ASHUMET VALLEY PLUME DIVERSION THROUGH THE USE OF PHYSICAL BARRIERS

by

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Abstract

A contaminant plume emanating from the Massachusetts Military Reservation (MMR) has formed in Ashumet Valley, Cape Cod. A significant portion of this groundwater plume is intercepting Ashumet Pond. There is concern that high phosphorus concentration levels measured from the plume discharge may be causing the pond to be eutrophic. Risk of further detriment to Ashumet Pond exists if the phosphorus loading is not stopped or decreased. Previous studies suggest that one containment approach is the development of plume diversion techniques to protect Ashumet Pond. The use of physical barriers to divert the plume away from the pond is studied in this thesis.

Groundwater modeling is used to provide a quantitative understanding of the flow in the aquifer. Computer simulations are run on two computer programs developed by Camp Dresser and McKee called DYNFLOW and DYNTRACK. DYNFLOW is used in order to generate the total head contours in the aquifer. DYNTRACK is used to determine the flow lines in the aquifer.

Two models are used in the study. The first model showing present conditions (i.e. without the wall) is used to determine which flow lines are responsible for transporting phosphorus in the pond. The second model is used to evaluate changes in flow patterns when a wall is introduced into the system.

Analyses were made for 190 ft deep walls having lengths of 1500 ft and 2000 ft. Both showed similar capabilities of cutting off the phosphorus plume from Ashumet Pond. A contaminant breakthrough analysis showed that the barrier only needed a thickness of 0.5 ft for a design life of 30 years and 0.75 ft for a design life of 75 years.

Four types of barrier installation techniques were considered in this thesis: slurry wall construction, deep soil mixing, sheet pile installation, and grout injection. Due to the large depth to a low permeability soil layer, slurry wall construction using grab or clamshell excavation is the most promising alternative among the four.

Thesis Supervisor : Dr. Charles C. Ladd
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LIST OF UNITS AND ABBREVIATIONS

UNITS

cm^2/sec - square centimeter per second

ft - feet

ft^2/day - square feet per day

m- meter

mg/L- milligrams (10^{-3} grams) per liter

mgd - million gallons per day

ABBREVIATIONS

AFCEE- Air Force Center for Environmental Excellence

BTEX- benzene, toluene, ethylbenzene, and xylene

DCE- dichloroethene

DEP- Massachusetts Department of Environmental Protection

FTA-1- Fire Training Area 1

MCL- maximum contaminant level

MMR- Massachusetts Military Reservation

MSL - Mean Sea Level

PCE- perchloroethylene

STP- sewage treatment plant

TCE- trichloroethylene

USEPA- U.S. Environmental Protection Agency

USGS- United States Geological Survey

VC- vinyl chloride

1. INTRODUCTION AND BACKGROUND

1.1 MMR Site Description

The Massachusetts Military Reservation (MMR) is located on the upper, western portion of Cape Cod, Massachusetts. The MMR covers 22,000 acres within the towns of Bourne, Mashpee, and Sandwich (Figure 1-1). It abuts the town of Falmouth and is bordered on the west by State Route 28 and on the north by U.S. Highway 6. Since 1936, the MMR has hosted various branches of the Armed Forces (LeBlanc, 1984b).

At its peak, the MMR was a primary staging ground for World War II and home to over 10,000 soldiers. The industrial and military activities associated with the MMR has had far-reaching impacts upon the environment of Cape Cod. In 1989, as a result of widespread groundwater contamination in the area, the MMR was placed on the National Priority List of Superfund sites.

1.2 MMR Population and Demographics

The MMR has a year round population of approximately 2,000. Additionally, there are approximately 800 non-resident employees of the MMR. The population of the four towns that border the MMR fluctuates between the winter (29,000) and the summer (70,000) due to the large number of summer vacationers that visit Cape Cod. The western, or Upper Cape, registered a population growth of 35% between 1980 and 1990. However, this area is still considered to be sparsely populated in relation to the rest of Cape Cod. The median age of residents of Barnstable County, which encompasses the entire Cape, is 39.5 years.

1.3 Objectives and Scope of Thesis

This thesis is a by product of a team design project on the Ashumet Valley Plume emanating from MMR. Among the primary goals in the project is the investigation of the health of Ashumet Pond (See Figure 1-1). A potential threat to its health is the high phosphorus loading infiltrating the pond. The project looked into the chemical and

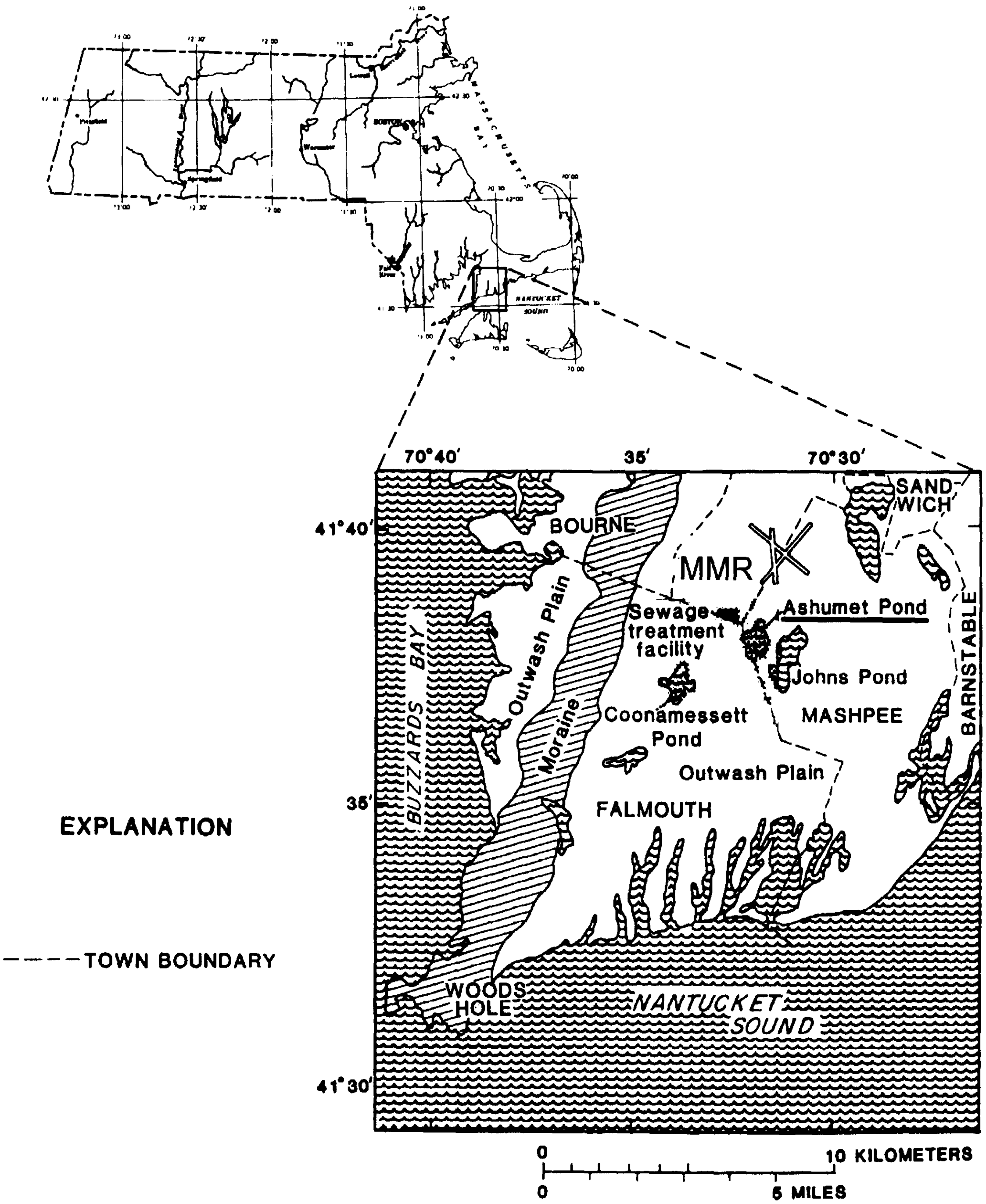


Figure 1-1. MMR Site Location Map (LeBlanc, 1984a)

biological effects the phosphorus had on the pond to check the danger involved with the current loading. Another part of the project looked into ways of trying to eliminate or reduce the load. This thesis addresses a way of stopping or reducing the transport of high levels of phosphorus into the pond.

The contaminant being addressed in this thesis is phosphorus. The study investigates the use of physical barriers as a plume diversion technique. The content of the thesis proceeds in the following form:

1. Chapter 1 provides an overview of the MMR, including its location and population.
2. Chapter 2 looks deeper into the specific study area: Ashumet Valley. Site characteristics, such as meteorology, geology, hydrogeology and historical pond use, are reviewed in this chapter. The contaminant sources are also discussed in this chapter.
3. Chapter 3 presents the problem of phosphorus containment in detail.
4. Chapter 4 discusses on the different techniques used for the installation of physical barriers.
5. Chapter 5 deals with criteria development and design methodology. It sets the design limits and discusses how the barriers are tested.
6. Chapter 6 presents the results of model simulations demonstrating flow with and without the barriers.
7. Chapter 7 makes a contaminant breakthrough analysis performed on the barrier to determine its required thickness.
8. Recommendations based on the study and a summary of the thesis are contained in Chapter 8.

2. ASHUMET VALLEY

This study focuses on the contaminant plume in the Ashumet Valley (Figure 2-1). In particular, the health of Ashumet Pond is the primary concern.

2.1 Site Location and Description

The Ashumet Valley area of Falmouth, Massachusetts, is located near the southern boundary of the MMR, downstream of the two source areas (Figure 2-1). To the east, the plumes infiltrate into Ashumet Pond. Sandwich Road runs along the approximate western boundary of the plume. Much of the area is forested or residential. A golf course is located between Sandwich Road and the southwest corner of Ashumet Pond.

Ashumet Pond is an example of one of the many "kettle-hole" ponds on Cape Cod. The pond was formed by the intersection of the groundwater table with a kettle depression formed by a melting glacial ice block (K-V Associates, 1991). Water recharge into the pond predominantly comes from groundwater feed. Ashumet Pond has no noticeable surface outlet.

2.1.1 Meteorological Conditions

The climate in the Ashumet Valley region is considered to be humid continental that is modified by close proximity to the ocean. The mean annual rainfall is around 50 inches per year. Net precipitation (total rainfall minus evaporation and other losses) is around 20 inches per year. Occasional tropical storms intersecting the Cape may produce 24-hour rainfall events of five to six inches. During a normal year, rainfall is fairly evenly distributed among the months.

Prevailing winds are from the northwest in the winter months, and from the southwest during the remainder of the year. Wind velocities range from a mean value of nine miles per hour from July through September to an average of twelve miles per hour during the fall and winter months (ABB, 1995).

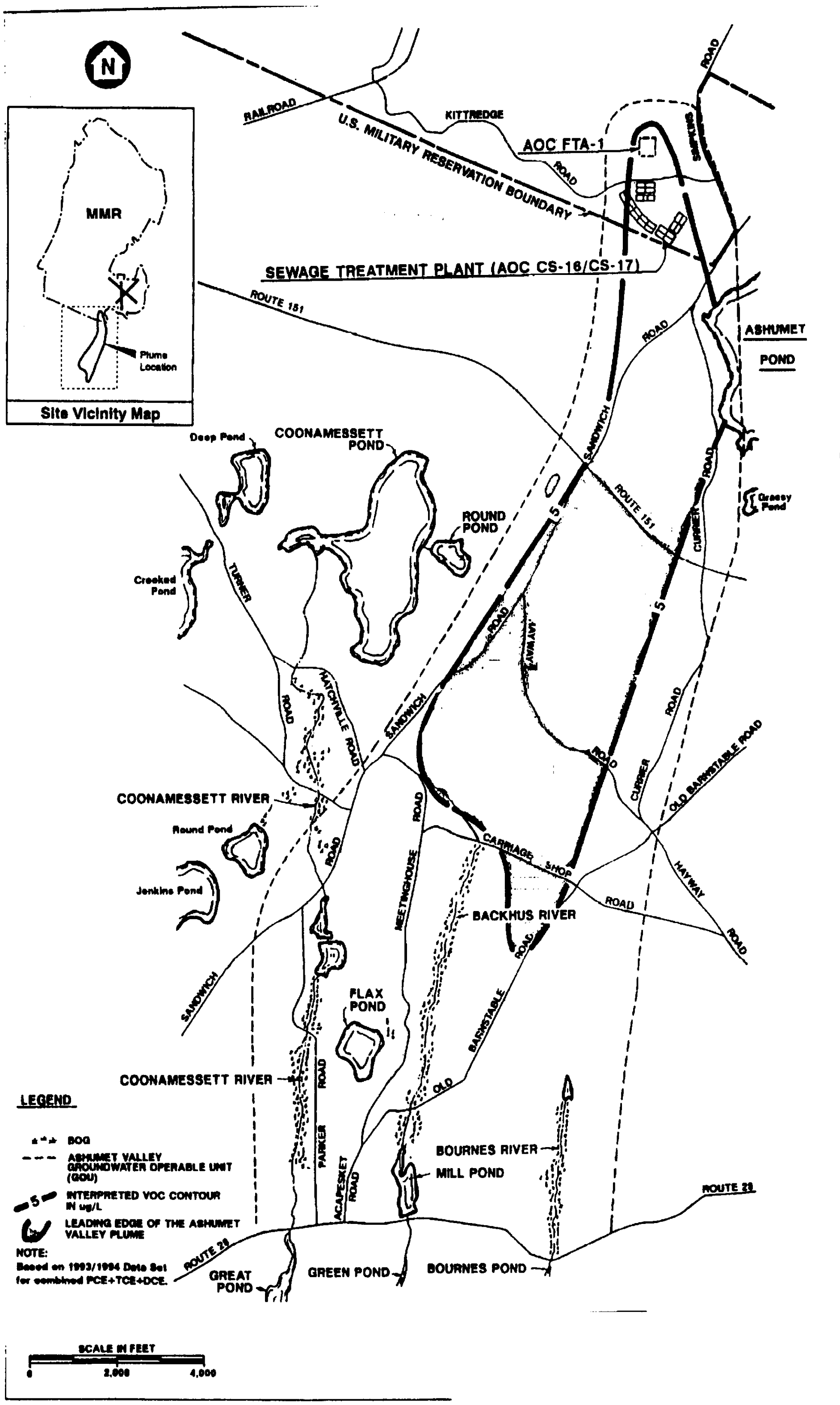


Figure 2-1. Ashumet Valley Plume Location Map (Adapted From ABB Environmental Services, Inc., 1995)

2.1.2 Geology

Ashumet Valley, located in what is known as Inner Cape Cod, was primarily formed by glacial deposits. These deposits are primarily composed of sands and gravels washed from three different glacial lobes during the Wisconsinan period, 7,000 to 85,000 years ago. A fan-shaped concave plain called the Mashpee Pitted Plain covers the Ashumet Valley. This outwash plain is formed mostly of gravelly sand and pebbly to cobbly gravel. A few boulders may also be found in the area.

Subsequent advancing and retreating of glaciers around the Cape led to the development of several kettle hole ponds. These were formed by ice that remained after glacier retreat and later melted. Ashumet Pond is one such kettle hole pond.

The ground surface elevation in the vicinity of Ashumet Pond ranges from 40 to 90 ft and averages at 70 ft above the mean sea level (msl). Soil profiles in the pond watershed show sandy topsoils with sandy loam to gravely sand underlain by sand or gravel. The topsoil, which extends roughly 2 to 4 ft below ground surface, is predominantly composed of Agawam and Enfield sandy loams. The Agawam soils are well-drained and are capped by a sandy loam. The appearance of gravel is common in the topsoil. The Enfield sandy loam is distinctly more crumbly and silty than the Agawam loam. Beneath the topsoil lies unconsolidated glacial sediments.

The glacial sedimentary deposits forming the Mashpee Pitted Plain can be divided into three types: the topset, foreset, and bottomset beds. The topset deposits are glaciofluvial sediments that consist of coarse sand and gravel. This layer extends roughly until 0 ft elevation (msl). The underlying foreset deposits are glaciolacustrine deposits that consist of medium to fine sand. This layer extends until an elevation of about -60 ft. Bottomset deposits beneath this layer down to an elevation of -150 ft are glaciolacustrine deposits of fine sand and silt.

Beneath the glacial deposits are lacustrine deposits of silty clay that sits on a crystalline bedrock that is predominantly grandiorite at an elevation of about -175 ft (Oldale, 1969). The bedrock elevation dips in a southeast direction towards Ashumet Pond.

2.1.3 Hydrogeology

The groundwater flow system of western Cape Cod is unconfined. Groundwater flows radially outward from a water table mound located to the north of the study area (see Figure 2-2). This water table mound has a maximum hydraulic head of about 70 ft above sea level. Groundwater flow in the study area is southward with water table elevations ranging from 44 to 55 ft above sea level. This flow occurs primarily in the topset and foreset beds (Walter et al., 1995).

Groundwater flow is predominantly horizontal with gradients in the range of 0.00147 to 0.00191 ft/ft (Walter, et al., 1995). However, strong vertical gradients of up to 0.0670 ft/ft (Walter, et al., 1995) exist near the pond shore indicating its recharge by groundwater feed.

Ashumet Pond is hydrologically well connected with the aquifer, and the pond is an expression of the local water table. Ashumet Pond has no significant surface inlet or outlet. The pond exhibits a flow-through condition in which groundwater discharges to the northern, or upgradient, part of the pond. This discharge occurs primarily along the pond shore, and pond water then recharges the aquifer from the southern or downgradient part of the pond.

Precipitation is the sole source of natural recharge to the aquifer. The Ashumet Valley groundwater eventually discharges to streams and coastal embayments.

2.1.4 Historical Ashumet Pond Uses

Ashumet Pond has two public landings, one in Falmouth and one in Mashpee. The Falmouth Landing lies on the western side of the pond and opens up to Fisherman's Cove (see Figure 2-3), while the Mashpee Landing lies on the northeast corner of the pond. Both landings provide access for residents to the beaches and for recreational activities such as swimming, power boating, sailboating, canoeing, and fishing.

Ashumet Pond is managed as a fisheries resource by the Massachusetts Division of Fisheries and Wildlife. Since the 1930's, the pond has been stocked with different species of fish. Because of heavy recreational use, the welfare of Ashumet Pond is a high priority for many of the year-round and seasonal residents of Cape Cod.

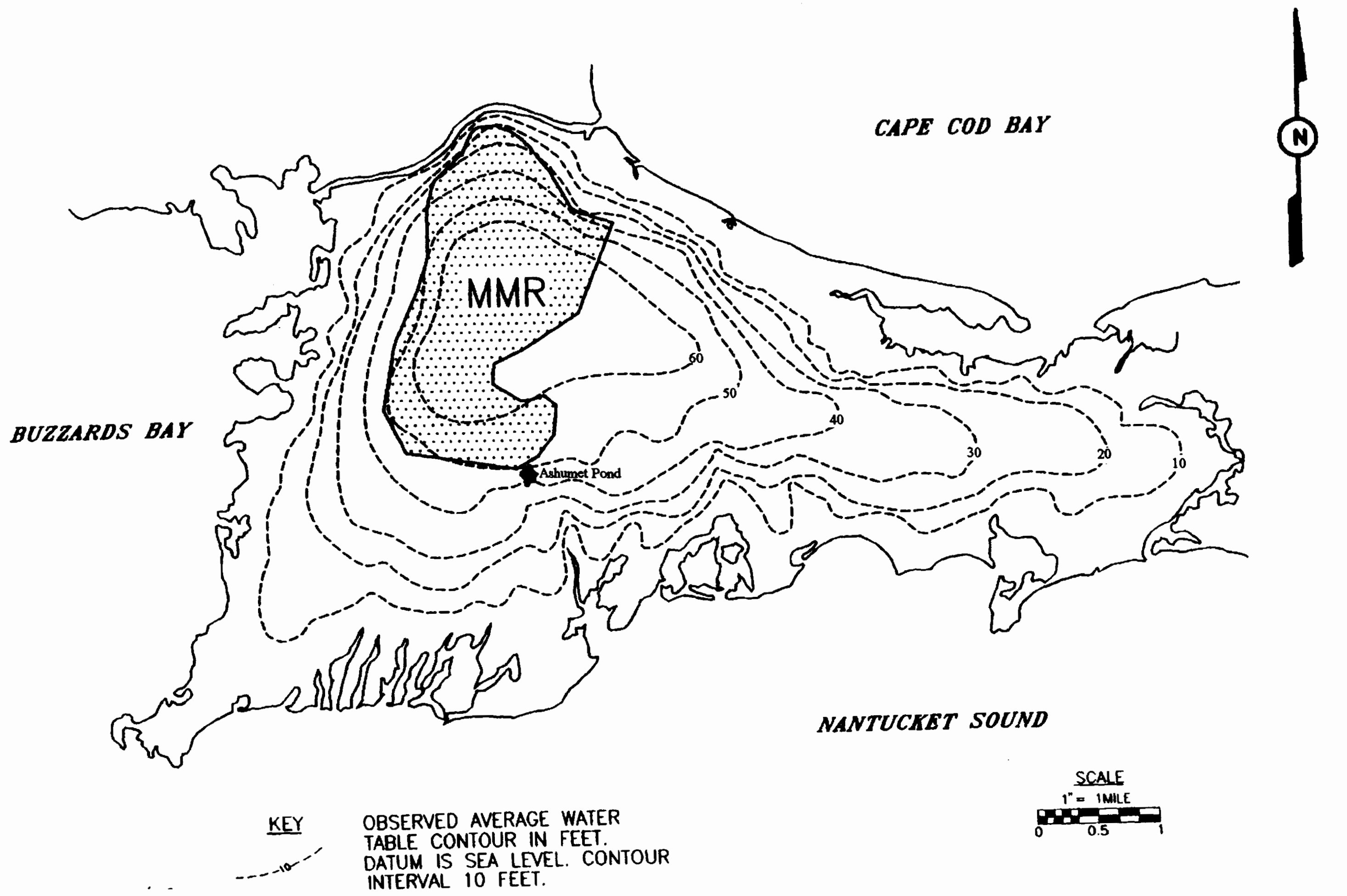


Figure 2-2. Groundwater Levels in Western Cape Cod (Adapted from CDM, 1995)

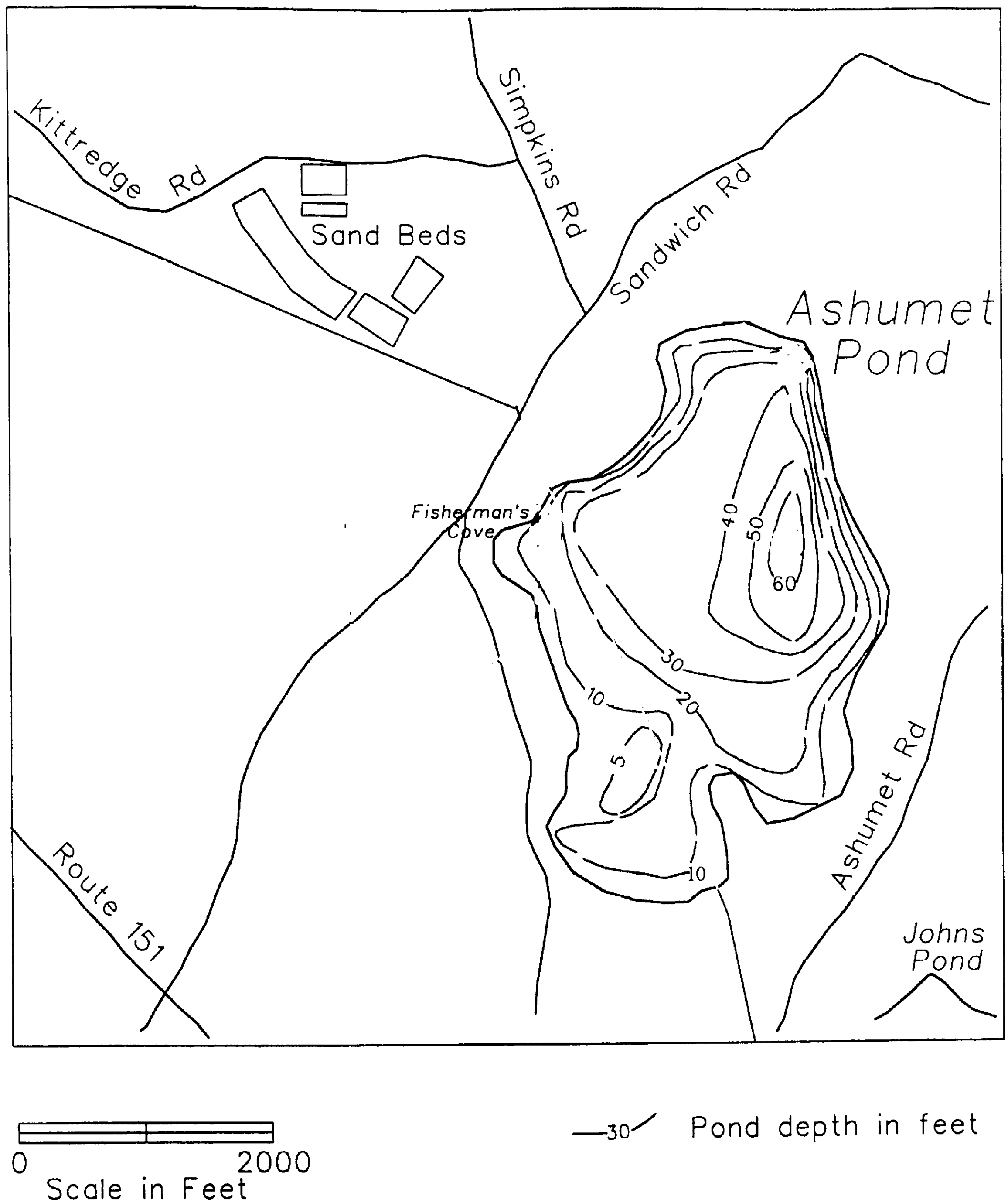


Figure 2-3. Bathymetric Map of Ashumet Pond (adapted from Shanahan, 1996)

2.2 Sources of Contamination

The Ashumet Valley area is one of the areas most affected by activities on the MMR. There have been two major sources of contamination to the Ashumet Valley Region. The first source is known as Fire Training Area Number 1 (FTA-1) (see Figure 2-1). Through the use of FTA-1 for military fire training activities, there is a plume emanating from this site that is composed of hydrocarbons from jet fuel, including benzene, toluene, ethylbenzene, and xylene (BTEX), and chlorinated organic compounds such as trichloroethylene (TCE) and perchloroethylene (PCE).

The second major source of contamination to Ashumet Valley is the MMR Sewage Treatment Plant, located approximately 1600 ft upgradient of Ashumet Pond (See Figure 2-1). Sewage disposal began at this site in the 1930's. Since that time it is estimated that nearly 10 billion gallons of wastewater have infiltrated to the groundwater that eventually flows towards Ashumet Pond. As a result of this sewage disposal, there is now a plume originating from the sewage disposal beds that contains high levels of dissolved solids, chloride, sodium, boron, detergents, and various forms of nitrogen and phosphorus. Chlorinated solvents, arsenic, and chloroform have also been detected in the wastewater plume at levels above maximum contaminant level (MCL) guidelines for drinking water published by the U.S. Environmental Protection Agency (USEPA). Groundwater samples taken at Fisherman's Cove on the western side of the pond (see Figure 2-3) reveal elevated concentrations of phosphorus and other sewage chemicals. This demonstrates that the sewage plume intercepts the groundwater flow discharging into Ashumet Pond.

2.2.1 Fire Training Area (FTA-1)

Former Fire Training Area 1 (FTA-1) is located 500 ft north of Kittredge Road near the southern boundary of the MMR (see Figure 2-1). It consists of a level, cleared area of approximately three acres of land that was used by the MMR fire department for fire training exercises from 1958 to 1985. The area was closed in November 1985 due to air emissions permitting difficulties.

Six to 16 fire training exercises per year were conducted in designated areas of FTA-1. Flammable waste liquids were burned and extinguished with water, foam, or dry chemicals. The residual mixture was allowed to infiltrate overnight and then burned off the next day to eliminate any remaining fire hazard. The materials burned include jet fuel, aviation gasoline, motor gasoline, diesel fuels, waste oils, solvents, paint thinners, transformer oils, and spent hydraulic fluids. Substances used to extinguish the fires include carbon dioxide, protein foam, aqueous film-forming foam, a bromine-based dry powder, and liquid chlorobromomethane.

Several previous investigations have been performed by ABB (1995), HAZWRAP (1995), and others to document site history and the nature and extent of contamination. These studies concluded that, although several chemicals impacted soils and groundwater downstream of FTA-1, the estimated risks are within or below the acceptable USEPA target Hazard Index.

2.2.2 Sewage Treatment Plant (STP)

The sewage treatment plant (STP) on the MMR was first built in 1936 to treat, on average, a capacity of 0.9 million gallons per day (mgd). In 1941, the plant was expanded to an average capacity of 3 mgd, with a peak capacity of 6 mgd (Shanahan, 1996). From 1941 to 1977, the sewage treated with the expanded plant was alternately disposed of in 20 half-acre sand infiltration beds. The 1941 design called for the operation of 8 beds (4 acres) at any given time, with occasional rotation of the beds. However, from 1977 to 1984 only the four infiltration beds nearest to Ashumet Pond (Figure 2-1) were used (LeBlanc, 1984b). In order to dispose of treated wastewater, the infiltration beds were flooded with wastewater, which then slowly percolated to the groundwater.

Following World War II, the number of troops stationed at the MMR decreased. Consequently, flow to the treatment plant decreased significantly as well. The average flow during the 1980s and 1990s was less than 0.3 mgd (Shanahan, 1996). As a result of the large amount of unused capacity, as well as the aging of the plant, the plant was decommissioned in December, 1995. A new, smaller plant was then brought online next to the location of the old plant, and use of the infiltration beds ceased.

The first recognition that groundwater has been and was being contaminated by the wastewater plume occurred in the 1970s. At that time, the Town of Falmouth closed a public water supply well located 9,000 ft downgradient of the wastewater treatment plant because water coming from the well was foaming. The foaming was determined to be a direct result of detergents that had entered the groundwater from the sewage infiltration beds. In 1977, the U.S. Geological Survey (USGS) conducted a study which showed that the plume of contaminated groundwater originating from the wastewater treatment plant extended more than 11,000 ft downgradient of the disposal beds and had a width of 2,500 to 3,500 ft (LeBlanc, 1984a). Currently, the Ashumet Valley plume (as defined by conservative constituents such as boron and sodium) extends more than 17,000 ft from the wastewater treatment plant (Walter et al., 1995).

3. PROBLEM STATEMENT

A significant portion of the Ashumet Valley plume, consisting of contaminants from FTA-1 and the STP, is intercepting Ashumet Pond as described above. Although ABB (1995) determined that contaminants from FTA-1 pose no significant risks (Section 2.2.1), there is still concern over the high discharge of phosphorus from STP into Ashumet Pond. About 2 milligrams per liter of phosphorus currently discharges into Ashumet Pond (Walter, et al., 1995). Walter et al. (1995) further propose that this phosphorus loading may cause the pond to be eutrophic. Eutrophication is believed to be the cause of at least two fish kills in the pond in July 1985 and June 1986 (E. C. Jordan Co., 1988; K. V. Associates, 1991). Risk of further detriment to Ashumet Pond exists if the inflow of phosphorus is not stopped or decreased. Previous studies suggest that one remedial approach is the development of plume diversion strategies (Shanahan, 1996) to protect Ashumet pond. The underlying principle of this containment approach is to cut off the plume from the groundwater recharging the pond.

The use of physical barriers is being proposed in this study to prevent pond recharge of deleterious chemicals, particularly phosphorus. Physical barriers are flow restrictive. Their low permeability characteristics enable them to retard flow. It should be noted though that accumulated water that builds up at barriers eventually moves along the boundary in a lateral motion. The presence of barriers only slows flow and diverts it downgradient. Although use of barriers is not a remediation technique in itself, physical barriers may be used as hydraulic controls to redirect the plume to a location where either it can be remediated or its deleterious effects are less serious.

The main focus of this study is to investigate the ability of using barrier walls as containment options for the protection of Ashumet Pond. The capability of the barriers in eliminating or reducing high phosphorus loading into the pond is tested. A groundwater model is developed to predict the change in behavior of groundwater flow with the presence of a physical barrier in the subsurface.

4. PHYSICAL BARRIERS

There are several types of physical barriers being used by industry for containment. The following discussion of the various types of physical barriers is abstracted from Rumer and Ryan (1995). The methods are considered as design alternatives for dealing with the Ashumet Pond contamination problem. Issues on constructability and costs need to be addressed when choosing among the methods.

4.1 Slurry Walls

Slurry walls are among the most common barriers used for plume containment. There are two basic material types for slurry wall construction: Soil-Bentonite and Cement-Bentonite. In both cases, a trench is excavated bordering the plume of concern. The construction process involved in slurry walls is diagrammed in Figure 4-1. This process is detailed in the following sections 4.1.1 and 4.1.2.

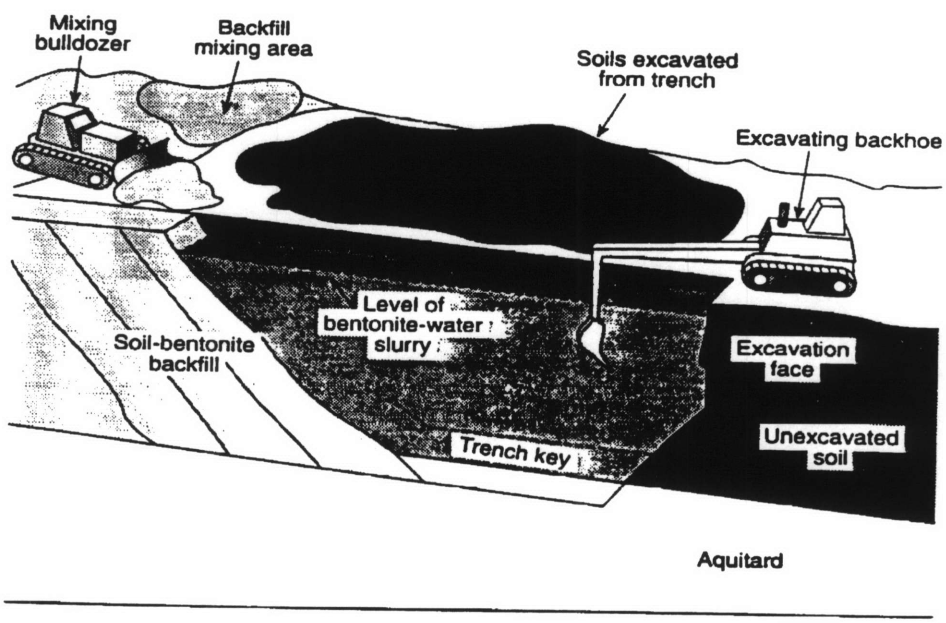


Figure 4-1. Slurry Wall Construction (from Rumer & Ryan, 1995)

4.1.1 Soil-Bentonite Slurry Walls

Excavating equipment in the form of backhoes, clamshells, or grabs are used to dig the trench where the slurry wall will be placed. During excavation, a bentonite water mixture of 3-5% bentonite by weight is used to fill the trench to prevent trench collapse. This gel like mixture infiltrates the trench walls and forms a residual cake. This cake serves as a membrane that prevents further infiltration of the bentonite mixture. Wet excavation proceeds until the desired depth is reached. Excavated soil is then mixed with more bentonite to form a slurry. The bentonite- water mixture is displaced as the bentonite-soil slurry is backfilled into the trench. The bentonite water mixture can then be reused as the construction proceeds longitudinally. Once the slurry materials solidify, they reach low permeabilities of 10^{-6} to 10^{-8} cm/sec.

4.1.2 Cement-Bentonite Slurry Walls

A cement-bentonite wall is constructed in a similar manner to the soil-bentonite wall. The two differences in the construction method for the cement bentonite wall are that cement is added to the bentonite water mixture being used for trench stabilization and no future backfilling is needed. With cement in the mixture, a wall is formed as the gel hardens to form the final wall structure. Once the material solidifies, a low permeability of 10^{-5} to 10^{-6} cm/sec is reached. Ex-situ mixing of soil-bentonite and backfilling is omitted in this procedure. This results in faster construction. However, additional cost results due to the need for disposal of the excavated soil. Special disposal requirements will be required if the excavated soil is contaminated.

4.2 Deep Soil Mixing

Another method used in constructing barrier walls, which is popular in Japan, is deep soil mixing. Deep soil mixing requires a very specialized rig. After special auger mixing shafts are rotated into the ground, bentonite (often with cement) is added to the mixed soil in the form of a slurry. The resulting wall is typically 20 to 36 inches thick. The main advantage in using this type of system compared to slurry walls is the elimination of the above ground mixing process or removal of excavated soil. Deep soil mixed walls approach a hydraulic conductivity of 10^{-7} cm/s.

4.3 Metal Sheet Piles

Interlocking metal sheet piles are often used as physical barriers. Sheet piling is driven into the ground to the level desired. One disadvantage of sheet piles is that driving into the ground becomes difficult in high strength soils. Another disadvantage is that the piles are permeable at the interlocking between sheets. Sealants are therefore required to make these interlocking boundaries impermeable.

A steel sheet pile barrier wall was used to contain contaminated soil and groundwater at the Southern Maryland Wood Treatment Plant Site (Johnson, 1996). This method was chosen over a slurry wall because of site-specific characteristics pertaining to structural integrity, chemical compatibility, and property access constraints. With the use of a high-solids bentonite grout as a joint sealant, the wall exhibited lower permeability than a conventional slurry wall.

4.4 Grout Injection

Another way to create physical boundaries is through the use of pressurized injection of grout into the soil. The grout is composed of cementitious materials that set in the ground. The method of installation is through injection of the grout into staggered holes that form a two or three-row grid pattern. The grout solidifies in the interstitial pores of the soil and therefore reduces its porosity. This decrease produces a reduction in permeability. Experience is required when choosing the type of grout, injection rates and spacing of holes in order to create an impermeable barrier.

5. DESIGN CONSIDERATIONS AND METHODOLOGY FOR ASHUMET POND

5.1 Approach

Plume containment can be achieved through several techniques that make use of groundwater hydraulic control. For example, a well-head pump and treat system can be used to generate a capture zone for contaminated groundwater. Such a system is currently being used at the MMR to prevent the advance of the Chemical Spill 4 (CS-4) plume. One disadvantage of pump and treat systems is that they often have high operation and maintenance costs due to power generation and carbon filter replacements.

An alternative to conventional pump and treat systems is the use of physical barriers installed in the subsurface. These barriers are comprised of low permeability vertical cut off walls that divert or block the movement of contaminants. Low permeability walls have regularly been used in construction to reduce unwanted seepage. Vertical cut off wall enclosures have also been successfully used to contain point sources of contamination. Such walls are most effective for blocking flow when they are keyed into relatively impermeable boundaries such as clay layers or bedrock. This alternative can be less costly than pump and treat systems due to the elimination of power requirements. However, if the wall is not properly oriented or sufficiently deep, unrestricted lateral or vertical flow of water may occur and thus defeat the barrier's intended purpose.

This study investigates the feasibility of installing a barrier wall to protect Ashumet Pond from excessive infiltration of phosphorus due to the STP plume. The type of vertical cut-off wall being considered is a wall system meant to control groundwater hydraulics. Another option, but one that will not be discussed in this thesis, is a reactive wall system that allows flow but actively degrades the contaminants.

The main focus of this chapter is to describe the influence of a low permeability wall system on the flow fields affecting Ashumet Pond. Flow field effects are the most critical issue in the design of containment systems. An assessment of the predicted performance of this barrier can be obtained only through groundwater modeling.

Due to the large depth of about 220 to 245 ft to low permeability cohesive soil layers and bedrock in the aquifer (see Section 2.1.2), vertical keying of the wall may be a problem at the site. A three-dimensional (3-D) model incorporating anisotropic differences in the hydraulic conductivities is required to represent existing and modified aquifer conditions. This model, if properly executed, should give a reasonable estimate of the optimum wall dimensions needed to divert the plume away from the pond. Such a model is described in detail in Chapter 6.

5.2 Phosphorus Limit

According to Walter et al. (1995) ambient phosphorus concentrations in the aquifer measured outside the plume are typically less than 0.05 mg/L. Figure 5-1 shows the areal distribution of the phosphorus plume and the location of the STP disposal beds. A significant concentration of about 6.2 mg/L was measured about 1350 ft downgradient of the beds. The area of very high phosphorus concentrations (more than 3 mg/l) extends 1,150 ft long and 450 ft wide and is about 750 ft upgradient of Ashumet Pond. The vertical extent of the plume is illustrated in Figure 5-2 where section A-A' is a longitudinal cross section along the plume, B-B' is a transverse cross-section of the plume 750 ft upgradient the pond, and C-C' is a transverse cross-section of the plume at the edge of the pond.

The plume center is indicated in section B-B' at -5 ft elevation. Phosphorus concentrations of greater than 0.1 mg/l at this section extend vertically from 40 ft to -60 ft. Section C-C' just at the pond entrance indicates a plume center at around 15 ft elevation. Phosphorus concentrations of greater than 0.1 mg/l at the pond entrance extends vertically from 30 ft to -60 ft.

The design criteria being selected in this thesis is reduction in phosphorus loading from the STP plume to 0.1 mg/l. It is assumed that this load will not produce significant eutrophic impacts in Ashumet Pond. Therefore, the phosphorus plume that needs to be blocked just at the pond entrance extends from 30 ft to -60 ft along the pond. Figure 5-1 indicates that the width of interception is about 800 ft starting from Fisherman's Cove.

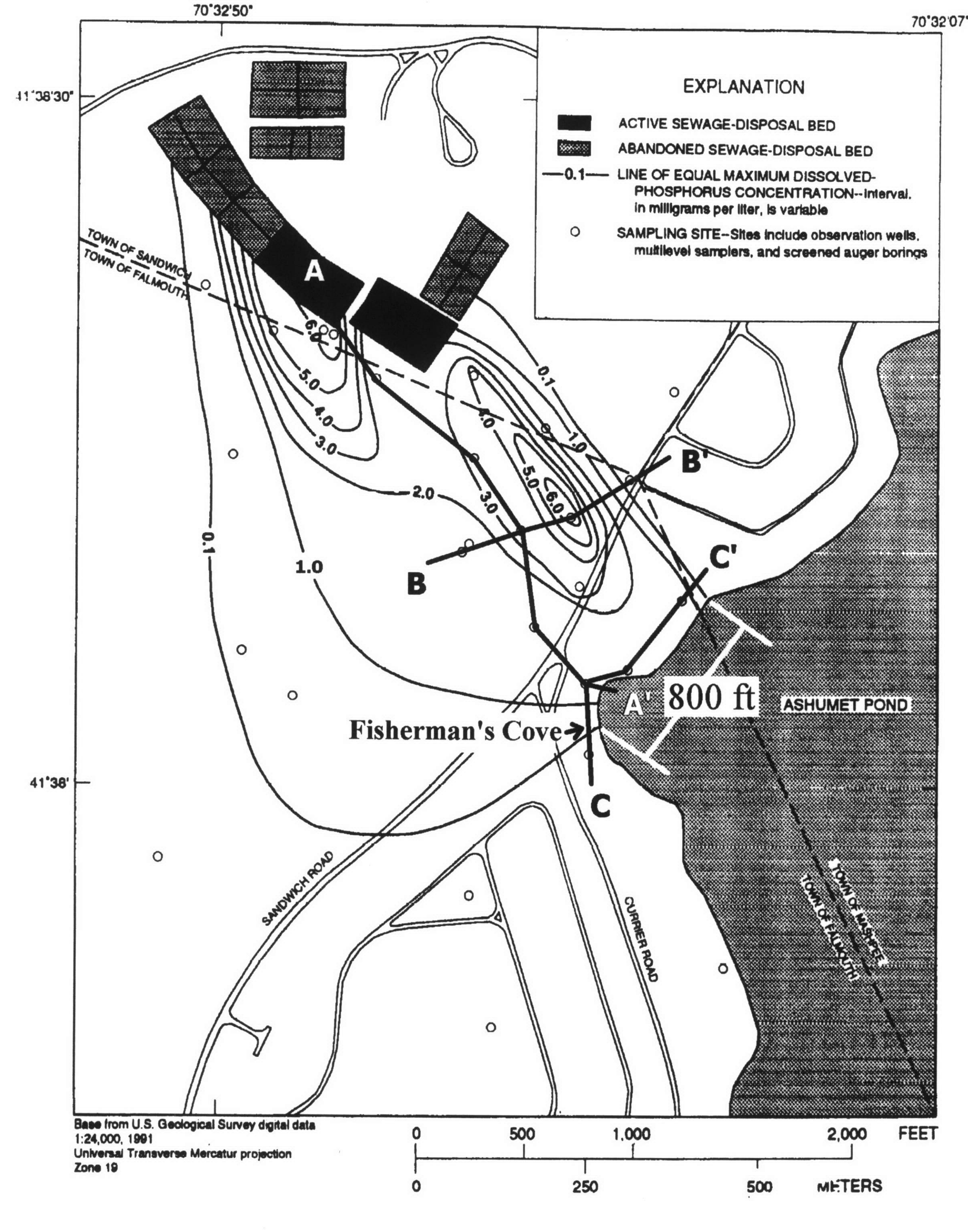


Figure 5-1. Areal Distribution of Maximum Dissolved Phosphorus Concentrations in Groundwater near Ashumet Pond, Massachusetts, August to November 1993 (adapted from Walter et al., 1995)

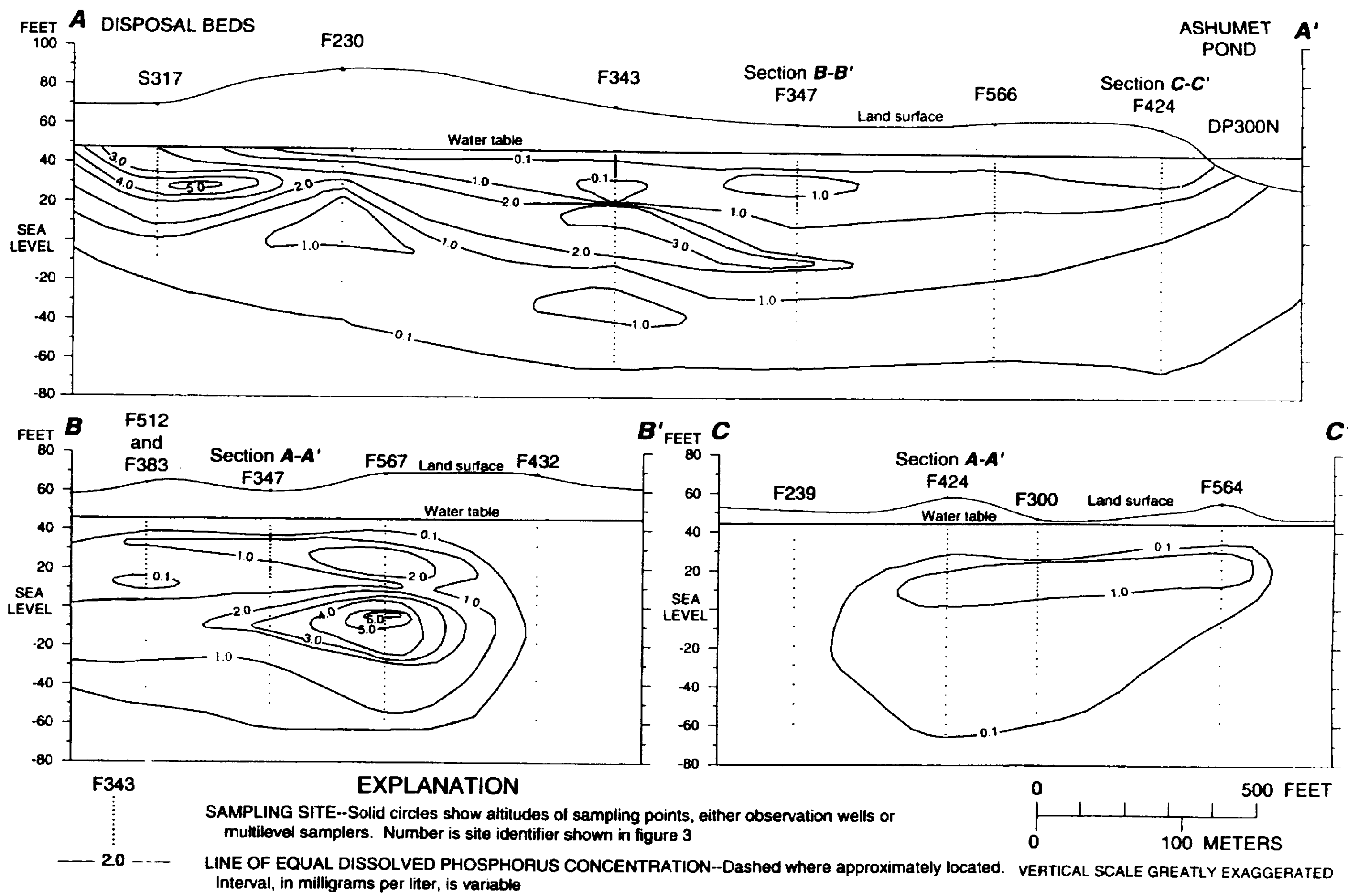


Figure 5-2. Vertical Distribution of Dissolved Phosphorus Concentrations in Groundwater Along Geochemical Sections A-A', B-B', and C-C' (key in Figure 5-1) near Ashumet Pond, Massachusetts, August through November, 1993 (Walter et al., 1995)

5.3 Wall Requirements

The wall should be oriented in such a way as to block flow of contaminated groundwater from the STP source area. The trial wall depth to be tested in this thesis is selected based of the following points:

1. It may be unreasonable to install a wall that is 220 ft deep in order to reach the impermeable silty clay layer at elevation -150 ft. Therefore the wall being studied will have a shallower depth.
2. It is stated in Section 2.1.3 that the groundwater flow occurs primarily in the topset and foreset beds. If the wall is selected to block most of the groundwater flow, it should reach the bottomset beds of glaciolacustrine fine sand and silt at elevation -60 ft (see Section 2.1.2).
3. Section 5.2 states the phosphorus plume extends to an elevation of -60 ft. A wall reaching -60 ft is needed to block this plume.
4. The wall requires embedment (penetration) into a layer of significantly lower hydraulic conductivity, such as the bottomset bed , at elevation -60 ft, in order to reduce flow under the wall.

Hence a 190 ft deep wall extending to elevation -110 ft is selected for analysis.

5.4 Design Methodology

Two groundwater models have been created using a mathematical 3-D ground-water flow computer program. These models are used to provide quantitative predictions of how groundwater flow behaves upstream of Ashumet Pond. The first model is used as a benchmark to simulate current aquifer flow conditions. It is compared to the second model, which simulates aquifer flow conditions when a wall is introduced. Both models assume steady-state conditions.

Site characterization is needed to obtain the relevant data required in generating a groundwater model. The inputs needed are water table elevations and site stratigraphy with soil hydraulic conductivity. These data will be obtained from the results of investi-gations conducted by LeBlanc (1984a) and E.C. Jordan (1988b).

Known water elevation heads are important in setting the boundary conditions of the model. Water table elevations will be obtained from contours generated by the USGS using measurements from monitoring wells (LeBlanc, 1984a). Another important parameter for the model is stratigraphic information that shows the layering of the aquifer. The hydraulic conductivities of each layer are also needed for generation of the flow field. Stratigraphy and hydraulic conductivities of the layers are obtained from Galloni (1997) who performed groundwater modeling studies on MMR.

Two computer programs are used in this study: DYNFLOW and DYNTRACK. Both programs were developed by Camp Dresser & McKee (1995). DYNFLOW is used to generate head contours in the model based on specified boundary conditions. DYNFLOW, however, does not generate flow paths. DYNTRACK, a companion mass transport program to DYNFLOW, is used to generate the flow paths.

DYNFLOW employs linear finite elements to solve aquifer flow equations. Head contours are generated from this program with the use of appropriate boundary conditions. Measured head boundaries from LeBlanc (1984a) are used to develop a base case condition absent of barriers. The model will then be modified to incorporate a wall in the path of the groundwater recharging Ashumet Pond. A new flow field will be generated with this modification. The efficiency of the wall will then be evaluated by comparing both steady state (equilibrium) flow fields.

The governing three-dimensional groundwater flow equation in its generalized form as used by these models is (Bear, 1972)

$$S_s \frac{\partial H}{\partial t} = \frac{\partial}{\partial x}\left(K_x \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial H}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial H}{\partial z}\right) \qquad (5.1)$$

where H represents the total head; K_x, K_y, and K_z represent the hydraulic conductivity in the principal orthogonal coordinate directions; S_s is the specific storativity; and t is time. The specific storativity is a coefficient that indicates the aquifer response time to changes in head under transient conditions. For steady-state conditions, the change in head with respect to time is zero (Equation 5.2).

$$\frac{\partial H}{\partial t} = 0 \qquad (5.2)$$

Plugging Equation 5.2 into Equation 5.1 leads to:

$$0 = \frac{\partial}{\partial x}\left(K_x \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial H}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial H}{\partial z}\right) \tag{5.3}$$

The finite element method is used by DYNFLOW to simultaneously solve the groundwater flow equation for each element in the system. The solution leads to the development of head contours.

DYNTRACK is used to produce flow lines based on the heads generated through the generalized Darcy equation:

$$\vec{q} = \left[\overline{\overline{K}}\, \nabla H\right] \tag{5.4}$$

where $\nabla = \frac{\partial}{\partial x}\hat{i} + \frac{\partial}{\partial y}\hat{j} + \frac{\partial}{\partial z}\hat{k}$,q is flow and $\hat{i}, \hat{j}$ *and* $\hat{k}$ are the gradients in orthogonal directions.

Two types of boundary conditions are used to define the system. The first is a boundary of specified head called a Dirichlet boundary condition. This condition may be specified in the model using known elevation heads of the water table, since the aquifer is unconfined. The second type of boundary condition is a boundary of specified flux called a Neumann boundary condition. The Neumann boundary conditions used in this model denote no flow or zero flux boundaries. These no flow boundaries will be defined by flow lines generated from earlier studies (E. C. Jordan Co., 1988b).

Upon selection of the appropriate wall length and depth, a contaminant breakthrough analysis can be performed to determine the wall thickness required. This analysis accounts for the retardation mechanisms associated with phosphorus in the barrier wall. These mechanisms are highly dependent on the partitioning and sorption capacity of the wall system. For earthen barriers, it is common practice to choose partitioning coefficients similar to those of the soil that is being used for the wall material. Once this analysis is performed, a breakthrough curve as a function of design life and thickness can be generated. This analysis is performed in Chapter 7.

6. MODEL SIMULATIONS

6.1 Model Generation

Two groundwater models have been created with DYNFLOW (see Chapter 5). The first model is used as a benchmark to simulate current aquifer flow conditions. It is compared to the second model, which simulates aquifer flow conditions when a wall is introduced. The boundary conditions that will be used for both models is based on the current flow patterns presented by E. C. Jordan Co., (see Figure 6-1)

The grid generated for the model is shown in Figure 6-2.

1) Flow lines represented by line 1-3 and line 2-5 are no flux boundaries described by the Neumann boundary condition.
2) Lines 1-2, 3-4, and 4-5 represents points of known heads as described by the Dirichlet boundary condition.
3) Line 1-2 has a specified head condition of 53.5 ft.
4) Lines 3-4 and 4-5 both have a specified head condition of 44.5 ft.

The locations of FTA-1 and STP are also shown in the figure. The difference in hydraulic head between lines 1-2 and 3-4-5 shows flow in a southern direction.

The phosphorus plume extent, as shown in Figure 5-1, indicates that the plume intercepts Ashumet Pond on its northwestern side. Figure 6-2 shows the location selected for evaluation of barrier walls.

The baseline model (i.e., without the wall) in DYNFLOW shows the present flow characteristics. Placing the wall directly upstream of the pond, where contaminant infiltration occurs, should generate a recharge zone free of contamination, or a zone with reduced contaminant concentrations in the second model (i.e., with the wall). Line W-W' represents the location of the wall.

Stratigraphic information was incorporated in the DYNFLOW models through the interpolation of stratigraphic data used by Susanna Galloni (1997) in her study of regional flow in western Cape Cod. Most of this stratigraphic data comes from USGS reports (Masterson, 1996). The information gathered by Galloni (1997) is summarized in Table

6-1, which shows layer properties arranged by increasing depths. The depositional origin of the sediments and resulting stratigraphy came from Masterson (1996).

Table 6-1. Depositional Origin, Stratigraphy, and Hydraulic Conductivity of Sedimentary Facies used in Depositional Model of Western Cape Cod. (Adapted from Masterson, 1996 and Galloni, 1997)

Layer No.	Sedimentary Facies	Depositional Origin	Stratigraphy	K_H (ft/day)	K_H:K_V	K_V (ft/day)
1	Topset Bed	Glacio-fluvial	Sand; coarse to fine gravel	230	3:1	77
2	Topset Bed	Glacio-fluvial	Gravel, sand, medium to fine	185	3:1	62
3	Foreset Bed	Glacio-lacustrine	Sand, medium to fine, some silt	140	5:1	28
4	Bottomset Bed	Glacio-lacustrine	Sand, fine; Silt	70	30:1	2.3
5	Lake-Bottom Bed	Lacustrine	Silty Clay	10	100:1	0.1

The three distinct glacial sedimentary layers described in Section 2.1.2 were glaciofluvial topset beds, glaciolacustrine foreset beds, and glaciolacustrine bottomset beds. The lacustrine silty clay layer is also shown in the table. The table also shows the horizontal hydraulic conductivities of each layer and its ratio to the vertical conductivities. The ratio of the horizontal to the vertical hydraulic conductivities indicates the anisotropy of the layer.

Figure 6-3 shows the resulting aquifer layers used in the model. The left side of the figure represents the upgradient side of the model study area, while the right side of the figure represents the pond's recharge side.

Particle tracking is used in the model to generate flow lines. These lines show the paths being followed by particles under advection. Through the use of DYNTRACK (Camp Dresser and McKee, 1996), a number of particles were introduced in the model at the upgradient boundary at horizontal intervals of 140 ft. The particles are located at depth intervals of 25 ft starting at an elevation just beneath the water table (El. 50 ft) and extending down to El. -100 ft.

6.2 Trial Wall Sections

The horizontal lengths of the walls studied are 1500 ft and 2000 ft. These lengths are shown in Figure 6-4. The walls were oriented in a direction of N50°W for the simulations. The stratigraphic information suggests the wall should be placed to at least reach the glaciolacustrine fine sand and silt layer number 4 at an elevation of -60 ft where the hydraulic conductivity abruptly decreases. The horizontal hydraulic conductivity in this layer is half of layer number 4. More significantly, this layer exhibits a twelve fold reduction in vertical hydraulic conductivity compared to the overlaying layer. The wall tested extends to an elevation of -110 ft to allow for 50 ft of embedment into the glaciolacustrine fine sand and silt layer. The total wall depth tested is therefore around 190 ft. The depth of the wall is shown in Figure 6-5.

Common barrier wall permeabilities are in the range of 10^{-6} to 10^{-8} cm/sec (Rumer and Ryan, 1995). Therefore an average value of 10^{-7} cm/sec or 3 x 10^{-4} ft/day is chosen for use in this model.

6.3 Baseline Model

The baseline model produced from DYNFLOW gives the head contours shown in Figure 6-6a. These head contours indicate piezometric heads at zero ft elevation (msl). They closely approximate the water table elevations in Figure 6-1. Flow proceeds in a southern and southwestern direction as shown by the head contours. The cross-section shown on Figure 6-6b further illustrates the present head contours. The last head contour at the right side of the figure shows upward seepage at the pond edge.

Flow lines intercepting the pond were determined with the use of the DYNTRACK particle tracking program. These are shown in Figures 6-7a-g. Note that the elevations in these figures refer to the initial elevations of the flow lines at the constant head 1-2 boundary (e.g., in Figure 6-2). Contaminated flow paths 16, 17 & 18 cross both the location of STP and the pond. These flow lines recharge the pond on its upstream side at a width of about 800 ft starting from Fisherman's Cove. Figure 5-1 shows that 800 ft is the plume width that intercepts Ashumet Pond. The wall used in this study is designed to block these flow lines.

6.4 Flow Field Induced by the Introduction of the Wall

With the introduction of the wall, water build up on the upgradient side causes the flow to move laterally away from the pond. A 1500 ft wide wall is used in the first model simulation. Figures 6-8a-g show the head contours and the path of flow lines 16, 17 & 18. Flow lines 16, 17, and 18 are contained within the wall's boundaries and are deflected to a southwestern direction at elevations -50 ft and above. Figure 6-8f and Figure 6-8g show that flow line 18 at initial elevations of -75 ft and -100 ft dives under the wall and eventually reach the pond. Figures 6-9a-g present similar information for a 2000 ft long wall. The behavior of these flow lines is summarized in Table 6-2

Table 6-2. Contaminant Transport With the Walls Installed

Wall Width	1500 ft			2000 ft		
Flow Line	16	17	18	16	17	18
50 ft	X	X	X	X	X	X
25 ft	X	X	X	X	X	X
0 ft	X	X	X	X	X	X
-25 ft	X	X	X	X	X	X
-50 ft	X	X	X	X	X	X
-75 ft	X	X	O	X	X	O
-100 ft	X	X	O	X	X	O

Legend: X - Flow Diverted O - Flow Reaching the Pond

Simulations for the 1500 ft wall and the 2000 ft wall showed similar containment capacities. The 1500 ft wall is already capable of diverting flow lines 16, 17, and 18 at elevations of -50 ft and above. It may also be possible that a smaller wall length could have been used in order the block these flow paths.

6.5 Evaluation of Wall Efficiency

The phosphorus plume at the pond entrance based on Section 5.2 extends from 30 ft to -60 ft. Simulations on the 1500 ft wall show that flow lines 16, 17, & 18 are diverted at elevations of -50 ft and above (see Section 6.4). However, flow line 18 is not contained at elevations -75 ft and -100. The fully effective containment depth is then from elevation 50 ft to somewhere between -50 ft and -75 ft. But for all practical purposes, a wall 1500 ft wide reaching a depth of -110 ft is capable of diverting the phosphorus plume emanating from the STP.

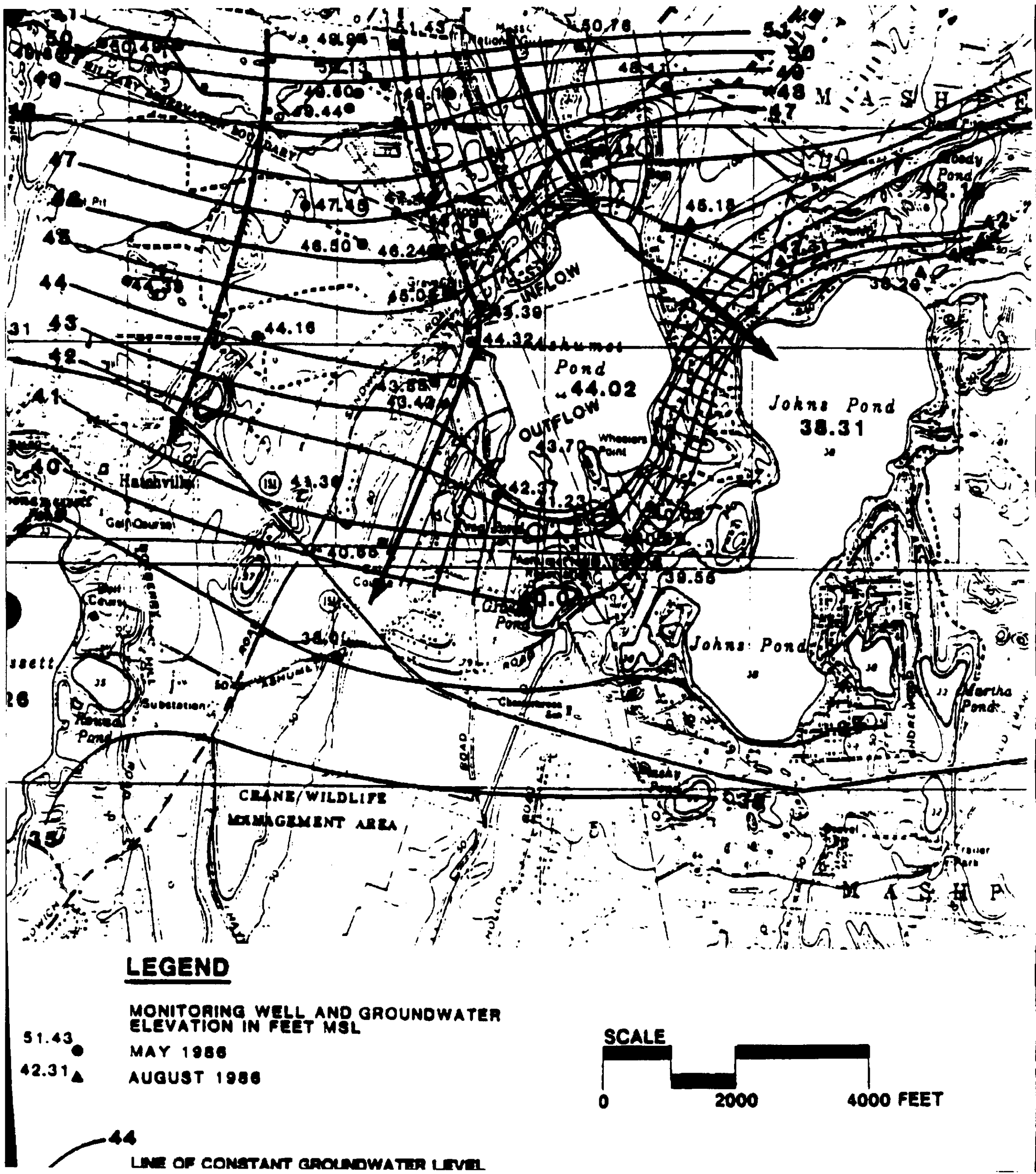


Figure 6-1. Water Table Elevations and Flow Lines in the Vicinity of Ashumet Pond (E. C. Jordan Co., 1988b)

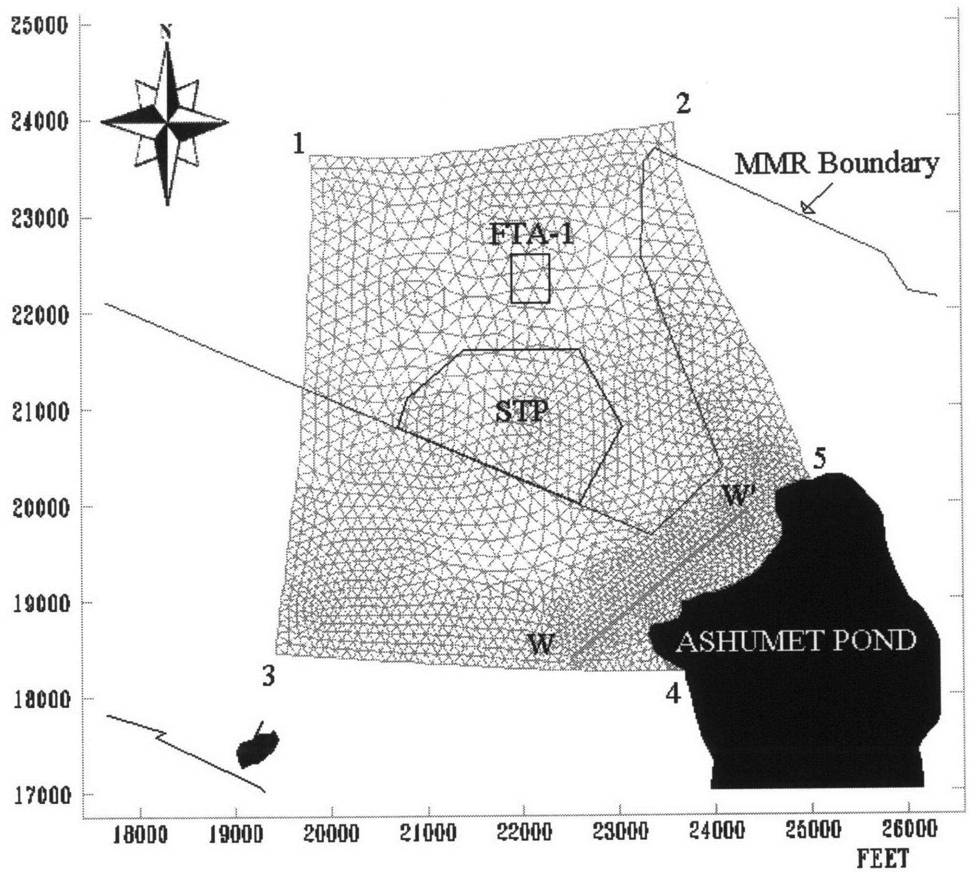
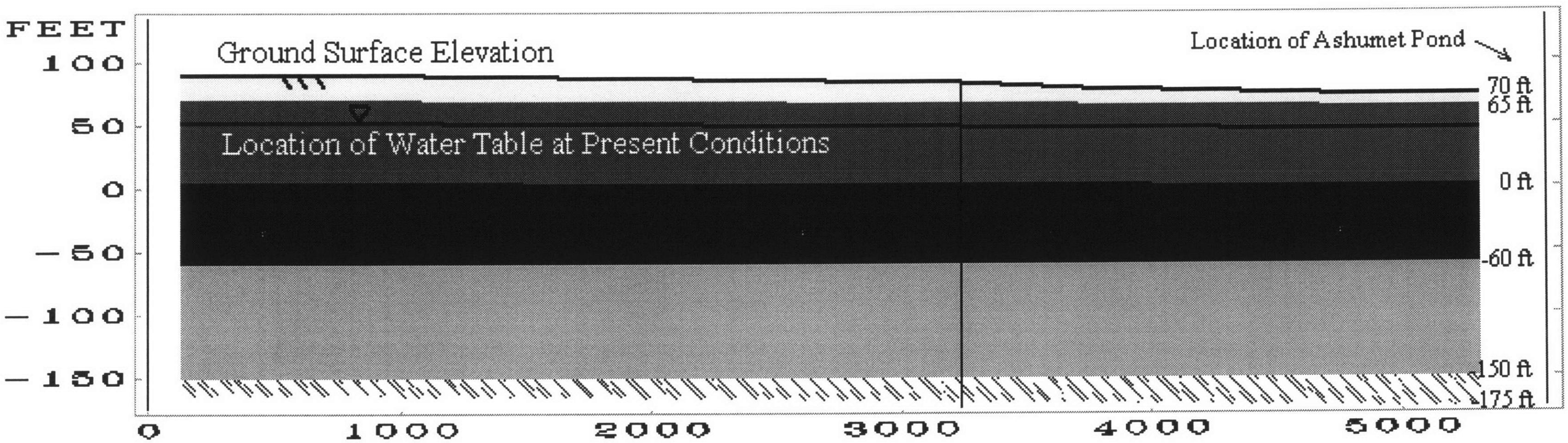


Figure 6-2. Groundwater Model Grid used in DYNFLOW (Shown With Cut-Off Wall)



MATERIALS CROSS-SECTION AA

Layer No.	Elevation	Description	Kh (ft/day)	Kh:Kv	Kv (ft/day)
Layer 1	70 ft to 65 ft	Coarse to Fine Gravel; Sand	230	3:1	77
Layer 2	65 ft to 0 ft	Gravel; Sand, Medium to Fine	185	3:1	62
Layer 3	0 ft to -60 ft	Sand, Medium to Fine; Some Silt	140	5:1	28
Layer 4	-60 ft to -150 ft	Sand, Fine; Silt	70	30:1	2.3
Layer 5	-150 to -175 ft	Silty Clay	10	100:1	0.1

CROSS SECTION AA

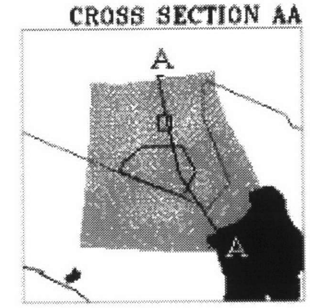
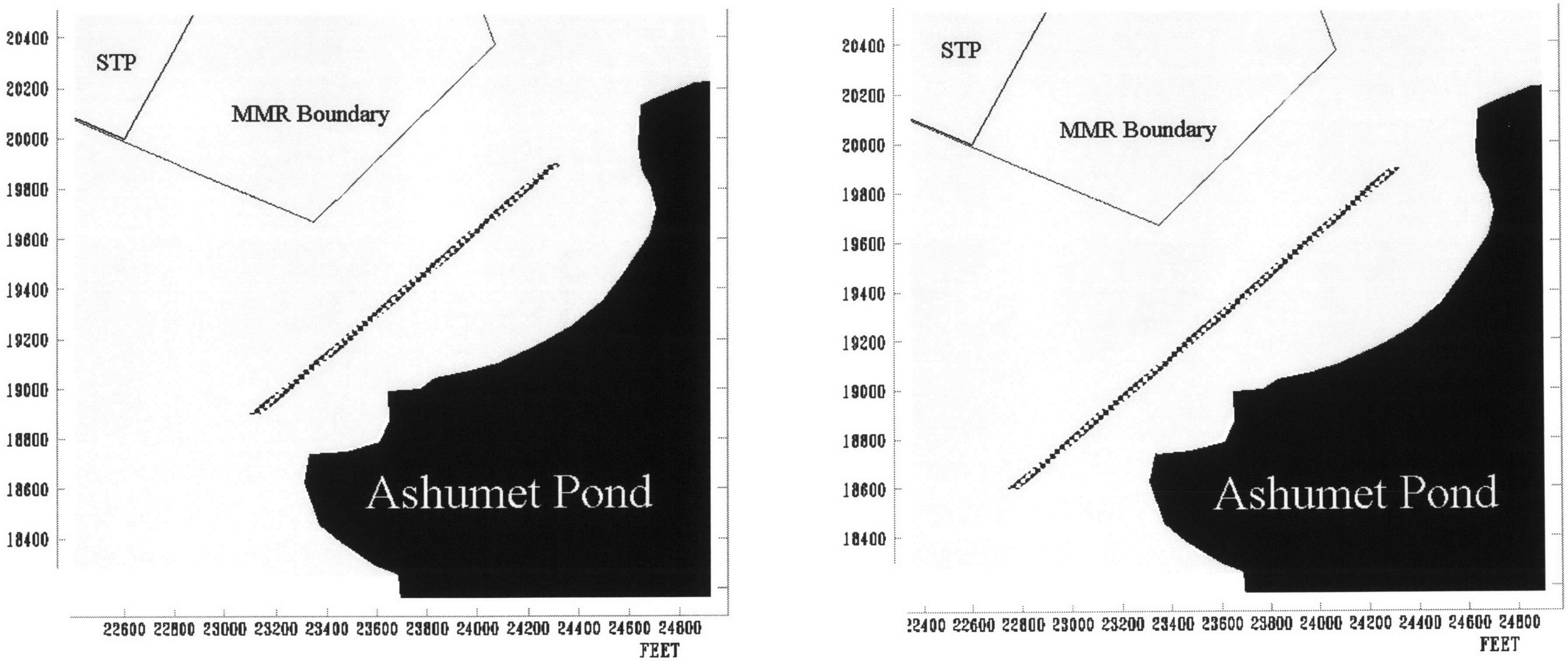


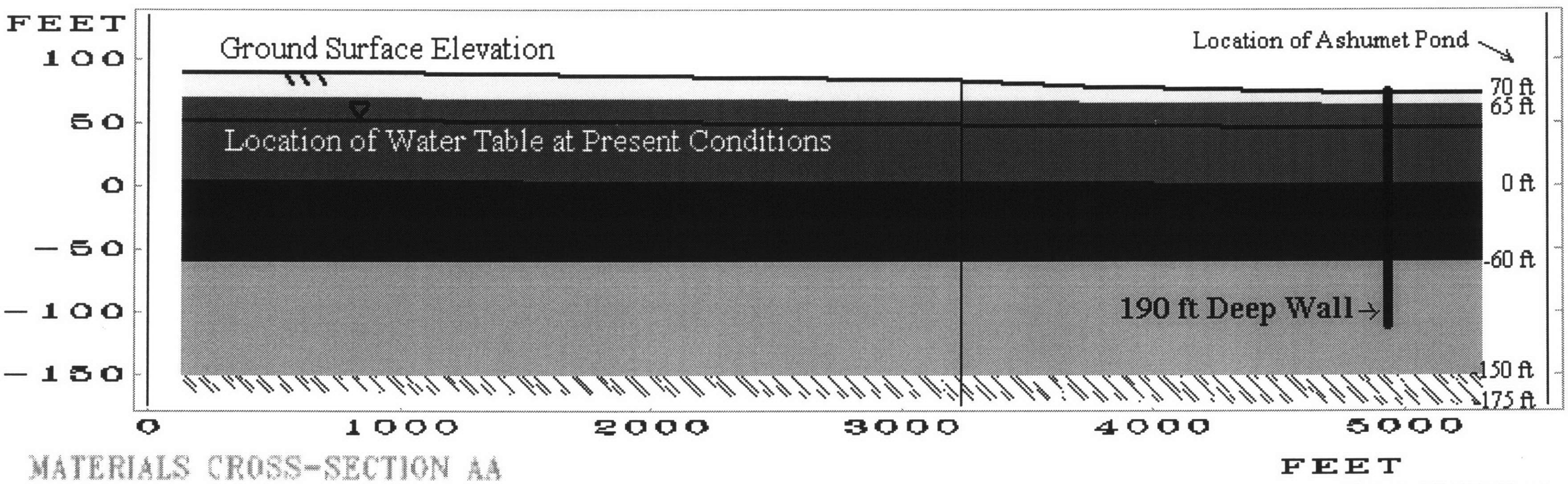
Figure 6-3. Stratigraphic Layering Along Centerline A-A of DYNFLOW Model



1500 ft Barrier

2000 ft Barrier

Figure 6-4. Plan View of 1500 ft and 2000 ft Long Walls



MATERIALS CROSS-SECTION AA

Layer No.	Elevation	Description	Kh (ft/day)	Kh:Kv	Kv (ft/day)
Layer 1	70 ft to 65 ft	Coarse to Fine Gravel; Sand	230	3:1	77
Layer 2	65 ft to 0 ft	Gravel; Sand, Medium to Fine	185	3:1	62
Layer 3	0 ft to -60 ft	Sand, Medium to Fine; Some Silt	140	5:1	28
Layer 4	-60 ft to -150 ft	Sand, Fine; Silt	70	30:1	2.3
Layer 5	-150 to -175 ft	Silty Clay	10	100:1	0.1

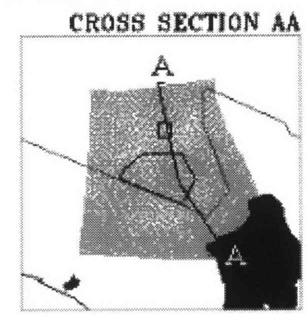
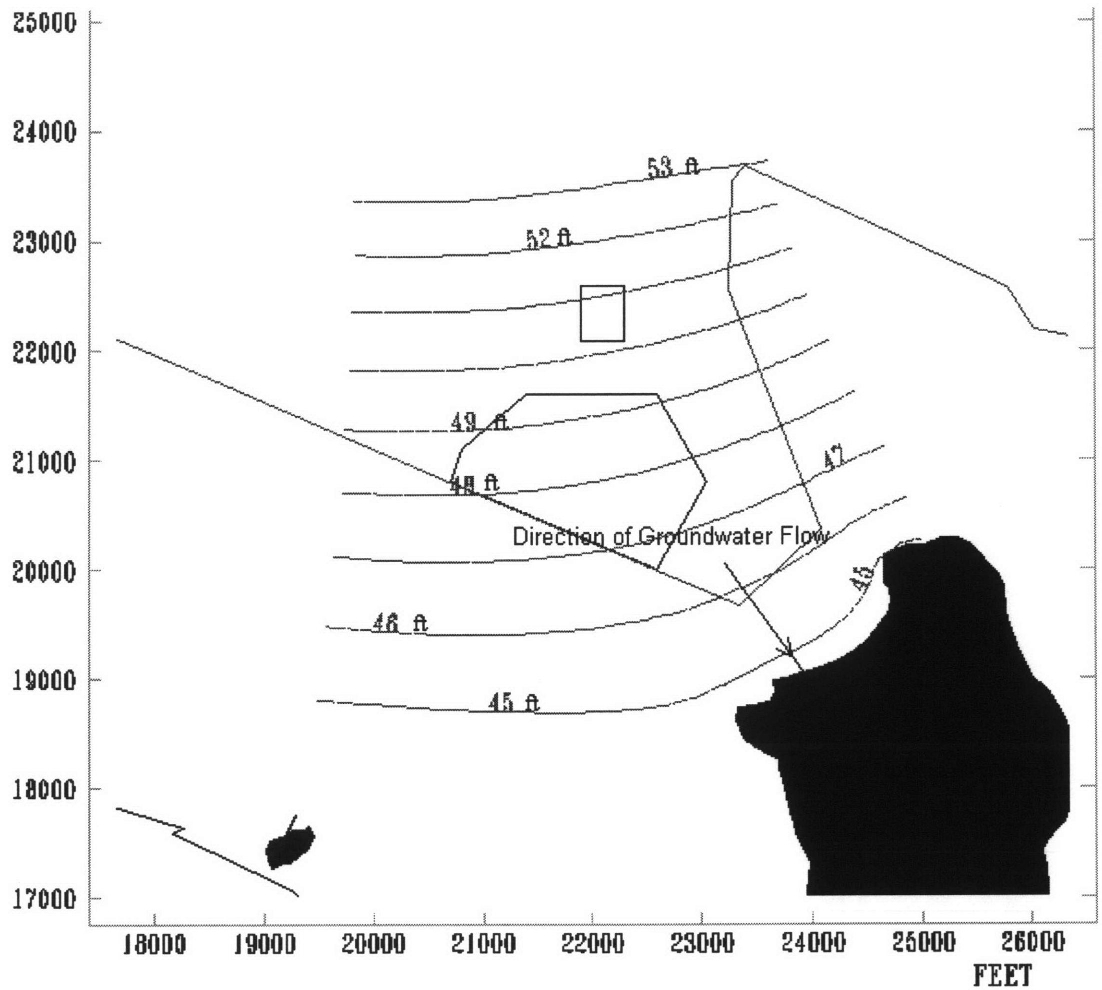
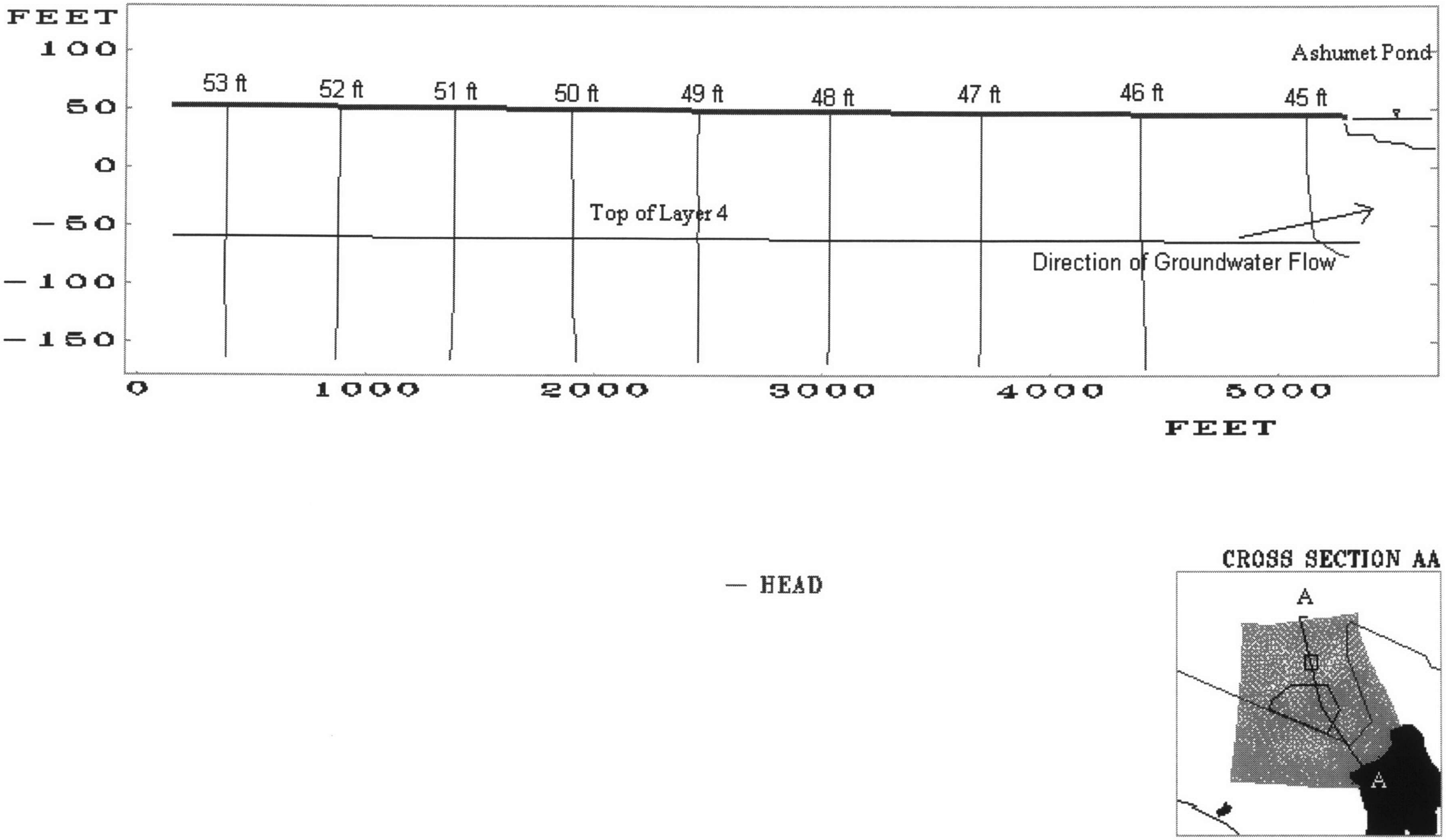


Figure 6-5. Cross-Sectional View Along Centerline A-A With Wall



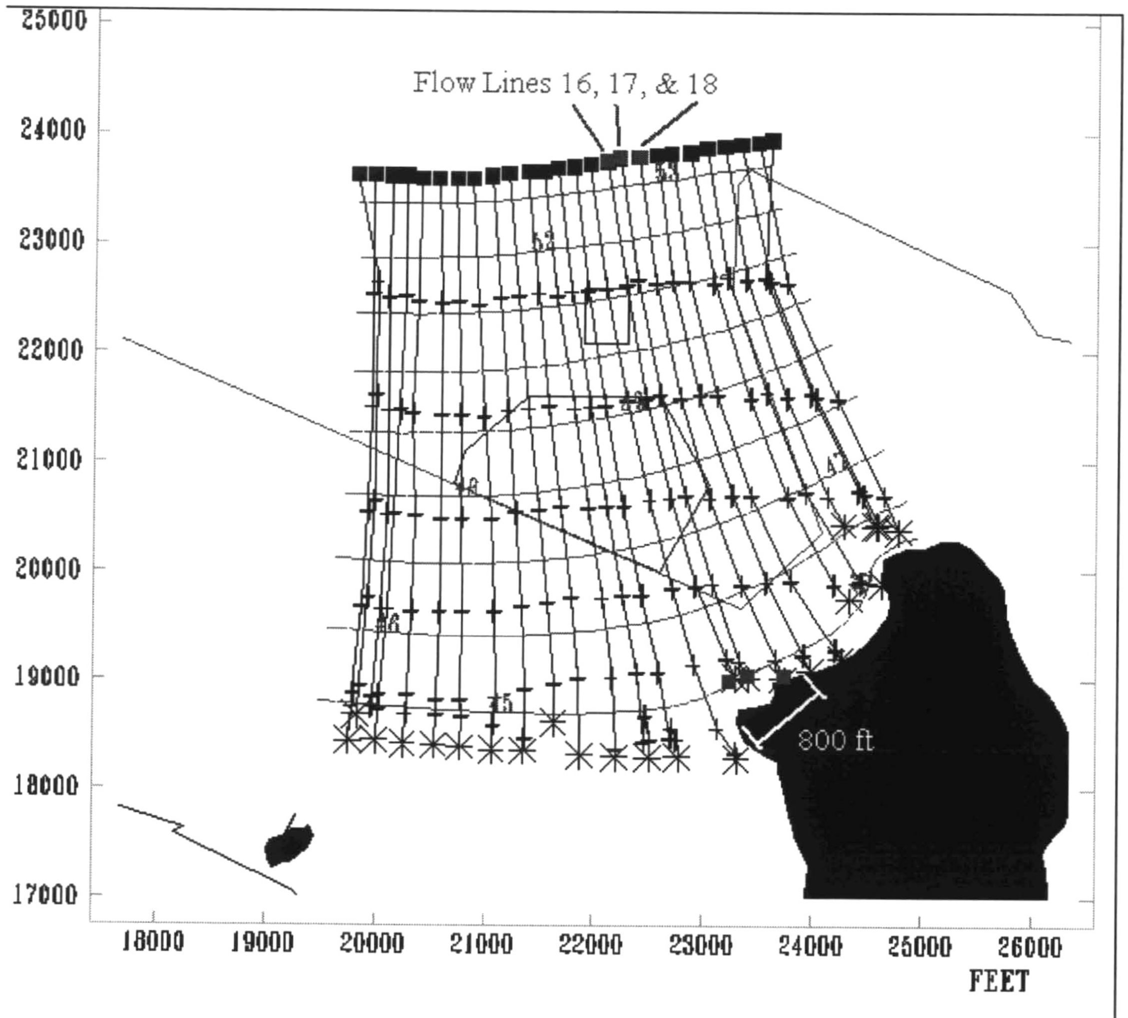
a) Head Contours At Elevation 0 ft (Plan View)

Figure 6-6. Head Contours Under Present Conditions



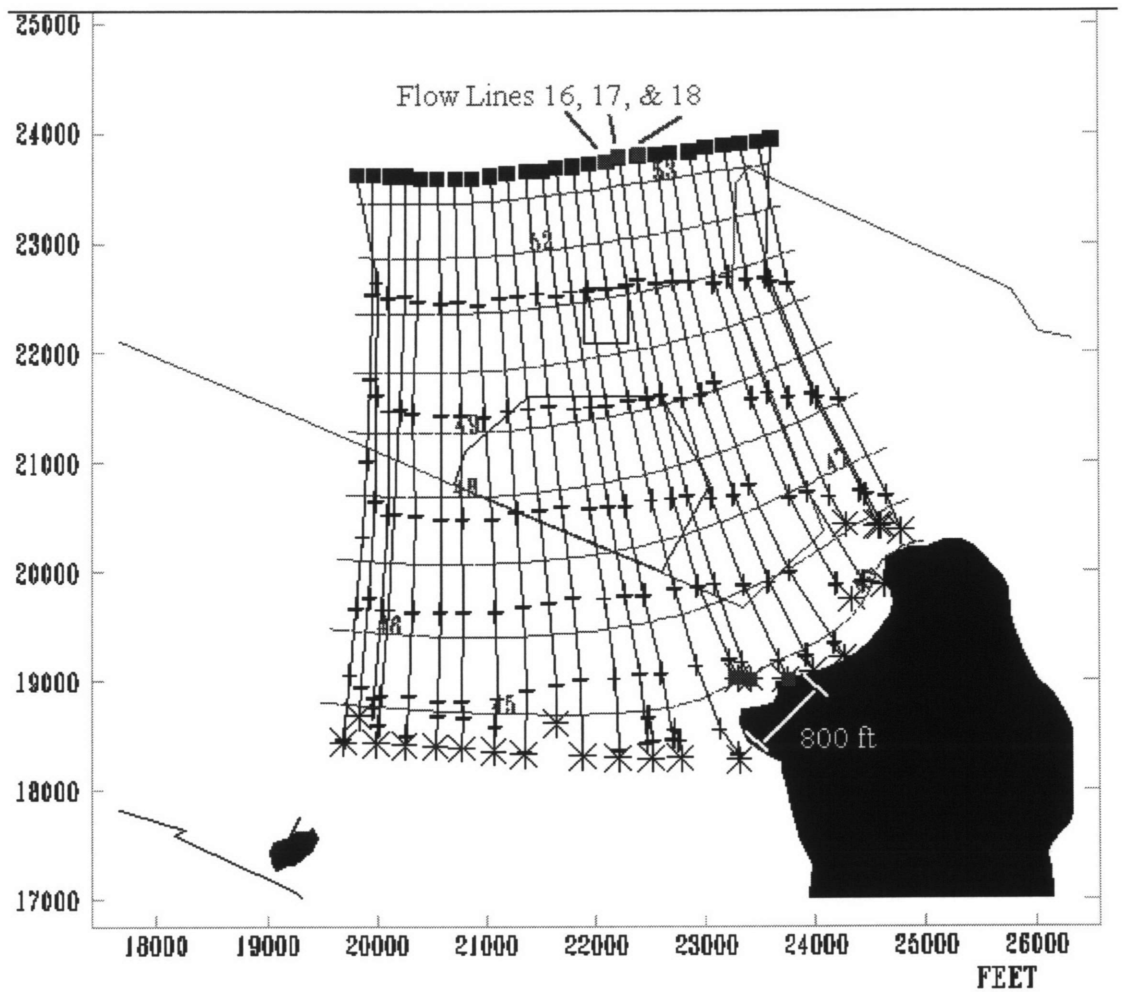
b) Cross-Sectional View of Head Contours

Figure 6-6. Head Contours Under Present Conditions



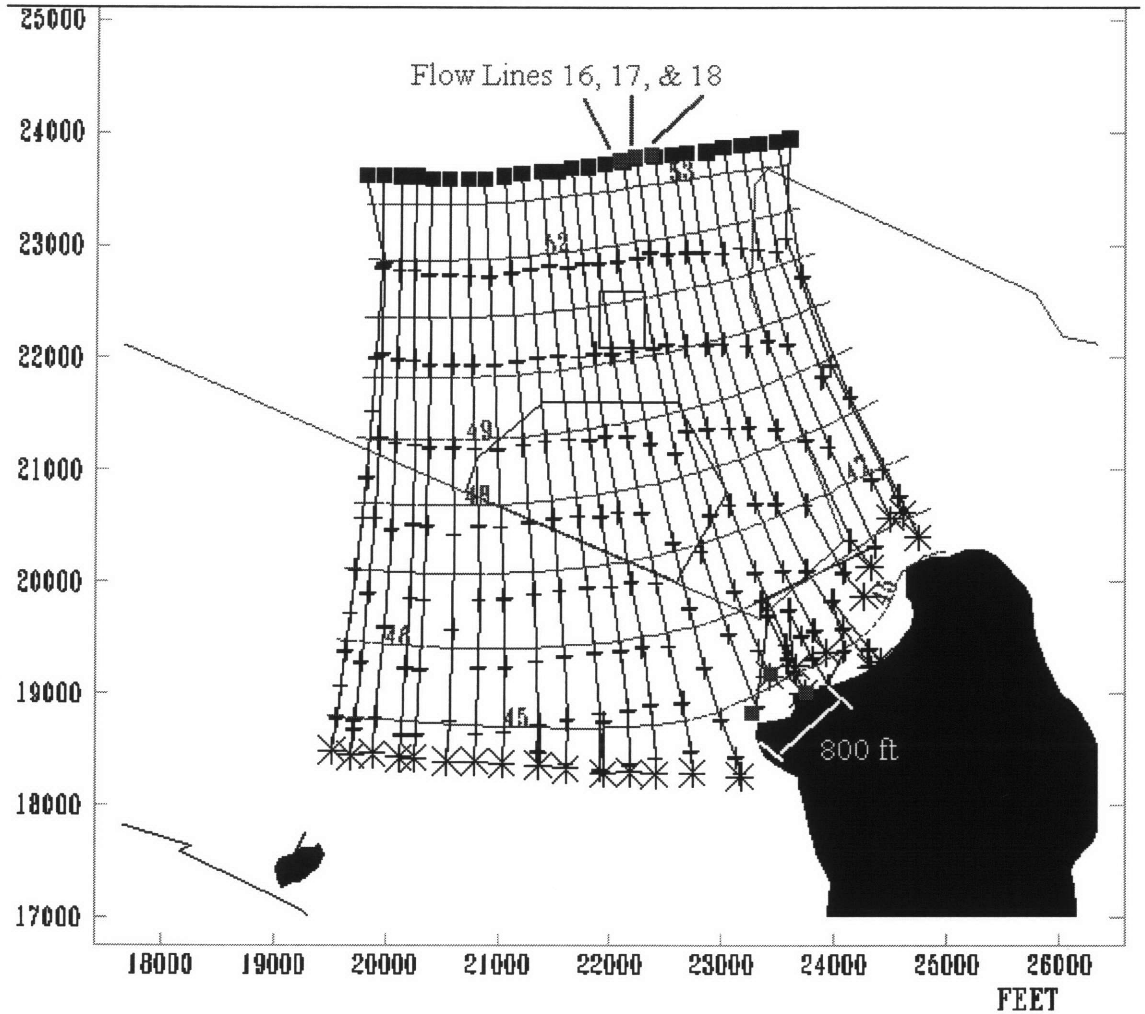
a) Flow Lines at 50 ft Elevation

Figure 6-7. Flow Lines at Present Conditions



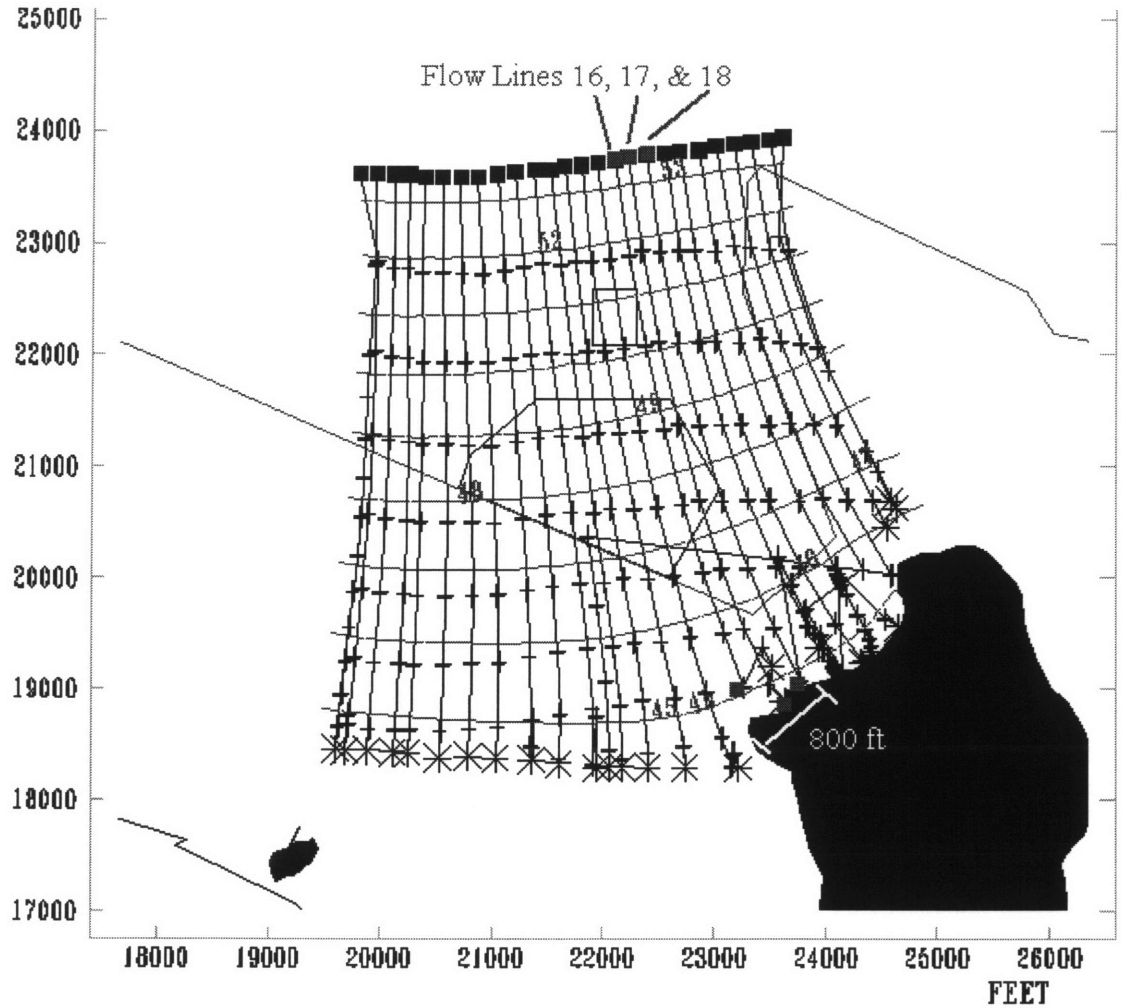
b) Flow Lines at 25 ft Elevation

Figure 6-7. Flow Lines at Present Conditions



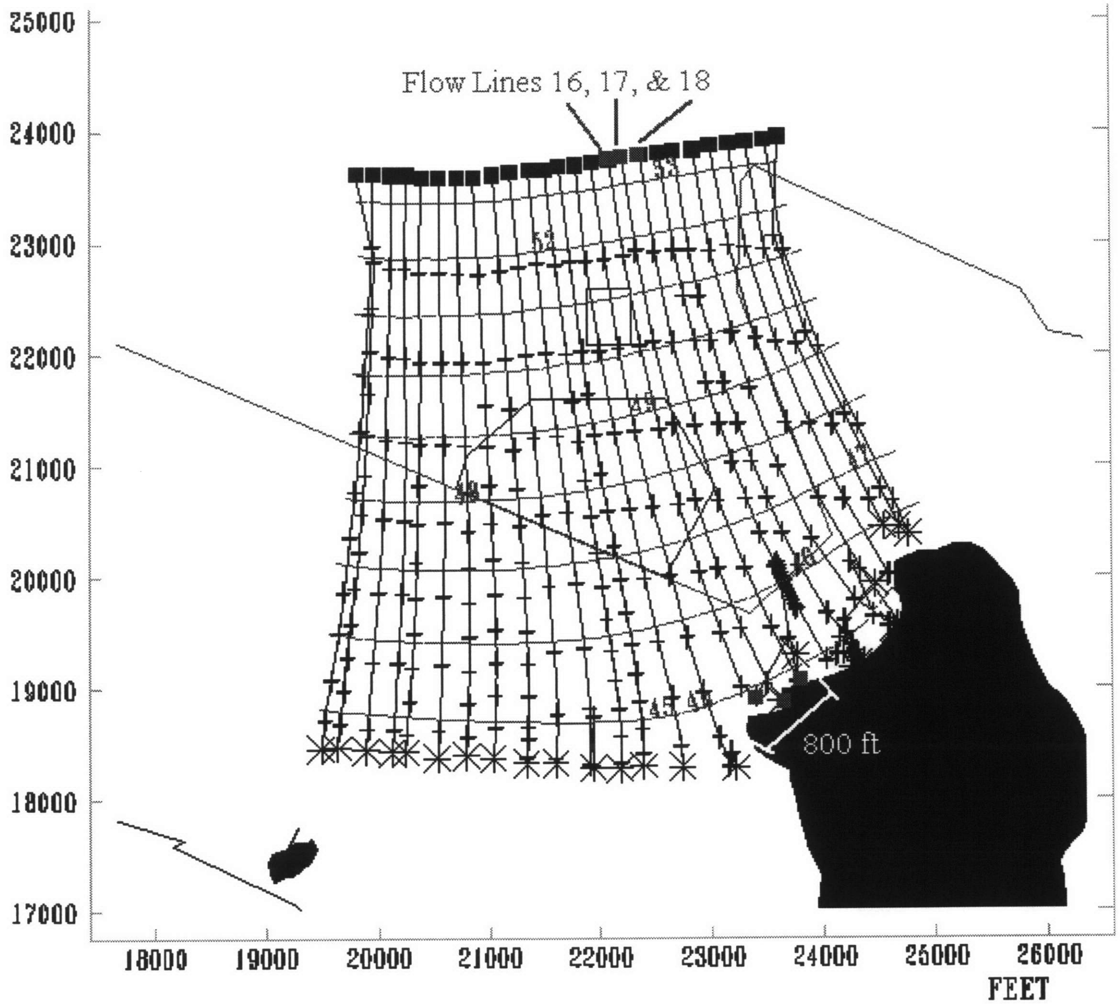
c) Flow Lines at 0 ft Elevation

Figure 6-7. Flow Lines at Present Conditions



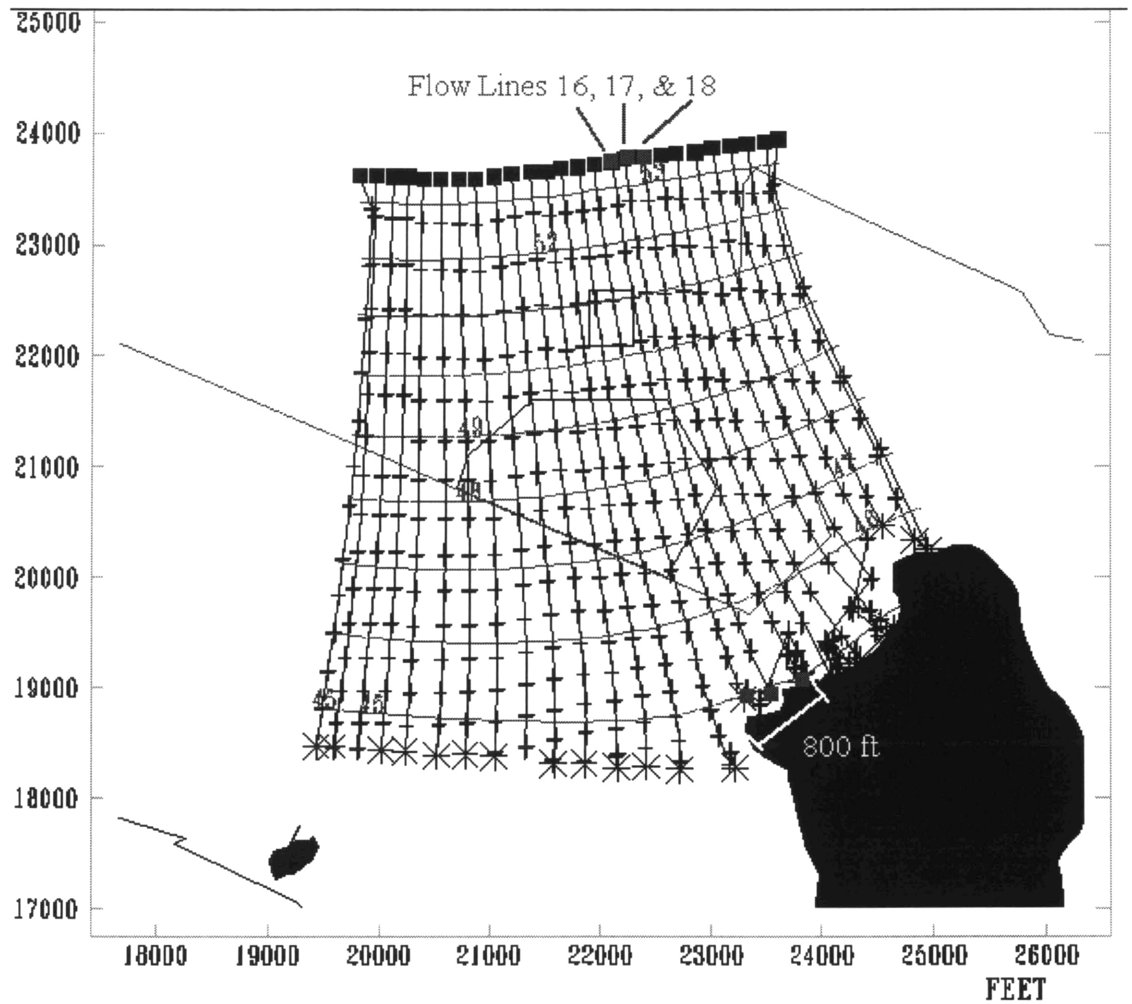
d) Flow Lines at -25 ft Elevation

Figure 6-7. Flow Lines at Present Conditions



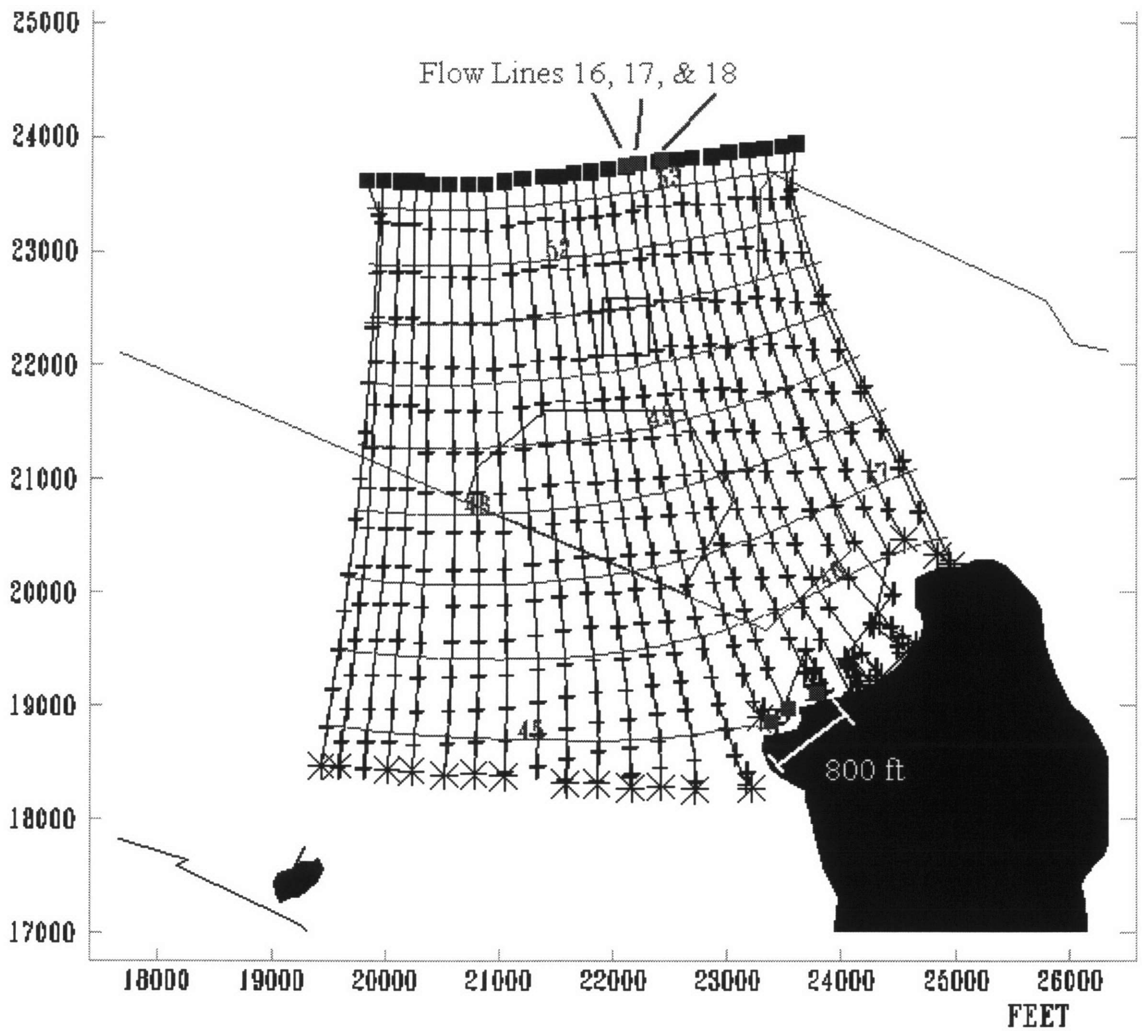
e) Flow Lines at -50 ft Elevation

Figure 6-7. Flow Lines at Present Conditions



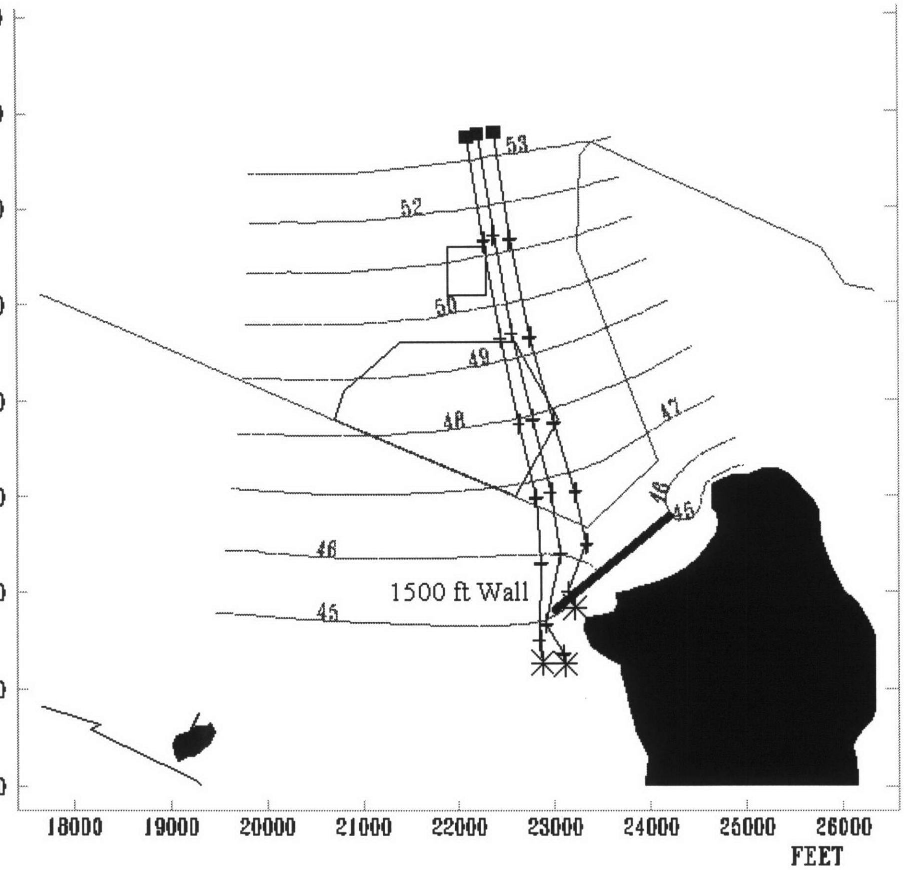
f) Flow Lines at -75 ft Elevation

Figure 6-7. Flow Lines at Present Conditions

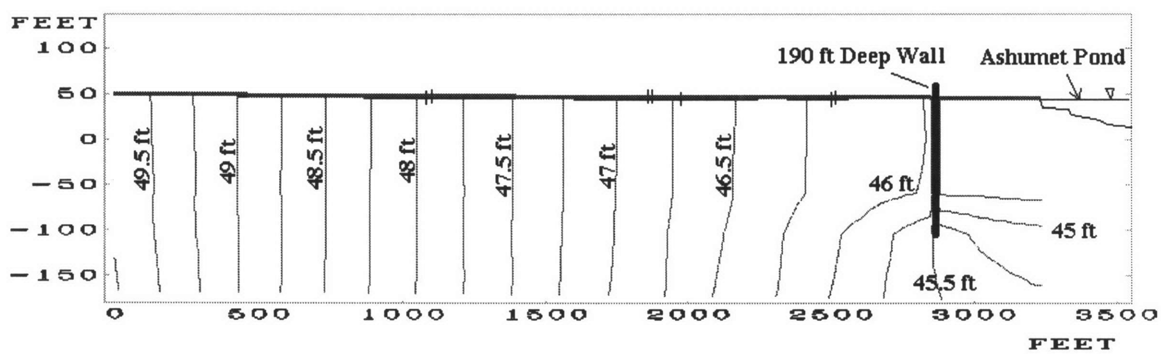


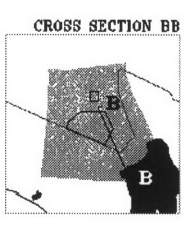
g) Flow Lines at -100 ft Elevation

Figure 6-7. Flow Lines at Present Condtions



Plan View

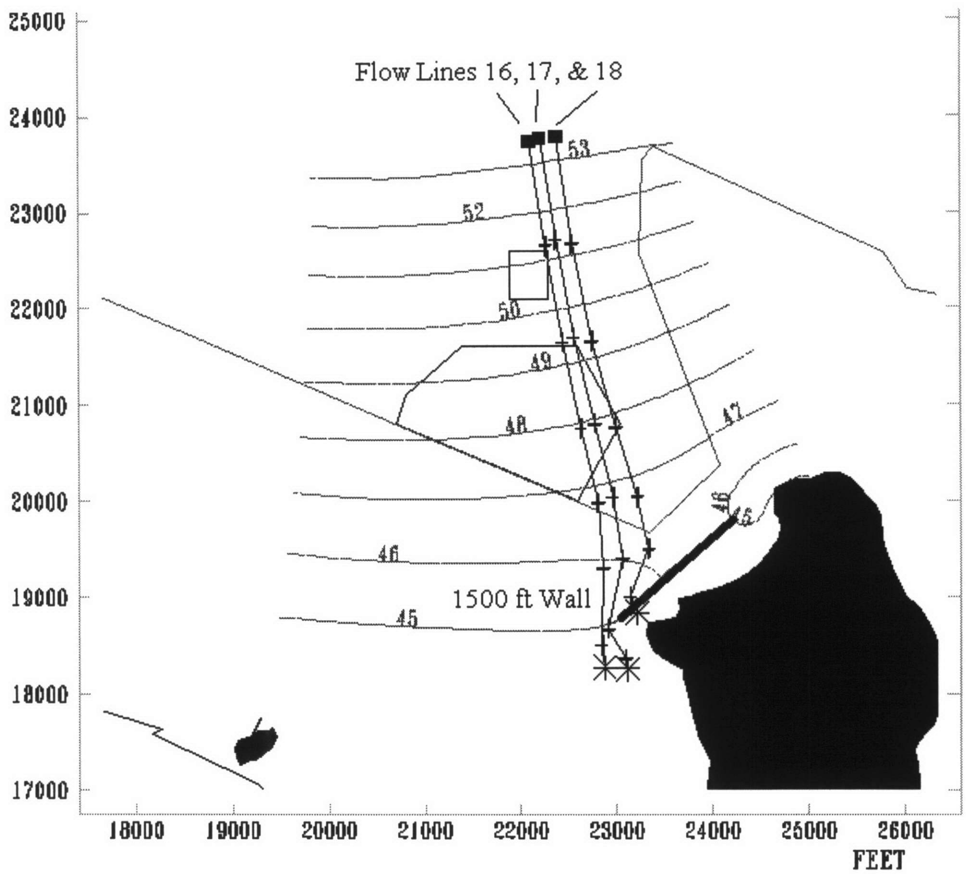




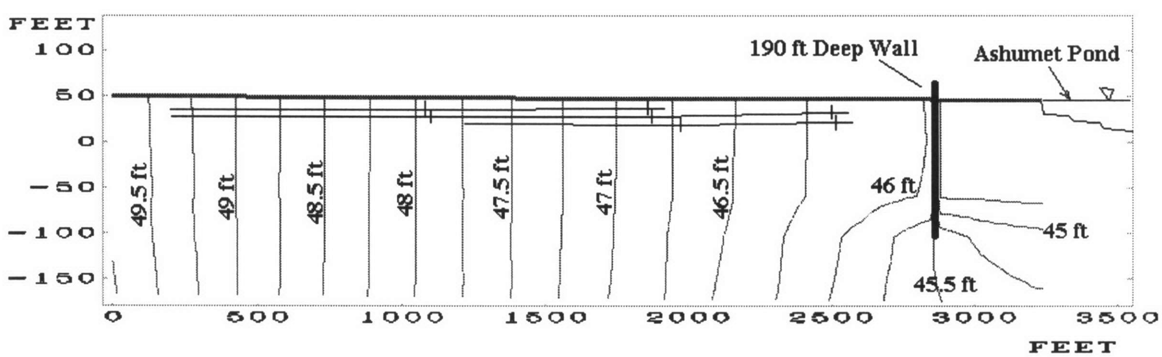
Cross-Section B-B Along Centerline of DYNFLOW Model

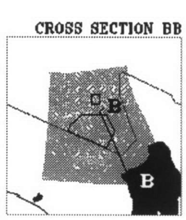
a) Flow Lines 16, 17, & 18 at 50 ft Elevation

Figure 6-8. Flow Lines 16, 17, & 18 with the Introduction of 1500 ft Long Wall



Plan View

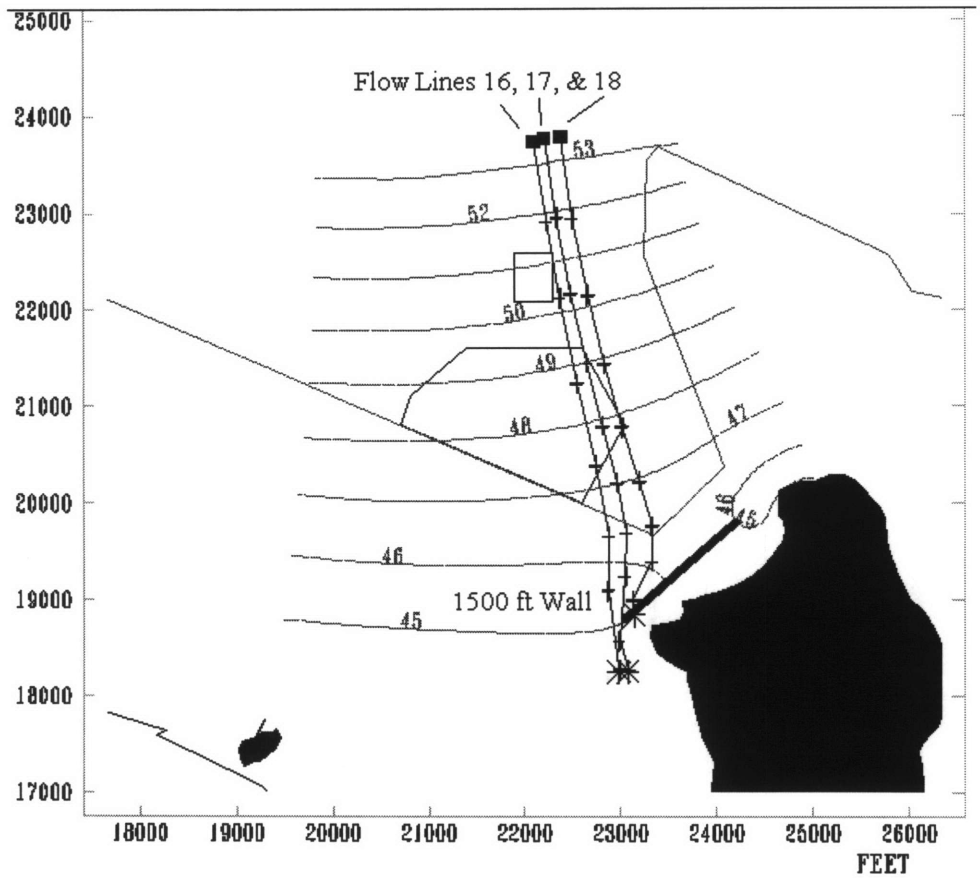




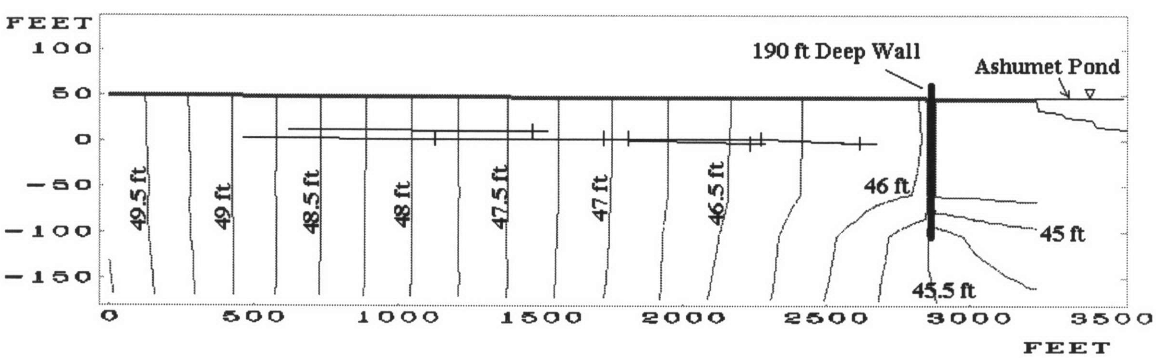
Cross-Section B-B Along Centerline of DYNFLOW Model

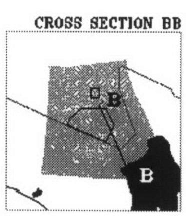
b) Flow Lines 16, 17, & 18 at 25 ft Elevation

Figure 6-8. Flow Lines 16, 17, & 18 with the Introduction of 1500 ft Long Wall



Plan View

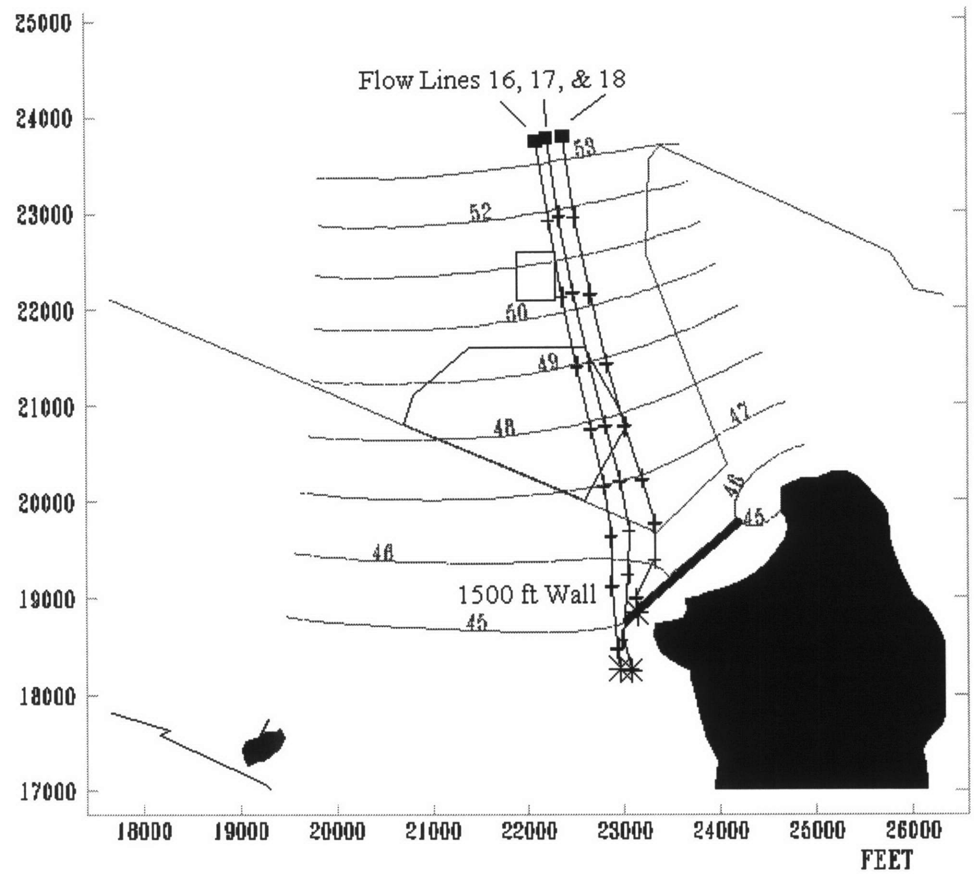




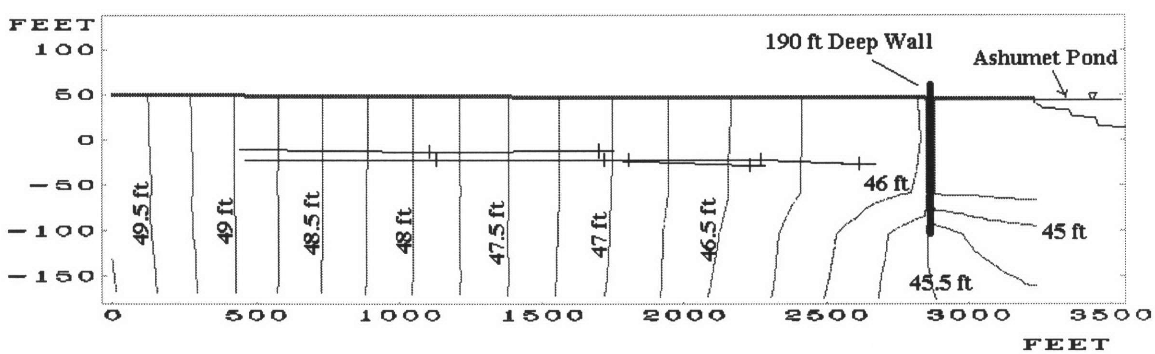
Cross-Section B-B Along Centerline of DYNFLOW Model

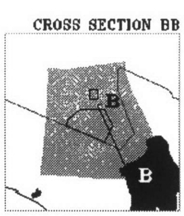
c) Flow Lines 16, 17, & 18 at 0 ft Elevation

Figure 6-8. Flow Lines 16, 17, & 18 with the Introduction of 1500 ft Long Wall



Plan View

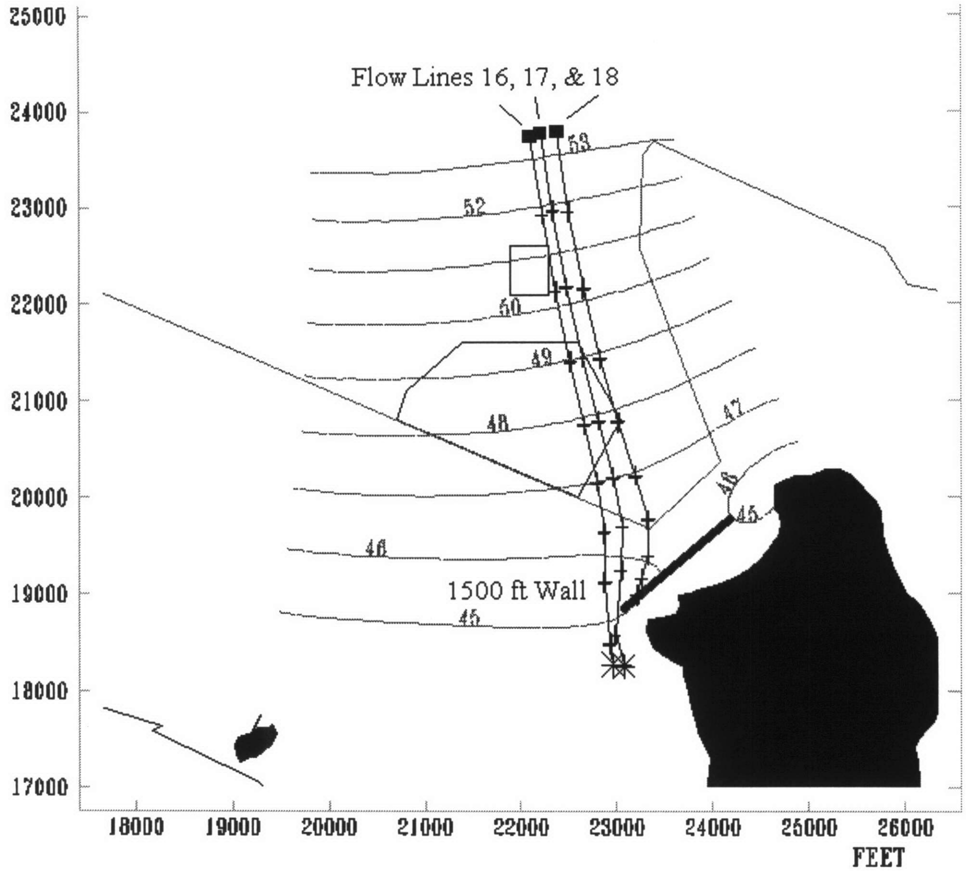




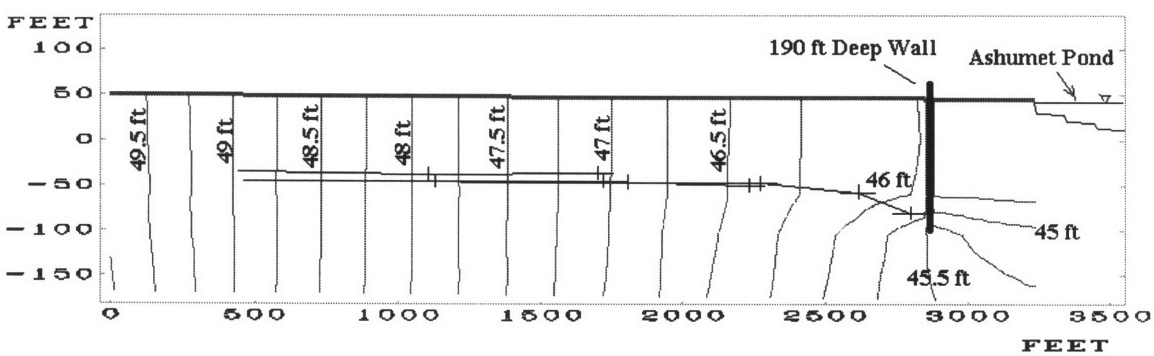
Cross-Section B-B Along Centerline of DYNFLOW Model

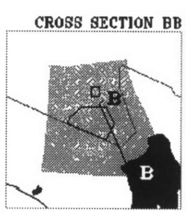
d) Flow Lines 16, 17, & 18 at -25 ft Elevation

Figure 6-8. Flow Lines 16, 17, & 18 with the Introduction of 1500 ft Long Wall



Plan View

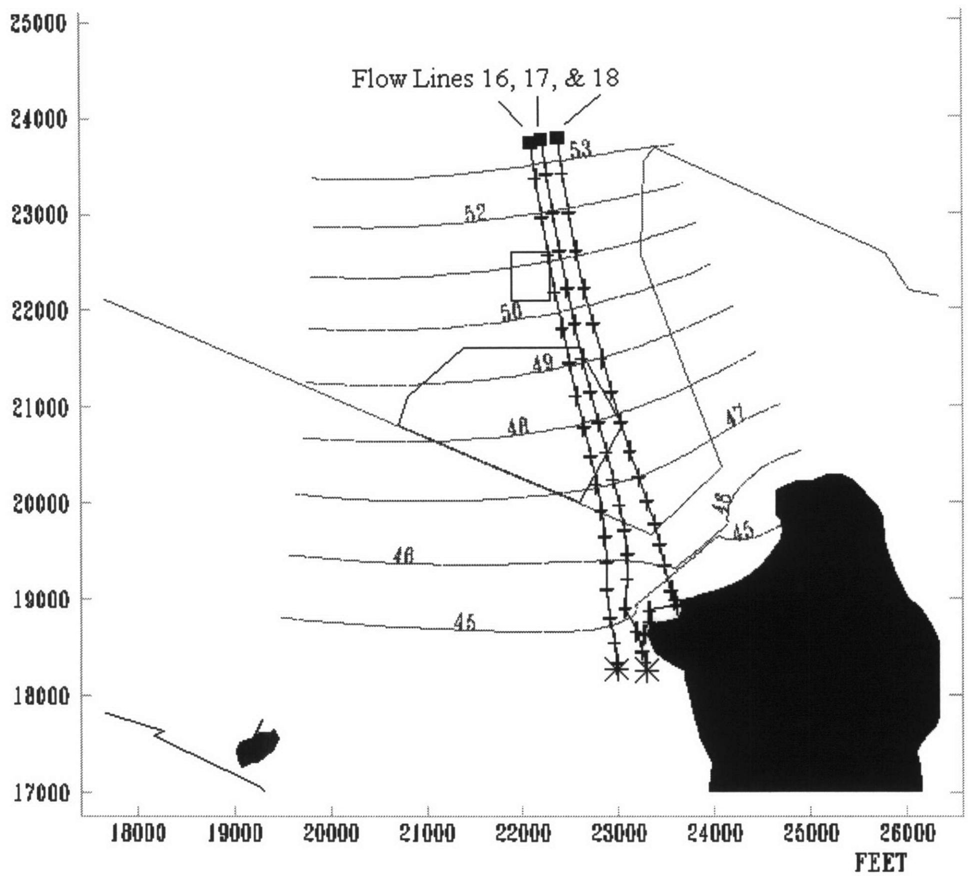




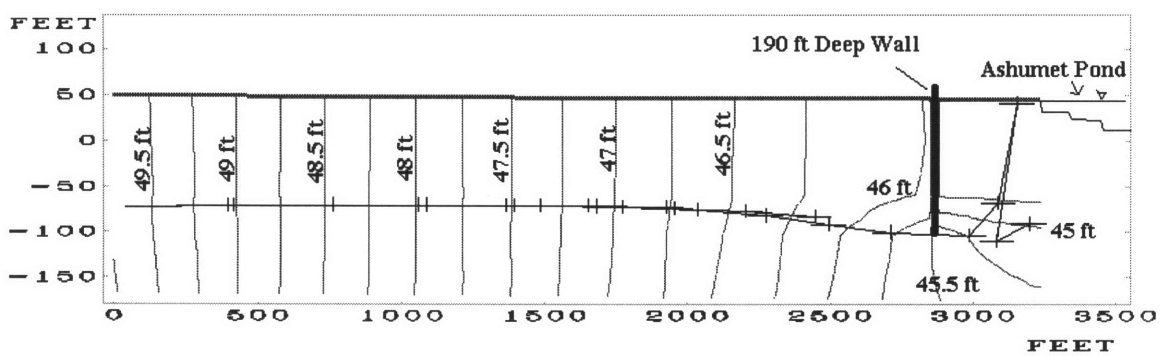
Cross-Section B-B Along Centerline of DYNFLOW Model

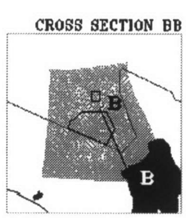
e) Flow Lines 16, 17, & 18 at -50 ft Elevation

Figure 6-8. Flow Lines 16, 17, & 18 with the Introduction of 1500 ft Long Wall



Plan View

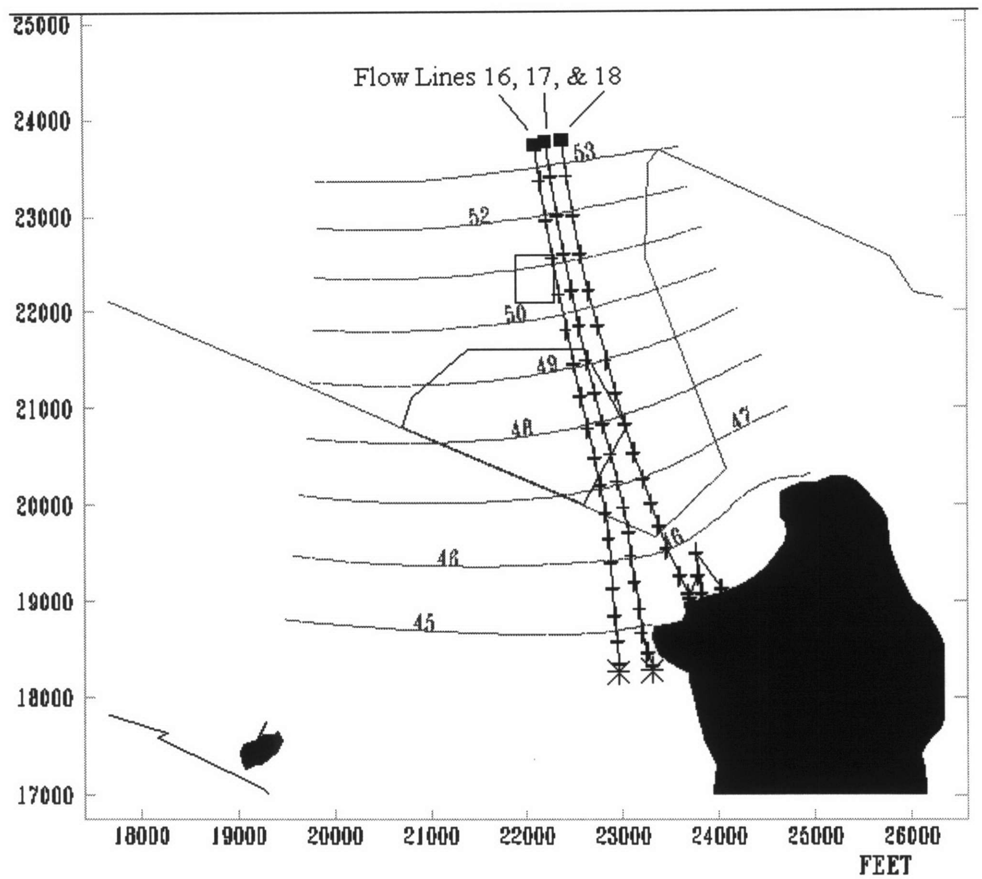




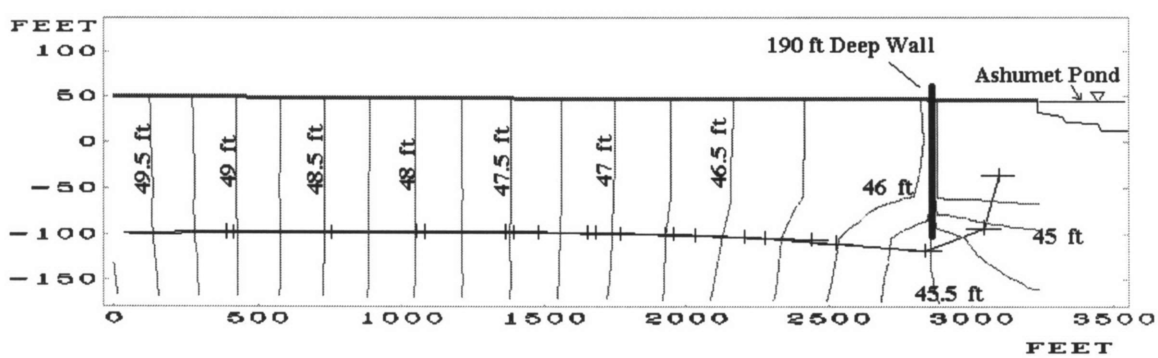
Cross-Section B-B Along Centerline of DYNFLOW Model

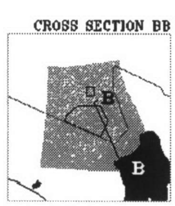
f) Flow Lines 16, 17, & 18 at -75 ft Elevation

Figure 6-8. Flow Lines 16, 17, & 18 with the Introduction of 1500 ft Long Wall



Plan View

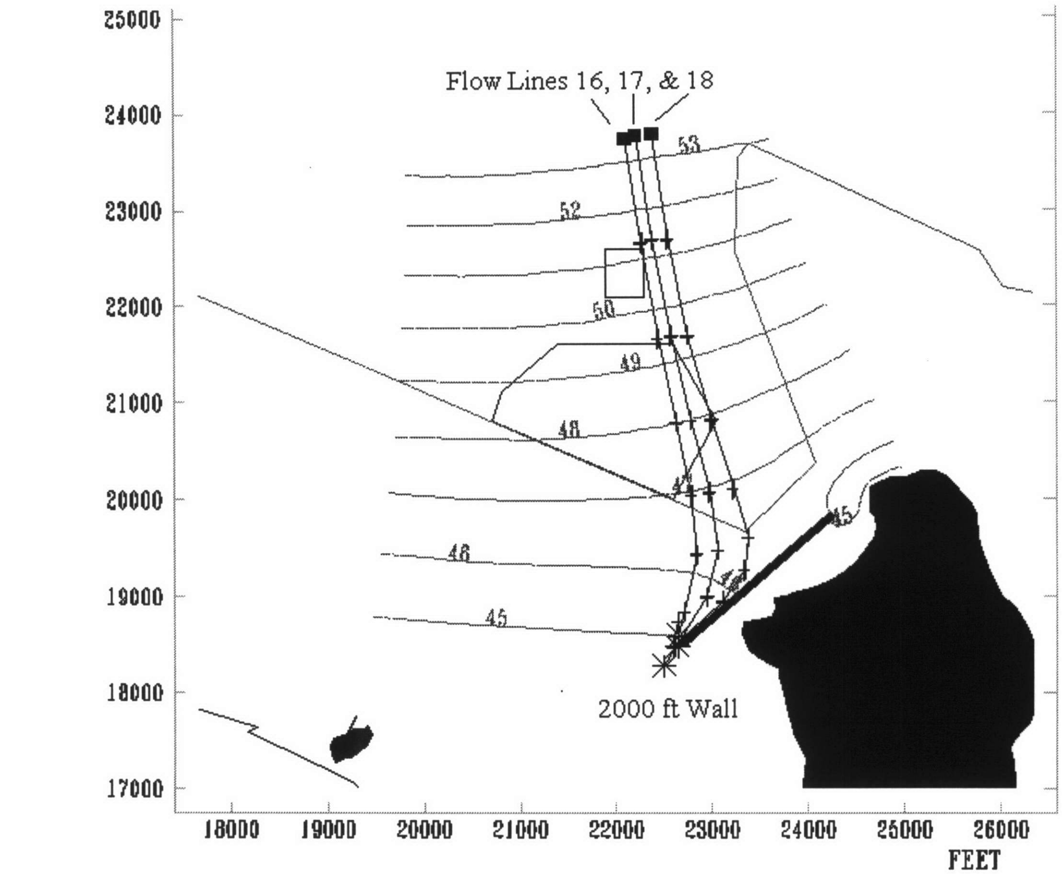




Cross-Section B-B Along Centerline of DYNFLOW Model

g) Flow Lines 16, 17, & 18 at -100 ft Elevation

Figure 6-8. Flow Lines 16, 17, & 18 with the Introduction of 1500 ft Long Wall



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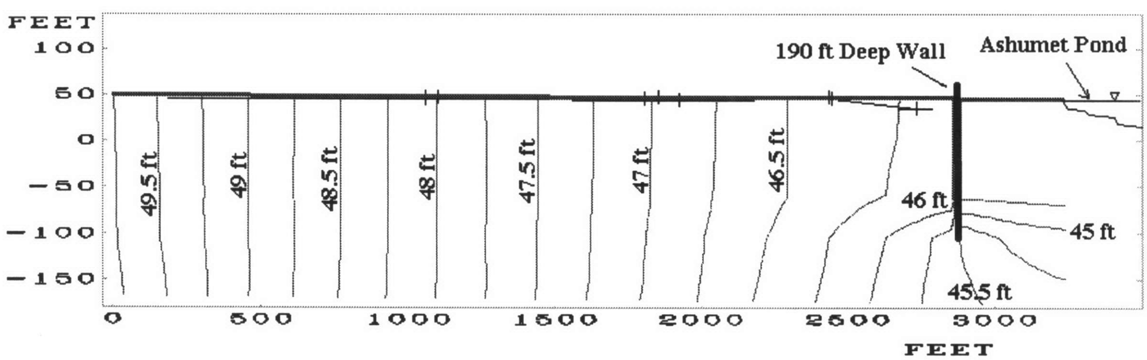
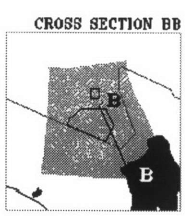
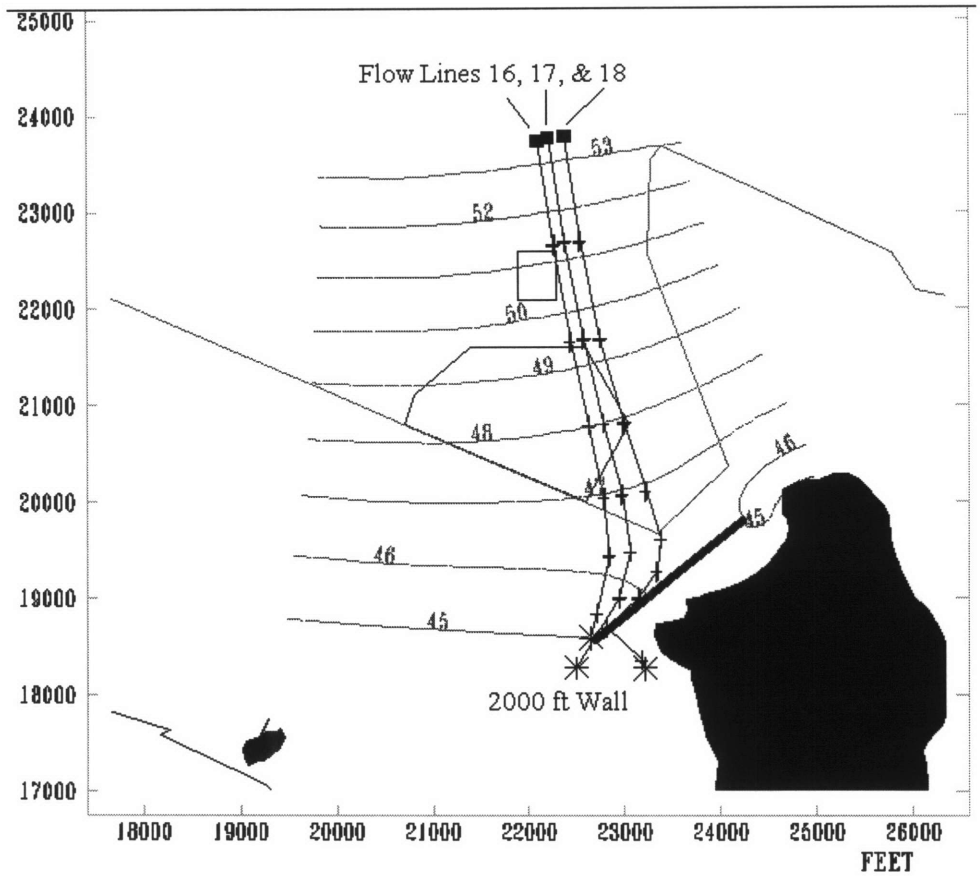




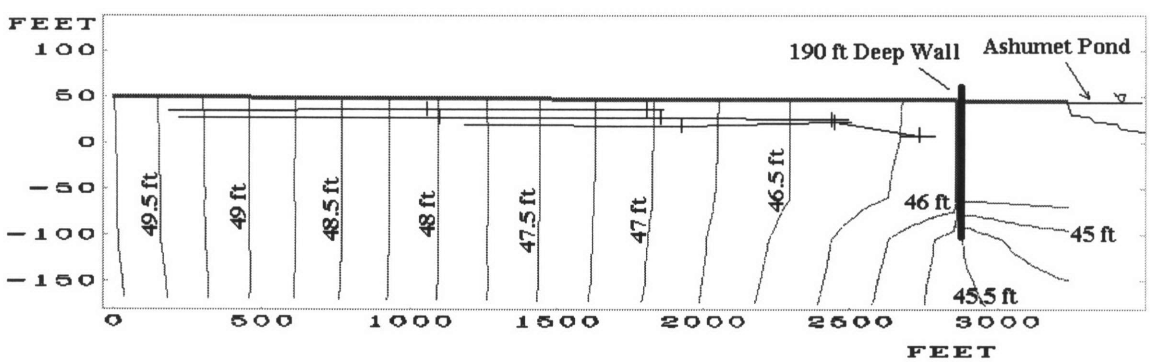
Cross-Section B-B Along Centerline of DYNFLOW Model

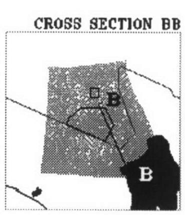
a) Flow Lines 16, 17, & 18 at 50 ft Elevation

Figure 6-9. Flow Lines 16, 17, & 18 with the Introduction of 2000 ft Long Wall



Plan View

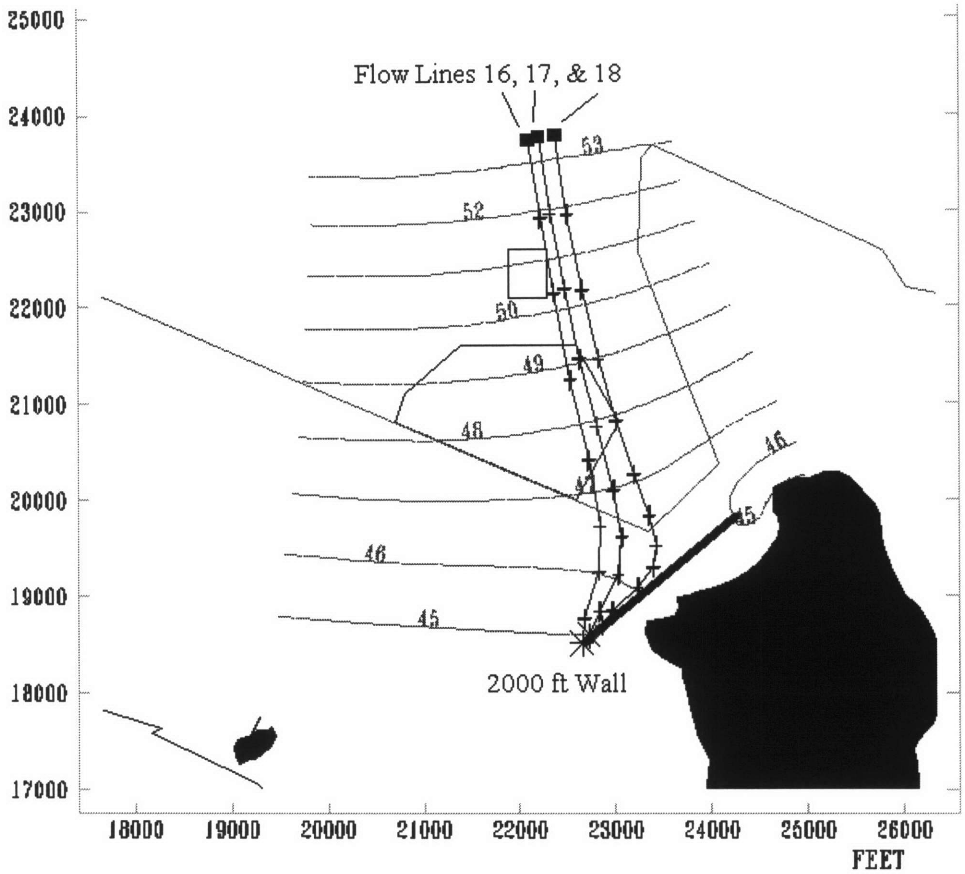




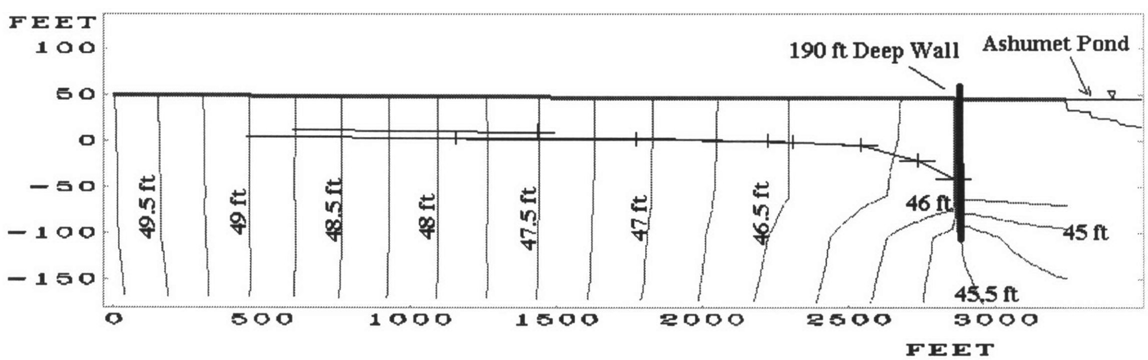
Cross-Section B-B Along Centerline of DYNFLOW Model

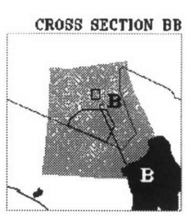
b) Flow Lines 16, 17, & 18 at 25 ft Elevation

Figure 6-9. Flow Lines 16, 17, & 18 with the Introduction of 2000 ft Long Wall



Plan View

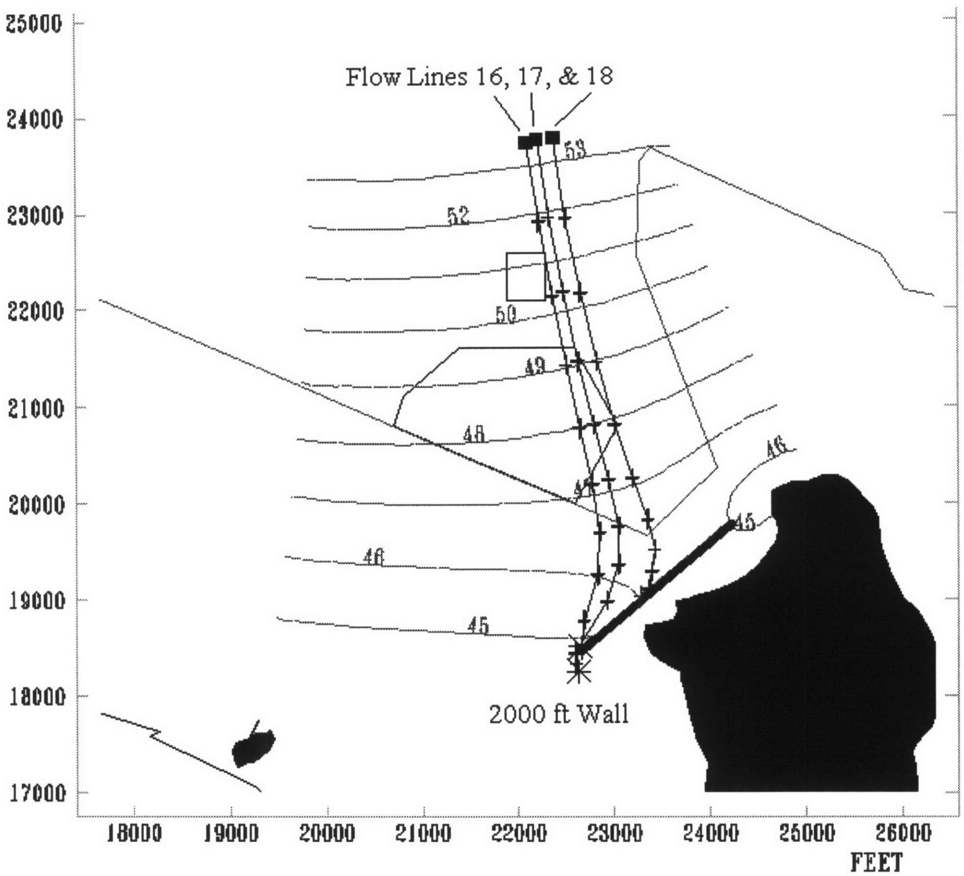




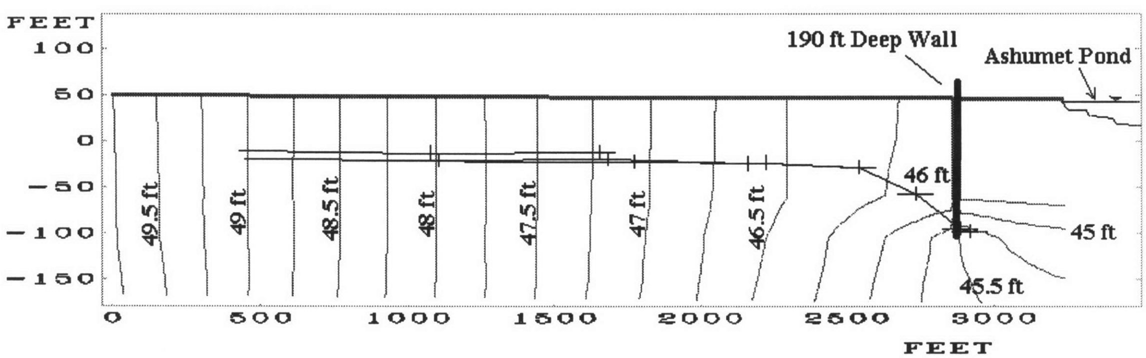
Cross-Section B-B Along Centerline of DYNFLOW Model

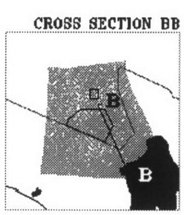
c) Flow Lines 16, 17, & 18 at 0 ft Elevation

Figure 6-9. Flow Lines 16, 17, & 18 with the Introduction of 2000 ft Long Wall



Plan View

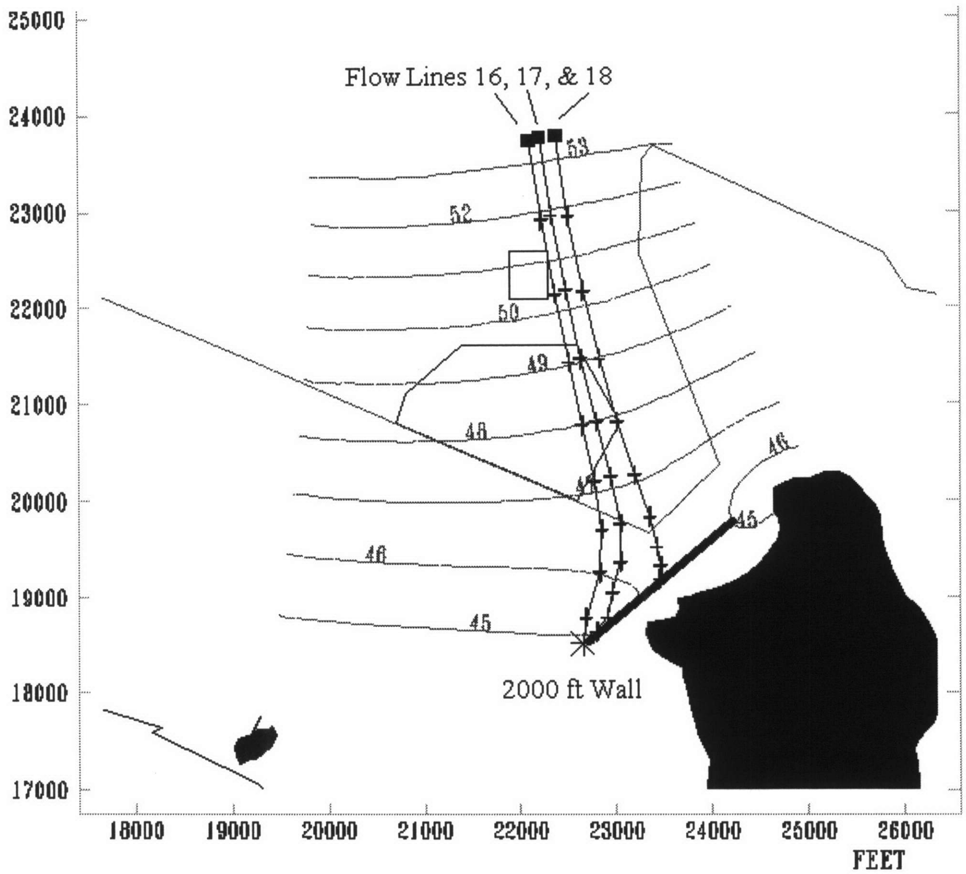




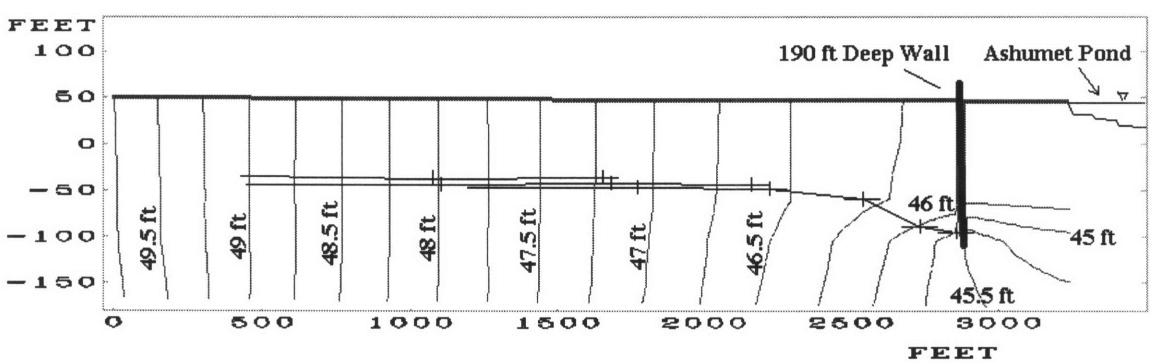
Cross-Section B-B Along Centerline of DYNFLOW Model

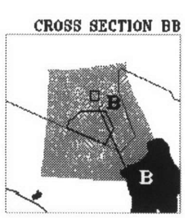
d) Flow Lines 16, 17, & 18 at -25 ft Elevation

Figure 6-9. Flow Lines 16, 17, & 18 with the Introduction of 2000 ft Long Wall



Plan View

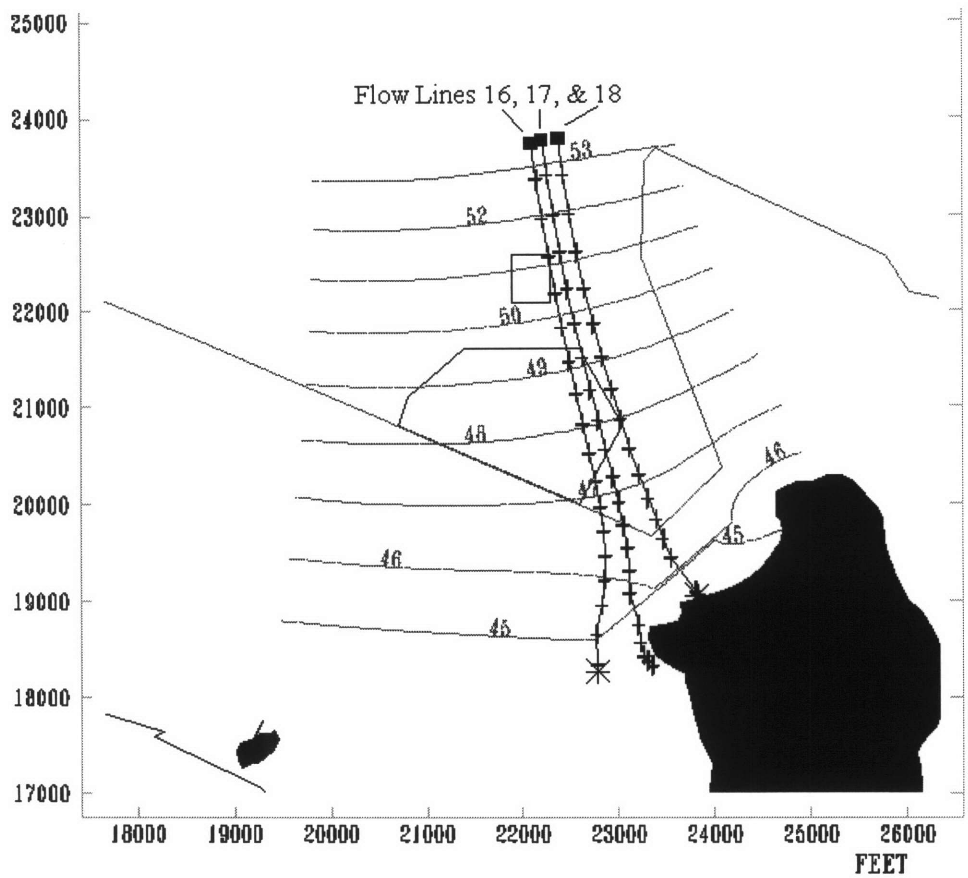




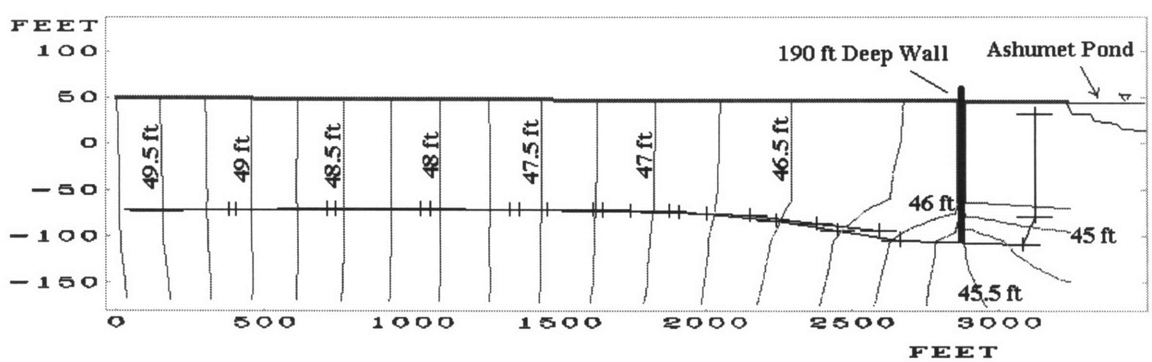
Cross-Section B-B Along Centerline of DYNFLOW Model

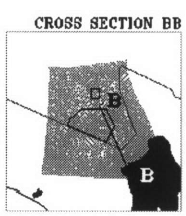
e) Flow Lines 16, 17, & 18 at -50 ft Elevation

Figure 6-9. Flow Lines 16, 17, & 18 with the Introduction of 2000 ft Long Wall



Plan View

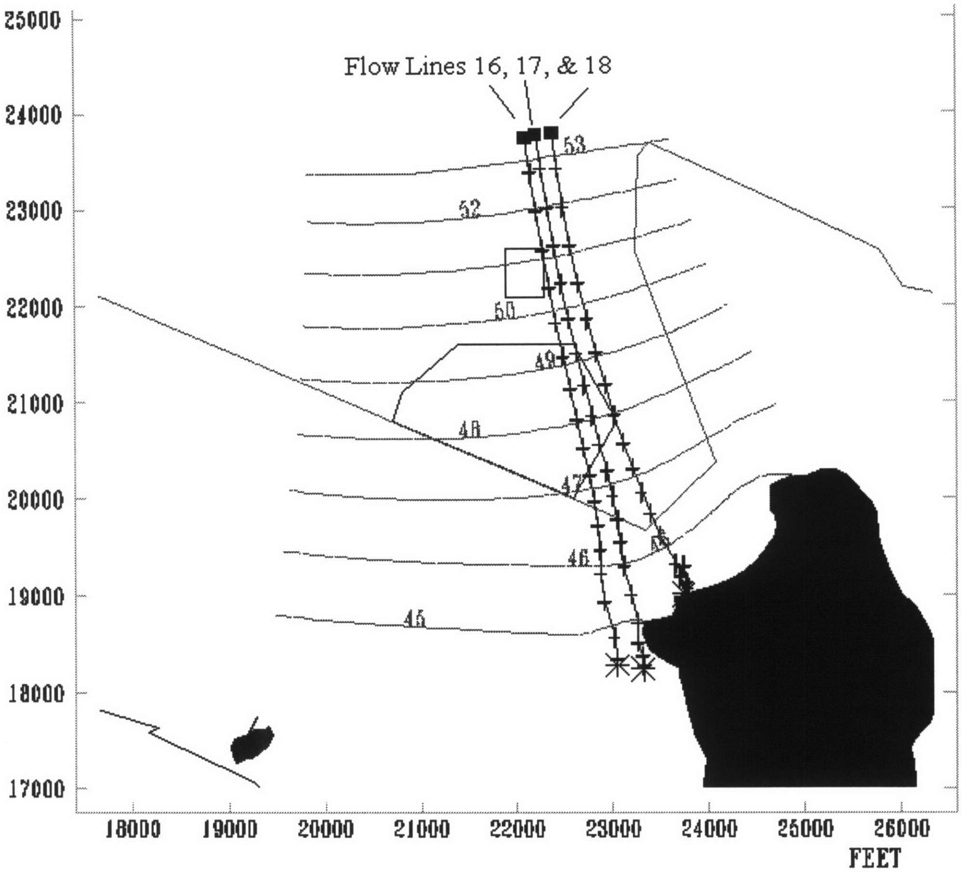




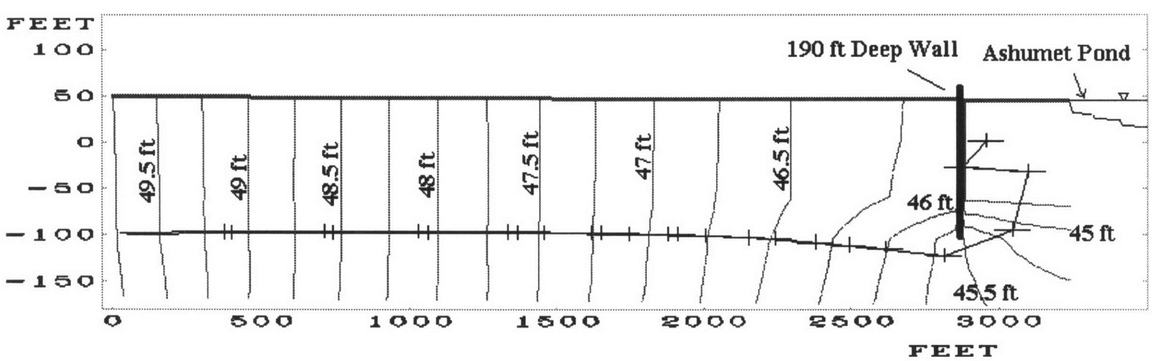
Cross-Section B-B Along Centerline of DYNFLOW Model

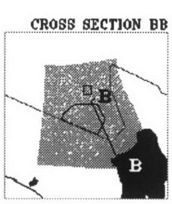
f) Flow Lines 16, 17, & 18 at -75 ft Elevation

Figure 6-9. Flow Lines 16, 17, & 18 with the Introduction of 2000 ft Long Wall



Plan View





Cross-Section B-B Along Centerline of DYNFLOW Model

g) Flow Lines 16, 17, & 18 at -100 ft Elevation

Figure 6-9 Flow Lines 16, 17, & 18 with the Introduction of 2000 ft Long Wall

7. CONTAMINANT BREAKTHROUGH IN PHYSICAL BARRIERS

Slurry wall barriers cannot be constructed to be perfectly impermeable, i.e., there will be some transport of contaminants through the barrier. However, the rate of flow will be very low because of the barrier's low permeability characteristics. It is necessary to design the barrier with a thickness that is sufficient in slowing down the flow so that containment is achieved over a certain design period. A contaminant breakthrough analysis is performed in this chapter to determine the thickness required for the barrier. This analysis is applicable to earthen barrier types such as slurry wall construction.

Chemicals in groundwater are transported through three mechanisms: advection, dispersion, and diffusion. Advection is the transport of chemicals in the general direction of flow. This mode of transport is dependent on the flow's average velocity. Dispersion is the lateral spreading of chemicals due to the heterogeneity of the aquifer and the tortousity of groundwater pathways. This is highly dependent on the aquifer grain size. Lastly, diffusion is the transport of chemicals due to the differences in its concentration within the soil medium.

The three transport mechanisms of contaminants as mentioned above can be modeled using the following contaminant breakthrough equation (Freeze and Cherry, 1979):

$$C(x,t) = \frac{C_o}{2} erfc\left[\frac{R_d x - ut}{2(R_d D_h t)^{\frac{1}{2}}}\right] \tag{7.1}$$

where C = Particle Concentration

C_o = Initial Particle Concentration

erfc = Complimentary error function

R_d = Retardation Coefficient

x = Distance

u = Average approach velocity

D_h = Coefficient of Hydrodynamic Dispersion

t = Time

This equation expresses the concentration of the chemical at a location x at some time t after a certain initial particle concentration ($C=C_o$) and location (x=0). The reader is referred to Freeze, R. A. and Cherry, J. A. (1979) for this equation's derivation. The complimentary error function (erfc) in the equation is just a mathematical function equal to:

$$erfc(z) = 1 - (2/\sqrt{\pi})\int_0^z e^{-\varepsilon^2} d\varepsilon \tag{7.2}$$

Values of erfc can be interpreted from the following table by Freeze and Cherry (1979):

Table 7-1. Values of erfc(z) (adapted from Freeze and Cherry, 1979):

z	erfc(z)	z	erfc(z)	z	erfc(z)
0	1.0	0.7	0.322199	1.8	0.010909
0.05	0.943628	0.75	0.288844	1.9	0.007210
0.1	0.887537	0.8	0.257899	2.0	0.004678
0.15	0.832004	0.85	0.229332	2.1	0.002979
0.2	0.777297	0.9	0.203092	2.2	0.001863
0.25	0.723674	0.95	0.179109	2.3	0.001143
0.3	0.671373	1.0	0.157299	2.4	0.000689
0.35	0.620618	1.1	0.119795	2.5	0.000407
0.4	0.571608	1.2	0.089686	2.6	0.000236
0.45	0.524518	1.3	0.065992	2.7	0.000134
0.5	0.479500	1.4	0.047715	2.8	0.000075
0.55	0.436677	1.5	0.033895	2.9	0.000041
0.6	0.396144	1.6	0.023652	3.0	0.000042
0.65	0.357971	1.7	0.016210		

R_d in Equation 7.1 is a measure of how much the flow of contaminants is slowed because of sorption mechanisms. Contaminants usually possess sorption affinities to soil solids. Since a certain amount of the contaminants would be sorbed onto soil solids, transport of these are slowed. R_d can be expressed as:

$$R_d = 1 + \frac{sorbed\ concentration}{mobile\ concentration} \tag{7.3}$$

The coefficient of hydrodynamic dispersion (D_h) is a measure of the spreading of contaminant concentrations. This has two components and can be expressed in the following equation:

$$D_h = D^* + D_m \tag{7.4}$$

where D^* = Effective Diffusion Coefficient

D_m = Coefficient of Mechanical Dispersion

The first component is a measure of contaminant spreading due to differences in chemical concentration. This effective diffusion coefficient expresses the tendency for contaminants to move from a higher concentration location to a lower concentration location. The second component takes into account the deflection of contaminant flow paths caused by the tortuousity. This coefficient of mechanical dispersion can be expressed in the following equation:

$$D_m = \alpha_L u \tag{7.5}$$

where α_L = Dispersivity or scale of heterogeneity; also taken as the mean grain size of the porous medium

u = Average approach velocity

Equation 7.1 could then be expressed in the following form:

$$2\frac{C(x,t)}{C_o} = erfc\left[\frac{R_d x - ut}{2\left(R_d(D^* + \alpha_L u)t\right)^{\frac{1}{2}}}\right] \tag{7.6}$$

A study by Acar and Haider (1990) prescribes several steps in determining barrier thickness from the breakthrough Equation 7.1 mentioned above. This procedure can be outlined in the following:

1. Develop a design criteria for the barrier.
    a. Select design life for the barrier.
    b. Determine approach velocity in the barrier.
    c. Decide upon the maximum allowable breakthrough concentration of the contaminant, C_e.
2. Determine initial concentrations of contaminants in the plume, C_o.
3. Calculate the breakthrough level C_e/C_o.
4. Estimate the diffusion coefficient of the contaminant.
5. Determine the retardation factor, R_d.
6. Use these parameters in the contaminant breakthrough equation to determine the barrier thickness.

A study of contaminant degradation periods can help determine a suitable containment design life. Economics and legislation may also influence this variable. Design periods ranging from 30 to 75 years were chosen for this study

The approach velocity in the wall is solved from Darcy's Law:

$$u = ki \tag{7.7}$$

where u = Approach velocity

k = Hydraulic conductivity of the barrier

i = Hydraulic gradient

The barrier is being designed to achieve a low hydraulic conductivity of 1 x 10^{-7} cm/sec or 1 x 10^{-9} m/sec. The hydraulic gradient is a function of the head difference directly upstream and downstream of the barrier and the barrier thickness. It equals:

$$i = \frac{\Delta h}{L} \tag{7.8}$$

where Δh = Difference in total head

L = Barrier thickness

The difference in head, Δh, can be determined from head data in the groundwater model developed from DYNFLOW. Table 7-2 shows the maximum head difference directly upstream and downstream of the barrier. The head is based on a wall of 1500 ft length and 190 ft total depth.

The approach velocity from Equation 7.7, is then equal to the hydraulic conductivity multiplied by the maximum head difference divided by barrier thickness, L. The maximum velocity in m/sec is therefore:

$$u = 10^{-9} \frac{0.45}{L(m)} \tag{7.9}$$

Based on Section 5.2, the limiting contaminant concentration, $C_{e,}$ was chosen as 0.1 mg/l. Section 5.2 also described the presence of zone with maximum concentrations of 6.2 mg/l. Assuming this to be a future load concentration that will eventually reach the wall, C_o was taken as 6.2 mg/l. The ratio, C_e/C_o, is then equal to 0.1/6.2 = 0.016.

Table 7-2. Heads Upstream and Downstream of Wall and Head Difference in Feet

Upstream		Dowstream		
node	head	node	head	Δh (ft)
11	45.16	42	44.96	0.20
12	45.43	43	44.82	0.61
13	45.60	44	44.75	0.85
14	45.73	45	44.72	1.01
15	45.83	46	44.70	1.13
16	45.91	47	44.68	1.23
17	45.98	48	44.68	1.30
18	46.04	49	44.68	1.36
19	46.10	50	44.69	1.41
20	46.14	51	44.70	1.44
21	46.18	52	44.72	1.46
22	46.20	53	44.74	1.46
23	46.22	54	44.76	1.46
24	46.23	55	44.78	1.45
25	46.23	56	44.81	1.42
26	46.22	57	44.84	1.38
27	46.19	58	44.88	1.31
28	46.14	59	44.93	1.21
29	46.07	60	45.00	1.07
30	45.96	61	45.12	0.83
31	45.71	62	45.38	0.33
Maximum Head Difference (ft)				1.46
Maximum Head Difference (m)				0.45

Note: Location of Nodes Shown in Figure 7-1

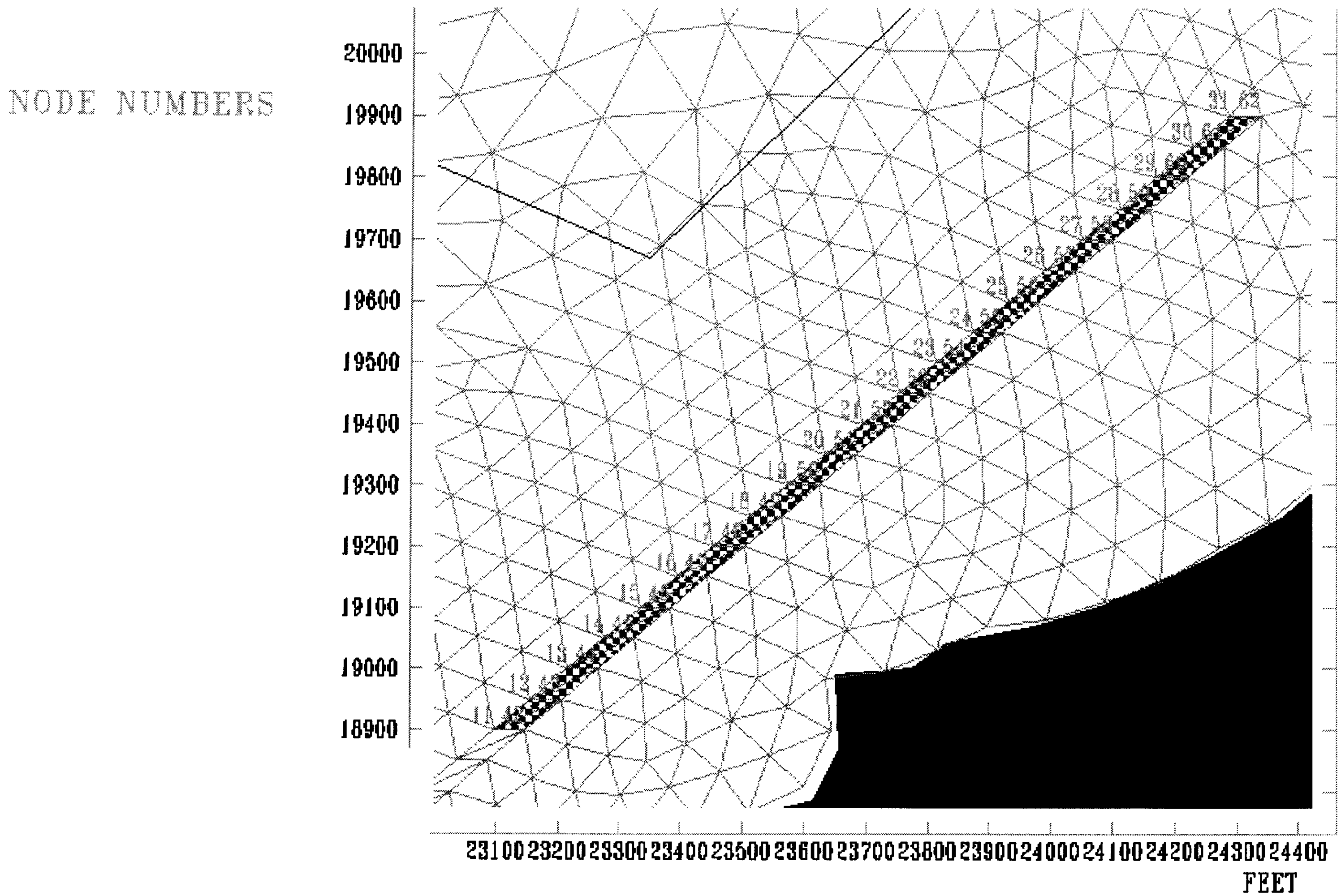


Figure 7-1. Groundwater Grid of 1500 ft Long Wall Showing Wall Node Points at Elevation 0 ft

Wood (1996) states that effective diffusion coefficients generally range from 1 x 10^{-10} to 1 x 10^{-11} m^2/sec depending on the media. A higher value is more applicable to clastic sediments, while a lower value is more applicable to crystalline rocks. The higher value of 1 x 10^{-10} m^2/sec seems to be more appropriate for this study if in-situ granular soils are mixed with bentonite for the barrier.

The mechanical dispersion coefficient, D_m, from Equation 7.5 equals the approach velocity multiplied by the dispersivity, α_L. The dispersivity is usually equated to the median grain size of the soil in the barrier. Since the barrier is composed mainly of in-situ soil in the case of soil-bentonite slurry walls, the median grain size of the in-situ soil was chosen as the dispersivity. LeBlanc et. al. (1991) measured this value at about 0.5 mm. D_m can then be expressed in the following expression by substituting 0.0005 m for α_L and Equation 7.9 for u:

$$D_m(m^2/s) = 0.0005\left[10^{-9}\frac{0.45}{L(m)}\right] \qquad (7.10)$$

The average ratio of sorbed to dissolved phosphorus ranged from 25:1 to 410:1 (Walter, et al., 1995). As a conservative estimate, a ratio of 25:1 is chosen in solving for R_d with Equation 7.3. R_d is therefore equal to 26 (R=1+25=26).

By choosing C(x,t) = C_e, the ratio C_e/C_o from above reduces equation 7.6 to:

$$2\frac{C(x,t)}{C_o} = 2(0.016) = 0.032 = erfc\left[\frac{R_d x - ut}{2\left(R_d(D^* + \alpha_L u)t\right)^{\frac{1}{2}}}\right] \qquad (7.11)$$

Interpolating 0.032 into Table 7-1, gives a z value of about 1.5. Contaminant breakthrough will occur when

$$\left[\frac{R_d x - ut}{2\left(R_d(D^* + \alpha_L u)t\right)^{\frac{1}{2}}}\right] = 1.5 \qquad (7.12)$$

Plugging in the parameters estimated above and substituting Equation 7.9 for the value of u and L for x, one obtains:

$$\left[\frac{26L - 10^{-9}\dfrac{0.45}{L}t}{2\left(26\left[10^{-10} + 0.0005\left[10^{-9}\dfrac{0.45}{L}\right]\right]t\right)^{\frac{1}{2}}}\right] = 1.5 \qquad (7.13)$$

where L (m) and t (sec). Equation 7.13 was solved for a range of design lives from 30 to 75 years. The plot in Figure 7-2 shows the results of the analysis.

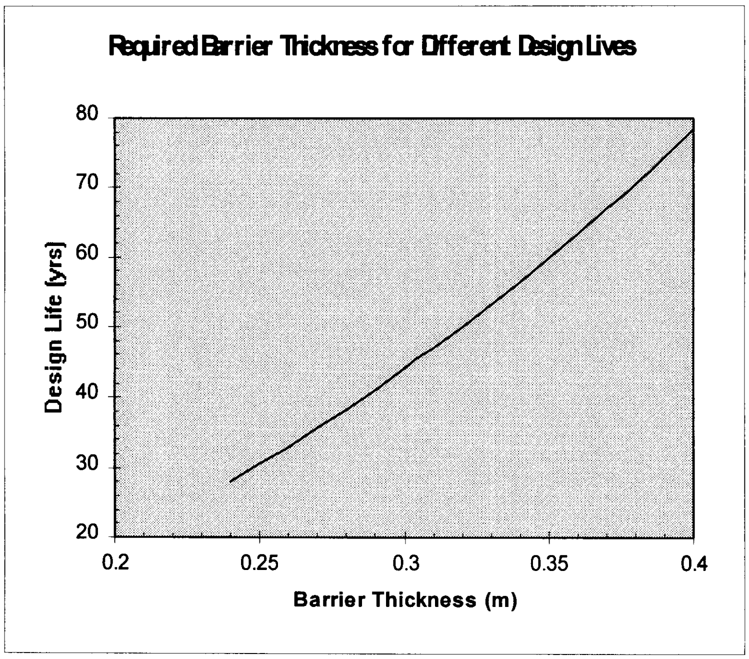


Figure 7-2. Plot of Required Barrier Thickness for Different Design Lives

Figure 7-2 shows that a barrier thickness of 0.25 m (0.82 ft) is required for a design life of 30 years and a barrier thickness of 0.39 m (1.28 ft) for a design life of 75 years. Therefore the design wall thickness will be based on constructability, rather than contaminant breakthrough, since a wall thickness of 1.28 ft or less is not feasible.

8. SUMMARY AND RECOMMENDATIONS

8.1 Summary

A contaminant plume containing high phosphorus concentration levels emanating from a former sewage treatment plant on the Massachusetts Military Reservation (MMR) has formed in Ashumet Valley, Cape Cod. There is concern that the plume discharge into Ashumet Pond may be producing a eutrophic condition in the pond. The thesis studied the use of physical barriers to divert that portion of the plume having phosphorus concentration exceeding 0.1 mg/l away from the pond.

Groundwater modeling used two computer programs developed by Camp Dresser & McKee: DYNFLOW to generate total head contours and DYNTRACK to generate flow lines in the aquifer upstream of Ashumet Pond. The first set of steady state analyses modeled the existing flow conditions with a 270 ft thick aquifer containing five soil layers having K_H decreasing with depth from 230 ft/day to 10 ft/day, and K_V decreasing from 77 ft/day to 0.1 ft/day. This set showed that the contaminant plume is intercepting the pond along a 800 ft wide portion of the shoreline.

The second set of analyses modeled the groundwater behavior after installing a 190 ft deep impermeable wall having lengths of 1500 ft and 2000 ft. Both wall lengths showed very similar containment capabilities, i.e., deflection of flow lines having the highest phosphorus concentrations away from the pond, but with some flow of low contamination under the wall and into the pond.

Four types of barriers were considered: slurry wall construction, deep soil mixing, sheet pile installation, and grout injection. Because of the need for a very deep barrier, slurry wall construction using a grab or clamshell excavation is most promising. A contaminant breakthrough analysis using a hydraulic conductivity of $K = 2.8 \times 10^{-4}$ ft/day (1×10^{-7} cm/sec) for the wall gave a minimum thickness of 1.28 ft for a design life of 25 years. Hence the actual thickness of a slurry wall will be based on constuctability.

8.2 Recommendations

The models used were able to demonstrate the capability of physical barriers to divert flow. However, additional simulations are required to determine optimum designs of the wall's orientation, length and depth.

Since simulations showed that a 1500 ft long and 190 ft deep wall is already capable of diverting the phosphorus plume, additional simulations on shorter and shallower walls are warranted.

The walls were oriented in a N50°E direction and located some 300 ft upgradient of the pond. This orientation and location should be checked regarding the presence of obstructions and problems with right-of-way and to optimize its diversion capabilities.

The model limits did not include the whole of Ashumet Pond, i.e., only the top edge of the pond was included in the model. New simulations should include the whole pond in order to show how the contaminants are infiltrating along the pond bottom, and hence help in making better estimates of areal discharge of phosphorus into the pond.

The stratigraphy used in the model was based on a regional interpolation of Galloni's (1997) model of Western Cape Cod. More focused stratigraphic information from borings near Ashumet Pond is recommended for future simulations.

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10. GLOSSARY

aerobic - containing oxygen and/or nitrate

advection - a mechanism contaminant movement through groundwater via hydraulic groundwater flow

anaerobic- containing no oxygen or nitrate

anisotropy - directional differences in aquifer properties

anoxic - containing no oxygen

anthropogenic - originating from human activity

bentonite - expansive clay

biodegradation - degradation of chemicals via microbial activities (microbial metabolism)

borehole - drilled well in the ground for observation and sampling purposes

calibration - the procedure by which a model is adjusted to be able to fit actual data

chlorinated organic compound - an organic compound that contains one or more chlorine molecules in its molecular structure

chlorinated solvent - a solvent that contains one or more chlorine molecules in its molecular structure

clamshell - excavating tool suspended from a crane

containment - isolation of contaminant sources

dispersion - a transport mechanisms of chemical mass via movement of molecules through diffusion processes resulting in an apparent decrease in chemical concentration

degradation - a decrease in chemical concentration caused by chemical or biological reactions, often accompanied by breakdown products

Dirichlet boundary condition - Specified head boundary condition used in groundwater modeling

downgradient - in the direction of decreasing hydraulic head

eutrophic - a condition of high nutrient content in a surface water body, leading to heavy biological productivity *eutrophication* - an increased growth of aquatic biota, particularly algae and macrophytes, relative to the normal rate of productivity in the absence of perturbations to the system

glacial moraine - loosely packed soils deposited after the retreat of a glacier

grab - excavating tool suspended from a crane

granodiorite - bedrock beneath Cape Cod consisting of granite that has been partially metamorphosed to diorite

grouts - cementitious mixture

hydraulic head - the level to which water will rise, due to potential and kinetic energy of ground water, in a piezometer that is placed in an aquifer

hydraulic gradient - the change in hydraulic head over distance

hydrodynamics - the study of water movement

infiltration beds - sandy areas where the treated groundwater is discharged and can rapidly infiltrate in the soil

neumann boundary condition - no flow boundary condition used in groundwater modeling

nutrient - elements and compounds necessary for biological processes to occur

organic - containing the elements carbon and hydrogen

plume - an area of pollution in any environmental medium

pump and treat - a remediation method whereby ground water is pumped from one or several wells and treated at the surface

recharge zone - area recharging surface waters

remediation - clean-up or restoration of contaminated site

retardation - physical phenomenon where the transport of a chemical specie in the soil is retarded

sealants - cementing agents used to seal permeable boundaries

slurry - mixture of bentonite and soil

stratigraphy - layering of subsurface

vertical gradient - a hydraulic gradient in the vertical direction