US Army Corps
of Engineers
Philadelphia District

CHESAPEAKE & DELAWARE CANAL - BALTIMORE HARBOR CONNECTING CHANNELS (DEEPENING) DELAWARE & MARYLAND

Hydrogeologic Report

1 November 1999

Executive Summary

A) Problem Identification

Groundwater is a valuable resource in the Chesapeake and Delaware Canal (C&D Canal) study area. It is the principal source of potable water for citizens, industry and agriculture. In addition, it provides non-contact industrial make-up and cooling water for a number of major existing and potential industrial concerns including the Star refinery, Occidental Chemical and Standard Chlorine. It is also subject to pollution from residential, industrial and agricultural uses. For these reasons, groundwater is a prized commodity subject to intense scrutiny from citizens and State and Federal regulators. The C&D Canal study area is shown on the attached Figure 1.

The C&D Canal system provides a continuous sea level channel connecting the Port of Baltimore to the northern ports of Wilmington, Philadelphia and the northern trade routes [USACE, 1996]. The idea for a canal to connect the Delaware River and the Chesapeake Bay originated in the late 1800s. The head waters of Back Creek already extended inland from the Upper Chesapeake Bay to Chesapeake City, Maryland and an unnamed tributary to the Delaware River extended west toward St. Georges, Delaware. A canal to connect these existing surface water features was deemed a cost-effective option. Therefore, a private concern constructed just such a canal in the late 1800s. The first canal was not a sea level canal and ships depended on locks in order to transit the canal. In 1919, the canal was adopted (purchased) as a Federal project and was later modified to a sea level canal in 1927. This modification greatly deepened and widened the existing project and removed the existing locks. An additional modification of the canal was authorized in 1954 and constructed in the late 1960s/early 1970s. This major modification provided for a channel depth of 35 feet and a width of 450 feet from the Delaware River to the existing deep water of the lower Chesapeake Bay near Baltimore, Maryland. This modification required an enormous amount of excavation, especially in the "deep cut" portion of the canal which extended from approximately just east of Summit, Delaware to the Delaware/Maryland state line. The location of the deep cut excavation is shown on Figure 2. Further deepening was authorized in 1996. The new project will have a depth of 36 to 40 feet mean low water.

It is likely that prior to the construction of the C&D Canal, the existing streams were sinks for groundwater in the study area. Certainly, the water-table aquifers in the study area including the Columbia Formation, the Talbot Formation and Upland gravels discharged to these surface water features. It is not known if the deeper confined aquifers such as the Mount Laurel, Magothy or the Potomac discharged to these features. Prior to canal construction, the disposition of groundwater discharge/recharge from St. George, Delaware to Chesapeake, Maryland (future "deep cut" area of canal) is unknown. Since construction of the sea level canal, especially after excavating the "deep cut" modification, the canal has become a discharge area for both water-table and deeper confined aquifers.

The potential groundwater impacts from dredging projects have not previously been studied in great detail within the Army Corps of Engineers. The main types of impacts include potential salt-water intrusion from dredging itself and potential leaching impacts from dredged material containment areas. A third problem in some project areas is the increased loss of groundwater in newly dredged areas in the canal or in former upland areas. This type of activity results in the canal or channel becoming a prominent groundwater sink where it may not have been before. These three potential problems were identified during the conduct of prior studies and were evaluated for this report.

B) Identification of Study Areas

The C&D Canal study area extends from the Delaware River to the Upper Chesapeake Bay down to the Port of Baltimore, Maryland. Groundwater is a valuable resource in all of these areas. In order to evaluate the three potential groundwater problems detailed above, it was necessary to determine appropriate groundwater study areas. Several factors were considered in evaluating potential study areas including the hydrogeologic setting, the extent of dredging required for a new 40 feet deep project, location of large pumping wells, the location of confined disposal facilities (CDF) and the review of historical groundwater problems.

After a review of these factors, several groundwater study areas were identified. In Maryland, the Courthouse Point CDF and the Pearce Creek CDF were identified as areas for possible study. The Pearce Creek CDF has been previously studied by several investigations under the Army Corps of Engineers operation and maintenance program. Currently, the Philadelphia District and the Maryland Department of the Environment (MDE) are discussing potential remedial actions for portions of the Pearce Creek site. Accordingly, Courthouse Point was chosen for detailed study. The Courthouse Point study area is shown on Figure 3. The Courthouse Point CDF was chosen for a variety of reasons. First, the site is underlain by the Magothy and Potomac aquifers, which supply drinking water to area residents. Second, the site is adjacent to a large municipal water well for the Harborview community. The pumping influences from this well could potentially exacerbate any groundwater problems. Lastly, this site would be used during any dredging operation. As such, it was postulated that saline-water might enter subsurface aquifers during periods of elevated pools within the CDF. The plan of study developed for Courthouse Point included a large field investigation, preparation of a geologic model, and preparation of a three-dimensional groundwater computer model of the site. These sub-studies are discussed in more detail later in this report.

In Delaware, the study area was delineated as the portion of the canal from the Delaware River west to St. Georges, Delaware. This area includes several dredged material containment areas including the Biddles Point CDF. The study area and the Biddles Point CDF are shown in Figures 4 and 5. This study area was chosen for a number of reasons. First, it is an area of maximum dredging. Potentially a full five feet of canal deepening may occur. Second, the Delaware River is source of higher salinity. Increased salt-water intrusion may occur in sand aquifers along deepened portions of the canal. Third, this portion of the project contains a number of dredged material containment areas. Lastly, this area has the largest potential impact on people and industry. A large number of both municipal and industrial pumping wells exist in this area.

The plan of study to address concerns about groundwater salinity intrusion consisted of field investigations of existing conditions along the canal, the preparation of a geologic model of the area and analysis of proposed canal changes with a three-dimensional groundwater computer model the area. The computer model was utilized to address concerns about potential salinity intrusion into aquifers and for loss of drinking water due to canal deepening. These sub-studies are discussed in more detail later in this report.

C) Salinity Intrusion

Salinity intrusion or encroachment from surface water into groundwater aquifers has been recognized as a potential problem since the 1930s. This phenomenon had been noted along coastal areas dating back to 1929. Potential problems related to new sea-level canals constructed in coastal areas of low topographic relief were noted by Paige in 1936. Paige was an investigator from the Army Corps of Engineers who conducted a preliminary investigation of a sea-level canal across Florida. Paige noted the general relationship of groundwater elevation to topography; that is, that groundwater tends to flow from areas of high topographic relief to areas of low relief such as streams, rivers or canals. This was likely one of the first large-scale engineering projects where groundwater flow was considered in canal site location. In his final analysis, Paige recognized that a new canal would cause a substantial effect on groundwater levels near the canal, but these effects were negligible further inland [Paige, 1936]. Later studies by Brown and Parker [1945] along a completed portion of the canal showed that salt-water intrusion had been facilitated by hydraulic gradients created not by the canal but by nearby pumping [Domenico and Swartz, 1996].

Salinity intrusion in the vicinity of the C&D Canal has also been studied in the past. Groot and Depman [1958] evaluated this potential prior to the last project modification and concluded that there was not enough information to complete the evaluation. It was surmised by both authors that salt-water intrusion would be more severe in areas of pumping such as the Delaware City, Delaware area.

1) Topography

The topography in the study area varies from mean sea level to approximately 160 feet above mean sea level. The study area is situated atop a surface water divide that roughly corresponds to the Maryland and Delaware border. Rainfall run-off on a majority of the Delaware side of the canal flows toward the Delaware River, while a majority of the Maryland side of the canal flows toward the Chesapeake Bay. Figure 6 shows the topography on the eastern side of the study area.

2) Literature Search

An extensive literature search was completed prior to this report in order to develop a good database of information concerning groundwater flow, occurrence and nature within the study area. Office visits and meetings were held at the United States Geological Survey, the Delaware Geological Survey and the Maryland Geological Survey. Pertinent data including reports, core logs, well logs, geophysical information, water levels, precipitation records, and soil samples were all reviewed and retained as necessary. Extensive phone interviews were conducted with notable investigators including Geraghty and Miller, Inc.; Ken Woodruff; Stephanie Baxter; Al Depman; S. Lovell; and others, to discuss groundwater conceptual models and computer models. In addition, these authors were helpful in identifying data gaps that existed in our knowledge base. All of this information was incorporated into the study process, analyzed and utilized as necessary in order to complete the groundwater computer models and this report.

3) Data Collection

For this report, existing information was utilized where possible. Where the necessary information was not available, field data collection was planned and completed. Several types of data were collected to augment the existing information that was available.

First, additional water level information was gathered at existing monitoring wells near Delaware City, Delaware. This data provided additional information on pumping effects adjacent to the Star refinery.

Second, additional information concerning total dissolved solids (TDS) concentrations in monitoring wells along the canal was gathered to determine if salinity intrusion was already occurring. The Philadelphia District contracted with the Maryland Environmental Service (MES) to collect TDS measurements at 60 groundwater wells along the canal. The 60 wells were selected to encompass multiple aquifers and a wide areal extent of the study area, including adjacent to existing dredged material containment areas. The MES utilized measurements of specific conductance (uS/cm) to develop estimates of TDS concentrations (mg/L) in the 60 wells. In Otton [1988], a good approximation of the TDS concentration was developed based on existing water quality data. By multiplying the specific conductance by 0.75, one may estimate the TDS concentration in a well within the study area. This approximation was adopted for this study in order to correlate the MES sample results. In general, all of the wells sampled in this study effort had a TDS concentration of less than 500 mg/l which is the recommended EPA limit for potable water supplies. Further information concerning the MES report, entitled "*A Groundwater Study of Sixty Wells Along the Chesapeake and Delaware Canal in Maryland and Delaware*", is available in the Geotechnical Appendix of the Design Memorandum. Based on the field data, it does not appear that salinity intrusion into sandy aquifers is currently occurring.

Additionally, the Philadelphia District contracted with MES to gather more information concerning the condition and disposition of groundwater wells in the study area. This information supplemented State computer database information covering wells in Delaware and Maryland. It was discovered early on in the study process that existing computerized well inventory databases were incomplete and that a mail survey to contact land owners with wells was necessary. The MES developed and sent a mail survey to approximately 430 well owners in the study area to gather additional information concerning well construction, water quality, installation date and comments. Out of the 430 surveys sent, approximately 145 (40%) were returned with information. This excellent response is considered a good cross section of the study area population and seems to confirm the results of the well sampling detailed above. In general, it does not appear that the canal is currently impacting groundwater aquifers. In addition, the survey points to other groundwater problems unrelated to the canal, including fecal coliform contamination attributed to septic systems or agricultural activities. Further information from the mail survey is available in the report entitled "*A Mail Survey of Wells Along the Chesapeake and Delaware Canal and Adjacent Dredged Material Disposal Areas in Maryland and Delaware*" which is located in the Geotechnical Appendix.

Lastly, a field data collection program was developed and performed at the Courthouse Point CDF. For this program, approximately 15 groundwater monitoring wells were installed in the Potomac Aquifer to monitor groundwater beneath and adjacent to the CDF. These wells were logged to discern the subsurface geology; slug-tested to determine pertinent aquifer properties; and sampled to determine water quality parameters. Although observed concentrations of some constituents were slightly elevated, it does not appear that the site is impacting the Potomac Aquifer in a negative fashion. Also, Potomac Aquifer groundwater levels beneath the site show the flow direction to be toward the Chesapeake Bay for the most part. Observed vertical gradients adjacent to the Chesapeake Bay also indicate discharge from the Potomac Aquifer to the Bay. Additional information concerning Courthouse Point is available in the Geotechnical Appendix of the Design Memorandum in a report entitled "*A Hydrogeologic Evaluation of the Courthouse Point Dredged Material Containment Area*" by Geotechnical Services, Inc.

4) Geology

4.1) Physiography

A large part of Delaware and Maryland, including the C&D Canal study area, is located within the Atlantic Coastal Plain physiographic province (Figure 7). The province is bounded on the northwest by the Appalachian Piedmont physiographic province and on the southeast by the Atlantic Ocean. The boundary between the Atlantic Coastal Plain and the Piedmont provinces is a several-mile-wide zone known as the Fall Zone. In the Fall Zone, the physiography undergoes a transition from the gently rolling hills of thin sediments and exposed bedrock in the Piedmont to the low, mostly featureless, frequently marshy, Atlantic Coastal Plain. The basement (bedrock) contact changes from an undulating surface in the Fall Zone to a gently-dipping feature extending southeast to the submerged continental shelf in the Atlantic Ocean.

In Delaware and Maryland, the Coastal Plain province extends from a line through Trenton, New Jersey to Baltimore, Maryland southeastward for approximately 150 miles to the edge of the continental shelf (Figure 7). The land portion of the province is bounded on the northeast by the Delaware River/Atlantic Ocean and on the west by the Chesapeake Bay. The line of maximum elevation run from the Newark, Delaware Highlands southwestward to the west Baltimore, Maryland area, with the land rising gradually from the sea as a moderately dissected plain to an elevation of approximately 160 feet in the center, from where it slopes toward the Delaware River and Chesapeake Bay drainage systems. The submerged portion of the plain slopes gently southeastward at 5 or 6 feet per mile for nearly 100 miles to the edge of the continental shelf. The surface of the shelf consists of broad swell and shallow depressions with evidence of former shore lines and extensions of river drainage systems.

The Coastal Plain was formed from complex erosional and depositional environments. The opening and closing of the proto-Atlantic Ocean formed the Appalachian massif and the crystalline bedrock basement which would be overlain by sediments. Spreading of the Atlantic Ocean then allowed Pre-Jurassic sedimentary basin development over the bedrock [USACE, 1996]. (All references are available at the end of this report.) Extensive erosion during the Jurassic period removed the sediments above the Precambrian to Early Palezoic bedrock. Unconsolidated fluvial and marine sediments were then deposited during the Cretaceous and Tertiary periods. During the Plio-Pleistocene, sea level fluctuations and glacial action allowed erosion of the late Tertiary sediments and then flooding of the eroded valleys. This action within the Delaware Drainage and Susquehanna Drainage systems led to the development of the Delaware and Chesapeake Bays, respectively. Those areas still lying above sea level following the Pleistocene glaciation were then subject to deposition of coarse clastic material which exists as a cap on the higher elevations in the Atlantic Coastal Plain.

Sundstrom and Pickett [1971], have divided Delaware into two regional geologic provinces: the Appalachian Piedmont and the Atlantic Coastal Plain. Northeastern

Delaware lies within the Piedmont which is characterized by small hills and hummocks. The surface of this complex consists of very old metamorphic and igneous rocks that slope seaward and form the basement upon which all the coastal plain deposits lie. Most of the Piedmont in Delaware is underlain by the Wissahickon Schist. Smaller amounts of marble, gabbro, amphibolite and granite are also present.

4.2) Coastal Plain Geology

The Coastal Plain consists of beds of gravel, sand and clay, which dip gently towards the southeast. Certain identified fossils show the beds to be of the Cretaceous, Tertiary, and Quaternary ages. The Coastal Plains of Delaware and Maryland cover approximately 3,000 square miles in area and are part of the larger Atlantic Coastal Plain. The older and lower layers appear at the surface along the northwest margin of the coastal plain and pass beneath successively younger strata in the direction of their dip. The parallel outcrops of successive strata make this a "belted coastal plain". Since the Formations dip toward the southeast, successively younger layers appear along the shore and progress southward. The Atlantic Coastal Plain consists of sedimentary Formations overlying a crystalline rock mass known as the "basement". From well drilling logs, it is known that the basement surface slopes at about 75 feet per mile to a depth of more than 3,000 feet near the coast. Geophysical investigations have corroborated well-log findings and have permitted determination of the profile seaward to the edge of the continental shelf. A short distance offshore, the basement surface drops abruptly but rises again gradually near the edge of the continental shelf. Overlying the basement are semi-consolidated beds of lower Cretaceous sediments. The beds vary greatly in thickness, increasing seaward to a maximum thickness of 13,000 feet then decreasing to 8,000 feet near the edge of the continental shelf. On top of the semi-consolidated material lie unconsolidated sediments of Upper Cretaceous and Tertiary Formations. These materials, in relatively thin beds on the land portion of the coastal plain, increase in thickness to a maximum of 5,000 feet near the edge of the continental shelf. The approximate outcrops of various Coastal Plain formations is shown on Figure 8 which details the regional geology. Table 1 depicts a correlation chart for the geology of Delaware, Maryland and New Jersey.

The bedrock beneath the Coastal Plain in Delaware and Maryland mainly consists of crystalline rocks of the Wissahickon Formation. The Wissahickon Formation is made up of schists, mica-schists, gabbros and gneisses. In the Philadelphia area, a layer of "saprolite" occurs on top of the basement complex. This material is composed of sandy soil and decomposed bedrock which has been cemented to some degree. In some locations 7 to 15 feet of saprolite is present [Krajnik, 1996].

The oldest sediments of the Delaware and Maryland Coastal Plain are sands, silts, and clays of continental origin which have been grouped into a unit known as the Potomac Group. Cretaceous deposits consist of continental sediments that were transported from the Appalachian Mountains by streams about 120 to 130 million years ago (early Cretaceous) and eventually deposited in a series of wedge-shaped bodies during the late

Table 1
Geologic Correlation

Geologic Age		New Jersey	Delaware	Maryland	
Quaternary	Pleistocene	Cape May Formation Bridgeton Formation	Columbia Formation	Parsonsburg Sand Pamlico Formation Talbot Formation Sunderland Wicomico Formation Beaverdam Sand	Columbia Group
Tertiary	Pliocene	Beacon Hill Gravel Pennsauken Formation	Brandywine, Bryn Mawr, and Beacon Hill Gravels	Brandywine, Bryn Mawr, and Beacon Hill Gravels Pennsauken Formation (Upland Gravels)	Bryn Mawr Group
	Miocene	Cohansey Sand Kirkwood Formation	Pocomoke Formation Manokin Formation Frederica Formation Cheswold Sand	Yorktown and Cohansey Formations St. Marys Formation Choptank Formation Calvert Formation	Chesapeake Group
	Oligocene	*Missing*	*Missing*	*Missing*	
	Eocene	Piney Point Formation Shark River Formation Manasquan Formation	Piney Point Formation Nanjemoy Formation Aquia Formation	Chickahominy Formation Piney Point Formation Nanjemoy Formation Aquia Formation	Pamunkey Group
	Paleocene	Vincentown Formation Hornerstown Formation	Rancocas Formation	Brightseat Formation Hornerstown Formation	Rancocas Group
Cretaceous	Upper Cretaceous	Tinton Formation Redbank Formation Navesink Marl Mount Laurel Sand	Redbank Formation Navesink Marl Mount Laurel Sand	Monmouth Formation	Monmouth Group
		Wenonah Formation Marshalltown Formation Englishtown Formation Woodbury Clay Merchantville Formation	Marshalltown Formation Englishtown Formation Merchantville Formation	Matawan Formation	Matawan Group
		Magothy Formation	Magothy Formation	Magothy Formation	Magothy Group
		Raritan Formation Patapsco Formation	Potomac Formation	Raritan Formation Patapsco Formation Arundel Clay	Potomac Group
	Lower Cretaceous	Patuxent Formation		Patuxent Formation	

Table adapted from Overbeck [1958], Jordan [1962], Sundstrom and Picket [1971], Spoljaric [1986], Higgins and Connant [1986], Zapecza [1989] and Brown [1997].

Cretaceous. This was followed by a marine transgression that resulted in the deposition of sediments practically without interruption until Eocene time, including the Raritan and Magothy Formations. Other Formations developed during the Cretaceous include the Merchantville Formation, the Woodbury clay, the Englishtown Formation, the Marshalltown Formation, the Wenonah Formation, the Mount Laurel sand, and the Navesink Formation.

The Tertiary sediments of the Delaware and Maryland Coastal Plain overly the upper Cretaceous deposits. The tertiary sediments generally consist of greenish sands and other marine deposits. They are present in Delaware and Maryland in the form of several units. Formations developed during the Tertiary include (from oldest to youngest) the Hornerstown Formation, the Vincentown Formation, the Manasquan Formation, the Piney Point Formation, the Cheswold Formation, the Frederica Sand and the Bridgeton/Pennsauken/Bryn Mawr/Beacon Hill gravel.

Based on visual identification alone, it is often difficult to distinguish the boundary between Cretaceous sediments and Tertiary sediments. In New Jersey, it is common practice to use down-hole geophysical data to aid in the hydrogeologic interpretation of these units. Common geophysical methods utilized include spontaneous potential, single point resistance, electric and natural gamma radiation. These geophysical methods have been found to be very beneficial when marking out contacts between different Formation types. Typically, these methods are more reliable than driller's logs or geologists' descriptions of drill cuttings [Zapecza, 1989]. More detailed descriptions about geophysical investigations relating to groundwater projects can be found in many publications prepared by the United States Geological Survey (USGS) and others.

Deposits of Pleistocene and Recent age form a thin covering over portions of the Coastal Plain. These Quaternary sediments consist of a series of well-defined terraces composed of gravel, sand, peat, silt and clay. These materials were deposited during various stands of sea level associated with last ice age, and are developed as a series of terraces due to successively lower elevations of erosion. The main Formation developed during the Quaternary time was the Columbia or Talbot Formation. This formation correlates to the Cape May Sand in New Jersey. In many areas where this Formation overlies the Frederica Sand or the Vincentown Sand, these formations are difficult to distinguish on the basis of composition and they are lumped together as part of the water table aquifer.

In most portions of the C&D Canal study area, the Columbia or Talbot Formation overlies the older Tertiary or Cretaceous formations which "subcrop" beneath it. Precipitation that recharges the Columbia or Talbot Formation also recharges all of the other major aquifers through their respective subcrops. Geologic cross-sections were drawn parallel to the canal as shown in Figure 9. The resulting cross-sections are shown in Figures 10 and 11. Both sections are drawn looking north.

The following paragraphs detail the specific geologic and hydrogeologic units located within the study area. The text is a combination of new original work and historical work completed by other authors including Sundstrom, Pickett, Connant, Otton, Overbeck, Jordan, Martin, Spolijaric, Baxter, Higgins, Zapecza, Navoy, Rogers, Krajnik, Andres, Woodruff, Talley, Rasmussen, Groot, Rima, Depman, Lazor and Brown. A lot of the previous work was summarized by Rogers, Golden and Halpern (RGH) in 1986 under contract to the Philadelphia District, U.S. Army Corps of Engineers. In addition, Geraghty and Miller performed groundwater salinity intrusion modeling for the Philadelphia District as part of the *C&D Canal – Baltimore Connecting Channels Deepening Feasibility Study* which provided additional information.

5) Hydrogeology

5.1) Description of Important Hydrogeologic Units

The following sections detail and describe the most important hydrogeologic units identified in the study area.

5.1.1) Bedrock

The crystalline rocks of the Piedmont, which consist of metamorphosed sedimentary and igneous rocks (e.g., schists, quartzites, marbles, and gneisses), make up the bedrock in this province and extend to great depth. These metamorphic rocks have been intruded by granites, pegmatites, quartz veins, gabbros, and diabase dikes. To the east, the bedrock surface slopes gently toward the ocean and is present beneath the sediments of the Coastal Plain at increasing depth to the east. This surface, which is somewhat irregular as the result of its exposure to a long period of erosion, dips rather steeply away from the Fall Zone at about 125 feet per mile. It then dips to the southeast at about 40 feet per mile beneath the Coastal Plain, increasing to about 100 feet per mile near the coast of Maryland. A dip of approximately 75 feet per mile is a good average for the basement.

There are five general categories of rock type represented in the Piedmont:

Mica gneiss, the only rock in the five categories with a sedimentary origin, is a schistose rock ranging from a coarsely crystalline muscovite-biotite gneiss to a finer-grained muscovite-chlorite gneiss or a chloritic quartzite. This rock may be conglomeratic or may show distinct beds (e.g., quartzite, gneiss, mica schist), and strikes about N60-75°E with a dip of 30-60° southeast. This rock is not very resistant and is usually deeply weathered. It is present only in the northeast corner of Cecil County, Maryland, but is extensively found in southeastern Pennsylvania.

Granitic gneiss is a medium-grained, light-colored rock irregularly marked by dark biotite or hornblende inclusions. It crosses Cecil County, Maryland, in a band trending northeast and disappears beneath Pleistocene gravels near Newark. The schistosity of this rock strikes about N60°E and dips about 30° southeast. As the granitic gneiss approaches the mica gneiss it becomes progressively more micaceous.

Gabbro and meta-gabbro are found in a belt which borders the granitic gneiss to the north. It is composed of hypersthene gabbro (norite), quartz-hornblende gabbro, hornblende gabbro, or meta-gabbro. Outliers of this rock are also found at Grays Hill, Iron Hill, and Chestnut Hill. An increase in the quartz content of the gabbros is seen toward the more southern exposures.

Meta-pyroxenites and peridotites are a diverse group of greenstones that include amphibolites, serpentines, and soapstones. They occur in a belt from the northern limit of the gabbros to the vicinity of Bald Friar, Maryland; a few isolated lenses are found at and to the south of Conowingo. The rocks consist of metamorphosed, non-feldspathic igneous rocks, most of which have been altered to serpentine.

Intrusives comprise the other two categories of rock type in the Piedmont, and are not very significant in terms of volume or exposure. The intrusives include dikes of meta-rhyolite and gabbroic material and diabase dikes that are probably of Triassic or Jurassic age.

The bedrock beneath the Coastal Plain, often referred to as basement, is not well-known except near the Fall Zone. Most studies assume that it is equivalent to the same metamorphosed rocks that occur in the Piedmont, based on samples obtained from a few deep wells that have been drilled on the Eastern Shore. In these deep boreholes, crystalline rocks that appear to be equivalent to the Wissahickon Formation and Baltimore gabbro have been encountered. Most of the Coastal Plain in Delaware appears to be underlain by the Wissahickon; the older Cockeysville marble is exposed only in two unroofed anticlines. These two units belong to the Glenarm Series, a group of rocks that were probably deposited in late Precambrian or early Paleozoic time and have since been severely metamorphosed. The metamorphism has obscured the age relationship of most of the rocks of the Piedmont. [USACE 1996]

Groundwater flow in the Piedmont is a controlled by a combination of primary porosity and secondary porosity. Primary porosity is the actual pore spaces within the bedrock mass. Sandstones can have a relatively high primary porosity while diabase or quartzite has a low primary porosity. Secondary porosity consists of zones of higher hydraulic conductivity caused by bedrock fractures or dissolution cavities. These void spaces often transmit a majority of all of the bedrock groundwater. The degree of fracturing depends on a number of factors including degree of mechanical/chemical weathering, degree of metamorphism and geologic history. In general, rock types that exhibit a higher degree of fracturing have a higher hydraulic conductivity.

5.1.2) Potomac Group

The oldest sediments of the Coastal Plain are sands, silts, and clays of continental origin which have been grouped into a unit known as the Potomac Group. In Delaware, where individual formations are difficult to distinguish, the entire unit is referred to as the Potomac Formation. Cretaceous deposits consist of continental sediments that were transported from the Appalachian Mountains by streams about 120-130 million years ago (during the early Cretaceous) and eventually deposited in a series of wedge-shaped bodies during the late Cretaceous.

The Potomac Group lies unconformably on the basement rock as a southeastward thickening homoclinal wedge and consists of three formations, where it can be subdivided. These include the Patuxent Formation, the Arundel Clay, and the Patapsco Formation. These three lithologic units are seen as discrete entities only in Maryland; the

Patuxent Formation is not separable from the Patapsco Formation in Delaware because of a lack of correlatable units, and the Arundel Clay has been identified only in southeastern Maryland.

Earlier reports include the Raritan Formation, an upper Cretaceous formation that is extensively developed in New Jersey, with the Potomac sediments. Hydrologically, this is probably a valid approach because the two units are in essence part of a multi-aquifer sequence; however, most modern reports place the Raritan in conjunction with the overlying Magothy Formation, on the basis of stratigraphic and paleontologic characteristics.

All three units of the Potomac Group are apparently bounded by unconformities, and consist mainly of arkosic sands and clays with some gravel beds. The Potomac Group is characterized by considerable lithologic variability both horizontally and vertically; individual beds within the unit are restricted in areal extent and thickness. Where the formations cannot be subdivided, the Potomac is separated into two zones on the basis of mineralogy: the lower zone, referred to as the Patuxent zone, contains abundant staurolite, and the upper zone, referred to as the Patapsco-Raritan zone, contains only stable heavy minerals such as tourmaline, zircon, and rutile. Only the latter zone is encountered in outcrop in the canal.

The Potomac Group outcrops in a wide and irregular band immediately along and southeast of the Fall Zone; the top of the formation dips to the southeast until it is about 2500 feet below sea level at Ocean City, Maryland. The formation also thickens downdip, increasing from about 100 feet at the Fall Zone to over 4700 feet off the coast of Delaware and over 5400 feet at Ocean City, Maryland. North of the canal, the Potomac Group is overlain unconformably by sands and gravels of the Columbia Formation; south of the canal, the overlying sequence becomes more complex and includes marine upper Cretaceous units.

Sediments of the Potomac Group were deposited under estuarine, river delta, and fluvial conditions, and therefore exist mainly as a complex of lens-shaped and channel deposits rather than as sheets of uniformly-graded materials. These sediments are reddish-brown, and range in texture from a series of coarse channel deposits (Patuxent Formation) characteristic of alluvial valleys, to thick clay (Arundel) and fine-to-medium sand and silt beds (Patapsco Formation) characteristic of back-swamp and flood-plain deposits. These depositional environments shifted laterally, coalescing with one another in a large delta-like system. The individual sand, silt, and clay units therefore have little lateral continuity. On the Eastern Shore and in southern Maryland, the Potomac sediments tend to have more clay and be slightly thicker than those farther north. In Delaware, the composition of these sediments is dominated by silts and vari-colored clays; sand bodies within the silty matrix resemble shoestring channel deposits formed by unidirectional currents originating in the north and northwest.

Patuxent Formation. The Patuxent Formation is the basal unit of the Potomac Group and outcrops in an irregular belt 1 to 6 miles wide just southeast of the Fall Zone. The formation has been described as irregularly stratified, cross-bedded, lenticular, white to light gray to orange to brown, moderately sorted, angular sands and subrounded gravels. The Patuxent Formation, which is also referred to as the Lower Potomac Aquifer, is the most prolific aquifer in the study area. A majority of the large municipal and industrial water supply wells including Delaware City, DE; Starr Enterprises; Chesapeake City, MD; and Elkton, MD, tap this aquifer for drinking water. Well yields up to 1000 gallons per minute (GPM) have been reported.

Arundel Clay. The Arundel Clay unconformably overlies the Patuxent Formation. The formation apparently occupies post-Patuxent drainage lines, is best developed in the Baltimore-Washington area, and has not been encountered north of Cecil and Kent Counties, Maryland. This unit is composed almost entirely of clay, and is ordinarily dark-colored and lignitic. In places, it contains so many iron concretions that it was formerly mined as ore. In other locations, the clay contains nodules, flakes, and ledges of earthy iron carbonate and siderite. Sands, where they are present, are a minor component and resemble the sands of the underlying Patuxent Formation. The Arundel Clay is not well developed in Delaware so it is not recognized there. In Delaware, the clays are more discontinuous vertically and Martin [1984] classifies the Potomac into three separate aquifers based on hydrologic considerations. In Maryland, the Arundel Clay is an excellent confining unit due to its thick accumulation and low hydraulic conductivity. The Arundel has been reported to be as much as 150 feet thick is some locations near Baltimore, Maryland.

Patapsco Formation. The Patapsco Formation also was formed under fluvial and estuarine conditions, and consists of irregularly stratified silts, clays, and subrounded, fine to medium quartzose sands, with occasional small deposits of gravel. The overall sediment size is generally finer than the Patuxent Formation, and the percentages of sand range from 25 to 50. The clays are dominantly brick-red or red and gray-mottled, tough, and weather into small angular fragments. The formation can be roughly distinguished from the Patuxent by the lack of mica and feldspar, and from the Raritan by the lack of fine sand. The Patapsco Formation outcrops in Maryland and Delaware. In Maryland, it is present in an irregular belt about 5 miles wide. The Patapsco Formation, which is also referred to as the Upper Potomac Aquifer, is also a large water bearing aquifer. Both Earleville and Cecilton, MD withdraw well water from the Patapsco Formation.

5.1.3) Magothy and Raritan Group

The Raritan and Magothy Formations unconformably overlie the Potomac Group sediments, and consist of sands and clays of estuarine and perhaps fluvial origin. These formations mark the transition from the underlying continental sediments to the glauconitic marine sediments of the Matawan and Monmouth Groups. It is these upper Cretaceous units that are so well-exposed in the banks of the canal. Most present authors assign the Raritan Formation to the Potomac Group, however, hydrogeologically, it acts as an excellent confining clay unit for a majority of the study area. Therefore, it is broken out separately from the Potomac Group for this report.

Raritan Formation. The Raritan Formation is a non-marine series of sands and clays that locally contains some tongues of marine sediments. The sands are usually white or buff and are more common in the upper part of the formation. The clays are variegated or are white, drab, or pink. These strata change rapidly both horizontally and vertically. The sands are occasionally coarse-grained and gravelly, and occur as irregular lenses in the finer-grained matrix. The formation can sometimes be distinguished from the Patapsco Formation by a higher proportion of sand, although this may be difficult. The Raritan Formation is present at the surface in Cecil County as the capping of hills along the Elk Neck peninsula and to the southeast. The outcrop is only 4 miles wide in Maryland, thinning to the north and providing only scattered exposures in Delaware. The Raritan Formation which is currently taken as part of the Potomac Group, is seen as an excellent confining clay unit within the study area. Boreholes and wells installed as part of this study and previous studies show the clay to be as much as 40 feet thick and mostly continuous across the study area.

Magothy Formation. The Magothy Formation unconformably overlies the Potomac Group south of Cecil County and the Raritan Formation to the northeast of this. Its distinctive lithology of white sands alternating with black, lignitic silts provide a marker of the transition from continental to marine sedimentation. The formation was apparently deposited in a shoreline environment and includes elements of strand line, barrier island, and lagoon conditions or sheet sands. The presence of siderite in beds of clay within the formation indicates deposition in a swampy environment. This formation is one of the most clearly-defined of the Coastal Plain units (in outcrop), and retains a fairly uniform thickness in outcrop of about 10 feet. The Magothy Formation crops out in Maryland in a two-mile band extending from the canal entrance along the Elk River to Grove Point on the Sassafras River. The Magothy Formation is very well-exposed in the canal, and it underlies almost all of the Eastern shore area except for the northern three-quarters of Cecil County. The Magothy Formation is the second most productive aquifer in the study area. Well yields of up to 300 GPM have been reported.

5.1.4) Matawan Group

The Matawan Group is part of a series of sedimentary formations that was deposited during marine transgressions and regressions during the upper Cretaceous period. The Matawan unconformably overlies the Magothy Formation. In the Coastal Plain of Maryland, Delaware, and New Jersey, differing sedimentary environments and sediment sources resulted in the deposition of sediment bodies that are variable in composition, texture, spatial orientation, and lateral extent.

Where the Matawan Group can be subdivided into formations, it consists of the basal Merchantville Formation and the Wenonah Formation (in Maryland) or the Merchantville, Englishtown, and Marshalltown Formations (in Delaware and New

Jersey). In New Jersey and possibly northern Delaware, the Woodbury Clay is also present between the Merchantville and Englishtown Formations. In Maryland, the formation crops out in a 1- to 2-mile wide belt from the Delaware state line near Chesapeake City southwest across Cecil County. As a formation, its identifying characteristics are abundant mica and glauconite, but marine fossils are rare. It has been described as dark gray to bluish gray, micaceous, slightly glauconitic sandy silt.

The Matawan Formation sediments were probably deposited in shallow, open marine areas, possibly with some embayments, as indicated by the presence of glauconite and distinctive fossil assemblages. However, the Englishtown Formation sands represent shoreline deposition during a marine regression (sea level falling), based on formation lithology and location of fossil burrows. In general, the coarser-grained, more glauconitic sediments reflect marine transgressions, while the finer-grained, more quartz-rich sediments reflect marine regressions. Therefore, the basal Merchantville, Marshalltown, Wenonah, basal Mount Laurel, and Redbank Formations are interpreted as representing periods of regression, and the upper Merchantville, Englishtown, and upper Mount Laurel-Navesink Formations are indicative of transgression.

The Matawan Group, which forms the Matawan confining unit, contains three main mappable formations in Maryland [Otton, 1988]. These area the Merchantville, Englishtown and the Marshalltown Formations. In Delaware, the Woodbury Clay and the Wenonah Formation have also been indentified in several locations. The Woodbury Clay is almost indistinguishable from the Merchantville except for slight differences in shear strengh. Dames and Moore commented upon this fact during investigation of the Summit Power Station in the 1970s. The Wenonah can be identified in the southeastern portion of the study area. Together, all of these formations, whose combined thickness ranges up to 100 feet thick, form an excellent confining unit protecting the underlying Magothy Aquifer.

Merchantville Formation. The Merchantville Formation is the basal unit of the Matawan Group and lies unconformably on the Magothy Formation. The formation consists mainly of dark, micaceous, glauconitic silty sand and sandy silt. The uppermost layer is more sandy, gray, and well-sorted. In places, the upper two feet have been observed to consist of cinnamon brown sediment (where overlain by Pleistocene deposits) and probably represents a weathering surface.

Woodbury Clay. The Woodbury Clay is a slightly micaceous, generally non-glauconitic clay which weathers to a light chocolate brown color, and breaks into blocks often showing conchoidal fracture. This formation does not appear in the canal outcrops, but may be present in Delaware to the southeast of its exposures in southwestern New Jersey.

Englishtown Formation. The Englishtown Formation has been described from the subsurface in Maryland in a siting study, although other workers have noted that the upper Cretaceous marine formations are relatively thin in Maryland and are difficult to correlate with the better-developed sequence in New Jersey. The Delmarva study described the formation as thin beds of black, silty clay and white micaceous sand, with pebbles up to 1/4-inch in diameter common in many of the sands.

Marshalltown Formation. The Marshalltown Formation consists of a nearly pure greensand marl in New Jersey, but these sediments are not observed in outcrop in the canal. Its presence in the subsurface has been inferred by characteristic fossils (Exogyra ponderosa) that have been dredged from the canal between the Penn Central railroad bridge and St. Georges, Delaware. In Maryland, the Marshalltown has been described in the subsurface as a massive dark gray glauconite quartz sand, grading into a dark clay quartz silt. In the vicinity of the canal, the formation has been described as a dark greenish-gray, highly glauconitic, very fine silty sand.

Wenonah Formation. The Wenonah Formation consists of a rust brown to gray, well-stratified, fine, subangular, well-sorted, micaceous quartz sand with some glauconite and numerous fossils that appear to be tubes (referred to as Halymenites major). In several locations, the formation contains thin clay laminae. Where the formation is visible in the canal, the Wenonah overlies the Merchantville Formation conformably and grades into it. There appears to be an unconformity at the top of the formation, although many other workers consider the boundary with the overlying Monmouth Group sediments to be gradational. In the canal outcrops, there is an abrupt change from fine sand to the coarse silt of the Mount Laurel Formation. Since the contact appears to be gradational at other places, the unconformity may be a local phenomenon.

5.1.5) Monmouth Group

The Monmouth Group represents a series of marine upper Cretaceous formations that overly the Matawan sediments or, particularly in Delaware, appear to be gradational from the Matawan. The separation between the Matawan and Monmouth groups has been identified in Delaware as the zone containing numerous Exogyra cancellata fossils.

The Monmouth sediments, as a group, consist mostly of dark green, glauconitic sand, and beds of clay are usually absent. These sediments are generally coarser and more glauconitic, and are distinguished from the Matawan Formations only in outcrop because the sediments all form essentially a single lithic unit in the subsurface. The Monmouth Group is also difficult to distinguish from the overlying Aquia Formation (Eocene age). The Monmouth Group formerly was divided into the Navesink and Redbank Formations (in Maryland), but is now considered to be one lithologic group with two general subdivisions. In the eastern portion of the canal and just to the south, the Monmouth Group can be separated into the basal Mount Laurel-Navesink Formation and Redbank Formation. In these canal outcrops, the Monmouth is characterized by reddish-brown sediments with a moderately high glauconite content, and argillaceous sand or sandy clay. The basal part of the formation contains numerous fossils and siderite concretions at some locations.

The Monmouth Aquifer which is recognized in Maryland, consists of the sandier portions of the Monmouth Group including the Mount Laurel and the Red Bank Formations. The degree of sandiness is variable and only supports appreciable well yields south of the study area. In Delaware, the Monmouth Aquifer gives way to the Mount Laurel Aquifer. The Mount Laurel is an important aquifer in Delaware south of the study area. Within the study area, only a few small wells tap the aquifer for dependable water supply. South of the study area, well yields range from 8 to 42 gpm [Otton, 1988].

Mount Laurel. The Mount Laurel and Navesink Formations are treated as separate units in New Jersey, but it is difficult to separate the two in Maryland. The formation has been described as a dark green to brown with numerous rust spots, fine to very fine, poorly sorted, subangular, glauconitic quartz sand with some silt and clay and a little mica to a dark green to black, coarse silt with abundant glauconite. The surface of this formation weathers greenish-white where there is abundant clay.

Navesink Formation. The Navesink Formation is described as a dark green to grey sandy silt. There is little mica and some glauconite.

Redbank Formation. The Redbank Formation consists of a reddish-yellow to red-brown with some rust brown spots, fine to medium, well-sorted, subrounded, slightly dirty quartz sand with some glauconite and black minerals and a little mica and feldspar. Most of the quartz grains are stained with iron hydroxides. The unit is gradational into the Mount Laurel-Navesink below, and becomes slightly more clayey and glauconitic toward its base. The formation is indurated to various degrees, which may be due to the oxidation of glauconite.

5.1.6) Rancocas Group

The Paleocene sediments of the Rancocas Group represent the oldest units of Tertiary age in this area and overly the upper Cretaceous deposits. The Tertiary sediments generally consist of greensands and other marine deposits and are found several miles south of the canal and beneath much of the Coastal Plain. However, the similarity between the late Cretaceous and early Tertiary sediments in this area makes stratigraphic correlation difficult, particularly since some of the contact between units appear to be gradational.

In a hydrogeologic sense, Otton has defined the Aquia-Hornerstown Aquifer in Maryland, while Delaware refers to the same water bearing zones as the Rancocas Formation. These formations are not reliable water supply units in the study area and are only found south of the study area. The aquifer has abundant glauconite and well yields vary widely. Dependable yields are reported in Chestertown, Maryland and for several industrial concerns in Kent County, Delaware.

Rancocas Formation. The Rancocas Formation is a green and gray, fine to medium grained, silty, glauconitic sand. In weathered outcrops, it is indurated by limonite, and it is found in Delaware only in isolated outcrops. These sediments possibly correlate with the Hornerstown and Vincentown Formations in New Jersey; the Rancocas is sometimes referred to as the Aquia Formation in Delaware and Maryland. Some reports classify the Aquia Formation as Paleocene; however, most of the reports that were reviewed classify the Aquia as Eocene in age and part of the Pamunkey Group, and it is discussed in that section in this report. The Rancocas Formation also correlates with Brightseat Formation in Maryland.

5.1.7) Pamunkey Group

The sedimentary formations of Eocene age in the vicinity of the canal include the Pamunkey Group, divided into the Aquia and Nanjemoy-Piney Point Formations. In early reports, these formations were further divided into the Piscataway and Paspotansa members (Aquia) and the Potapaco and Woodstock members (Nanjemoy). The Aquia Formation is best-developed in Maryland, whereas the Nanjemoy is best-developed in Virginia. These sediments are of marine origin, unconformably overly the upper Cretaceous formations (in Maryland and Delaware), and consist mainly of calcareous and argillaceous greensands.

Aquia Formation. The Aquia Formation was deposited in a shallow water marine environment during the late Paleocene or early Eocene, and outcrops in Maryland in western Charles County to southeast Cecil County. The outcrop belt on the western shore is wide, but on the Eastern shore it is covered with Quaternary sediments so that the outcrops are seen only in stream valleys. the formation has been described as fine to coarse-grained sand containing layers of gray-green silt and clay, with indurated, calcite-cemented sand and fossil beds composed of shell debris. The green color is from the materials glauconite and goethite, which compose 20 to 70 percent of the formation. The grain size is generally coarser toward the top of the formation, and silt and clay begin to predominate downdip until the formation changes to a clay in the vicinity of Denton, Maryland.

Nanjemoy and Piney Point Formations. The Nanjemoy and Piney Point Formations, which conformably overly the Aquia, are composed of two distinct groups of sediment that are not present north of southern Queen Anne's County. the Piney Point Formation overlies the Nanjemoy Formation in eastern Maryland, but does not outcrop; it is observed only in wells in the southern counties of the Eastern Shore. the Nanjemoy differs from the Aquia in that it is more argillaceous, and contains no calcareous zones. The formation is a greenish-drab, glauconitic, argillaceous, fine-grained sand containing scattered gypsum crystals and scattered iron concretions. The Nanjemoy Formation is a relatively impermeable series of silts and clays, changing to a sandier facies on the western shore. In much of southern Maryland, the basal layer of the Nanjemoy is a tough, pink clay known as the Marlboro clay member. The Piney Point Formation is composed of medium to coarse sand and some layers of shell debris, with fine sand and clay. The grain size generally increases toward the top of the formation, where some of the layers have been cemented by calcite. After deposition, the top of the formation was truncated by erosion prior to being overlain by the Calvert Formation in Miocene time. Downdip, the Piney Point Formation changes from sand to sandy clay to clay.

5.1.8) Chesapeake Group

The Miocene sediments in the vicinity of the canal are represented by the Chesapeake Group, consisting of the Calvert, Choptank, St. Mary's, and Yorktown Formations. The Yorktown is present far to the south of the canal. The Chesapeake Group sediments are chiefly of marine origin, and are slightly unconformable, although this is not apparent in some areas. The sediments consist of layers of unconsolidated silt, sand, and clay, and were eroded to some degree prior to the deposition of the overlying Quaternary sediments. Thus, these sediments do not outcrop but are present beneath the thin veneer of Pleistocene sands and gravels.

Calvert Formation. The Calvert Formation is the basal unit of the Miocene sequence, which lies unconformably on the Eocene formations. The Calvert Formation has been described as light cream-colored sand and clay, at places replaced by blue or drab clay, diatomaceous sandy clay, and indurated fossiliferous beds. The formation is areally extensive and is found on both sides of the Chesapeake Bay. The outcrop/subcrop areas are located in a 20- to 30-mile wide belt across the Eastern Shore, but the formation is covered in most places by Quaternary sediments. These sediments continue to the northeast into New Jersey, where they roughly correlate with the Kirkwood Formation. The formation can be easily distinguished from the underlying Eocene sediments, but the contact between the Calvert and overlying Pleistocene sand and clay is difficult to define. At most places, a coarse gravel bed is present at this boundary.

Choptank Formation. The Choptank Formation unconformably overlies the Calvert Formation and consists of fine, yellow quartz sand, bluish-green sandy clay, slate-colored clay, and locally, layers of indurated material. The formation has two well-defined fossiliferous zones. The Choptank Formation is easily distinguished from the underlying Calvert (dark clays) by its yellowish sands. The outcrop/subcrop belt of this unit is about 20 miles wide across the Eastern Shore, where it is exposed in stream banks and ravines. In most places, it is covered by Quaternary sediments.

St. Mary's Formation. The St. Mary's Formation unconformably overlies the Choptank Formation, and is described as greenish-black fossiliferous clay, sandy clay, and sand. The subcrop belt of the formation is located to the southeast of the Choptank belt, and like the Choptank, it is mostly covered by Quaternary sediments. No outcrops of the St. Mary's are known on the Eastern Shore. The St. Mary's is present through Virginia, Maryland, and Delaware, and the sediments continue northeast into New Jersey, where they correlate with the Cohansey sand and gravel or are absent.

5.1.9) Bryn Mawr Group

Sediments of tentative Pliocene age have been identified at isolated locations in northern Maryland and Delaware. These sediments are part of a sequence of poorly-sorted to moderately-sorted continental materials that were deposited and modified during the relatively rapid fluctuations in sea level that accompanied the last ice age. These sediments, which are usually not differentiated and include materials of Pliocene, Pleistocene, and Recent ages, were initially deposited as extensive deltas, channel deposits, or floodplain sediments at or near sea level. Subsequent erosion during later rises in sea level removed much of the previous layers of sediment and created a series of terraces where the sediments were left above the highest water level. These terrace deposits have been classified on the basis of their elevation (the oldest terrace being the highest) and composition, and include the Beacon Hill, Bryn Mawr, and Brandywine gravels.

Bryn Mawr/Beacon Hill Gravel. The term Bryn Mawr gravel has been applied to isolated patches of gravel that occur in northern Maryland and Delaware between the elevations of 390 to 480 feet above sea level. In earlier reports, these sediments are sometimes referred to as the Lafayette Formation. This formation is so widely-scattered and poorly-exposed that it is not clear if the sediment was deposited above or below sea level, and no fossils are present to indicate exact stratigraphic relationships with older underlying sediments. The Bryn Mawr gravel consists of a poorly-sorted agglomeration of gravel and coarse sand, about evenly distributed, with a few cobbles present. The color of the formation generally is orange to light gray. At places a thin bed of white clay derived from underlying sediments may be present.

Brandywine Gravel. Small isolated patches of gravel in the hills of the Elk Neck peninsula have been termed the Brandywine gravel, although other workers consider this material to be related to the Pleistocene terraces developed at lower elevations. These gravels occur between elevations of 220 to 280 feet above sea level, and consist of well-rounded pebbles of rock materials that are resistant to erosion, with varying but lesser amounts of clay, silt, and sand. The Brandywine Formation unconformably overlies older sediments on an irregular boundary, and often is cemented with iron.

5.1.10) Columbia Group

Deposits of Pleistocene and Recent age form a thin covering over most of the Coastal Plain in the study area. They consist of a series of well-defined terraces composed of gravel, sand, peat, silt, and clay. As described above, these materials were deposited during various stands of sea level associated with the last ice age, and are developed as a series of terraces due to successively lower elevations of erosion. These materials obscure all older deposits beneath the Coastal Plain, except for the Cretaceous sediments exposed in the canal, deeper ravines and stream valleys, and sand and gravel quarries. Some reports consider the Pliocene deposits to be a part of this group, since the sediments are very similar and are difficult to distinguish on the basis of composition.

The Pleistocene and Recent sediments are nearly all of fluvial or estuarine origin; the fluvial sediments occur mostly as upland deposits consisting of sand, gravel, and clayey silt. The estuarine deposits consist mostly of clay, silty clay, and sandy gravel containing fossil shells and some woody material. These sediments are collectively referred to as the Columbia Group, which is divided into at least three members on the basis of terrace elevation. These members, from oldest (highest) to youngest (lowest), are the Sunderland, Wicomico, and Talbot. The Columbia Formation correlates to the Cape May/Pennsauken/Bridgeton Formations in New Jersey and the Talbot Formation in Maryland. Older descriptions in Maryland include the Parsonsburg Sand, Pamlico Formation and the Beaverdam Sand.

All of the Columbia Group combined with portions of the Bryn Mawr Group and the Chesapeake Group form the water table aquifer within the study area. This group supplies water to a multitude of local residential users. Well yields up to 800 gpm have been reported in areas where the saturated thickness of the aquifer is large. Since the these formations overly the other aquifers mentioned previously, they provide direct recharge to the deeper aquifers. Also, since these formations area at the surface, they are subject to pollution from industrial plants, septic systems, road salt, etc. The water table aquifer is especially contaminated adjacent to industrial plants in the Delaware City, DE area.

Columbia Formation. The Columbia materials consist of clay, loam, sand, gravel, peat, and ice-rafted boulders. These materials do not generally occur as distinct beds, but grade laterally and vertically into one another. The coarse sediments are often cross-bedded, and are mainly found in the lower part of the formations. Each terrace deposit is generally not thicker than 25 to 50 feet. The deposits are generally unconsolidated, although some beds may be partially indurated due to interstitial clay or iron oxides. Heavy bands of limonite-cemented conglomerate are common toward northern Delaware.

The Columbia sediments in New Castle County (Delaware) were deposited by Pleistocene streams which formed relatively straight channels north of the canal, and a series of braided channels south of the canal. Based on the mean direction of the paleocurrent vectors as measured from tabular cross-beds, the transporting streams moved across the area to the southwest from the present path of the Delaware River, then swung east and rejoined the current river channel in the southern part of Delaware Bay. Some of the sediments to the south also appear to represent coastal, shoreline, or nearshore depositional environments.

A striking feature of the Columbia sediments in New Castle County is the distinct bedding; although the degree of sorting may vary, beds of all sizes are discrete units and retain their textural characteristics along exposed sections. Pebbles are usually segregated into beds of gravel, and beds of silt may be present, reflecting the rapidly-changing current environment common to many streams. The gravel beds, boulders, and cobbles are more prevalent in northern Delaware, whereas beds of silt are more common and thicker toward the south. Cross-bedding is generally well-developed, tabular, and may persist over hundreds of feet. The gradual decrease in grain size to the south indicates that the down-current velocities of the Pleistocene streams decreased in a systematic way. The areal distribution of these sediments appears to have been controlled by the topography and composition of the underlying Potomac sediments. Valleys in the Potomac surface were developed on finer-grained sediments, so the main Pleistocene streams also developed there and became transport routes for the Columbia sands. Therefore, deposits of sand in the Columbia Formation are usually underlain by fine-grained Cretaceous sediments (although there are exceptions).

Sunderland Formation. The Sunderland Formation is a terrace deposit that occurs between the elevation's of 90 and 200 feet above sea level. It occurs in small areas in Cecil County, principally along the Fall Zone and on the Elk Neck peninsula. The formation rests unconformably on crystalline rock or on Cretaceous deposits, and consists of sand, clay, and lesser amounts of gravel. The formation probably is of fluvial origin.

Wicomico Formation. The Wicomico Formation is a terrace deposit occurring between the elevations of 45 and 90 feet above sea level, and is the most widespread of the Pleistocene formations. It is divided into two physiographic types: terrace and plains deposits. The chief difference between these two types is that the distance between the upper and lower scarps bounding the formation is small for the terrace type (generally less than a mile) and large for the plains type (up to 40 miles).

Talbot Formation. The Talbot Formation is a terrace deposit that occurs between the elevations of 10 and 45 feet above sea level. This formation is widely-developed on the Coastal Plain, and consists of deposits of fluvial, estuarine, and possibly marine origin. They are composed of sand, clay, sandy clay, silt, and gravel. The gravel layers are thin and fine-grained, and are mixed with sand and sandy clay. Beds of clay are contorted and broken at places, probably due to the action of ground frost. The sand is generally coarse or medium-grained and is usually strongly cross-bedded.

5.2) Hydrogeologic Properties

Hydrogeologic information in the study area is extensive. Because of the numerous studies conducted along the C&D Canal, in New Castle County, Delaware and in Cecil County, Maryland, extensive information exists on hydrogeologic properties of various aquifers and confining units within the study area. This information is summarized in the attached Table 2. The table presents available information such as transmissivities (T), horizontal hydraulic conductivities (Kh), vertical hydraulic conductivities (Kv), and their source. This information is grouped by aquifer and confining unit. Much of the information was gathered from aquifer tests, well installation data, or geotechnical laboratory testing. This information was summarized as part of the conceptual model preparation prior to construction of the numerical models.

Table 2
Hydrogeologic Properties

Formation	Location	T (Ft*Ft/day)	Kh (Ft/day)	Kv (Ft/day)	Source
Columbia	Central and Southern Delaware	1,900 to 10,000	50 to 250		Rogers, Golden & Halpern (RGH) [1986]
Columbia	Southern New Castle County, DE	4,500			Woodruff [1970]
Adopted Values			100	0.1	
Navesink	New Jersey		2		Rush [1968]
Navesink	New Jersey		0.06	0.02118	NJDEP [1996]
Adopted Values			0.06	0.015	
Vincentown	Springhaven, DE	1,787			Groundwater Associates [1994]
Vincentown	Smyrna, DE	2,647			Delaware Geological Survey [1981]
Vincentown	Delaware Correctional Center	1,867 to 2,560			Sundstrom [1967]
Vincentown	New Jersey	1,058	17.83	3.56	NJDEP [1996]
Adopted Values					
Hornerstown	New Jersey			0.0044	NJDEP [1996]
Adopted Values					

<u>LEGEND</u>

T - Transmissivity

K_h - Horizontal hydraulic conductivity

K_v - Vertical hydraulic conductivity

Table 2
Hydrogeologic Properties

Formation	Location	T (Ft*Ft/day)	Kh (Ft/day)	Kv (Ft/day)	Source
Mount Laurel	Middletown, DE	241	2.8		Rima [1964]
Mount Laurel	Summit, DE	317 to 850	7 to 13.1		RGH [1986]
Mount Laurel	Cecil County, Maryland	100 to 730 (270 Median)			Otton [1988]
Mount Laurel	Southern New Castle County, DE	331 to 815			Delaware Geological Survey [1996]
Mount Laurel	New Jersey	858	13.9		NJDEP [1996]
Mount Laurel	Summit Power Station, DE		7 to 12	0.4	Dames & Moore [1974]
Adopted Values			3	0.3	
Marshalltown	New Jersey			0.008124	NJDEP [1996]
Matawan Sands	C&D Canal, DE		0.0028 to 0.28		Fetter [1988]
Adopted Values			0.3	0.03	
Englishtown - Clayey	Biddles Point, DE			0.0051	Woodward-Clyde [1998]
Englishtown - Sand	New Jersey	1173	21.7		NJDEP [1996]
Adopted Values			5	0.5	

LEGEND

T - Transmissivity

K_h - Horizontal hydraulic conductivity

K_v - Vertical hydraulic conductivity

Table 2
Hydrogeologic Properties

Formation	Location	T (Ft*Ft/day)	Kh (Ft/day)	Kv (Ft/day)	Source
Merchantville	Biddles Point, DE			0.000096	Woodward-Clyde [1998]
Merchantville	Summit Power Station, DE			0.00001 to 0.002	Dames & Moore [1974]
Merchantville	New Jersey			0.0000072 to 0.0004	Luzier [1980]
Merchantville	New Jersey			0.000071	NJDEP [1996]
Adopted Values			0.0000005	0.0000001	
Magothy	Middletown, DE	536	27		Rima [1964]
Magothy	Cecil County, Maryland	290 to 3300 (490 Median)			Otton [1988]
Magothy	South of C&D Canal, DE	413 to 1655			Delaware Geological Survey [1996]
Magothy	New Jersey	5949	82.5		NJDEP [1996]
Adopted Values			50	0.1	

LEGEND
T - Transmissivity
K_h - Horizontal hydraulic conductivity
K_v - Vertical hydraulic conductivity

Table 2
Hydrogeologic Properties

Formation	Location	T (Ft*Ft/day)	Kh (Ft/day)	Kv (Ft/day)	Source
Potomac Confining Units	New Castle County, DE			0.000005 to 0.00075	Martin [1984]
Potomac Confining Units	Chesapeake City, Maryland			0.000024	Woodward-Clyde [1998]
Potomac Confining Units	Summit Power Station, DE			0.000028	Dames & Moore [1974]
Potomac Confining Units	Star Refinery, DE			0.000094 to 0.0026	Sundstrom [1967]
Adopted Values			0.0005	0.0001	
Potomac Undifferentiated	New Castle County, DE	454 to 8440			Martin and Denver [1982]
Potomac Undifferentiated	New Castle County, DE	660 to 2527			Delaware Geological Survey [1996]
Potomac Undifferentiated	New Jersey	5325	165		NJDEP [1996]
Adopted Values			5	0.5	

LEGEND
T - Transmissivity
K_h - Horizontal hydraulic conductivity
K_v - Vertical hydraulic conductivity

Table 2
Hydrogeologic Properties

Formation	Location	T (Ft*Ft/day)	Kh (Ft/day)	Kv (Ft/day)	Source
Upper Potomac	Cecilton, Maryland	1500			Otton and Mandle [1984]
Upper Potomac	Earleville, Maryland	214			Otton [1988]
Upper Potomac	Star Refinery, DE	550 to 1005	11 to 20		Sundstrom [1967]
Upper Potomac	St. Georges, DE	3610	30 to 120		Geraghty and Miller [1967]
Upper Potomac	St. Georges, DE	817 to 871	7 to 27		Sundstrom [1967]
Upper Potomac	Canal Realty, DE (along C&D Canal)	188	7		Geraghty and Miller [1967]
Upper Potomac	Courthouse Point, Maryland	324 to 372	6.5 to 7.5		Army Corps of Engineers, [1997]
Upper Potomac	New Jersey	6234	81		NJDEP [1996]

LEGEND
T - Transmissivity
K_h - Horizontal hydraulic conductivity
K_v - Vertical hydraulic conductivity

Table 2
Hydrogeologic Properties

Formation	Location	T (Ft*Ft/day)	Kh (Ft/day)	Kv (Ft/day)	Source
Lower Potomac	Star Refinery, DE	630 to 1541	9 to 22		Sundstrom [1967]
Lower Potomac	Chesapeake City, Maryland	5092	85 to 137		Geraghty and Miller [1967]
Lower Potomac	Chesapeake City, Maryland	1608 to 2546	27 to 69		Sundstrom [1967]
Lower Potomac	Cecil County, Maryland	60 to 3900 (440 Median)			Otton [1988]
Lower Potomac	Sparrows Point, Maryland	6666			Bennett and Meyer [1952]
Lower Potomac	New Jersey	5499	118		NJDEP [1996]

LEGEND
T - Transmissivity
K_h - Horizontal hydraulic conductivity
K_v - Vertical hydraulic conductivity

5.3) Regional Groundwater Use

Groundwater use in the study area is varied including municipal water supply, irrigation, industrial cooling, and residential use. Major municipal users of groundwater in the study area include the towns of Elkton, Maryland; Chesapeake City, Maryland; Delaware City, Delaware; and Saint Georges, Delaware. Major industrial users of groundwater in the study area include the Summit Airport, Delaware and the Star refinery, Delaware. The industrial users typically withdraw groundwater from the lower portions of the Potomac aquifer. Pumping at the Star refinery has caused a persistent drawdown in the Potomac aquifer which may exacerbate any potential groundwater salinity intrusion from the Delaware River or the C&D Canal. This potential was analyzed with a groundwater model discussed later in this report.

5.4) Regional Groundwater Flow

Hydrogeologic information in the study area is extensive. Because of the long history of the C&D Canal, numerous geotechnical and groundwater studies have been conducted in the vicinity of the project. Woodruff, Groot, Baxter and others have conducted studies in the area. Their findings indicate groundwater generally flows from higher topographic elevations toward the principal surface water features in the study area. These include Dragon Run Creek, Scott's Run, Long Creek, Delaware River, C&D Canal and the Chesapeake Bay. While this behavior is true for all of the water table formations (unconfined aquifers) in the study area including the Columbia, Talbot or Upland gravels, it is not true in the deeper confined aquifers of the study area namely the Mount Laurel, Magothy or the Potomac. In these areas, pumping by large municipal or industrial wells has disrupted natural groundwater flow patterns. In some cases, groundwater may flow opposite its natural direction. It is possible in areas of heavy pumpage that the principal surface water features recharge the deeper confined aquifers instead of getting their recharge from the aquifers.

6) Hydrogeologic Conceptual Model

Geraghty and Miller define a conceptual model as a concise description of the components of the aquifer system being studied, and is developed from regional, local, and site-specific data. A conceptual model is a precursor to any mathematical modeling effort, and identifies the hydrogeologic configuration of the aquifer system, ground-water sources and sinks, and aquifer system property values. The conceptual model focuses the calibration process and interpretation of model results by presenting a general understanding of the flow system. Numerical modeling aids further development of the conceptual model by identifying data gaps and problem areas [USACE, 1996].

After initial data collection, geologic analysis and extensive coordination; a detailed hydrogeologic site conceptual model was developed. This conceptual model encompassed a much larger area than that to be modeled to gain a regional understanding of the area surrounding the project and to ensure adequate data coverage for the groundwater model. Figure 12 depicts the extent of the site conceptual model. The hydrogeologic conceptual model was developed from existing information obtained from the Delaware Geological Survey (DGS), Maryland Geological Survey (MGS), Corps' files, local engineering consulting firms and a few local citizens. The information utilized for development of the conceptual model included borehole logs, well logs, downhole geophysical logs, soil testing information, precipitation information, Canal salinity levels, groundwater elevations and groundwater vertical gradients.

6.1) Recharge

Annual precipitation recorded in the study area is approximately 44 inches. Out of this , a portion becomes surface water runoff, a portion is absorbed into the unsaturated soil zone, a portion evaporates into the atmosphere, plants transpire a portion, and a portion directly recharges groundwater. Typically, in most parts of the Coastal Plain area, recharge amounts to 10 to 20 inches per year. Johnston estimated that approximately 1 cubic foot per second per square mile (13.6 inches/year) recharged the Columbia Formation [Johnston, 1973]. The estimate was derived from a baseflow separation analysis of streamflow hydrographs in the Delaware Coastal Plain. Groot and others used a more conservative estimate of 10.5 inches/year of recharge in their study of the availability of water in southern New Castle County, Delaware [Groot, 1983]. In the C&D Canal study area, 10 to 15 inches per year was adopted based on historical reports and extensive coordination with state agencies. During model calibration, a recharge value of 13 inches/year was adopted.

6.2) Salinity

Salinity intrusion is a slow process due to the low groundwater velocities noted along the Canal. Therefore, the model used average salinity values for boundary conditions along the canal. Average salinity levels in the C&D Canal vary from 3 to 6 parts per thousand (PPT) at the Delaware River entrance to less than 1 PPT on the Chesapeake Bay/Elk River entrance. For the model, average conditions are assumed to occur throughout the year and provide a continuous stress on groundwater aquifers.

Previous salinity investigations by the United States Geological Survey, New Jersey District, as part of the Delaware River Main Channel Deepening PED study, indicate that even under the most adverse salinity conditions (based on levels recorded during the drought of 1962), local municipal wells along the project portion of the Delaware River would not be impacted. This is significant because the USGS analyzed impacts in an area adjacent to the Camden/Gloucester county municipal well field where pumping can be as high as 42 MGD. Computer modeling efforts by the USGS concluded that that impacts would not occur under average conditions. Their study showed that objectionable concentrations of salt in local wells would only occur if the aquifers were exposed to at least 30 continuous days of high pumping combined with the worst case salinity values. In addition, based on historical data, the USGS determined these conditions could occur only under the most extreme circumstances.

Furthermore, a two dimensional cross-sectional type model along the C&D Canal, completed by Geraghty and Miller under contract to the Philadelphia District, concluded that "deepening the canal by 5 feet does not significantly impact the groundwater flow regime." Because a two dimensional cross-sectional model includes several assumptions and inherent limitations relative to a fully three-dimensional approach, the Philadelphia District agreed to conduct additional modeling as part of this study. This modeling, which was fully three-dimensional and capable of modeling density driven flow, is discussed in further detail below.

6.3) Hydrogeology and Groundwater Flow

The C&D Canal and streams that are cut into the uppermost formations of the Coastal Plain, act as the primary groundwater sinks or outlets for groundwater discharge within the study area. The surface water drainage area of the Canal extends from the Delaware River to the Chesapeake Bay and covers an area of approximately 65 square miles. Streams draining into the Canal include Long Creek, Lums Pond, Guthrie Run, Back Creek, Georgia Run, Hog Creek, Crystal Run, Joy Run, Scotts Run and two unnamed tributaries along the south bank of the Canal. Large municipal and industrial water supply wells provide the other major groundwater sink within the study area. These wells draw water mainly from the deeper Potomac Formation. Without the pumping wells, groundwater in the Potomac Formation would flow toward the Canal or beneath the Canal and to the southeast (toward the Atlantic Ocean).

The main unconfined aquifer in the study area is the Columbia Formation that mantles the older and deeper Cretaceous and Tertiary sediments. Groundwater in the Columbia Formation recharges underlying units along their subcrop areas, which then becomes part of the regional groundwater flow system to the Coastal Plain [USACE, 1996]. Groundwater that does not recharge the deeper formations flows in short pathways from areas of recharge to discharge areas such as the Canal, small streams, the Delaware River and the Chesapeake Bay. The hydraulic gradient in the Columbia Formation is from recharge areas to those aforementioned discharge sites. Figure 13 illustrates the hydrogeologic conceptual model within the study area. Further information is available in Section 8.

7) Model Development

The FEMWATER model [Yeh et al, 1997] was chosen for this study because of its ability to model density driven flow (salinity transport) in variably saturated media. The model's unstructured nature also allows variable size mesh spacing that permits accurate definition of complex hydrogeologic conditions and the selective use of resolution where it is needed to define salinity transport, creeks, water supply wells, and other physical features.

The scale and domain of the computer model was determined by two over-arching needs. The first was the need for very fine mesh resolution to accurately model salinity intrusion. The second was the need for model boundaries that extended laterally and with depth to encompass all potential receptors and provide stable, easily defined boundary conditions. Boundaries were selected a sufficient distance from the canal to recreate regional flow patterns and minimize boundary effects in the canal area. These competing needs resulted in the utilization of a two-step modeling approach. A coarse scale model defined regional flow patterns. Then a more refined inset model predicted salinity transport. Figure 14 shows the location and extent of the two models.

In the first step, a large-scale model was developed to recreate regional flow patterns and determine the impacts of pumping in the Upper Potomac on aquifers above it. As related earlier in this report, the Upper Potomac aquifer provides much of the municipal and industrial water supply within the study area. Several previous investigators [Woodruff, 1969] have noted that the pumping impacts on potential salinity intrusion had not been studied adequately. In fact, Ken Woodruff, formerly of the Delaware Geological Survey, has investigated several incidents of salinity intrusion in the vicinity of the C&D Canal related to pumping of Getty Oil/Star refinery production wells. In August of 1966, well EC13-11 was abandoned because of high chloride levels. Levels within the well reached 360 PPM before pumping of the well was reduced. At the time it was theorized that the origin of the salty water was either the C&D Canal or the Delaware River. Therefore, the need for the coarse model as a way to test various conceptual flow pathways was considered paramount.

In the second step, a smaller more refined salinity transport model was developed within the boundaries of the coarser regional model. The refined inset model used the regional model as a source of boundary conditions. The greater refinement in the inset model made it possible to analyze salinity intrusion into the formations surrounding the canal as well as calculate any increase in fresh water lost to the canal as a result of the deepening.

The inset model also provided a means for analyzing groundwater impacts from the operation of Biddle's Point CDF. To model operation of the Biddle's Point CDF, various ponded conditions were simulated within the disposal area to predict effects on the surrounding groundwater. A separate model was created to do a similar analysis on the Courthouse Point CDF. Model development is detailed in the following sections.

7.1) Coarse Model

As a precursor to the final salinity intrusion model, a coarse resolution groundwater model was developed in the vicinity of the canal. The purpose of this model was to determine the effects of deep pumping from municipal and industrial production wells on groundwater elevations (heads) within the surfacial geologic units that outcrop into the bed of the C&D canal. This mesh was also used to develop an understanding of the regional groundwater patterns.

Specifically, the model was used to determine if any large drawdowns occurred in shallow aquifers due to the large pumping stresses imposed within the deeper Potomac Aquifer. In addition, the coarse model was used to assess the chances for salinity intrusion into the Potomac Aquifer. If the model revealed little connection between shallow aquifers and the Potomac Aquifer, it was reasoned that the Potomac Aquifer could be incorporated into the final inset model implicitly, (observed groundwater heads in the Potomac would serve as a boundary in the base of the model), which would allow the use of more resolution to define the canal and surrounding geology.

7.1.1) Site Specific Conceptual Model

General hydrogeologic concepts were previously discussed in Section 7. The site-specific hydrogeology was developed from existing information including well logs, borehole logs and geophysical data. Based on this data, the coarse model extends from the ground surface vertically downward to the top of the basement rock. Figure 15 shows the area covered by the model and the approximate locations of the cross sections. Figures 16 and 17 show hydrogeologic cross sections generated from the coarse model based on available information.

7.1.2) 3D Mesh

To ensure adequate coverage in the study area, the extent of modeling was selected to include all areas of concern and potential receptors. To accurately represent the three dimensional nature of the study area, topography and geology along with groundwater sources and sinks were coded into the 3D mesh. Model topography mimics real ground surface elevations, which varies from 0 to 115 feet NAVD. Surface elevations were obtained from USGS 7.5 minute Digital Elevation Models (DEM). Figure 18 shows the adopted 3D mesh which is composed of 49,735 elements and 27,601 nodes in 24 vertical layers.

7.1.3) Boundary Condition Assignment

Boundary conditions are shown on Figure 18. Known and assumed potentiometric heads were modeled as Specified Head (Dirichlet) boundaries. Recharge and groundwater withdrawals were modeled as Constant Flux (Cauchy) boundaries. No Flow Boundaries were assigned in areas were groundwater flow does not cross the model exterior.

Specified head boundaries were used to model the Delaware River and adjacent marshes, C&D Canal, Lums Pond and all perennial streams. Streams along the interior of the model were only modeled as specified head boundaries at the model's surface to allow the modeled streams to drain groundwater. Along the exterior of the model, specified heads were applied from the surface downward to the first confining unit to model the saturated conditions that exist beneath streams. Below the first confining unit, potentiometric heads may be very different than in the unconfined aquifer directly above. To depict these differences in the model, specified heads along the model exterior were interpolated from observed groundwater level data supplied by the DGS, Delaware Department of Natural Resources and Environmental Control (DNREC) and the Maryland Environmental Service (under contract to Philadelphia District). In a few cases, large municipal wells located outside the model boundary resulted in groundwater drawdowns within the model study area. In the model, specified head boundary conditions were coded to mimic drawdown from these wells. Along the western portion of the model, specified heads based on observed water levels were used.

No-Flow boundaries were assumed along the bottom of the model to represent the basement rock that underlies the Potomac Formation. This assumption is based on the fact that basement rock conductivities are several orders of magnitude lower than those of the Potomac Formation directly above it. No-Flow boundaries were also used along the model exterior for all clay layers. Horizontal flow in the various clay layers can be considered to be negligible.

Based on published information discussed previously in section 7.1, the estimated annual recharge for the study area is approximately 10 to 15 inches/year. Recharge was varied throughout the model based on the ability of the ground to receive it. Topography, depth of unsaturated zone and ground cover were used as indicators to adjust recharge. Over

all, 13 inches of recharge per year was used in the calibrated model.
Under normal conditions (average annual recharge), there is very little flow from the canal to the adjacent groundwater system. To understand how the system would react to drought conditions, recharge was completely removed from the model. This causes the groundwater table on either side of the canal to be lower than under natural conditions. Since the total head in the canal is kept constant, flow out of the canal would be magnified while flow into the canal would be minimized. This technique was utilized in order to determine the worst potential case for salinity intrusion from the C&D Canal.

A list of all pumping wells in New Castle County was obtained from DNREC. This list was augmented by well information obtained from DGS and the USGS. Important wells were incorporated into the model during its initial development. Where pumping rate information was unavailable, representative values were developed based on the water use type (i.e. domestic, commercial, agricultural, etc. A proposal for a series of new computer chip plants capable of pumping from 2.5 to 10 million gallons per day was identified during the collection of the pumping well information. At the request of DNREC, one 2MGD groundwater withdrawal was added in the Potomac formation to portray potential impacts. The plant location and withdrawal rate were estimated by DNREC.

In order to model the unsaturated flow properties of the system; moisture content, relative conductivity, and water capacity curves were developed for each material. These curves were developed using the van Genuchten functions based on representative soil parameters for the various soil types. The reader is referred to [Fetter, 1988], for additional information concerning the van Genuchten soil moisture relationships.

7.1.4) Steady State Calibration

The coarse model was calibrated to observed groundwater elevations by trial and error adjustments of recharge and hydraulic conductivities. Parameters were varied within a reasonable range in order to achieve the best match between computed and observed groundwater elevations. The coarse model was calibrated in a cursory manner since it was only utilized to test various hydrogeologic hypotheses and examine the regional flow system. More rigorous calibration, performed during preparation of the inset model, showed that the hydrogeologic parameters used in both models (coarse and inset) were reasonable.

Model calibration achieved reasonable results using approximately 13 inches/year of recharge and hydraulic conductivities presented previously in Table 2. The Root Mean Square Error (RMSE) was approximately ten percent of the total head change across the model domain and the Mean Error is near zero. Residual Error plots and Computed vs. Observed groundwater elevation plots are presented in Figures 19 and 20 respectively.

There are a number of sources of error in this model. Chief among them is the observation wells themselves. Large parts of the model do not contain observation wells.

Model fit in these areas must be inferred from general behaviors. In areas with observation wells, well locations and screened depths are not known with a great deal of accuracy. In areas of steeper hydraulic gradients, small changes in well locations results in feet of change in computed heads. Also, the majority of the water levels used for calibration were obtained from pumping wells. The variable nature of pumping makes observed water levels in these wells highly unreliable as indicators of surrounding groundwater levels. Also, errors in topography are a factor in model accuracy for the unconfined aquifers. Topography controls the elevations for sources and sinks within the model. Model topography was derived largely from USGS DEM data with an accuracy of $\pm$ 2.5 to 5ft based on the contour interval available. Given these uncertainties, the model calibration is reasonable for purposes of the understanding regional flow patterns.

7.1.5) Conclusions

Coarse model results provided insights into groundwater flow pathways, connections between aquifers, and the potential for salinity intrusion from the C&D Canal into the Potomac Aquifer.

As shown in Figure 19, model behavior in the upper aquifers generally follows the conceptual model flows presented in Section 8.1.1 and illustrated in Figure 13. Recharge flows from higher topographic areas to lower ones. The C&D Canal along with major streams and the Delaware River generally acts as groundwater sinks.

For the Potomac, Figure 21 shows that pumping dominates flow regimes within the aquifer. The large cones of depressions are due to pumping from the Star Enterprises refinery, the town of St. Georges, DE and the proposed computer chip plant. The majority of this water comes from the subcrop of the Potomac below the Columbia aquifer. To judge the interconnection of the Potomac with aquifers above it, comparison plots were made of head difference between model simulations of pumping verses no pumping in the Potomac. Most head difference plots showed no impacts to upper aquifers from pumping in the Potomac. This is reasonable due to the thick clay layer that overlays the Potomac isolating it from upper aquifers. Figure 22 is a pressure head difference plot that portrays changes in Magothy Aquifer pressure heads due to pumping in Potomac wells. It indicates a slight localized vertical connection between the Magothy aquifer and the Potomac Aquifer in the vicinity of St Georges DE. The connection occurs where a Pliestocene sand channel (paleo-channel) has eroded the thick surface clays that exist at the top of the Potomac Formation (see Figure 17). The downward movement of waters is exacerbated by pumping from municipal and industrial wells screened within the Potomac Aquifer. Groundwater drawdown was observed in the Magothy Aquifer, which is located stratigraphically above the Potomac Clay. However, little to no effect from this deep pumping is expressed above the Merchantville Clay, which is a thick clay layer above the Magothy Aquifer. This leads to two conclusions. First, pumping in the Potomac has very little effect on the upper aquifer so it may be modeled implicitly in the refined inset model. And secondly, the lack of connection between the canal and the Potomac aquifer would indicate that the Delaware River was the source of salinity intrusion seen by Woodruff [1969] and others - specifically with regards to salinity seen at the Getty Oil/Star refinery production well EC13-11.

As discussed previously, the calibrated model showed very little loss of water by the canal to the adjacent aquifer systems. This indicates there is very little chance for salinity intrusion from the canal to the adjacent aquifers. To increase modeled potential for aquifer recharge from the canal and hence salinity intrusion, recharge was completely removed from the coarse model. This approximates a severe drought condition. Without recharge, the water table on either side of the canal drops to the level of the perennial streams. Lower heads on either side of the canal make it easier for the canal to recharge the aquifers. Even under these conditions, very little water moves from the canal to the aquifer systems. The "drought " model scenario provided boundary conditions for production runs of the refined inset model.

7.2) Inset Model

Following completion of the coarse groundwater model study, a more detailed inset model was developed in the vicinity of the canal to evaluate salinity intrusion potential into subsurface aquifers as well as evaluate the loss of fresh water from aquifers to the Canal. The inset model location and areal coverage is shown on Figure 14.

This section details construction and flow calibration of the inset model. Section 9 discusses the development and findings of WES's salinity transport modeling using the inset model.

7.2.1) Site Specific Conceptual Model

The conceptual model for the inset model is identical to that of the coarse model discussed previously in Section 7 and Section 8.1.1.

7.2.2) 3D Mesh

Within the inset model domain, the coarse model showed a lack of hydraulic connection between the Potomac formation and the aquifers above it. To simplify model geology, the Potomac formation was not included in the inset model mesh. However, modeled heads in the Potomac Clay were used as boundary conditions along the bottom of the inset model. This simplification, combined with the decrease in model domain, allowed more mesh detail along the C&D Canal.

Vertically, the inset model extends from ground surface down to the bottom of the Magothy aquifer/top of the Potomac Clay. Horizontally, the Eastern model boundary remained at the Delaware River, while the western extent of modeling was chosen at the point where the Magothy outcrops into the bed of the canal. Dragon Creek was chosen as the new northern boundary. A well-defined southern boundary could not be chosen. To minimize boundary effect in the canal area, the southern boundary was chosen approximately two miles South of the canal. Figure 23 depicts the final adopted 3D mesh. Land surface elevation variations are from 0 to 90 ft NAVD. Observed potentiometric heads range from a high of 58 ft to a low of -12 ft. The mesh is comprised of 148,149 elements and 82,787 nodes in 12 layers.

7.2.3) Boundary Condition Assignment

Boundary condition assignment followed the same general guidelines outlined for the coarse mesh. Most inset model boundaries were chosen along perennial waterways. Specified heads were used to model these boundaries. In areas without well defined boundaries, such as the southern boundary, computed groundwater elevations from the coarse model were assigned as specified head boundaries. This includes the assignment of Potomac Clay groundwater elevations along the bottom of the inset model. Figures 23 and 24 show the assigned boundary conditions for the inset model.

7.2.4) Steady State Flow Calibration

As with the coarse model, the inset model was calibrated with an estimated recharge of 13 inches/year. The steady state calibration for the inset model is good. Residual Error plot and Computed vs. Observed groundwater elevation plots are presented in Figures 25 and 26 respectively. Computed statistic for the inset model are Mean Error = -0.9 ft, Mean Absolute Error = 6.8 ft and the Root Mean Square Error = 9.5 ft. These measures of residual error are all well below 10 percent of the total head change across the model domain.

As with the coarse model, lack of observation well coverage along with inaccuracies in well locations and groundwater measurements (especially at pumping wells) are sources of error in the model. Also, errors in topography are a factor in model accuracy for the unconfined aquifers. Topography controls the elevations for sources and sinks within the model. Model topography was derived largely from USGS DEM data with an accuracy of $\pm$ 2.5 to $\pm$ 5ft based on the contour interval available.

The calibrated model showed little indication of exfiltration from the canal to the surrounding aquifer systems. In an effort to force water from the canal to the surrounding aquifers, subsequent runs were made with the recharge removed from the model. As discussed previously with the coarse model, this will increase modeled salinity intrusion.

7.2.5) Inset Model Results and Conclusions

After the existing conditions were adequately matched with model results, predictive simulations were run with the C&D Canal bottom set five feet lower. This canal deepening extended along the entire length of the model. By examining the difference between the "existing " and "proposed" project scenarios, the net effect of the deepening can be evaluated. The Waterways Experiment Station determined canal deepening impacts on groundwater losses to the canal and potential salinity intrusion. The results of that study are presented in Section 9 of this Appendix.

7.3) Biddle's Point Model

The Biddles Point dredged material containment area is located along the northern bank of the C&D canal approximately 2 miles West of Delaware City. This site is approximately 300 acres in size and is being considered for placement use during any Canal deepening project. This site has not been utilized for the placement of dredged materials to any large extent since the last major modification of the C&D Canal that was completed in the early 1970s. Figure 27 shows the pertinent site features including the location of the inflow discharge pipe, location of the outflow sluice, location of the baffle dike and other site aspects.

7.3.1) Previous Investigations

Biddles Point has been the subject of past groundwater investigations completed by the Delaware Geological Survey (DGS). DGS reported high chloride concentrations in well Ec23-6 [Woodruff, 1969]. This well, which supplied some water to the Gunning-Bedford School, is located just north of the Biddles Point site across the Kirkwood-Saint Georges Road. In January 1968, chloride concentrations were measured at greater than 800 PPM. The well was screened in the Columbia Aquifer and geophysical logging determined that high chloride water existed at a depth of 70 to 100 feet below land surface. At the time, DGS hypothesized that the chlorides were related to use at the Biddles Point site during the last Canal modification. Because of the problems identified at the site historically and the potential for salinity intrusion from the Canal itself, the site was added to the groundwater plan of study for the PED study.

7.3.2) Current Model

The calibrated inset model was used to study Biddles Point. Slight modifications were made to dredge material vertical conductivities, recharge and pond elevations within the disposal area to study potential project impacts on surrounding aquifers due to operation of Biddles Point. In an effort to minimize these impacts, model runs were made with different sizes and orientations of containment areas within the Biddles Point site. While alterations reduced impacts, they were not eliminated.

7.3.3) Conclusions

The Biddles Point site was modeled to evaluate potential groundwater impacts resulting from its use as a placement facility for a deeper C&D Canal. Modeling results indicate that use of the site, as configured currently, would cause minor impacts to the Columbia Aquifer. These impacts would be of limited aerial extent and would not impact any potable wells (the original Gunning-Bedford well was replaced with a deeper one).

However, impacts can be minimized by changes in site dike configuration, ponding depth and sluice operations. Additional model runs were completed to evaluate engineering and operational changes at the site that could minimize or eliminate potential groundwater impacts. Multiple model runs revealed that impacts could indeed be minimized but they could not be eliminated completely. Results shown on Figure 28 & 29 are typical of groundwater impacts from using Biddles Point. As shown on Figure 28, the zone of influence of the fully ponded CDF reaches north of the site to vicinity of the school.

Therefore, consideration should be given to utilizing another placement site instead of Biddles Point. If another site is not viable, appropriate mitigation and monitoring efforts should be included in the final engineering plan.

7.4) Court House Point Model

The Courthouse Point study area is an active dredged material containment area along the upper approach channel to the C&D Canal. The site, which is approximately 170 acres in size, is utilized to contain sediment routinely dredged from the navigation channel. Figures 30 and 31 show the pertinent site features including the location of the inflow discharge pipe, location of the outflow sluice, location of the baffle dike and other site aspects.

The Courthouse Point study area was identified as an area of potential groundwater impact during previous coordination with the State of Maryland and the EPA. Although no groundwater problems associated with site operation have been reported to date, the Philadelphia District agreed to pursue further studies of the site as a preventative measure. The field investigations were completed in 1997 and 1998 and findings reported in a *Hydrogeologic Investigation Report* prepared by Geotechnical Services, Inc. The final report is available in the Geotechnical Appendix of the Design Memorandum. In addition to the field investigations, a groundwater computer model was prepared utilizing the FEMWATER finite-element code. The model was prepared based on the site-specific information and provided a useful means of measuring potential groundwater impacts from site use. Model development, use and conclusions are described in the following sections.

7.4.1) Site Specific Conceptual Model

As mentioned in the geological descriptions above, the underlying geology at the Courthouse Point confined disposal facility (CDF) is the result of deposition from a fluvial system. The result of this depositional environment over an extensive period of time has resulted in a complex series of gravel, sand, silt and clay. Subsurface investigations encountered portions of the Talbot/Columbia Formation, the Potomac Formation, the Arundel Clay and possibly the Magothy Formation. These formations have been described previously.

The stratigraphic boreholes/well locations near the Courthouse Point site are shown on Figure 32, which is a map of the model study area. The boreholes revealed the complex nature of the site geology including a northeast-southwest trending paleochannel approximately 60-70 feet below grade. The nearby municipal wells for Harbor View are completed in this paleochannel as it thickens toward Elk River to the north. The boring logs all show the same fining upward sequence, which is indicative of a fluvial open channel flow system. A detailed view of the 2 Cluster (including CECE-56) is also included on Figure 32.

The fence diagram (Figure 33) shows generalized conceptual interpretations of the geology below the Courthouse Point site. The site is positioned on top of a fine sand and gravel bed with thicknesses of up to 20 feet. These sands and gravels contain numerous thin layers of silts and clays, all lenticular and impossible to correlate from one well to another. Below this surface layer, there was another layer of fine sand. In some areas these two sand sequences were separated by erratic layers of clay and could represent semi-confined conditions. In other areas, there was little clay between the two sand layers, and the whole sequence probably exhibited unconfined conditions.

There are some exceptions to the fine sand layer at the surface. The deposited dredge material inside the site is mostly tight clay; however, there may be some small areas of coarser material near the discharge pipe. Another area of surface silts and clays lies proximal to the CHP-2 cluster of wells.

For modeling purposes, this surfacial sequence was represented as two layers. "Surface" corresponds to the shallowest sand layer but is replaced by clay or silt material as appropriate. (Clay was used inside the site dikes, for example.) The next layer was called "Unconfined Sand" and corresponds to the deeper sand. This allowed the "Surface" layer to represent sands, silts, or clays (as appropriate), while retaining a sand zone below. To ensure numerical stability, the properties of geologic materials can not change too rapidly from material to material, or layer to layer. Because of this, there was a " buffer material" placed around the dredged material inside the site. This acts as a transitional material to bridge the difference between the tight clays that comprise the dredged material and the sands around it.

Below the unconfined/semi-confined surface sequence there is a fining-upward sequence of silt and clay encountered in most boreholes. This first clay bed (designated "clay" in the model) varies from only a few thin layers (as seen in CHP-6C) up to 45 feet thick (as seen in CHP-3C). The absence of the clay in CHP-6C represents a significant "hole" in the confining layer between the Unconfined Sand and the Potomac Sand below. Though the model was constructed before CHP-6C was drilled, there was evidence to suggest that the confining layer was breached in this area. CHP-3B water levels are close to the levels seen in CHP-3C, even though there is 45 feet of clay separating the sands at this drilled location. In addition, the analytical data from water samples taken in the deep zones in this area suggested a possible communication with the surface.

The third major hydrologic layer encountered was a massive, silty sand up to 70 feet thick as recorded in CHP-2C. This sand was designated "Potomac sand" in the groundwater model. This layer represents the erosional base of the paleochannel mentioned above.

The final layer encountered is the Arundel Clay or Middle Potomac Confining Unit. This regional confining unit was only penetrated a maximum of 80 feet by the CHP borings; however, CECE-56 was drilled to 420 feet. The logs from well CECE-56 indicate that clay is the predominate material encountered from 150 to 420 feet below ground surface. This clay layer represents an effective lower boundary for the groundwater model at Courthouse Point.

7.4.1) 3D Mesh

The 3D mesh used for modeling at Courthouse Point is shown in Figure 34. It is composed of a total of 23,400 nodes and 42,070 wedge elements. For purposes of numerical accuracy, each hydrogeologic layer described above was subdivided into additional layers. "Surface" was subdivided into 7 sub-layers. (Increased vertical refinement is needed in areas where the model changes from unsaturated to saturated conditions.) Both "Unconfined Sand" and "Clay" were subdivided into 2 layers. "Potomac Sand" was subdivided into 3 layers. This represents a total of 14 layers in the Courthouse Point model.

7.4.2) Boundary Condition Assignment

Boundary conditions are shown in Figure 35. Because Courthouse Point is a peninsula, the coastline represents points of fixed water elevation (sometimes called "wet boundaries"). These were set as constant head nodes (Dirichlet boundaries) and given an elevation of zero feet (NAVD).

The northeast and southeast borders of the model domain were designed to follow perennial streams to their source. These "wet boundaries" were also assumed to have a fixed elevation and were set equal to topography.

All model nodes located vertically beneath these "wet boundaries" were also assigned Dirichlet values corresponding to the surface value. This is a simplification due to the paucity of water level information for the deeper model layers. While this simplification may not exactly match the physical system, it is not considered to be deleterious to model performance. In the actual physical system, the Chesapeake Bay and Elk River would act as discharge points of both shallow and deep flow systems. Due to the fact that most of the aquifer layers actually outcrop in the bay, there is not considered to be an effective confining mechanism which would create a significant disparity between the shallow and deep water levels.

Perennial streams inside the model domain were also designated as constant head nodes (for the surface layer only). These perform the useful function of removing the water that flows into the perennial streams and prevents ponding in the numerical simulations.

The only border of the model not represented by a "wet boundary" is the eastern side. This area is located on the topographic crest of the peninsula. As such, it is reasonable to assume that it lies in an area of radial groundwater flow, especially for the shallow layers. This produces flow lines from the topographic crest into the streams. These flow lines were interpreted as a no-flow border in the numeric model. No simulations were conducted which violated the assumption of radial flow from this topographic crest. The no-flow boundary was assumed for all model layers along this segment.

Water levels in the site were set at an elevation of 40 feet (Dirichlet boundary). This elevation is controlled by the outflow sluice and represents the maximum head that can be sustained in the CDF during operations or slack time. Because the dredged material below this ponded water is dense clay, there is little effect on groundwater velocities in the more conductive layers below, regardless of ponded elevation.

Recharge represents another boundary condition that is applied to the upper face of surface elements. Figure 35 shows the elements that were assigned a Cauchy boundary condition, which consists of a fluid flux prescribed at a boundary element face. The elements located northeast of the site were assigned a constant recharge rate of 15 inches per year. The elements located southwest of the site were assigned a constant recharge of 9.5 inches per year. The composite effect of these areas agrees nicely with the published recharge values of approximately 13 inches per year.

7.4.3) Steady State Calibration

The model was calibrated to steady state groundwater levels measured on March 31, 1998. The calibration database is shown in Table 3. Except for CECE56, all wells beginning with the letters CE represent historic water levels. They were not sampled for this investigation because they are privately owned wells requiring permission of the owners to sample plus elaborate safety protocols. These wells all lie in the 100-160 foot depth range and were completed between 1946 and 1981. Since there is no indication of wholesale groundwater mining in this area due to over-pumping, these historic water levels are assumed to approximate current conditions.

TABLE 3

Well Number	Depth of Borehole	Screen Depths	Casing Elev	Water Elev (3-31-98 unless annotated)	Modeled GW Elev	Residual (error)
CHP-1A	17.0	5.0-15.0	14.21	6.70	6.75	0.05
CHP-1B	31.0	20.0-30.0	12.82	4.24	7.37	3.13
CHP-1C	160.0	50.0-60.0	12.80	6.11	5.86	-0.25
CHP-2A	17.0	5.0-15.0	40.25	36.79	32.21	-4.58
CHP-2B	40.0	28.0-38.0	39.17	33.21	30.08	-3.13
CHP-2C	139.0	118.0-138.0	39.43	7.55	10.49	2.94
CHP-3B	35.0	22.0-32.0	41.91	22.78	21.52	-1.26
CHP-3C	209.5	82.0-92.0	42.02	20.32	19.52	-0.80
CHP-4C (boring)	180.0	NA	NA	NA	NA	NA
PZ-1	130.0	118.0-128.0	39.53	7.82	10.50	2.68
PZ-2	130.0	118.0-128.0	39.05	8.25	10.52	2.27
CECE-56	420	115-121	40 (est.)	6.53 (est)	10.48	3.95
CEDE-53	135	130-135	40 (est)	14.5 (est 1958)	16.81	2.31
CECE-79	157	152-157	74 (est)	15 (est 1978)	17.43	2.43
CEDE-49	126	121-126	70 (est)	17 (est 1981)	18.00	1.00
CECE-62	124	114-124	65 (est)	17 (est 1972)	15.77	-1.23
CECE-60	112	107-112	65 (est)	13 (est 1981)	10.43	-2.57
CEDE-19	163	153-163	70 (est)	-9 (est 1946)	5.73	14.73*

Note: All measurements are in feet. CHP-1C and 3C were sealed with bentonite slurry to the screen depth. * Calibration for CEDE-19 was considered anomalous and removed from total accounting.

Monitoring wells CHP–4CR, -5C, -6C, and –7C were drilled after calibration of the model, at the regulator's request. As such, their data were not used in this steady state calibration. Additional calibration can be performed; however, seasonal adjustments to recharge may be required for the new data. It is not expected that the addition of these data would degrade the present calibration. The additional data fit into the regional water level trends established with the previous wells. The wells were drilled primarily to add stratigraphic information.

The only pumping stress applied to the calibrated model was the municipal system at the Harbor View development. This system is operated by Cecil County Public Works and is comprised of two wells. Because these wells are located close to each other, and reported pumping totals are averaged together, these wells were simulated as a single sink. Pumping records for 1997 indicate that the system pumped a yearly average of 9855 gpd. The highest monthly average was 12071 gpm, so that value was used to be conservative. There is continuing development in the subdivision, so average pumping rates may be expected to increase.

Because state records can omit important data, a field reconnaissance was performed to locate other high-volume wells. All neighboring subdivisions and farms were investigated and found to be on individual, low-volume wells.

Calibration of the model is shown in Figure 36. This is a bar-and-whiskers plot that is helpful in revealing the spatial characteristics of the calibration error. The color bar represents the error. The "whisker" represents the target, which is 2 feet in this case, or 2.5% of the total range. Green on the bar indicates residual values within the target (2 feet). Yellow indicates residual values within 200% of the target (4 feet). Red indicates values greater than 200% of the target. The mean error of all the observation points is 0.43 feet, the mean absolute error is 2.16, and the root-mean-square is 2.5. The maximum residual was 14.5 feet (CEDE-19), but this was from an old well (1946) with questionable accuracy (reported water levels were 9 feet below sea level). For this reason, it was omitted from the total error accounting. The next worst residual was only 4.58 feet (CHP2A). Considering there is an 80-foot elevation range in values across the model, these results are considered excellent. Calibration is usually considered sufficient when error values fall within 10% of the total range.

7.4.4) Conclusions

An extensive focused groundwater investigation was performed at the Courthouse Point Confined Disposal Facility to determine if there were adverse ground water effects from site operations. Fifteen new wells or borings were installed. Ten were installed to support groundwater modeling investigations. Five additional wells were installed to add geologic information; however, results from these new wells came too late to be incorporated into the calibration of the model.

Results of this investigation show that there are basically two aquifers separated by a clay layer that varies in thickness from only a few thin layers (as seen in CHP-6C) up to 45 feet thick (as seen in CHP-3C). The absence of the clay in CHP-6C represents a significant "hole" in the confining layer between the Unconfined Sand and the Potomac Sand below. Even before the results of the new drilling had arrived, the model required a "hole" in the clay to achieve calibration. CHP-3B water levels are close to the levels seen in CHP-3C, even though there is 45 feet of clay separating the sands at this drilled location. Figure 37 shows the approximate areal extent of the "hole" (or fenster) which was used in the model for calibration. Instead of Clay, this "hole" was filled with Unconfined Sand, the material located in the layer above the clay. The effect of this "hole" was to allow movement of water from the Unconfined Sand into the Potomac Sand below. This lowered the water levels in the shallow aquifer and elevated levels in the deeper, a condition proven by water level data in the wells.

In addition to the geologic and modeling data, analytical data from water samples taken in the deep zones in this area suggested a possible communication with the surface. Additional information concerning this data is available in the *Final Hydrogeologic Investigation Report* which is located in the Geotechnical Appendix to the Design Memorandum.

The groundwater flow regime is illustrated by Figure 38 ("Unconfined vectors") which shows flow vectors in the Unconfined Sand aquifer. (Vector arrows are scaled to the magnitude of flow. Large arrows indicate large velocities.) Flow direction is dominated by groundwater moving toward the shorelines and toward the "hole" in the clay layer. Since the exact areal extent of the "hole" is not completely known, these flow patterns were extrapolated from available information. It is known that the old stream valley and the entire bottom of Courthouse Point are filled with dredge material exhibiting extremely low hydraulic conductivities. This clay serves to impede any movement of contaminants from the site to the shallow aquifer, an effect that is evident on the flow vectors. The predominant flow of water into the "hole" is from the south, areas where recharge into the aquifer is not impeded by the clays of the CDF. Flow vectors coming from the direction of the Courthouse Point site are quite small.

Figure 39 ("Potomac Vectors") shows the flow regime in the deeper Potomac Sand aquifer. This is the aquifer in which the production wells of Harborview are completed. As can be seen in the figure, the Harborview wells do not draw enough water to affect the regional flow pattern. Below the "hole" in the clay, there is a radial flow pattern, but the predominant flow in the area is toward the north where the aquifer outcrops under the bay.

Though the "hole" represents a potential avenue of solute transport from the shallow to the deeper aquifer, flow directions indicate that the groundwater originating in the CDF will not be intercepted by the production wells of Harborview. Instead, this water will travel on a northwest course and recharge into the Chesapeake Bay. Conservative estimates of Harborview pumpage can not reverse the powerful regional flow in this aquifer.

8) WES Appendix

A Numerical Model Study of Groundwater Flow and Salinity Transport Impacts from C&D Canal Deepening

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US Army Corps of Engineers
Waterways Experiment Station

8.1) Summary

An inset numerical model of a larger regional groundwater model was used for studying the impacts of deepening the C&D Canal navigation channel (400 ft wide) from 40 ft to 45 ft deep. The head boundaries needed for the inset model were taken from the regional model. Groundwater flow and salinity transport was simulated for a period of ten years. The simulated velocity patterns indicated that the C&D Canal system is a sink for

groundwater flow (receiving fresh water from the adjacent groundwater system). The groundwater simulations indicate that the loss of groundwater to the Canal, due to channel deepening, is sufficiently small as to have a negligible impact (about 225 ft^3 per day per mile). Salt intrusion into the Canal or the adjacent groundwater will not substantially deviate from existing conditions.

8.2) Scope of Study

The scope of the numerical model study was to evaluate the impacts of deepening navigation channel from 40 ft to 45 ft in the C&D canal.

8.3) Introduction

The FEMWATER numerical model was used to study the impacts of channel deepening in the C&D Canal system. A coarse resolution regional model was developed to provide the boundary conditions for an inset model (fine resolution mesh) near the Canal. The coarse model was used to determine the effects of deep pumping in the Potomac Aquifer on the upper geologic units and of pumping on the surficial geologic units that outcrop into the bed of the Canal. This mesh was also used to simulate the regional groundwater flow pattern.

8.4) Model Application

8.4.1) 3D Mesh

An inset mesh, developed from a portion of a larger regional model, was used for the C&D Canal groundwater flow and salinity transport study. The bottom of the mesh was set at the interface between the Potomac Clay and the Magothy Sand stratigraphic units. The eastern boundary was set at the Delaware River, while the western boundary extends to where the Magothy outcrops into the bed of the canal. The north boundary was set at Dragon Creek and the southern boundary was set about two miles south of the Canal. The 3D mesh is shown on Figure 40. Figure 41 depicts an orthographic view of the 3D mesh.

8.4.2) Boundary Conditions

Head boundary conditions were assigned along the four sides of the mesh. The bottom of the mesh was also assigned a head boundary condition. Head boundary conditions were taken from the coarse regional model. A constant head of 0.0-ft NGVD was assigned at the canal. The average salinity concentration of 6.0 ppt (parts per thousand) was assigned at the canal nodes representing a long term average salinity condition.
Transient Flow and Transport Simulation

Figure 42 shows the location of cross-sections F-F' and G-G'. The cross-section F-F' is located between Delaware City and St. Georges where the Magothy Sands are intersected by the canal. The cross-section G-G' is located in the vicinity of Lums Pond. Existing conditions were simulated for a period of ten years with a coupled flow and salinity transport simulation. Figure 43 shows the flow patterns at cross-section G-G'. Figure 44 shows the flow patterns at cross-section F-F'. Figures 45 and 46 show the salinity contours at the cross section F-F' for both with and without project conditions.

The proposed project conditions with deepening 5 ft (400 ft wide) in the navigation channel of the canal were simulated for an identical period of ten years as was simulated in the existing condition. The salinity differences between the existing condition and the proposed project are shown in Figure 47. This figure indicates that saltwater intrusion is concentrated near the canal and does not migrate farther inland.

The comparison of groundwater flow into the canal was listed in Table 4. The results indicated that losses of groundwater due to the proposed project are negligible (225 ft^3 per day per mile).

Table 4. Comparison of Groundwater Flows into Canal for the Existing and Proposed Project

Groundwater Flows into C&D Canal (ft^3/day)			
Canal Side Nodes		**Canal Bottom Nodes**	
Existing	**Proposed**	**Existing**	**Proposed**
2.60×10^6	2.60×10^6	2.5×10^4	2.7×10^4

8.5) Conclusions

The simulated flow patterns indicate that the C&D Canal receives the fresh water from adjacent groundwater sources. The navigation channel deepening from 35 ft to 40 ft in the C&D Canal system causes no significant loss of groundwater into the Canal. Groundwater salt concentrations will not deviate from the existing conditions based on the ten year simulation results.

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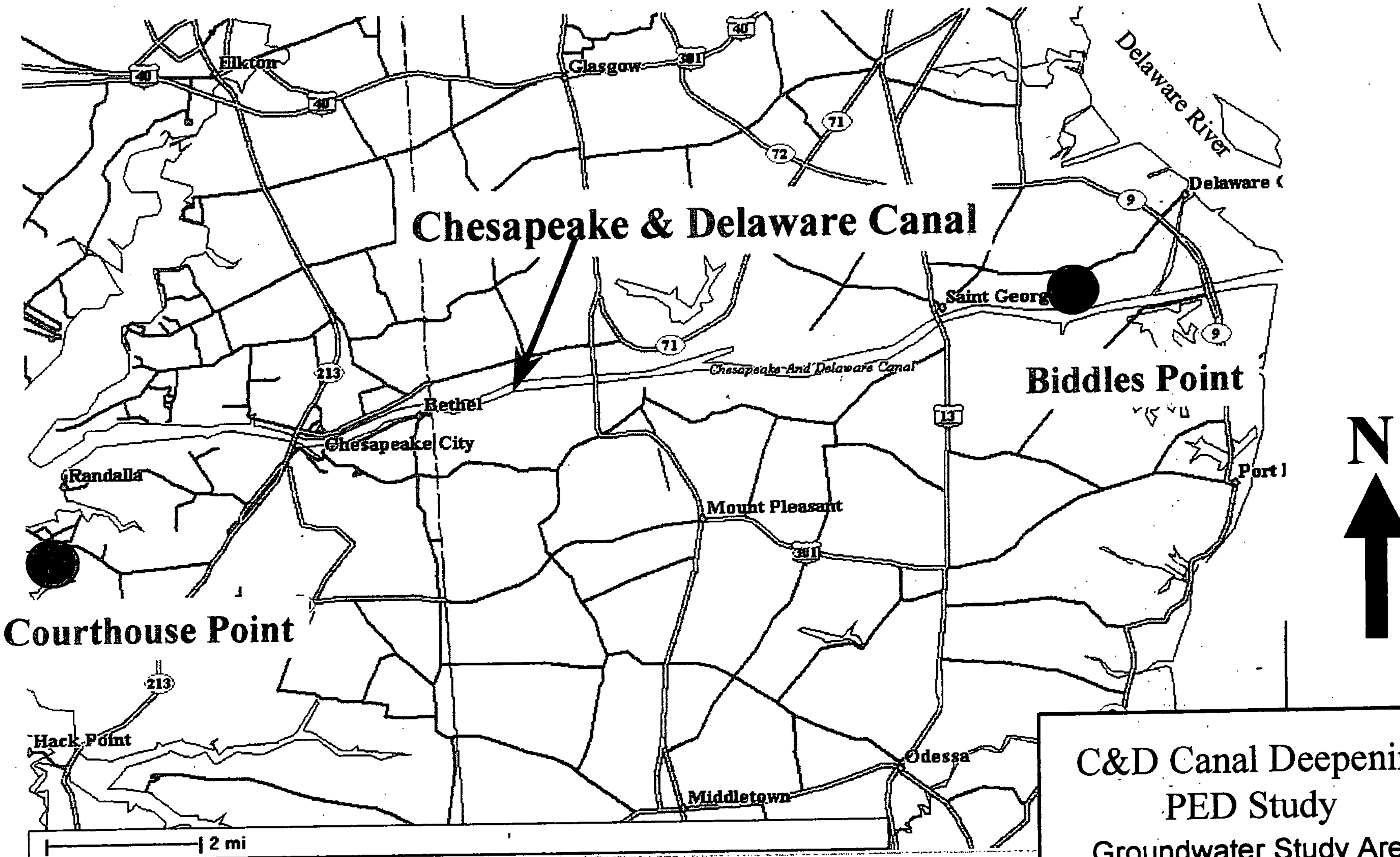
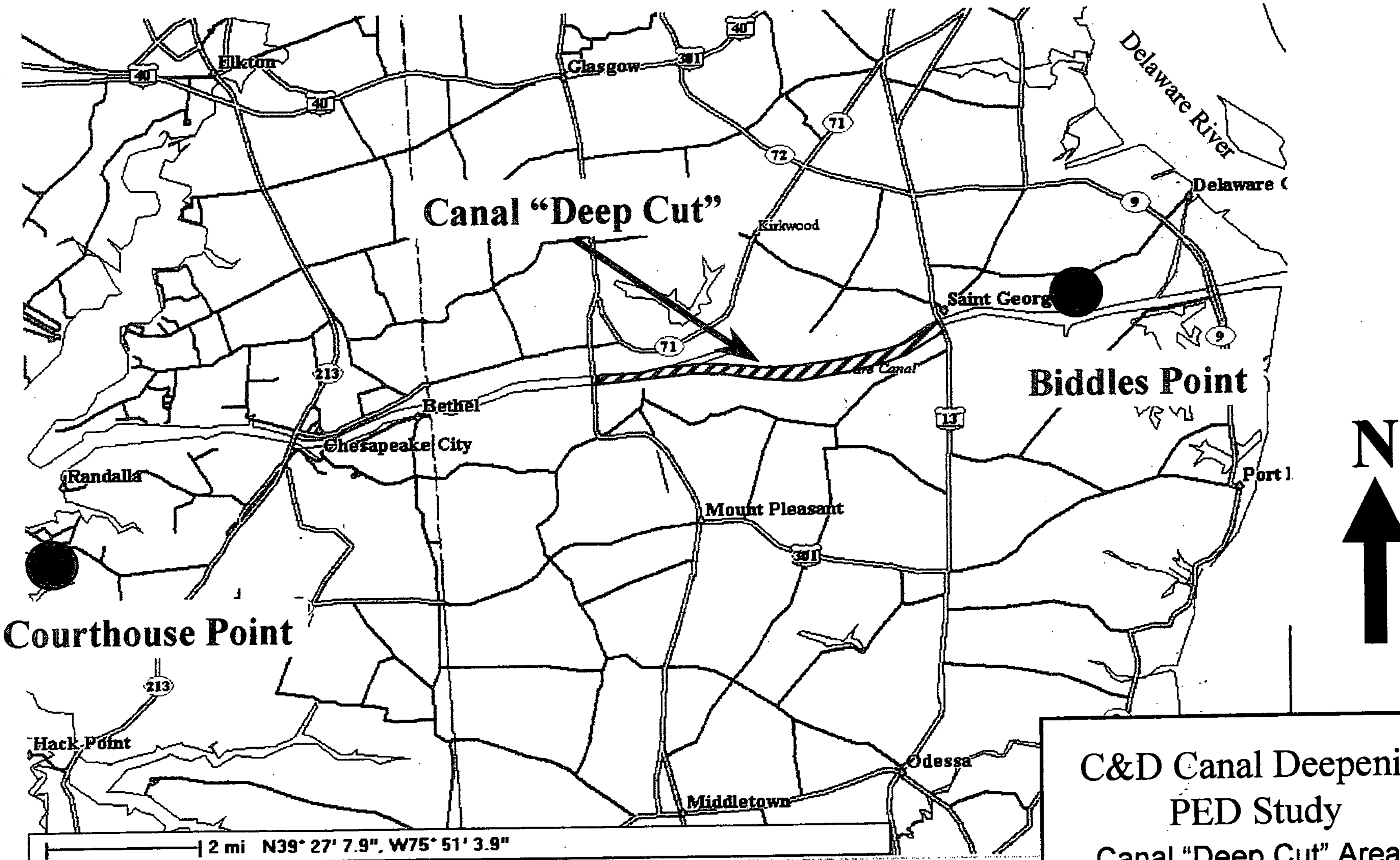


Scale

Basemap from Map Expert, Inc.

C&D Canal Deepening
PED Study
Groundwater Study Area

Figure 1



Scale

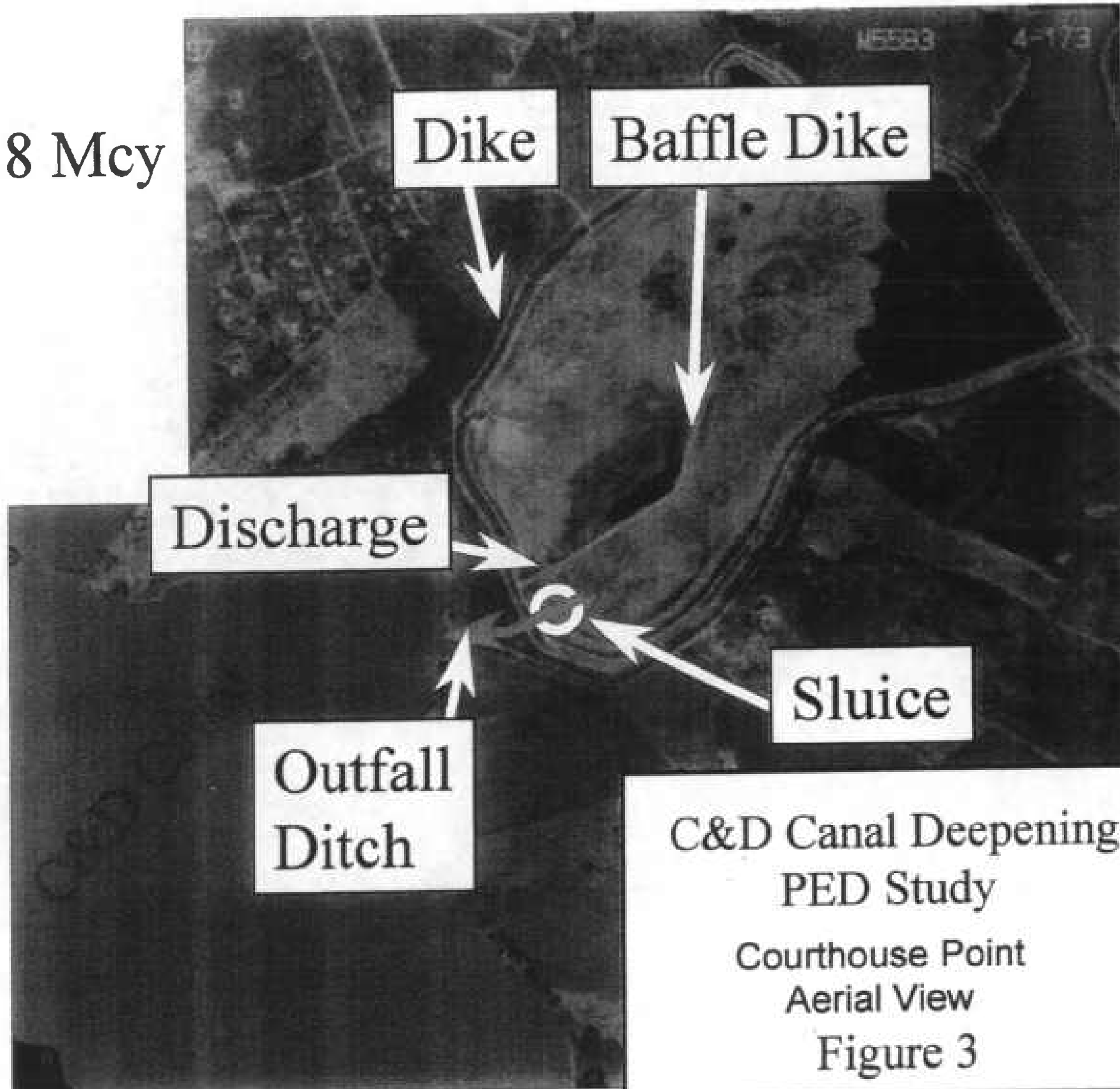
Basemap from Map Expert, Inc.

C&D Canal Deepening
PED Study
Canal "Deep Cut" Area

Figure 2

Courthouse Point DA

- Area = 170 Acres
- Perimeter = 12,000 Ft
- Existing Capacity = 3.8 Mcy
- Sluice operable = Yes
- New Topo 1997
- Outfall to ditch
- Inspected 1998



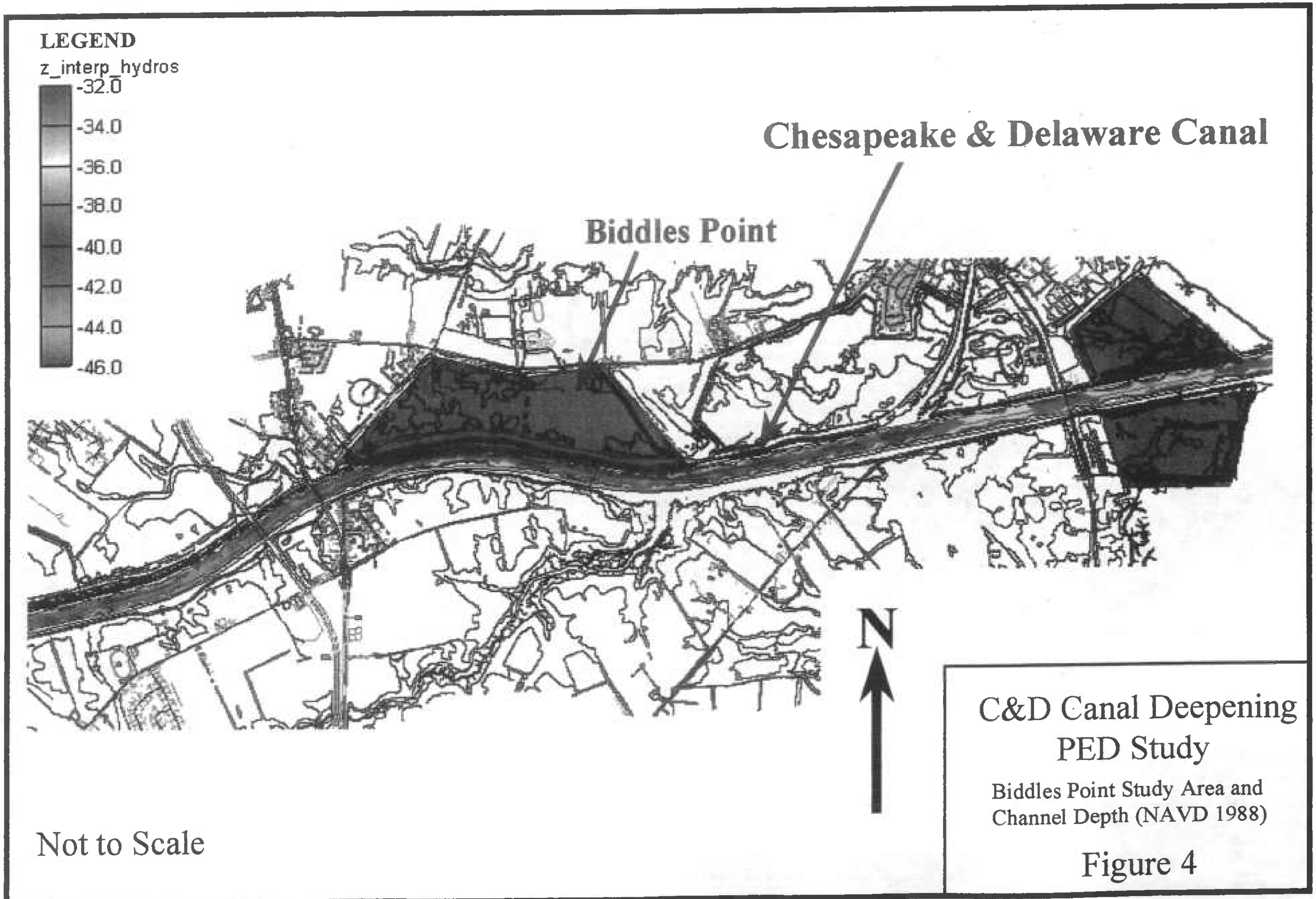
N

Not to Scale

C&D Canal Deepening PED Study

Courthouse Point Aerial View

Figure 3



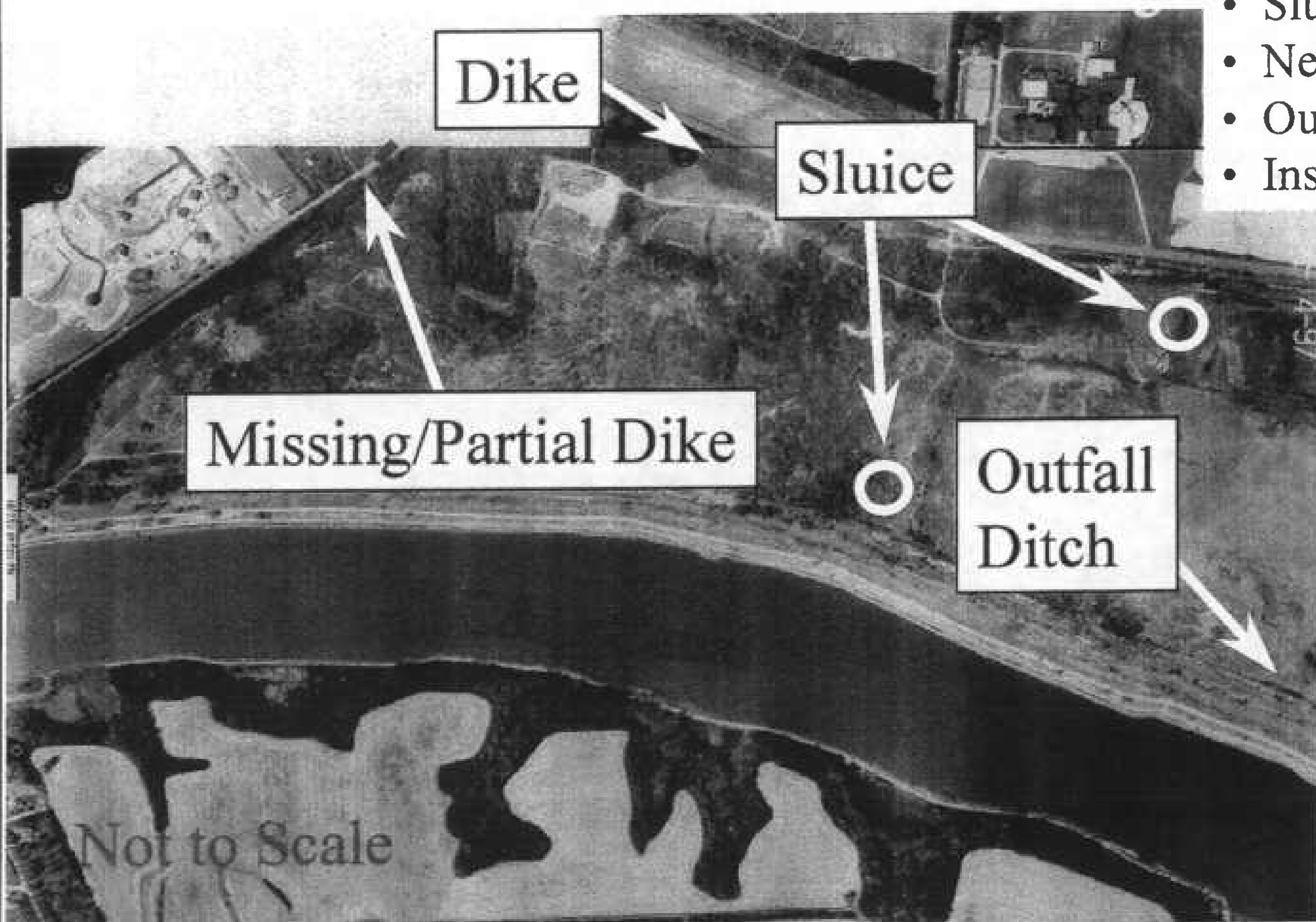
C&D Canal Deepening PED Study

Biddles Point Study Area and Channel Depth (NAVD 1988)

Figure 4

Biddles Point DA

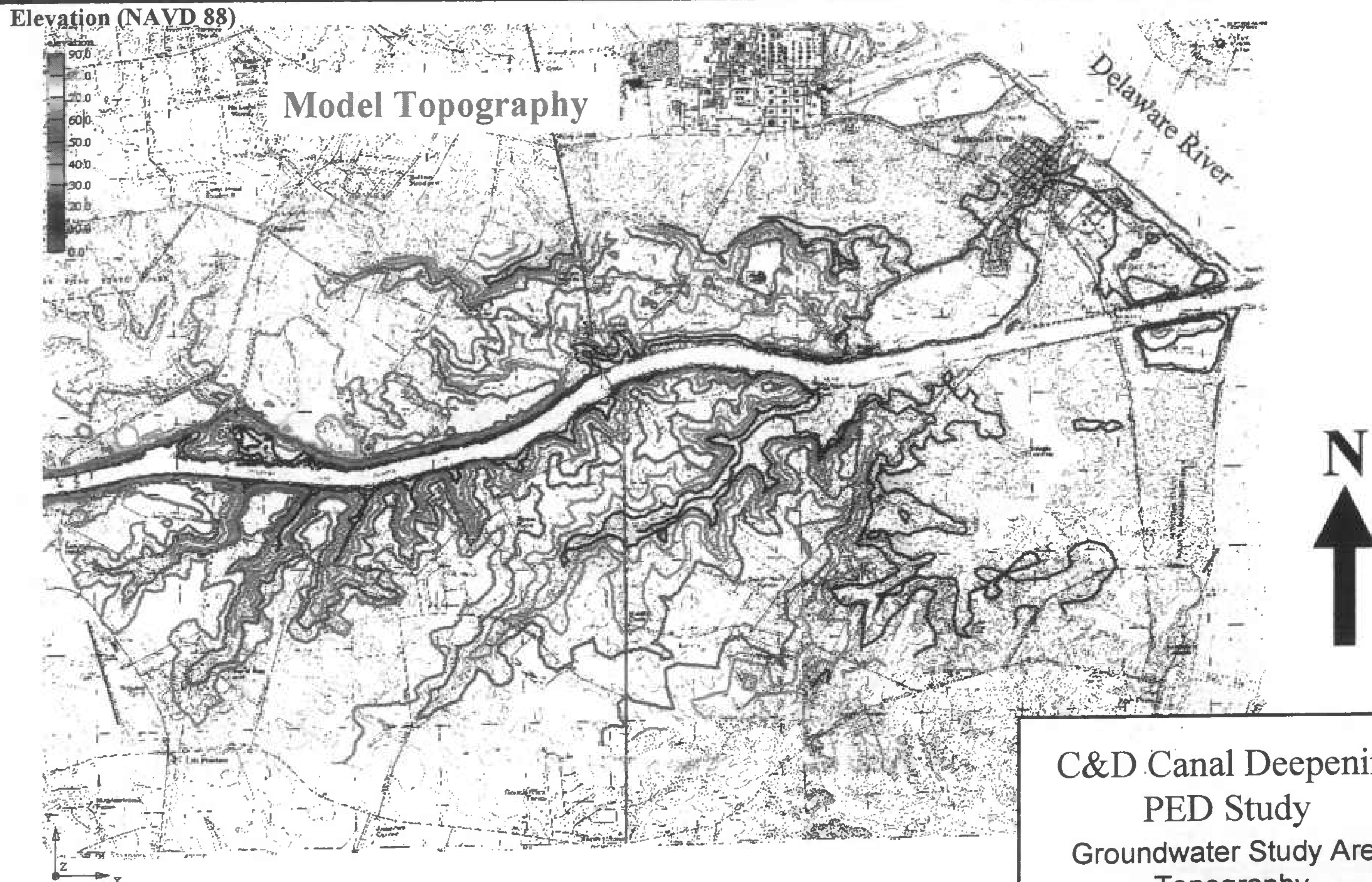
- Area = 300 Acres
- Perimeter = 19,000 Ft
- Existing Capacity = 1.4 Mcy
- (with dike repair on West)
- Sluice operable = Yes
- New Topo 1997
- Outfall to ditch
- Inspected 1998



N

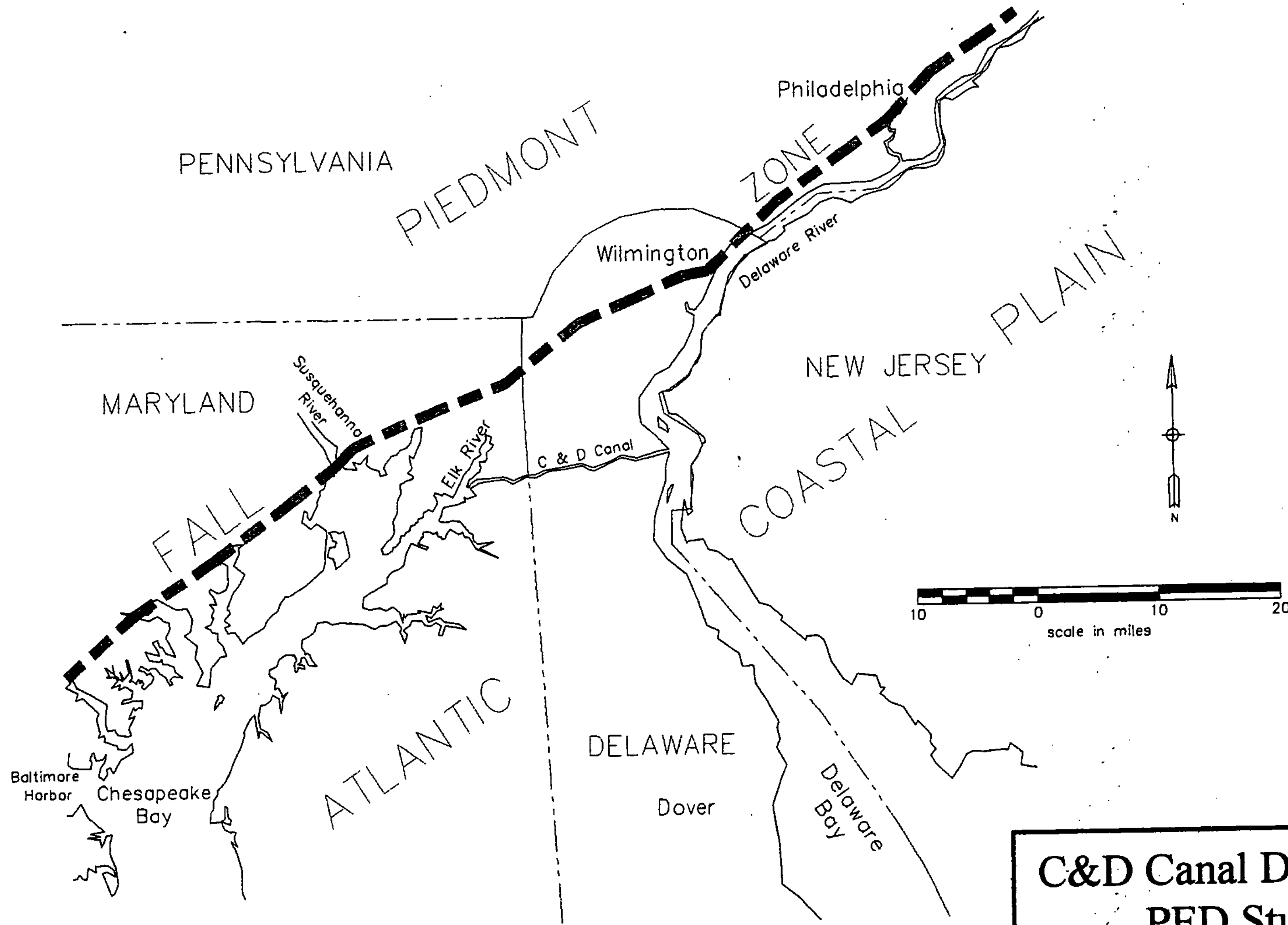
C&D Canal Deepening
PED Study
Biddles Point Aerial View

Figure 5



Not to Scale

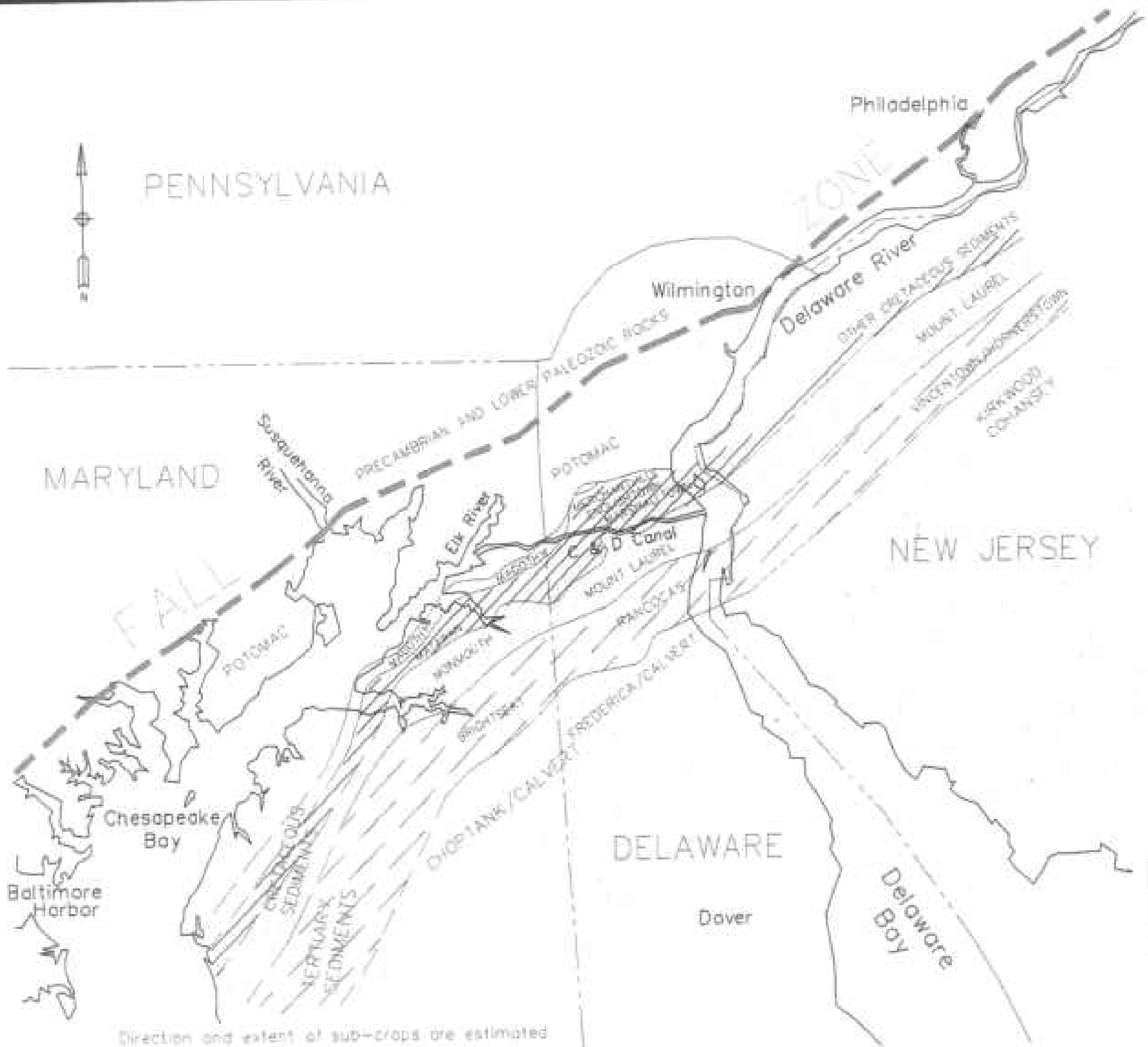
C&D Canal Deepening
PED Study
Groundwater Study Area
Topography
Figure 6



C&D Canal Deepening PED Study

Physiography Map

Figure 7



NOTES:

1. Northwest of and including the Fall Zone, "Precambrian and Lower Paleozoic Rocks" refers to outcropping gabroic, gneissic, and schistose bedrock.

2. Southeast of the Fall Zone, subcrop boundaries below the Columbia Group and other Quaternary sediments are shown.

3. In Maryland, "Cretaceous Sediments" refers to the Monmouth, Matawan, Magothy, and Potomac Groups, and "Tertiary Sediments" refers to the Pamunkey and Chesapeake Groups.

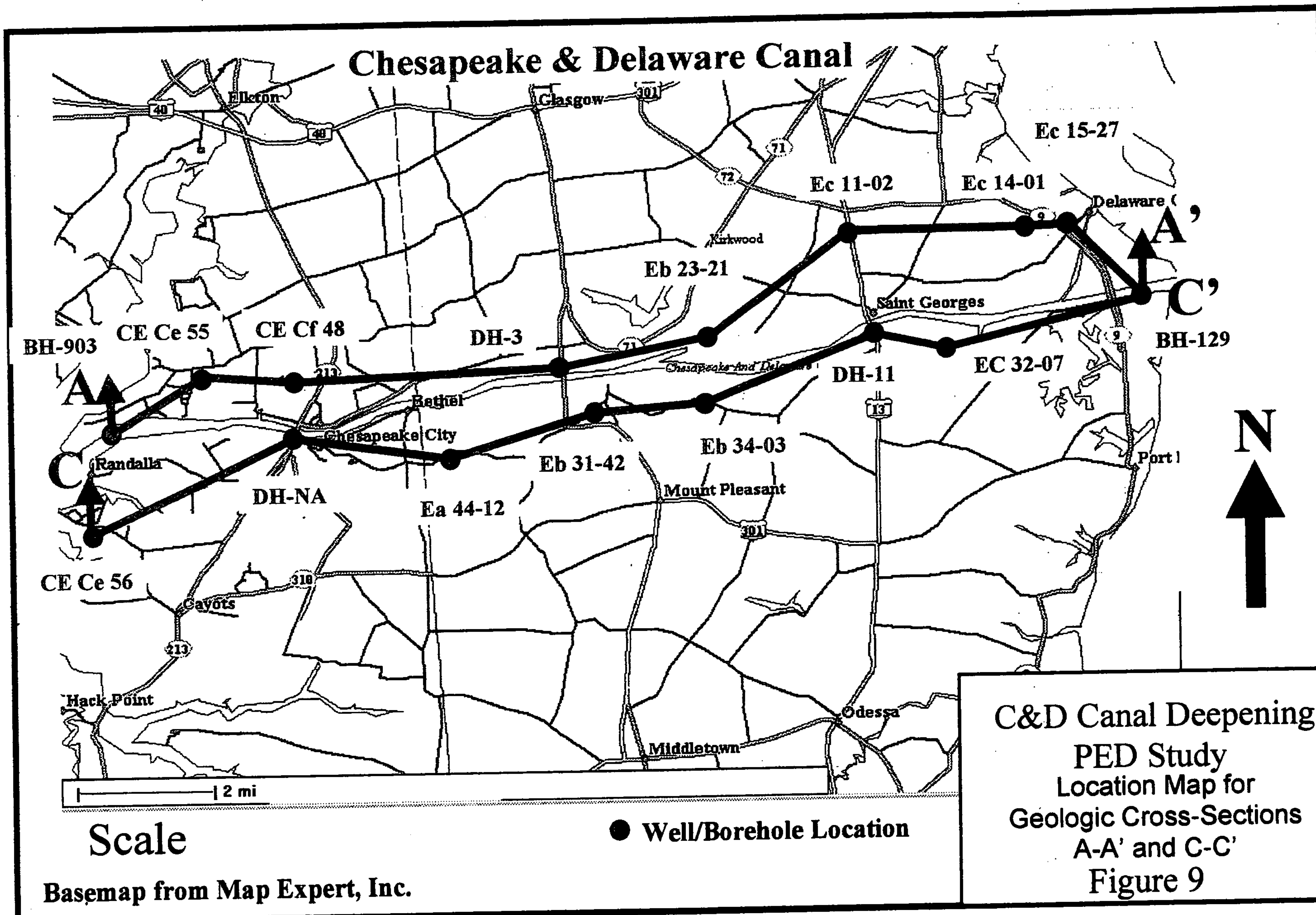
4. In New Jersey, "Other Cretaceous Sediments" refers to the Marshalltown, Englishtown, Woodbury, Merchantville, Magothy, and Raritan units.

10 0 10 20
scale in miles

C&D Canal Deepening PED Study

Geologic Outcrop Map

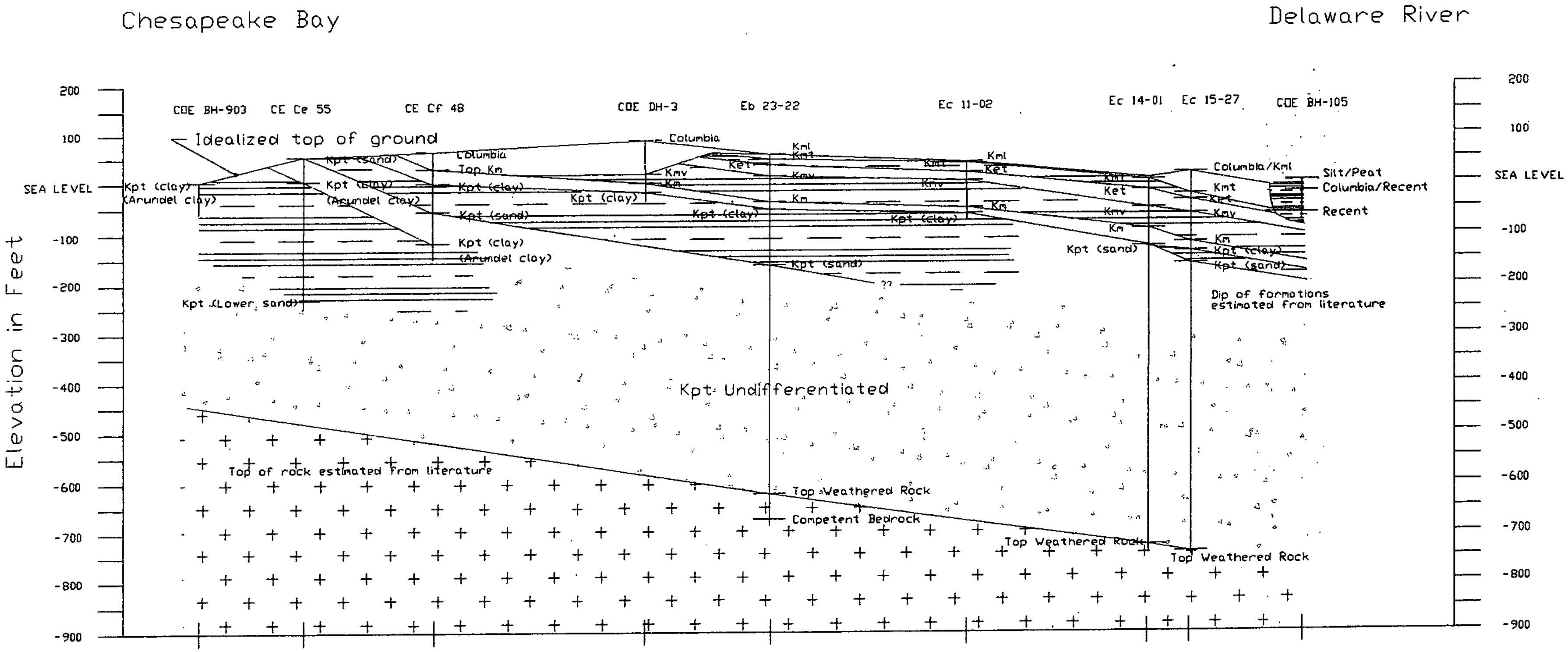
Figure 8



C&D Canal Deepening PED Study

Location Map for Geologic Cross-Sections A-A' and C-C'

Figure 9

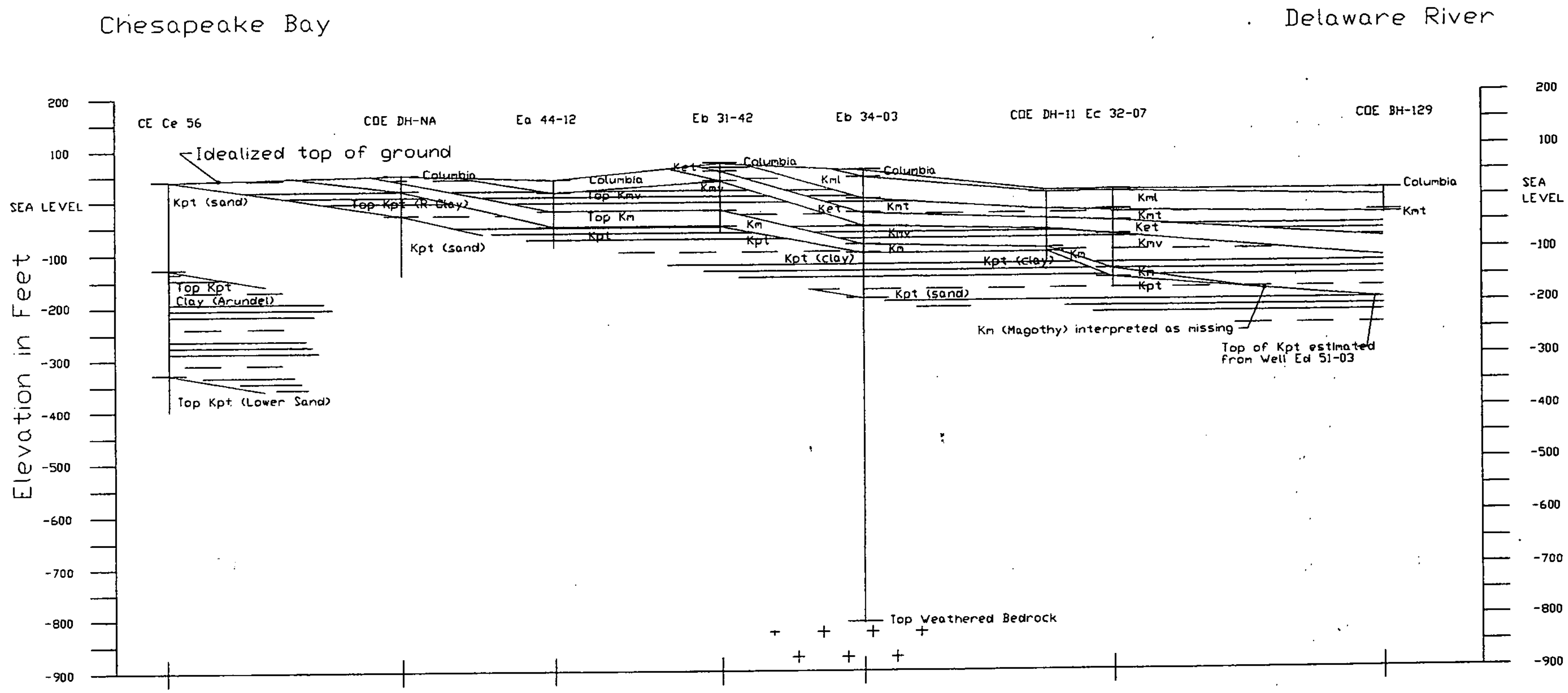


Notes:
COE - Corps of Engineers
CE - Cecil County, Maryland well designation
Kpt - Potomac Formation
Km - Magothy Formation
Kmv - Merchantville Formation
Ket - Englishtown Formation
Kmt - Marshalltown Formation
Kml - Mount Laurel Formation
Bedrock consists of Schist
- Geology inferred from literature

CORPS OF ENGINEERS
GEOLOGIC CROSS SECTION A-A'

Horizontal Scale
0 10000 Feet

C&D Canal Deepening PED Study
Geologic Cross Section A-A'
Figure 10



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COE - Corps of Engineers
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Km - Magothy Formation
Kmv - Merchantville Formation
Ket - Englishtown Formation
Kmt - Marshalltown Formation
Kml - Mount Laurel Formation
Bedrock consists of Schist
╲ - Geology inferred from literature

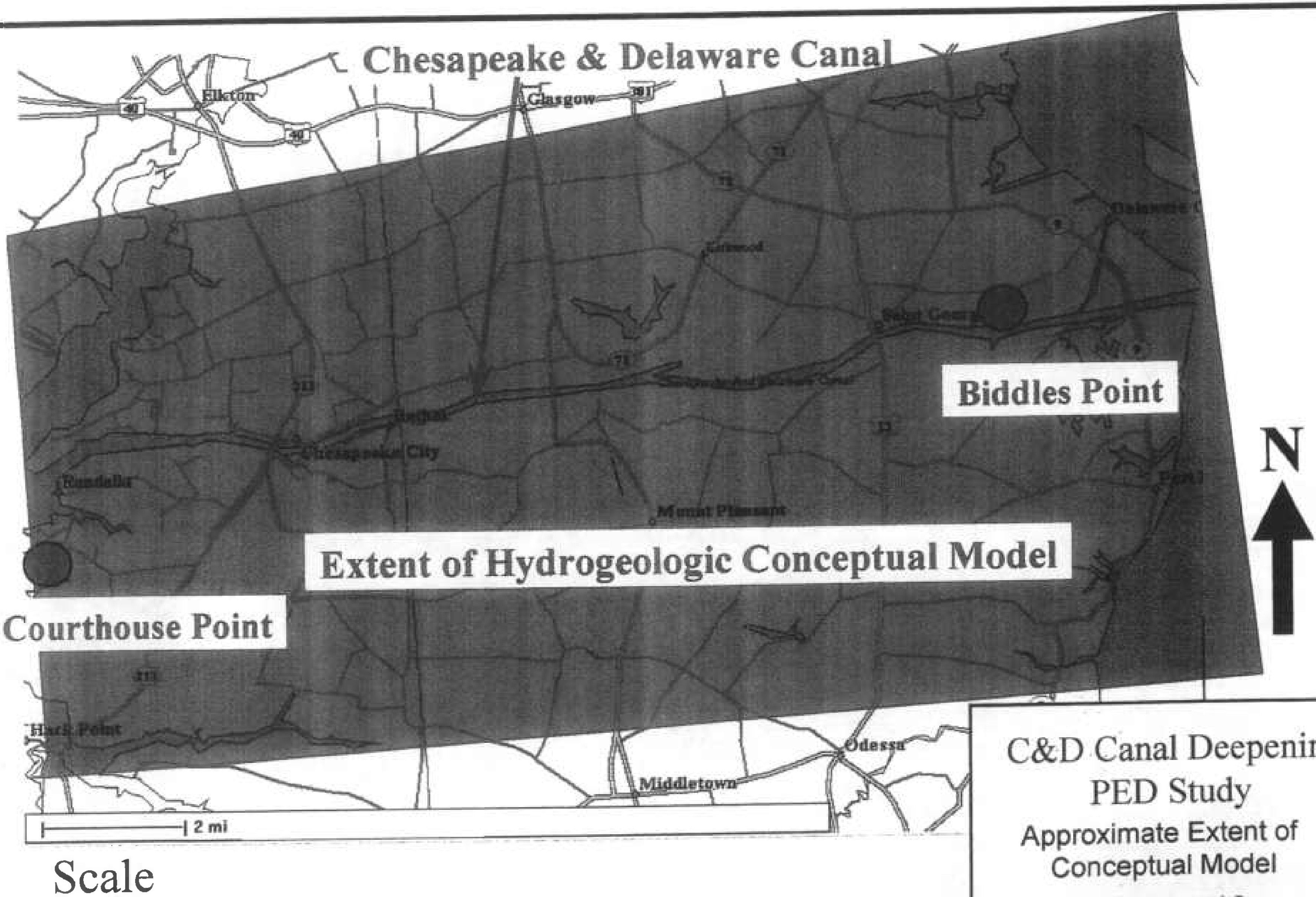
CORPS OF ENGINEERS
GEOLOGIC CROSS SECTION C-C'

Horizontal Scale

0 10000 Feet

C&D Canal Deepening
PED Study
Geologic Cross Section C-C'

Figure 11

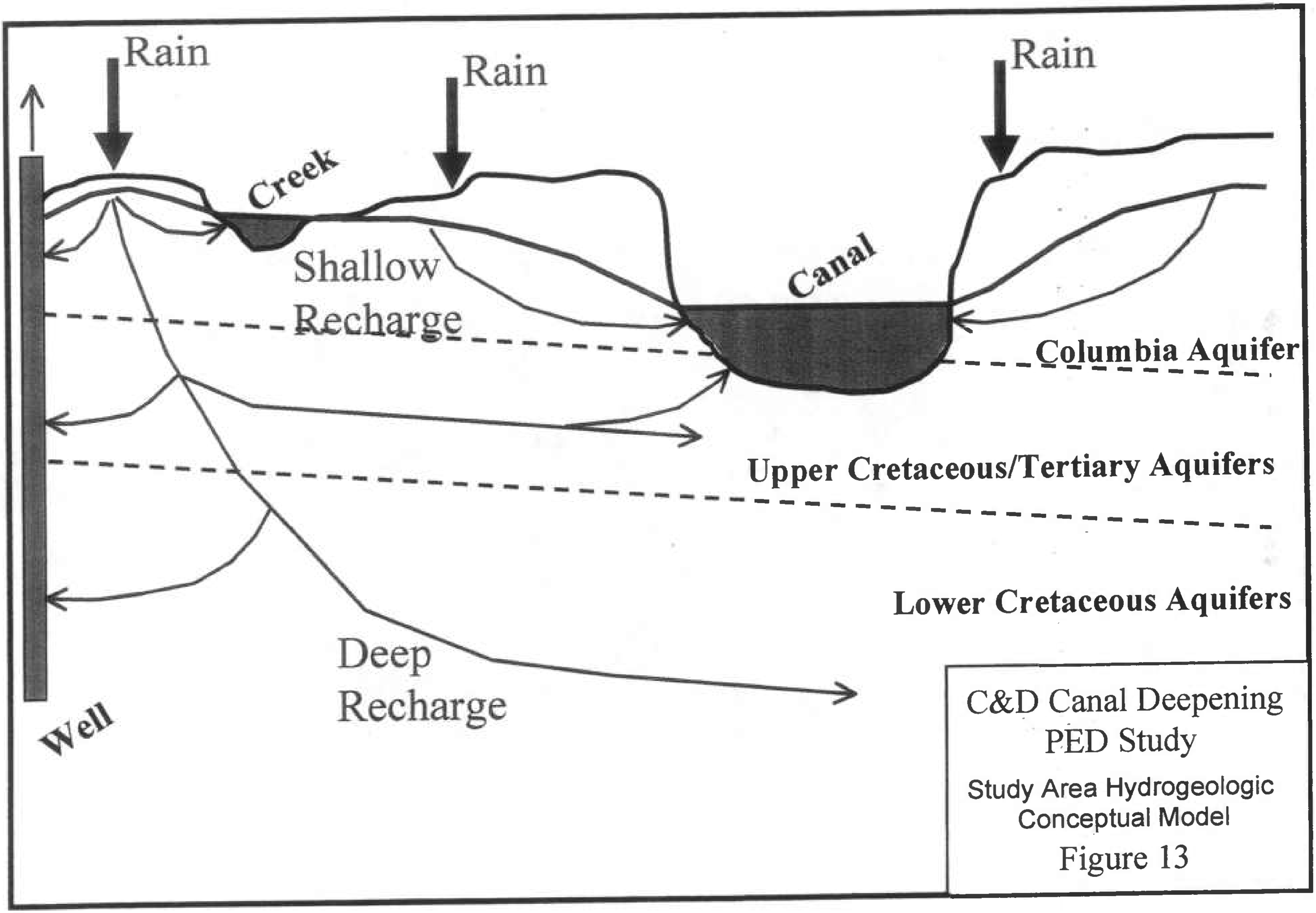


Basemap from Map Expert, Inc.

C&D Canal Deepening PED Study

Approximate Extent of Conceptual Model

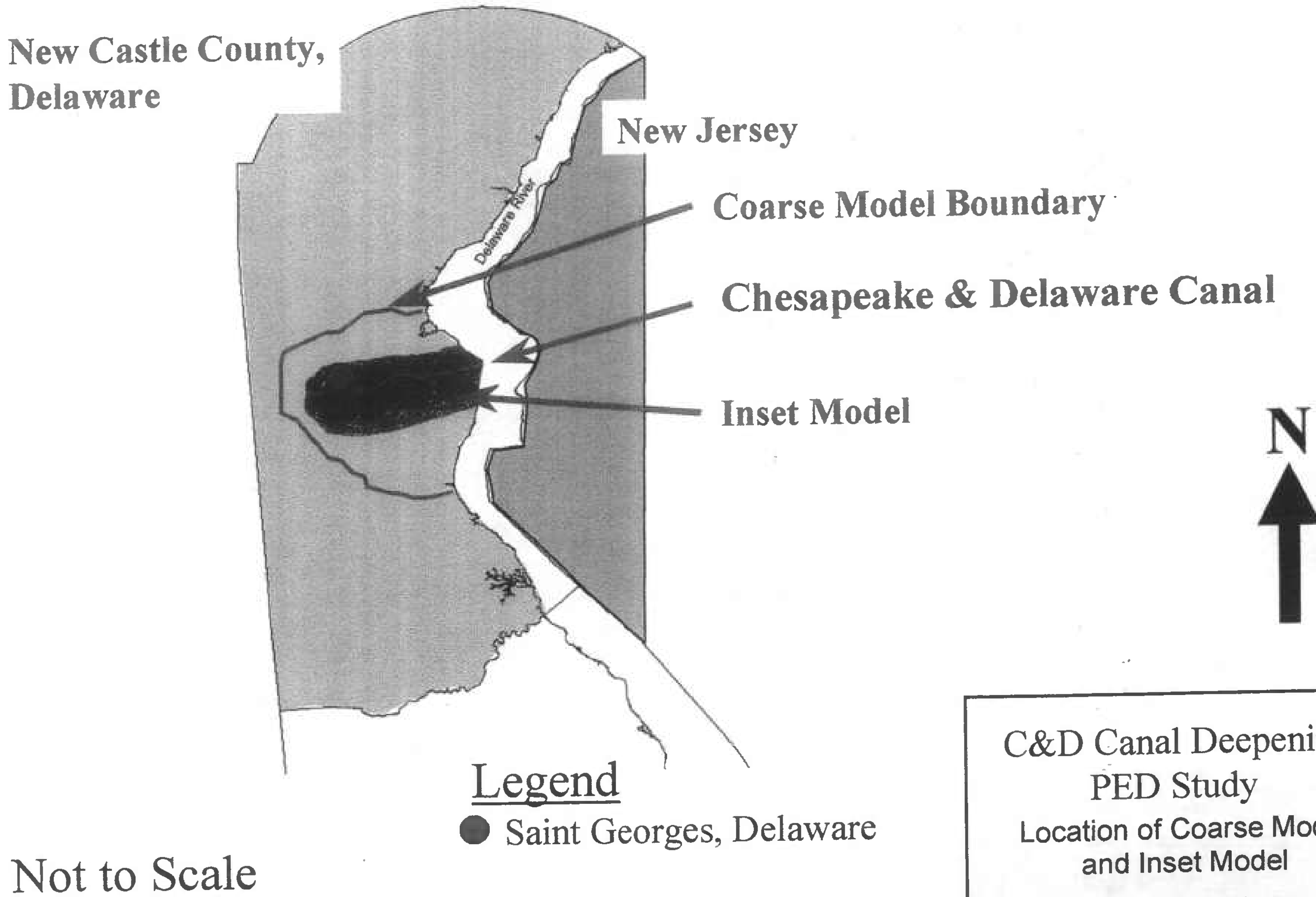
Figure 12



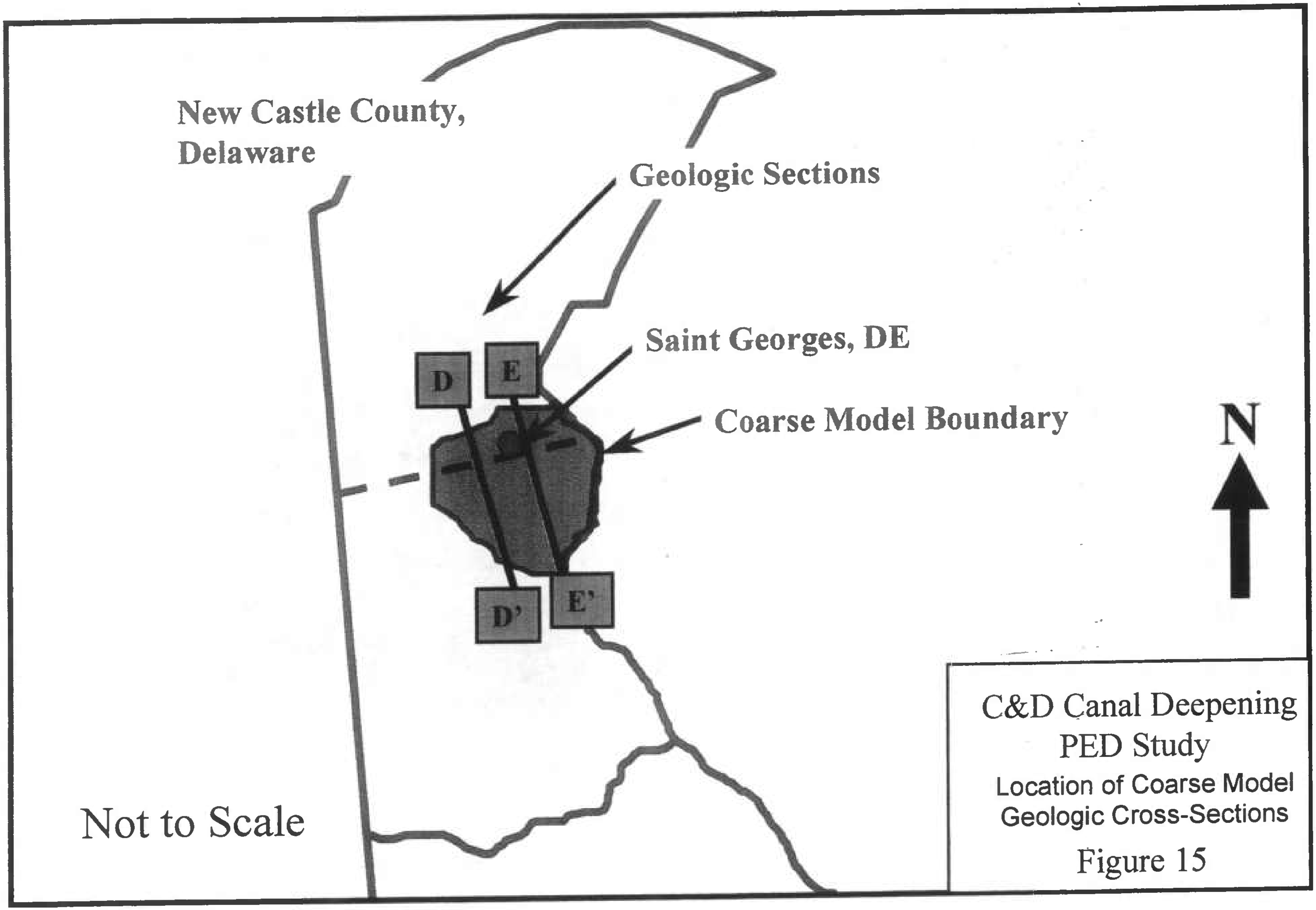
C&D Canal Deepening PED Study

Study Area Hydrogeologic Conceptual Model

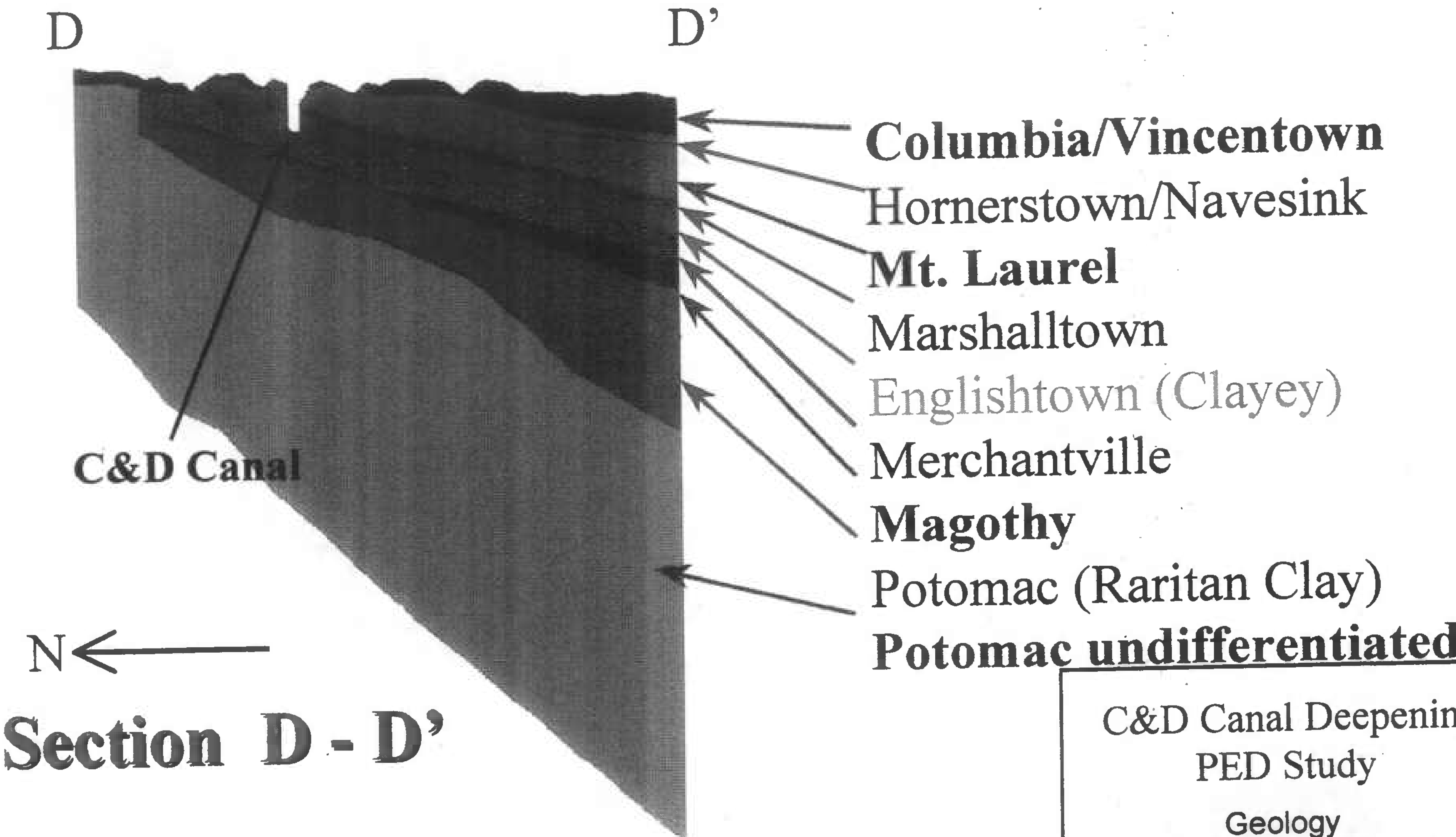
Figure 13



C&D Canal Deepening
PED Study
Location of Coarse Model
and Inset Model
Figure 14



C&D Canal Deepening
PED Study
Location of Coarse Model
Geologic Cross-Sections
Figure 15

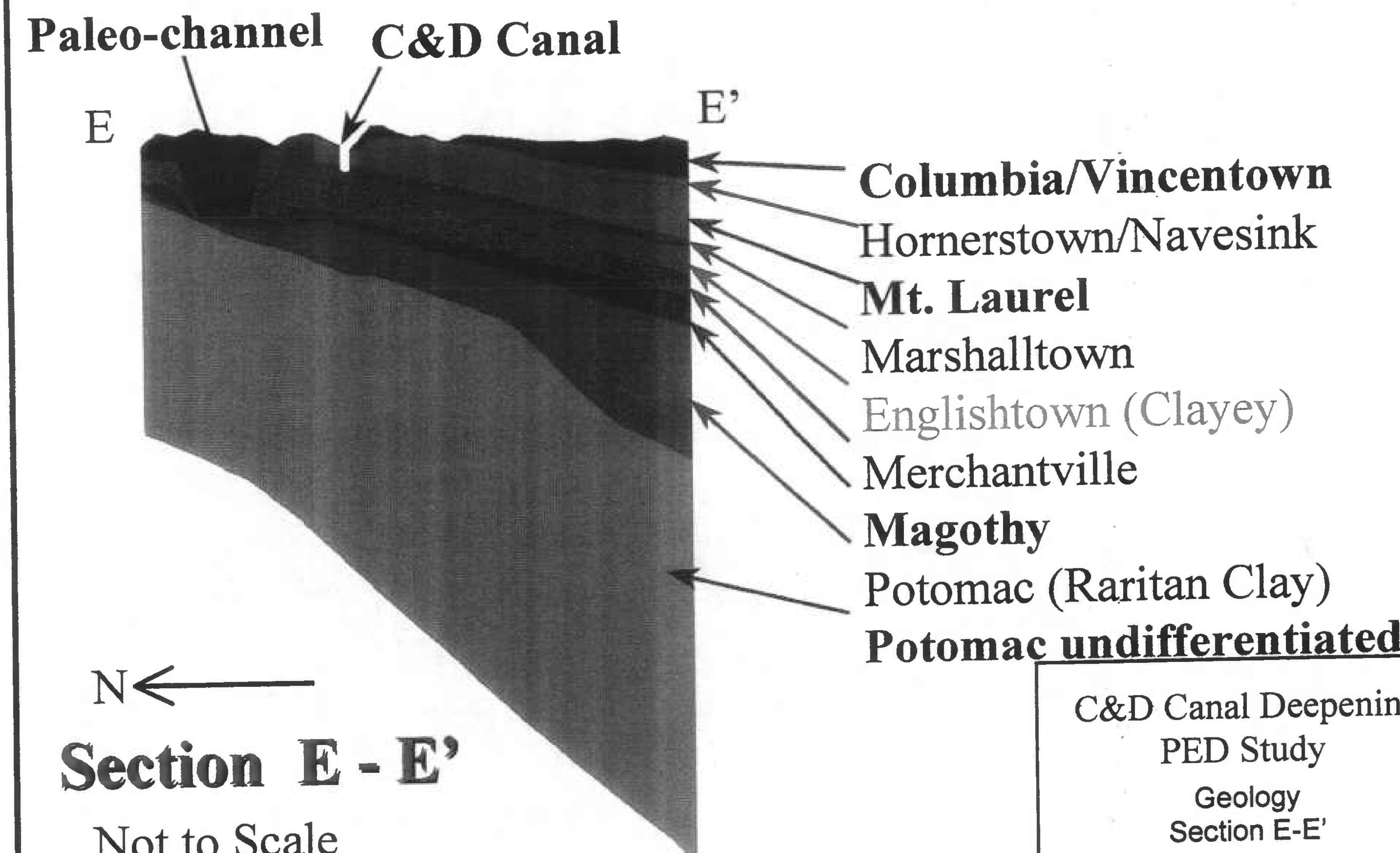


Section D - D'

Not to Scale

C&D Canal Deepening
PED Study

Geology
Section D-D'
Figure 16



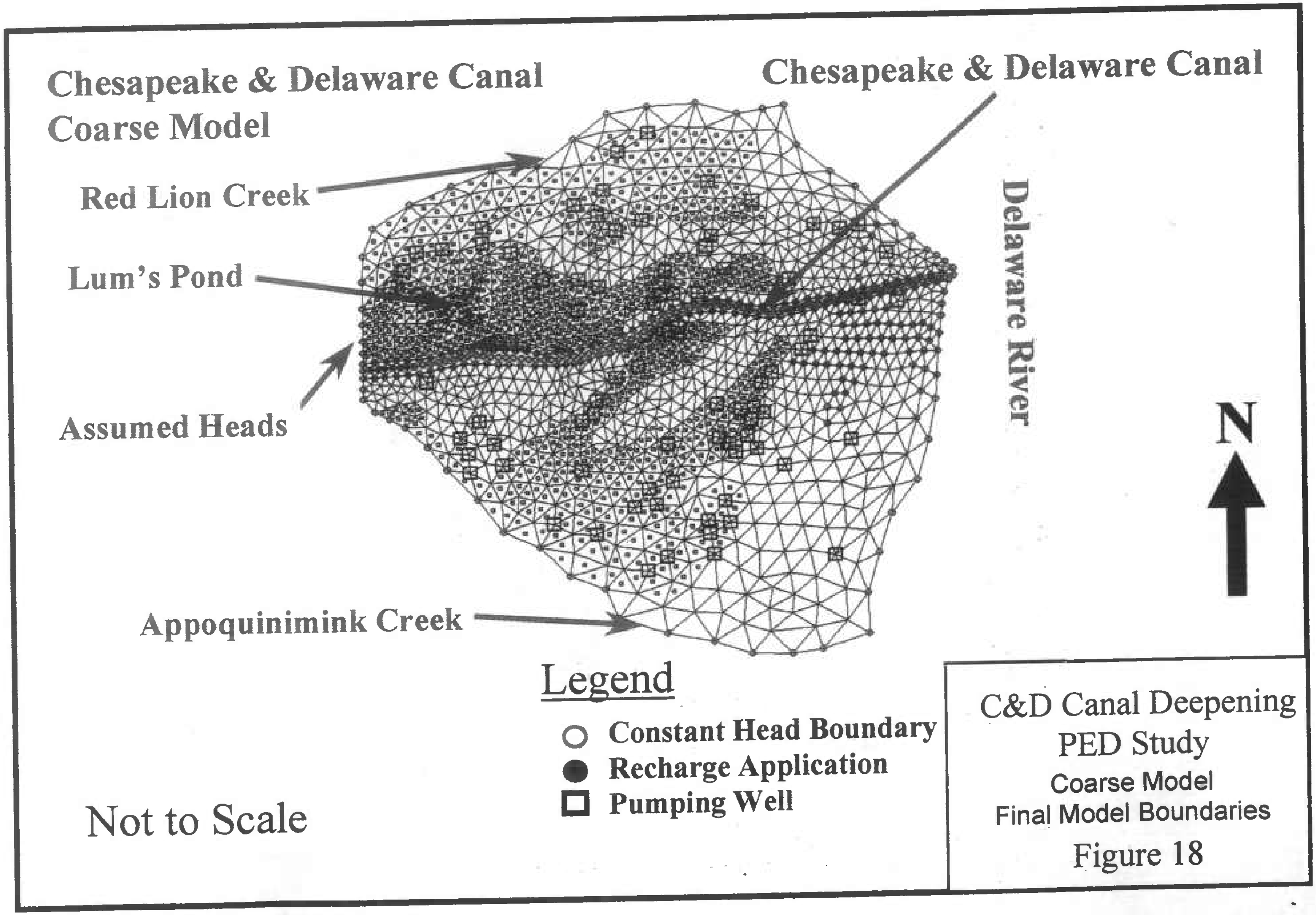
Section E - E'

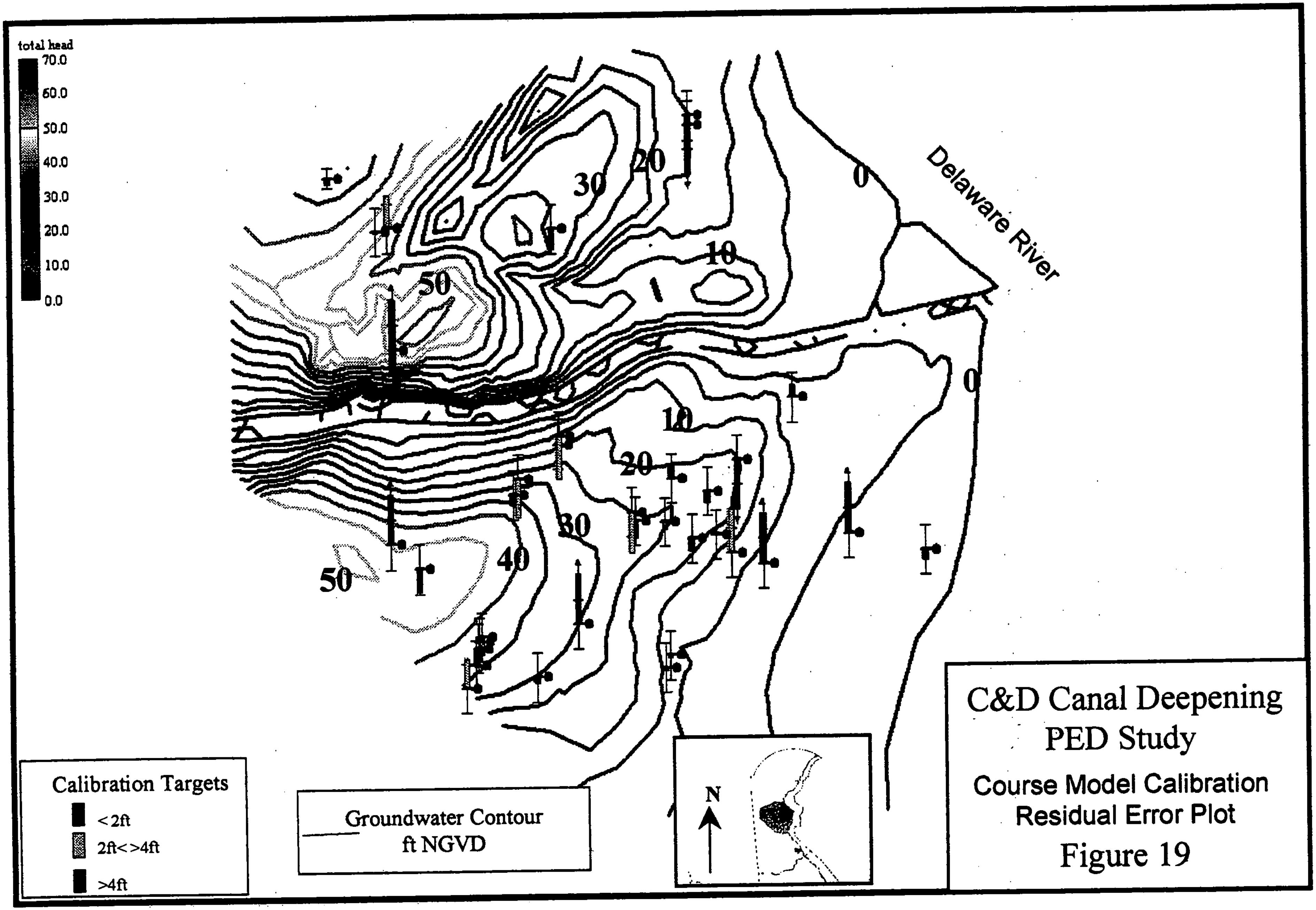
Not to Scale

C&D Canal Deepening
PED Study

Geology
Section E-E'

Figure 17

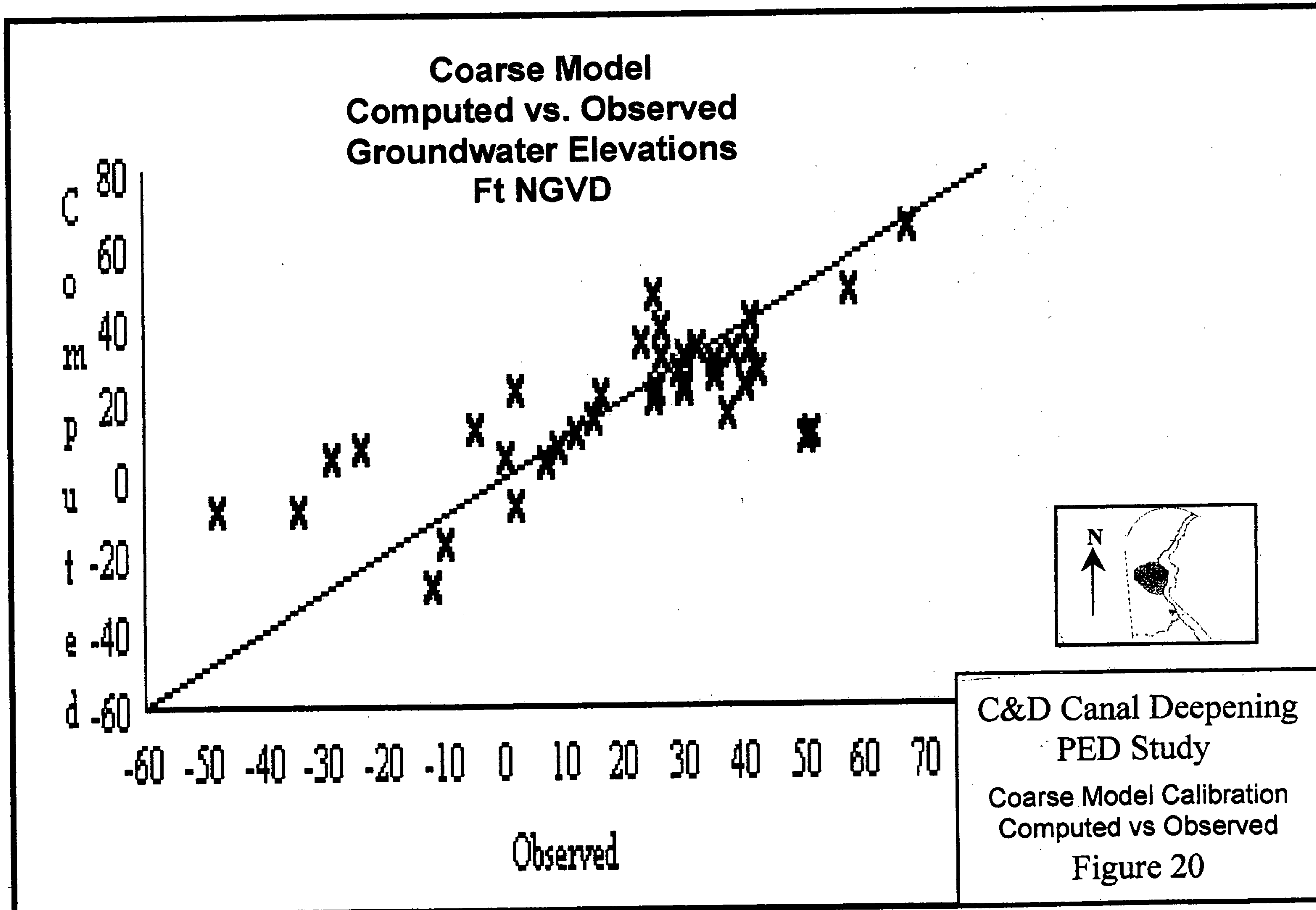

Chesapeake & Delaware Canal
Coarse Model
Chesapeake & Delaware Canal
Red Lion Creek
Lum's Pond
Assumed Heads
Delaware River
N
Appoquinimink Creek
Legend
Constant Head Boundary
Recharge Application
Pumping Well
Not to Scale
C&D Canal Deepening
PED Study
Coarse Model
Final Model Boundaries
Figure 18



C&D Canal Deepening PED Study

Course Model Calibration Residual Error Plot

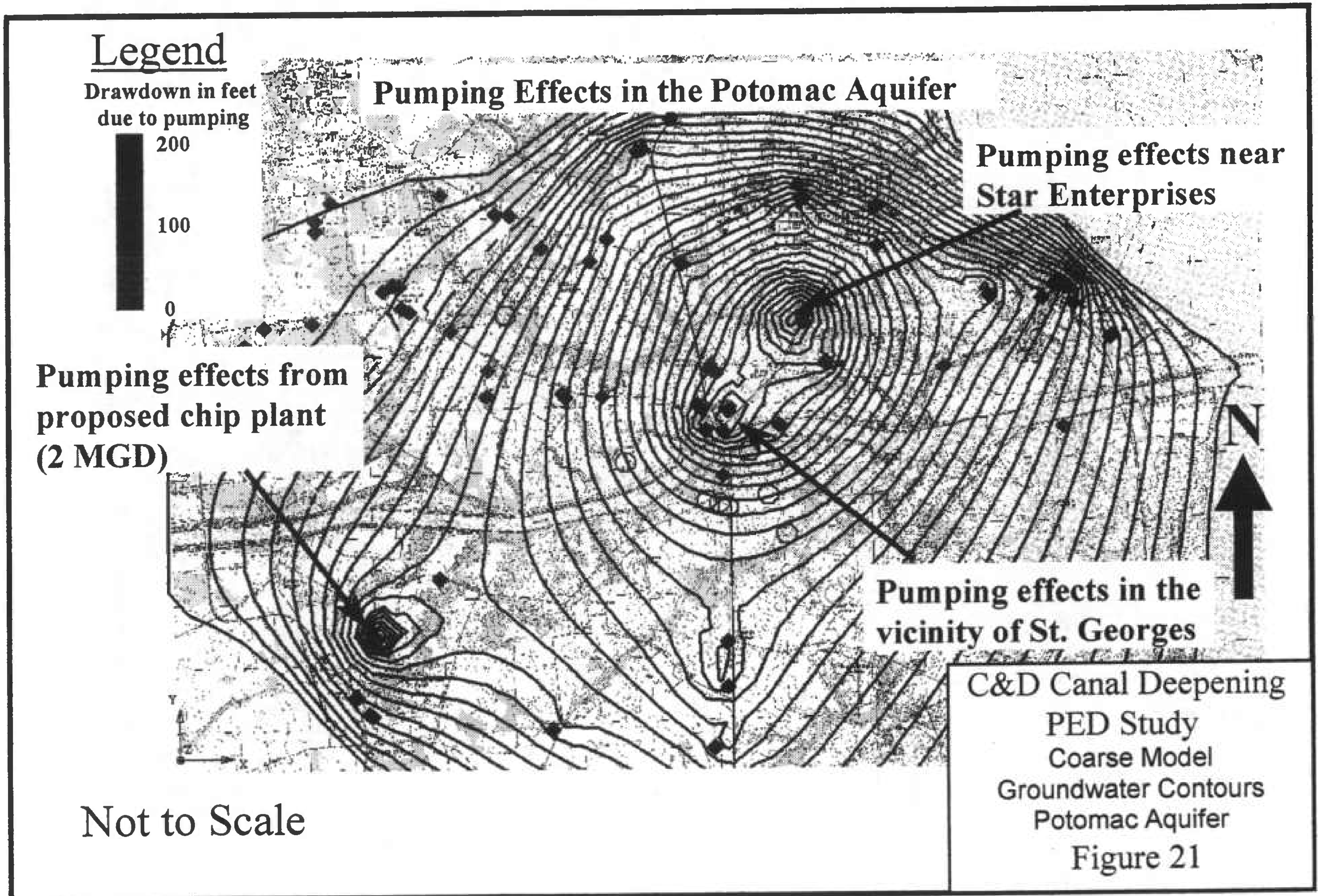
Figure 19



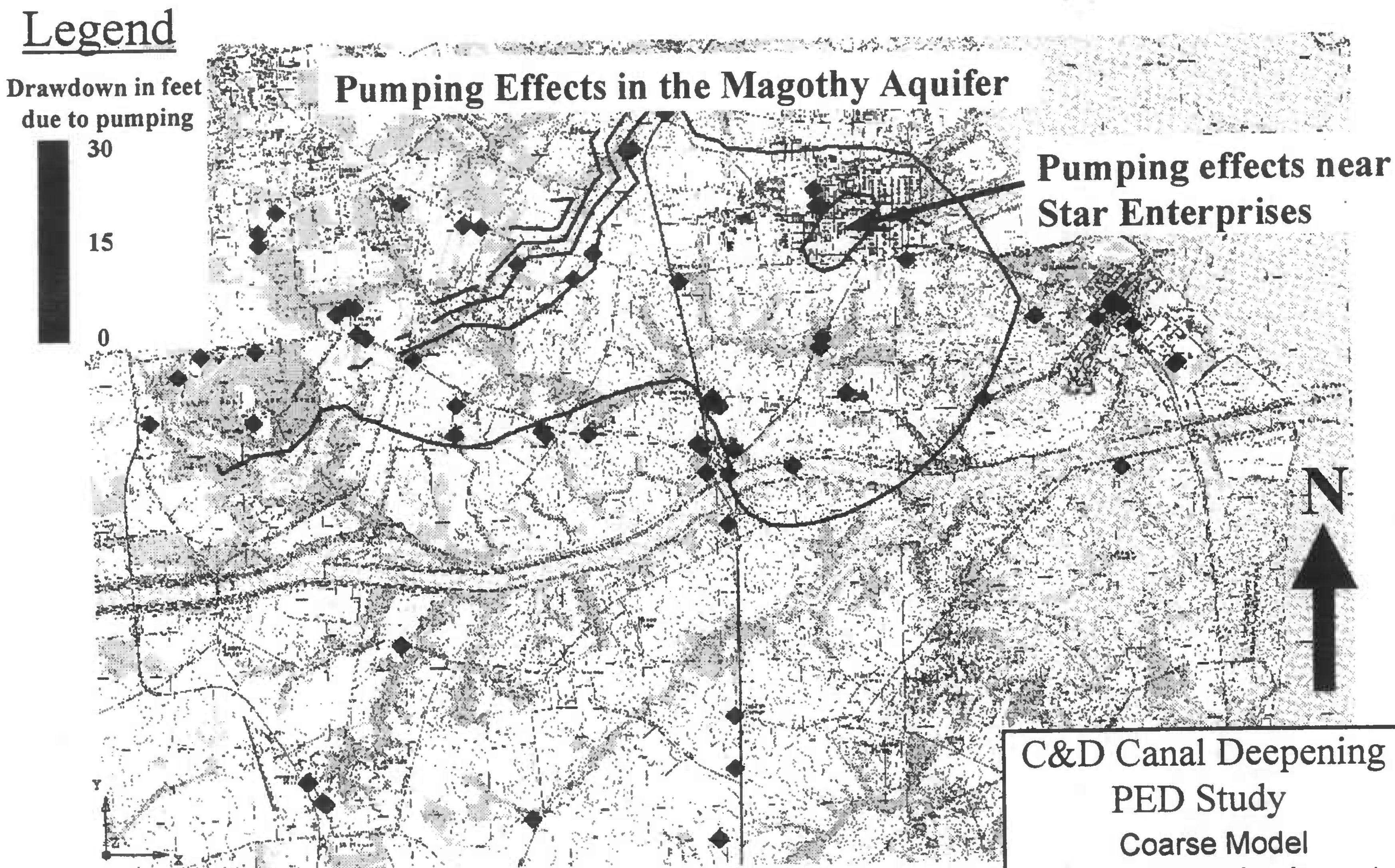
C&D Canal Deepening
PED Study

Coarse Model Calibration
Computed vs Observed

Figure 20

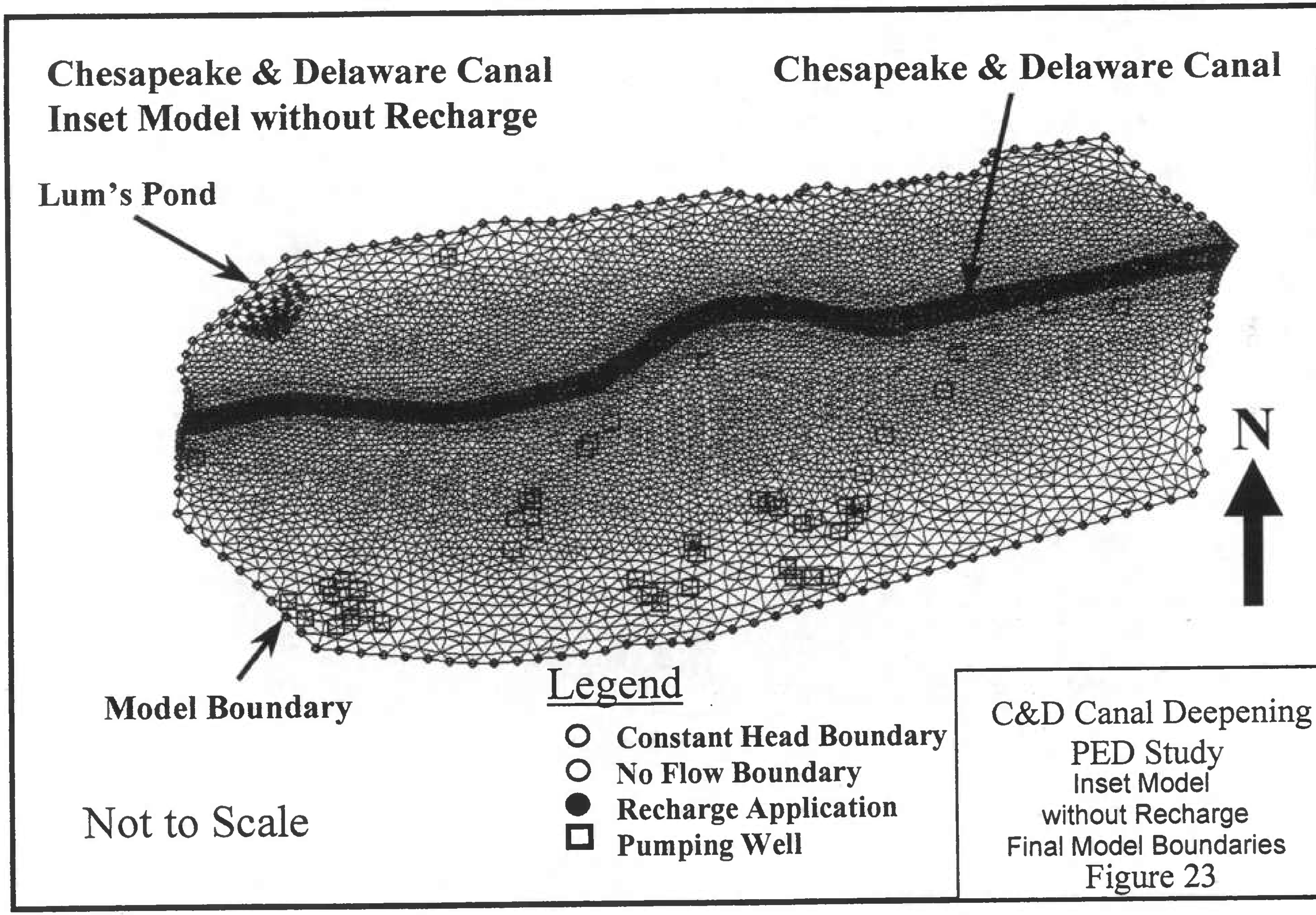


C&D Canal Deepening PED Study
Coarse Model Groundwater Contours Potomac Aquifer
Figure 21

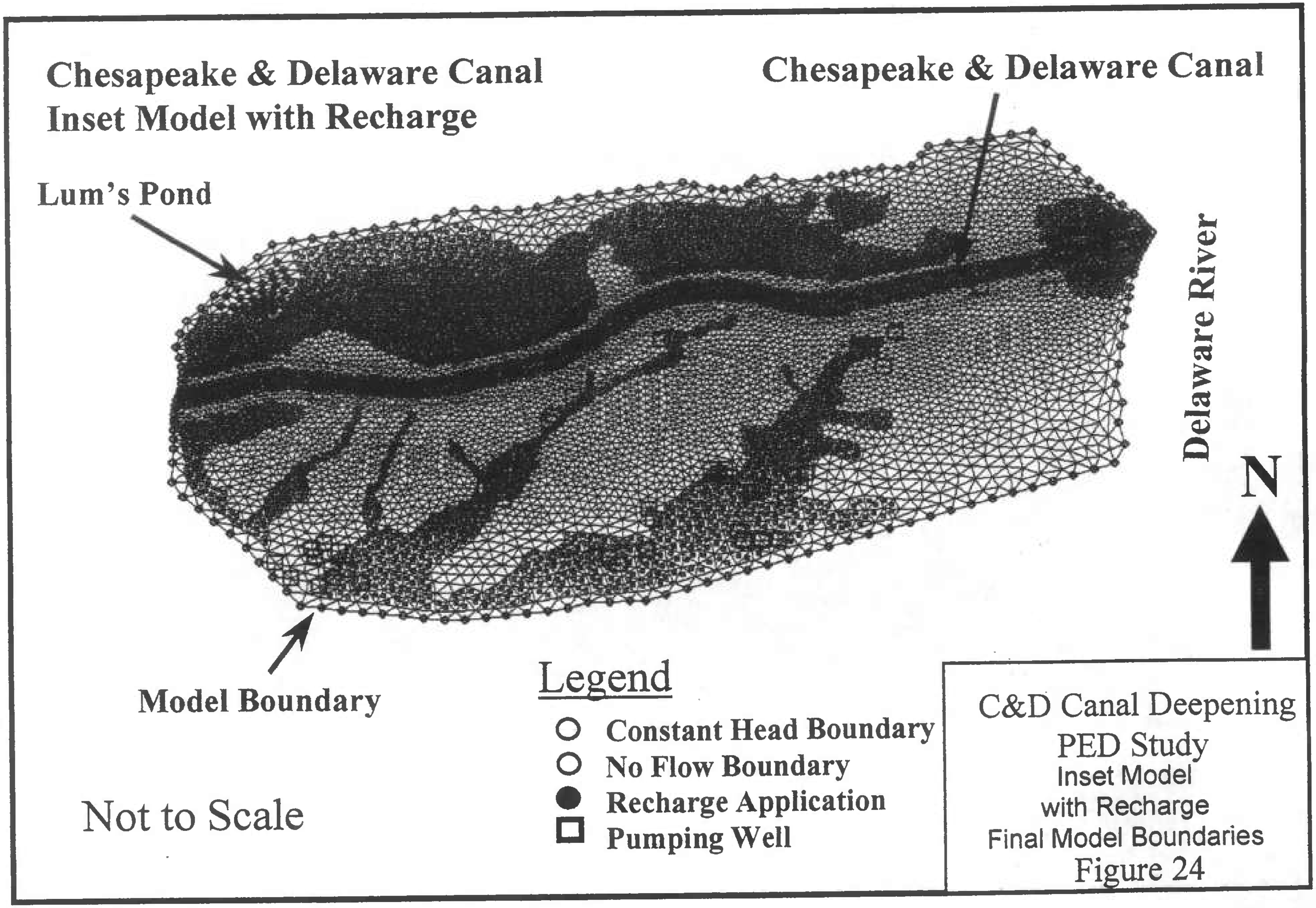


Not to Scale

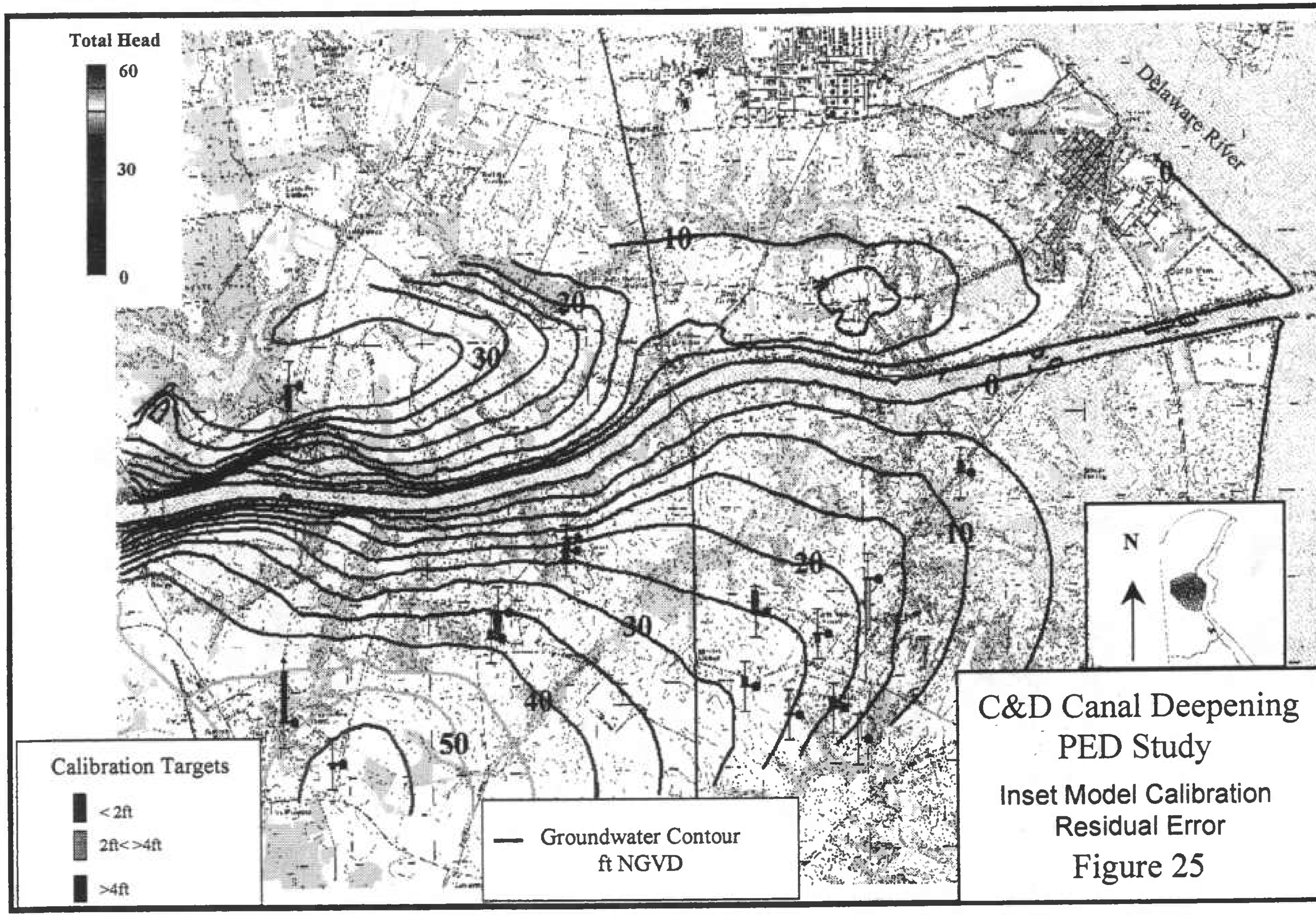
C&D Canal Deepening
PED Study
Coarse Model
Potomac Pumping Impacts on Magothy Aquifer Heads
Figure 22



C&D Canal Deepening
PED Study
Inset Model
without Recharge
Final Model Boundaries
Figure 23



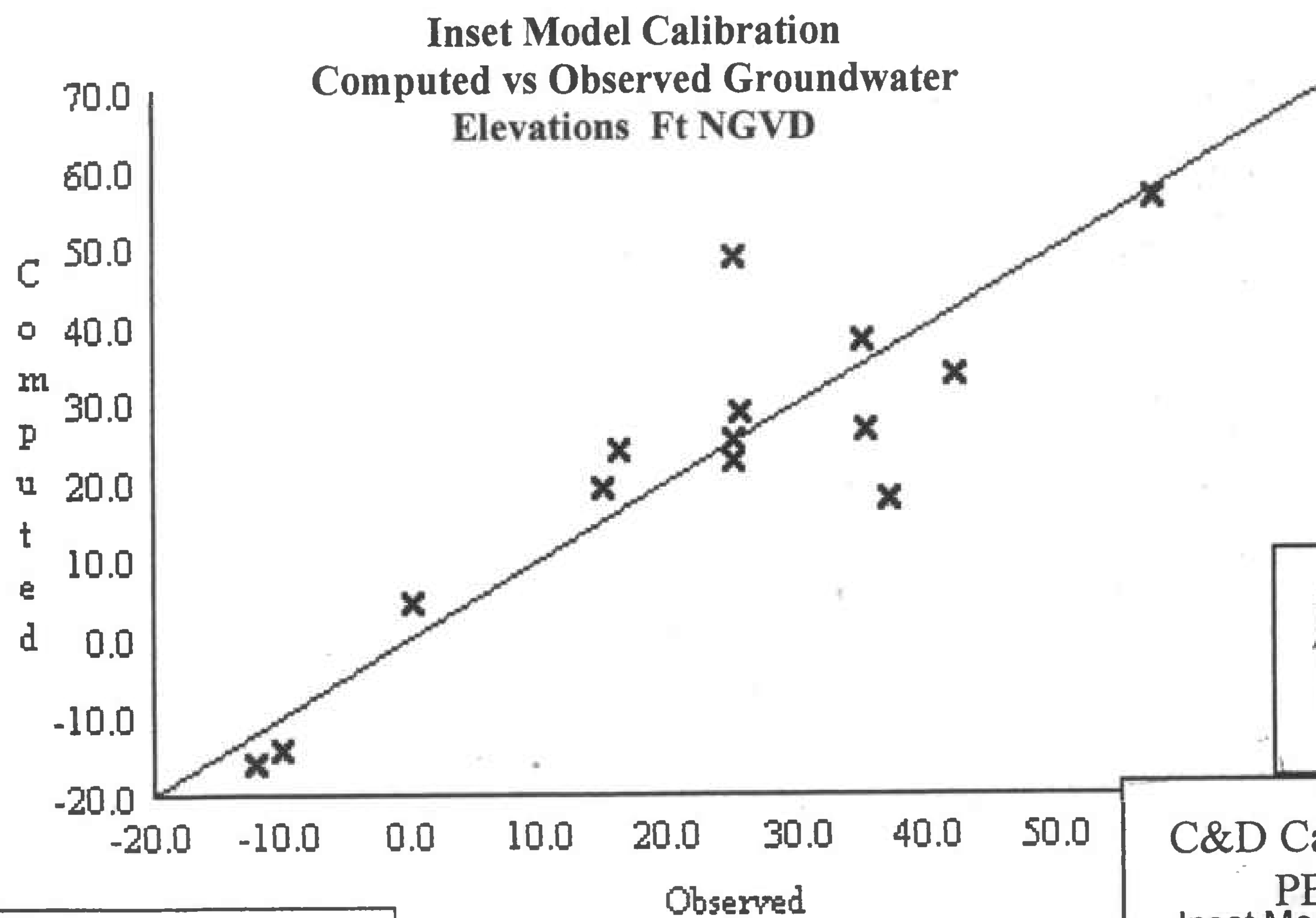
C&D Canal Deepening
PED Study
Inset Model
with Recharge
Final Model Boundaries
Figure 24

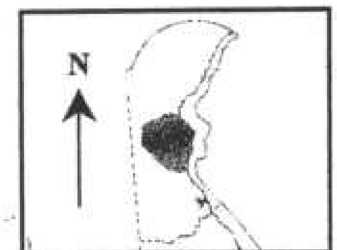


C&D Canal Deepening PED Study

Inset Model Calibration Residual Error

Figure 25





Error Statistics

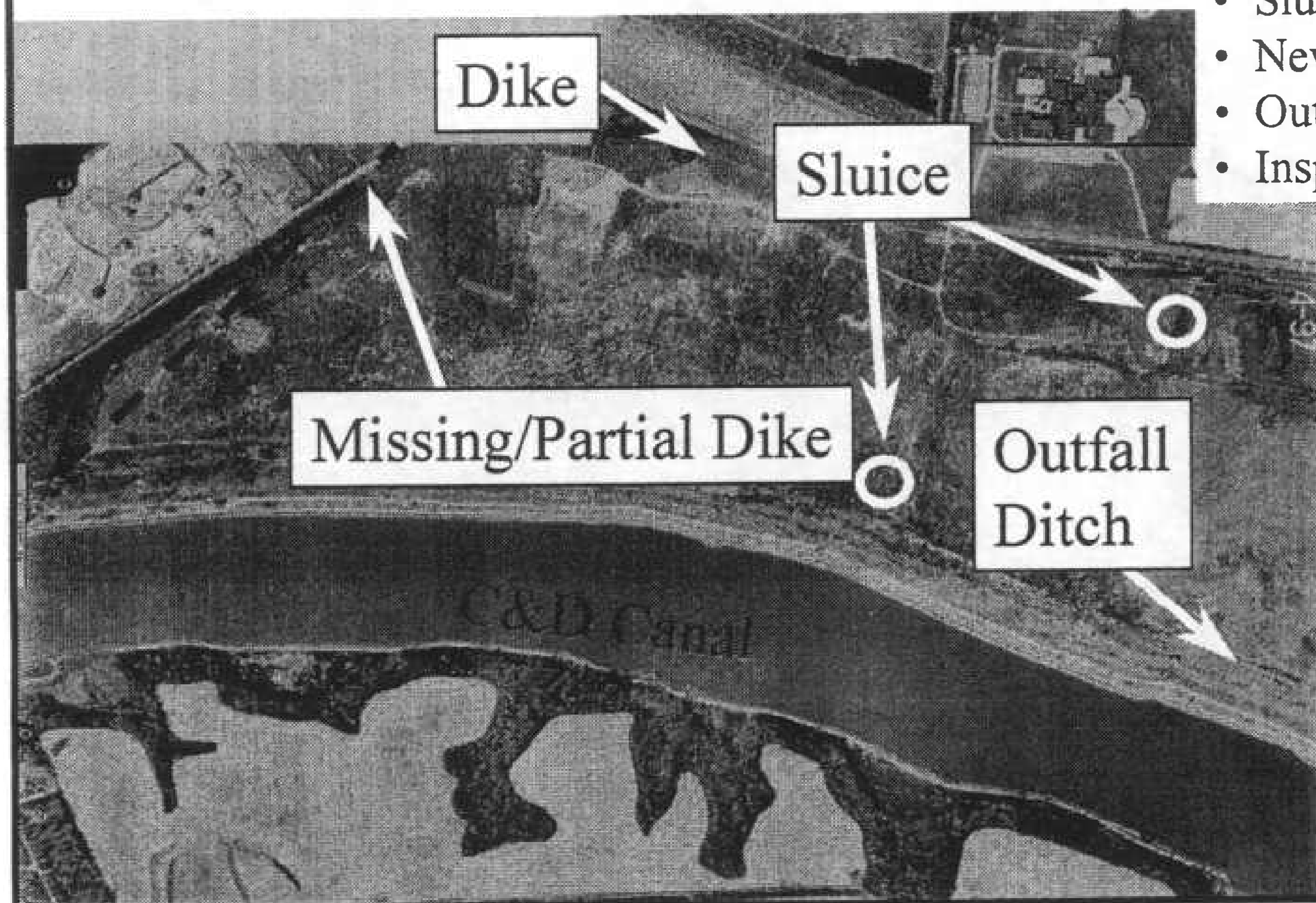
Mean Error = -0.09 ft
Mean Absolute Error = 6.81 ft
Root Mean Squared Error = 9.46 ft

C&D Canal Deepening
PED Study
Inset Model Calibration
Computed Vs Observed
Groundwater Elevations
Figure 26

Not to Scale

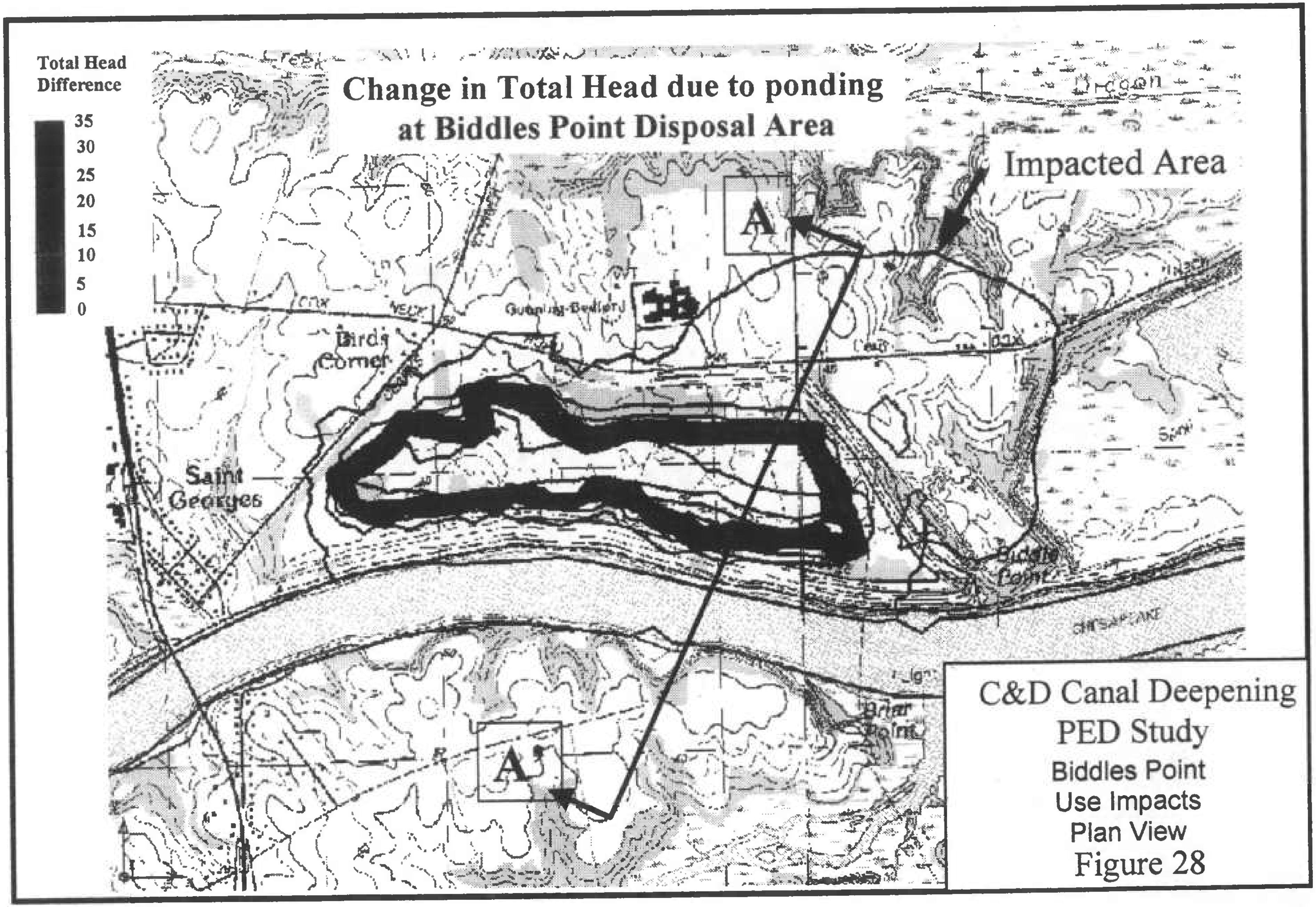
Biddles Point DA

- Area = 300 Acres
- Perimeter = 19,000 Ft
- Existing Capacity = 1.4 Mcy
- (with dike repair on West)
- Sluice operable = Yes
- New Topo 1997
- Outfall to ditch
- Inspected 1998

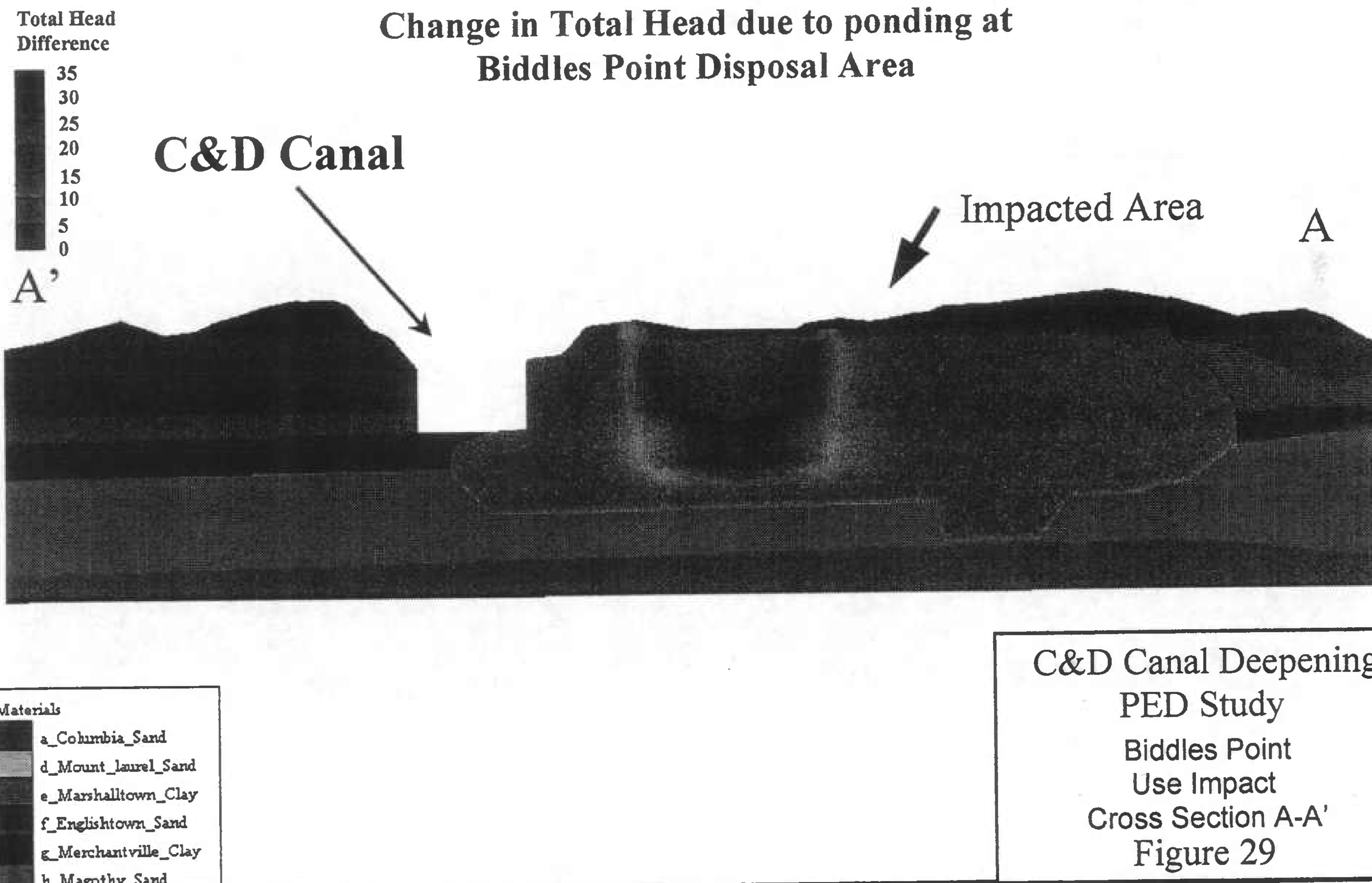


N

C&D Canal Deepening
PED Study
Biddles Point
Aerial View
Figure 27


Total Head Difference
35
30
25
20
15
10
5
0
Change in Total Head due to ponding at Biddles Point Disposal Area
Impacted Area
A
A'
Birds Corner
Saint Georges
Biddle Point
Briar Point
C&D Canal Deepening PED Study
Biddles Point Use Impacts Plan View
Figure 28

Change in Total Head due to ponding at Biddles Point Disposal Area



C&D Canal Deepening
PED Study
Biddles Point
Use Impact
Cross Section A-A'
Figure 29

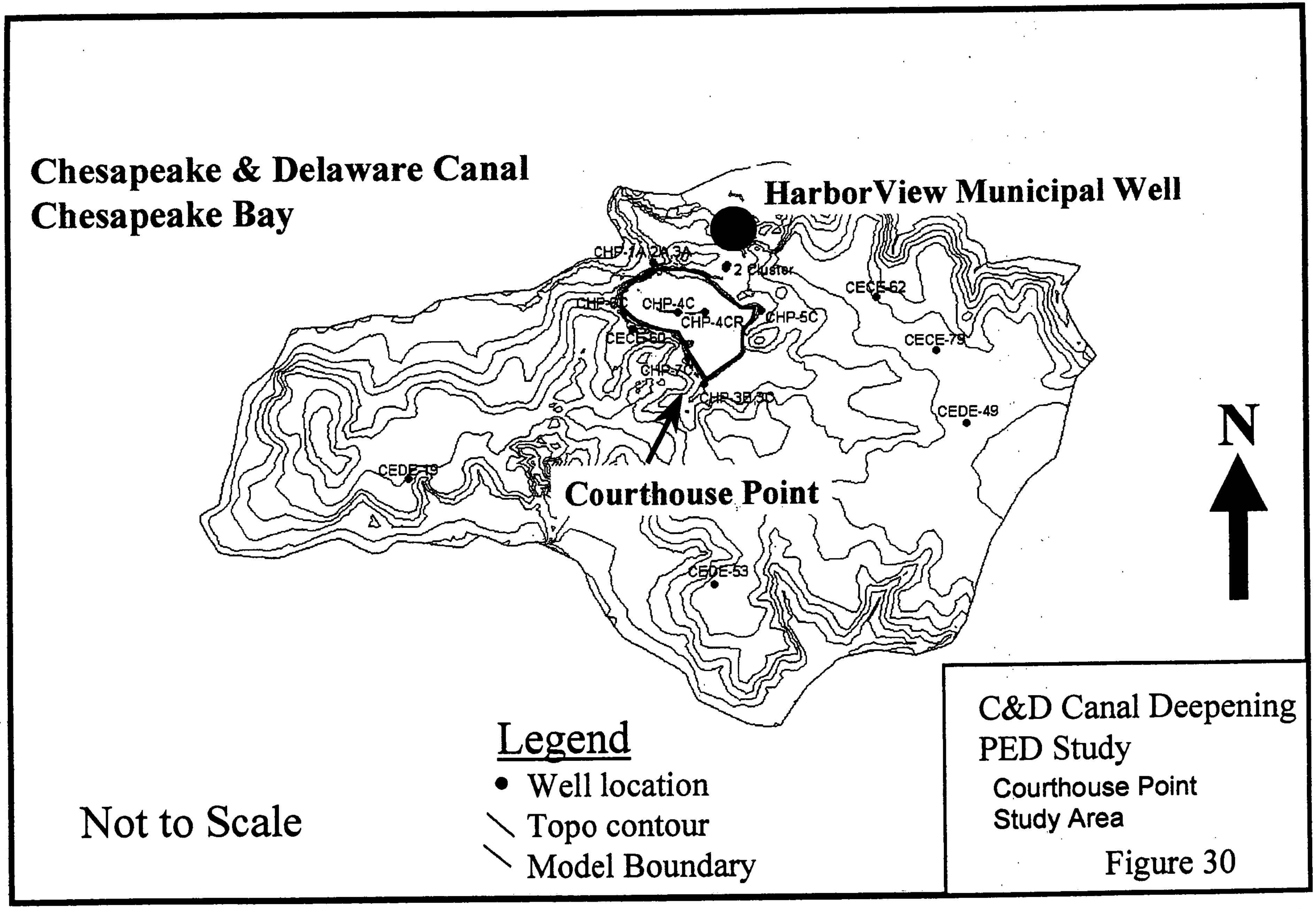
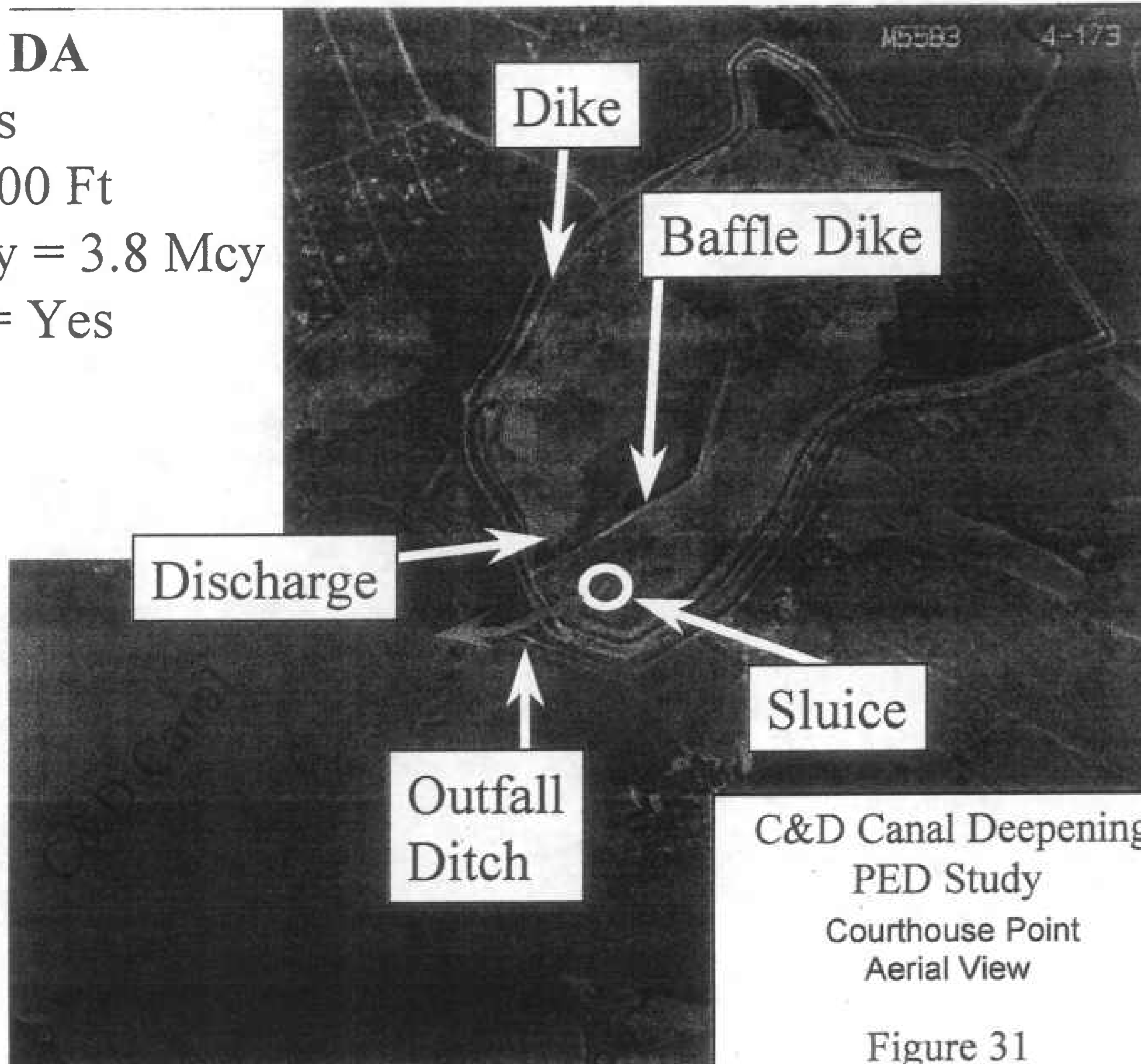

Chesapeake & Delaware Canal
Chesapeake Bay
HarborView Municipal Well
CHP-1A,2A,3A
2 Cluster
CECE-62
CHP-6C
CHP-4C
CHP-4CR
CHP-5C
CECE-60
CECE-79
CHP-7C
CHP-3B,3C
CEDE-49
N
CEDE-19
Courthouse Point
CEDE-53
Legend
Well location
Topo contour
Model Boundary
Not to Scale
C&D Canal Deepening
PED Study
Courthouse Point
Study Area

Figure 30

Courthouse Point DA

- Area = 170 Acres
- Perimeter = 12,000 Ft
- Existing Capacity = 3.8 Mcy
- Sluice operable = Yes
- New Topo 1997
- Outfall to ditch
- Inspected 1998

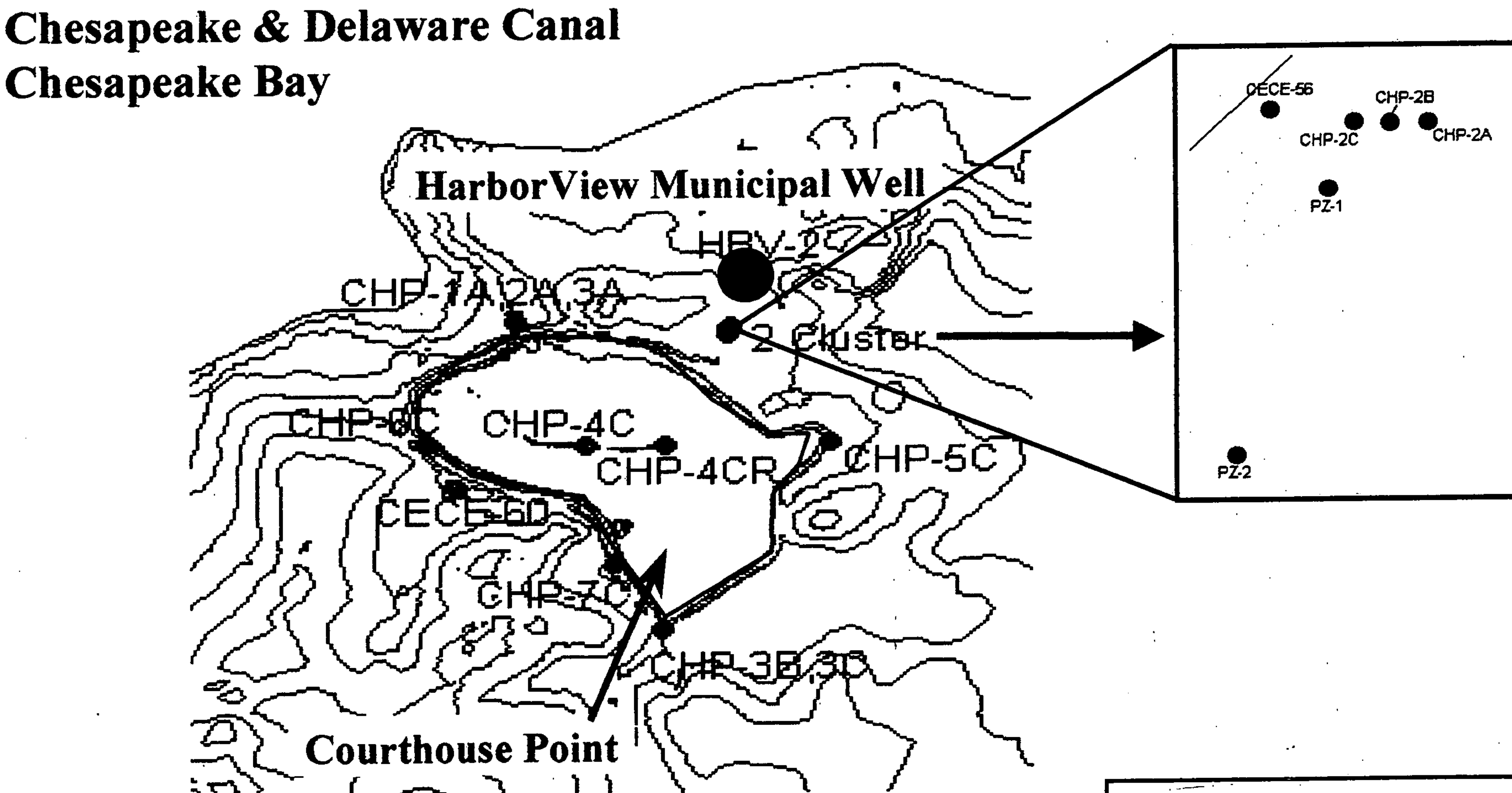


N

Not to Scale

C&D Canal Deepening
PED Study
Courthouse Point
Aerial View

Figure 31

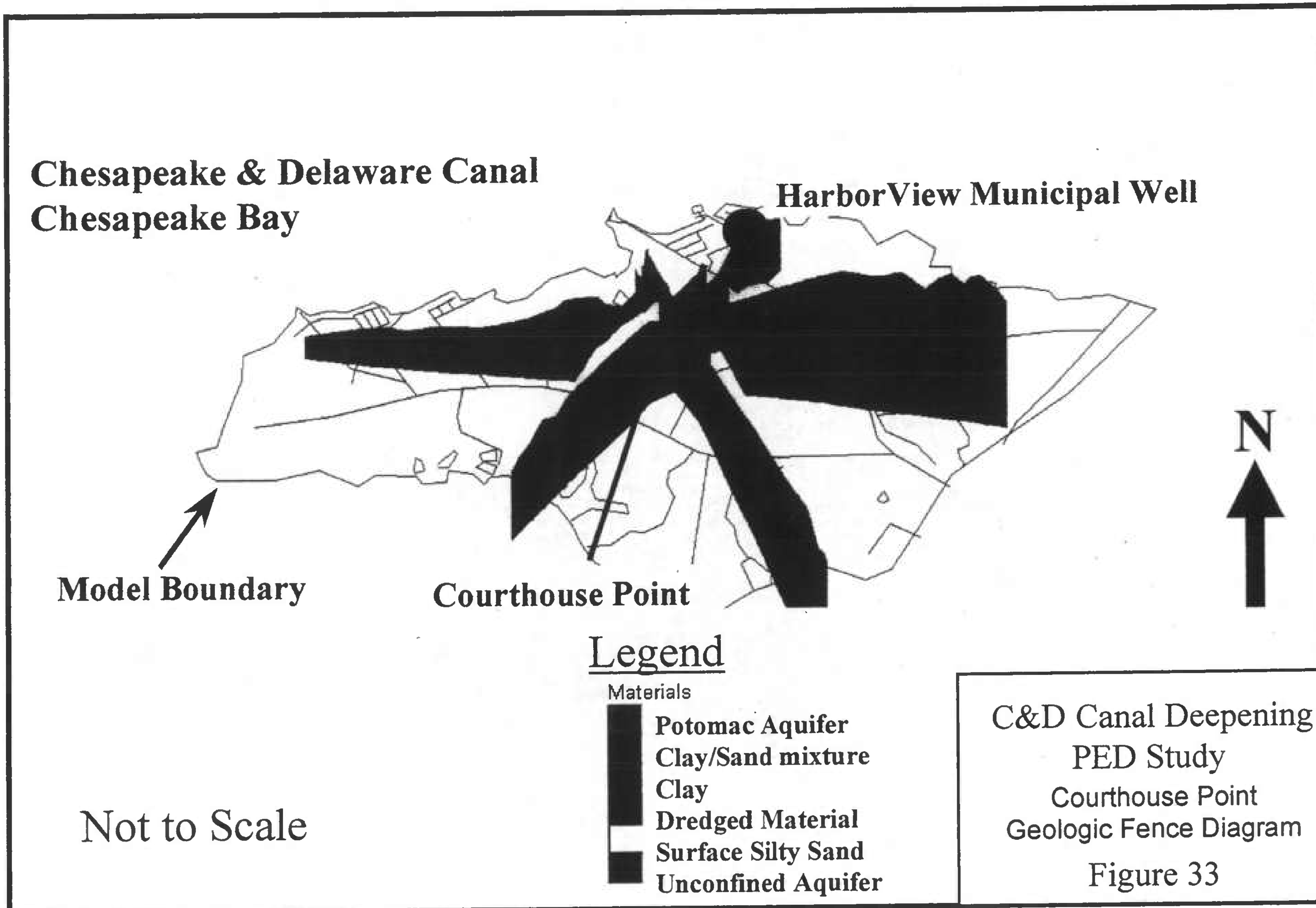


Not to Scale

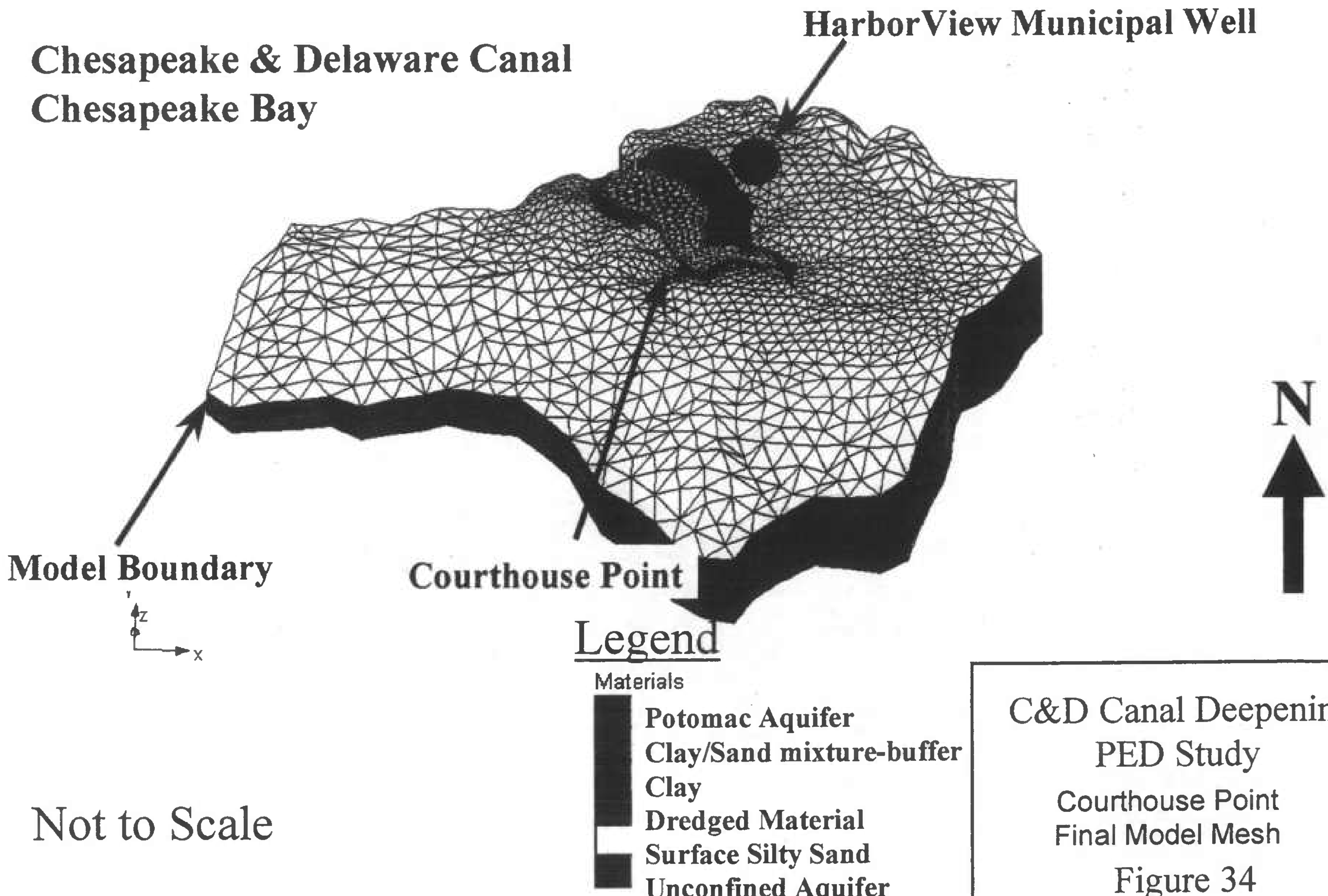
Legend
- ● Well location
- ╲ Topo contour
- ╲ Model Boundary

N

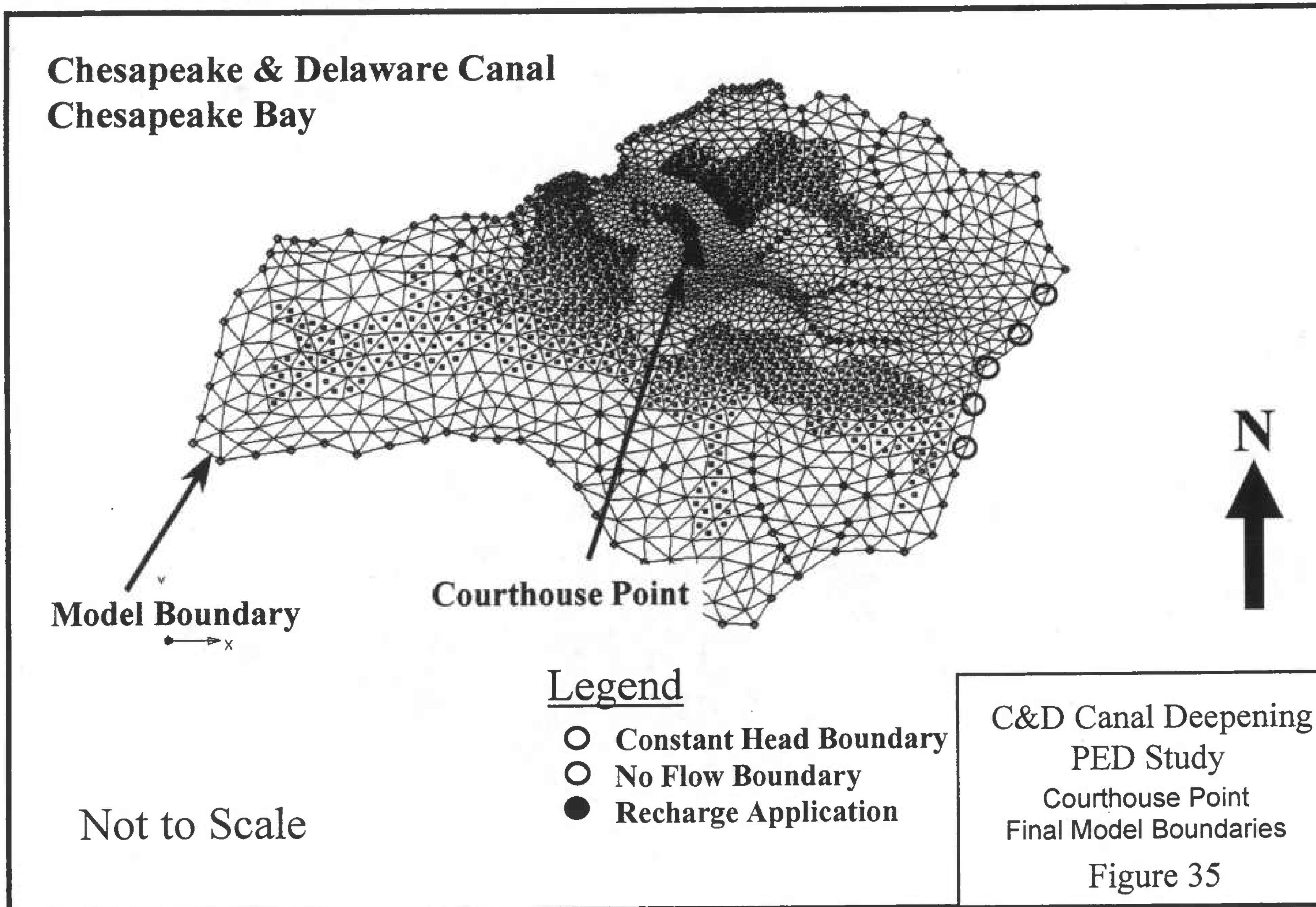
C&D Canal Deepening PED Study
Courthouse Point
Study Area - close up
Figure 32



C&D Canal Deepening
PED Study
Courthouse Point
Geologic Fence Diagram
Figure 33

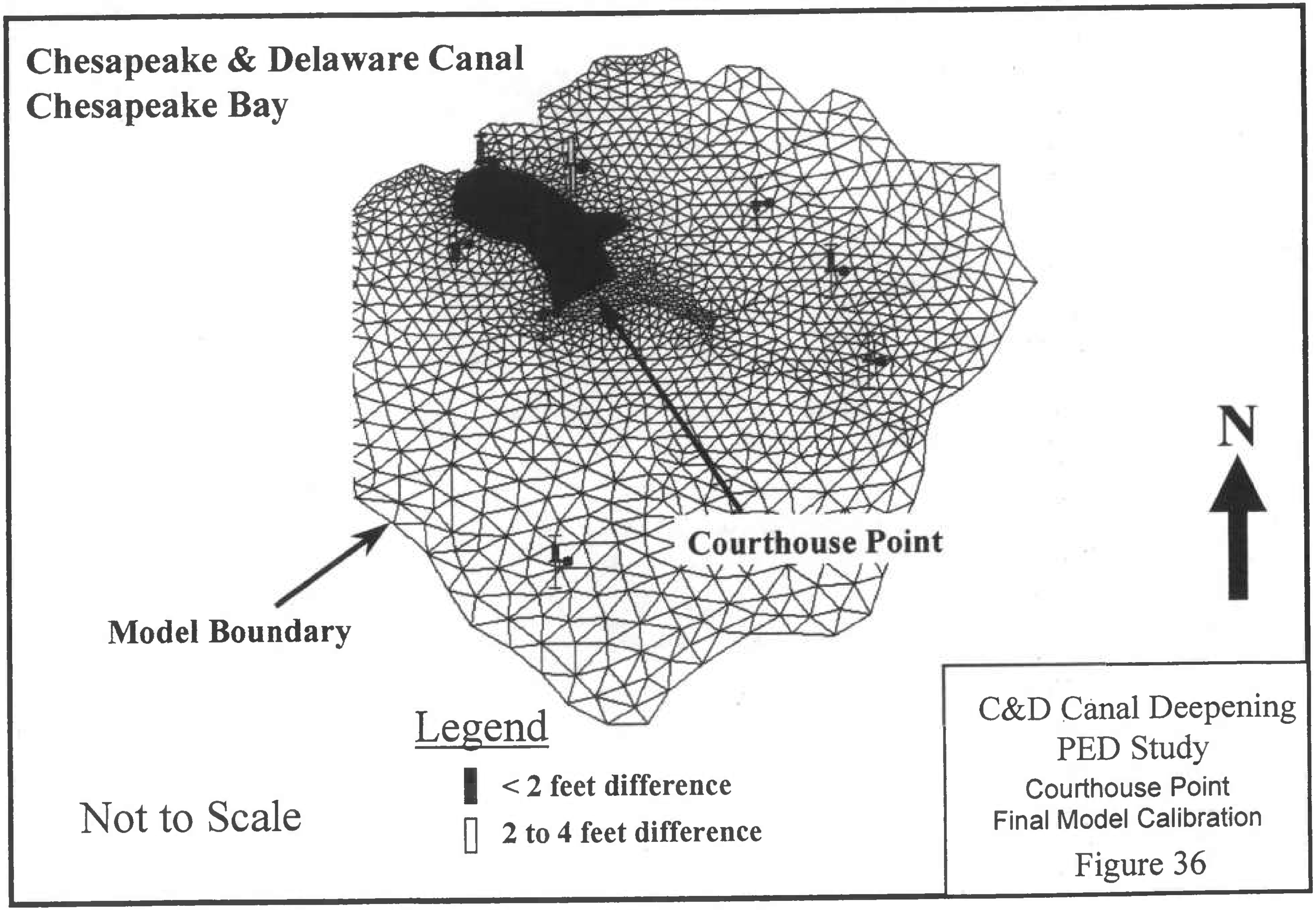


C&D Canal Deepening
PED Study
Courthouse Point
Final Model Mesh
Figure 34



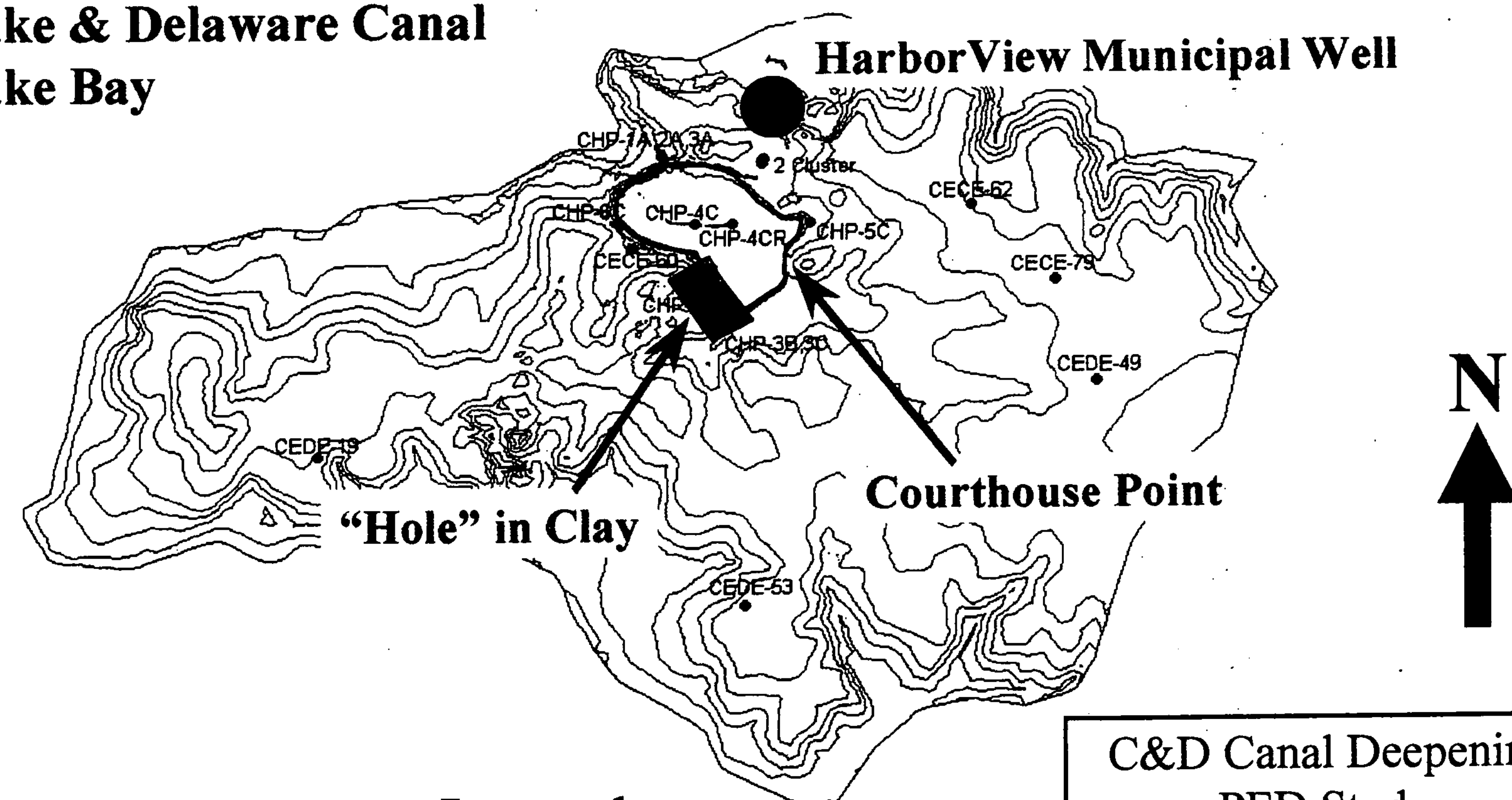
Chesapeake & Delaware Canal
Chesapeake Bay
Model Boundary
Courthouse Point
N
Legend
Constant Head Boundary
No Flow Boundary
Recharge Application
Not to Scale
C&D Canal Deepening
PED Study
Courthouse Point
Final Model Boundaries

Figure 35



C&D Canal Deepening
PED Study
Courthouse Point
Final Model Calibration
Figure 36

Chesapeake & Delaware Canal
Chesapeake Bay



Not to Scale

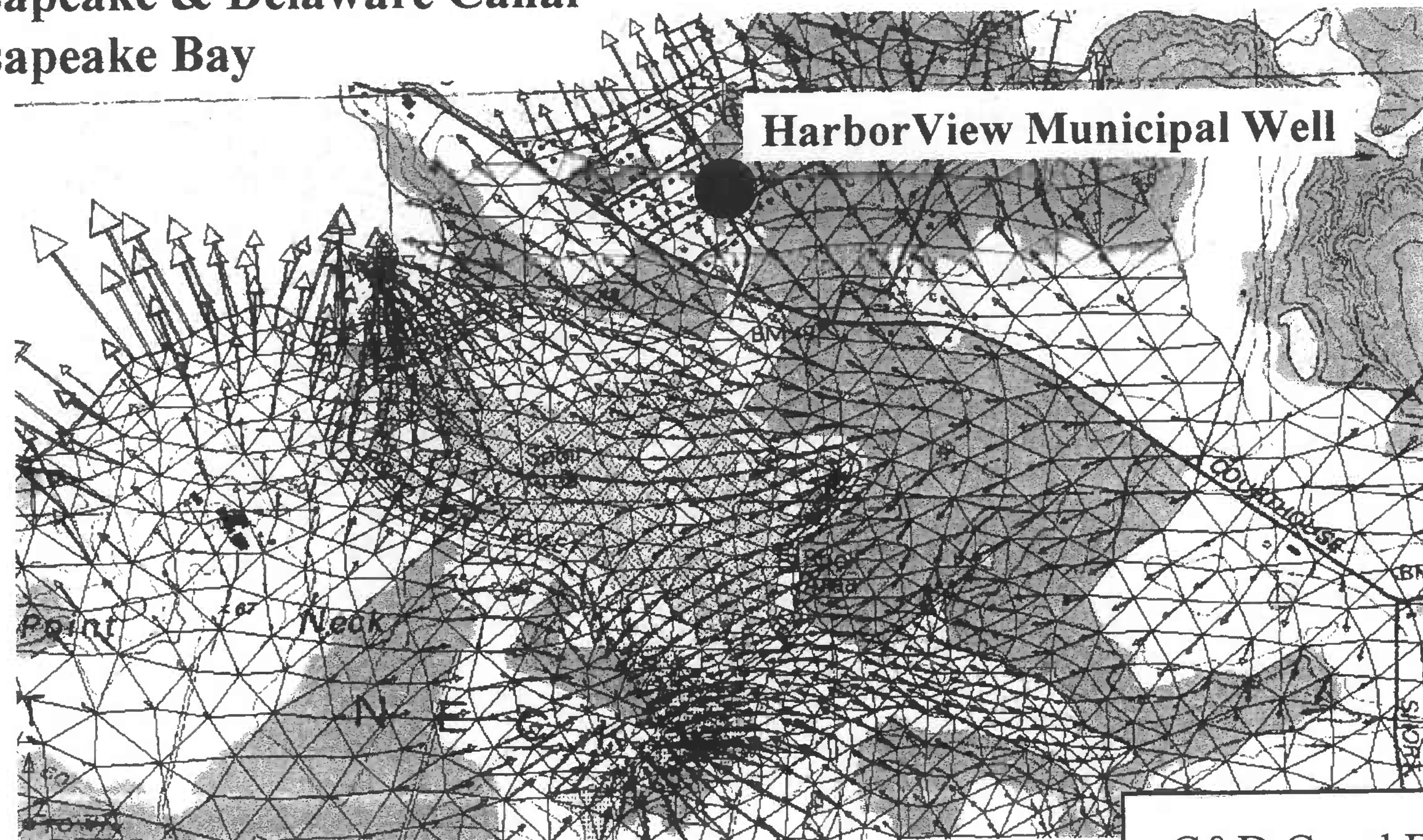
Legend
- • Well location
- Topo contour
- Model Boundary

C&D Canal Deepening
PED Study

Location of "Hole" in Confining Clay Layer

Figure 37

Chesapeake & Delaware Canal
Chesapeake Bay



N

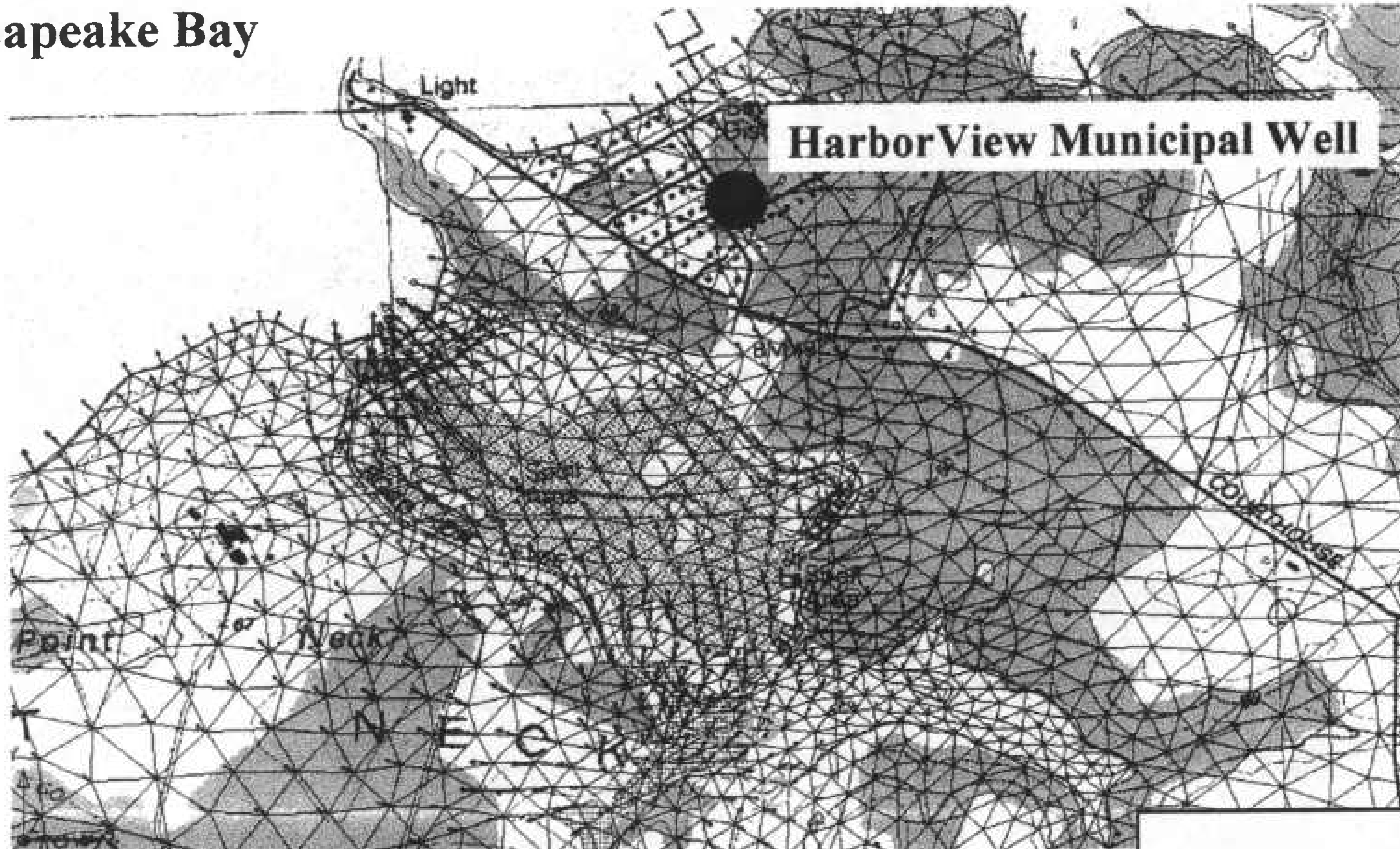
Legend

Flow Vector

Not to Scale

C&D Canal Deepening
PED Study
Flow Vectors in the
Unconfined Aquifer
Figure 38

Chesapeake & Delaware Canal
Chesapeake Bay



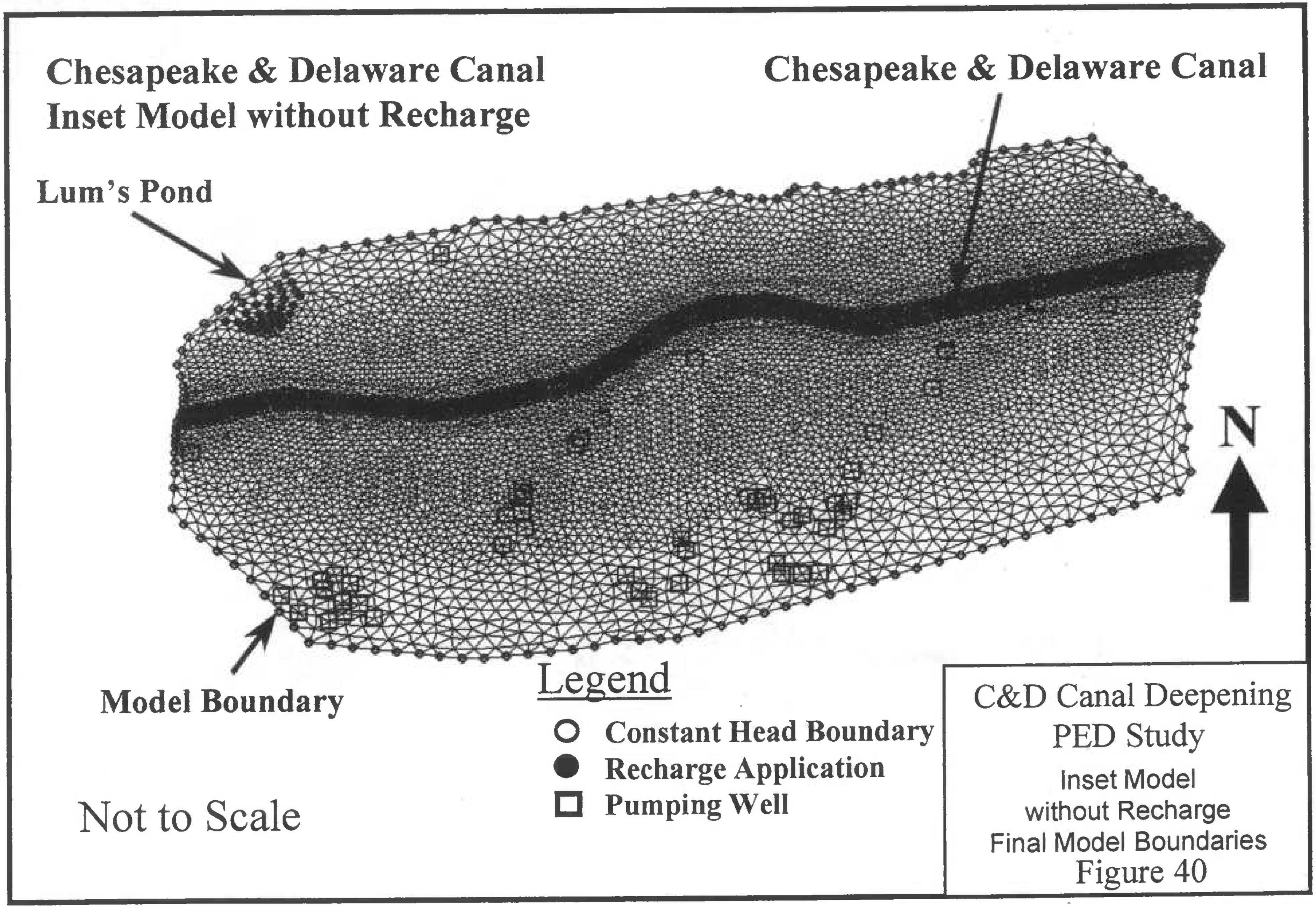
N

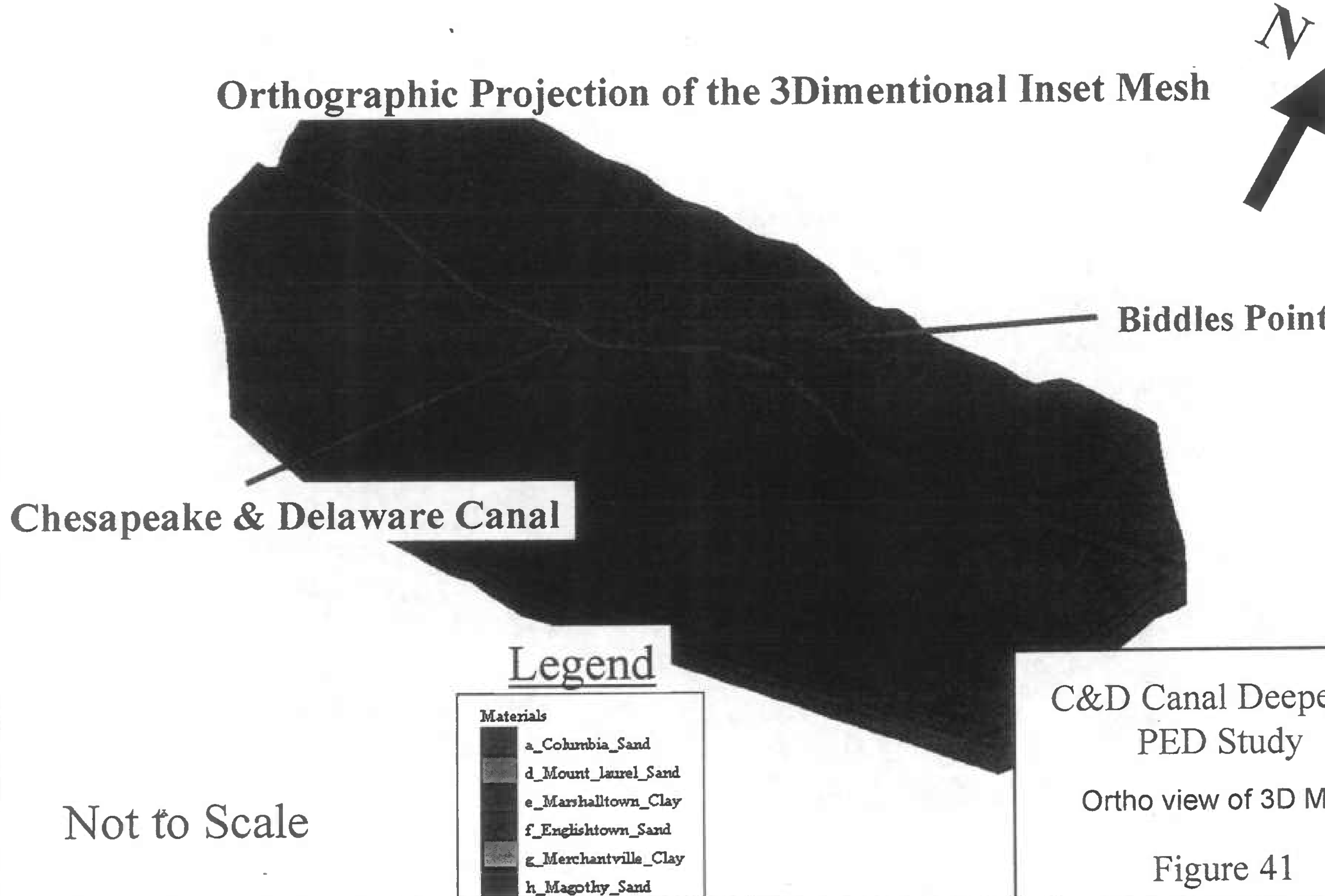
Legend

↖ Flow Vector

Not to Scale

C&D Canal Deepening
PED Study
Flow Vectors in the
Potomac Aquifer
Figure 39

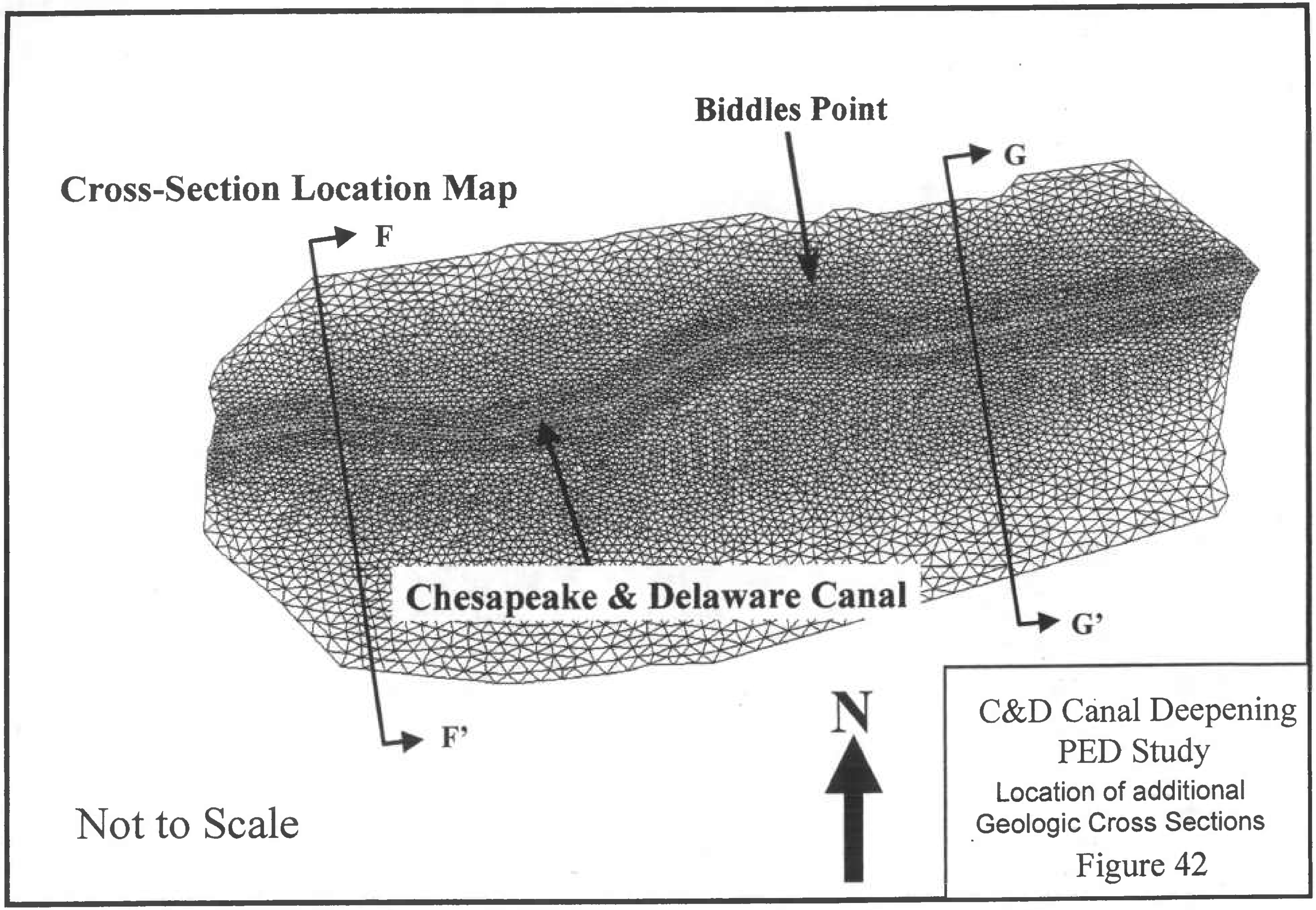

Chesapeake & Delaware Canal
Inset Model without Recharge
Chesapeake & Delaware Canal
Lum's Pond
N
Model Boundary
Legend
Constant Head Boundary
Recharge Application
Pumping Well
Not to Scale
C&D Canal Deepening
PED Study
Inset Model
without Recharge
Final Model Boundaries
Figure 40



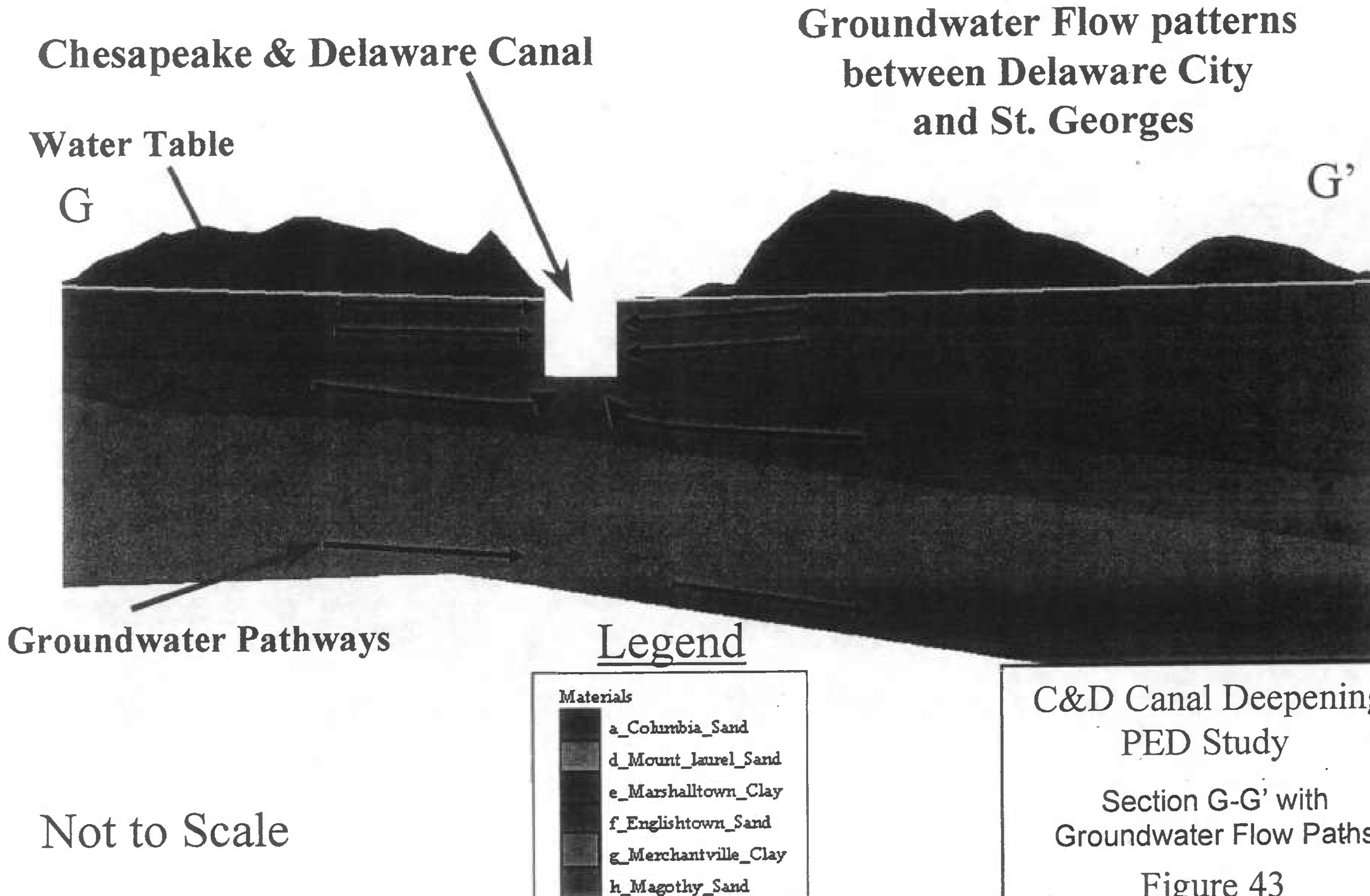
C&D Canal Deepening PED Study

Ortho view of 3D Mesh

Figure 41



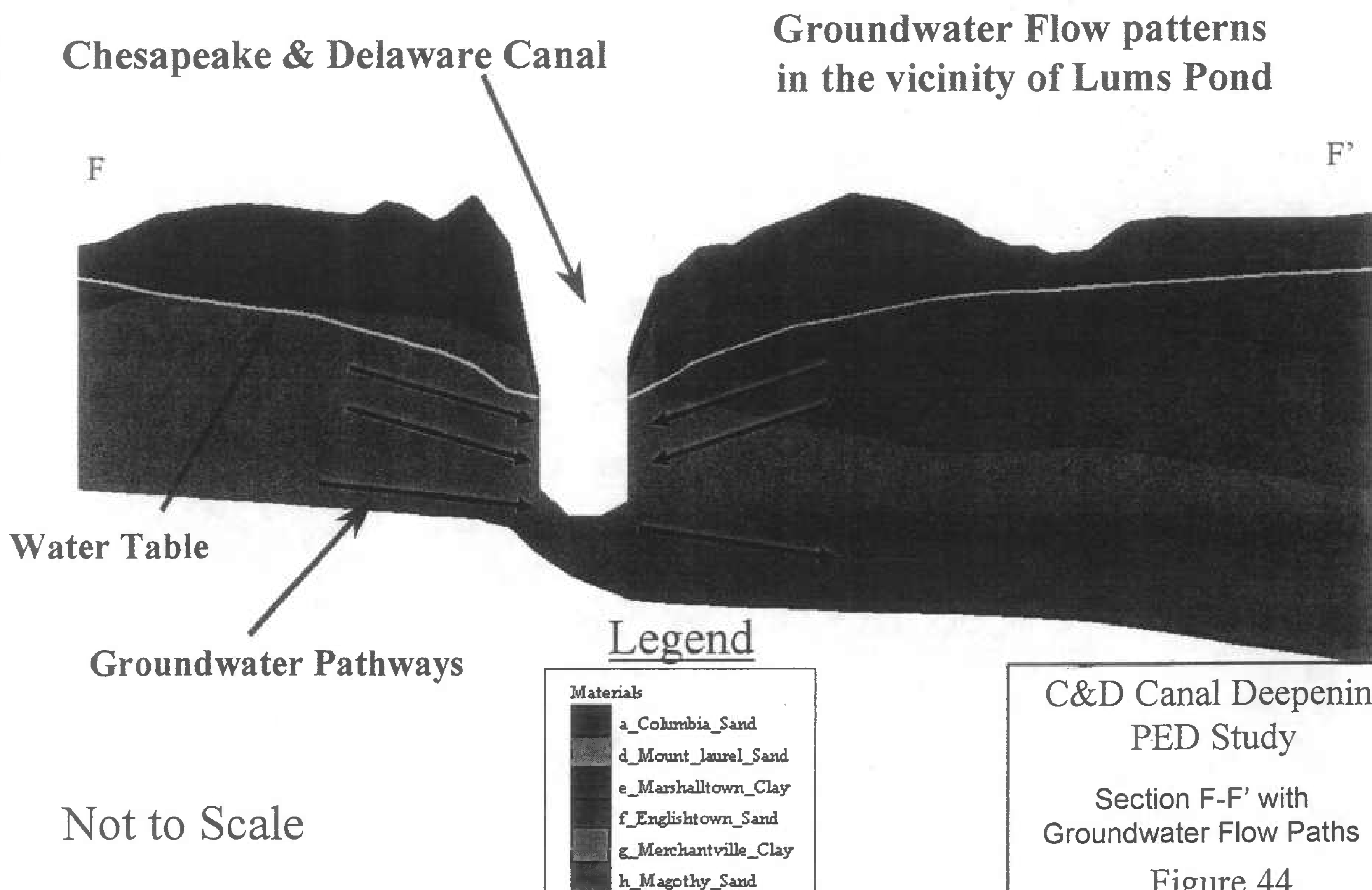
C&D Canal Deepening
PED Study
Location of additional
Geologic Cross Sections
Figure 42



C&D Canal Deepening PED Study

Section G-G' with Groundwater Flow Paths

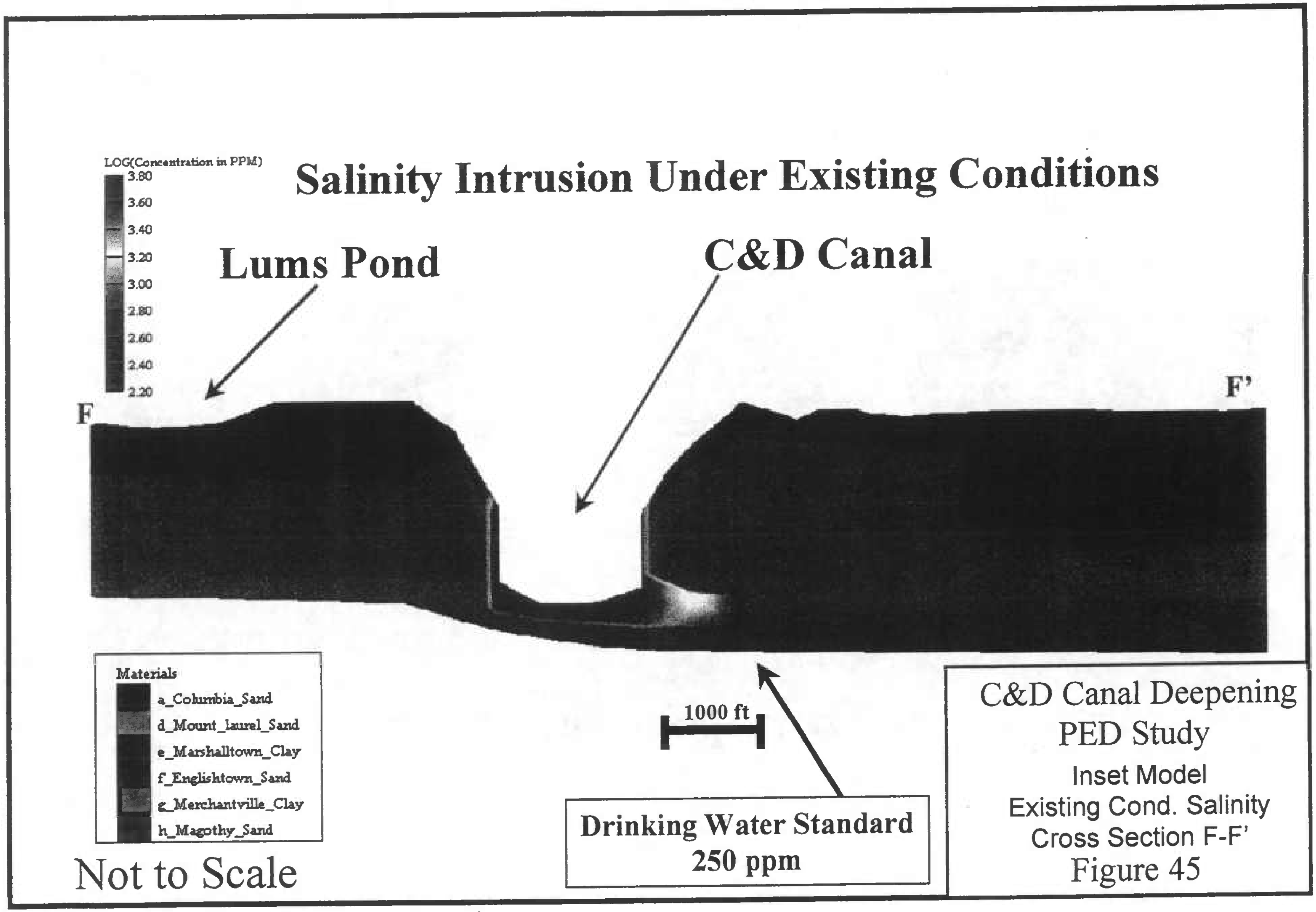
Figure 43



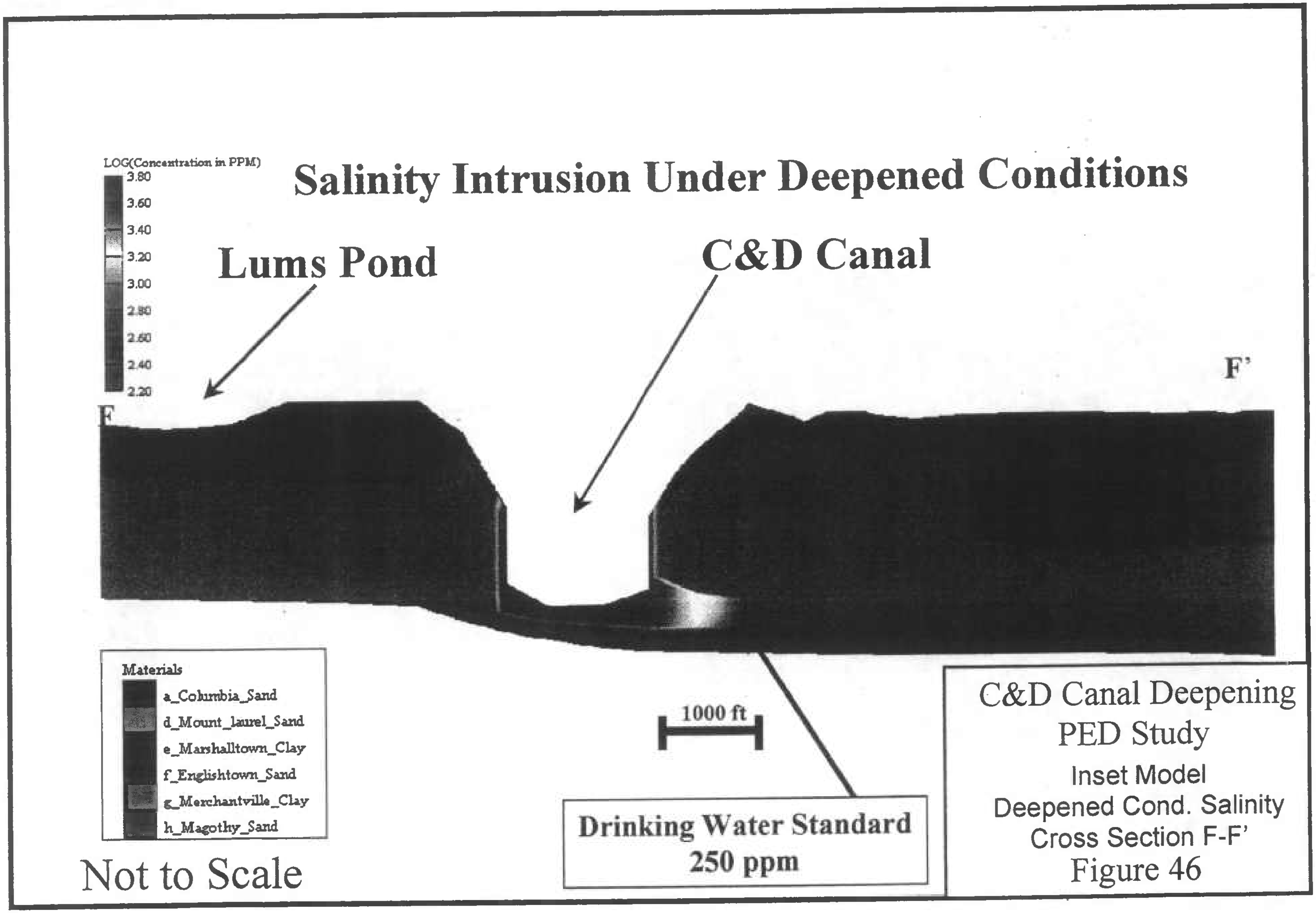
C&D Canal Deepening PED Study

Section F-F' with Groundwater Flow Paths

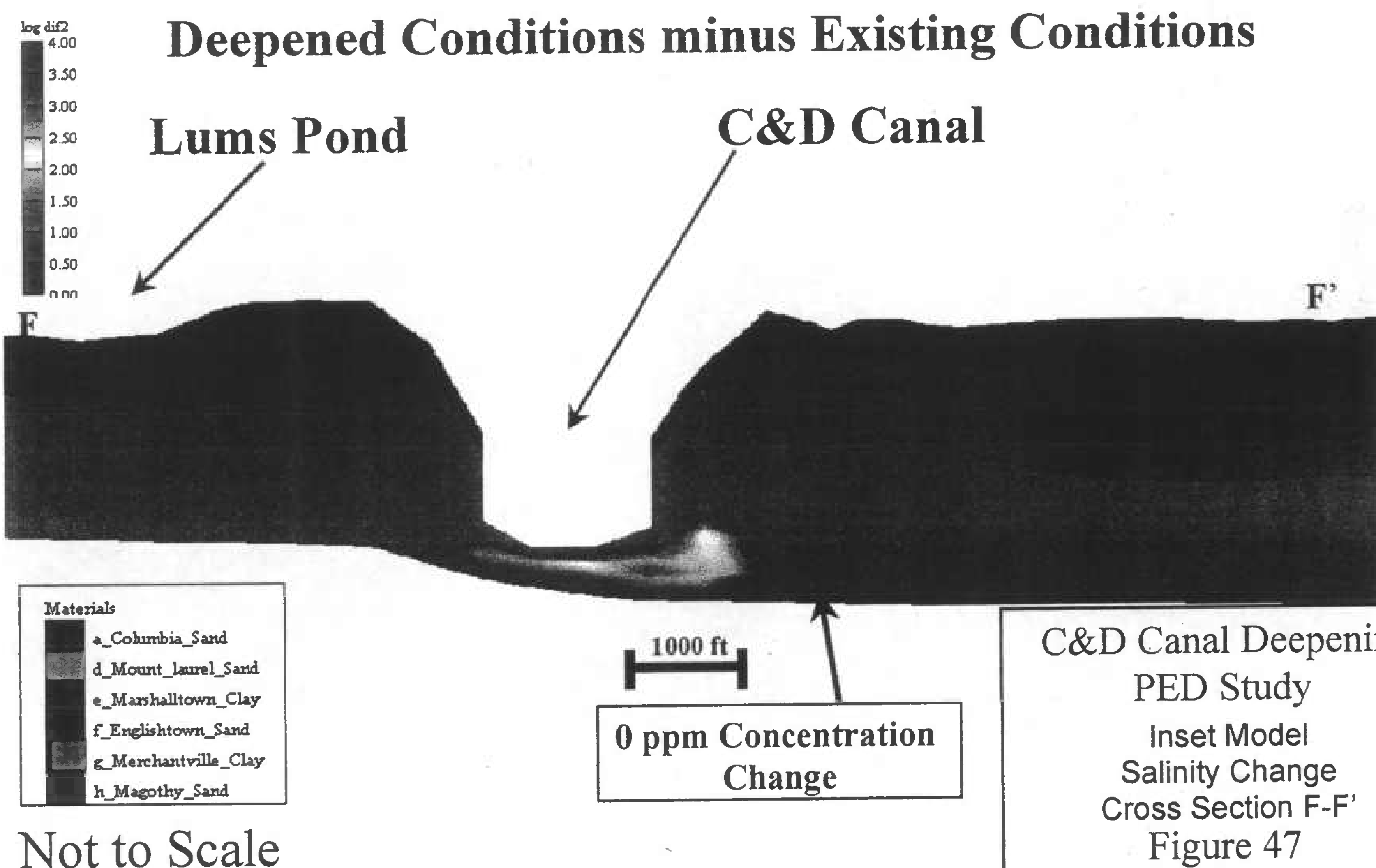
Figure 44



Salinity Intrusion Under Existing Conditions
LOG(Concentration in PPM)
3.80
3.60
3.40
3.20
3.00
2.80
2.60
2.40
2.20
Lums Pond
C&D Canal
F
F'
Materials
a_Columbia_Sand
d_Mount_laurel_Sand
e_Marshalltown_Clay
f_Englishtown_Sand
g_Merchantville_Clay
h_Magothy_Sand
Not to Scale
1000 ft
Drinking Water Standard
250 ppm
C&D Canal Deepening
PED Study
Inset Model
Existing Cond. Salinity
Cross Section F-F'
Figure 45



C&D Canal Deepening
PED Study
Inset Model
Deepened Cond. Salinity
Cross Section F-F'
Figure 46



C&D Canal Deepening
PED Study
Inset Model
Salinity Change
Cross Section F-F'
Figure 47