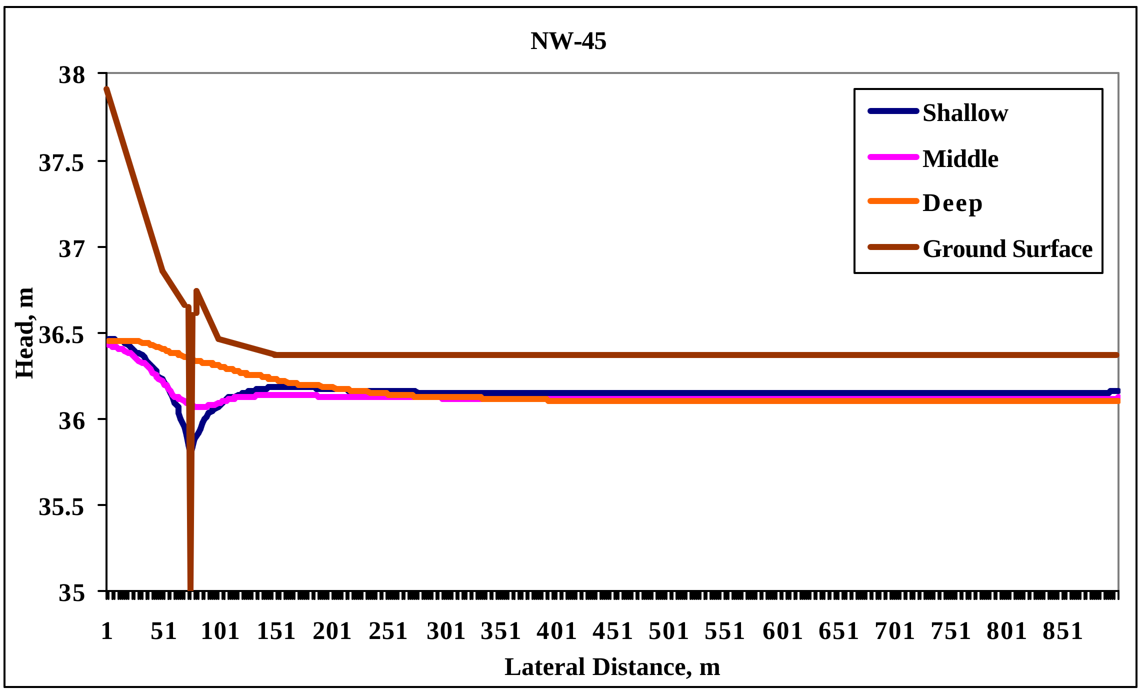

Figure 4.15 Heads in the three conducting layers at the NW transect on 15 February 2004.

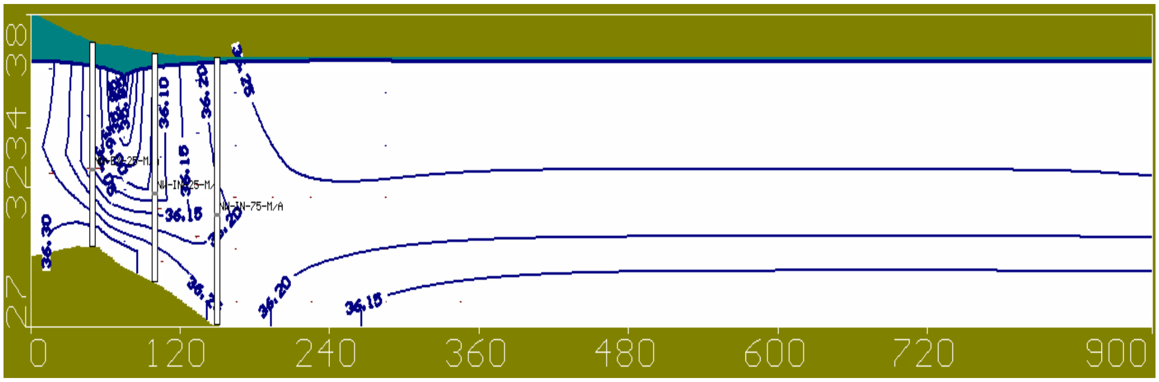

Figure 4.16 Equipotential Lines on 13 May 2004 at the NW transect extended model.

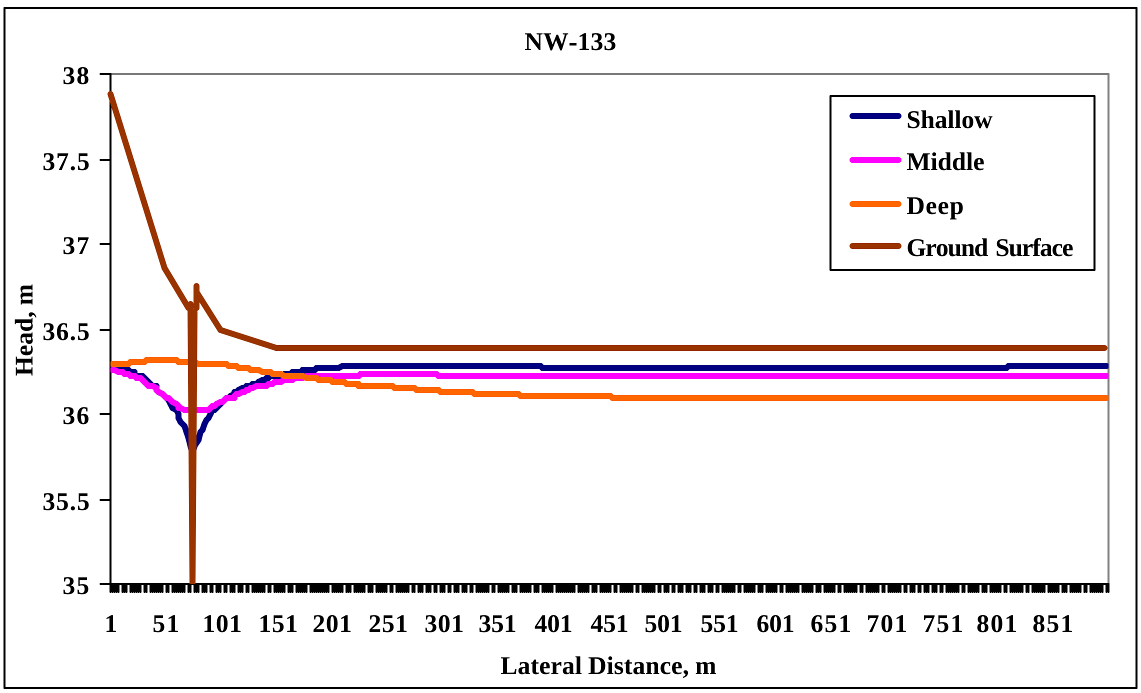

Figure 4.17 Heads in the three conducting layers at the NW on 13 May 2004.

The groundwater flows were calculated 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 4.18. 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 76 ft^3/ft (7.1 m^3/m) and the corresponding inflow through the lower sands was approximately 28 ft^3/ft (2.6 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 4.18. The total inflow for the NW transect was approximately 105 ft^3/ft (9.72 m^3/m). Table 4.3 gives a summary of daily averages of groundwater inflows at the NW transect.

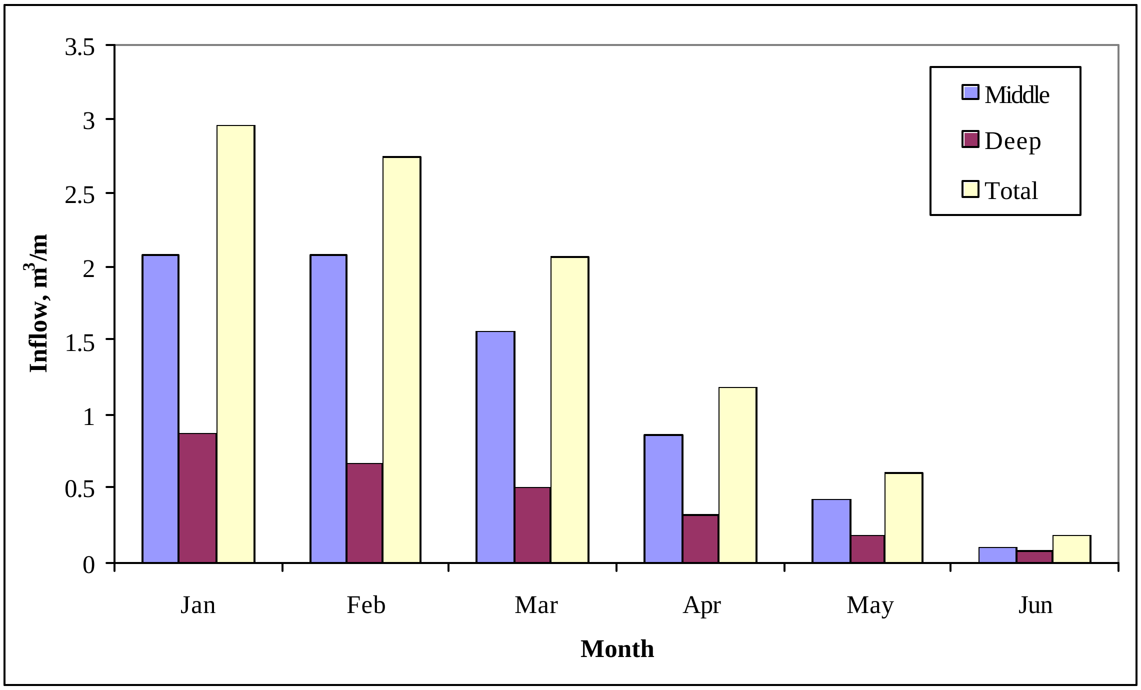

Figure 4.18 Inflow rates at the NW transect.

Northeast Transect

The northeast transect extended model was calibrated using the piezometric heads. An example of the calibration plot is shown in Figure 4.19. The absolute error varied between 0 and 1.6 ft in all the piezometers. Figure 4.20 and Figure 4.22 show the NE transect model outputs on 15 February 2004 and 13 May 2004, representing the wet and dry periods respectively. Flow lines indicate that the perimeter ditch drains water from both sides in the surface layer. The flow lines in the lower sands indicate groundwater inflow.

The head distribution can be viewed in a better manner in Figure 4.21 and Figure 4.23, 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 Figure 4.21 and Figure 4.23. Lateral gradients are lower in middle and deep sands for the dry conditions.

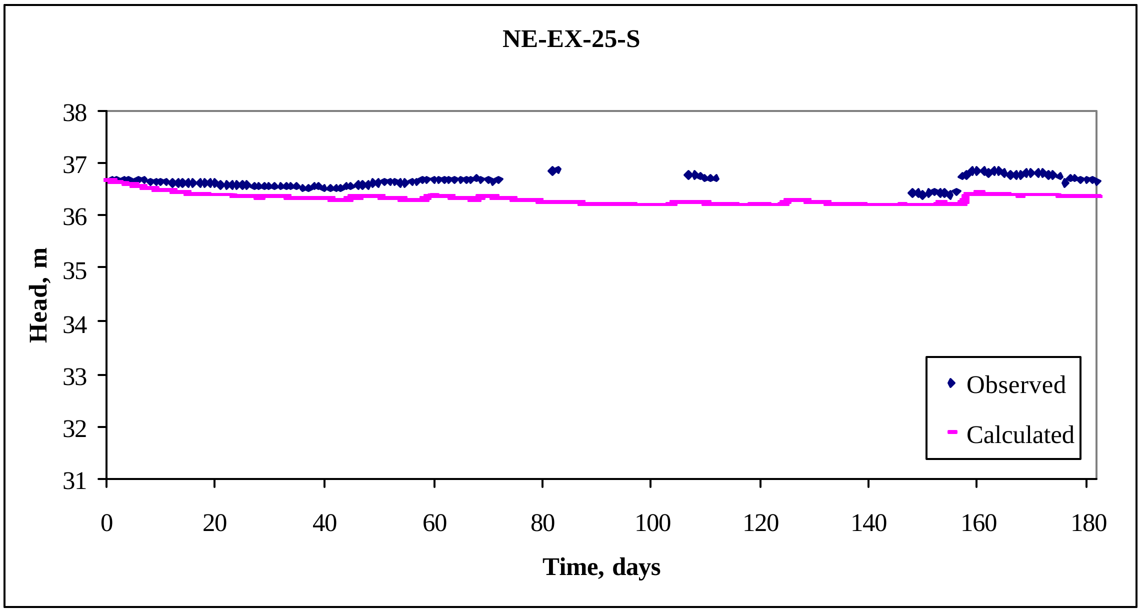

Figure 4.19 Calibration plot example (at exterior 25 m piezometer nest) at the NE transect.

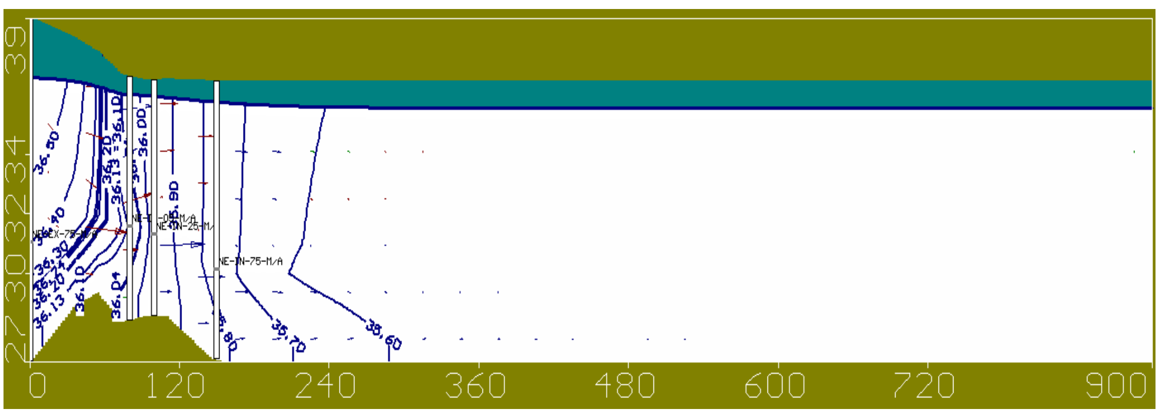

Figure 4.20 Equipotential Lines on 15 February 2004 at the NE transect extended model.

Spatial distributions of heads in the three sand layers, as shown in Figure 4.21 and Figure 4.23, were used to estimate the zone of influence of the perimeter ditch. The perimeter ditch had an influence to the lateral distance of approximately 100 to 165 ft (30 to 50 m) and to a depth of 13 to 16 ft (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.

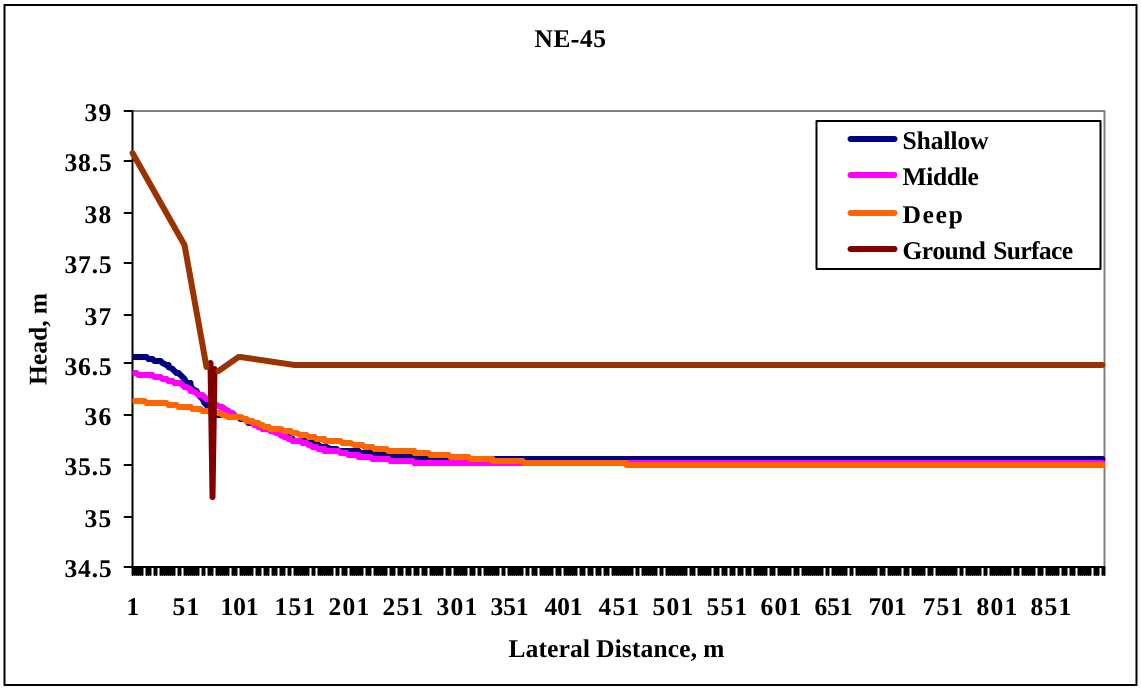

Figure 4.21 Heads in the three conducting layers at the NE transect on 15 February 2004.

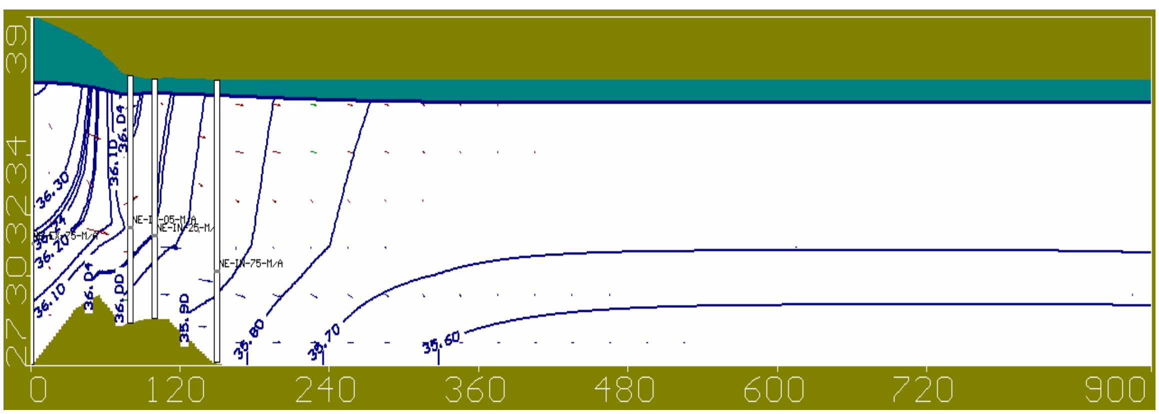

Figure 4.22 Equipotential Lines on 13 May 2004 at the NE transect extended model.

Figure 4.21 and Figure 4.23 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 4.25. 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 240 ft^3/ft (21.9 m^3/m) and the corresponding inflow through the lower sands was approximately 43 ft^3/ft (4.0 m^3/m). The total amount of groundwater coming into the site at the NE transect is also shown in Figure 4.24. Total inflow contributed for the NE transect is approximately 280 ft^3/ft (25.9 m^3/m). The daily average flows from the middle and deep layers are shown in Table 4.3.

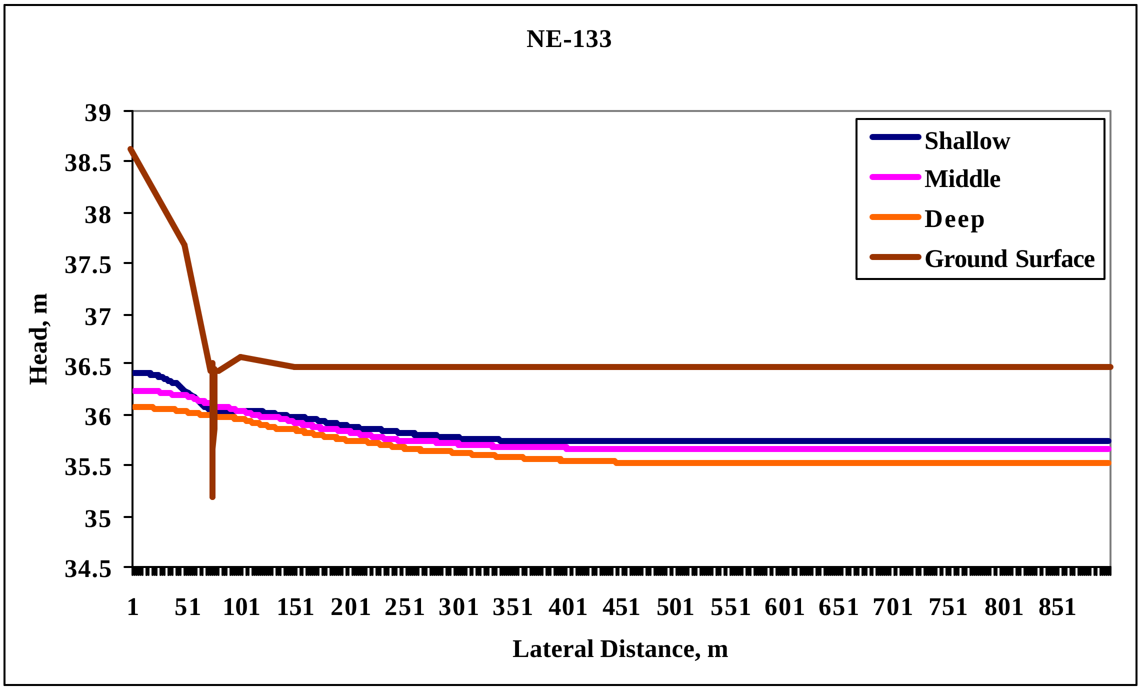

Figure 4.23 Heads in the three conducting layers at the NE transect on 13 May 2004

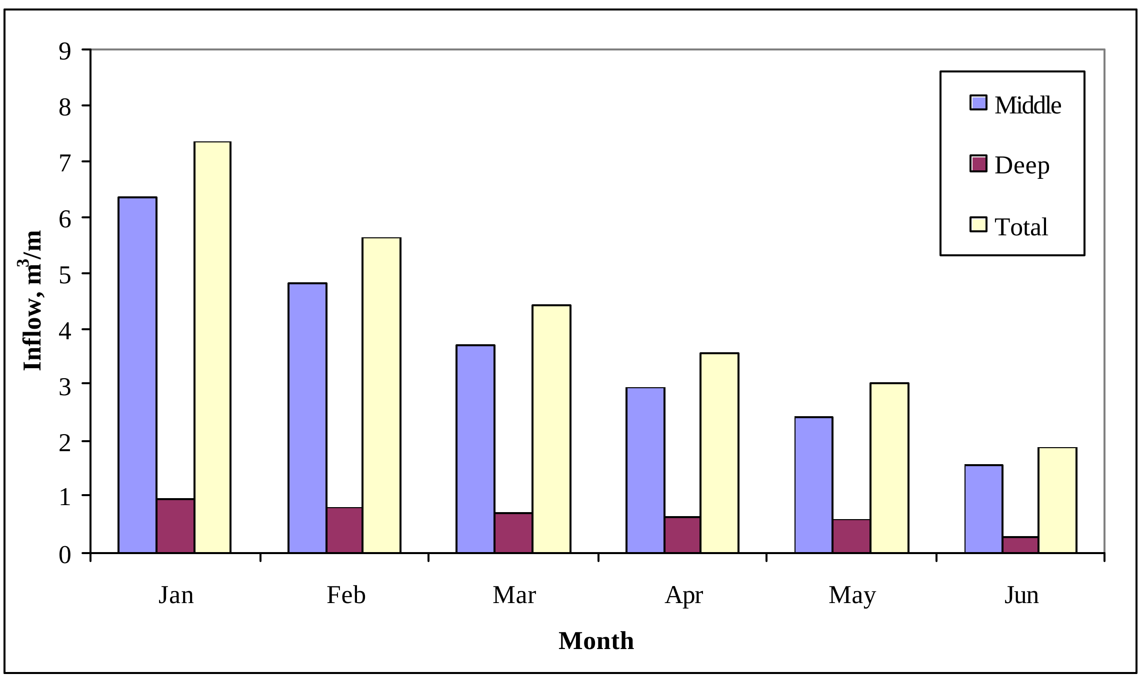

Figure 4.24 Inflow rates at the NE transect.

Southeast Transect

The Southeast transect was modeled and calibrated using piezometer heads. An example of the calibration is shown in Figure 4.25. The absolute error was between 0 and 1.6 ft (0 and 0.5 m) for all the piezometers. Figure 4.26 and Figure 4.28 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 surfacial sand layer. In the lower sands, however, lateral gradients indicate groundwater inflow. The spatial distributions of heads in all three sand layers, as shown in Figure 4.27 and Figure 4.29, 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 4.27) when compared to dry conditions (Figure 4.29). The vertical gradients across the layers could be because of the thick clay layers between sand layers. The perimeter ditch could be influencing approximately 165 ft (50 m) laterally and 16 ft (5 m) deep from the surface.

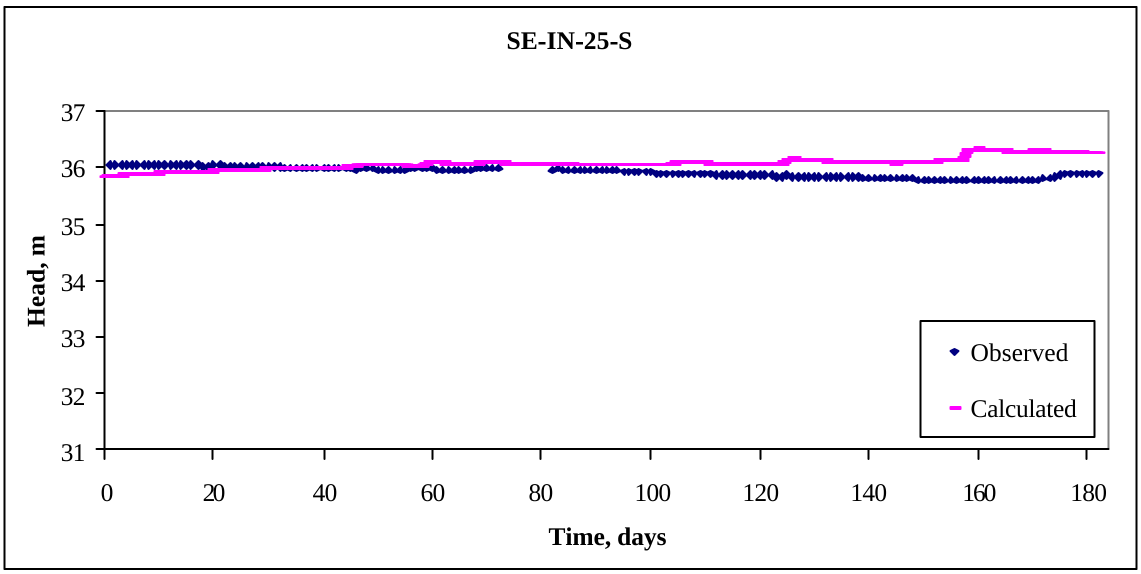

Figure 4.25 Calibration plot example (at interior 25m piezometer nest) at the SE transect.

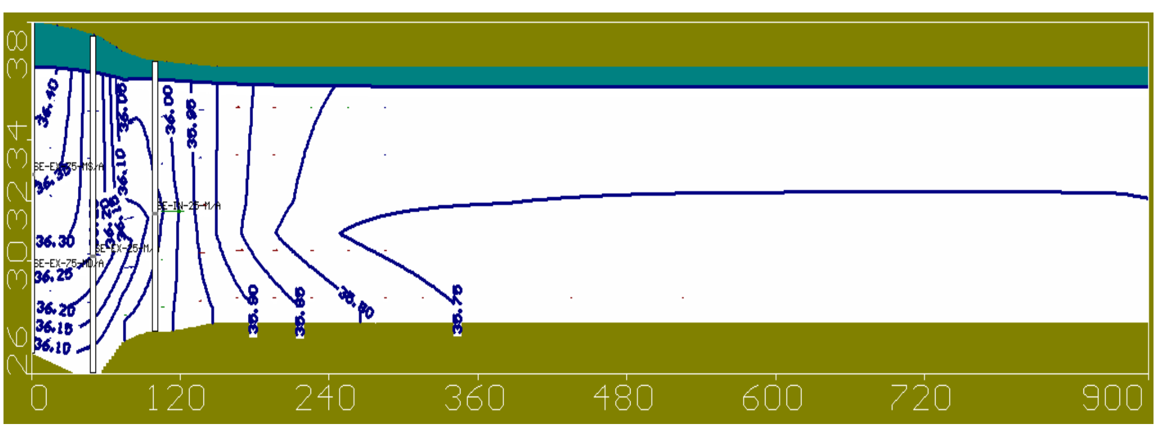

Figure 4.26 Equipotential Lines on 15 February 2004 at the SE transect extended model.

Figure 4.27 and Figure 4.29 indicate that groundwater is clearly flowing into the bay through the middle and deep sand layers at the SE transect. As shown in Figure 4.30, 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 180 ft^3/ft (16 m^3/m) and the corresponding inflow through the lower sands was approximately 17 ft^3/ft (1.56 m^3/m). The total amount of groundwater coming into the site at the SE transect is also shown in Figure 4.30. Total inflow for the SE transect was estimated as 190 ft^3/ft (18 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.

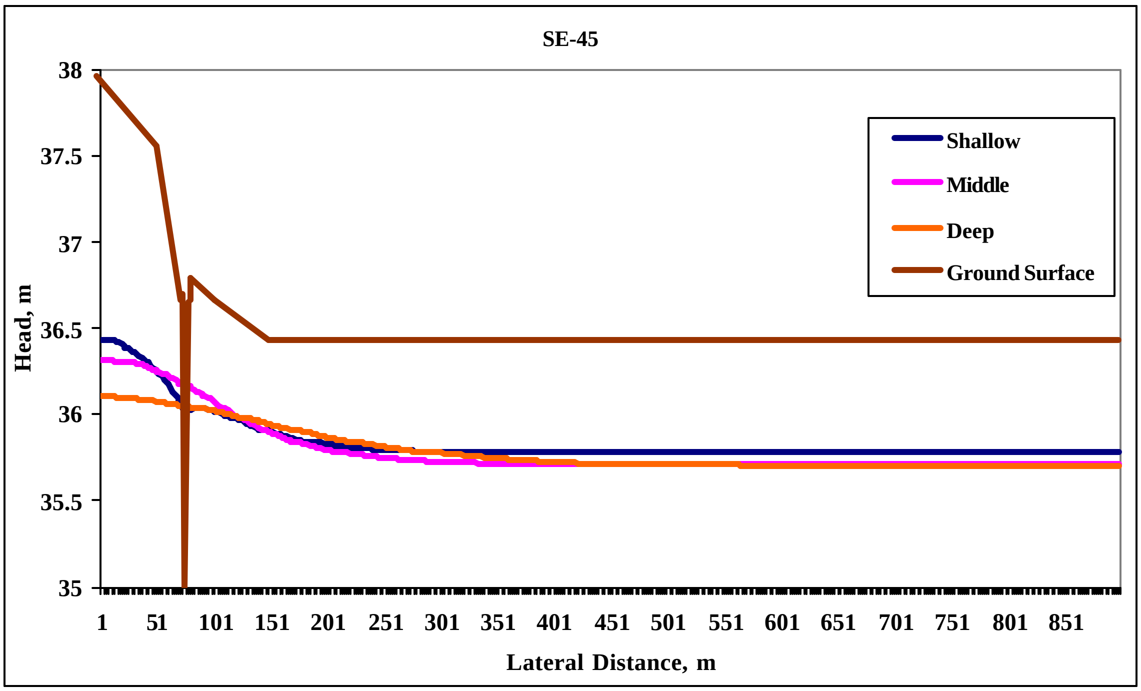

Figure 4.27 Heads in the three conducting layers at the SE transect on 15 February 2004.

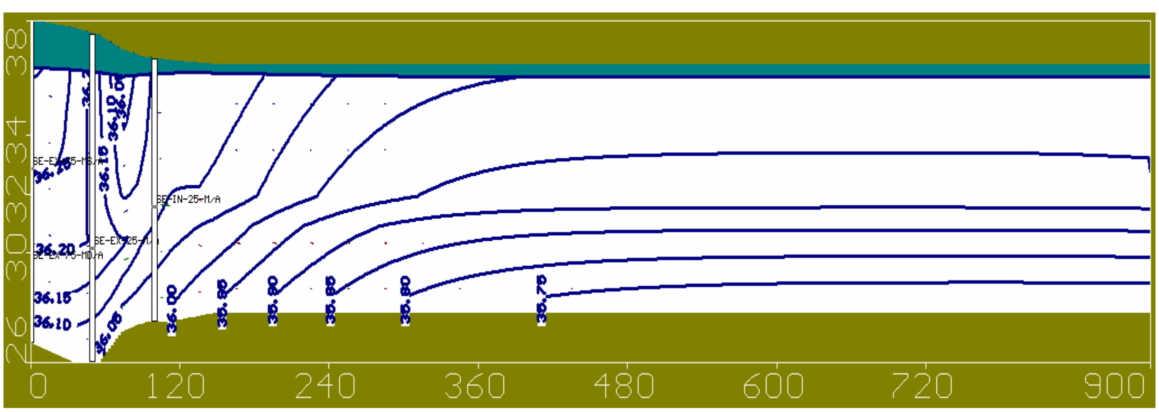

Figure 4.28 Equipotential Lines on 13 May 2004 at the SE transect extended model.

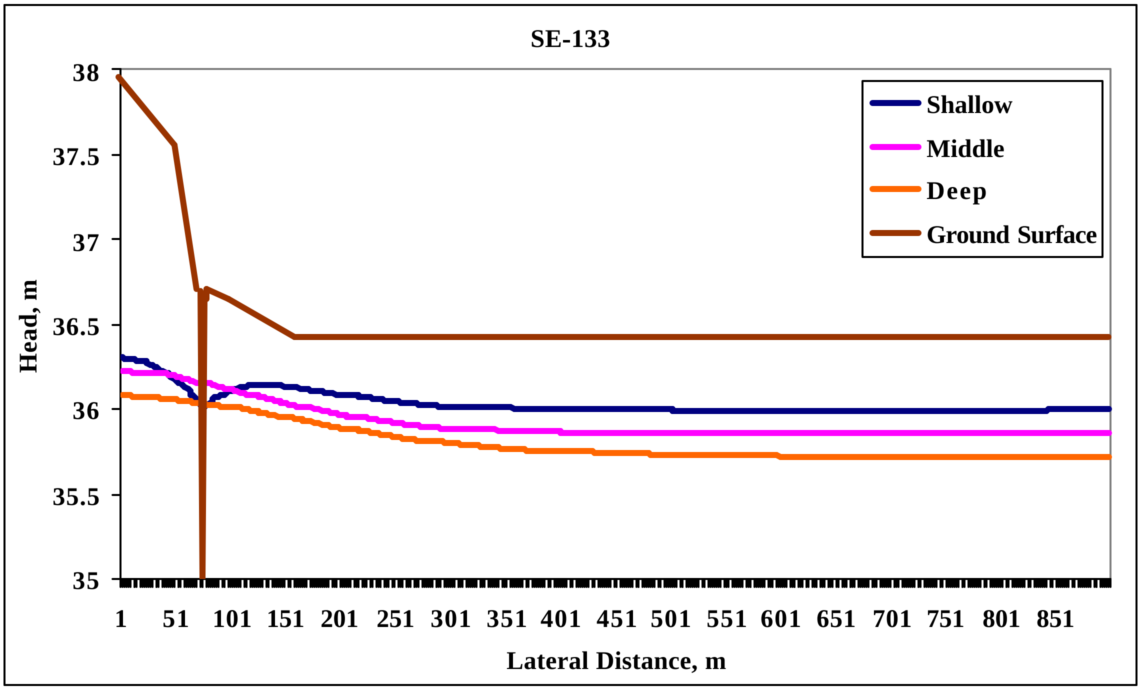

Figure 4.29 Heads in the three conducting layers at the SE transect on 13 May 2004.

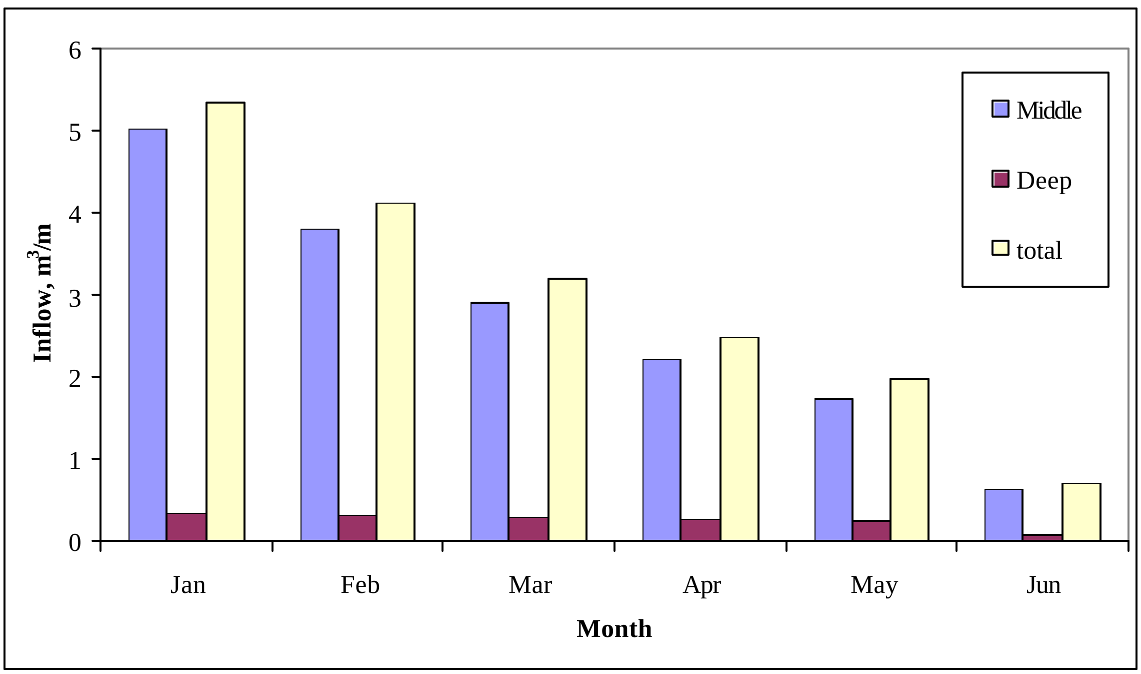

Figure 4.30 Inflow rates at the SE transect.

Southwest Transect

The simulations results with equipotential lines in the flow domain of the SW transect are shown in the Figure 4.32 and Figure 4.34 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. Figure 4.33 and Figure 4.35 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 (Figure 4.33 and Figure 4.35). 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 260 to 330 ft (80 to 100 m) laterally and 20 ft (6 m) deep from the surface.

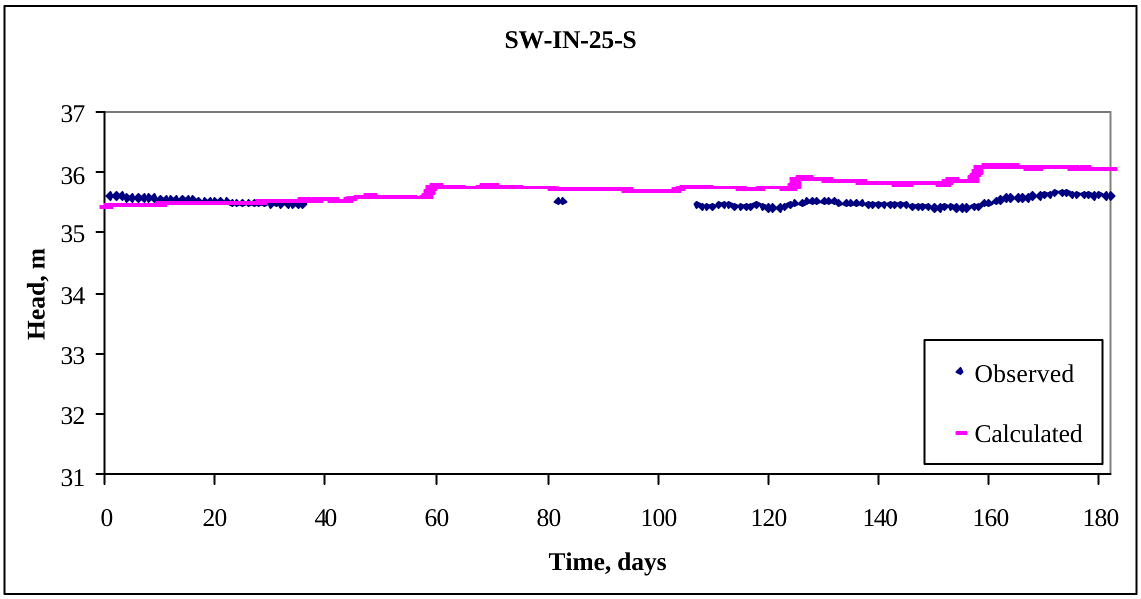

Figure 4.31 Calibration plot example (at interior 25m piezometer nest) at the SW transect.

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.

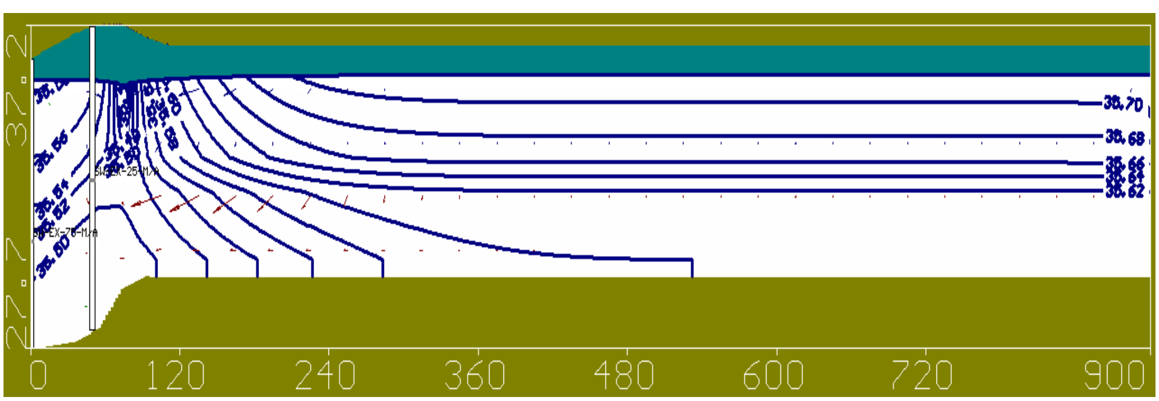

Figure 4.32 Equipotential Lines on 15 February 2004 at the SW transect extended model.

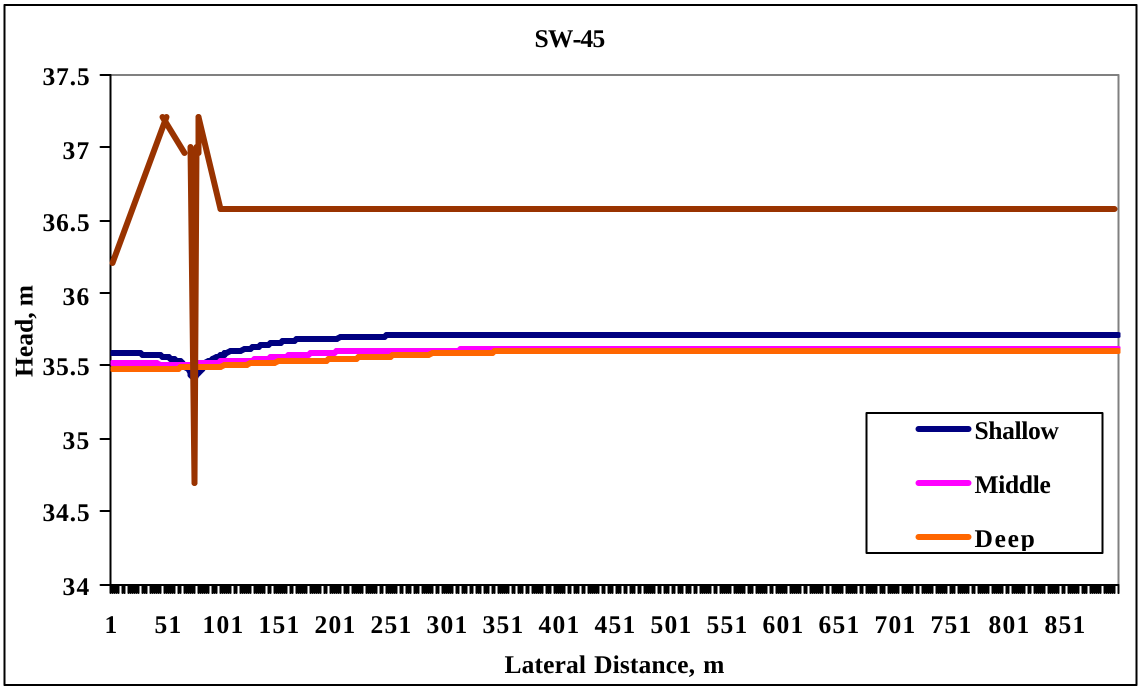

Figure 4.33 Heads in the three conducting layers at the SW transect corresponding to dry period (15 February 2004).

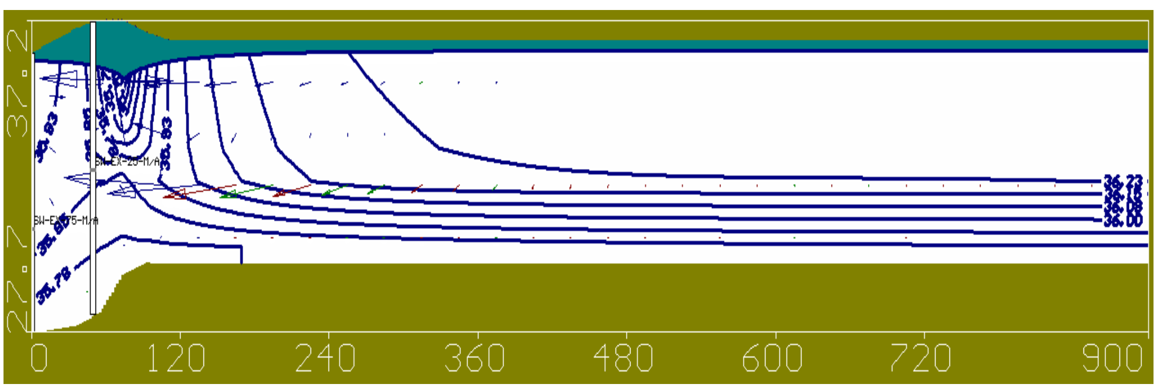

Figure 4.34 Equipotential lines on 13 May 2004 from the SW transect extended model.

Flow analysis suggests outflows from the SW transect (Figure 4.33 and Figure 4.35). Figure 4.36 shows the approximate quantity of groundwater flowing out of the site at the SW transect through the middle and deep sand layers. Figure 4.36 also shows total groundwater outflows at the SW transect. As shown in Figure 4.36, the amount of groundwater outflow increases as the season changes from winter to summer. The month of June contributes most to outflows and the outflows are lowest in January. Outflows were approximately 33 ft^3/ft (3.1 m^3/m) and 2.9 ft^3/ft (0.27 m^3/m) through the middle and deep sands. Total outflows through the SW transect were approximately 36 ft^3/ft (3.4 m^3/m). Table 4.3 gives the summary of daily average flows at the SW transect.

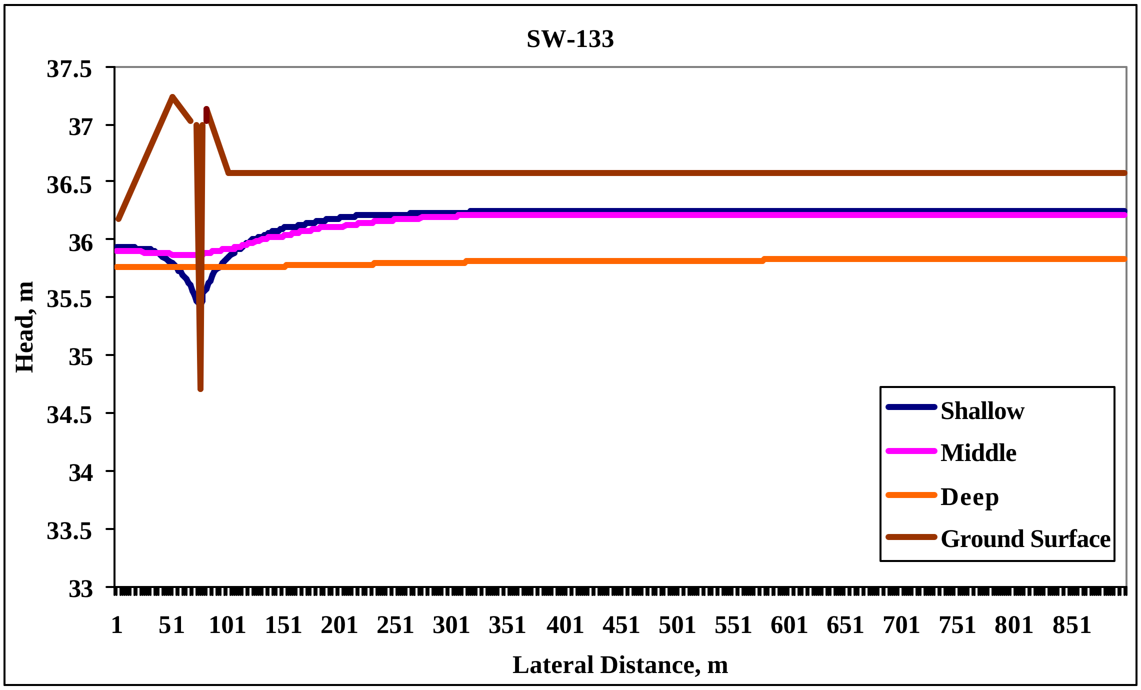

Figure 4.35 Heads in the three conducting layers at the SW transect corresponding to dry period (13 May 2004).

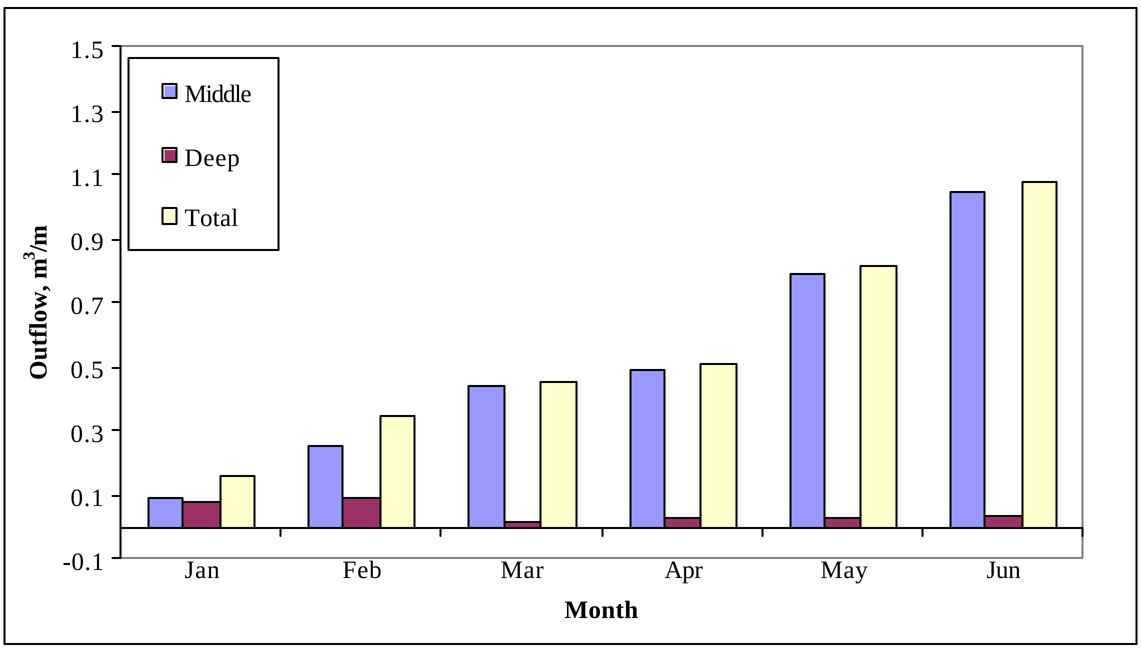

Figure 4.36 Outflow rates at the SW transect.

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 4.37. 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 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. 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 as 0.24 ft^3/ft (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 4.9 in. (125 mm) over the entire bay.

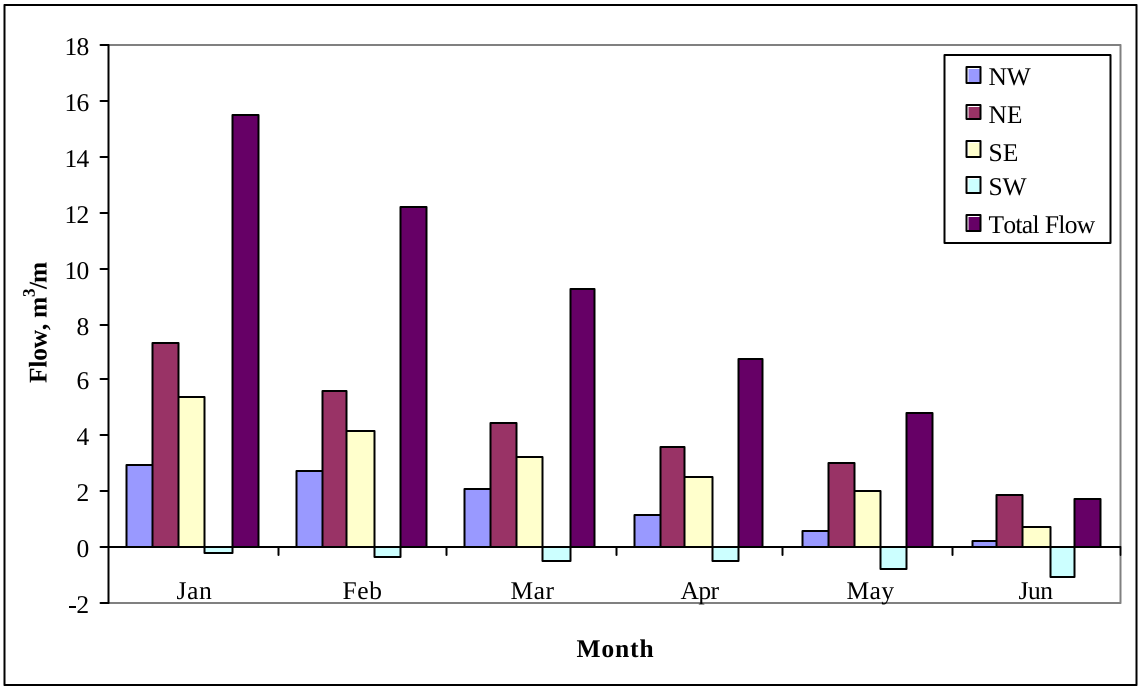

Figure 4.37 Comparison of monthly groundwater flows at all transects.

Table 4.3 Summary of Groundwater Flows for the First Half of 2004

Transect	*Sand Layer*	*Total* ft^3/ft	*Daily Average* ft^3/ft	*Daily Max* ft^3/ft	*Daily Min* ft^3/ft
NW (Inflow)	Middle	76	0.42	0.89	0.011
	Deep	28	0.15	0.30	0.022
	Total	105	0.57	1.2	0.032
NE (Inflow)	Middle	235	1.3	2.3	0.52
	Deep	43	0.24	0.36	0.086
	Total	278	1.6	2.7	0.60
SE (Inflow)	Middle	176	0.98	1.9	0.16
	Deep	17	0.097	0.12	0.022
	Total	192	1.1	2.0	0.17
SW (Outflow)	Middle	33	0.18	0.41	0.0
	Deep	2.9	0.011	0.032	0.0
	Total	36	0.20	0.44	0.0

4.4. Summary

The collection of hydraulic head data was started late 2003 and data collection continued into 2005. 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. The maximum absolute error between observed heads and calibrated heads was 1.6 ft (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 in the surficial and, to some extent, in the middle sand layers. Analysis indicated groundwater inflow from the 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 (2600 ft) from the perimeter ditch. The center of the bay was modeled as a no-flow boundary. All transects had 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 4.38 gives a summary of flow directions and the influence of the perimeter ditch. The perimeter ditch influenced 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 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 330 ft (100 m) and to a depth of 20–23 ft (6–7 m), corresponding to the middle sand layer at the NW transect. Influence is to a maximum extent of 250 ft (75 m) at the NE transect and to the depth of 13–16 ft (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 250 ft (75 m) and to the depth of 13–16 ft (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 330 ft (100 m) inside the bay and 165 ft (50 m) outside the bay. Depth of influence was to the middle sand layer, which is 20–23 ft (6–7) m deep.

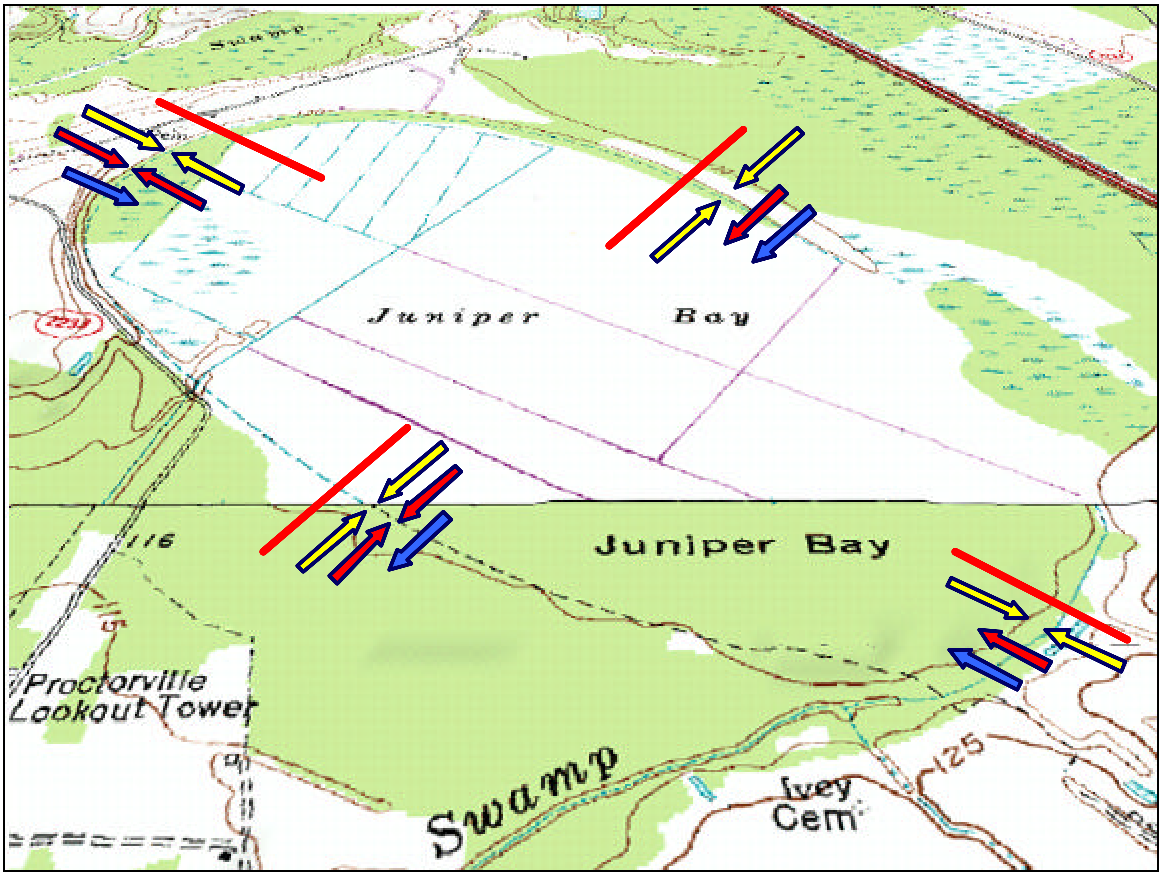

Figure 4.38 Summary of flow directions in significant sand layers. Light (yellow) arrows are for the surficial sand layers, medium (red) arrows are for the middle sand layers, and dark (blue) arrows are for the deep sand layers.

Table 4.4 Influence of the Perimeter Ditch

	Influence of the Perimeter Ditch, ft				
	Laterally, InsideBay		*Laterally, OutsideBay*		*Depth from Ground Surface*
Transect	*Wet Conditions*	*Dry Conditions*	*Wet Conditions*	*Dry Conditions*	
Northwest	250	330	250	250	20–23
Northeast	100	165	250	250	13–16
Southeast	165	250	250	250	13–16
Southwest	330	390	165	165	20–26

5. Perimeter Ditch Management

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 analyses of groundwater flows for different control levels in the ditch, individually for each transect. Control levels were fixed at 0.66-ft (0.2-m) increments from 116.5 to 119.8 ft (35.5 to 36.5 m) MSL. Discussions for individual transects in the following sections have two phases. In the 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.

The results from individual transects were extrapolated to estimate approximate net groundwater flows at Juniper Bay for the various 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. The analyses assumed that the water level in the ditch would be equal to the control level, although that might require introduction of water into the ditch at some of the higher levels.

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. Figure 5.1 and Figure 5.2 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 119.1 ft (36.3 m) at NW transect would reverse the drainage function of the perimeter ditch. Water levels higher than 119.1 ft (36.3 m) would make the perimeter ditch function as a water source instead of a drainage ditch.

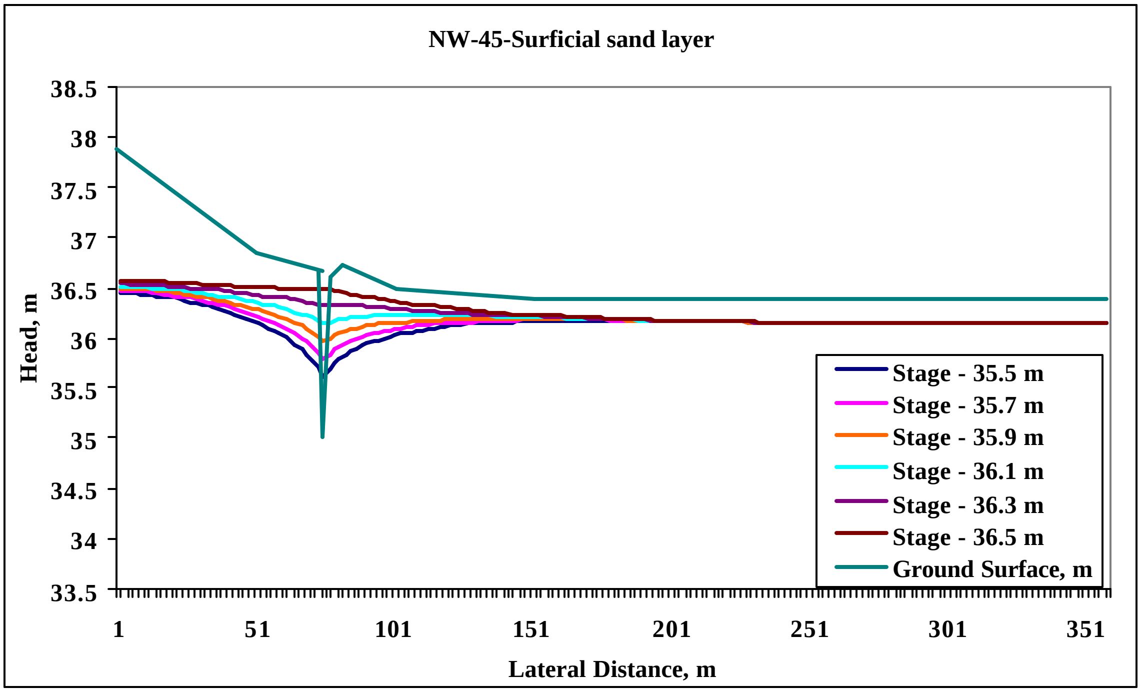

Figure 5.1 Spatial distribution of heads in surficial sand layer at the NW transect for different ditch control levels on 15 February 2004.

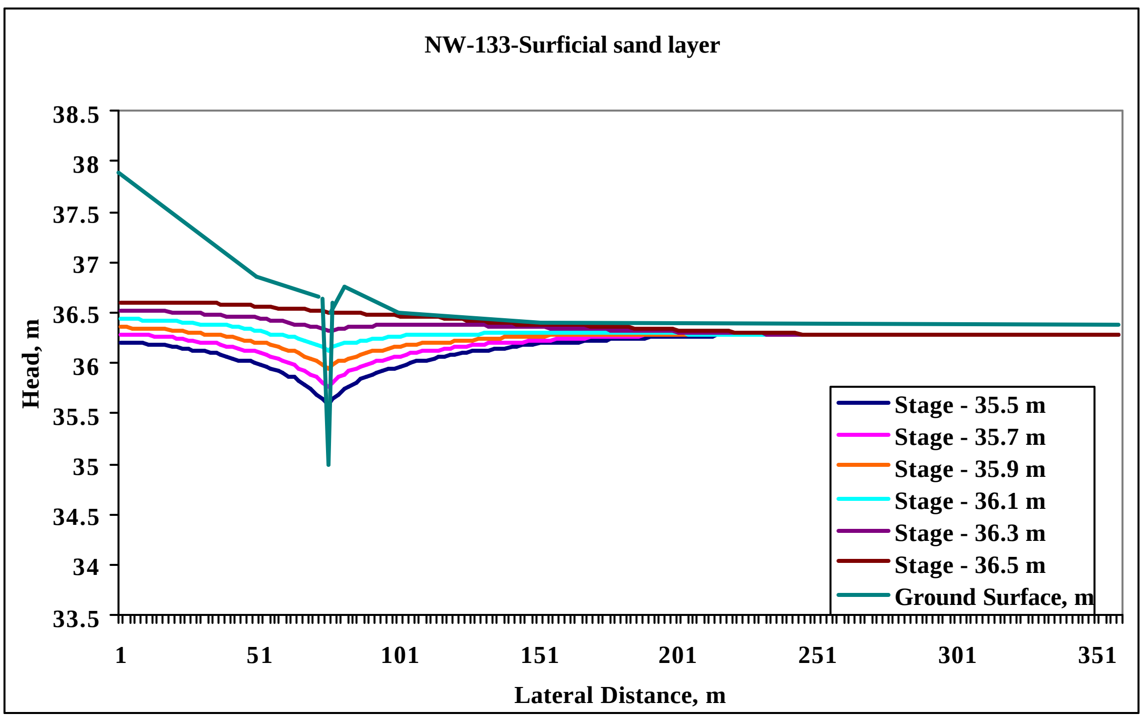

Figure 5.2 Spatial distribution of heads in surficial sand layer at the NW transect for different ditch control levels on 13 May 2004.

In a similar manner, analysis from the middle sand layer, as shown in Figure 5.3 and Figure 5.4, 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 Figure 5.5 and Figure 5.6, control levels have very little effect on groundwater flows.

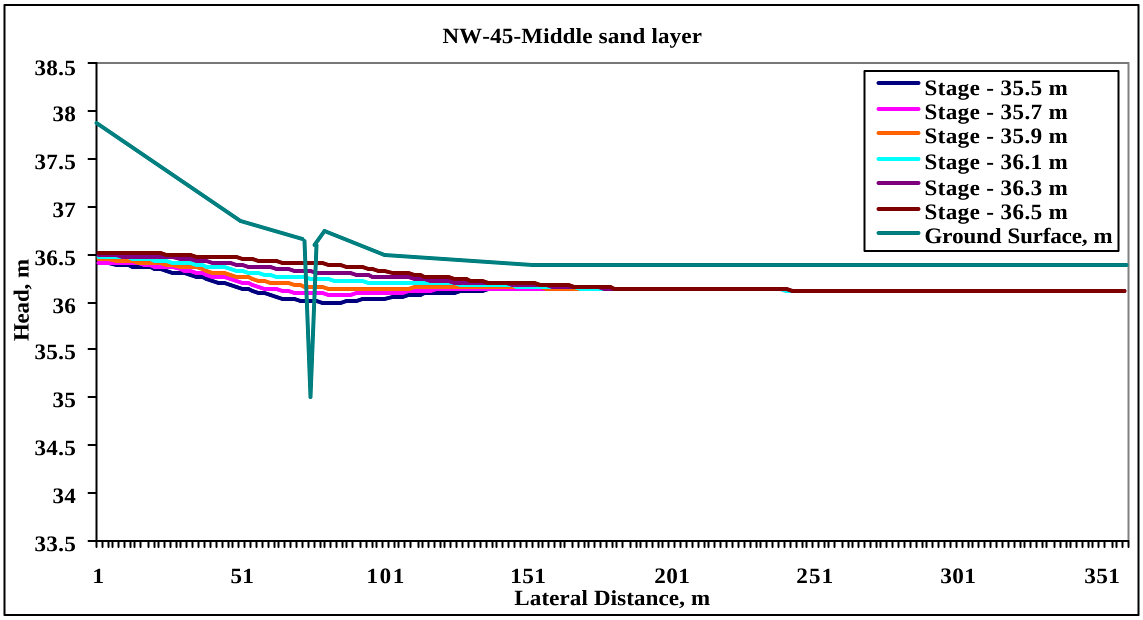

Figure 5.3 Spatial distribution of heads in middle sand layer at the NW transect for different ditch control levels on 15 February 2004.

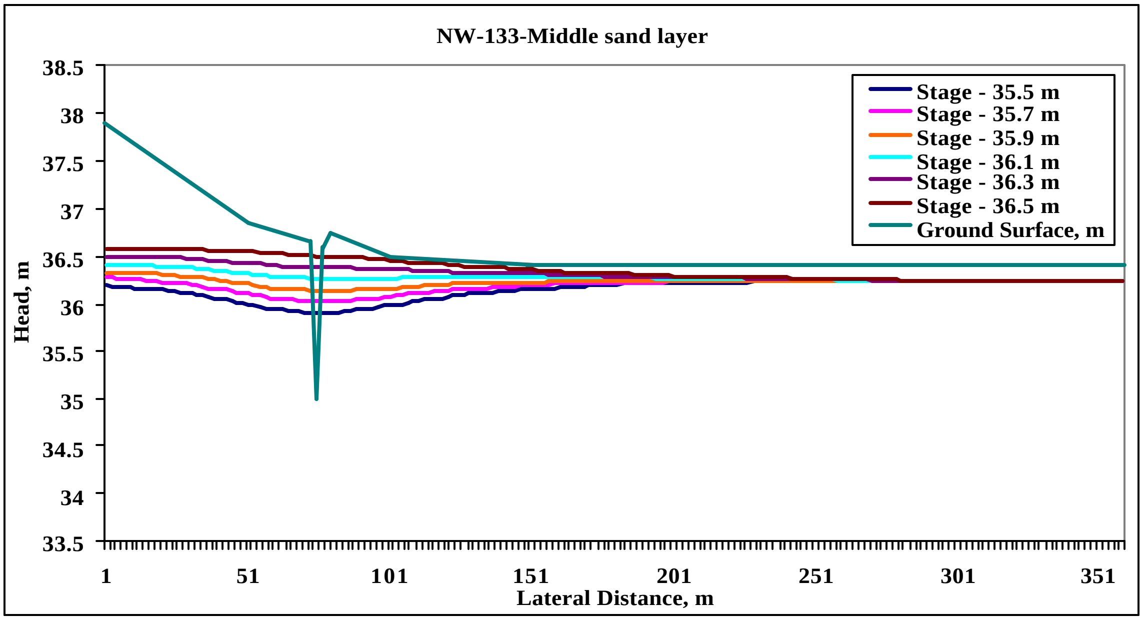

Figure 5.4 Spatial distribution of heads in middle sand layer at the NW transect for different ditch control levels on 13 May 2004.

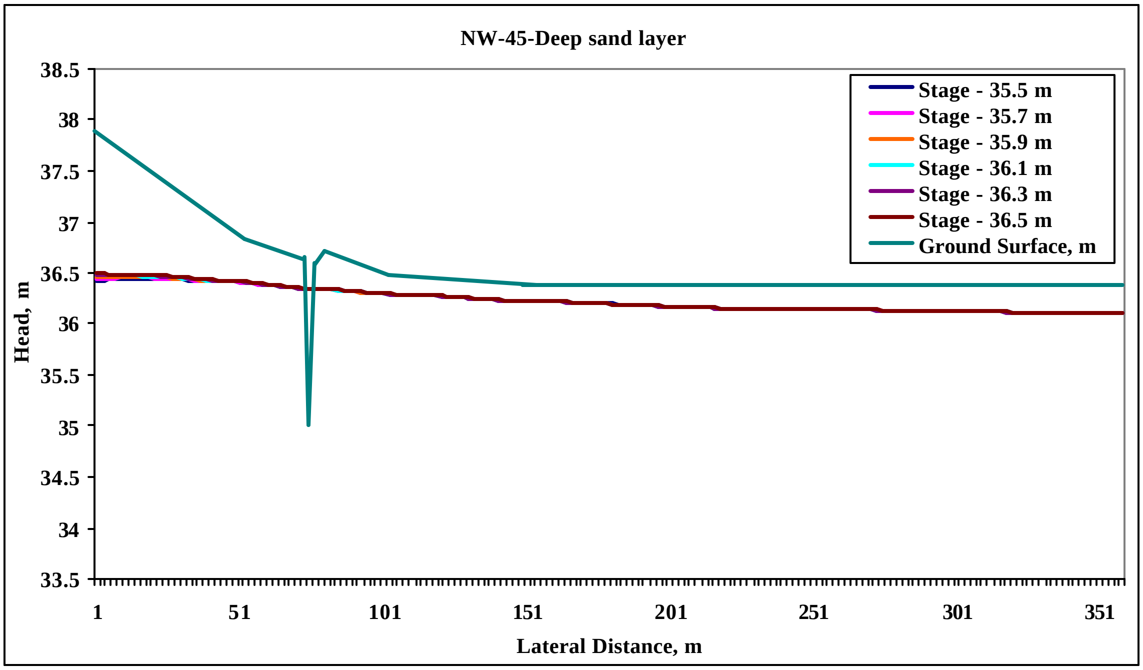

Figure 5.5 Spatial distribution of heads in deep sand layer at the NW transect for different ditch control levels on 15 February 2004.

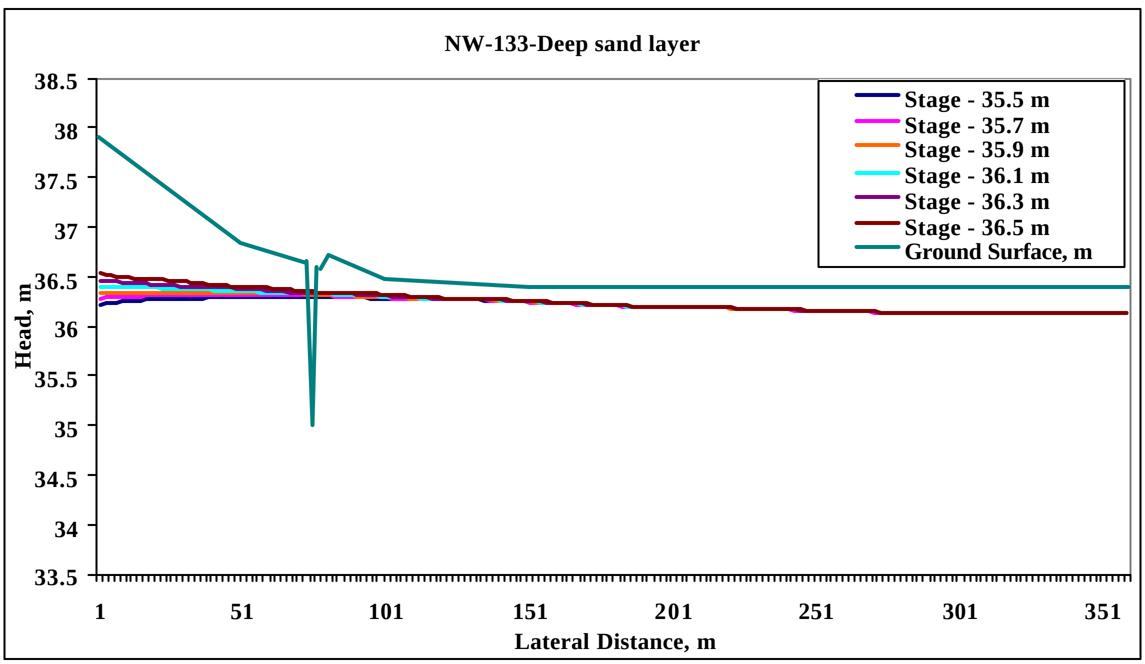

Figure 5.6 Spatial distribution of heads in deep sand layer at the NW transect for different ditch control levels on 13 May 2004.

Net Groundwater Flows at the NW Transect

Net groundwater flows, as shown in Figure 5.7, 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 5.1, 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.

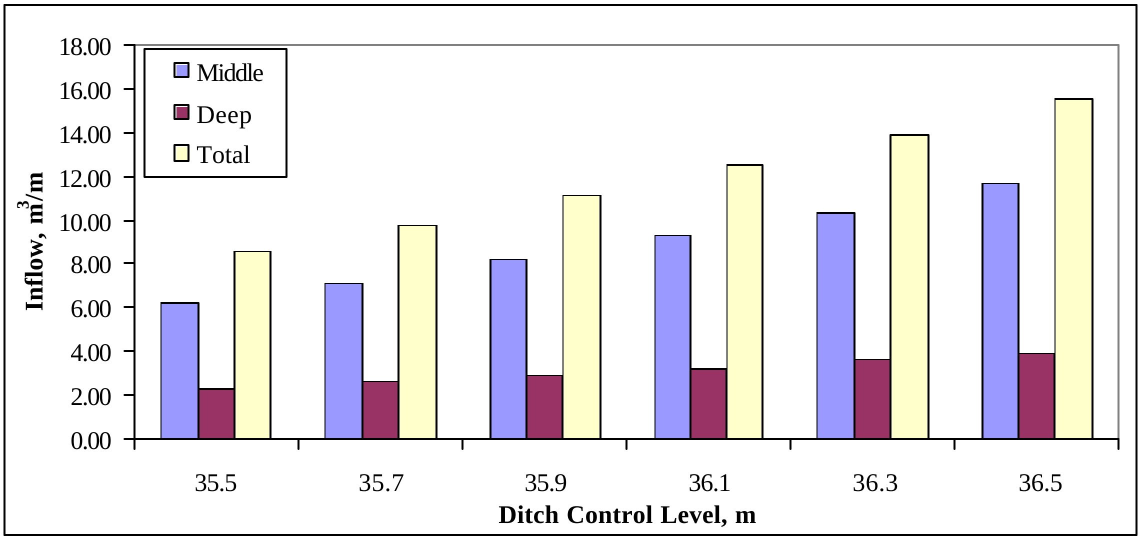

Figure 5.7 Net inflows at the NW transect from different control levels.

Table 5.1 Net Flow at the NW Transect for Different Control Levels

Control Level, ft MSL	*Month*	*Net Inflow, ft³/ft* Middle	*Net Inflow, ft³/ft* Deep	*Net Inflow, ft³/ft* Total
116.5	Jan	22.1	9.3	31.3
	Feb	21.4	7.1	28.4
	Mar	15.1	5.1	20.1
	Apr	6.8	2.8	9.7
	May	1.6	1.0	2.6
	Jun	0.2	0.0	0.2
	Total	67.2	25.3	92.4
117.1	Jan	22.4	9.4	31.6
	Feb	22.3	7.2	29.5
	Mar	16.8	5.4	22.2
	Apr	9.3	3.4	12.7
	May	4.5	1.9	6.6
	Jun	1.1	0.9	1.9
	Total	76.3	28.3	104.6
117.8	Jan	22.8	9.4	32.2
	Feb	23.0	7.3	30.4
	Mar	18.4	5.7	24.1
	Apr	11.6	4.1	15.7
	May	7.6	3.0	10.5

Control Level, ft MSL	*Month*	*Net Inflow, ft³/ft*		
		Middle	*Deep*	*Total*
	Jun	4.4	2.2	6.6
	Total	87.8	31.6	119.5
118.4	Jan	23.3	9.4	32.6
	Feb	23.8	7.4	31.2
	Mar	20.0	6.1	26.2
	Apr	14.0	4.8	18.7
	May	10.7	4.0	14.6
	Jun	7.8	3.4	11.2
	Total	99.4	35.1	134.4
119.1	Jan	23.6	9.4	32.9
	Feb	24.5	7.4	32.1
	Mar	21.6	6.5	28.1
	Apr	16.3	5.5	21.9
	May	13.7	5.2	18.8
	Jun	11.3	4.7	16.1
	Total	111.1	38.6	149.7
119.8	Jan	24.3	9.4	33.7
	Feb	25.3	7.5	32.8
	Mar	23.3	6.8	30.0
	Apr	18.6	6.2	24.9
	May	17.1	6.2	23.4
	Jun	16.5	6.1	22.7
	Total	125.2	42.3	167.5

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

Analysis of Spatial Distribution of Heads at the NE Transect

Figure 5.8 and Figure 5.9 show spatial distributions of the heads in the surficial sand layer for various ditch water levels. The influence of the perimeter ditch, located at lateral distance of 75 m in the flow domain, changes its function for water surface elevations of 119.1 ft (36.3 m) or higher both on 15 February 2004 and 13 May 2004. Therefore, the ditch water level of 119.1 ft (36.3 m) would be critical, as the perimeter ditch converts into a water-contributing source instead of a drainage ditch.

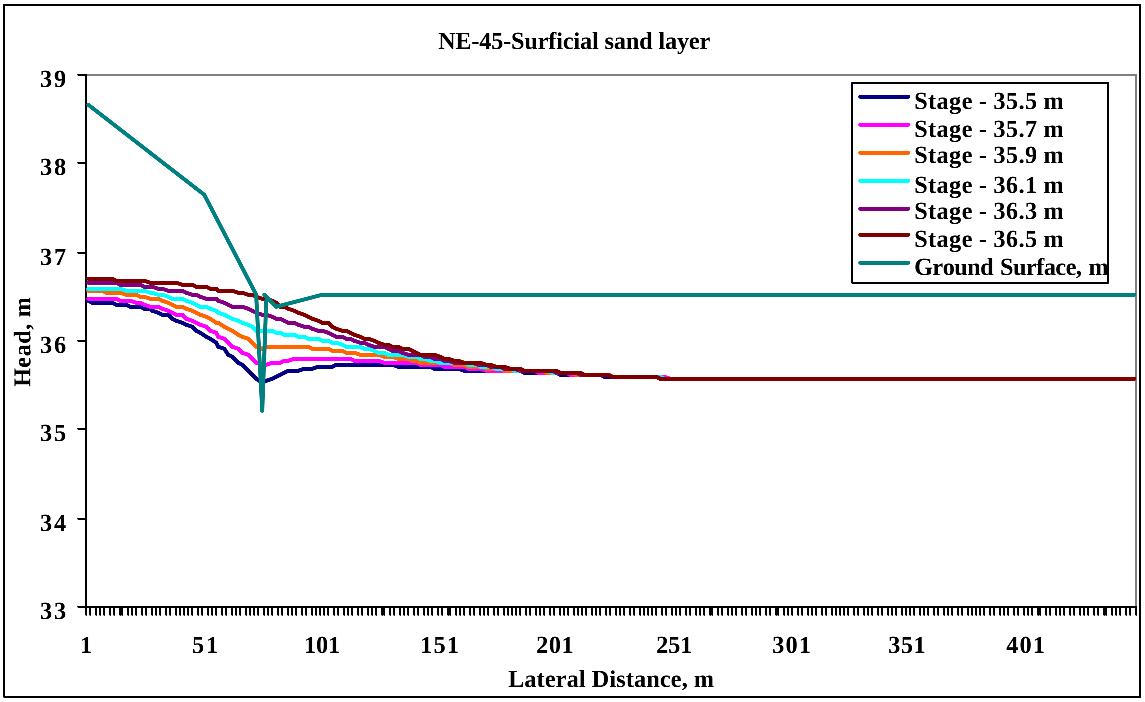

Figure 5.8 Spatial distribution of heads in surficial sand layer at the NE transect for different ditch control levels on 15 February 2004.

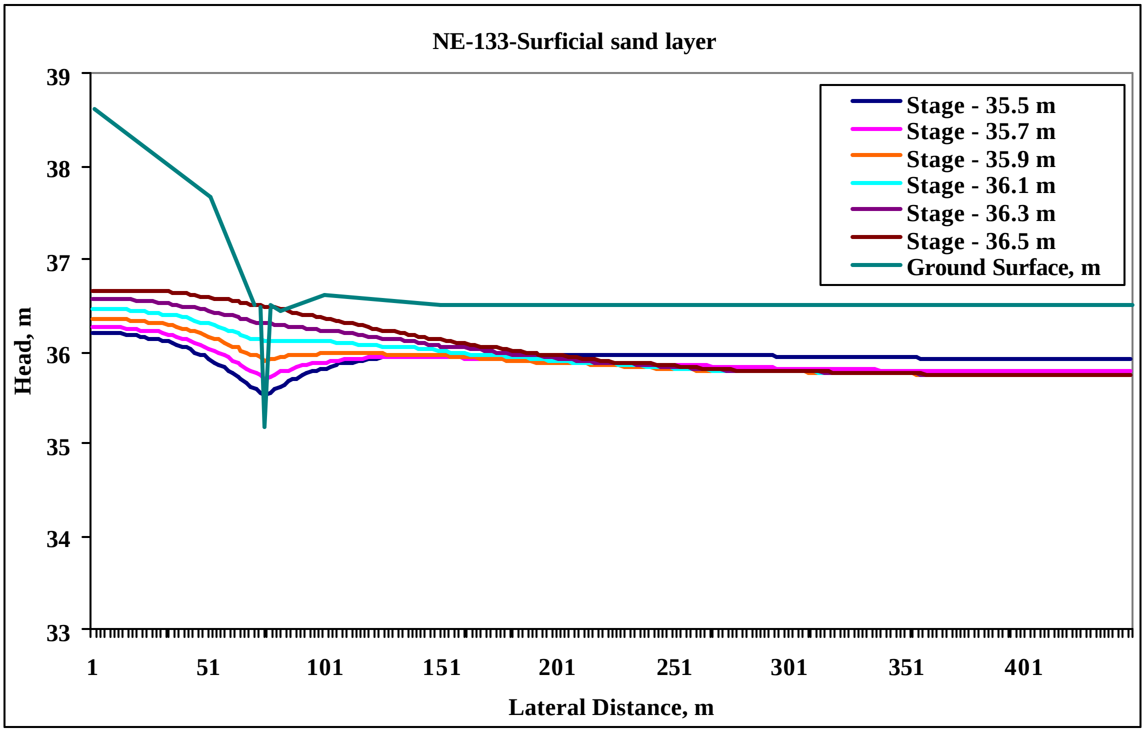

Figure 5.9 Spatial distribution of heads in surficial sand layer at the NE transect for different ditch control levels on 13 May 2004.

Figure 5.10 and Figure 5.11 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. The gradient increases with increases in water level elevation. There is a similar pattern in the deep sand layer also, shown in Figure 5.12 and Figure 5.13, except that the gradients are smaller than those in the middle sand layer.

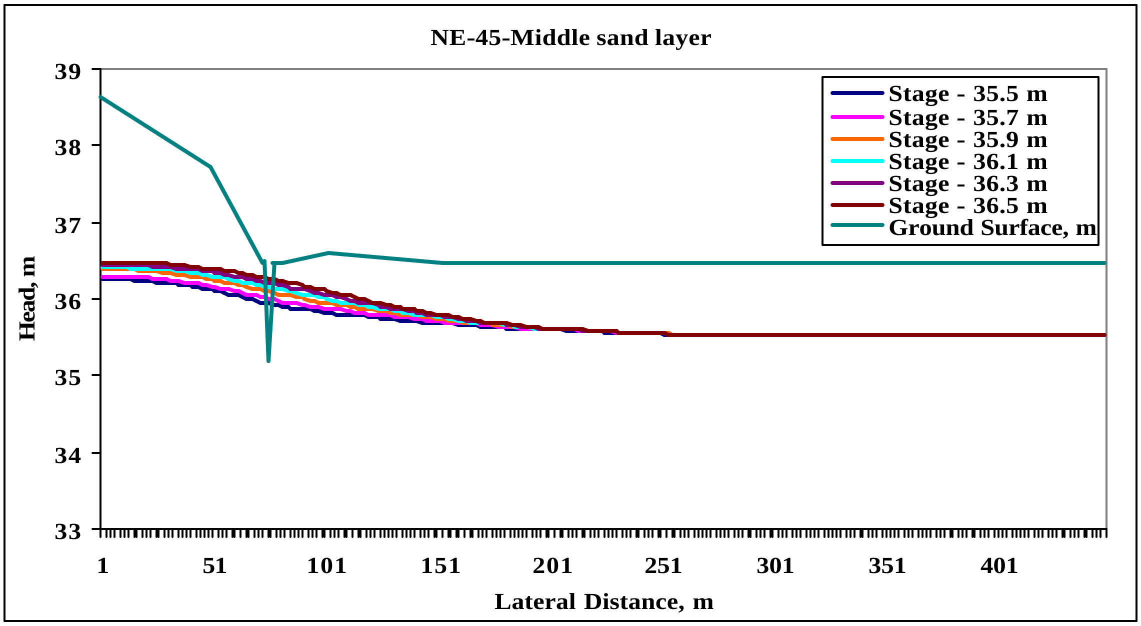

Figure 5.10 Spatial distribution of heads in middle sand layer at the NE transect for different ditch control levels on 15 February 2004.

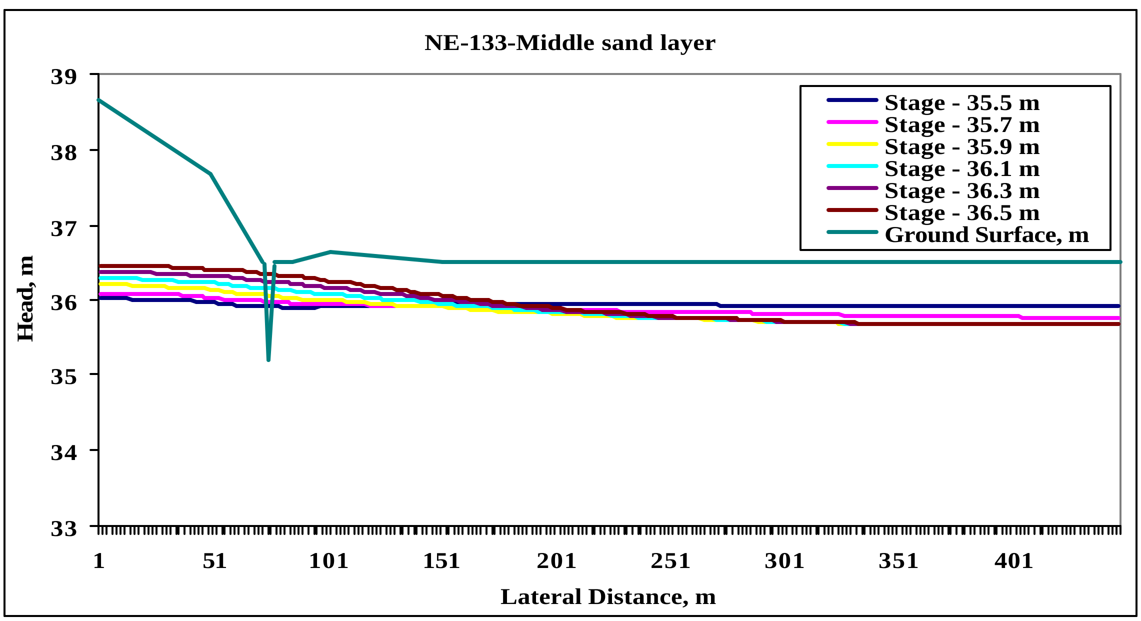

Figure 5.11 Spatial distribution of heads in middle sand layer at the NE transect for different ditch control levels on 13 May 2004.

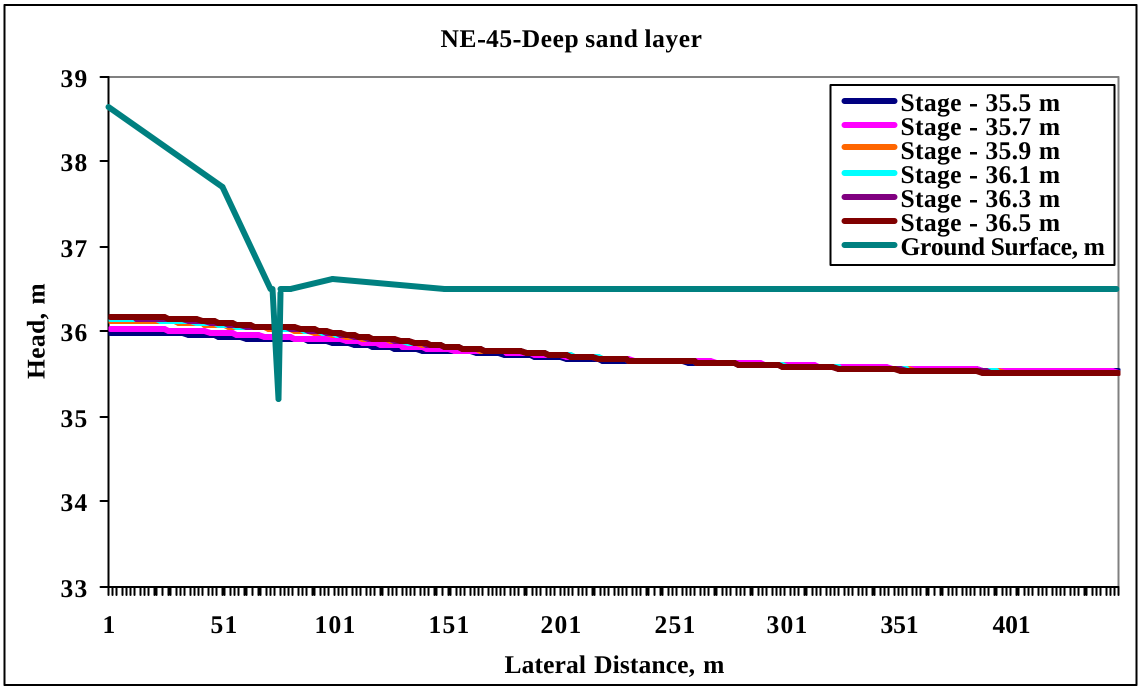

Figure 5.12 Spatial distribution of heads in deep sand layer at the NE transect for different ditch control levels on 15 February 2004.

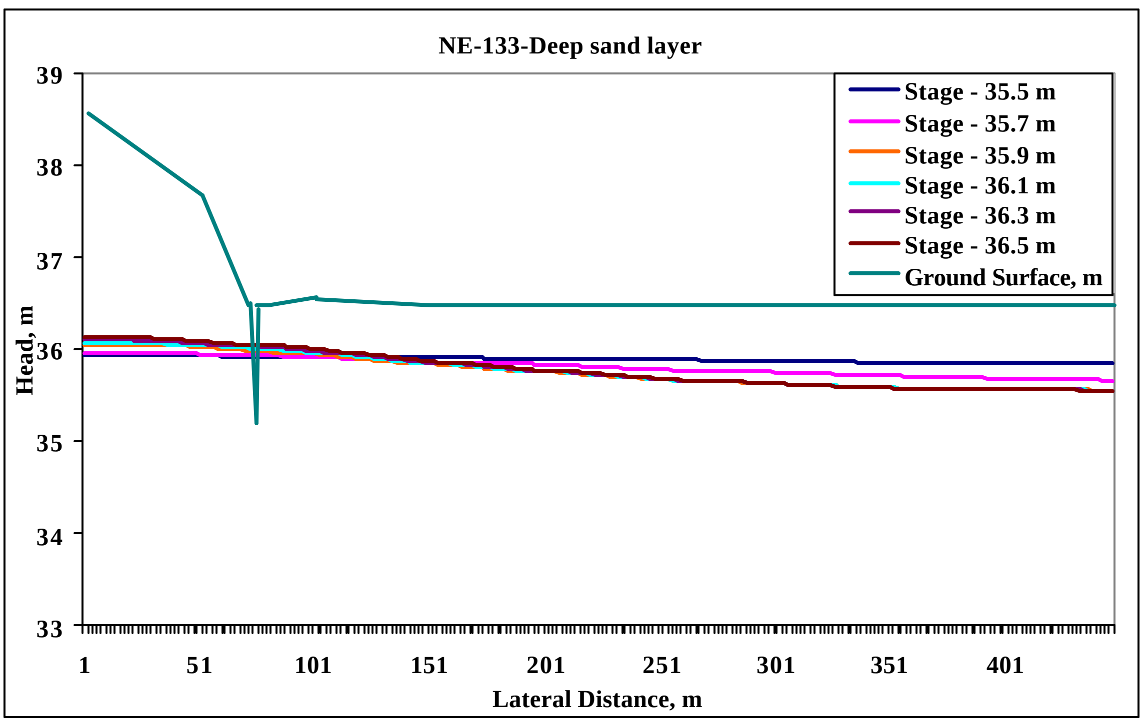

Figure 5.13 Spatial distribution of heads in deep sand layer at the NE transect for different ditch control levels on 13 May 2004.

Net Groundwater Flows at the NE transect

Net flow estimates for each scenario are shown in Figure 5.14. The net groundwater inflows increase with increases in water level in the ditch. Monthly inflow estimates are given in Table 5.2. There is an increase in groundwater flows with an increase in water level in the ditch, and the 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.

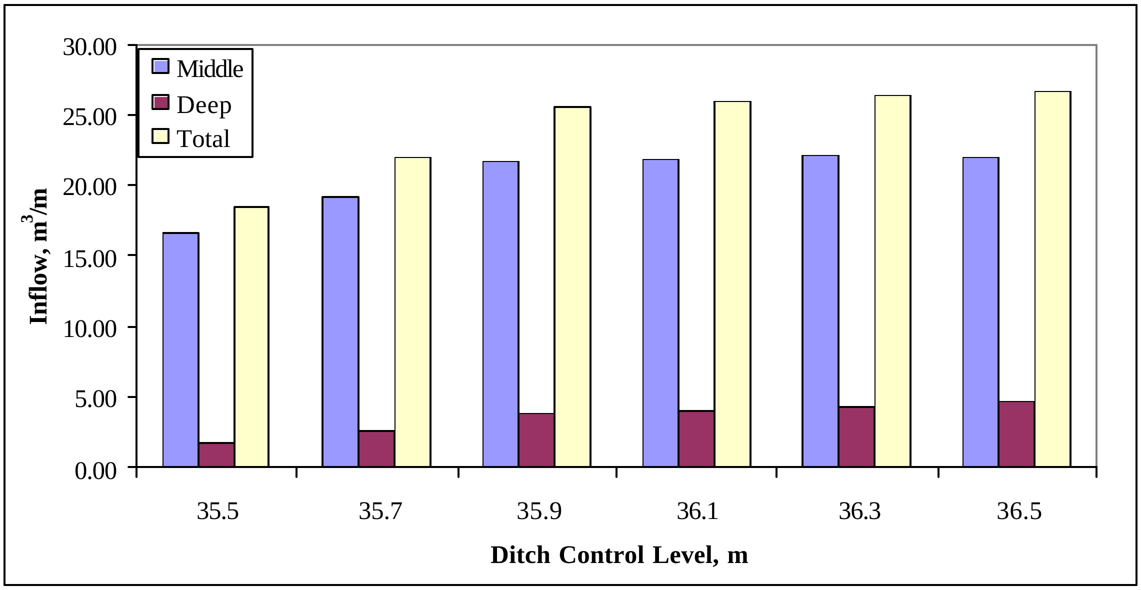

Figure 5.14 Net inflows at the NE transect from different control levels.

Table 5.2 Net Flow at the NE Transect for Different Control Levels

Control Level, ft MSL	*Month*	*Net Inflow, ft³/ft* *Middle*	*Deep*	*Total*
116.5	Jan	63.3	6.9	70.2
	Feb	49.3	6.0	55.3
	Mar	26.9	2.8	29.6
	Apr	22.6	2.7	25.3
	May	12.4	1.1	13.5
	Jun	5.5	0.1	5.6
	Total	180.0	19.6	199.5
117.1	Jan	62.8	7.0	69.8
	Feb	49.4	6.5	55.8
	Mar	38.1	6.0	44.1
	Apr	29.6	5.4	35.0
	May	17.0	2.5	19.5
	Jun	10.5	1.3	11.8
	Total	207.3	28.5	235.8
117.8	Jan	68.5	10.1	78.6
	Feb	52.2	8.6	60.8

Control Level, ft MSL	*Month*	*Net Inflow, ft³/ft*		
		Middle	*Deep*	*Total*
	Mar	40.3	7.6	47.9
	Apr	31.6	6.8	38.3
	May	25.9	6.2	32.2
	Jun	15.3	2.6	17.9
	Total	233.7	42.0	275.7
118.4	Jan	68.6	10.5	79.1
	Feb	51.5	8.8	60.3
	Mar	39.7	7.9	47.6
	Apr	31.6	6.9	38.5
	May	26.5	6.6	32.9
	Jun	17.5	3.3	20.9
	Total	235.3	44.0	279.3
119.1	Jan	69.0	11.3	80.3
	Feb	50.7	9.1	60.0
	Mar	39.2	8.1	47.3
	Apr	31.5	7.2	38.8
	May	27.0	6.8	33.8
	Jun	19.8	4.3	24.1
	Total	237.2	46.9	284.2
119.8	Jan	68.8	12.1	80.8
	Feb	49.4	9.5	59.0
	Mar	38.2	8.3	46.5
	Apr	31.3	7.4	38.6
	May	27.4	7.1	34.4
	Jun	20.8	5.9	26.7
	Total	235.9	50.2	286.2

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

Analysis of Spatial Distribution of Heads at the SE Transect

Figure 5.15 and Figure 5.16 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 suggests that 119.1 ft (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 approaches 119.8 ft (36.5 m), gradients indicate there will be flow coming into the site in the surficial sand layer.

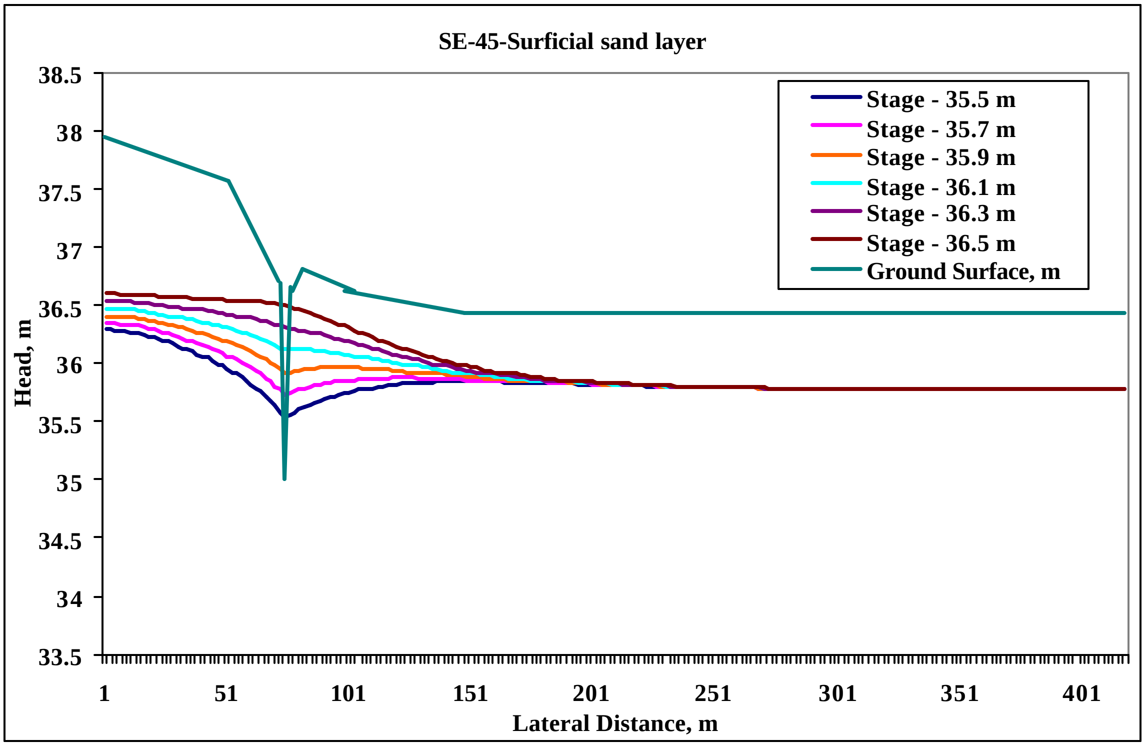

Figure 5.15 Spatial distribution of heads in surficial sand layer at the SE transect for different ditch control levels on 15 February 2004.

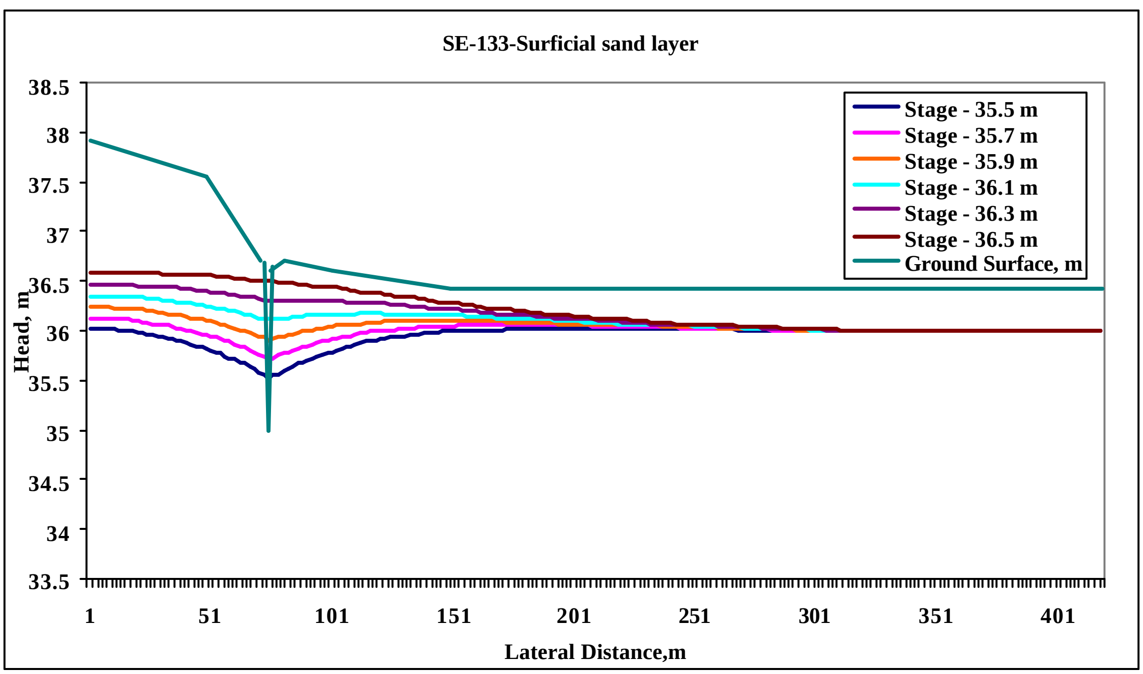

Figure 5.16 Spatial distribution of heads in surficial sand layer at the SE transect for different ditch control levels on 13 May 2004.

The influence in the middle sand layer of water level elevation is larger in summer months (Figure 5.18) when compared to winter months (Figure 5.17). Hydraulic gradients increase with the increase in water levels in the ditch. Figure 5.19 and Figure 5.20 suggest that water levels in the perimeter ditch have no significant influence on the flows in deep sand layers.

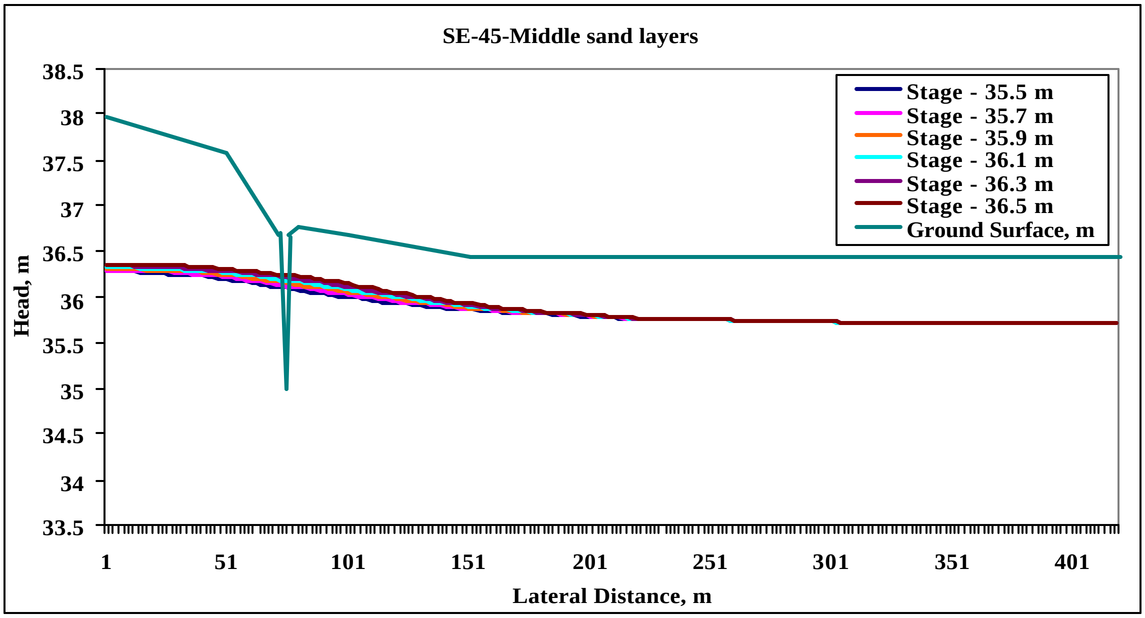

Figure 5.17 Spatial distribution of heads in middle sand layer at the SE transect for different ditch control levels on 15 February 2004.

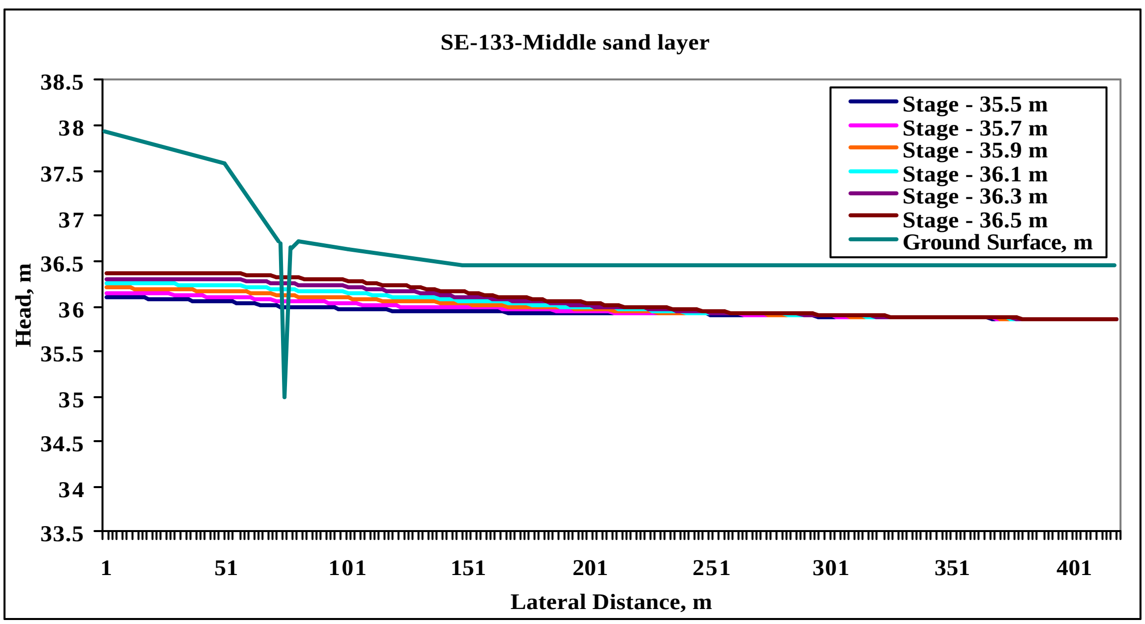

Figure 5.18 Spatial distribution of heads in middle sand layer at the SE transect for different ditch control levels on 13 May 2004.

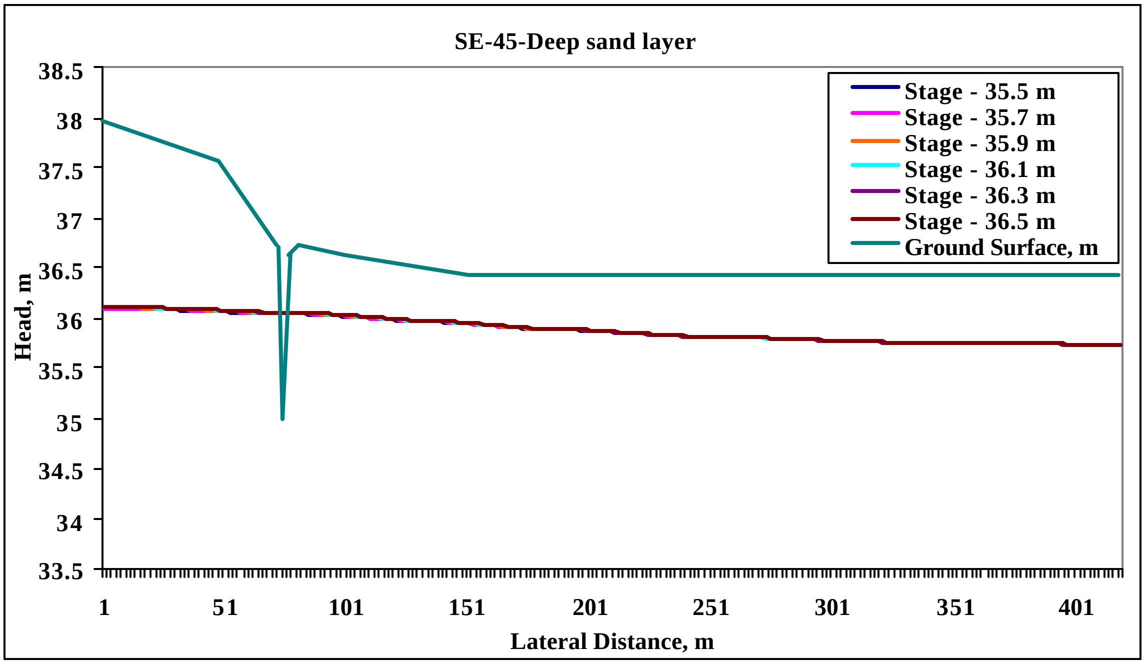

Figure 5.19 Spatial distribution of heads in deep sand layer at the SE transect for different ditch control levels on 15 February 2004.

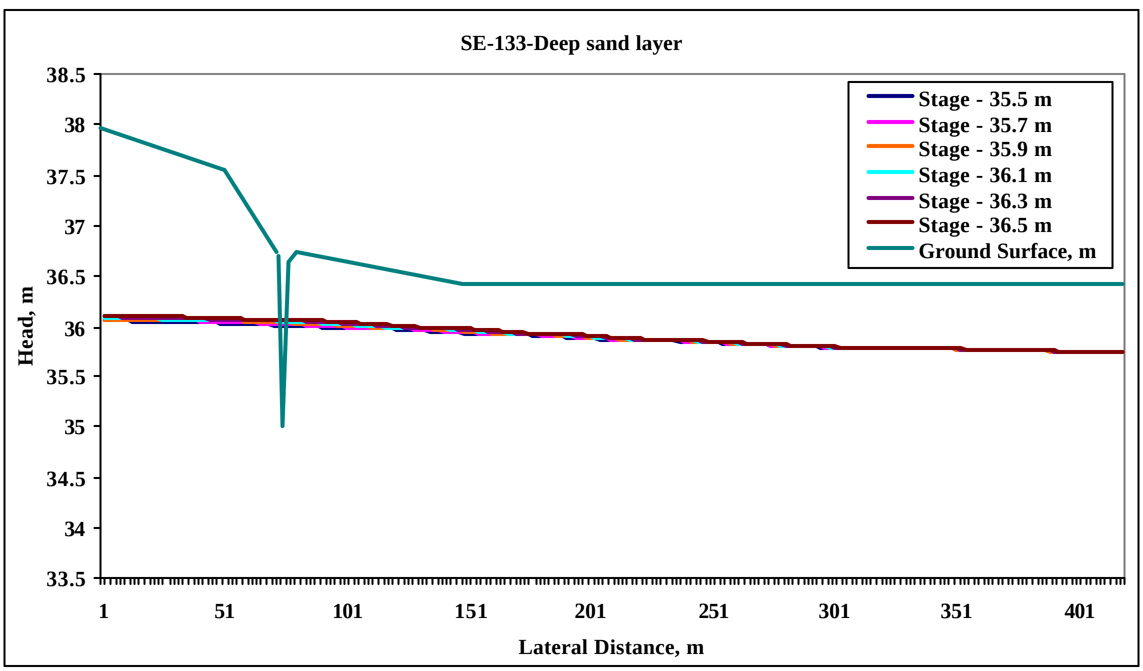

Figure 5.20 Spatial distribution of heads in deep sand layer at the SE transect for different ditch control levels on 13 May 2004.

Net Groundwater Flows at the SE Transect

The net flows at the SE transect from various scenarios are shown in Figure 5.21. Figure 5.21 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 5.3 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.

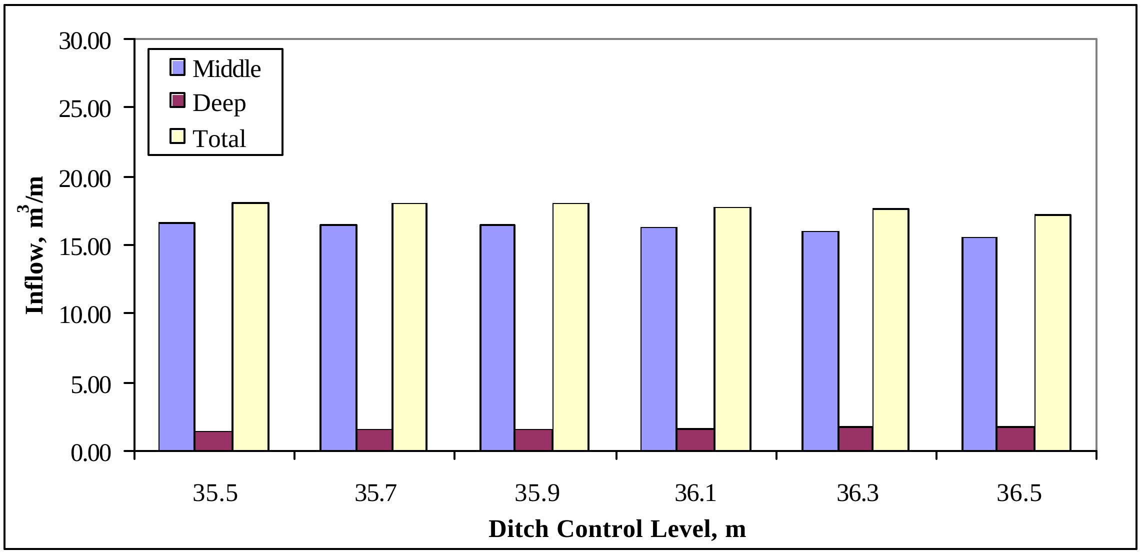

Figure 5.21 Net inflows at the SE transect from different control levels.

Table 5.3 Net Flow at the SE Transect for Different Control Levels

Control Level, ft MSL	*Month*	*Net Inflow, ft^3/ft*		
		Middle	*Deep*	*Total*
116.5	Jan	55.6	3.7	59.3
	Feb	44.3	3.3	47.7
	Mar	34.2	3.1	37.4
	Apr	25.8	2.7	28.5
	May	19.4	2.5	21.9
	Jun	-0.1	-0.1	-0.2
	Total	179.3	15.2	194.5
117.1	Jan	55.0	3.7	58.7
	Feb	43.1	3.3	46.4
	Mar	33.2	3.1	36.3
	Apr	25.1	2.8	27.9
	May	19.2	2.6	21.7
	Jun	2.6	0.3	2.9
	Total	178.0	15.8	193.9
117.8	Jan	54.5	3.7	58.0
	Feb	41.8	3.3	45.1

Control Level, ft MSL	*Month*	*Net Inflow, ft³/ft*		
		Middle	*Deep*	*Total*
	Mar	32.0	3.1	35.1
	Apr	24.4	2.9	27.2
	May	18.9	2.7	21.6
	Jun	5.4	0.8	6.1
	Total	176.9	16.5	193.3
118.4	Jan	53.6	3.7	57.3
	Feb	40.1	3.3	43.5
	Mar	30.6	3.2	33.7
	Apr	23.5	2.9	26.4
	May	18.5	2.8	21.3
	Jun	8.1	1.3	9.4
	Total	174.3	17.2	191.5
119.1	Jan	52.9	3.7	56.4
	Feb	38.4	3.4	41.9
	Mar	29.1	3.2	32.3
	Apr	22.4	3.0	25.4
	May	18.0	2.9	20.9
	Jun	10.8	1.9	12.7
	Total	171.5	18.1	189.6
119.8	Jan	51.7	3.7	55.4
	Feb	36.6	3.4	40.0
	Mar	27.4	3.2	30.7
	Apr	21.3	3.0	24.3
	May	17.4	3.0	20.3
	Jun	12.2	2.6	14.7
	Total	166.6	18.9	185.6

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

Analysis of Spatial Distribution of Heads at the SW transect

Figure 5.22 and Figure 5.23 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 117.7 ft (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 118.4 ft (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 117.8 ft (35.9 m) or lower to avoid causing an excessively high water table in the adjacent land.

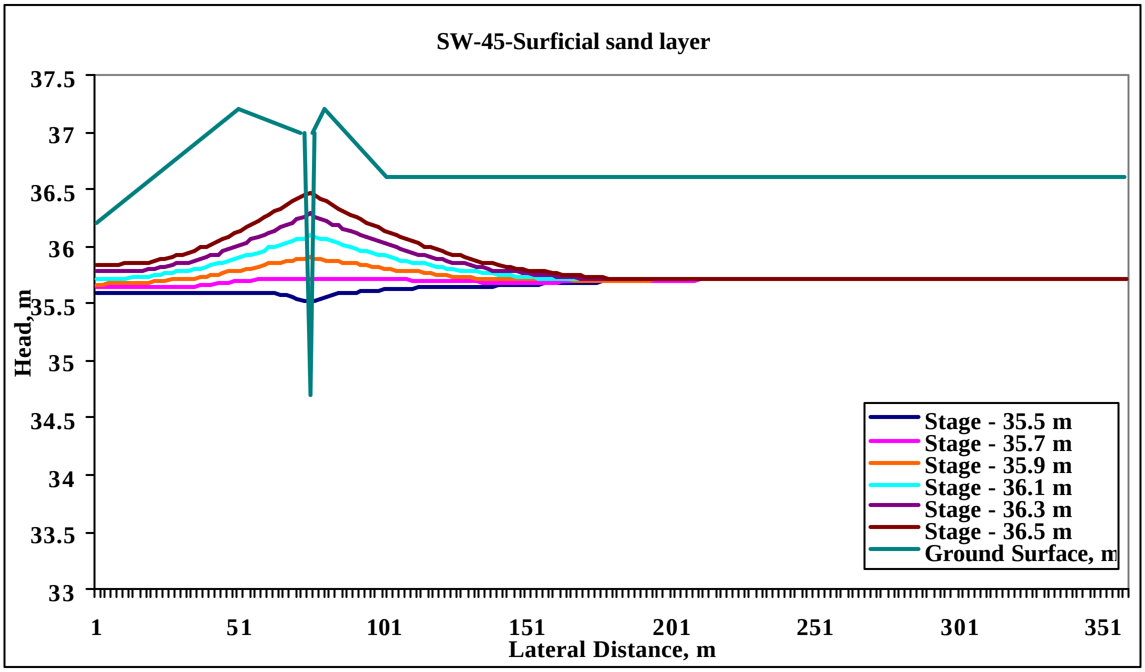

Figure 5.22 Spatial distribution of heads in surficial sand layer at the SW transect for different ditch control levels on 15 February 2004.

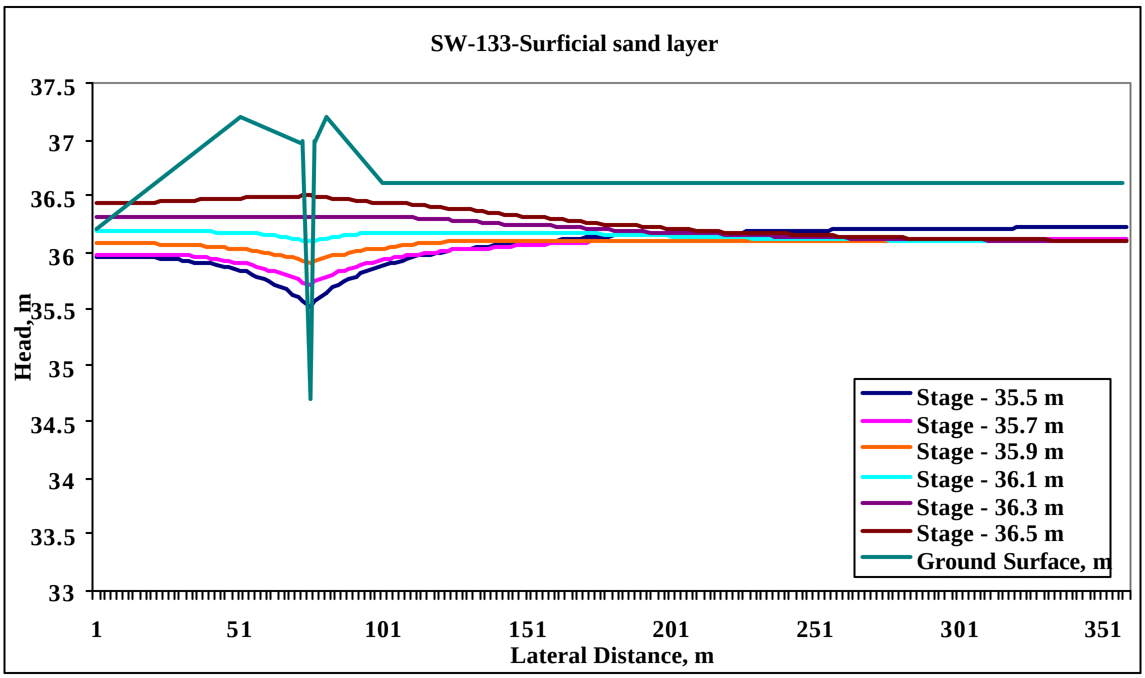

Figure 5.23 Spatial distribution of heads in surficial sand layer at the SW transect for different ditch control levels on 13 May 2004.

Figure 5.24 and Figure 5.25 show head distributions in the middle sand layers. 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 117.8 ft

(35.9 m) suggests groundwater flows towards the interior of the bay, reversing the flow direction. Figure 5.26 and Figure 5.27 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 116.8 ft (35.5 m), as shown in Figure 5.25. This could be because of the deeper perimeter ditch at the SW transect and relatively low water level in the ditch.

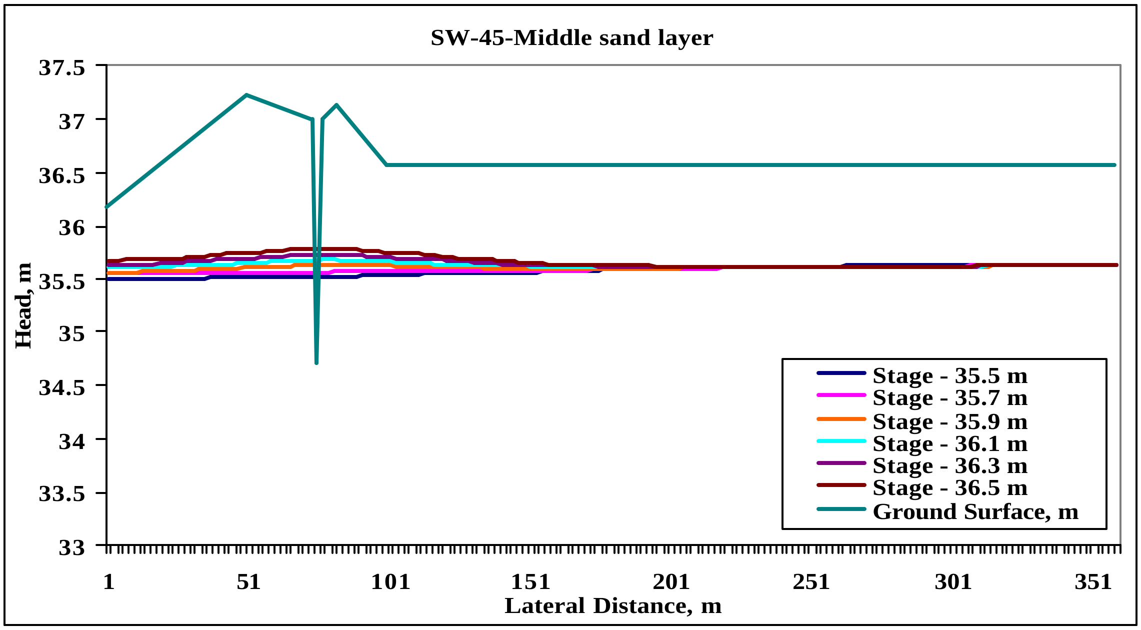

Figure 5.24 Spatial distribution of heads in middle sand layer at the SW transect for different ditch control levels on 15 February 2004.

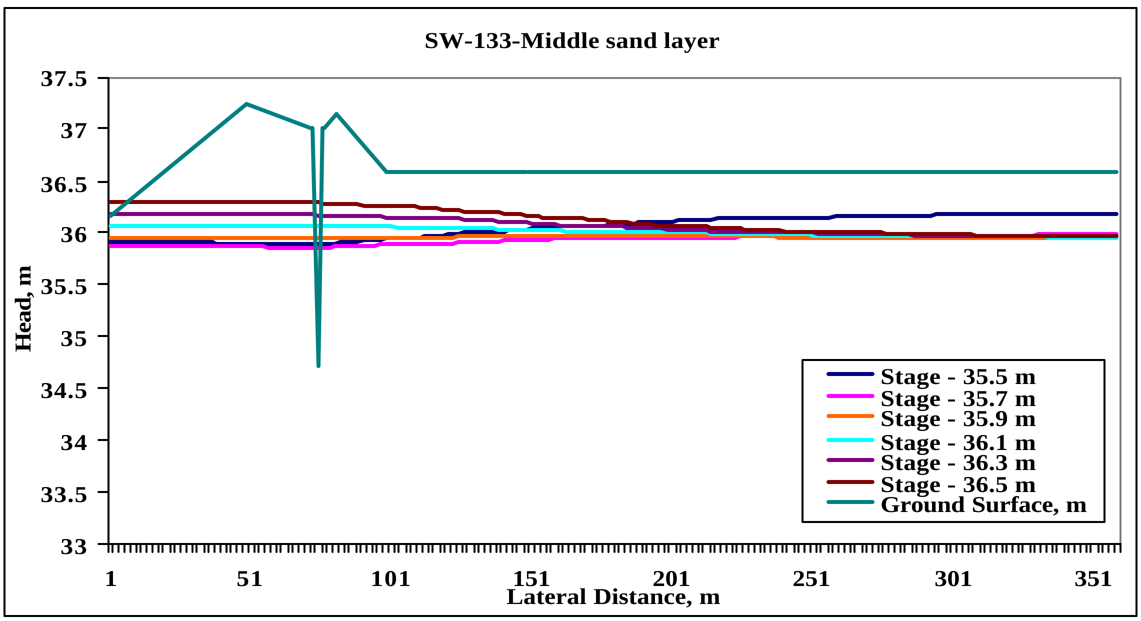

Figure 5.25 Spatial distribution of heads in middle sand layer at the SW transect for different ditch control levels on 13 May 2004.

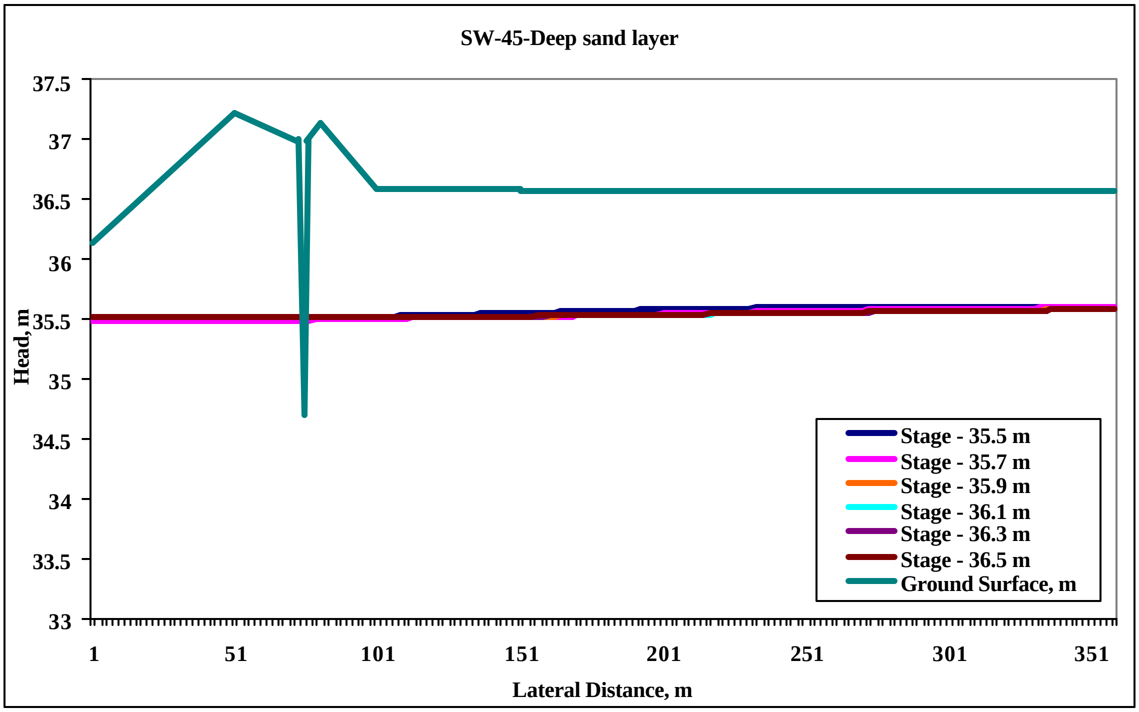

Figure 5.26 Spatial distribution of heads in deep sand layer at the SW transect for different ditch control levels on 15 February 2004.

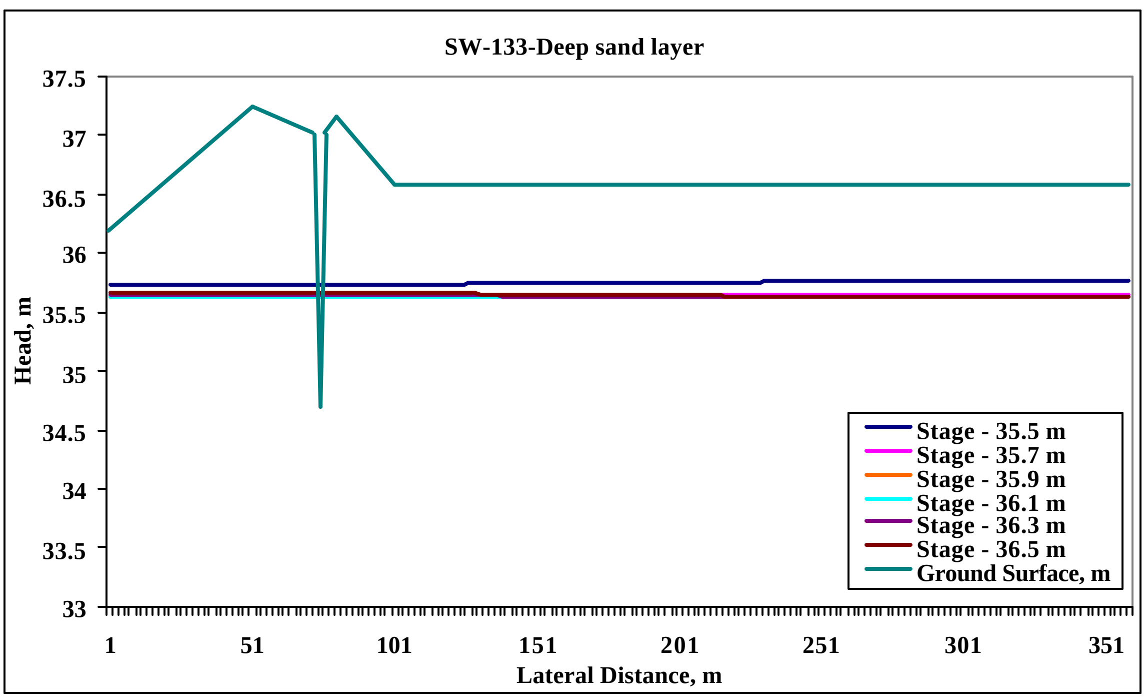

Figure 5.27 Spatial distribution of heads in deep sand layer at the SW transect for different ditch control levels on 13 May 2004.

Net Groundwater Flows at the SW Transect

The net flow estimates at the SW transect, as shown in Figure 5.28, indicate that for any water level higher than 117.8 ft (35.9 m) there will be a net groundwater inflow into the site. Table 5.4 presents the net groundwater flows at the SW transect in the middle and deep sand layers. The net groundwater flow increases with the increase in water level in the ditch. Control levels that are 117.8 ft (35.9 m) or lower will produce groundwater outflows at the SW transect. A control level of 118.4 ft (36.1 m) or above would produce groundwater inflows at the SW transect.

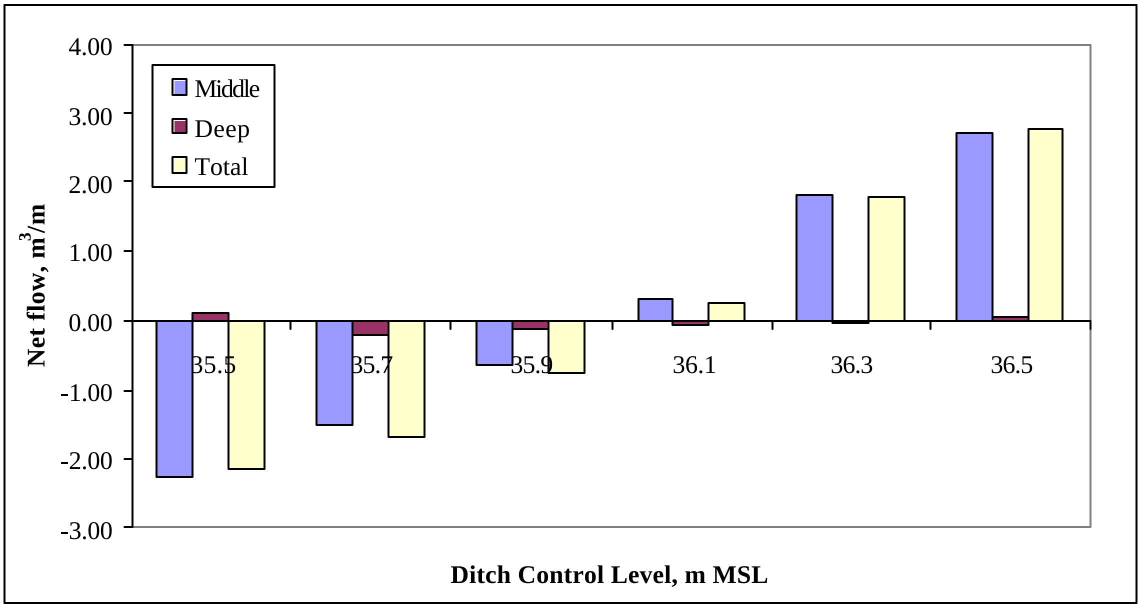

Figure 5.28 Net flows at the SW transect from different control levels.

Table 5.4 Net Flow at the SW Transect for Different Control Levels

Control Level, ft MSL	*Month*	*Net Inflow, ft^3/ft*		
		Middle	*Deep*	*Total*
116.5	Jan	4.7	2.9	7.5
	Feb	-3.1	-0.9	-4.0
	Mar	-4.2	-0.1	-4.3
	Apr	-4.6	-0.2	-4.8
	May	-7.3	-0.2	-7.5
	Jun	-9.8	-0.3	-10.1
	Total	-24.4	1.3	-23.1
117.1	Jan	-0.1	-0.8	-1.0
	Feb	-2.2	-1.0	-3.1
	Mar	-2.3	0.0	-2.3
	Apr	-2.5	-0.1	-2.6
	May	-3.4	-0.2	-3.7
	Jun	-5.7	-0.1	-5.8
	Total	-16.1	-2.3	-18.3

Control Level, ft MSL	*Month*	*Net Inflow, ft³/ft*		
		Middle	*Deep*	*Total*
117.8	Jan	-0.4	-0.5	-1.0
	Feb	-1.8	-0.4	-2.3
	Mar	-0.8	0.1	-0.8
	Apr	-0.5	-0.1	-0.6
	May	-1.0	-0.1	-1.1
	Jun	-2.5	-0.1	-2.7
	Total	-7.0	-1.3	-8.3
118.4	Jan	0.0	-0.5	-0.5
	Feb	-1.2	-0.4	-1.6
	Mar	1.1	0.1	1.3
	Apr	1.6	0.0	1.6
	May	1.7	-0.1	1.6
	Jun	0.0	0.1	0.1
	Total	3.3	-0.9	2.5
119.1	Jan	0.4	-0.5	-0.1
	Feb	-0.6	-0.4	-1.1
	Mar	3.1	0.2	3.3
	Apr	3.9	0.1	4.0
	May	4.3	0.0	4.4
	Jun	8.4	0.3	8.7
	Total	19.6	-0.3	19.3
119.8	Jan	1.1	-0.5	0.4
	Feb	0.1	-0.4	-0.3
	Mar	5.2	0.3	5.6
	Apr	6.2	0.2	6.5
	May	7.2	0.1	7.3
	Jun	9.6	0.8	10.3
	Total	29.3	0.4	29.8

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 5.5 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 5.29. Net flow into the site was positive, indicating groundwater inflow at Juniper bay, varying from 4.2 to 6.1 in. (107 to 155 mm). The net groundwater inflow increases with the increase in water level elevation in the perimeter ditch.

Table 5.5 Net Groundwater Flows for January 2004 to June 2004

Ditch Control Level, ft MSL	*Net Flow at Transect, in.* NW	*NE*	*SE*	*SW*	*Total Net Flow, in.*
116.5	0.85	1.83	1.78	-0.21	4.24
117.1	0.96	2.16	1.78	-0.17	4.73
117.8	1.09	2.52	1.77	-0.08	5.31
118.4	1.23	2.56	1.75	0.02	5.56
119.1	1.37	2.60	1.74	0.18	5.89
119.8	1.53	2.62	1.70	0.27	6.13

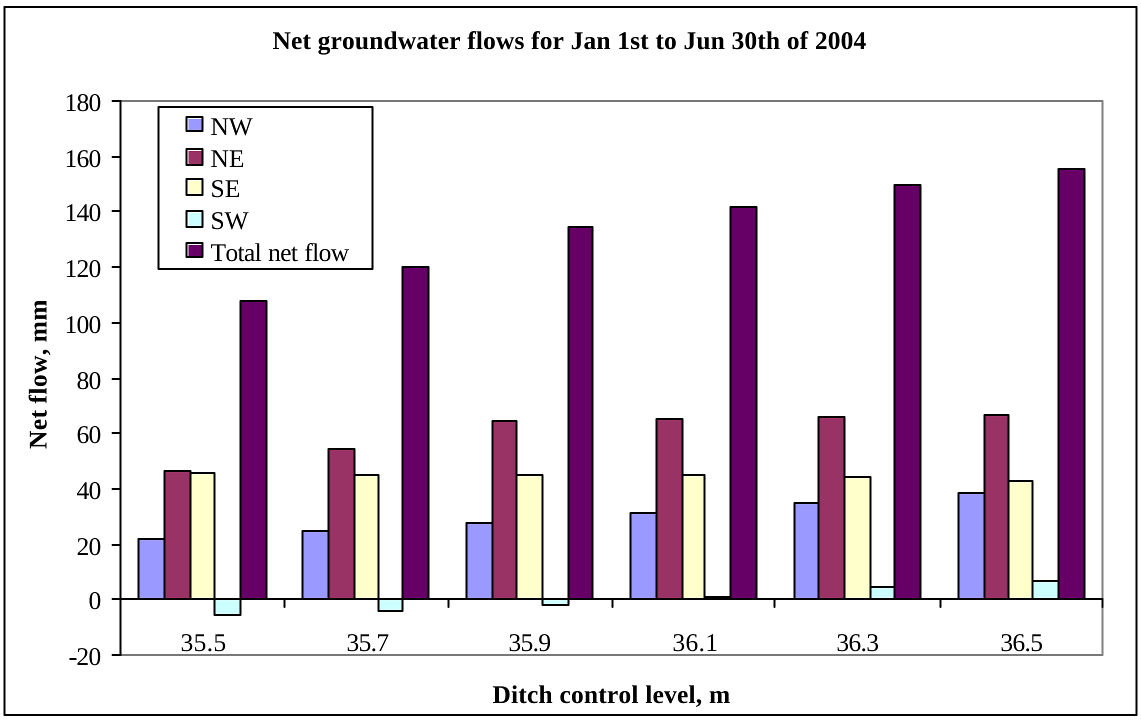

Figure 5.29 Net groundwater flows for 01 January 2004 to 30 June 2004.

5.7. Summary

Analysis of the model runs with controlled water levels in the perimeter ditch showed that offsite impacts are most likely at the SW transect. Table 5.6 presents the summary of critical depth of water in the perimeter ditch at each transect. Critical control level is defined as the water level above which the perimeter ditch would be a recharge source instead of a drainage ditch. At the critical level, the perimeter ditch has no effect on the groundwater flows. Table 5.6 shows that the ditch water level must be maintained below 117.8 feet (35.9 m) MSL to reduce outflows through the SW transect. Critical levels at the NW, NE, and SE transects are 118.4 ft (36.1 m), 119.1 ft (36.3 m), and 117.8 ft (35.9 m) respectively.

Net groundwater inflow into Juniper bay for a ditch level of 117.8 ft was estimated as 5.3 in. (135 mm) for the first six months of 2004.

Table 5.6 Summary of Critical Ditch Control Levels, ft MSL

	Critical Ditch Control Levels		
Transect	*Wet Conditions*	*Dry Conditions*	*Ditch Top Elevation*
NW	118.4	119.1	120.2
NE	119.1	119.8	119.8
SE	117.8	119.1	120.4
SW	117.8	118.4	121.4

If the perimeter ditch outlet is controlled, the control elevation should be selected to prevent hydraulic trespass while maximizing wetland area within the project boundary. Given that inflows are expected around approximately three quarters of the perimeter, the ditch could also serve to intercept some of the inflow and thereby reduce excess water in the interior. While the models provided indication of the expected behaviors, appropriate control level should be determined experimentally, using these results as a starting point.

6. Summary and Recommendations

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 only drainage after filling the interior main ditches for restoration, and 3) develop recommendations for maintenance of the perimeter ditch to avoid offsite impacts and maximize wetland area.

6.1. Summary

The Black Creek Confining Unit, a fine textured impervious layer, was found at the depths of 26 to 36 ft (8 to 11 m) at all four transects, except along the interior section of the SE transect, where consolidated shell beds were found at about 30 ft. A distinct surficial sand layer and the two underlying sand layers were identified at most of these core locations

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

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.

The models were extended to the center of the bay (2600 ft [800 m] from the perimeter ditch) to simulate the conditions after the interior ditches are blocked. This extended model was used to estimate the gradients and the range of influence of the perimeter ditch towards the inside of the bay. All transects had 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, gradients in the middle sand layer indicated groundwater inflow. Flow in the lower sands at the NW, NE, and SE transects showed groundwater inflow with 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 only area where hydraulic trespass onto the adjacent land is a concern.

The influence of the perimeter ditch was analyzed at each transect. This analysis showed that the lateral influence extended to a maximum of about 330 ft (100 m) laterally and the vertical influence to a depth of about 20 to 23 ft (6 to 7 m). This depth corresponds to the middle sand layer at the NW transect. At the NE transect, the lateral influence of the perimeter ditch extended to a maximum 250 ft (75 m) and the vertical influence to a depth of 13 to 16 ft (4 to 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 toward the exterior of the bay. At the SE transect, the influence of the perimeter ditch extends laterally to a maximum of 250 ft (75 m) and vertically to the depth of 13 to 16 ft (4 to 5 m) (surficial sand layer). At the SW transect, the influence was to a lateral maximum of 330 ft (100 m) inside the bay and 165 ft (50 m) outside the bay. Vertical influence was to the depth of the middle sand layer, which is 20-23 ft (6-7 m) deep.

The results from the individual transects were extrapolated to the entire lateral boundary of the project site to estimate the net groundwater flows. With the present conditions at Juniper Bay, groundwater inflow can be expected through approximately three quarters of the boundary corresponding to the NW, NE, and SE transects. Groundwater outflow could be expected through the quarter of the boundary corresponding to the SW transect. The net inflow to the bay was estimated as 4.9 in. (125 mm) for the first six months of 2004.

Critical control levels for the perimeter ditch were identified at all the transects, and they were 118.4 ft (36.1 m) for the NW transect, 119.1 ft (36.3 m) for the NE transect, 117.8 ft (35.9 m) for the SE transect, and 117.8 ft (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 117.8 ft (35.9 m). This analysis also suggested that offsite impacts are a possibility near the southwest transect. The net groundwater inflow of Juniper Bay for a perimeter ditch control level of 117.8 ft (35.9 m) was estimated as 5.3 in. (135 mm) for the first six months of the year 2004.

6.2. Recommendations

This study found that the net groundwater influx into the Bay is a significant part of the overall water budget. Maintenance of the perimeter ditch is recommended for two purposes. First, by intercepting the potential influx in most of the upper and middle sands and conducting it to the outlet, a portion of the excess water in the Bay could be eliminated. Second, there is the potential for hydraulic trespass in the area along the SW portion of the perimeter. Maintaining an effective drain in that area will be needed to intercept and control the potential efflux from the Bay as the water table rises after the internal drainage system has been blocked.

The results presented in Chapter 5 show the potential for management of the perimeter ditch by zones. Control structures (weirs) could be installed at strategic points in the perimeter ditch to provide different water levels for different sections. In particular, the SW section of the perimeter would need to be maintained at a lower level than would be most advantageous for the remainder. While this study provides some guidance for initial control settings, installation of variable-height controls would be preferred to permit adjustment as experience and weather conditions dictate. These would also allow free drainage to draw the water levels down occasionally for maintenance.

Realization of the benefits of the control of the perimeter ditch will require a program of regular maintenance to keep the perimeter ditch clear of brush, debris, and beavers. Mowing and clearing should be done at least 2-3 times per year.

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