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# Assessment of groundwater and surface water quality impacts in the vicinity of the Brunner Island Steam Electric Station coal pile using groundwater modeling

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# ASSESSMENT OF GROUNDWATER AND SURFACE WATER QUALITY IMPACTS IN THE VICINITY OF THE BRUNNER ISLAND STEAM ELECTRIC STATION COAL PILE USING GROUNDWATER MODELING

by

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# Approvals

This thesis is accepted and approved in partial fulment of the requirements for the degree of Master of Science.

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(date)

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# Abstract

This thesis presents a groundwater modeling effort conducted at the Brunner Island Steam Electric Station (SES). The Brunner Island SES is a coal-fired steam electric generating station, owned and operated by the Pennsylvania Power & Light Company, and located on the west bank of the Susquehanna River in York County, PA.

The Brunner Island SES coal pile site is underlain by approximately 30 feet of alluvial sand and gravel which occur over a weathered, fractured siltstone and sandstone formation. Groundwater occurs in both the alluvial and fractured bedrock aquifers, and flows predominately in an eastern direction for eventual discharge to the River. The site is located within a regional groundwater discharge zone, as evidenced by upward vertical gradients between the rock and alluvial aquifers on the site.

The USGS MODULAR three-dimensional groundwater flow model was calibrated to a portion of Brunner Island in the vicinity of the coal storage pile. This modeling analysis indicates that approximately one-half of the groundwater exiting the downgradient side of the pile originates within the coal pile area as precipitation or surface water infiltration, while the other half originates as upgradient flow, primarily from the

Basin No. 3 area with minor amounts from upland areas. Additional test case modeling analyses were conducted to evaluate methods for more accurately simulating regional groundwater underflow. Contaminant mass loading rates from the coal pile area to the Susquehanna River and resulting surface water quality impacts were evaluated, and indicate little degradation in water quality in the Susquehanna river except in along shorelines under low-flow conditions.

Simulations of a combination slurry wall/drain remedial system at the coal pile were also performed. These simulations indicated such a system could be effective in containing contaminant migration from the coal pile area. However, resulting changes to Susquehanna River surface water quality are minimal, since surface water quality degradation initially attributable to the coal pile is minor.

# 1.0 Introduction

## 1.1 Background

The Pennsylvania Power & Light Company (PP&L) owns and operates the Brunner Island Steam Electric Station (SES), a coal-fired electric generating station, located on the west bank of the Susquehanna River, in East Manchester Township, York County, PA. As indicated in Figure 1, the generating station and associated facilities span both Brunner Island and Lows Island, and are mostly separated from the mainland by Conewago Creek and Black Gut. Coal burned at the station is stockpiled in an area to the northwest of the power plant. Bottom ash, fly ash, coal cleaning wastes (pyrites), and miscellaneous other wastes are treated and disposed in surface water impoundments located adjacent to the station.

Previous hydrogeological investigations at the station have documented groundwater quality degradation, consisting of low pH groundwater with high levels of iron, sulfate, arsenic, manganese, nickel, and zinc. The contamination is primarily due to oxidation and subsequent leaching of pyrite-bearing materials (coal and coal cleaning wastes) stored or disposed in the coal stockpile area, retired Basins No. 1, 2, and 3, and active Basin No. 4 (Figure 2) [Baker 1986, Dunn 1985, PP&L-1 1988]. Although significant groundwater quality degradation has occurred, no human health risks are likely, since the groundwater system is essentially separate from that on the mainland, and no residential wells exist on the island [Baker, 1986]. Impacts of the degradation appear limited to slight water quality degradation of some of the surrounding surface water bodies under low flow conditions. Measurable increases in iron and sulfate may be observed in Conewago Creek and the Susquehanna River near the power plant under low flow conditions [Baker 1986, PP&L-2 1988].

PP&L initiated the Brunner Island Groundwater Remediation Program in 1988 to identify , evaluate, and implement, if necessary, cost-effective remedial measures for the facilities contributing to the degradation. Based on previous field data and recommendations of the PA DER, the Remediation Program focused primarily on impacts associated with the coal storage pile, one of the primary contaminant sources at the site. The program is a four-phased approach, including additional field data collection, a more detailed modeling assessment, investigation of remedial action alternatives, and review or revision of previous and current waste management practices at the site [PP&L-3, 1988]. This thesis provides the results of one of these four efforts: the detailed modeling assessment in the vicinity of the coal storage pile.

Additional field data collected in 1989 included installation and packer testing of four boreholes in the vicinity of the coal pile, installation of four coal pile monitoring wells and one upgradient well, slug, pump, and recovery aquifer testing of these wells, and water quality sampling and analysis. Potential remedial measures identified for the coal storage pile included a synthetic liner, a slurry wall, a pumping/drain collection system, or a combination of these. Although collection of this additional field data and identification of potential remedial measures were performed in conjunction with this thesis, they are separate tasks and are described elsewhere [Dunn, 1989; PP&L 1989].

## 1.2 Scope and Objectives

The primary objective of this thesis is to apply a groundwater flow and contaminant transport model to the Brunner Island SES site in order to evaluate the performance of potential remedial measures for the coal pile area, and to assist in the design of any such measures. A secondary objective of the thesis is to use the model to provide a better understanding of groundwater flow patterns in the vicinity of the coal pile, especially the importance of the upper bedrock aquifer in transmitting flow. A final objective of this thesis is to improve estimates of mass loading rates of contaminants discharging from the coal pile area to surrounding surface waters.

In order to achieve the objectives outlined above, the scope of this thesis includes:

- Compilation, review and evaluation of existing hydrogeological, water quality, and plant operational data relevant to groundwater conditions;

- Calibration of a 3-D groundwater flow model to site conditions (USGS Modular Model) [McDonald and Harbaugh, 1978];

- Application of a 2-D cross-sectional groundwater flow model to the site (EPRI's FASTCHEM Package) and application of a 3-D groundwater flow test case (USGS Modular Model) to better understand groundwater flow patterns and constraints on application of models to the site [McDonald and Harbaugh, 1978; EPRI, 1988];

- Performance of limited sensitivity analyses, to determine the model's sensitivity to variations in input parameters, and to develop a "level of confidence" in model results;

- Development of a water budget for the coal pile area, estimating mass loading rates of contaminants to surface water bodies and resulting surface water quality impacts;

- Simulation of a selected remedial measure in the vicinity of the coal storage pile, to aid in evaluating its effectiveness and design.

Although the primary emphasis of this modeling effort was to assess remedial measures for the coal pile, modeling was conducted across the entire central portion of the island, thereby allowing selection of appropriate locations for model boundaries. More approximate modeling (coarser grid) performed in areas other than the coal pile can be used as a basis for potential future modeling work aimed at assessing remedial actions at other site areas, if desired. Additionally, use of the FASTCHEM Package in this work provides initial groundwater flow analyses, upon which potential future geochemical modeling can be based, if desired.

## 2.0 Site Description

This section provides an overview of Brunner Island SES operations, site geology, hydrogeology, hydrology, and water quality data. Detailed descriptions of this information have been provided in several previous reports [Baker, 1984; Baker, 1986; Baker, 1987; Dunn, 1985; Dunn, 1989; PP&L-4, 1988]. Although some general site data necessary for properly performing this modeling assessment are provided here, particular emphasis is placed on summarizing pertinent information related to conditions in the vicinity of the coal storage pile. Emphasis is also placed on recent hydrogeologic and water quality data collected in the vicinity of the coal storage pile, which have not been included in previous studies.

### 2.1 Plant Operations

Provided below are design and operational details of the Brunner Island SES, coal pile, and other waste storage and disposal units associated with groundwater impacts. Although groundwater conditions in the vicinity of the coal pile are the primary focus of this thesis, information on adjacent facilities (Basin Nos. 1, 2, and 3) is provided here also. Such information is necessary to interpret results of previous field investigations and to accurately assess groundwater impacts in the vicinity of the coal storage pile.

### 2.1.1 General

The Brunner Island Steam Electric Station (SES) is located on the west bank of the Susquehanna River, in East Manchester Township, York County, PA. The facilities actually span both Brunner Island and Lows Island, which are partially separated from the mainland by Conewago Creek and Black Gut. The station consists of three pulverized coal-fired boilers and associated generating facilities capable of supply a peak power load of approximately 1500 megawatts. Plant construction began in 1958 and operations began in 1961. Prior to construction of the plant, the site was used for farming and sand and gravel quarrying and processing. During construction, much of the area underlying the generating facilities was raised from the original surface elevations of 265-275 feet MSL to present grade of 280-285 feet MSL by emplacement of fill materials excavated from basin construction.

The primary wastes produced and disposed on-site at the Brunner Island SES are fly ash and bottom ash from coal combustion. Fly ash is collected in either electrostatic precipitators or bagfilters, and sluiced with water to nearby ash disposal basins for disposal. Bottom ash is sluiced in a similar manner. The basins are large earthen settling basins, in which the ash settles to the bottom and clarified water is decanted from the surface of the pond and discharged under a National Pollutant Discharge Elimination System (NPDES) permit. As indicated on Figure 2, large portions of the Brunner Island site are either retired or existing ash disposal facilities, owing to the large volumes of ash produced and disposed annually (400,000 tons/yr).

Although by far the largest volume of waste disposed at the site, ash disposal is not the primary source of the groundwater degradation observed at the site. Previous investigations have identified the oxidation and subsequent leaching of pyrite-bearing materials as the primary source of groundwater degradation at the site [Baker, 1986]. Pyrite-bearing materials include coal stockpiled in a 30 acre area northwest of the plant and coal cleaning wastes (also called pyrites or coal mill rejects) currently disposed in Basin No. 4 and previously disposed in retired Basins Nos. 1, 2, and 3. Trace metals leaching from fly ash which has been brought into contact with the low-pH seepage from pyritic materials (via co-disposal in the retired basins) may also constitute a secondary, although minor, contaminant source. This investigation focuses on impacts due to seepage from pyrite-bearing materials in the coal stockpile.

### 2.1.2 Waste Description

#### 2.1.2.1 Fly Ash and Bottom Ash

Fly ash and bottom ash are the two "high volume" wastes produced and disposed at the Brunner Island SES. Fly ash is very fine, powdery, noncombustible residue from coal incineration which is carried from the boiler with the flue gases and collected in the particulate emissions control equipment. Bottom ash is larger, heavier particles which are collected at the bottom of the boiler. Fly ash and bottom ash are both currently disposed in Basin No. 6, although they have been previously disposed in all basins on the island in varying amounts.

Table 1 provides leachate quality data from Brunner Island fly ash and bottom ash, based on the American Society of Testing and Materials (ASTM) Method "A" water extraction method. Brunner Island fly ash produces a slightly acidic leachate containing various concentrations of trace metals, with sulfate as a dominant constituent. Relatively inert bottom ash produces a near neutral pH leachate with few dissolved constituents. Fly ash produces a more concentrated leachate than bottom ash due to (1) its greater surface area available for leaching, and (2) the surface enrichment of fly ash particles with certain trace metals which volatilize in the boiler during the combustion process and condense on the surface of the ash particles as the ash exits with the flue gases.

### 2.1.2.2 Coal Cleaning Wastes

Coal cleaning wastes are believed to be one of the primary sources of groundwater quality degradation at Brunner Island [Baker, 1986]. These wastes, similar to that produced by the mining industry, are coal particles which contain a high degree of mineral matter. They may contain up to seven percent by weight pyritic matter, which may promote the generation of acid leachate if the material is exposed to oxidation and weathering. Leachate quality is similar to acid mine drainage, with low pH and high levels of sulfate, iron, aluminum, manganese, nickel, and zinc. Coal cleaning wastes are currently disposed in Basin No. 4, and were previously disposed in retired Basins No. 1, 2, and 3.

Although little data are available, Table 1 also provides analytical results of a sample of ponded runoff collected from the coal cleaning wastes stockpile in the northeast corner of Basin No. 4. These analytical results show extremely high levels of dissolved constituents. Such levels are likely representative of pyrite runoff quality which has been concentrated to some extent, since it was collected from a partially-evaporated standing pool with calcium- and iron-sulfate evaporites observed around the edges of the pool [Baker, 1986].

Most oxidation, weathering, and resulting acid production from coal cleaning wastes on the Brunner Island site is believed to occur in pyrites which are not submerged, and exposed to the atmosphere or other sources of oxygen [Beak, 1989]. Acid production in pyrites which are submerged is generally limited due to the limited solubility of oxygen in water, especially groundwater. Conditions which may promote the oxidation of pyrites and generation of acid leachate occur in the coal cleaning waste stockpile in Basin No. 4, and in those portions of retired Basins Nos. 1, 2, and 3 above the water table where pyrites were previously disposed. Oxygen-rich rainfall recharge and the resulting fluctuations in the water table may also encourage pyrite oxidation and leachate generation.

#### 2.1.2.3 Coal Pile Seepage and Runoff

Precipitation on the coal storage pile results in both rainfall infiltration to the pile, runoff from the pile, and resulting seepage to groundwater as described in Section 2.1.3. Like coal cleaning wastes, coal can produce acidic drainage due to the oxidation/weathering and subsequent leaching of pyrites in the coal. The quality of coal pile drainage is highly variable, due to varying intensity and amounts of precipitation over time, the varying residence time of water in the coal pile, different coal sulfur contents owing to different coal sources and varying degrees of coal cleaning, and changing grading, topography and surface compaction of the pile and runoff collection moats. However, constituents in coal pile drainage can approach concentrations found in coal cleaning waste leachate [Baker, 1986]. Thus, coal pile seepage is believed to be another primary source of groundwater quality degradation at the site, and the source which this modeling effort focuses on.

Table 1 also provides analytical data from a sample collected from the coal pile runoff moat at Brunner Island. Although these data are representative for coal pile runoff, coal pile seepage to groundwater might be expected to contain higher concentrations of dissolved constituents, due to less dilution with rainfall runoff and longer residence time with the coal [Baker, 1986].

### 2.1.3 Coal Pile and Basins

Figure 2 provides a site plan of the Brunner Island SES, showing the locations of the coal storage pile, both active and retired basins, and waste treatment basins.

Coal is stockpiled on a 30 acre parcel just northwest of the plant. The pile is reported to be underlain by 1-2 feet of anthracite silt. Although no data is available regarding the permeability of this "liner", its is suspected to be no less permeable than native soils on site. Coal pile runoff collects in a ponded area to the northwest of the pile and is channeled through unlined moats to the Industrial Waste Treatment Basin (IWTB) for treatment prior to discharge (Figure 2). Thus, seepage to the groundwater may occur both from rainfall infiltration on the pile and induced infiltration from these runoff collection areas. Prior to construction of the IWTB in the early 1970's, coal pile runoff was discharged directly to the Susquehanna River.

Basin Nos. 1, 2, and 3 are retired basins used for the disposal of virtually all waste streams generated at the plant during approximately the first 15 years of plant operations (1961 to late-1970's). Thus, these three basins received fly ash, bottom ash, coal cleaning wastes, office trash, construction debris, boiler cleaning acid wastewaters and miscellaneous other plant wastewaters. The basins are unlined, and constructed of raised earthen dikes of native alluvial soils with the interiors excavated to rock. As part of the general site construction, fill was placed in areas surrounding the basins, so their dike crests now generally coincide with present surface grades of approximately 283 feet MSL at the site.

Basin No. 4 is currently used for coal cleaning waste disposal and treatment of miscellaneous plant wastewaters from the East and West Lagoons. Previously this basin had been used for the disposal of ash, office trash, and construction debris. Basin construction is similar to that of the retired basins. A large portion of the basin is filled, with pyrite waste stockpiles exposed above the water elevation and subject to weathering. Average daily flow through this basin is 3 MGD. Significant seepage from this unlined basin occurs as evidenced by water table mounding in the area, which is further discussed in Section 2.3.2.

Both Basin Nos. 5 and 6 are located on the southern portion of the island (Figures 2 and 3), south of the central plant area where the most significant groundwater degradation has occurred. Prior to its retirement in 1988, Basin No. 5 was used for both fly ash and bottom ash disposal. The northeastern corner of the basin is currently being used for bottom ash reclamation. Basin construction is also similar to the retired basins. Basin No. 6 is currently used for both bottom ash and fly ash disposal. Construction of this basin also consists of an unlined bottom excavated to rock, although design drawings for the basin show the interior of the dike slopes to be lined with "select impermeable soils". Basin No. 7 is a recently constructed basin, located north of the central plant area, and is scheduled for service in 1990.

Various plant wastewaters are treated in both the IWTB and the East and West Lagoons. The IWTB also receives coal pile runoff. Both facilities are constructed of raised earthen dikes, and the interior side slopes and bottom of the IWTB are lined with one foot of compacted clay. Prior to construction of the IWTB and Lagoon in the early 1970's, plant wastewaters were directed to Basin Nos. 1, 2, or 3. Water level data collected from wells near the IWTB show no pronounced water table mounding near this basins.

## 2.2 Geology

### 2.2.1 Regional Geology

The Brunner Island SES facilities are located in southeastern Pennsylvania in the Piedmont physiographic province. Brunner and Lows Islands are point-bar deposits of alluvial silts, sands, gravel, and boulders located along the west bank of the Susquehanna River. These alluvial deposits most likely were formed from sediment-laden glacial meltwater during the late Pleistocene and early Recent time. The alluvial deposits range from 5 to 40 feet thick. They consist of a mantle of silty sands overlying coarser grained soils which generally become coarser with depth. This alluvial fabric is disrupted in places by channel cut and fill sequences from Conewago Creek and Hartman Run/Black Gut, which originate to the west of the island and enter the River adjacent to the island [Baker, 1984; Baker, 1986].

Most of Brunner Island is underlain by New Oxford Formation sandstones and shales of Triassic age, as indicated in Figure 3. The southeastern end of the island is underlain by Cambrian carbonate rocks. The contact between these two formations is formed by a normal fault and a thin band of Triassic age conglomerate, which marks the boundary of the Triassic Basin in this area. The New Oxford strata strike at approximately N 60o E and dip northwest at about 22o. Two predominant vertical joint sets have been mapped in this formation, generally in the north-south and east-west directions. A third joint set parallels bedding planes. Bedrock is weathered to a depth of 5 to 30 feet or more below the rock surface. The contact between weathered and unweathered rock is gradational and highly variable [Baker, 1984].

### 2.2.2 Local Geology

The central island and coal pile area has been investigated under numerous previous boring programs, as shown in Figure 4.

The geology of this area largely conforms to the general description provided above.

Overburden thickness in the central island area ranges from 5 to 40 feet, as indicated on Figure 5. The alluvial material is generally thicker toward the center of the island, and thins toward the edges of the island bordered by surrounding streams and the river. Native alluvial material also tends to coarsen with depth from clayey/silty/sandy soils to sandy gravel and cobbles. Two cross sections through the coal pile area, provided on Figure 6, show this layer of coarse-grained soils to vary from 2 to 15 feet in thickness. No apparent areal trends in thickness of this coarser layer are discernable from existing data in the central island area.

Cut and fill activities associated with construction of the plant have radically altered the thickness and nature of the alluvial material in the central island area. In retired Basin Nos. 1, 2, and 3, the natural alluvial material has been removed to bedrock and replaced with ash fill. In the power plant area, coal pile area, and areas adjacent to the retired basins, material excavated from basin construction has been used as fill to raise natural grades from 265-275 feet MSL prior to construction to their current elevation of 283-285 feet MSL [PP&L, 1961]. Under roadbeds, railroad beds, and basin dikes, this fill material was compacted during placement, further altering the properties of the natural alluvial material. The two cross sections through the site provided in Figure 6 show the significance of these man-made features.

Bedrock elevation and topography across much of the central island and coal pile area is constant and uniform, as shown in Figure 7. Bedrock across most of the site occurs at elevation 252-255 feet MSL. Bedrock elevations drop to 250-254 feet MSL along the river bank, and rise to 260-266 feet MSL in the former sand and gravel quarry area just northwest of Basin No. 3. Slight depressions in the bedrock surface appear to exist along the Susquehanna River at former mouths of old, buried stream channels for Conewago Creek and Black Gut. In the highland area west of Basin No. 3, bedrock elevations increase sharply. Bedrock rises from 255 ft MSL beneath Basin No. 3 to 298 feet MSL at MW-19, 200 feet west of the basin. Bedrock topography continues to increase to the west, climbing from the floodplain to adjacent highland areas.

Bedrock in the Central Island consists of New Oxford Formation fine to coarse-grained micaceous sandstones, interbedded with thin shale, siltstone, and conglomerate layers. Borings in the vicinity of the coal pile and central island area show the upper portion of this rock to be weathered, with significant jointing, some porous beds, and beds often weakly cemented to the point of crumbling easily [Dunn, 1989]. Weathered rock extends to depths of between 5 to 30 feet or more, and rock tends to become more competent with depth, although no clearly defined weathered/unweathered interface exists. Section 2.3.3 provides results of hydraulic testing of the rock, which provides additional insight into the depth of this weathered zone.

## 2.3 Hydrogeology

### 2.3.1 Regional Hydrogeology

Groundwater in the region generally occurs under unconfined conditions, although in some areas confined conditions may occur in the bedrock due to the nature of the bedrock joint system. Groundwater flow in the shallow water table system and deeper regional systems generally mirror surface topography, with recharge in topographically high areas and discharge to creeks and rivers. Significant fracture and fault zones may alter this pattern by locally redirecting flow [Baker, 1986].

Groundwater flow beneath Brunner Island is influenced by a combination of both regional and local flow patterns, as depicted in Figure 8. Brunner Island is located in a regional groundwater discharge area adjacent to the Susquehanna River.

As such, groundwater flowing within the bedrock in deeper regional systems would be expected to exhibit upward flow components, exiting deeper rock flow systems for eventual discharge to the river. Indeed, slight upward vertical gradients are observed in several deep multi-level cluster wells installed in the vicinity of the coal pile, indicating that the island is located in a regional groundwater discharge zone. These data are described detail in Section 2.3.2.

The local flow systems depicted on Figure 8 most likely dominate groundwater flow on the island relative to the influences of the regional flow systems. These local flow systems are fed by recharge from rainfall infiltration and existing basin seepage, travel in the alluvial and shallow bedrock aquifers, and eventually discharge to Black Gut Creek, Conewago Creek, or the Susquehanna River. Ultimately, groundwater flow beneath the island discharges to the Susquehanna River, either directly or shortly after discharge to nearby tributaries.

Groundwater is the primary source of potable water for domestic and commercial supplies in the region. Most wells are drilled bedrock wells with yields from 1-350 gpm and depths from 25 to 200 feet. Bedrock permeability is essentially due to secondary porosity from fracture and joint systems. Groundwater occurs in reasonable quantities at depths up to 300 feet of rock; below this depth the frequency of water bearing fractures is greatly reduced [Baker, 1986].

### 2.3.2 Local Hydrogeology

The alluvial soils and upper weathered bedrock form the primary, uppermost aquifer beneath Brunner Island. This aquifer is unconfined and extends from the water table down to the base of the weathered bedrock zone. Depth to water is generally shallow, ranging from 5 to 20 feet. Beneath this surficial aquifer, groundwater is contained in fractures within the underlying bedrock.

The groundwater system beneath Brunner Island is largely self-contained and isolated from the adjacent "mainland" areas opposite the creeks and rivers surrounding the island. Groundwater generally flows radially outward from the center of the island toward the Susquehanna River, Black Gut Creek, Conewago Creek, and the flood control channel. One exception to this occurs in that portion of the island contiguous with the mainland just west of retired Basin No. 3. Here groundwater flows in an easterly direction from topographically higher mainland areas onto the island, after which flow takes on the radial patterns described above. The water table occurs within the bedrock in the highland area, and enters the alluvial material on the western boundary of

Basin No. 3. Figure 9 provides a February 1989 water table map showing these patterns of groundwater flow on the central portion of the island.

Groundwater in the area north of the coal pile discharges to the flood diversion channel, which serves to hydraulically separate the main plant area from the Basin No. 7 area to the north. Groundwater beneath the southern part of the coal pile and in the main plant area flows eastward, discharging to the Susquehanna River. Groundwater in the southern portion of the main plant area and Basin No.4 discharges to the cooling water discharge channel, prior to reaching the Susquehanna River. In the central island area, cut and fill activities associated with construction of the plant and basins have radically altered the nature of the alluvial aquifer, as described in Section 2.2.2. Comparison of pre- and post-construction water level data suggest groundwater levels have risen on the order of 10-15 feet in some portions of the central island, partially in response to these filling activities. This fill material and ash in the retired basins now comprise much of the alluvial aquifer in the power plant, coal pile, and Basin No. 1, 2, and 3 area.

Operational activities at the plant strongly influence groundwater flow on the island. Recharge from the large water-filled basins, particularly Basin Nos. 4 and 6, increases water levels, gradients, flow rates, and exaggerate the flow patterns outward from these basins. Historical plant operational changes, including changing water levels in existing basins and the prior operation of retired basins, has also affected recharge rates and thereby influenced groundwater flow.

Old stream channels, buried during construction of the plant, may also serve as conduits for preferential groundwater flow. One such area includes the old Conewago Creek flood channel which once routed through what is now retired Basin No. 3 (Figure 4). The former Middle Gut previously bisected what is now Basin No. 5, just south of the area shown on Figure 4.

The influence of construction, operation, and natural hydrogeologic conditions on water levels across the central island area can be discerned from examining water level data provided in Figure 9. Groundwater gradients across retired Basin No. 3 are flat, and elevated as compared to the coal pile area. These elevated water levels are most likely caused by a combination of the lower permeability dikes surrounding Basin No. 3, causing a "bathtub effect", and lower permeability ash within the basin, which results in higher heads due to the greater resistance to flow within the ash. Water levels in CL-1 are 15 feet lower than those in the adjacent Basin No. 3, due to the presence of the high-conductivity buried channel for the former Black Gut Creek in this area. The effects of Basin No. 4 operations can be seen in the high water levels observed in CL-4, 5, and 6.

Vertical patterns of groundwater flow have been defined across the central island area, with the installation of 10 multi-level cluster wells. Since the island is in a regional discharge area, one would generally expect upward gradients from deeper bedrock zones to shallow bedrock or the alluvial aquifer, eventually discharging to the river. Indeed, upward gradients of 0.03 to 0.05 were consistently observed throughout 1989 around the coal pile in CL-7, CL-9, and CL-10. These gradients correspond to observed water levels 0.3 to 1.5 feet higher in wells screened in the upper 30 feet of bedrock as compared to corresponding alluvial wells, which typically were screened in the alluvial material or at the alluvium-bedrock interface (20-40 feet higher than the bedrock wells). Less pronounced upward gradients of 0.0 to 0.007 were also observed frequently in CL-3 and CL-8 in the vicinity of the coal pile. On average, upward gradients of approximately 0.025 appear to occur beneath most of the coal pile area, between the upper fractured rock aquifer (top 30 feet) and the overlying alluvial aquifer.

Upward vertical gradients in the coal pile area may be caused locally by the presence of Basin No. 3, in addition to the influence of regional gradients. Higher water levels within Basin No. 3 due to the low permeability dikes may be transmitted through the shallow underlying fractured bedrock aquifer and manifest themselves as upward gradients emanating out of the bedrock downgradient of the basin. The combined lower permeability ash/dikes of Basin No. 3 may also cause groundwater flowing onto the island from upland areas to "dip" into the fractured bedrock aquifer beneath Basin No. 3, once again emanating as upward vertical gradients out of the rock downgradient of the basin.

Vertical gradients are not well defined across the rest of the central island area, due to both a scarcity of monitoring data and mixed trends in some areas where data are available. Downward gradients of 0.006 to 0.03 typically occur both to the south and north of Basin No. 4 in CL-1 and CL-2 (Figure 4). Gradients in these areas may be reversed (downward) due to the strong influence of recharge from Basin No. 4. No significant trends in vertical gradients in CL-4, CL-5, and CL-6 are discernable, since these wells are only screened in the shallow alluvial material, and due to these wells' proximity to Basin No. 4 and their response to changing water levels in the basin.

### 2.3.3 Aquifer Properties

A significant amount of hydraulic testing has been performed in numerous wells and borings at the site. Testing in the central island area includes single well pump and recovery tests, slug tests, and bedrock pressure tests. Additional falling-head permeability tests were performed in boreholes on the northern and southern portions of the island in conjunction with construction of Basin Nos. 6 and 7. Table 2 provides a summary of hydraulic conductivity data collected on the central portion of the island. Appendix 1 contains a summary of all hydraulic testing data performed on the island [Baker, 1984; Baker, 1986; Dunn, 1985; Dunn, 1989].

Hydraulic conductivity of the alluvial soil aquifer in the central island area ranges over three orders of magnitude, from 0.1 to 21 ft/day, with a median value of 1.9 ft/day, and log average value of 2.2 ft/day. Data obtained from the different test methods (e.g., pump, recovery, slug tests) were generally in agreement. No significant areal trends in the hydraulic conductivity data are apparent. However, shallow cluster wells near the coal pile (CL-3, CL-7, CL-8, CL-9, and CL-10) showed slightly higher conductivities (median of 5.2 ft/day) than that indicated over the rest of the central island area. Also, wells which were installed to monitor expected high transmissivity buried stream channels (MW-4 and MW-10) showed higher hydraulic conductivities, as expected.

Aquifer test data from wells screened in the coarser alluvial material at the bedrock interface were analyzed separately from that from wells screened in the alluvial material only. Central Island wells screened in this interval showed hydraulic conductivity values ranging from 0.2 to 11 ft/day, with a median of 3.0 ft/day, and log average value of 2.5 ft/day. This summary suggests a zone of somewhat higher permeability occurs in this coarser alluvial material at the bedrock interface.

Bedrock hydraulic conductivity data reveal appreciable permeability in the shallow rock which decreases markedly with depth. Data from both pressure testing of core holes and pump/recovery/slug testing of wells screened within rock show hydraulic conductivity which decreased markedly below 30 feet into rock. Hydraulic conductivity of the upper 30 feet of bedrock ranged from near 0.0 to 11 ft/day, with a median value of 1.9 ft/day, and log average value 1.6 ft/day. Below 30 feet, bedrock permeability ranged from near 0.0 to 3.1 ft/day, with a median value of only 0.2 ft/day, and log average value of 0.3 ft/day. Zones of significant permeability are directly related to the presence of fractures and jointing, which noticeably decrease with depth. Unfractured bedrock is essentially impermeable, as observed by correlation of pressure test data and coring logs.

A few pump, recovery, and slug tests performed on CL-4, Cl-5, and CL-6 provide some insight into ash hydraulic conductivity, since these wells are screened directly within the ash in Basin No. 4. Hydraulic conductivity data from these wells ranged from 0.2 to 4.9 ft/day, with a median value of 0.7 ft/day and log average value of 0.8 ft/day. These values are representative of fly ash, bottom ash, and pyrites mixtures found in Basin No. 4 and retired Basins No. 1, 2, and 3.

## 2.4 Hydrology

### 2.4.1 Precipitation and Recharge

Annual precipitation in southern York County averages approximately 41 inches per year. Of this amount, approximately 27 inches (66%) is lost to evapotranspiration while 14 inches (34%) becomes stream flow, based on average stream flow reported for the area [Baker, 1986]. Two-thirds of stream flow is estimated to originate from groundwater discharge, which is the equivalent of approximately 9.3 inches per year [Lloyd, 1977]. Thus, net recharge to the groundwater system on Brunner Island from precipitation might be expected to average approximately 9.3 inches per year.

These estimates of net recharge rates may not be directly applicable to the central portion of Brunner Island for several reasons. First, recharge rates in this area are strongly controlled by local features related to plant construction and operations. Net recharge may be higher in areas which have been graded level, where water is allowed to pond, or where the texture of surface materials such as gravel, bottom ash, or coal encourage infiltration. Higher recharge rates may be expected to occur in the swampy area to the northwest of the coal pile or in the northern portion of the coal pile itself, due to the collection and ponding of rainfall runoff in these areas. Conversely, recharge would likely be lower in areas where runoff is encouraged or which have been covered with impervious material. Such lower recharge rates are likely in the main plant area and portions of retired Basin No. 2 due to buildings and impervious pavement.

Another important factor which may influence local recharge rates is the location of the site relative to the drainage basin as a whole. The 9.3 inches of estimated annual average aquifer recharge to due precipitation is a basin average. In reality, greater recharge occurs in highland recharge areas of the drainage basin with correspondingly lower recharge rates in lowland areas of the basin. This "lower" recharge actually becomes net negative recharge, or discharge, along streams and rivers to which groundwater discharges. Given Brunner Island's location along a major river and regional discharge zone, net precipitation recharge to the aquifer may be significantly less than the 9.3 inches estimated above.

Unfortunately, recharge rates across the island and in the primary area of interest, the coal pile area and retired Basin No. 3, are largely unknown. Quantification of such recharge rates is critical to fully understanding contaminant transport processes at the site, since contaminant sources in the coal pile area and retired basins are largely governed by precipitation recharge. To accurately gauge recharge rates in these areas, infiltrometer studies and/or measurement of rainfall and runoff flow would be required.

### 2.4.2 Surface Water Hydrology

The Brunner Island SES is bordered by three surface water bodies, including the Susquehanna River to the east, Conewago Creek to the northwest, and Hartman Run/Black Gut to the southwest. Conewago Creek and Black Gut discharge to the River at the northern and southern ends of the island, respectively. A flood diversion channel, intended to handle flood flows from Conewago Creek, also bisects the island just north of the coal pile. Surface water elevation data recorded on site from 1986 - 1988 provided in Appendix 2.

A significant database exists on flow characteristics of the Susquehanna River. The nearest USGS gauging station is located seven miles downriver, at Marietta, PA. The drainage area at this point is 25,990 square miles. Based on 53 years of record through 1984, average discharge was 37,110 cubic feet per second (cfs), and the 7-day, 10-year low flow is 2,605 cfs [Baker, 1986]. River elevations at the Brunner Island SES plant gauge over this range of flow rates range from approximately 254.2 ft MSL (at 30,000 cfs) to approximately 251.3 ft MSL (at 4,000 cfs) [PP&L, 1988].

Flow statistics are available for Conewago Creek from a USGS gauging station at Manchester, PA, approximately two miles upstream from the Brunner Island SES. The drainage area at this point is 510 square miles. Based on 56 years of record, average discharge was 592 cfs and the 7-day, 10-year low flow is 9.8 cfs [Baker, 1986].

No gauging data are available for the Hartman Run/Black Gut watershed, located south of this study area on the southern portion of the island. However, previous investigations have estimated this watershed to be approximately 4.4 square miles, with average and 7-day, 10-year low flows of 5.2 and 0.4 cfs, respectively. [Baker, 1986]

The large water-filled basins on the site exert a profound influence on both surface and groundwater hydrology, as mentioned previously. In addition to these basins, several other smaller surface drainage features in the vicinity of the coal pile also influence the hydrology of this area.

A small area of ponded water exists in a low-lying area just northwest of the coal pile, as shown in Figure 2. This water originates as runoff from the northern portion of Basin 3 and that area just north of the basin. Ground and surface water elevation data suggest this pond to be a recharge area to the shallow alluvial aquifer. Similarly, ponded water in runoff collection areas on the northern portion of the coal pile may serve as localized recharge areas to the alluvial aquifer.

Surface water runoff and seepage from the western portion of Basin No. 3 leaves the site via the old Conewago stream channel to the west. A portion of the seepage from the coal pile area, northern portions of Basins 1 and 2, and the eastern portion of Basin 3 surface in a swampy also just north of the coal pile. Overland flow from this wet area discharges to the Susquehanna River to the east.

## 2.5 Water Quality

### 2.5.1 Groundwater Quality

Groundwater quality data have been collected from four wells (MW-11, MW-12, MW-14, and CL-3) in the central island and coal pile area quarterly since 1984. Four cluster wells around the coal pile (CL-7, CL-8, CL-9, CL-10) and an upgradient well (MW-19) have provided additional groundwater monitoring data since their installation in early 1989. Table 3 provides average 1989 groundwater quality data from these wells for selected parameters.

These data show significant degradation in groundwater quality in the vicinity of the coal pile, consisting of low pH, high specific conductance, and elevated levels of sulfate, iron, manganese, aluminum, arsenic, nickel, zinc, and several other metals. Primary sources of these contaminants are coal pile seepage and seepage from the pyrites previously disposed in retired Basins No. 1, 2, and 3. Fly or bottom ash disposal is not the cause of this degraded groundwater quality, since contaminant concentrations present in the groundwater far exceed those present in ash leachate [Baker, 1986].

The average 1989 data provided here may not convey a complete picture of the temporal variations in contaminant transport at the site. Prior to 1989, water quality in CL-3B and MW-14 (the only coal pile wells sampled prior to 1989) showed higher levels of many constituents. Lower concentrations observed in the remaining wells in 1989 may be due to dilution from the high rainfall events which occured just prior to some sampling events, or to a general improvement in water quality which appears to have occurred since 1985 at the site.

Aerial concentration distributions provide some insight into the contaminant sources and hydrology of the site. CL-3 shows the worst water quality in the vicinity of the coal pile, most likely due to its location centered immediately downgradient of the pile. Wells CL-9, CL-10, and MW-14 reveal lower contaminant concentrations, since they are located somewhat laterally downgradient of the pile as compared to CL-3 and/or are farther downgradient. Degradation in wells upgradient of the coal pile (CL-7, CL-8, MW-11, MW-12) indicate that Basin No. 3 (and possibly Basin Nos. 1 and 2) are also significant contaminant sources. Water quality in MW-11 and MW-12, installed in the downgradient portion of Basin No. 3, is worse than that observed in all coal pile wells, with the exception of CL-3. Figure 10 provides a map of sulfate concentrations observed in the vicinity of the coal pile, which reflects these aerial concentration distributions.

Variations in concentrations with depth provide additional insight into contaminant transport and the hydrology of the site. Lower concentrations in the shallow monitored zones of wells upgradient of the pile (CL-7, CL-8) indicate that rainfall recharge may serve to dilute shallow upgradient contaminant sources (MW-11, MW-12). Conversely, elevated concentrations in shallow monitoring zones immediately downgradient of the coal pile are most likely due to lower quality recharge from the coal pile. The somewhat lower concentrations in the deeper monitoring zones of all cluster wells result from the mixing of lower quality shallow "source" water with better quality groundwater at depth.

The degraded groundwater quality in deeper monitoring zones is contradictory to the generally upward gradients in the coal pile cluster wells. Such upward gradients would be expected to limit the downward vertical migration of contaminants. However, significantly degraded groundwater is observed to a depth of at least 60 feet in the cluster wells. This degraded water quality at depth could be due to a number or combination of factors. Previous operation of Basin Nos. 1, 2, and 3 most likely created downward gradients; degraded water quality observed in the bedrock beneath the coal pile may be a remnant of downward contaminant migration driven by higher heads during previous operations at Basin No. 3. Temporary or localized downward gradients may also occur and drive contaminants deeper into the fractured rock aquifer in response to recharge events or due to the ponding of water in the northeast corner of the coal pile area. Although CL-8 usually reveals upward vertical gradients, downward gradients were observed in the upper two monitored zones in at least one sampling event, supporting the possibility of temporal changes in the direction of gradients in response to recharge events.

### 2.5.2 Surface Water Quality

Surface water quality in the vicinity of Brunner Island has been investigated in numerous previous studies [Baker 1986, Dunn 1985, PP&L-2 1988]. Impacts to surface water quality are most likely to be observed during low flow events, when groundwater recharge constitutes a greater proportion of streamflow. Thus, water quality data collected during low-flow periods may be most valuable in assessing impacts to surface waters. Table 4 presents surface water quality data collected by PP&L in July 1988 during low flow events to assess potential impacts of degraded groundwater seepage on surface water quality. Figure 11 indicates the location of these sampling points on Conewago Creek and the Susquehanna River.

These data show minimal impacts to surface water bodies which may be receiving degraded groundwater quality seepage from the coal pile area [PP&L-2, 1988]. Although the Conewago Creek does not receive any groundwater from the coal pile area, such data are provided here since it does receive some groundwater flow from the northern portion of Basin No. 3, which has been included in the area modeled as part of this thesis. Seepage from Basin No. 3 appears to have little, if any, impact on the Conewago Creek, with the possible exception of slight increases in iron, manganese, calcium, and sulfate.

More pronounced impacts to water quality are noted along visibly iron-stained seepage zones on the Susquehanna River near the coal pile. Decreased pH and elevated levels of calcium, magnesium, aluminum, iron, and manganese occur in the near-bank water quality immediately downgradient from the coal pile. However, these impacts decrease in the river toward the southern end of the island, with pH recovering and only sulfate and iron remaining significantly elevated over upstream levels. Other trace metals were nondetectable in all surface water samples, as indicated on Table 4.

## 3.0 Site Analysis

In conjunction with performing the computer simulations, supplemental analyses of key hydrologic and geochemical phenomenon at the site was performed. These analyses provide a quantified, conceptual framework of site conditions, which can be used to judge the accuracy, reliability, and limitations of model results. These analyses may also provide information not likely to be gleaned from a flow modeling effort. Collectively, this information proves useful in model calibration and fully interpreting and using model results.

Two components of the site analyzed in this manner included evaluating the quantity of groundwater flow which may be attributable to upward gradients in the vicinity of the coal pile, and developing groundwater and contaminant travel time estimates.

### 3.1 Vertical Flow Components

As described in Section 2.3, upward vertical groundwater gradients in the vicinity of the coal storage pile infers the upward movement of groundwater in this area, most likely due to regional groundwater flow patterns. Evaluation of these upward gradients and the resulting quantity of upward groundwater flow is necessary in accurately simulating the site and ultimately in designing effective remedial systems. A brief analysis of these gradients and potential groundwater flow is provided below.

Figure 12 provides a conceptual diagram illustrating this analysis, along with supporting calculations. This analysis is aimed at determining the quantity of water which might be entering the alluvial aquifer beneath the coal pile area from deeper flow systems in the bedrock. The quantity of groundwater flow moving upward out of the rock can be calculated by application of Darcy's Law in the vertical direction. As shown in Figure 12, in order to apply Darcy's Law, the stratigraphy, vertical hydraulic conductivity ($K_v$), gradient (i), and area contributing to flow (A) must be known.

As described in Section 2.3, the cluster wells in the vicinity of the coal storage pile show upward vertical gradients ranging from 0.0 to 0.05 ft/ft, averaging approximately 0.023 ft/ft. These gradients have been observed between wells screened in the upper 30 feet of bedrock and in the overlying alluvial material. Although these gradients exhibit both aerial and temporal variations, and no data are available on deeper gradients, an assumed annual average value of 0.023 ft/ft occurring to at least 80 feet into rock appears reasonable for use in this analysis.

No site-specific data on vertical hydraulic conductivity are available for the Brunner Island SES. However, numerous authors cite typical vertical:horizontal conductivity ratios ($K_v:K_h$) on the order of 1:10, or as low as 1:100 for highly anisotropic sediments or sedimentary rocks [Freeze, 1979; Walton, 1988; Driscoll, 1986]. The horizontal hydraulic conductivity data used for each layer are based on aquifer test data described in Section 2.3.3. The vertical hydraulic conductivity for each layer shown in Figure 12 was then assumed, based on $K_v:K_h$ ratios of 1:10, 1:100, or 1:1000. An overall $K_v$ for all layers can then be calculated, as shown in Figure 12.

The estimated upward vertical quantity of groundwater flow was then calculated, varying the $K_v:K_h$ ratio for all 4 layers from 1:10 to 1:1000. As shown on Figure 13, predicted upward vertical flows across the 22 acre coal pile area range from approximately 20,000 gpd (12 in/yr) for $K_v:K_h$ of 1:10 for all layers to 200 gpd (0.1 in/yr) for $K_v:K_h$ of 1:1000 for all layers.

An intermediate value of upward groundwater flow of 2060 gpd across the coal pile area was selected for use in the subsequent modeling analysis and appears most reasonable for several reasons. First, this flow rate corresponds to $K_v:K_h$ ratios of 1:10 for the alluvial aquifer and 1:100 for the bedrock aquifer, well within the range of values quoted in the literature. A $K_v$:$K_h$ ratio of 1/100 appears reasonable for the bedrock aquifer, based on the distinctly horizontally-layered stratigraphy of this unit revealed by borings. Second, flows much greater than this (corresponding to $K_v$:$K_h$ ratios of 1:10 or greater for all layers) simply could not be accommodated by the 1-2 foot saturated thickness of the alluvial aquifer along the river bank (as shown in subsequent modeling analyses). Finally, flows much less than this would require $K_v$:$K_h$ ratios on the order of 1:1000, much lower than that reported as likely in the literature.

Thus, it can be expected that between 200 - 20,000 gpd of groundwater from deeper flow systems could be expected to enter the alluvial bedrock aquifer, with a likely intermediate value of 2000 gpd. Further work to define actual $K_v$ values in the vicinity of the coal pile may be warranted to better estimate such quantities of flow as part of actual remedial system design work.

## 3.2 Travel Times

Estimates of groundwater velocities and travel times across the site are developed in Table 5. This table provides travel times calculated from the center of the coal pile area and from the center of the northern half of Basin No. 3 to the river. These rates were calculated using Darcy's Law for both the alluvial and bedrock aquifers. These groundwater velocity and travel time data are useful in evaluating model results, especially those relating to the implementation of remedial measures.

Groundwater velocities on the order of 0.4 ft/day occur in the alluvial aquifer, while velocities of approximately 1.3 ft/day occur in the underlying bedrock aquifer. The higher bedrock velocities are attributable to the lower effective porosity of the bedrock, as compared to the alluvial soils. Given these velocities, groundwater or travel times of 2-8 years from the coal pile to the river and of 6-25 years from Basin No. 3 to the river were estimated. These velocities and corresponding travel times represent averages, based on averaged field data.

Actual groundwater velocities and contaminant travel times in the field may vary, due to aquifer heterogeneities. Lower velocities in the alluvial aquifer may occur due to the presence of low-conductivity basin dikes, which are not accounted for in this analysis. Likewise, higher velocities may occur in the bedrock aquifer, due to the presence of small, discrete fracture zones. Effective porosities of fractured rock aquifers may approach 0.001 [Freeze, 1979], which would result in groundwater velocities in the bedrock on the order of 60 ft/day.

## 3.3 Modeling Approach and Numerical Model Selection

Several numerical computer models of groundwater flow and contaminant transport were evaluated for application to the site in this thesis. These included (1) the USGS **"MOC"** 2-D groundwater flow and contaminant transport model, which was calibrated to the site during previous investigations [Baker, 1986; PP&L-1, 1988], (2) the USGS **"MODULAR"** 3-D groundwater flow model, (3) several 3-D groundwater flow and contaminant transport models, such as GEOTRANS' **"SWIFT"** model, and (4) EPRI's **"FASTCHEM"** groundwater flow and contaminant transport model package. Model selection was governed largely by the remedial measures which were to be simulated, and to a lesser extent by the author's access and familiarity to the model.

Modeling approaches considered included (1) fully 3-dimensional groundwater flow and transport modeling, (2) 3-dimensional flow and 2-dimensional transport modeling, (3) and 2-dimensional flow and transport modeling, in either plan or cross-sectional perspective. Although a fully 3-dimensional flow and transport model would provide the best representation of both the alluvial and bedrock aquifers and the site in general, such a model is generally difficult and/or expensive to apply, and site geohydrologic data appeared insufficient to warrant use of such a model. The second potential approach, 3-dimensional flow and 2-dimensional transport modeling, could provide almost the same level of representation as the 3-dimensional model, but given the models considered here, would require using two separate models. The third option, modeling the site in 2-dimensional plan view, as was done previously, would require less site data and be easier to perform, but would provide only a crude representation of remedial measures given the layered nature of the aquifer. Modeling the site as a 2-dimensional cross-section would provide a good representation of both the alluvial and bedrock aquifer, but would not define conditions aerially across the site, especially in simulating stresses induced by remedial measures.

The approach selected for this thesis was 3-dimensional groundwater flow modeling. The 3-dimensional flow model provides the most accurate representation of groundwater flow in both the alluvial and bedrock aquifers. It also would reasonably simulate changes in groundwater flow occurring due to almost any potential remedial measure. Finally, together with some analytical evaluations of contaminant transport at the site, model results could be used to estimate changes in contaminant sources, fluxes to the aquifer, travel times, and loading rates to the river in response to remedial measures simulated.

The 3-dimensional flow model selected for use was the USGS Modular Groundwater Flow Model [McDonald and Harbaugh, 1978]. This model was selected based on its widespread use and excellent documentation, its ease of application, and its ability to simulate a variety of potential remedial measures, such as slurry walls, pumping systems, drains and caps. A PC-based version of the model was used in this thesis. This 3-dimensional flow model is described in Section 4.0. Some supplemental 3-dimensional flow modeling was also performed on a small hypothetical test case to evaluate effects of changing boundary conditions on the larger model of the Brunner Island coal pile, as described in Section 5.1.

Some limited 2-dimensional flow modeling was also performed in a cross-sectional perspective. The 2-dimensional flow and transport model selected for use was EPRI's new **FASTCHEM Package** [EPRI, 1988]. This model was selected based on its ability to easily simulate cross-sectional applications, to model both flow and contaminant transport, and to use a variable grid spacing for simulating slurry walls. Use of this model would also allow geochemical modeling of the site to be performed at a later date, which is also possible with the FASTCHEM Package, and which PP&L expressed interest in doing. However, this modeling effort was limited to only performing some general flow simulations and some stream line evaluations in the cross sectional perspective, due to difficulties encountered with application of the FASTCHEM Package, as described in Section 5.2.

## 4.0 3-Dimensional Flow Model Analysis

The 3-dimensional model analysis was performed to simulate groundwater flow through both the alluvial and fractured bedrock aquifers. This section describes the calibration of such a model to the Brunner Island coal pile site.

### 4.1 Site Conceptualization and Model Set-Up

#### 4.1.1 Model Grid

The site was modeled as a variable grid, 3-layer, steady-state case. A 37 x 37 variable-spaced grid was used to discretize the central island area, as shown on Figure 14. Since a slurry wall surrounding the coal pile was one of the primary remedial measures to be simulated, grid spacings were lessened to 10 feet near the edge of the coal pile to enable later simulation of a low-permeability wall just a few feet thick (without special modification to the basic horizontal conductance equations in the MODULAR code). Grid spacings increased with distance from the coal pile, to a maximum of 200 or 400 feet near grid boundaries in areas where greater resolution was not necessary.

Grid boundaries generally correlate to natural or man-made hydraulic boundaries at the site. Conewago Creek, the wetlands mitigation area on the former Black Gut channel, the flood control channel, the Susquehanna River, and the cooling water discharge channel all serve and are modeled as downgradient constant head boundaries which receive groundwater flow from the island. These water bodies bound the northwest, north, east, and southeast portions of the central island. A constant head boundary was also specified in the upland area along the western boundary of the grid, to simulate groundwater flow from this highland area to the western portion of Basin No. 3.

The southern boundary of the model grid was simulated as a no-flow boundary, with the exception of Basin No. 4 and a portion of retired Basin No. 3. Previous modeling and water level data from the site showed that a north/south groundwater divide occurred in this area, with groundwater flow trending due west and separating northerly flow components, which discharge to the diversion channel from southerly components, which discharge to Black Gut Creek or the Susquehanna River south of Basin No. 4.

Basin No. 4 was modeled as a constant head source of water seepage to the groundwater system in layer 1 using the river (RIV) module of the MODULAR model. A portion of the southern grid boundary along Basin No. 3 was modeled as a general head boundary. This boundary condition accounts for the influence of surface water bodies which lie beyond the model boundary. In this case it effectively extends the grid toward Black Gut and allows for groundwater discharge from all three layers to Black Gut Creek, resulting in lower water levels in the central Basin No. 3 area.

The boundary conditions imposed on this southern boundary of the model were limited in their ability to accurately simulate aquifer conditions along this boundary since: (1) the large grid spacings around Basin No. 4 areally approximated rapidly varying conditions; (2) portions of Basin No. 4 lying beyond the model grid significantly influence groundwater flow in the area; and (3) the location of the groundwater divide in this area was arbitrarily fixed by the locations of the model's boundary cells.

Surface water level data described in Section 2.4.2 were used to specify constant head boundary elevations.

### 4.1.2 Model Layers

The three layers simulated in this model included an upper alluvial soil layer, a middle coarse-grained alluvial soil layer above bedrock, and a lower fractured bedrock layer. Table 6 summarizes the distinguishing characteristics of each of these layers. Figure 15 shows a conceptualization of these layers overlaid on a cross section of the site previously provided as Figure 6.

Although all three layers exhibited similar hydraulic conductivities, as described in Section 2.3.3, they were modeled as three distinct layers since: (1) variations in porosity between the alluvial and fractured bedrock layers result in significant differences in groundwater velocities and rates of contaminant transport; (2) the vertical and areal extent of either water or ash-filled basins, alluvial soils, and corresponding hydraulic conductivities varied greatly across the island; (3) the slurry wall to be simulated penetrated only the upper two alluvial layers; and (4) a layered aquifer is necessary to reproduce the observed vertical variations in aquifer heads.

Layer 1 simulates the uppermost alluvial soil aquifer on the island. This layer consists of alluvial soils of silty clays and sands, varying textures of fill in filled areas, and ash within the retired and existing basins. Saturated thickness of this layer varies depending upon water table elevation and elevation of the underlying alluvial soil layer and bedrock. Saturated thickness generally ranged from 0 feet along downgradient discharge areas (where the water table fell below the bottom elevation of this layer) to a maximum of 15 feet in the Basin No. 3 area.

Layer 1 was modeled as an unconfined water table aquifer, since this was the uppermost layer of the aquifer. The bottom elevation of this layer was specified to coincide with the top elevation of Layer 2. Hydraulic conductivity of this layer was initially specified to be 2 ft/day, based on the data provided in Section 2.3.3.

Layer 2 simulates a lower alluvial soil aquifer occurring just above the top of rock. This layer consists of coarser-grained silty sands, gravel, cobbles, and boulders which appear to exhibit a higher hydraulic conductivity than the overlying finer alluvial soils, as described in Section 2.3.3. This layer also includes a limited thickness of severely weathered bedrock at the bedrock/soil interface, were present in the boring data. This layer may also consist of ash in basin areas where native alluvial soils have been removed to bedrock. Boring logs from the central island showed actual thicknesses of this layer to vary from 3 to 15 feet. However, since no trends of layer thickness were apparent from boring logs, thickness of this layer was modeled as a constant 10 feet across the site.

Layer 2 was modeled as a convertible unconfined/confined layer. This layer is unconfined near downgradient surface water discharge boundaries, where the water table occurs within layer 2. However, the water table elevation rises into layer 1 toward the center of the island, and therefore the full thickness of layer 2 is available for groundwater flow. In these areas the MODULAR model treats layer 2 as "confined" (transmissivity does not vary with aquifer head). The elevation of the bottom of this layer was specified to coincide with the top-of-rock elevation (top of layer 3). Elevation of the top of this layer was set at the top-of-rock elevation plus 10 feet, to achieve the constant 10-foot thickness as described above. Hydraulic conductivity of this layer was initially specified to be a constant 3 ft/day, slightly higher than the overlying soils or underlying rock, based on data provided in Section 2.3.3.

Layer 3 simulates the upper portion of the fractured bedrock aquifer. A constant thickness of 30 feet was selected based on aquifer test data, which show an order-of-magnitude decrease in hydraulic conductivity below 30 feet into rock, as described previously in Section 2.3.3. One exception to this constant 30-foot thickness was applied in the upland area to the West of Basin No. 3. In this area a simulated thickness of 20 feet of fractured rock was used, based on boring and water level data from MW-19, which show water levels occurring approximately 10 feet below the top of rock.

Layer 3 was modeled as a confined aquifer, since it its confined by water levels in layer 2 across most of the site, with the exception of the upland area to the west of Basin No. 3 as mentioned above. Since this layer is confined, hydraulic characteristics were specified in terms of the single parameter (transmissivity = hydraulic conductivity x layer thickness), rather than both layer thickness and hydraulic conductivity as with layers 1 and 2. Transmissivities for layer 3 were initially calculated using a constant hydraulic conductivity of 2 ft/day and layer thickness as described above. The elevation of the top of this layer was specified to coincide with known top of rock data shown in Figure 7.

### 4.1.3 Surface Recharge

Rainfall infiltration was initially simulated by applying recharge at a constant rate of 8 inches/year across the majority of the site. This rate was selected based on estimated regional infiltration rates as described in Section 2.4.1. Recharge was applied to the uppermost active layer at a given location. That is, recharge entered the layer within which the water table occurred, which in reality would initially receive this recharge.

Two other significant features incorporated into the model were simulation of the swampy area to the northwest of the coal pile and an area of ponded water within the northwest corner of the coal pile area. The swamp area receives and stores surface water runoff from the northern portion of Basin No. 3 and the area north of the basin. Water level data collected in this area indicate that this wetland is a localized area of increased recharge. The surface water on the northwest portion of the coal pile area results from the collection and incomplete drainage of coal pile runoff. Like the swamp, this area is also likely to be a localized source of increased recharge, based on water level data around the coal pile. Both of these areas were modeled as surface water seepage areas to the groundwater system using a river package option in layer 1 of the model.

The MODULAR model's river package uses a conductance parameter to specify seepage rates from such surface water sources [Konikow, 1978]. Conductance from a surface water body increases with increasing vertical hydraulic conductivity, increasing surface area, and decreasing thickness of the "riverbed", or soils underlying the surface water body. Higher conductance results in greater recharge rates, and greater "mounding" of groundwater heads in the vicinity of the surface water body. Conductance of the soils underlying these swampy areas was specified initially to coincide with a 5 foot thickness of 1 ft/day, fine-grained soils. During calibration, conductance was varied until a reasonable seepage rate and match of groundwater levels was achieved, as described in Section 4.3. An analysis of the final calibrated model's sensitivity to this parameter was also conducted as described in Section 4.4.

### 4.1.4 Regional Groundwater Inflow

One final feature incorporated into this model was the simulation of regional groundwater flowing upward and entering the fractured rock aquifer (layer 3) from below. As described in Section 2.3.2, water level data from cluster wells installed in the vicinity of the coal storage pile exhibit upward gradients, indicative of the island's location in a regional discharge zone. This data suggests that groundwater from deeper, regional flow systems is entering the shallow groundwater system being modeled.

The simulation of deep groundwater flow entering the shallow system was difficult since: (1) the MODULAR model does not allow for a flux to be specified as a boundary condition across the bottom of a layer (layer 3); and (2) reproduction of upward vertical gradients observed near the coal pile was not possible using only a 3-layer model of the shallow groundwater system.

To evaluate how best to represent this upward flux, a small 4-layer test case was modeled and is described in Section 5.1. Options evaluated for simulating this phenomenon included sloping model layers, varying vertical hydraulic conductivities and boundary conditions, addition of a fourth constant head layer beneath layer 3, and addition of recharge directly to layer 3 via a series of injection wells.

Based on this evaluation, the upward flux was modeled using a series of "injection wells" in layer 3. Water was added to layer 3 by placing an injection well in each active model grid node (no water was introduced into non-active nodes, constant head nodes, or along the upland area west of Basin No. 3) which introduced water at a rate of 1.3 inches/year across the modeled area. This flux was selected based on the analysis presented in Section 3.1 and represents upward fluxes which might be expected with $K_v:K_h$ ratios of 1:10 for the alluvium and 1:100 for the bedrock.

No detailed sensitivity analyses on this quantity of upward groundwater flow were performed. Impacts of this parameter on model results are discussed in Section 4.2, Assumptions and Limitations, and Section 4.5, Sensitivity Analyses below.

## 4.2 Assumptions and Limitations

The need to make simplifying assumptions regarding the characteristics of an aquifer system is inherent in any groundwater modeling effort. Although such assumptions allow one to model complex systems, they also tend to limit the accuracy of model results. Knowledge of how the assumptions may impact model results is crucial in proper interpretation of model results.

Assumptions made in this modeling effort include: (1) precipitation infiltration is a primary source of water to the system at a rate of approximately 8 inches/year; (2) the upward flux of groundwater due to regional influences is approximately 1.3 inches/year, based on $K_v$:$K_h$ ratios of 1:10 - 1:100; (3) rock at depths greater that 30 feet is impermeable compared to the more fractured, overlying bedrock; and (4) mean conditions at the site are represented by the model.

### 4.2.1 Rainfall and Surface Water Infiltration

A primary assumption of this modeling effort is the significance of rainfall infiltration to recharge of this aquifer system. Rainfall infiltration clearly provides a source of recharge to this aquifer system. However, site-specific infiltration rates have not been defined on the island. This modeling effort assumes a recharge rate due to infiltrating rainfall of 8 inches/year. At this rate, rainfall recharge is the primary source of water to the aquifer system.

However, if significant upward gradients and quantities of flow exist from rock at depth (that is, if deeper rock is not impervious as described below and if deep regional groundwater fluxes are significantly greater than the assumed 1.3 inches/year), recharge rates due to rainfall may be correspondingly less. This is significant since much of the contaminant source on the island is due to rainfall infiltration through either the coal storage pile or retired basins. As stated before, field measurement of recharge rates would be necessary to more accurately delineate the relative contribution between these two potential recharge sources.

### 4.2.2 Vertical Conductivity and Regional Groundwater Flow

Regional upward fluxes are assumed to be 1.3 inches per year, based on the analysis of vertical fluxes provided in Section 3.4. However, the critical variable in determining vertical fluxes, vertical hydraulic conductivity ($K_v$), has not been defined on the Brunner Island site. If $K_v:K_h$ ratios are significantly different from the 1:10 for the alluvium and 1:100 for the bedrock assumed in this analysis and used in this model, corresponding vertical fluxes may be significantly different as well.

The most significant impact occurs if $K_v$ is much greater than the 1:10 and 1:100 ratios assumed. In this case, regional groundwater flow entering this system from below may be significantly greater. Such flow may be up to 12 inches per year if all layers were $K_v:K_h$ of 1:10. In this instance, aquifer transmissivities set forth in this model would be significantly under-predicted, as would be quantities of water moving through the aquifer. Accurately estimating aquifer fluxes is important in design of drains used in remedial measures.

The model's sensitivity to $K_v$ values and corresponding vertical fluxes is described in more detail in the sensitivity analyses presented in Section 4.5.

### 4.2.3 Bedrock Characteristics

The assumption that rock at depths greater than 30 feet below top-of-rock is impervious also impacts groundwater fluxes and flow patterns. This assumption is supported from analysis of central island aquifer test data which, on average, show an order-of-magnitude decrease in bedrock hydraulic conductivity at depths greater than 30 feet below top of rock (Section 2.3.3, Table 2).

Based on the observed order-of-magnitude decline in hydraulic conductivity with depth, this effort assumes that: (1) other than the 1.3 inches/year flux described above, no significant inflows to or outflows from the upper fractured rock aquifer (layer 3) occur due to the deeper (>30 feet) rock; and (2) no significant horizontal flow occurs in the deeper rock. However, it should be noted that this deeper rock is not completely impervious. Although data generrally show this decline in hydraulic conductivity, some fractured rock zones tested at depths greater than 30 feet show hydraulic conductivities of up to 5 ft/day. The existence of deeper flow zones, and upward or downward gradients into those zones, can significantly influence groundwater flow patterns on the island in a manner not simulated by this modeling effort.

### 4.2.4 Mean Conditions

This modeling effort also simulates mean, steady-state conditions with respect to groundwater flow on the island. In other words, rates of water entering and leaving the aquifer and the overall head distribution are assumed to be a constant, average value. In reality, groundwater flow is a transient phenomena, controlled by changing recharge rates and surface water levels. Recharge changes both seasonally and in response to individual storm events. Surface water levels in surrounding rivers and streams change similarly, while operating levels of plant treatment basins vary with changing plant operations.

However, the assumption of steady-state flow is valid for this modeling effort, since changes in water levels across the site (of 0-3 feet) in response to such transient events are small relative to the overall gradient (of approximately 20 feet) and thickness (of 50+ feet) of the aquifer. Water levels simulated in this modeling effort are calibrated to observed water level data in February 1989, which approximate mean conditions on the island. This steady-state approach, of matching water levels and flow rates to average conditions, is particularly valid for estimating long term average rates of groundwater flow and discharge to the river.

## 4.3 Model Calibration

Model calibration involves changing model parameters until a satisfactory match of observed groundwater levels and fluxes is achieved. Primary model parameters typically varied during calibration include the magnitude and spatial distribution of hydraulic conductivity of each layer, the applied recharge rate due to rainfall, and the elevation of constant head boundaries. Secondary model parameters which may also be "tuned" during calibration include $K_v:K_h$ ratios and conductance, or seepage rates from surface water bodies.

The objective of this calibration was to match observed water levels in monitoring wells to within ±1.5 feet, while keeping predicted groundwater fluxes and model parameters within acceptable or expected ranges. Water levels calibrated to were those observed in a February 1989 sampling event, shown in Figure 9. These data were selected since it contained the most extensive set of water level recorded on the island, and since it generally matched average water levels observed at the site from 1986-89. Appendix 2 provides a comparison of the February 1989 versus average 1986-1989 water level data.

Calibration began by assigning each layer a constant hydraulic conductivity as described in Section 4.1 and applying a constant 8 inches of recharge across the site. Calibration proceeded by incorporating site-specific hydraulic conductivity data, to reproduce varying patterns of hydraulic conductivity measured in the field across the site for each layer. Where specific data were not available for a particular layer, either the average aquifer hydraulic conductivity was used, or expected aquifer hydraulic conductivity was applied, based on conditions in that area. For example, although hydraulic conductivity of ash was only measured at a few locations in Basin No. 4, similar representative hydraulic conductivities were also assigned to ash-containing areas in layers 1 and 2 of retired Basins No. 1, 2, and 3.

Changes made to model inputs to achieve a reasonable match of water levels included varying hydraulic conductivity values, recharge rates, and boundary conditions as described below. A summary table showing initial and final values of model parameters varied during calibration is provided in Table 7.

### 4.3.1 Hydraulic Conductivity

The following changes to initial hydraulic conductivity values were specified to calibrate this model:

- Hydraulic conductivity values across the entire model grid were increased 0.25 to 4 times median hydraulic conductivity values measured in the field and reported above in Section 2.3.3 and 4.1. The increase in hydraulic conductivity values during model calibration is not unexpected, since single well aquifer tests from which this data are drawn generally under-predict hydraulic conductivity and are estimated to be order-of-magnitude results [Baker 1985]. Although ultimate hydraulic conductivity values appeared higher than "average" values for the central island area, they fall well within the ranges of hydraulic conductivities observed in the vicinity of the coal pile. Figures 16A, 16B, and 16C show final hydraulic conductivity values for layers 1, 2, and 3 as compared to data measured in the field at well points.

- A hydraulic conductivity value of 2.0 ft/day was applied to ash in retired Basins No. 1, 2, and 3 and active Basin No. 4 in layers 1 and 2. This value compares to hydraulic conductivity values of 1.0 ft/day reported for ash in Basin No.4. A hydraulic conductivity value of 0.5 ft/day was applied to layer 1 and 2 dikes surrounding Basin No. 3, to simulate lower conductivities of these dikes. Although no comparable field data exist in this area, this value was selected in order reproduce the flatter water table surface occurring in Basin No. 3 due to the apparent "bathtub" effect of the dikes surrounding this basin. Use of this lower hydraulic conductivity value for Basin No. 3 dikes also allows water levels on the upgradient side of the coal pile to decline rapidly, as described in Section 2.3.2. Such lower hydraulic conductivity was not applied to dikes surrounding Basins 1, 2, or 4, since observed water levels do not suggest such a radical change in water levels (and correspondingly low hydraulic conductivities) around the perimeter of these basins.

- Hydraulic conductivity for the remainder of layer 1 was assigned to be 6 ft/day and 10 ft/day in the vicinity of the coal pile. Although this figure is greater than the slug and recovery test data of 2 ft/day reported as "average" for the central island area, layer 1 hydraulic conductivity in CL-7, 8, and 9 around the coal pile range from 1.6 to 9.5 ft/day.

- Layer 2 hydraulic conductivity in the vicinity of the coal pile and along the river was assigned as 12 ft/day, while the remainder of layer 2 was assigned a value of either 8 or 10 ft/day. As with layer 1, although these values are greater than the slug and recovery test data of 3 ft/day reported as "average" for the central island area, layer 2 hydraulic conductivity in CL-3, 8, and 10 around the coal pile range from 3.0 to 11.0 ft/day. Additionally, these values are slightly higher than layer 1 or 3 hydraulic conductivities, keeping with the simulation of a higher-permeability zone occurring in the coarse alluvial material above bedrock.

- Layer 3 hydraulic conductivity was specified to be 4 ft/day. As with layers 1 and 2, this value is higher than the average rock hydraulic conductivity of 2 ft/day for the central island area, but compares favorably to hydraulic conductivity values measured in the cluster wells surrounding the coal pile, which ranged from 0.1 to 11.0 ft/day, based on pressure, slug, and pump/recovery test data. Rock hydraulic conductivity was increased to 6 to 8 ft/day beneath the coal pile and along the Susquehanna River, to better calibrate to water levels in these areas. Rock hydraulic conductivity was decreased to 0.1 ft/day in the upland area to the west of Basin 3. This value corresponds well to values of 0.2 ft/day measured in MW-19, and was necessary to recreate the steep water table gradients which exist in this area. This low hydraulic conductivity also prevents the simulated heads in this upland area from over-predicting observed water levels in the Basin No 3. area.

### 4.3.2 Recharge Rates and Boundary Conditions

The following changes to initial recharge rates and boundary conditions were specified to calibrate this model:

- Precipitation rates described in Section 2.4.1 were decreased slightly from 8.0 to 7.5 inches/year across most of the modeled area. Furthermore, a reduced recharge rate of 4 inches per year was applied to the area in the immediate vicinity of the plant, to simulate reduced infiltration rates due to impermeable pavement and buildings in this area (Figure 17). Additionally, in the upland area to the west of Basin No. 3, precipitation rates were further reduced to correspond to lower infiltration expected due to the steeper slope and low bedrock hydraulic conductivity.

- Some changes to the elevations of constant head boundaries were made during calibration. Elevation of the discharge from the former red pond area to the wetlands mitigation area was reported to be 275 ft MSL. However, constant heads in this area were increased to 276 ft MSL to produce accurate match of water levels.

- Seepage rates from Basin No. 4 and resulting heads in the aquifer due to this source were varied by altering the conductance (KA/b) of the bottom of the basin. Final conductance selected corresponds to a vertical hydraulic conductivity of 20 ft/day and thickness of 5 feet for the basin bottom. This represents approximately an order-of-magnitude increase in conductance over that originally specified.

- Seepage rates from the swamp northwest of the coal pile and the ponded area of coal pile runoff and resulting heads in the aquifer due to these sources were modeled similar to Basin No. 4, by varying conductance of the swamp sediments. Final conductance selected corresponds to a vertical hydraulic conductivity of 0.01 feet/day and thickness of 5 feet for the sediments beneath the swamp and in the coal pile runoff collection area. This represents an order-of-magnitude decrease in conductance over that originally specified.

- The characteristics of the general head boundary along the southern grid boundary in Basin No. 3 were varied to achieve a reasonable match of water levels in the Basin No. 3 area and seepage rates to Black Gut Creek. Final general head parameters included simulation of a constant head discharge zone for all three layers (Black Gut Creek) located 1400 feet from the model boundary, with an aquifer hydraulic conductivity of 6 ft/day between the grid boundary and Black Gut Creek.

In some cases, changes to model parameters to achieve a better fit in one portion of the site may adversely affect water level matches in another portion of the site. In these instances, changes which improved the match of water levels in the immediate area of the coal pile were favored, since flow in the coal pile area is of primary importance in this thesis.

## 4.4 Results

Figures 18A, 18B, and 18C provide a comparison of water levels across the site predicted from model results for each layer compared to February 1989 data. Table 8 provides these same comparisons in tabular form. Overall, a reasonable match of water levels was attained, with predicted water levels within 1.5 feet of observed water levels in 24 out of 30 observation points.

Patterns and directions of groundwater flow simulated by this modeling effort correlate well to those determined by review of water level data or previous modeling studies. Groundwater beneath the coal pile flows in an easterly and northeasterly direction, driven by higher heads in the central portion of the island and Basin No. 3 toward lower head areas to the north along the diversion channel and east along the river.

### 4.4.1 Calibration Problem Areas

One primary location where water levels were not able to be matched to within 1.5 feet included the areas near CL-7 and CL-9. As discussed in Section 2.3.2 and shown in Figure 9, the water table gradients observed at the site are low in areas underlying Basin No. 3 and the coal pile. These gradients were not completely reproduced. This would have required the addition of unrealistically high aquifer conductivities beneath the coal pile and Basin No. 3 and unrealistically low conductivities in the area between the two.

The modeled system is actually a composite or average of these observations. The modeled water table slightly over-predicts heads in layer 1 near CL-7a, and slightly under-predicts water levels in layer 3 near CL-9b and CL-9c. However, predicted water levels in layers 2 and 3 at CL-7b and in layers 1 and 2 at CL-9a matched observed values to within 1.5 feet, as desired.

One possible explanation for the different accuracy of calibration between layers at these two locations might relate to the vertical hydraulic connection between the alluvial (layers 1 and 2) and bedrock (layer 3) aquifers across the coal pile. As described in Section 4.1, this simulation assumes a constant vertical hydraulic conductivity across the entire model grid. Greater interconnection between the alluvial and bedrock aquifers (higher layer 2/3 $K_v$) in the central coal pile area could result in lower heads in the upgradient alluvium near CL-7a and correspondingly higher heads in the downgradient bedrock near CL-9b and CL-9c.

Another minor "problem area" for calibration occurred in the highland area west of Basin No. 3 near MW-19. Water levels were under-predicted slightly in layer 3 in the highland area near MW-19, due to the abrupt rise in groundwater levels there.

A final "problem area" for calibration included that area between Basin No. 4 and the cooling water discharge channel near CL-4 and MW-8. Heads were under-predicted in layer 1 near CL-4, while being over-predicted in layer 3 at nearby well MW-8. Water levels in CL-4, located within the basin, and Basin No. 4 suggest a strong hydraulic communication between the basin water and that observed in CL-4. Similarly, water levels in MW-8, located outside of the basin dikes, are significantly lower and more closely match water levels in the adjacent cooling water discharge channel.

It therefore appears that not simulating lower-conductivity basin dikes in this area (which was not possible due to the coarse model grid and proximity of monitoring points to one another) results in this "averaging" and over-prediction of water levels just outside the basin dikes (MW-8) while under-predicting water levels just inside the dikes (CL-4). The fact that water levels were under-predicted in layer 1 (CL-4) and over-predicted in layer 3 (MW-8) also suggests that the vertical hydraulic conductivity in this particular area of the site may be lower than the 1:100 value assigned for the layer 3 bedrock in this area. However, further refinement in calibration in this area was not possible or deemed necessary since: (1) successful calibration was achieved in this vicinity in CL-2 in both layers 2 and 3; (2) the coarse grid in this area precluded further refinement of $K_v$, $K_h$, seepage areas from the basin, or the location of the constant head boundary simulating the cooling water discharge channel; (3) calibration in this area would not impact the prime area of concern, the coal pile.

### 4.4.2 Vertical Gradients

Over most of the site, the model predicts that groundwater tends to move downward from the upper alluvial aquifer into bedrock, driven by head differentials of 0.1 to 0.5 feet due to precipitation recharge to layer 1. In the swamp and area of ponded coal pile runoff northwest of the coal pile, heads in layer 1 are up to 1.5 feet greater than corresponding layer 3 heads, due to the additional seepage/recharge in these areas. Beneath Basin No. 4, layer 1 heads rise to up to 8 feet higher than corresponding layer 3 heads due to the overwhelming influence of seepage from Basin No. 4. This downward gradient near Basin No. 4 is confirmed by water level data from well CL-2. However, except for the coal pile area, the accuracy of such predictions is almost impossible to gauge across the rest of the site, due to the lack of alluvial/bedrock head data.

Near the coal pile, however, predicted vertical patterns of groundwater flow do not completely mirror that observed based on water level data. Across most of the coal pile area, observed water level data in layer 3 range from 0.2 to 1.0 feet greater than those observed in layers 1 or 2, suggesting upward vertical flow. However, upward gradients are predicted to occur in only a narrow area between Basin No. 3 and the coal pile near CL-7 and CL-8. This occurs due to (1) the rapid decline in layer 1 heads caused by the low-conductivity Basin No. 3 dikes in layers 1 and 2, and (2) regional groundwater underflow recharging to layer 3, simulated via injection wells in layer 3. Simulated layer 3 heads in this area are up to 1 foot greater than layer 1 heads.

Observed upward gradients are not reproduced by the model across most of rest of the coal pile area. Although upward regional flow <u>into</u> layer 3 is simulated via injection wells as described in Section 4.1.4, this upward flow pattern is not reproduced by the model to continue into layers 1 and 2 for two reasons. First, the influence of surface recharge due to precipitation infiltration (7.5 inches/year) overwhelms the simulated upward regional flux (1.3 inches/year). Secondly, downgradient boundary conditions allow only 2 feet of saturated thickness in the alluvial aquifer (layer 2). Thus, most simulated surface recharge is forced downward into the lower bedrock layer for eventual discharge from layer 3 into the River. Modeling the site with layers 2 and 3 subdivided into numerous thinner layers may help overcome these difficulties.

Observed water level data suggest regional upward flow from the bedrock. Conversely, precipitation recharge flows vertically downward into the upper saturated zone. These opposing gradients most likely equilibrate near the bedrock interface, resulting in primarily horizontal flow to the river along this interface.

### 4.4.3 Simulated Layer Transmissivities

The different modeled aquifer layers carry different percentages of flow in different areas of the site. Table 9 provides a summary of the transmissivities of different model layers in various areas. In the upland area west of Basin No. 3, the water table and all groundwater flow occurs within layer 3, the upper fractured bedrock aquifer, although transmissivity of this layer is low due to the rock's low hydraulic conductivity. In the Basin No. 3 and coal pile area, the water table occurs within layer 1, the upper alluvial aquifer. More than 3/4 of the flow beneath Basin No. 3 occurs in the fractured bedrock aquifer (layer 3), due to the higher bedrock conductivity and thickness and relatively low conductivity ash and basin dikes. Conversely, in the coal pile area, most of the flow occurs in the upper two alluvial aquifer layers, due to the high conductivities of these layers. Along the river and diversion channel, the water table generally occurs within 2 feet of the top-of-rock (top of layer 3). Thus, prior to discharge to surface waters, all flow in this area occurs in the upper rock aquifer (layer 3) and a small portion of the coarse alluvial aquifer (layer 2).

### 4.4.4 Water Budgets

Major sources and sinks of water in this model simulation are shown on Table 10. Overall, approximately 291,000 gpd of water passes through this modeled portion of the Brunner Island aquifer system. The main source of water to the aquifer is precipitation recharge (53%), with lesser amounts supplied by Basin No. 4 seepage (29%) and regional groundwater inflow (9%). Minor amounts of water are also supplied by the upland fractured rock aquifer west of Basin No. 3 (4%), by seepage from the area of ponded coal pile runoff (3%), and by seepage from the swamp northwest of the coal pile (2%). Collectively, over 80% of the water from the site discharges to the diversion channel, river, and cooling water discharge channel. Lesser amounts discharge to the wetlands area northwest of Basin No. 3 (13%), and the general head boundary simulating the Black Gut Creek drainage area south of Basin No. 3 (5%).

Since groundwater flow in the coal pile area is of primary interest in this thesis, a water budget of the coal pile was developed and is provided in Figure 19. Approximately 12,000 gpd of precipitation recharge infiltrates over the 22-acre coal pile (based on 7.5 inches/year). An additional 7300 gpd enters the aquifer from seepage from the ponded area of coal pile runoff. Finally, an additional 2100 gpd of regional groundwater flow discharges to the shallower local groundwater system. Thus, based on the previous modeling analysis a total of approximately 22,000 gpd of flow enters the shallow aquifer system beneath the coal pile.

Groundwater flow in the aquifer entering and leaving the coal pile was estimated using Darcy's Law (Q=KiA). This analysis indicates approximately 13,000 gpd of groundwater flow enters the aquifer beneath the coal pile from the upgradient side, and between 25,000 - 33,000 gpd of groundwater exits downgradient of the coal pile. This range is provided based on the variable width of the aquifer downgradient of the coal pile which could be considered as handling discharge from the pile. Assuming an average aquifer discharge value of 29,000 gpd, approximately 16,000 gpd then enters the aquifer across the coal pile area. This compares reasonably with the modeled prediction of 21,700 gpd entering the aquifer over the coal pile area above.

Given these analyses, approximately 50 - 65% of the groundwater flow leaving the downgradient side of the coal pile area originates as precipitation/infiltration from the coal pile.

## 4.5 Sensitivity Analyses

The results of this modeling effort are most sensitive to a few key model input parameters. These parameters include precipitation recharge, aquifer hydraulic conductivity, aquifer vertical hydraulic conductivity, and riverbed conductance. Implications of varying these parameters from those values selected in the calibrated model are described below.

### 4.5.1 Precipitation Recharge and Transmissivity

As described in Section 4.2.1, rainfall recharge is the primary source of water to the aquifer system modeled in this thesis. Thus, the assumption of recharge due to infiltrating rainfall of 7.5 inches/year largely defines the magnitude of the water budget for the model. Aquifer transmissivity (hydraulic conductivity times thickness) has been adjusted to calibrate the model, given this recharge rate. Thus, if recharge rates have been over-estimated in this effort, resulting aquifer transmissivities have likewise been over-predicted, in order to handle the larger volumes of water passing through the system. Conversely, if recharge rates have been under-estimated, transmissivities would likewise be lower than actual.

Like recharge values, selection of high or low transmissivities for the aquifer results in definition of correspondingly high or low recharge rates, in order to match water levels.

Estimates of precipitation recharge and transmissivity used for initial model inputs were obtained based on separate literature and field studies, respectively. Since model calibration was achieved without significant (order-of-magnitude) changes to either of these parameters, it can be safely assumed that the model water budgets presented in Section 4.4.4 are accurate to within an order of magnitude, at the minimum. The overall water budget for the model may even be accurate to within a factor of two or three, given the relatively small range of realistic precipitation recharge values, and the largely homogenous hydraulic conductivity field data collected on the island.

The relationship between precipitation recharge rates and transmissivity is significant since much of the contaminant source on the island is due to rainfall infiltration through either the coal storage pile or retired basins. If, due to errors in estimating transmissivities or rainfall infiltration, precipitation recharge is overestimated by a factor of two, contaminant mass loading rates to the river would likewise be over-predicted by a factor of two. The converse is also true. As stated before, field measurement of recharge rates would be necessary to more accurately delineate such source terms.

### 4.5.2 Vertical Hydraulic Conductivity

The $K_v:K_h$ ratios used in this modeling effort correspond to values of 1:10 for the alluvium and 1:100 for the bedrock, based on the analysis provided in Section 3.1. However, vertical hydraulic conductivity has not been defined on the Brunner Island site. If vertical hydraulic conductivity is significantly different than the 1:10 and 1:100 ratios assumed, corresponding changes in groundwater flow patterns, horizontal hydraulic conductivities, vertical fluxes, estimated regional groundwater flow, and precipitation recharge rates might also be expected.

Lowering vertical hydraulic conductivity values provides greater vertical resistance to flow, thereby changing groundwater flow patterns by increasing horizontal flow components. To maintain model calibration, increasing transmissivity (horizontal hydraulic conductivity) values may therefore be necessary. However, given the relatively flat (thin yet areally extensive) nature of the aquifer system modeled, changes in vertical hydraulic conductivity did not significantly alter overall groundwater flow patterns on the island.

Vertical hydraulic conductivity values selected also largely determine vertical groundwater fluxes. As described in Section 3.1, regional groundwater flow enters the aquifer system in the vicinity of the coal pile from below at a rate estimated at 1.3 inches/year, based on the assumed $K_v:K_h$ ratios. However, this regional flux may be significantly greater...up to 12 inches per year if all layers were $K_v:K_h$ of 1:10. In such an instance, aquifer transmissivities set forth in this model would be significantly under-predicted, as would overall quantities of water moving through the aquifer. To maintain model calibration, estimates of precipitation recharge might also have to be revised downward.

Finally, since changing vertical hydraulic conductivity values may result in differing amounts of water moving through the aquifer system, anything impacted by water flow through the system would likewise be affected. As described above, predicted contaminant mass loading rates to the river would change according to changing model water budgets. Additionally, accurately estimating aquifer fluxes is important in design of drains and slurry walls used in remedial measures in the vicinity of the coal pile.

### 4.5.3 Surface Water Seepage

Two areas, a ponded area of coal pile runoff, and the swampy area northwest of the coal pile, were modeled as surface water seepage areas to the groundwater system using a river package option in layer 1 of the model. The MODULAR model's river package uses a conductance parameter to specify seepage rates from such surface water sources [Konikow, 1978]. As shown on Figure 20, conductance from a surface water body increases with increasing vertical hydraulic conductivity, increasing surface area, and decreasing thickness of the "riverbed", or soils underlying the surface water body. Higher conductance results in greater recharge rates, and greater "mounding" of groundwater heads in the northwest portion of the coal pile area near these surface water bodies.

Conductance of the soils underlying these swampy areas was specified initially to coincide with a 5 foot thickness of 1 ft/day, fine-grained soils. During calibration, riverbed conductance was decreased in order to match groundwater levels (by decreasing seepage rates) to a value which coincided with a 5 foot thickness of 0.1 ft/day soils.

An analysis of the final calibrated model's sensitivity to this parameter was also conducted by varying the conductance of these "riverbeds". Figure 20 shows a plot of seepage rates from both of these areas vs. conductance of the underlying soils. Note that doubling or halving conductance results in a corresponding change in seepage rates. In design of remedial measures these seepage rates are significant, since most of the seepage from within the ponded runoff area is ultimately collected by the drainage system.

## 5.0 3-Dimensional Test Case Model Analysis

### 5.1 Test Case Overview

To determine how best to represent observed upward gradients from and within the bedrock aquifer to the overlying alluvium, a small test case modeling effort was conducted. Specific objectives of this test case modeling effort were to evaluate how vertical and horizontal head distributions across a modeled area would be affected by: (1) tilting of aquifer layers to approximate water table slope; (2) varying the $K_v$:$K_h$ ratio; (3) varying boundary head values, usually with deeper aquifer layers fixed to higher heads at boundaries; (4) varying the number of model layers; (5) adding a constant head "boundary" layer to the bottom of the grid; or (6) any combination of (1) through (5). These various model configurations and boundary conditions were evaluated to determine the most efficient and applicable methods for reproducing the vertical upward gradients observed in the vicinity of the coal storage pile (and corresponding quantities of upward groundwater flow). These test case analyses are very simplified, and their results may not be directly applicable to the 3-D modeling effort described in Section 4. However, they are described here for completeness.

## 5.2 Model Description

The test case established consisted of a 4-layer, 5 x 10 element grid with constant spacing. Element dimensions were defined to be 400 feet on each side, to approximate groundwater flow distances of approximately 4000 feet across the island. The section was generically established to simulate the central portion of the island from the upland area west of Basin No. 3, through Basin No. 3 and the coal pile to the River. Layer thicknesses and hydraulic conductivities were defined to generally coincide with observed field conditions at Brunner Island and parameter estimates used in the full-scale modeling effort described in Section 4.0. Figure 21 provides a conceptual diagram of the test case model. Layer 1 represents the alluvial aquifer (modeled as layers 1 and 2 in the full-scale model), layers 2 and 3 represent the upper 30 feet of fractured bedrock (modeled as layer 3 in the full-scale model), and layer 4 simulates a lower conductivity deeper bedrock system (an addition from the full-scale model). Rainfall recharge was applied at a uniform rate of 8 inches/year to layer 1 of the model.

## 5.3 Results

The goal of the initial runs (Test Cases No. 1 and 2) was to evaluate whether sloping model layers would significantly change vertical gradients observed between layers. Early runs conducted on the full-scale model of the site showed downward gradients. These downward gradients existed because all flow exiting the downgradient boundary of the model occurred in layer 3, while the primary source of water to the model entered upper layers 1 and 2 via recharge. Thus, water was routed vertically downward from layers 1 and 2 to layer 3 in the model, contrary to field data in the vicinity of the coal pile. A hypothesis to be tested was whether tilting model layers so that all three layers were saturated on the downgradient boundary would reduce (or possibly even reverse) the downward gradients predicted in previous simulations.

Figure 21A provides a comparison of heads observed in layers 1 and 4 along the 4000 ft groundwater flow path for a horizontally-layered system (Test Case No. 1) and a sloped-layer system (Test Case No.2), respectively. The model layers in Test Case No. 2 were sloped to approximate the water table slope. In both cases, layer 1 heads are higher than layer 4 heads, since recharge to layer 1 and discharge from lower layers dominated the flow field. As shown on Figure 22A, the differences in heads for the horizontal system is barely discernable. In Test Case No. 2, the disparity in heads worsens (greater downward gradients) due to the way layers were tilted which resulted in effectively "thinning" the thickness of higher-conductivity layer 1. Thus, with no other changes to the model grid, simply sloping layers does not reduce downward gradients.

Test Case No. 3 consisted of assigning higher constant head values to lower layers along boundaries and lowering $K_v:K_h$ ratios (VCONT) between layers, in an attempt to reproduce upward gradients. Higher constant head values were specified in lower layers at model boundaries to represent the upward gradients known or suspected to occur along these boundaries. Lower $K_v:K_h$ ratios (compared to the 1:10 or 1:100 used in the full-scale model) were then specified in an attempt to more effectively isolate heads in different layers from each other and maintain the upward head disparity specified at boundary nodes across the center of the model grid.

Maintaining upward gradients across the modeled area in this manner proved difficult, if not impossible. When recharge was applied to layer 1, $K_v:K_h$ ratios as low as 1:100,000 in the bedrock were required to effectively isolate layer 4 from the influx of water entering the model through layer 1. Additionally, constant head values in layer 4 along boundaries had to be defined at least 5 feet higher than constant head values in layer 1 to maintain an upward gradient in the center of the model grid away from boundary condition effects. Both of these conditions were deemed "too extreme" and not suitable for use in representing the groundwater system at Brunner Island, and therefore results of this test case are not shown here.

These same simulations were then performed as Test Case No 4 without recharge to more easily decipher why upward gradients could not be readily simulated across the model grid in this fashion. When no recharge was applied to layer 1, slight upward gradients could be maintained across the model grid with $K_v:K_h$ of approximately 1:1000 for the bedrock. However, these upward gradients were not constant and strongly influenced by boundary conditions, with head differences of 5 feet at boundaries and only a few tenths of a foot in the interior of the model grid (Figure 22B). Higher heads could not be maintained in layer 4 since water in this low conductivity layer routed itself to shallower higher-conductivity layers, resulting in a faster decline in layer 4 heads. Layer 4 heads recovered near the downgradient boundary due to constant heads specified there.

The final test case scenario investigated to simulate upward gradients, Test Case No 5, consisted of specifying a constant head boundary condition across the entire bottom of the model grid. This was accomplished by defining all nodes in layer 4 to be constant heads, with layer 4 constant head values arbitrarily selected to be approximately three feet greater than heads in layer 1. Recharge was again applied at a rate of 8 inches per year, and $K_v:K_h$ was specified at 1:100 for all layers.

This approach produced perhaps the most realistic simulation of vertical flow on Brunner Island, although the means used to achieve it were somewhat arbitrary. As shown in Figure 22B, except for areas near fixed boundary conditions, heads in layers 1 and 4 generally exceeded those in layers 2 and 3. Thus, downward flow occurred from layer 1 to layers 2 and/or 3, due to precipitation recharge to layer 1. Upward flow occurred from layer 4 to layers 3 and/or 2, due to the constant head nodes in layer 4 which simulated regional gradients.

Although this approach produced somewhat realistic head distributions, it was not deemed acceptable for use in the large-scale model analysis for a number of reasons. First and foremost, the approach was somewhat arbitrary, since the upward vertical gradients were produced by arbitrarily selecting constant head values in layer 4 to be 3-5 feet greater than those observed in layer 1 (although in the field head differences were observed to be less than 1.5 feet).

Second, the combination of shallow downward and deeper upward gradients do not truly match field data which reveal only upward vertical gradients near the coal pile. In effect, model parameters including layer 4 heads and $K_v:K_h$ ratios were arbitrarily selected to result in the desired quantity of underflow from layer 4 upward into the overlying aquifer layers.

Based on these test case runs, none of the approaches investigated were deemed suitable for application to reproduce upward flow components on the full-scale model. Instead, quantities of upward groundwater flow were calculated analytically, based on the observed upward gradients over a range of $K_v:K_h$ values (Section 3.1). A flow quantity corresponding to $K_v:K_h$ of 1:10 for the alluvium and 1:100 for the bedrock was selected as an average value for use in the modeling analysis. This quantity of groundwater flow was the introduced to layer 3 of the model using the modular WELL option, to simulate the upward flow components in to the system due to regional gradients.

## 6.0 Cross-Sectional Flow And Transport Model Analysis

The initial stages of this modeling investigation at the Brunner Island SES included two-dimensional flow modeling in a cross-sectional perspective using EPRI's FASTCHEM Package. This flow modeling was performed as a precursor to support contaminant transport modeling to be conducted using FASTCHEM. The original objectives of this effort were to: (1) calibrate a contaminant transport model to the site to simulate and quantify contaminant sources, groundwater quality impacts, and loading rates to the aquifer and river; and (2) use this calibrated model to simulate the effectiveness (in terms of reductions in loading rates or aquifer concentrations) of potential remedial measures at the coal pile. However, assumptions inherent within the design of the FASTCHEM Package, as well as difficulties encountered during its application to this site significantly restricted the usefulness of the results of this effort relative to meeting the objectives described above. This section provides a brief description of the modeling performed, results, and limitations of this effort.

### 6.1 Model Description

The model used in this cross-sectional modeling analysis was EPRI's FASTCHEM Package. The FASTCHEM Package is a finiteelement groundwater flow, geochemistry, and contaminant transport code with the following major modular components:

- EFLOW - flow code which predicts aquifer heads in 2-D, cross-sectional perspective;
- ETUBE - code which traces groundwater streamtubes based on the head distribution predicted by EFLOW;
- ECHEM - geochemistry code (optional);
- EICM - coupled transport/geochemistry code which predicts contaminant concentrations within ETUBE's streamtubes.

Additional information on these codes is provided in the FASTCHEM Package manuals [EPRI, 1988]. The work described here represents results of EFLOW and ETUBE simulations of the Brunner Island coal pile vicinity.

Two-dimensional flow modeling in cross-sectional perspective was performed along a path line roughly parallel to groundwater flow through the coal pile, between the two cross sections identified on Figure 4. The model extended from the wetlands area near the former red pond through Basin No. 3 and the coal pile to the Susquehanna River. Figure 23 provides a conceptual diagram of this cross sectional model, showing aquifer parameters specified. Note that distances are specified in metric units, with the ground surface of approximately 282 ft. MSL equivalent to +30 M depth on

Figure 23. Constant head values equivalent to 272 ft and 255 ft MSL were specified along the left and right model boundaries to represent the wetlands area and Susquehanna River, respectively. Recharge was applied to the upper surface of the model grid at a rate of eight inches per year. Modeling was performed to represent steady-state head distributions in the aquifer.

To calibrate the model to heads observed in monitoring wells along this cross section, hydraulic conductivity values of the aquifer were varied to represent the nonhomogeneous aquifer system. Final hydraulic conductivity values selected for this effort include values of 3 - 17.5 ft/day for the alluvial material, 0.5 - 1.0 ft/day for the bedrock, 0.5 ft/day for ash within retired Basin No. 3 and 0.01 ft/day for Basin No. 3 dikes, as shown on Figure 23. The $K_v$:$K_h$ ratio was fixed at 1:1. Recharge over Basin No. 3 was increased from the background value of 8 in/yr to 12 in/yr to reproduce the water table mounding which occurred in that area. Model input parameters for this effort differ from those used in the detailed 3-D modeling analysis described in Section 4.0 since (1) this cross-sectional modeling was performed prior to that analysis and (2) this effort resulted only in an "approximate" calibration.

## 6.2 Results

Figure 24 provides model results comparing predicted water table elevations (plotted as pressure head P=0) to observed water level data from February 1989. A reasonable match of all observed water levels was obtained with the exception of those areas near Basin No. 3 and CL-9, where heads were under-predicted by the model. Figure 24 also shows a plot of corresponding total head values. Rainfall recharge entering the system results in water table mounding in the center of the island, especially within the confines of the low-conductivity Basin No. 3. dikes. Groundwater flows outward from the center of the island, primarily toward the Susquehanna River with lesser amounts discharging to the wetlands area.

Finally, Figure 25 provides a plot of groundwater pathlines predicted using the ETUBE code with the EFLOW results described above. Four pathlines are shown, with two originating as rainfall recharge in Basin No. 3 (paths No. 1 and 2), and two originating as coal pile seepage bounding the edges of the coal pile (paths No. 3 and 4). Vertical downward flow through the unsaturated zone is predicted, as expected. Largely horizontal groundwater flow then occurs in the saturated zone. All flow originating as coal pile seepage discharges to the river, while flow originating as recharge from Basin No. 3 is split between both the river and wetlands areas. The tortuous path followed by pathline No. 2 reflects an upward flow component for a short distance immediately downgradient of Basin No. 3. This phenomenon, also indicated by the total head plot in Figure 24, is similar to that observed in the 3-D modeling analysis in this area and is caused by the combined effects of recharge to Basin No. 3, the basin's low conductivity dikes, and lower conductivity bedrock/higher conductivity alluvial aquifer downgradient of the basin.

## 6.3 Limitations

Several assumptions and limitations inherent in the previously-described cross-sectional modeling analysis bear mention since they significantly restrict the ability of this model to accurately simulate the aquifer system at Brunner Island. During the course of the flow modeling analysis described above, additional limitations on the yet-to-be-performed contaminant transport modeling were also discovered. Given these restrictions, additional modeling using the FASTCHEM package was deemed to be not applicable or practical for this site, and use of the FASTCHEM Package was discontinued.

### 6.3.1 Vertical Hydraulic Conductivity

The primary limitation in the previously-described cross-sectional flow modeling effort was the restriction of $K_v$:$K_h$ ratio to 1:1. As described previously in this thesis, $K_v$:$K_h$ ratio is a critical parameter governing groundwater flow at this site, with $K_v$:$K_h$ ratios of 1:10 to 1:100 likely. However, efforts to decrease the $K_v$:$K_h$ ratio in the cross-sectional model to anything much below 1:3 were unsuccessful due to convergence problems with the EFLOW code. Restriction of $K_v$:$K_h$ to such a near-isotropic condition results in significant adverse impacts to the simulation, including proportionally too much flow occurring deep within the system, insufficient vertical stratification of the aquifer system, the need for additional recharge, and the added difficulty in reproducing upward vertical heads near the coal pile.

### 6.3.2 Areal Complexity of Site

Another problem with adequately simulating the coal pile area using a cross-sectional flow modeling approach relates to the areal complexity of the Brunner Island aquifer system. Aerial variations in recharge rates due to precipitation or seepage from basins or ponds, in contaminant source areas, and in aquifer parameters makes selection of an ideal cross section (theoretically to be located along a groundwater flow pathline) difficult, if not impossible. Such areal variations influence heads, groundwater flow directions, and contaminant concentrations in such a way which cannot be simulated by a simple cross-sectional simulation. Calibration of such a model to match the 3-D flow model developed in Section 4.0 is not possible.

### 6.3.3 Streamtube Approach

The method in which FASTCHEM handles contaminant transport posed additional limitations on the proposed contaminant transport simulations. As mentioned previously, FASTCHEM performs contaminant transport calculations within streamtubes identified using the ETUBE module. Each streamtube represents an isolated groundwater flow path, with no mixing between streamtubes. Thus, no transverse (vertical or horizontal) dispersion is simulated; only longitudinal dispersion (along the streamtube length) is considered. Recharge, which typically represents a contaminant source boundary, enters the streamtube at the land surface, and is advected, dispersed, and/or adsorbed along the length of the streamtube with no interactions with water or contaminants in adjacent streamtubes. As shown in Figure 25, the result is a "vertically segregated" simulation, with the contaminant plume originating from the coal pile, following a very distinct path, and constricting contaminant flow to an area with a vertical depth of only two meters at the downgradient discharge point along the river. Additionally, since any streamtube originates within only one source are, no mixing of waters from different source areas occurs.

This vertically-discrete approach to contaminant transport does not adequately represent conditions at Brunner Island. Aquifer heterogeneities and local variations in recharge/seepage rates results in significant vertical and horizontal (transverse) dispersion at the site. This is evidenced by significant contaminant concentrations occurring from the water table surface to significant (50 feet +) depths in cluster wells. Additionally, mixing of groundwater, rainfall recharge, and recharge waters from different contaminant sources appears likely on the site due to the proximity of sources and the wide areal occurrence of these sources relative to effective aquifer depths. Finally, even if such "vertically discrete" flow was to occur on the island, collection of chemical analysis data from the monitoring wells near the coal pile with 10-30 foot screened intervals would produce chemical data representative of that 10-30 foot vertically-averaged aquifer section.

### 6.3.4 Summary

In the case of the aquifer system near the Brunner Island coal pile, the cumulative effects of the assumptions and limitations discussed above are so restrictive that application of the FASTCHEM model to this site is not worthwhile. The system simulated does not represent field conditions, making calibration of such a model impossible. Thus, further work using FASTCHEM was discontinued. Instead, results of the 3-D flow model described in Section 4.0, coupled with observed groundwater quality data and some analytical calculations is proposed for use in determining conditions related to contaminant transport and loading at the site.

## 7.0 Impact Analysis

### 7.1 Groundwater Quality Impacts

To evaluate impacts to groundwater quality at the Brunner Island SES coal pile, calculations of mass loading rates to the aquifer from the coal pile were performed, as presented in Table 11. These mass loading calculations are based on a combination of the groundwater quality data described in Section 2.5.2 and the coal pile water budget developed in Section 4.4.4. Contaminant mass loadings contributed by the coal pile were deduced based on the difference between mass loading rates calculated upgradient and downgradient of the coal pile, as indicated on Table 11.

This analysis shows that the approximately 16,000 gpd of seepage from the coal pile carries with it approximately 600 lbs/day of sulfates and 200 lbs/day of iron, as well as the other constituents listed. Although significantly degraded groundwater quality exists upgradient of the coal pile, seepage from the coal pile appears to be the major contributor to the mass loadings of contaminants entering the aquifer and ultimately the river in the immediate vicinity of the coal pile.

This analysis is limited by the accuracy of its inherent assumptions, including assuming average upgradient and downgradient concentrations, aquifer width, and other properties. The use of average upgradient and downgradient contaminant concentrations may not be completely appropriate since concentrations in new versus old monitoring wells varied over several orders of magnitude. The appropriate selection of aquifer width to use was not clear either since (1) flow in the area is somewhat radial and not strictly one-dimensional, and (2) observed concentrations of parameters vary significantly areally. However, this loading rate analysis appears reasonable since the calculated coal pile seepage quality generally matches (1) that described in Section 2.0 and (2) that used in previous modeling analyses [Baker, 1986].

Table 11 also provides drinking water quality standards as compared to the average water quality in the vicinity of the coal pile. Concentrations of iron, manganese, and sulfate in monitoring wells both upgradient and downgradient of the coal pile drastically exceed applicable secondary drinking water standards. However, since groundwater on the island is not used, the potential for impacts to human receptors is essentially nonexistent [Baker, 1986].

## 7.2 Surface Water Quality Impacts

Potential impacts to surface water quality from contaminated groundwater discharge in the vicinity of the coal pile was analyzed by examining predicted loading rates from the coal pile area in conjunction with river flow and quality data. Potential increases in in-stream river concentrations were calculated for both average and 7-day, 10-year low river flow scenarios, as shown in Table 12. These calculated increases were then added to upstream ambient water quality data to produce predicted downstream surface water chemistry, for comparison to surface water quality criteria.

As indicated in Table 12, based on the loading rates calculated previously, few measurable increases in any of the parameters listed would be expected to occur in the Susquehanna River due to contaminated groundwater discharge from the coal pile area. No impacts would be discernable under average river flow conditions, due to the tremendous amount of dilution afforded by the river. Slight increases in sulfate and iron <u>may</u> be discernable under low river flow conditions. These calculations are supported by the surface water quality studies performed by PP&L and described in Section 2.5.2 [PP&L-2, 1988].

## 8.0 Remedial Simulations

### 8.1 Remedial Alternatives

One primary objective of this investigation was to evaluate the effectiveness of potential remedial actions at the Brunner Island SES coal storage pile. PP&L has identified and performed a preliminary investigation of a number of remedial alternatives based on both technical and economic factors. These alternatives are aimed primarily at eliminating the source of coal pile seepage, containing the affected area, or a combination of the two approaches. Alternatives identified include [PP&L, 1989]:

- coal pile liner;
- slurry walls;
- pumping well or drain systems;
- coal pile enclosure or roof;
- revised coal pile operations and maintenance;
- any combination of the above alternatives.

### 8.2 Slurry Wall Remedial Simulation

A combination slurry wall and pumping/drain system appears to be a favorable remedial alternative, based upon preliminary cost and feasibility analyses conducted by PP&L [PP&L, 1989].

Thus, this modeling effort focused on technical evaluation of that alternative.

### 8.2.1 Slurry Wall Configuration

The remedial alternative simulated consists of a low-permeability bentonite slurry wall installed completely around the coal pile, and a drainage system installed in the interior of the area bounded by the slurry wall. The slurry wall is intended to limit the horizontal migration of groundwater flow and contaminants. The drain is designed to collect infiltrating rainfall recharge and slightly depress hydraulic head values within the confines of the slurry wall. This lower head within as compared to outside the confines of the slurry wall serves to prevent the outward migration of any contaminant-laden groundwater (both horizontally and vertically).

Slurry walls are typically installed in the field as a bentonite slurry and soil mixture backfilled into a backhoe trench. In this simulation, the slurry wall was simulated to be 10 feet thick (limited by the model's grid spacing) with a hydraulic conductivity of 3.3x10E-7 cm/s. This thickness and hydraulic conductivity correlates to typical as-installed slurry wall specifications of a 3-foot width of a 1x10E-7 material. The modeled slurry wall was assumed to extend through all alluvial material on site (approximately 30 feet deep through model layers 1 and 2) to the bedrock. The slurry wall was also assumed to completely surround the coal pile as shown in Figure 26.

A gravity drain system was modeled within the slurry wall to lower hydrostatic heads, as also shown in Figure 26. Drain layout and elevation was selected to meet the goal of maintaining lower heads within the slurry wall, and at the same time minimize the amount of water requiring collection. Thus, shallow drain segments were favored. Initial runs proved that adequately depressing the water table in the central area of the pile was difficult without excessively deep drains bordering the outside of the pile area. Thus a drain layout consisting of drains along the downgradient borders of the pile and one interior drain was selected, as shown in Figure 26. Drains were set on approximately 1% slopes at elevations ranging from 266 to 261 ft MSL. It was assumed these drains would be serviced by sumps installed at key locations to remove any water for treatment which had collected in the drains. The Modular Model's drain package (DRN) was used to simulate these drains, with a conductance factor of 0.9.

### 8.2.2 Results

The slurry wall and drain combination described above appears to be a successful method of containing groundwater contamination which originates at the coal storage pile. Figure 27 provides a predicted plan-view water table configuration as influenced by the slurry wall and drain. This figure shows predicted heads in layer 2, which generally match layer 1 heads within 0.2 feet. All flow lines which occur within the area encircled by the coal pile slurry wall terminate at one of the drains, thus precluding horizontal contaminant migration from the slurry wall enclosure.

Figure 28 provides three cross-sectional plots of the predicted heads in layers 1, 2, and 3. The locations of these cross-sections are shown on Figure 26. This figure shows that heads in layers 1 and 2 within the area bounded by the slurry wall are maintained equal to or lower than surrounding heads or those in layer 3 across most of the coal pile area. Thus, contaminated groundwater flow cannot exit via vertical or horizontal flow from the coal pile area.

One area not completely contained occurs in the northwest corner of the coal pile, as noted on Figure 28B. Here layer 1 and 2 heads remain slightly above layer 3 heads, indicating downward flow into layer 3, thus "escaping" the slurry wall containment. Additionally, heads in layers 1, 2, and 3 are approximately equal in the center of the coal pile area, also suggesting that only marginal hydraulic control has been achieved in this area. Installing additional drains in these areas, or setting simulated drains deeper, should be considered in final design of the slurry wall and drain system to adequately contain degraded groundwater within the coal pile area.

Based on the changes in groundwater flow due to installation of the slurry wall and drain, a revised model water budget was prepared as provided in Table 13. Approximately 30,000 gpd of seepage is predicted to be collected by the drainage system. Of the 30,000 gpd, approximately 13,000 gpd originates as precipitation recharge, an estimated 9000 gpd is attributable to seepage from the coal pile runoff pond, and the remaining 8000 gpd is assumed to be groundwater inflow. Some slight increases in groundwater underflow from upgradient constant head sources and from sources modeled as leaky rivers (Basin No. 4, coal pile swamp, and coal pile runoff pond) occurred due to the lowering of the water table near the coal pile.

A final analysis performed included examining changes in contaminant mass loading rates, groundwater quality, and river water quality impacts based on this removal of the coal pile source. Remediating the site using a slurry wall/drain system would effectively reduce to zero those contaminant loading rates attributable to coal pile seepage and described in Section 6.0. Groundwater quality improvements would then occur, but water quality would be expected to improve only to the level of the still-degraded quality observed upgradient of the coal pile and described in Sections 2.5 and 6.0. Additionally, this water quality improvement would occur very slowly, most likely over several years or tens of years, based on the groundwater velocities described in Section 4.0. Finally, although mass loading rates to the river would be reduced, no measurable changes in river water quality would occur since these loading rates do not contribute to measurable degradation of river water quality anyway, as described in Section 6.2. One possible exception to this may be an improvement in near-bank river water quality in the immediate vicinity of the coal pile under low-flow conditions.

## 9.0 Conclusions and Recommendations

Conclusions and recommendations based on this review of hydrogeological data and modeling assessment of the Brunner Island SES coal pile are listed in the following sections.

### 9.1 Conclusions

Conclusions drawn from analysis of hydrogeological data collected at the Brunner Island SES coal pile area include:

- The aquifer system beneath the coal pile is influenced both locally by precipitation recharge and plant operational activities, and regionally as a regional discharge area;

- Seepage from the coal pile and associated runoff moats enters the aquifer beneath the coal pile and is partially responsible for the degraded groundwater quality observed there. Groundwater quality in the immediate coal pile area is also influenced by degradation from Basin No. 3, upgradient of the coal pile.

Conclusions drawn from the modeling assessment of the Brunner Island SES coal pile area include:

- Approximately 20,000 gpd of the groundwater discharging from the downgradient boundary of the coal pile area (over 50% of total groundwater flow) originates within the coal pile area as precipitation recharge and seepage from ponded surface water. The remainder of the groundwater moving through the aquifer originates as groundwater from the upgradient Basin No. 3 area (approximately 13,000 gpd or 40 percent) or as regional discharge from upland areas (approximately 2,000 gpd of less than 10 percent). These are order-of-magnitude estimates subject to modeling assumptions and limitations;

- A combination slurry wall and drain system can be effective in containing and collecting contaminated groundwater seepage from the coal pile. Approximately 30,000 gpd of seepage and groundwater is estimated to be collected by the drainage system installed within the coal pile area. Additional modeling may be warranted to evaluate other slurry wall and drain configurations than the one evaluated here;

- The vertical hydraulic conductivity of the alluvial and fractured bedrock aquifers is an important parameter in determining the influence of regional upward gradients on the local groundwater system, and the resulting quantity of water discharging from deep aquifer systems. In future modeling or design of remedial measures for the coal pile, additional work may be warranted to better define this parameter;

## 9.2 Recommendations

Recommendations based on this review of hydrogeological data and modeling assessment of the Brunner Island SES coal pile are listed below.

Recommendations related to potential future modeling studies of the island include:

- Collection of several complete sets of groundwater level data from existing, new, and retired monitoring wells and piezometers, and concurrent monitoring of surface water levels would aid in more accurate model calibration;

- Work related to estimating both the magnitude and distribution of recharge rates due to both precipitation and surface water seepage would improve overall water budget estimates. This work could include field infiltrometer studies or more accurate measurement of surface water runoff or basin flows;

- Additional work may be warranted to better define vertical hydraulic conductivity values in the coal pile area and across the site. This work could include pumping tests or other field data collection;

- Additional data on vertical gradients between the alluvial, shallow rock, and deep rock aquifers on areas of the site other than the coal pile would aid in more accurate model calibration;

- Modeling analyses of alternative means to account for related regional groundwater flows may also improve model calibration;

- Extending the model grid area farther south in future modeling studies would eliminate the need to use less accurate boundary conditions such as the middle of Basin No. 4 or the general head boundary along Black Gut Creek, while at the same time allowing for model predictions on other site areas, including Basin Nos. 3 and 4.

Recommendations related to design and installation of remedial measures at the coal storage pile include:

- Additional modeling to evaluate slurry wall and drain configurations may be warranted to identify other more efficient or more effective systems;

- The work recommended above related to vertical hydraulic conductivity measurements may also aid in refining estimates of groundwater collection in the drain system.

Observations related to the overall groundwater monitoring program at the coal storage pile include:

- Comparisons of contaminant loading rates from the coal pile and other potential contaminant sources on site cannot be performed based on the results of this modeling analysis, since it focused on the coal pile area only. Additional modeling of the entire central island area would be required to allow for such comparisons;

- Some apparent disparities exist in some dissolved metals concentrations between old and new coal pile cluster wells. Further analysis of that condition and the site geochemistry may be warranted to refine current interpretations of site conditions, field data collection procedures, and possible impacts to potential remedial measures.

# TABLES

# TABLE 1
# ASH, PYRITES, AND COAL LEACHATE CHEMISTRY (ppm)

| | **FLY ASH LEACHATE [1]** | **PYRITES PILE RUNOFF [2]** | **COAL PILE RUNOFF [3]** |
|---|---|---|---|
| pH | 9.6 | 2.9 | 3.9 |
| Conductivity | 2380. | 46,600. | 1158. |
| Sulfate | 4640. | 110,000. | 370. |
| Calcium | 596. | N/A | N/A |
| Magnesium | 0.82 | N/A | N/A |
| Aluminum | 20.4 | 2,740. | 13. |
| Iron | <0.05 | 48,400. | 45. |
| Manganese | <0.005 | 374. | 0.70 |
| Nickel | <0.05 | 64. | 0.16 |
| Zinc | <0.05 | 266. | 0.47 |
| Arsenic | 0.15 | 38.8 | 0.007 |
| Selenium | 0.30 | 0.045 | <0.005 |
| Cadmium | <0.005 | 1.0 | <0.01 |
| Chromium | 0.11 | 0.88 | <0.05 |

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NOTES:

[1] - ASTM-A analysis of Brunner Island fly ash composite sample FA-1, 10/06/87 [PP&L].

[2] - Sample from standing pool/partially evaporated near rejects pile 11/21/86 [Baker,1986].

[3] - Sample from northeast corner of coal pile runoff ditch on 11/21/86 [Baker, 1986].

# TABLE 2
# AQUIFER TEST DATA SUMMARY [1]

| AQUIFER LAYER | HYDRAULIC CONDUCTIVITY (feet/day) | | | NO. TESTS |
|---|---|---|---|---|
| | Range | LogAvg | Median | |
| Alluvial Soils [2] | 0.1 - 21.0 | 2.2 | 1.9 | 11 |
| Alluvial Soils/ Bedrock Interface [3] | 0.2 - 11.0 | 2.5 | 3.0 | 9 |
| Bedrock | | | | |
| 0-30 feet in depth below rock surface | 0.0 - 11.0 | 1.6 | 1.9 | 51 |
| > 30 feet in depth below rock surface | 0.0 - 3.1 | 0.3 | 0.2 | 16 |
| Ash - Basin No. 4 | 0.2 - 4.9 | 0.8 | 0.7 | 7 |

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NOTES:

[1] Summary of pump, recovery, slug, and packer (pressure) tests performed at over 65 locations within the central island area, including the coal pile, power block, and Basins No. 1, 2, 3, and 4. Data provided in Appendix 1 [Baker, 1984; Baker, 1986; Baker, 1987; Dunn, 1985; Dunn, 1989].

[2] Data from wells screened within the alluvial soil aquifer.

[3] Data from wells screened at the alluvial soil/ bedrock interface.

TABLE 3

AVERAGE 1989 GROUNDWATER QUALITY DATA (ppm)

| | **Upgradient of Island** | **Upgradient of Coal Pile** | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **MW-19** | **MW-11** | **MW-12** | **CL-7A** | **CL-7B** | **CL-8A** | **CL-8B** | **CL-8C** |
| pH | 7.1 | 6.0 | 4.5 | 5.6 | 6.5 | 6.4 | 6.0 | 6.0 |
| Conductivity | 280. | 4260. | 3160. | 1000. | 2090. | 1820. | 3170. | 2490. |
| Sulfate | 16.3 | 3290. | 2110. | 381. | 1010. | 600. | 1870. | 1410. |
| Calcium | 32.5 | 479. | 327. | 90.7 | 332. | 110. | 513. | 418. |
| Magnesium | 4.1 | 171. | 57.0 | 40.1 | 107. | 65.8 | 176. | 101. |
| Aluminum | <0.10 | 0.20 | 64.0 | <0.10 | 0.12 | <0.10 | <0.10 | <0.10 |
| Iron | <0.05 | 739. | 536. | 18.0 | 0.24 | 0.21 | <0.05 | 2.34 |
| Manganese | 0.02 | 30.2 | 9.26 | 52.5 | 6.17 | 11.1 | 33.3 | 30.0 |
| Nickel | <0.05 | 0.12 | 0.21 | 0.07 | <0.05 | <0.05 | <0.05 | <0.05 |
| Zinc | <0.05 | 0.17 | 0.63 | 0.06 | <0.05 | <0.05 | <0.05 | <0.05 |
| No. of Obs. | [2] | [1] | [1] | [2] | [2] | [2] | [2] | [2] |

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NOTES:

[1] - Average of quarterly analyses for pH, conductivity, sulfate, iron, manganese; annually for metals since Fall 1986.

[2] - Average of two samples collected in 1989.

[3] - Average of two samples collected in 1984, 1985; no 1989 data available.

[4] - Dissolved metals.

## TABLE 3 (continued)
## AVERAGE 1989 GROUNDWATER QUALITY DATA (ppm)

| | Downgradient of Coal Pile | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **CL-3A** | **CL-3B** | **CL-3C** | **CL-9A** | **CL-9B** | **CL-9C** | **CL-10A** | **CL-10B** | **MW-14** |
| pH | 3.0 | 3.5 | 3.6 | 4.3 | 5.6 | 5.7 | 5.5 | 6.5 | 5.8 |
| Conductivity | 8060. | 6320. | 5100. | 2620. | 2970. | 2640. | 3230. | 3140. | 1640. |
| Sulfate | 8850. | 5870. | 3760. | 1700. | 1750. | 1510. | 2090. | 1880. | 522. |
| Calcium | 323. | 253. | 410. | 121. | 480. | 403. | 490. | 422. | 130. |
| Magnesium | 167. | 96.5 | 177. | 38.9 | 144. | 141. | 180. | 200. | 35.0 |
| Aluminum | 276. | 148. | 210. | 20.9 | <0.10 | <0.10 | 3.00 | <0.10 | <0.20 |
| Iron | 2590. | 2021. | 2630. | 543. | 0.55 | 0.06 | 22.7 | <0.05 | 15.8 |
| Manganese | 64.0 | 46.7 | 77.0 | 21.6 | 71.3 | 52.5 | 69.5 | 27.5 | 0.01 |
| Nickel | 4.65 | 2.70 | 4.39 | 0.42 | 0.11 | 0.11 | 0.29 | <0.05 | 0.06 |
| Zinc | 9.10 | 6.25 | 8.50 | 0.99 | 0.05 | 0.08 | 0.36 | <0.05 | 0.05 |
| No. of Obs. | [3] | [1] | [3] | [2] | [2] | [2] | [2] | [2] | [1] |

---

NOTES:

[1] - Average of quarterly analyses for pH, conductivity, sulfate, iron, manganese; annually for other metals since Fall 1986.

[2] - Average of two samples collected in 1989.

[3] - Average of two samples collected in 1984, 1985; no 1989 data available.

[4] - Dissolved metals.

# TABLE 4
# SURFACE WATER QUALITY DATA (ppm)

| | Conewago Creek | | | Susquehanna River | | | |
|---|---|---|---|---|---|---|---|
| | CC-1 | CC-2 | CC-3 | 16-1 | 14-1 | 13-1 | 02-1 |
| | Upstream | Railroad Trestle | Downstream | Upriver | At Coal Pile | At Coal Pile | Down-river |
| pH | 8.0 | 8.0 | 7.8 | 9.1 | 7.5 | 7.8 | 9.0 |
| Conductivity | 300. | 310. | 300. | 330. | 450. | 450. | 395. |
| Sulfate | 26.0 | 24.0 | 24.0 | 30.0 | 93.0 | 80.0 | 68.0 |
| Calcium | 26.4 | 30.1 | 31.1 | 31.8 | 36.7 | 35.3 | 31.9 |
| Magnesium | 7.2 | 8.2 | 8.5 | 8.9 | 11.1 | 10.3 | 10.1 |
| Aluminum | 0.30 | 0.30 | 0.30 | 0.20 | 0.70 | 0.40 | <0.10 |
| Iron | 0.29 | 0.39 | 0.40 | 0.20 | 5.22 | 1.72 | 0.37 |
| Manganese | 0.08 | 0.12 | 0.11 | 0.09 | 1.31 | 0.40 | 0.11 |

---

NOTES:

[1] Total metals.

[2] Samples collected during low-flow event on 7/13-14/88.
Susquehanna River flow = 4700 cfs; Conewago Creek flow = 44 cfs.

[3] Metals not detected include: Sb, As, Be, B, Cd, Cr, Cu, Pb, Li, Mo, Ni, Se, Ag, Th, Tl, V, Zn.

## TABLE 5
## GROUND WATER VELOCITIES AND TRAVEL TIMES

**Governing Equation:**

$$V = Ki/n_e$$

**Calculations:**

| Source/Sink Location | K [1] (ft/day) | i (ft/ft) | $n_e$ (%) | V (ft/day) | Distance (ft) [2] | Travel Time (years) |
|---|---|---|---|---|---|---|
| **Layer 1 - Alluvial Aquifer** | | | | | | |
| Coal Pile to River | 9 | 0.012 | 25 | 0.4 | 1200 | 7.6 |
| Basin No. 3 to River | 7 | 0.009 | 25 | 0.3 | 2400 | 25.0 |
| **Layer 2 - Bedrock Aquifer** | | | | | | |
| Coal Pile to River | 6 | 0.012 | 5 | 1.4 | 1200 | 2.3 |
| Basin No. 3 to River | 6 | 0.009 | 5 | 1.1 | 2400 | 5.8 |

---

NOTES:

[1] K is average K of layer; velocities and travel times may deviate significantly due to aquifer nonhomogeneities.

[2] Distance from center of source (coal pile or Basin No. 3) to the Susquehanna River.

## TABLE 6
## DESCRIPTION OF MODEL LAYERS

| LAYER | DESCRIPTION | LAYER TYPE | LAYER THICKNESS & VERTICAL LOCATION | SATURATED THICKNESS | HYDRAULIC CONDUCTIVITY |
|---|---|---|---|---|---|
| 1 | **Alluvial** clays, silts, sands and gravels; Ash in basin areas. | Unconfined | Variable thick - Extends from (TOR + 10 feet) to ground surface | Variable 0-15 feet | Initial:<br>2.0<br>Calibrated:<br>0.4 - 10.0 |
| 2 | **Coarse alluvial** sands, gravels, cobbles, and boulders; Ash in basin areas. | Convertible Confined/ Unconfined | 10 feet thick - Extends from TOR to (TOR + 10 feet) | Variable 2-10 feet | Initial:<br>3.0<br>Calibrated:<br>0.4 - 12.0 |
| 3 | **Bedrock**; Fractured shale, sandstone, siltstone, and conglomerate. | Confined | 30 feet thick - Extends from TOR to (TOR - 30 feet) | Constant 30 feet | Initial:<br>2.0<br>Calibrated:<br>0.1 - 8.0 |

---

NOTES:

[1] TOR = Top-of-rock elevation.

[2] Hydraulic Conductivity Distribution For Each Layer Shown on Figure 16 and Table 7.

## TABLE 7
## MODEL CALIBRATION SUMMARY

| PARAMETER & LOCATION | UNITS | INITIAL VALUE | FINAL VALUE | FACTOR CHANGE |
|---|---|---|---|---|
| **Hydraulic Conductivity** | ft/d | | | |
| Layer 1 | | | | |
| · Sitewide | | 2 | 6 | 3x |
| · Coal Pile | | 2 | 10 | 5x |
| · Ash | | 2 | 2 | 0 |
| · Basin 3 Dikes | | 2 | 0.4 | 0.2x |
| Layer 2 | | | | |
| · Sitewide | | 3 | 7 | 2.3x |
| · Coal Pile | | 3 | 12 | 3x |
| · Ash | | 3 | 2 | 0.7x |
| · Basin 3 Dikes | | 3 | 0.4 | 0.1x |
| Layer 3 | | | | |
| · Sitewide | | 2 | 5 | 2.5x |
| · Coal Pile | | 2 | 8 | 4x |
| · River | | 2 | 8 | 4x |
| · Upland | | 2 | 0.1 | 0.05x |
| **$K_v:K_h$** | ratio | | | |
| · Layer 1 | | 1:3 | 1:10 | 0.3x |
| · Layer 2 | | 1:3 | 1:10 | 0.3x |
| · Layer 3 | | 1:3 | 1:100 | 0.03x |
| **Precipitation Recharge** | in/yr | | | |
| · Sitewide | | 8 | 7.5 | 0.9x |
| · Central Island | | 8 | 4 | 0.5x |
| · Upland | | 1 | 0.3 | 0.3x |
| **Riverbed Conductance [1]** | K/b $(d^{-1})$ | | | |
| · Coal Pile/Swamp | | 1 | 0.02 | 0.02x |
| · Basin 4 | | 2 | 4 | 2x |

---

NOTES:

[1] - Assumes b = 5 feet in all cases

## TABLE 8
## OBSERVED VS. SIMULATED HEADS

| MODEL LAYER | LOCATION | OBSERVED WATER LEVEL (FT MSL) | SIMULATED HEAD (FT MSL) | DIFFERENCE (FT) |
|---|---|---|---|---|
| LAYER 1 | CL-8A | 270.4 | 271.5 | 1.1 |
| LAYER 1&2 | CL-4B | 277.2 | 274.0 | -3.1 |
| | CL-5A | 275.4 | 276.6 | 1.2 |
| | CL-5B | 276.6 | 276.6 | -0.0 |
| | CL-7A | 268.6 | 270.3 | 1.7 |
| | CL-9A | 266.9 | 265.9 | -1.0 |
| | MW-11 | 274.1 | 274.2 | 0.1 |
| LAYER 2 | CL-2A | 261.9 | 263.0 | 1.1 |
| | CL-3A | 261.5 | 262.2 | 0.8 |
| | CL-5C | 276.7 | 276.6 | -0.1 |
| | CL-8B | 270.6 | 271.7 | 1.1 |
| | CL-10A | 266.4 | 267.0 | 0.6 |
| | MW-12 | 276.4 | 274.9 | -1.5 |
| | TB-1 | 276.5 | 275.8 | -0.7 |
| | WC-1 | 278.0 | 277.0 | -1.0 |
| | WC-2 | 278.1 | 276.7 | -1.4 |
| | WC-3 | 277.7 | 276.4 | -1.3 |
| | WC-4 | 276.9 | 276.2 | -0.7 |
| LAYER 3 | CL-2B | 261.3 | 261.5 | 0.2 |
| | CL-2C | 261.6 | 261.5 | -0.1 |
| | CL-3B | 261.6 | 262.0 | 0.4 |
| | CL-3C | 261.7 | 262.0 | 0.3 |
| | CL-7B | 269.3 | 270.4 | 1.1 |
| | CL-8C | 270.6 | 271.8 | 1.2 |
| | CL-9B | 267.6 | 265.9 | -1.7 |
| | CL-9C | 267.9 | 265.9 | -2.0 |
| | CL-10B | 267.2 | 266.7 | -0.5 |
| | MW-8 | 257.4 | 260.0 | 2.6 |
| | MW-14 | 254.7 | 256.0 | 1.3 |
| | MW-19 | 285.7 | 284.0 | -1.7 |
| | | ROOT MEAN SQUARE = | | 1.33 |

NOTES:

[1] - WATER LEVELS OBSERVED FEBRUARY 1989

[2] - SIMULATED HEADS ARE FINAL CALIBRATED VALUES

# TABLE 9
# SUMMARY OF MODEL LAYER TRANSMISSIVITIES

| APPROXIMATE LOCATION/ LAYER | SATURATED THICKNESS (feet) | HYDRAULIC CONDUCTIVITY (feet/day) | TRANS- MISSIVITY ($\text{feet}^2$/day) |
|---|---|---|---|
| Downgradient - Along Susquehanna River | | | |
| Layer 1 | 0 | 10 | 0 |
| Layer 2 | 2 | 12 | 24 |
| Layer 3 | 30 | 8 | 240 |
| TOTAL | | | 264 |
| Downgradient - Along Diversion Channel | | | |
| Layer 1 | 0 | 10 | 0 |
| Layer 2 | 2.5 | 10 | 25 |
| Layer 3 | 30 | 5 | 150 |
| TOTAL | | | 175 |
| Upgradient - Upland Area West of Basin No. 3 | | | |
| Layer 1 | 0 | N/A | 0 |
| Layer 2 | 0 | N/A | 0 |
| Layer 3 | 20 | 0.1 | 2 |
| TOTAL | | | 2 |
| Basin No. 3 Area | | | |
| Layer 1 | 12 | 2 | 24 |
| Layer 2 | 10 | 2 | 20 |
| Layer 3 | 30 | 5 | 150 |
| TOTAL | | | 194 |
| Coal Pile Area | | | |
| Layer 1 | 7 | 10 | 70 |
| Layer 2 | 10 | 12 | 120 |
| Layer 3 | 30 | 5.5 | 165 |
| TOTAL | | | 355 |

# TABLE 10
# MODEL WATER BUDGET [1]

| **WATER SOURCES:** | FLOW (GPD) | FLOW (% of Total) |
|---|---|---|
| Groundwater Underflow From Upgradient Constant Head | 13,000 | 4 |
| Regional Ground Water Inflow | 26,800 | 9 |
| Precipitation Recharge | 154,300 | 53 |
| Basin No. 4 Seepage | 83,100 | 29 |
| Coal Pile Runoff Pond Seepage | 7,300 | 3 |
| Swamp Seepage | 6,500 | 2 |
| TOTAL | 291,000 | 100 |

| **WATER SINKS:** (discharge to:) | FLOW (GPD) | FLOW (% of Total) |
|---|---|---|
| Wetlands & Conewago Creek | 37,900 | 13 [2] |
| Diversion Channel & River | 134,300 | 46 [2] |
| Cooling Water Discharge Channel | 104,900 | 36 [2] |
| Black Gut Creek (general head boundary) | 13,900 | 5 |
| TOTAL | 291,000 | 100 |

---

NOTES:

[1] Represents that portion of the central island area within model boundaries.

[2] Estimated based on ground water flow patterns and sources contributing to different drainage areas.

TABLE 11
BRUNNER ISLAND COAL PILE
CONTAMINANT MASS LOADING ANALYSIS

| | UPGRADIENT OF PILE | | DOWNGRADIENT OF PILE | | CALCULATED PILE SOURCE [3] | | |
|---|---|---|---|---|---|---|---|
| PARAMETER | CONC. [1] (ppm) | MASS LOAD [2] (lbs/d) | CONC. [1] (ppm) | MASS LOAD [2] (lbs/d) | CONC. (ppm) | MASS LOAD (lbs/d) | DRINKING WATER STANDARDS (ppm) |
| Sulfate | 1200 | 130.26 | 3100 | 750.67 | 4644 | 620.41 | 250.00 |
| Iron | 93 | 10.10 | 870 | 210.67 | 1501 | 200.58 | 0.30 |
| Manganese | 23 | 2.50 | 48 | 11.62 | 68 | 9.13 | 0.05 |
| Aluminum | 11 | 1.19 | 73 | 17.68 | 123 | 16.48 | |
| Nickel | 0.05 | 0.01 | 1.4 | 0.34 | 2.5 | 0.33 | |
| Zinc | 0.12 | 0.01 | 2.8 | 0.68 | 5.0 | 0.66 | 5.00 |

=========== ===========

NOTES:

[1] Upgradient concentrations are average 1989 concentrations observed in CL-7, CL-8, and MW-12.
Downgradient concentrations are average 1989 concentrations observed in CL-10, CL-3, CL-9, and MW-14.

[2] Mass loadings calculated based on 13,000 and 29,000 gpd groundwater flow upgradient and downgradient of pile.

[3] Pile source based on difference in upgradient vs. dowgradient loading rates, at 16,000 gpd pile seepage.

## TABLE 12
## BRUNNER ISLAND COAL PILE
## RIVER QUALITY IMPACT ANALYSIS

| | COAL PILE SOURCE MASS LOAD [1] | UPSTREAM BCKGROUND CONC. [3] | CALC'D INSTREAM CONCENTRATION INCREAS | | CALC'D DOWNSTREAM CONCENTRATIONS | | WATER QUALITY CRITERIA [4] |
|---|---|---|---|---|---|---|---|
| | | | AVG. FLOW [2] | LOW FLOW [2] | AVG. FLOW [2] | LOW FLOW [2] | |
| PARAMETER | (lbs/d) | (ppm) | (ppm) | (ppm) | (ppm) | (ppm) | (ppm) |
| Sulfate | 750.67 | 45.50 | 0.0037 | 0.0529 | NC | 45.55 | |
| Iron | 210.67 | 2.02 | 0.0011 | 0.0148 | NC | 2.03 | 1.50 |
| Manganese | 11.62 | 0.48 | 0.0001 | 0.0008 | NC | NC | 1.00 |
| Aluminum | 17.68 | 0.988 | 0.0001 | 0.0012 | NC | NC | |
| Nickel | 0.34 | 0.014 | 0.0000 | 0.0000 | NC | NC | 0.16 |
| Zinc | 0.68 | 0.043 | 0.0000 | 0.0000 | NC | NC | 0.11 |

============

NOTES:

[1] Includes coal pile and upgradient sources from Table 1.

[2] Susquehanna River Average Flow = 37100 cfs (24,000 mgd), 7Q10 Low Flow = 2605 cfs (1700 mgd).

[3] Total Metals Concentration At Harrisburg, PA from [Baker, 1986].

[4] PA Code, Chapter 93.

NC- No Change In Concentration

# TABLE 13
# MODEL WATER BUDGET [1]
# WITH SLURRY WALL AND DRAIN

| **WATER SOURCES:** | FLOW (GPD) | FLOW (% of Total) |
|---|---|---|
| Groundwater Underflow From Upgradient Constant Head | 14,700 | 5 |
| Regional Ground Water Inflow | 26,800 | 9 |
| Precipitation Recharge | 154,300 | 52 |
| Basin No. 4 Seepage, Coal Pile Runoff Pond Seepage, and Swamp Seepage | 99,500 | 34 |
| TOTAL | 295,300 | 100 |

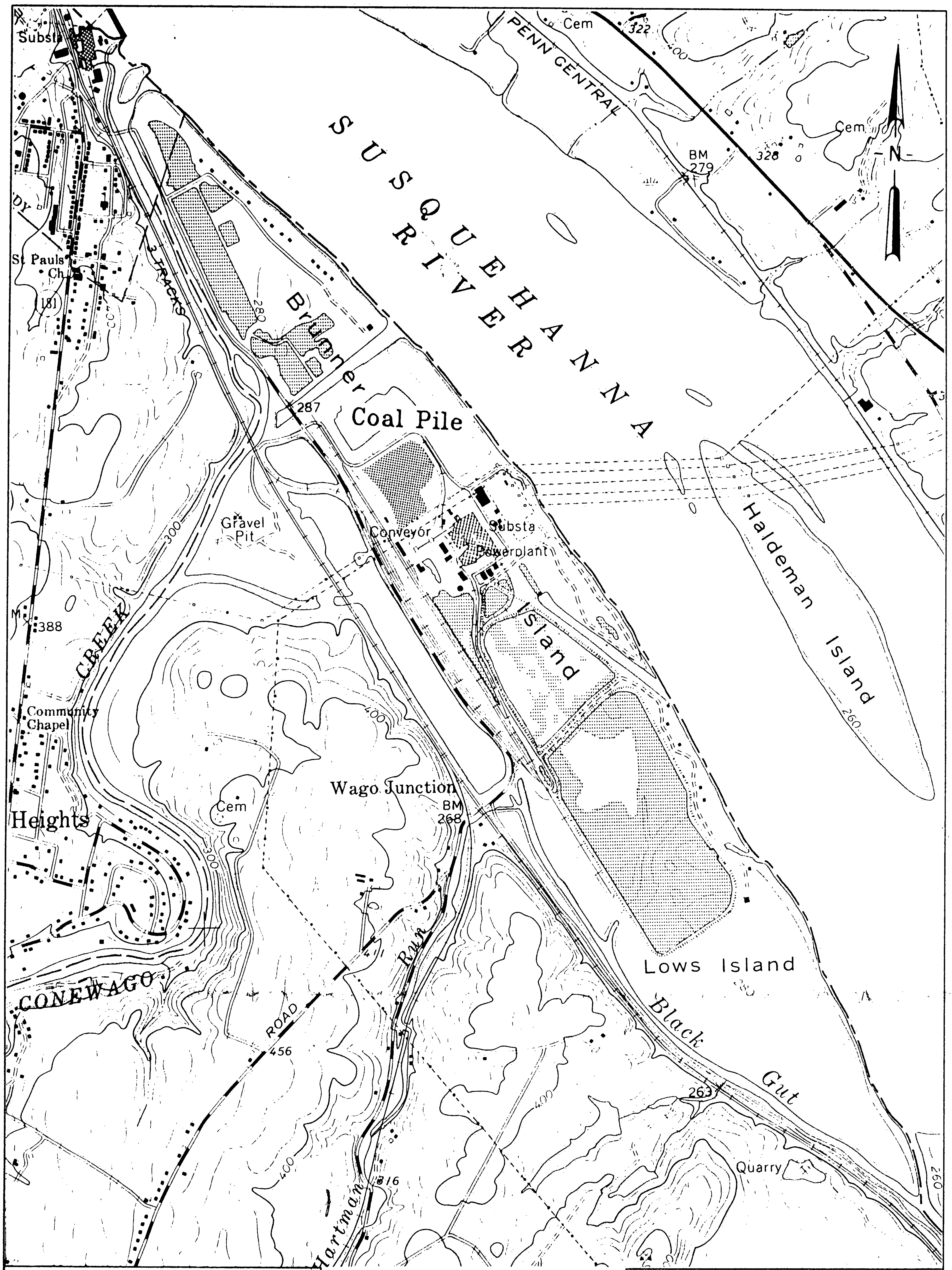
| **WATER SINKS:** (discharge to:) | FLOW (GPD) | FLOW (% of Total) |
|---|---|---|
| Surface Water Boundaries (Wetlands & Conewago Creek, Diversion Channel, River, Cooling Water Discharge Channel) | 252,000 | 85 |
| Black Gut Creek (General Head Boundary) | 13,600 | 5 |
| Coal Pile Drain | 29,700 | 10 |
| TOTAL | 295,300 | 100 |

---

NOTES:

[1] Represents that portion of the central island area within model boundaries.

# FIGURES



York Haven Quad.
PA – 7.5 Min.
Scale: 1" = 2000'

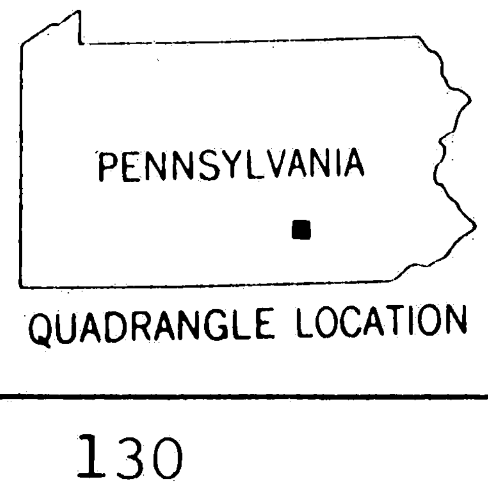
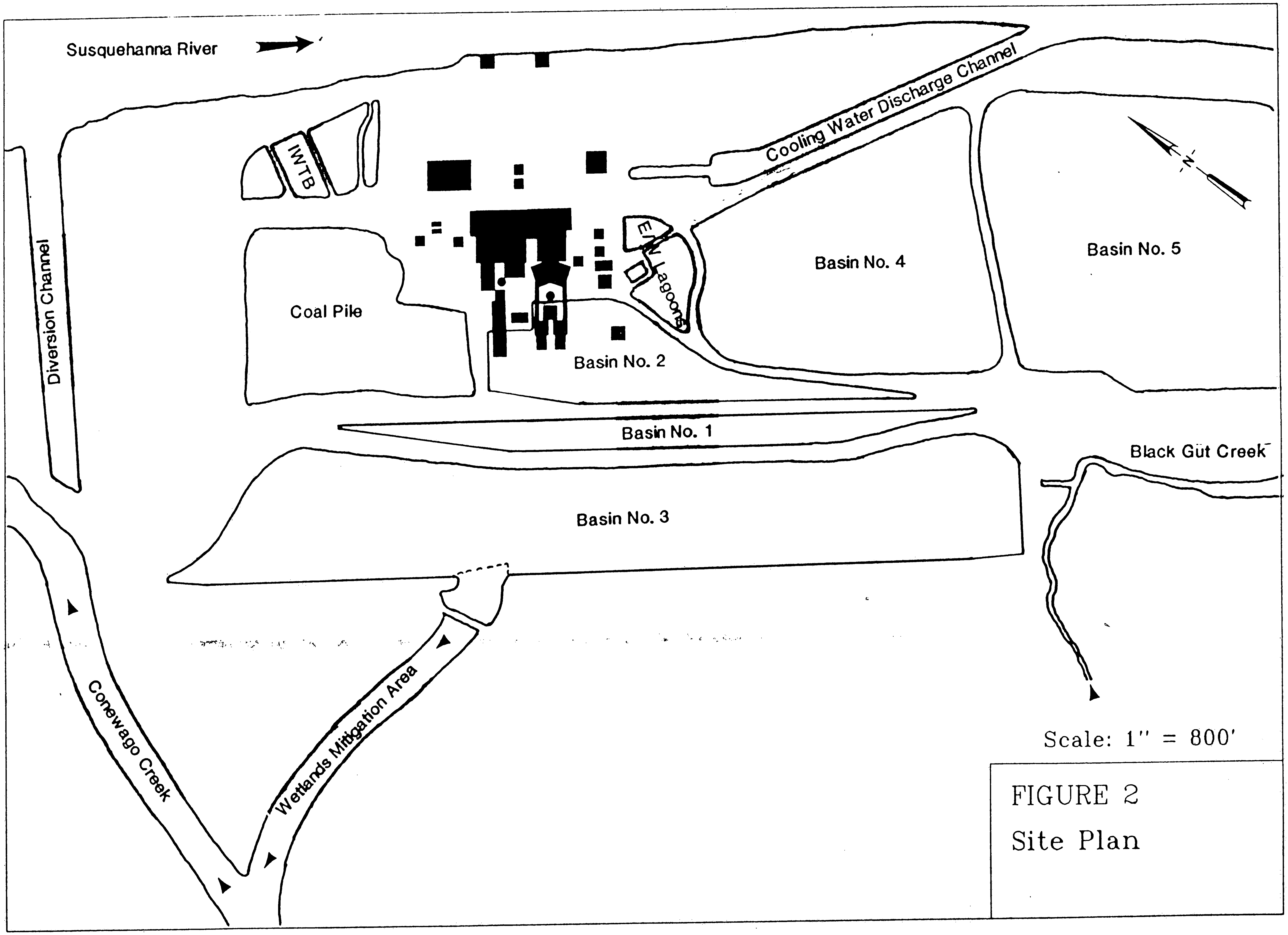
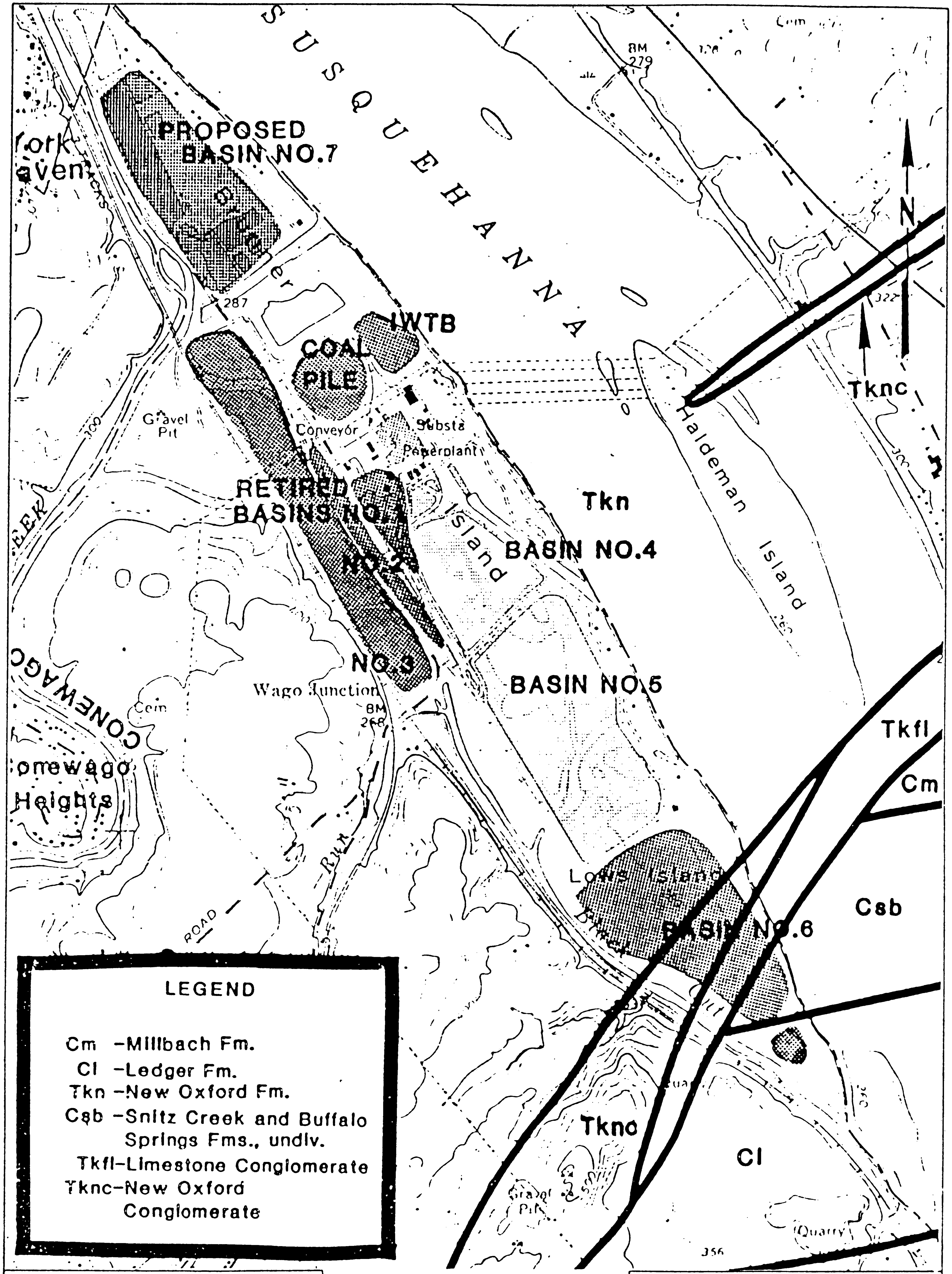


FIGURE 1
Site Location Map

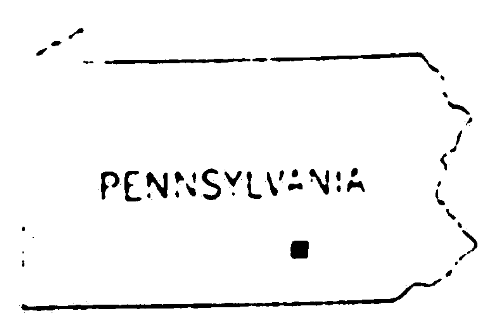


Scale: 1" = 800'

FIGURE 2
Site Plan



York Haven Quad.
PA – 7.5 Min.
Scale: 1" = 2000'



QUADRANGLE LOCATION

FIGURE 3

Geologic Map of Brunner Island

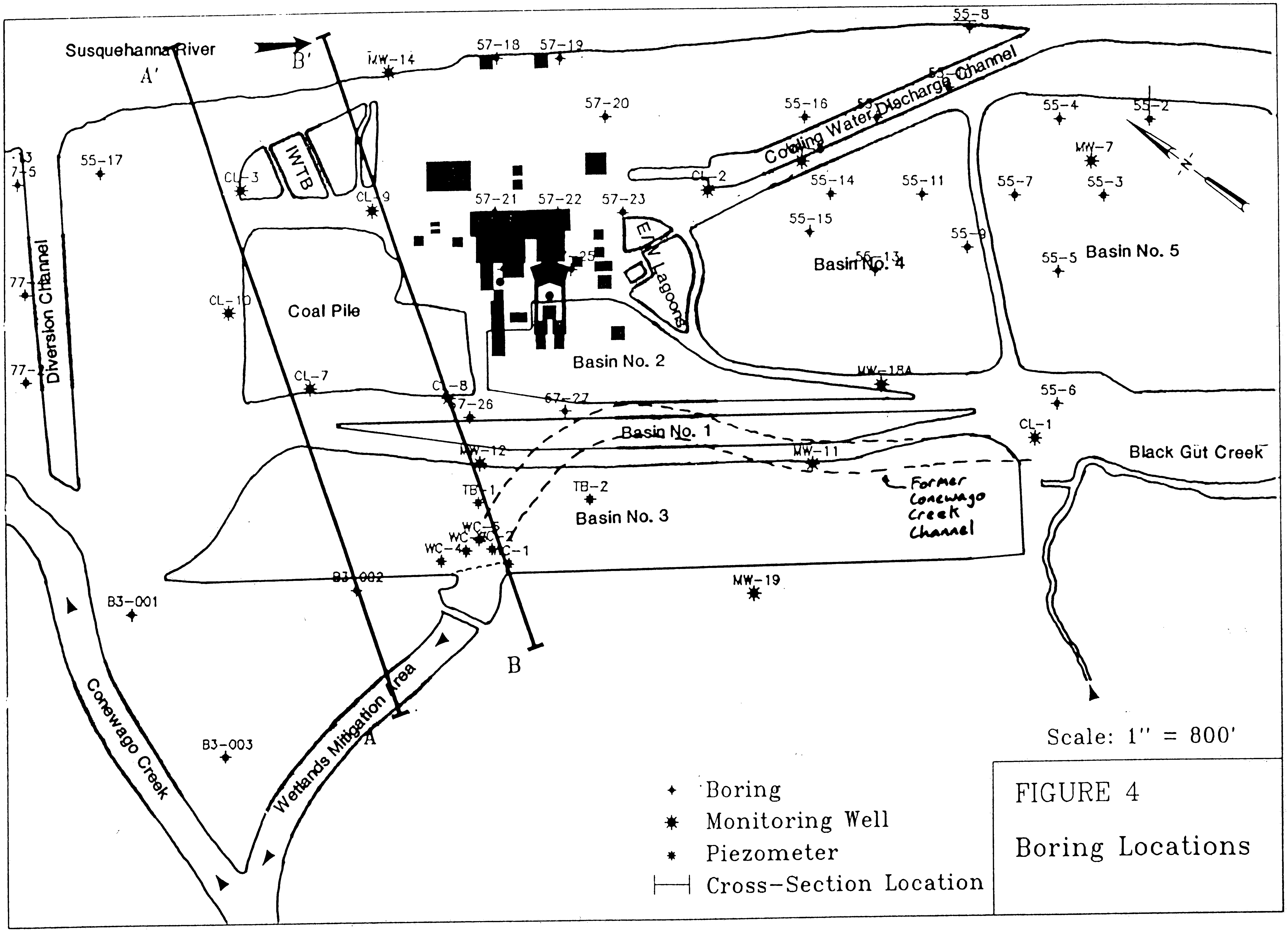


FIGURE 4

Boring Locations

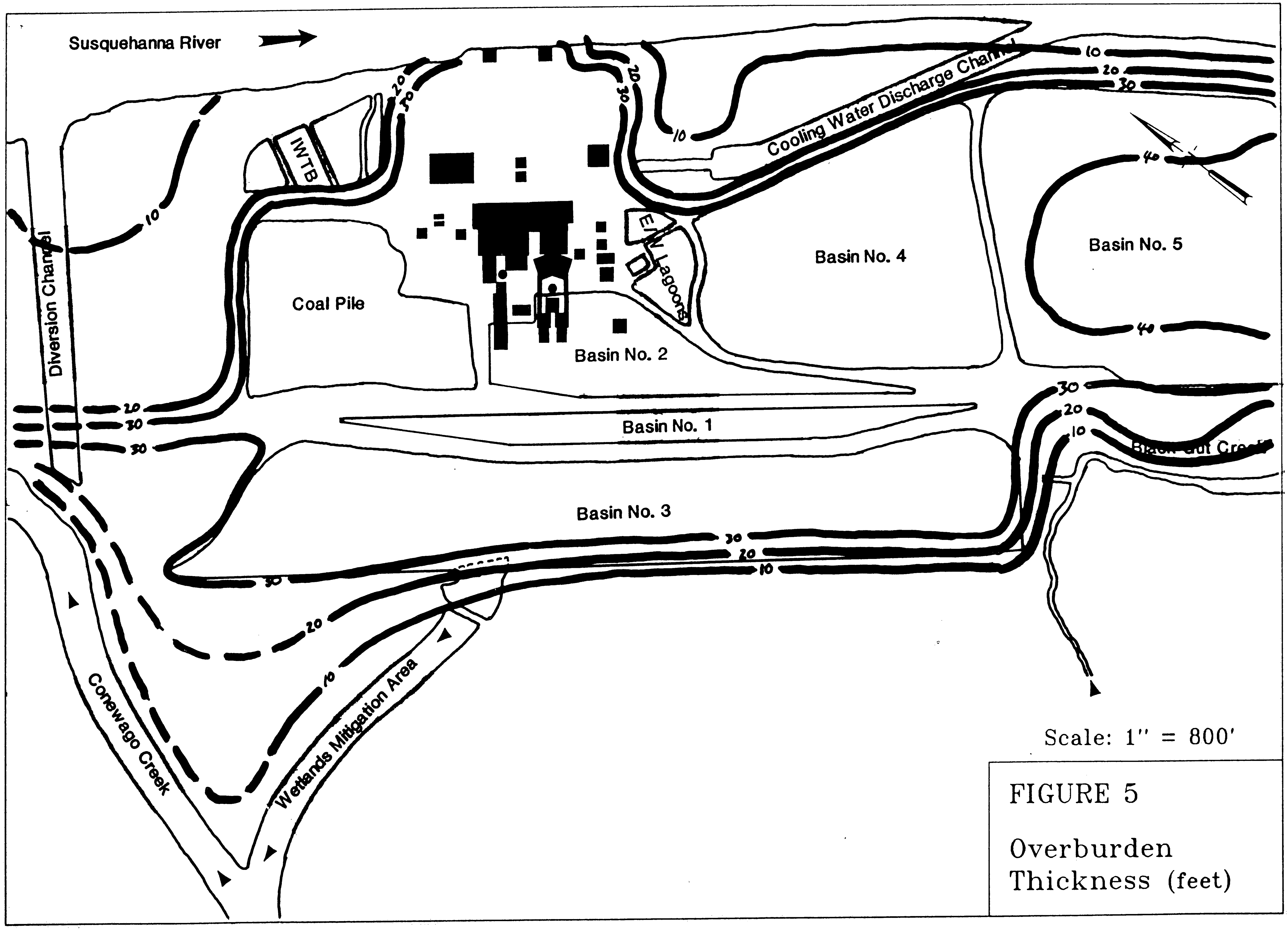


FIGURE 5

Overburden Thickness (feet)

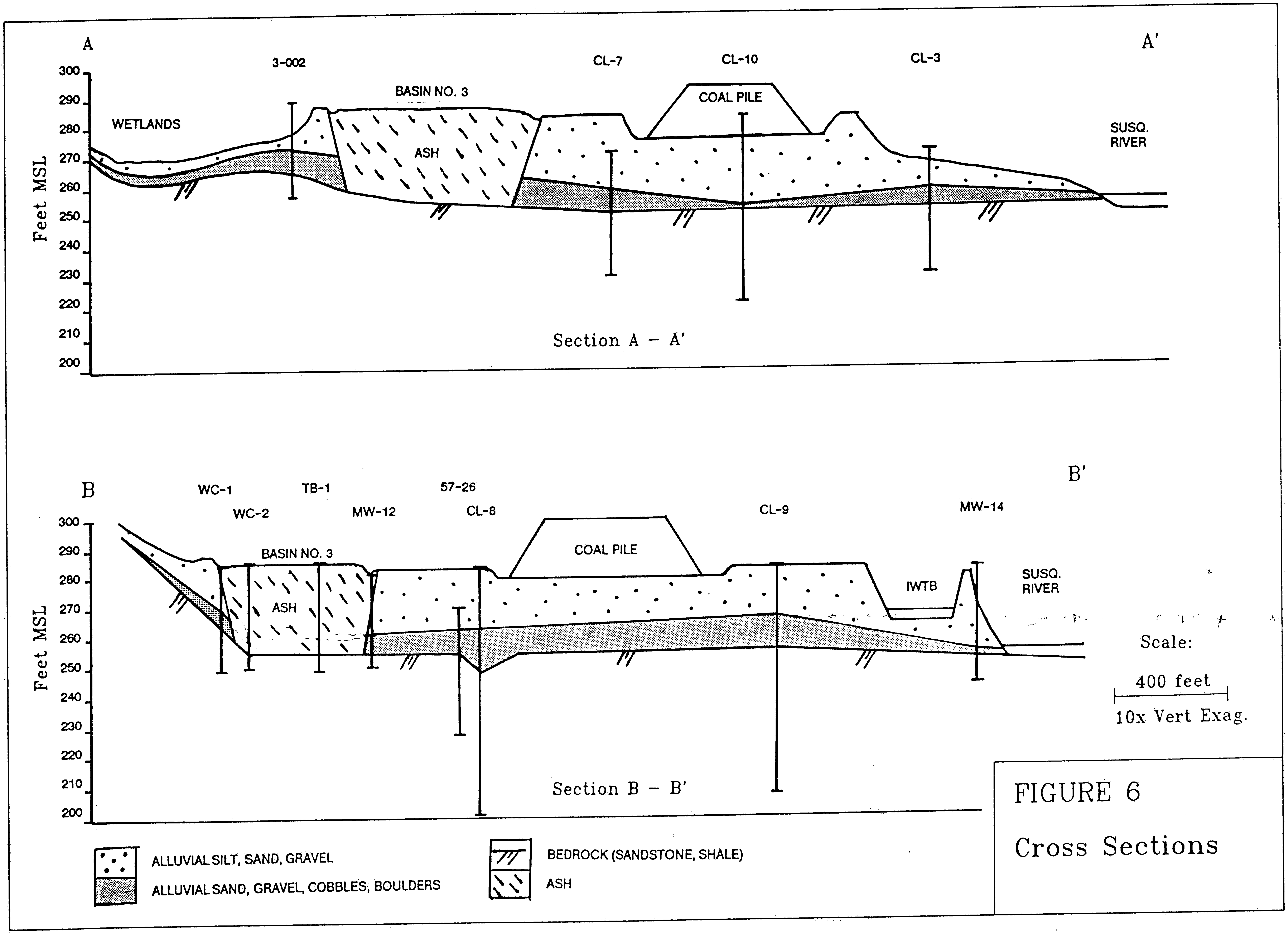


FIGURE 6

Cross Sections

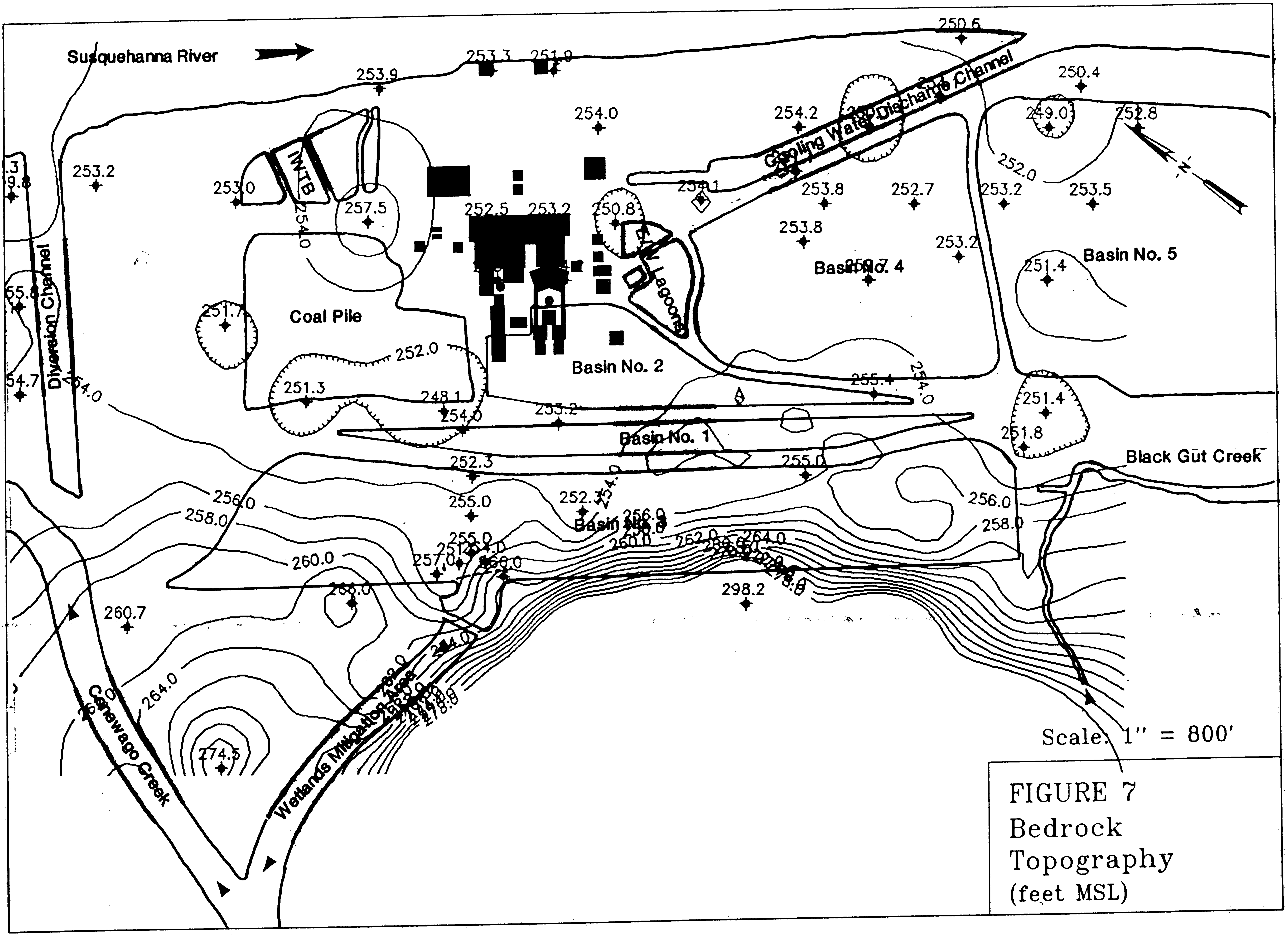


FIGURE 7
Bedrock
Topography
(feet MSL)

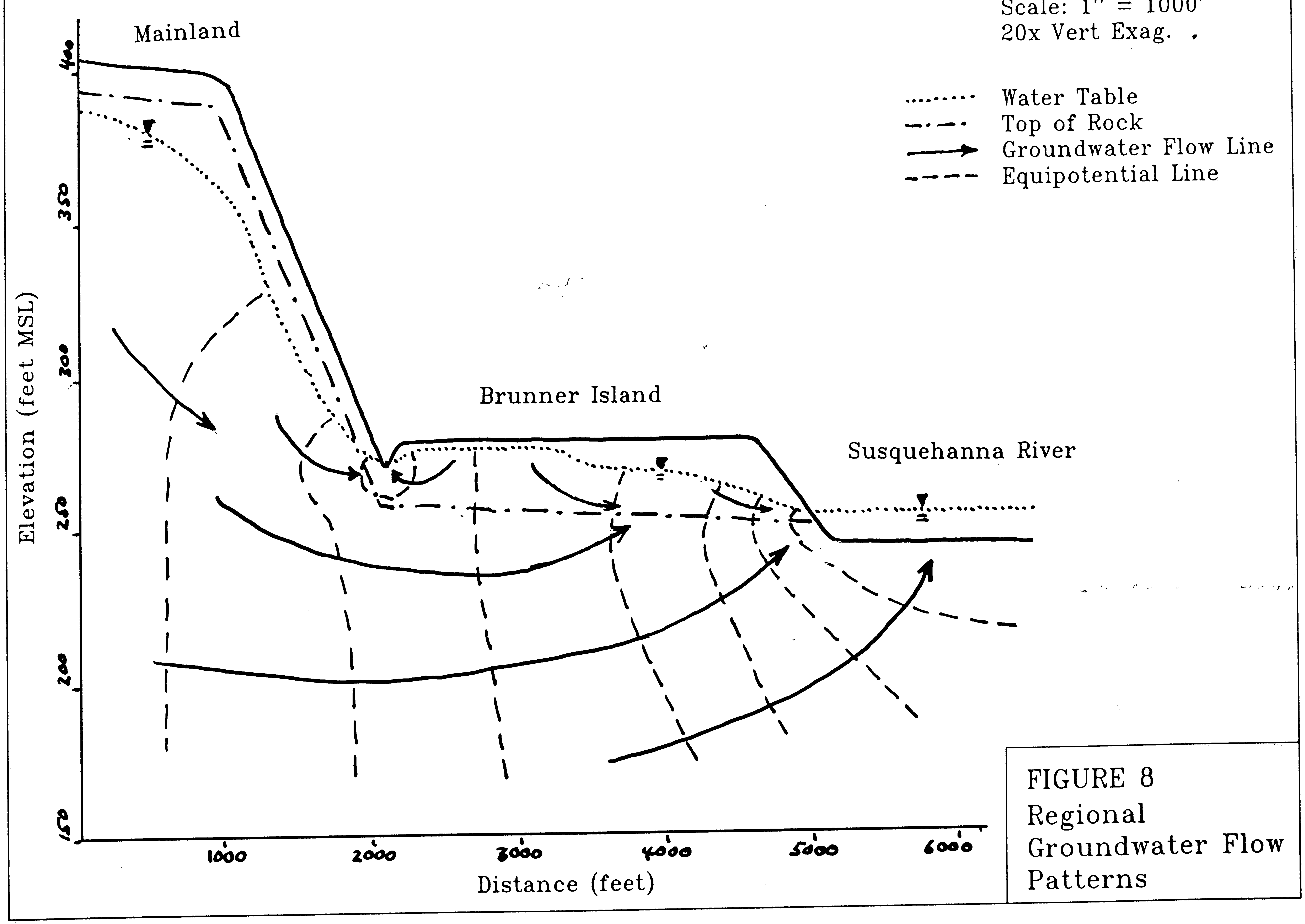


FIGURE 8
Regional
Groundwater Flow
Patterns

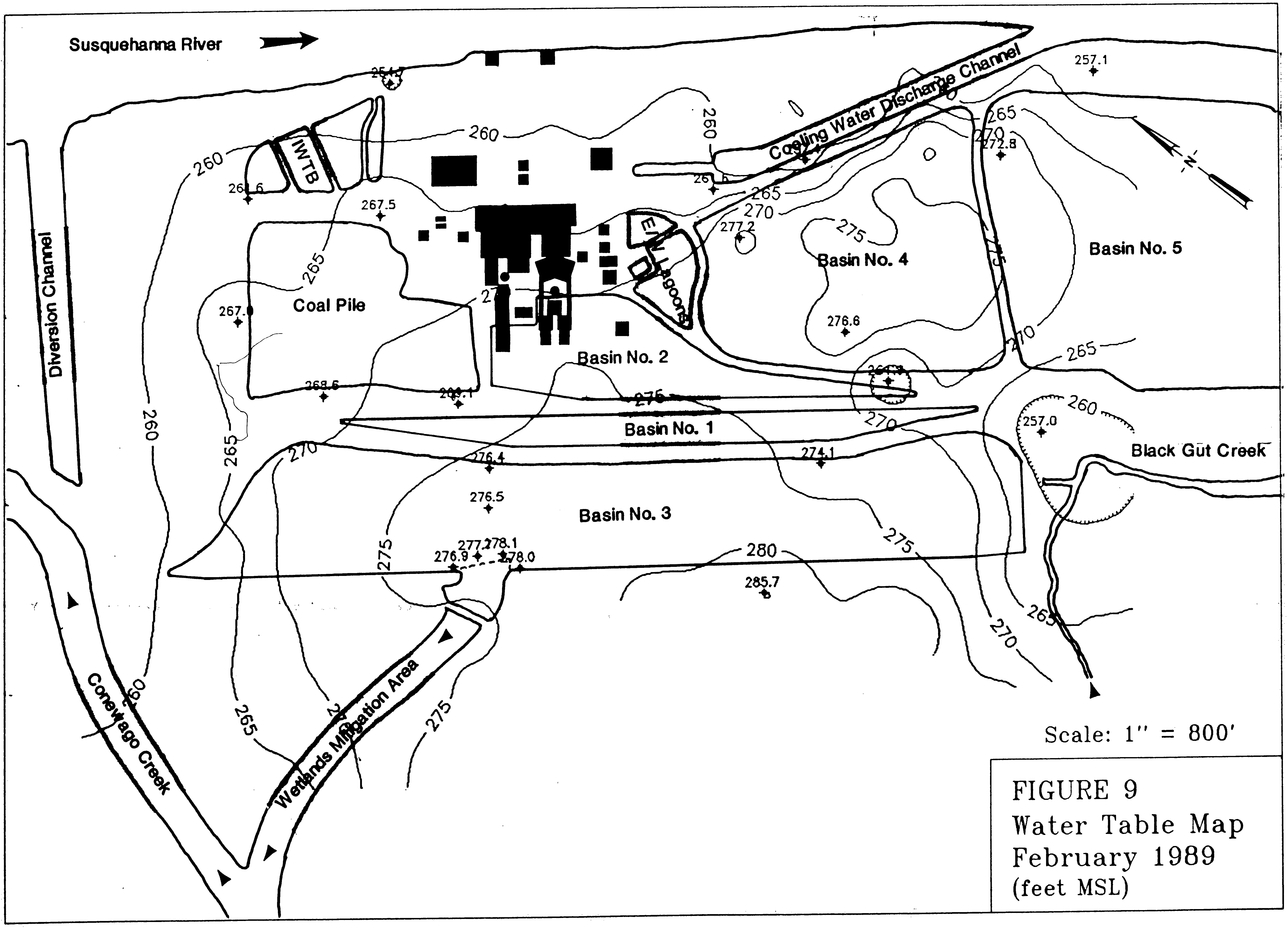
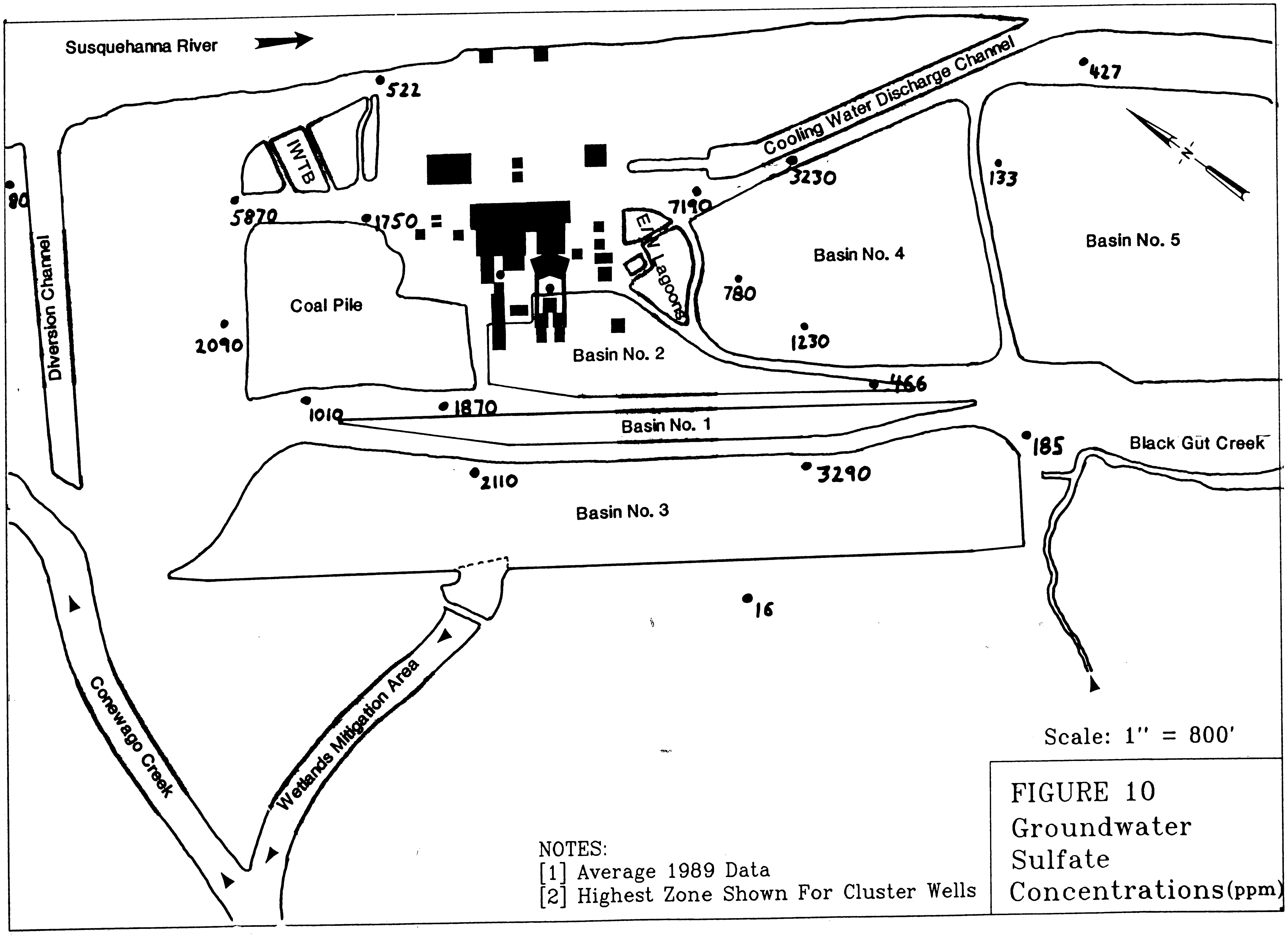


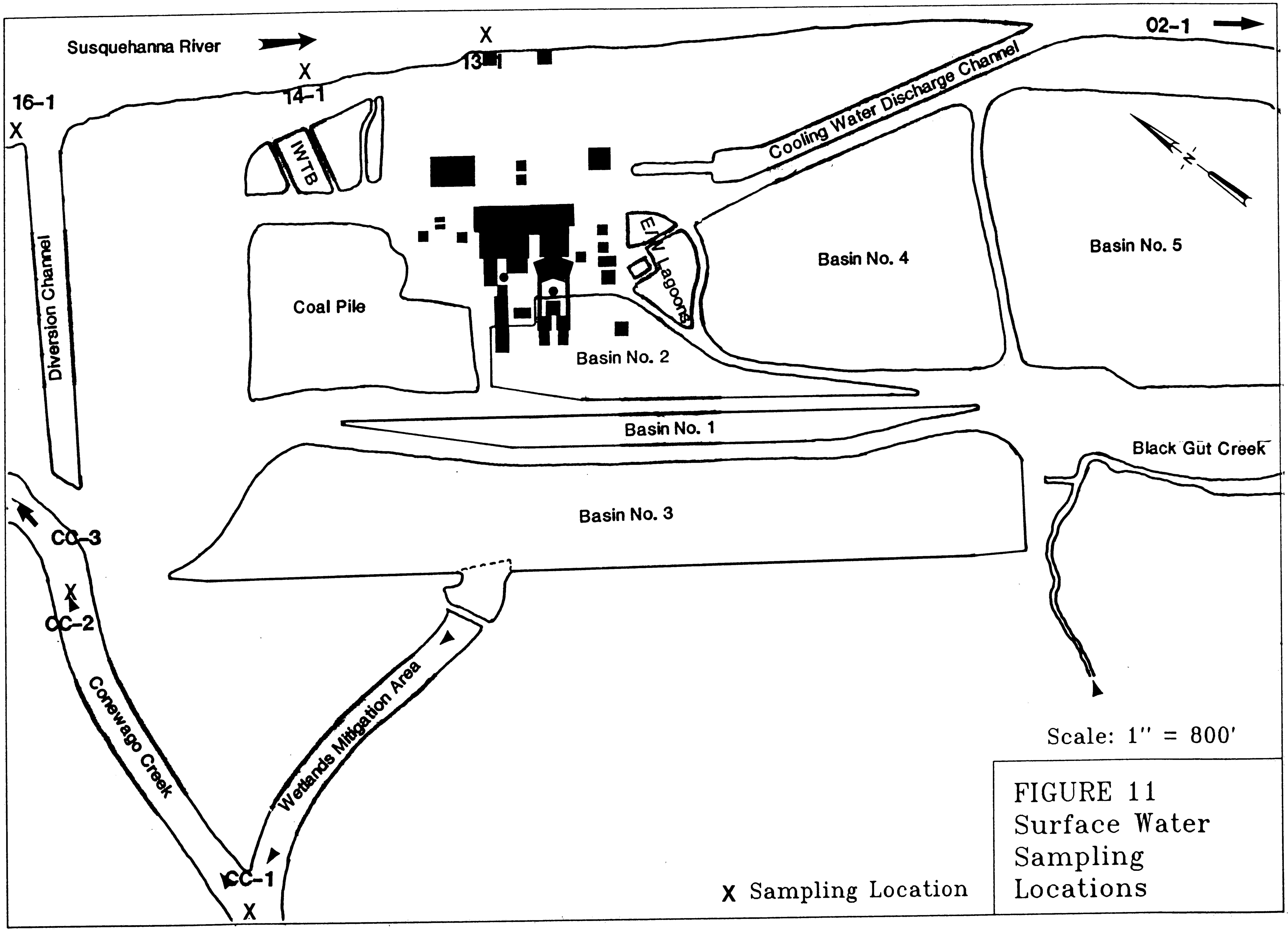
FIGURE 9
Water Table Map
February 1989
(feet MSL)



Scale: 1" = 800'

NOTES:
[1] Average 1989 Data
[2] Highest Zone Shown For Cluster Wells

FIGURE 10
Groundwater
Sulfate
Concentrations(ppm)

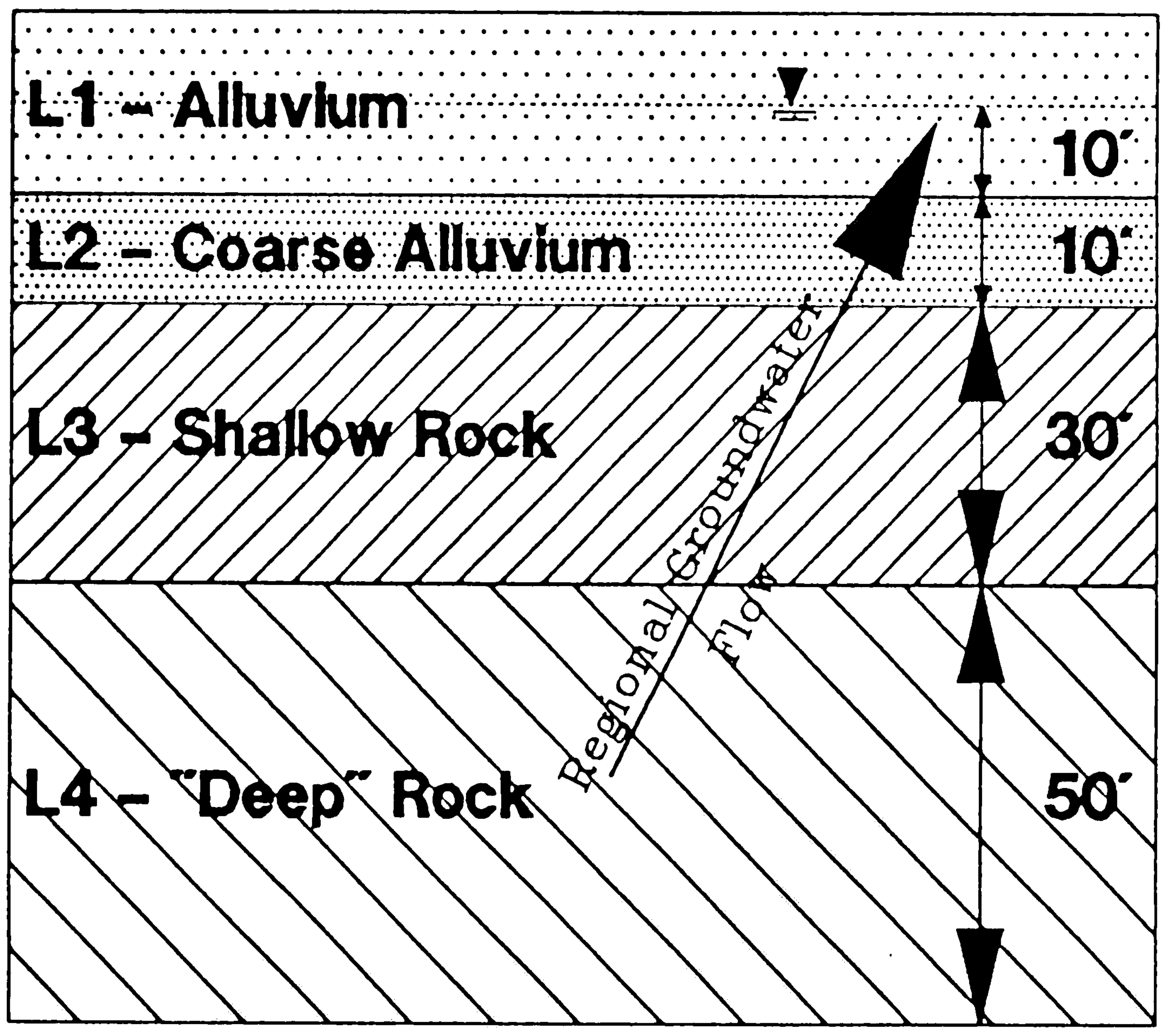


Scale: 1" = 800'

X Sampling Location

FIGURE 11
Surface Water
Sampling
Locations

## 1. Layer Conceptualization



| Kh (ft/d) | Kv (ft/d) | Kv/Kh |
|---|---|---|
| 8.0 | 0.8 | 1/10 |
| 10. | 1.0 | 1/10 |
| 5.0 | 0.05 | 1/100 |
| 0.5 | 0.005 | 1/100 |

## 2. Calculate K From Layer 4 to Layer 1

L/K = L1/K1 + L2/K2 + L3/K3 + L4/K4

70/K = 5/.8 + 10/1 + 30/.05 + 25/.005

K = 0.0125 ft/d

## 3. Calculate Q From Layer 4 to Layer 1

i = 0.023 ft/ft

A = 22 Ac (960,000 ft2)

Q = KiA

Q = 0.0125 ft/d * 0.023 ft/ft * 960,000 ft2 * 7.48 gal/ft2

Q = 2060 gal/d

FIGURE 12
Calculation of
Vertical
Groundwater Flow

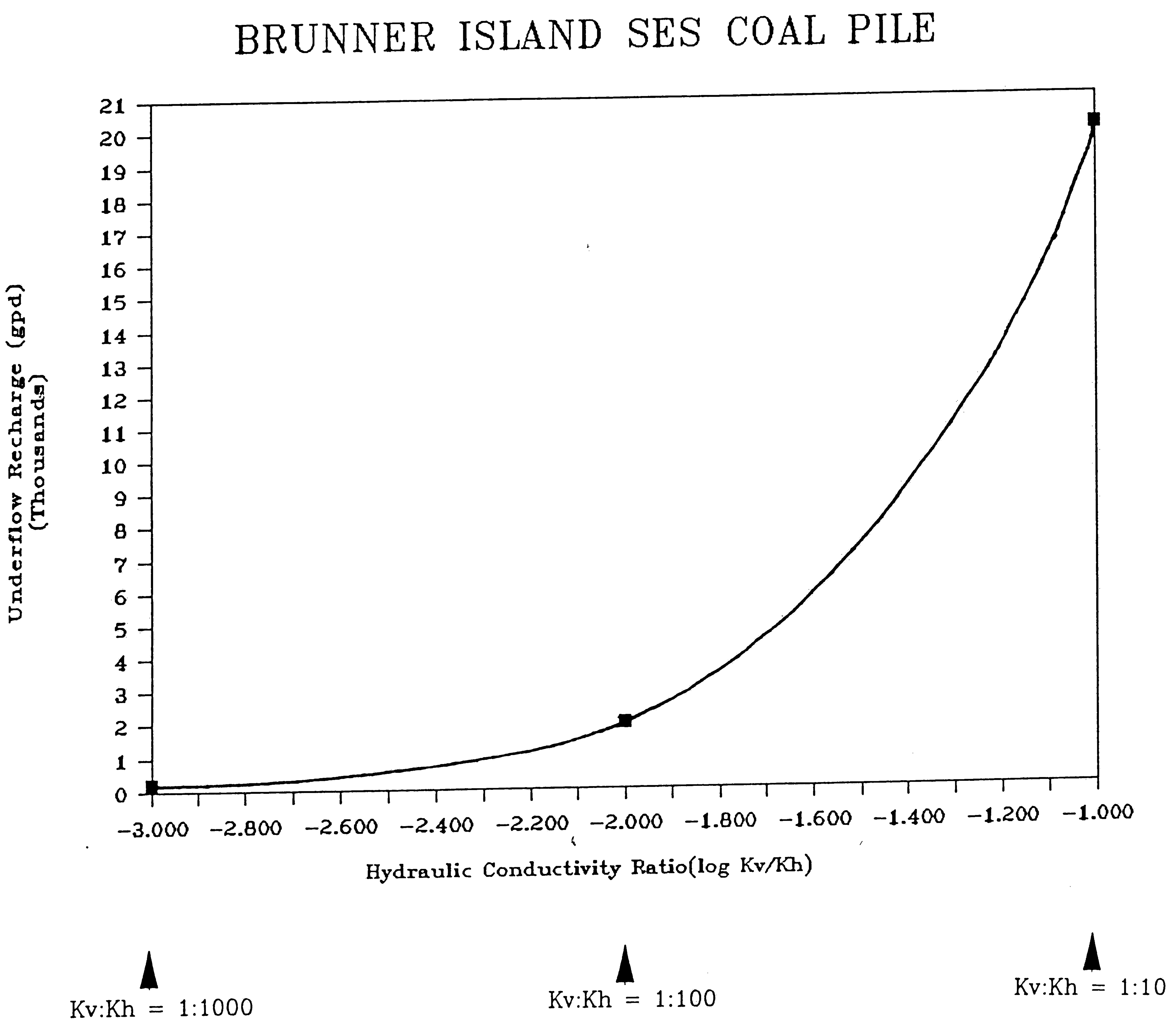


FIGURE 13
Underflow
Recharge vs.
Kv:Kh Ratio

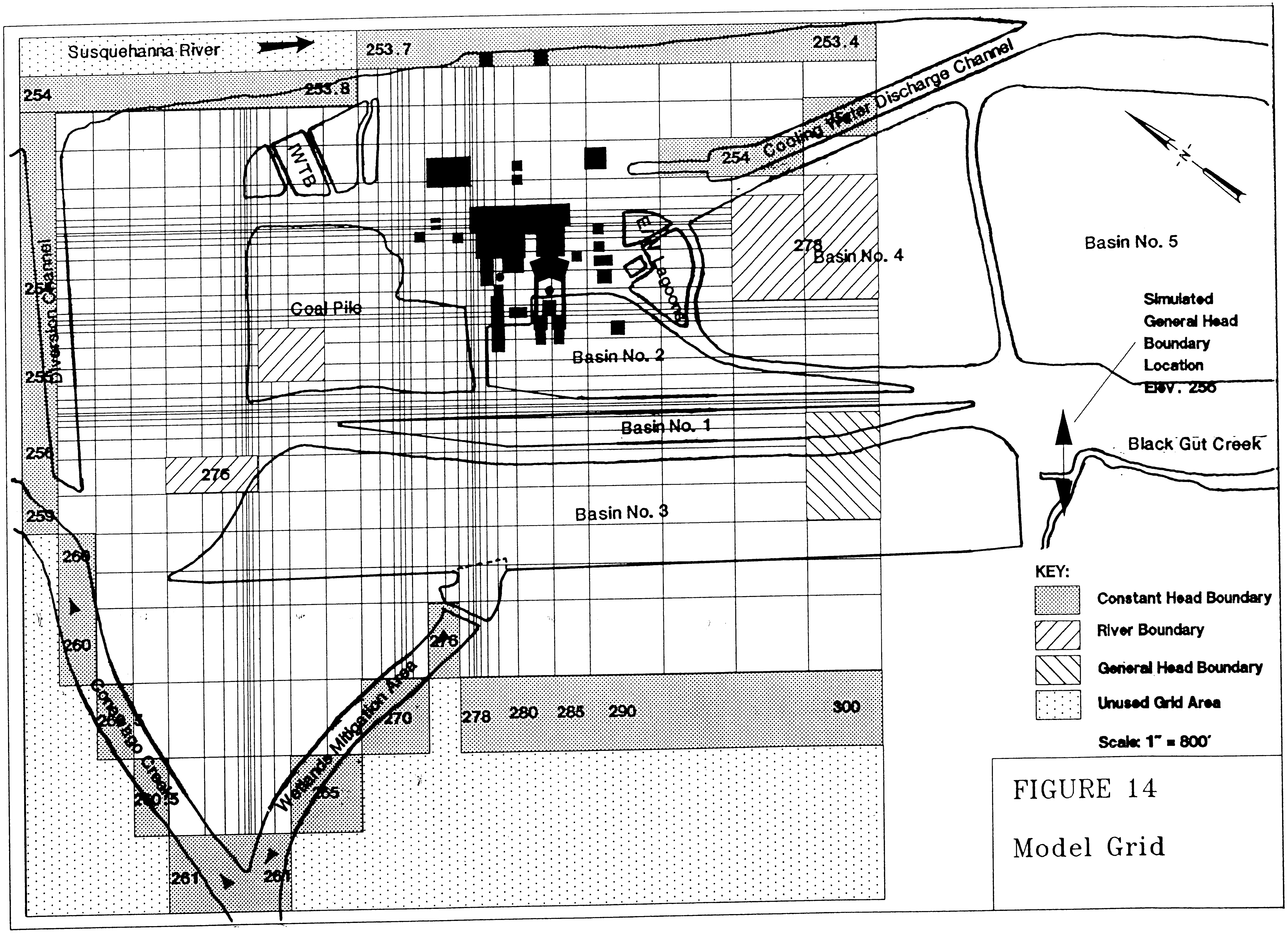


FIGURE 14

Model Grid

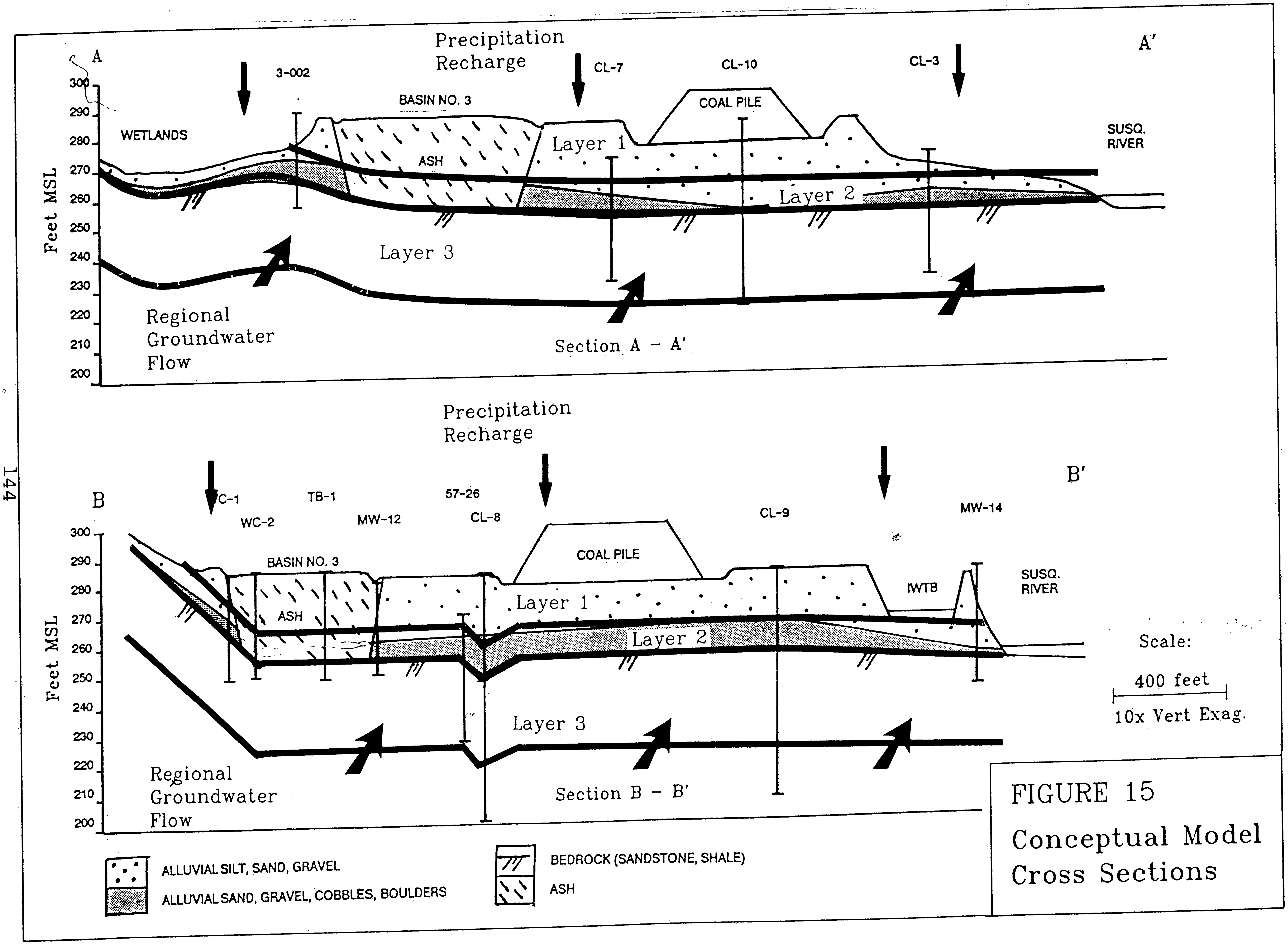


FIGURE 15

Conceptual Model Cross Sections

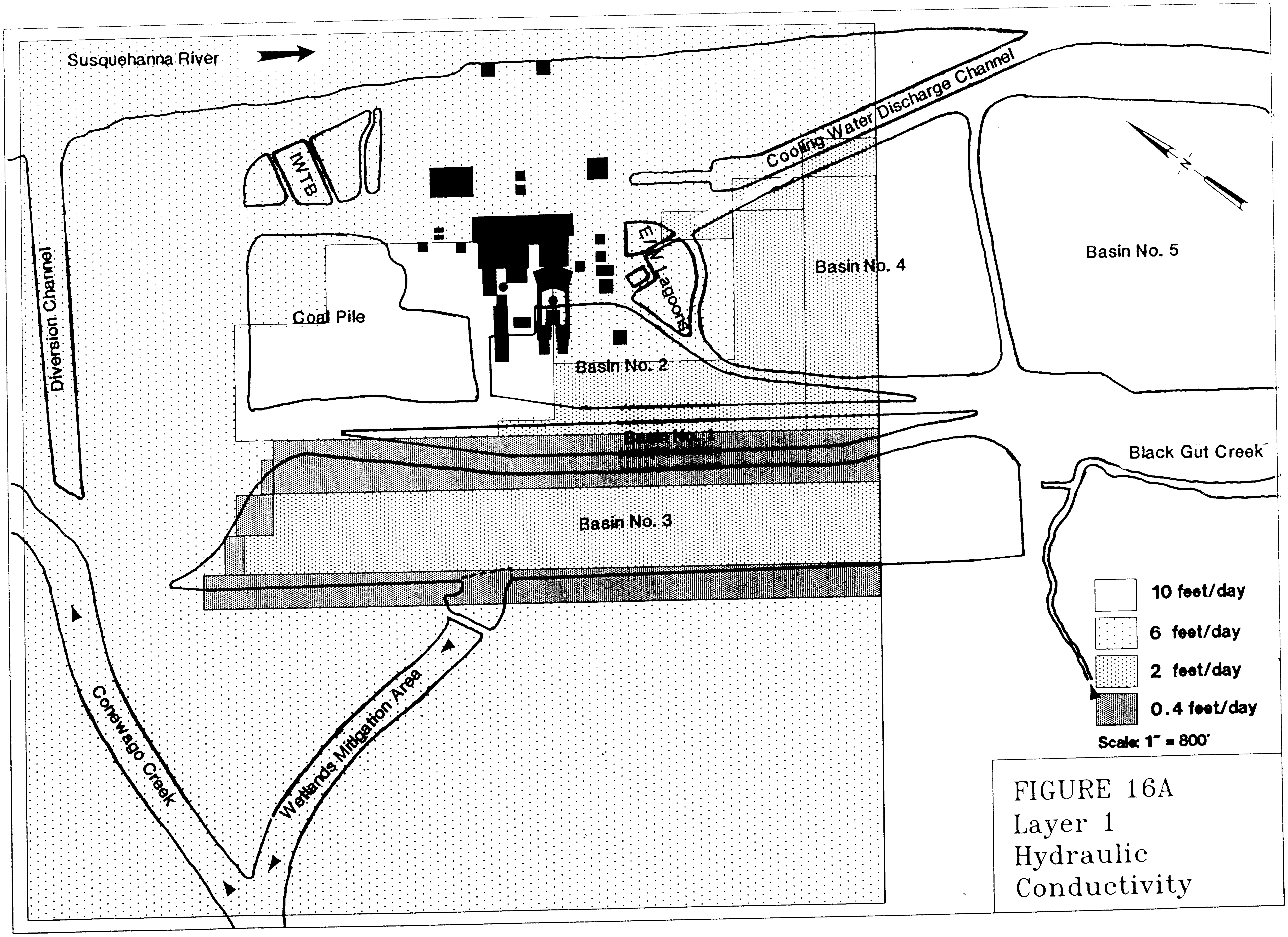


FIGURE 16A
Layer 1
Hydraulic
Conductivity

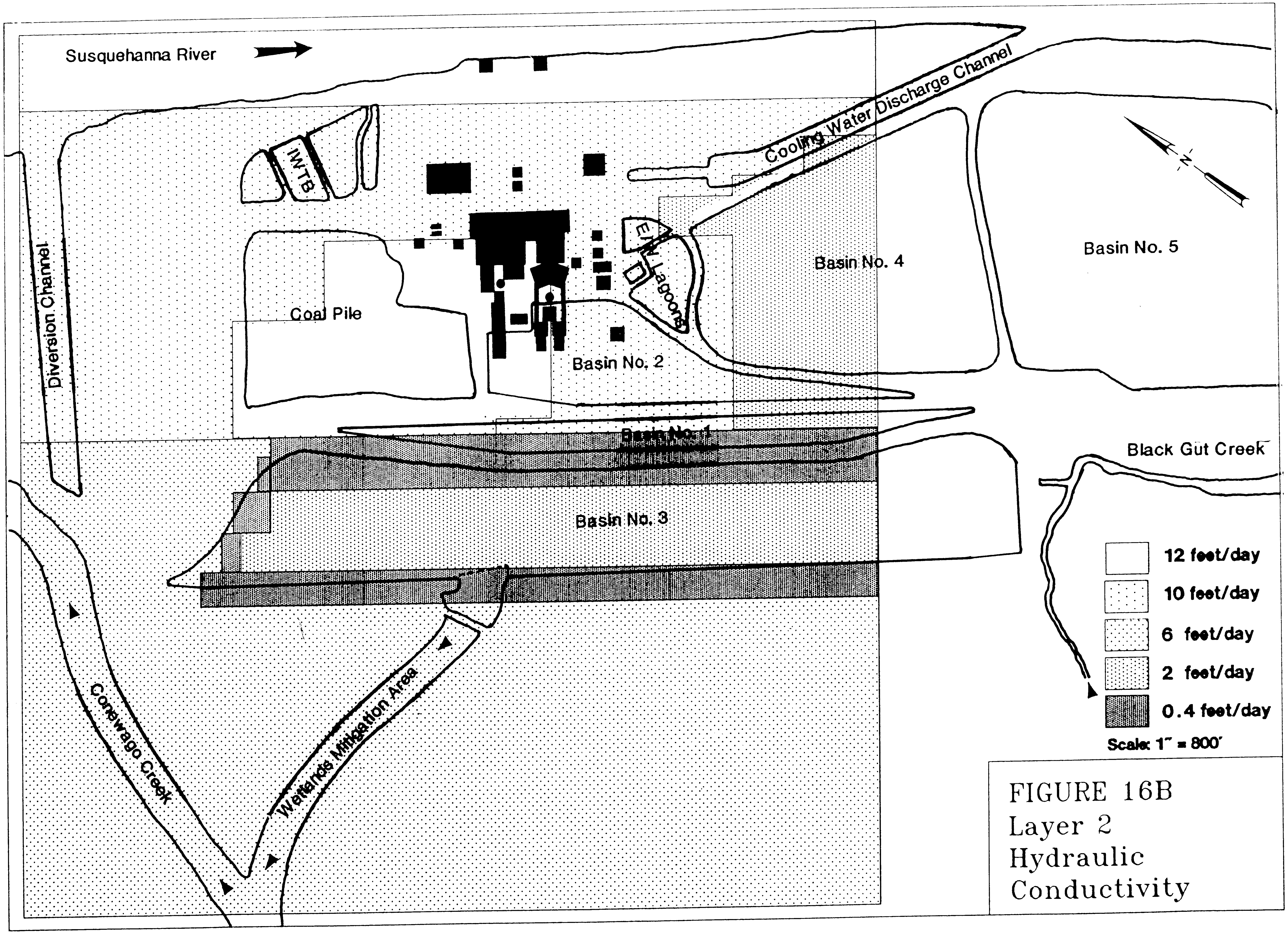


FIGURE 16B
Layer 2
Hydraulic
Conductivity

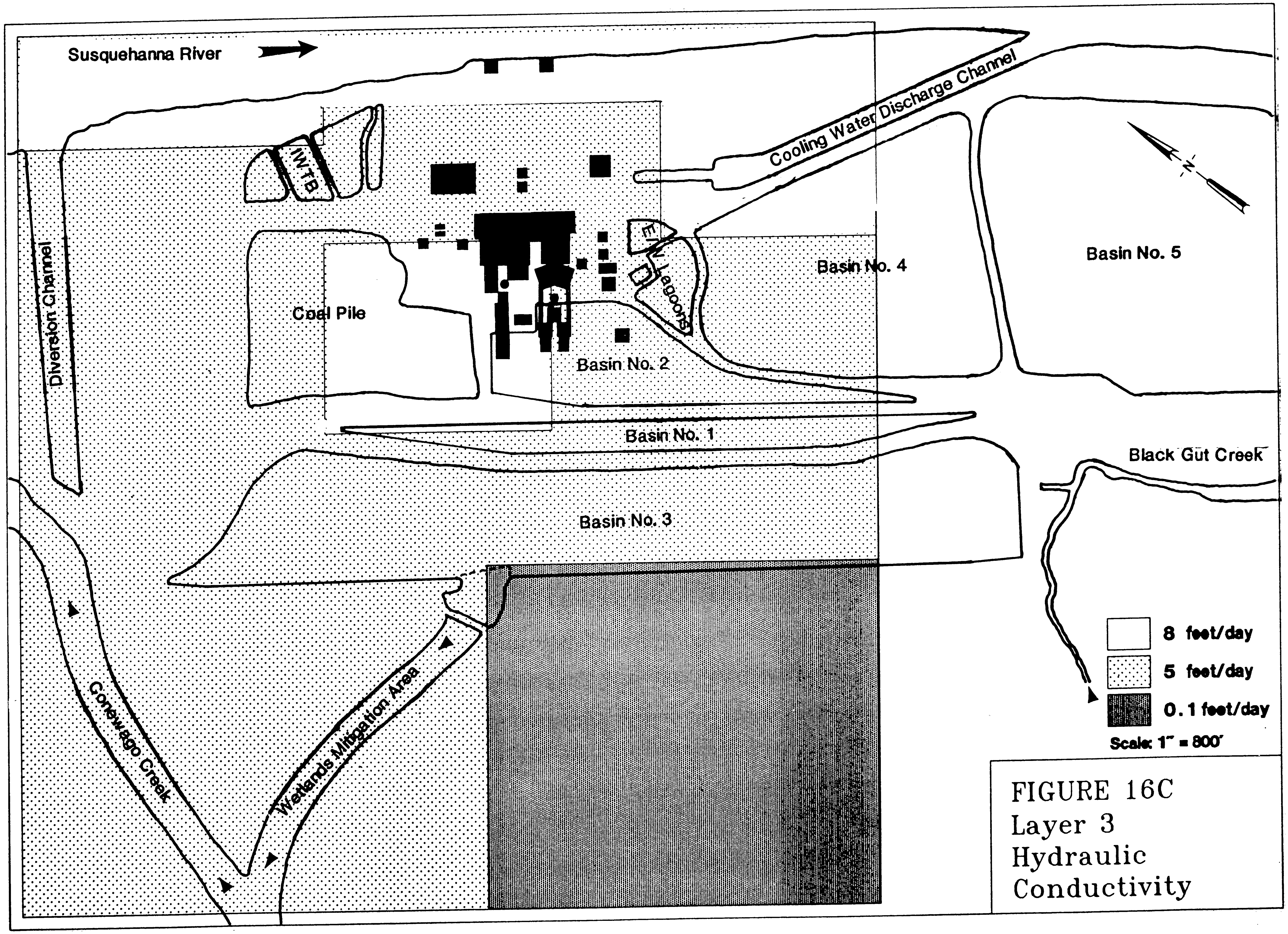


FIGURE 16C
Layer 3
Hydraulic
Conductivity

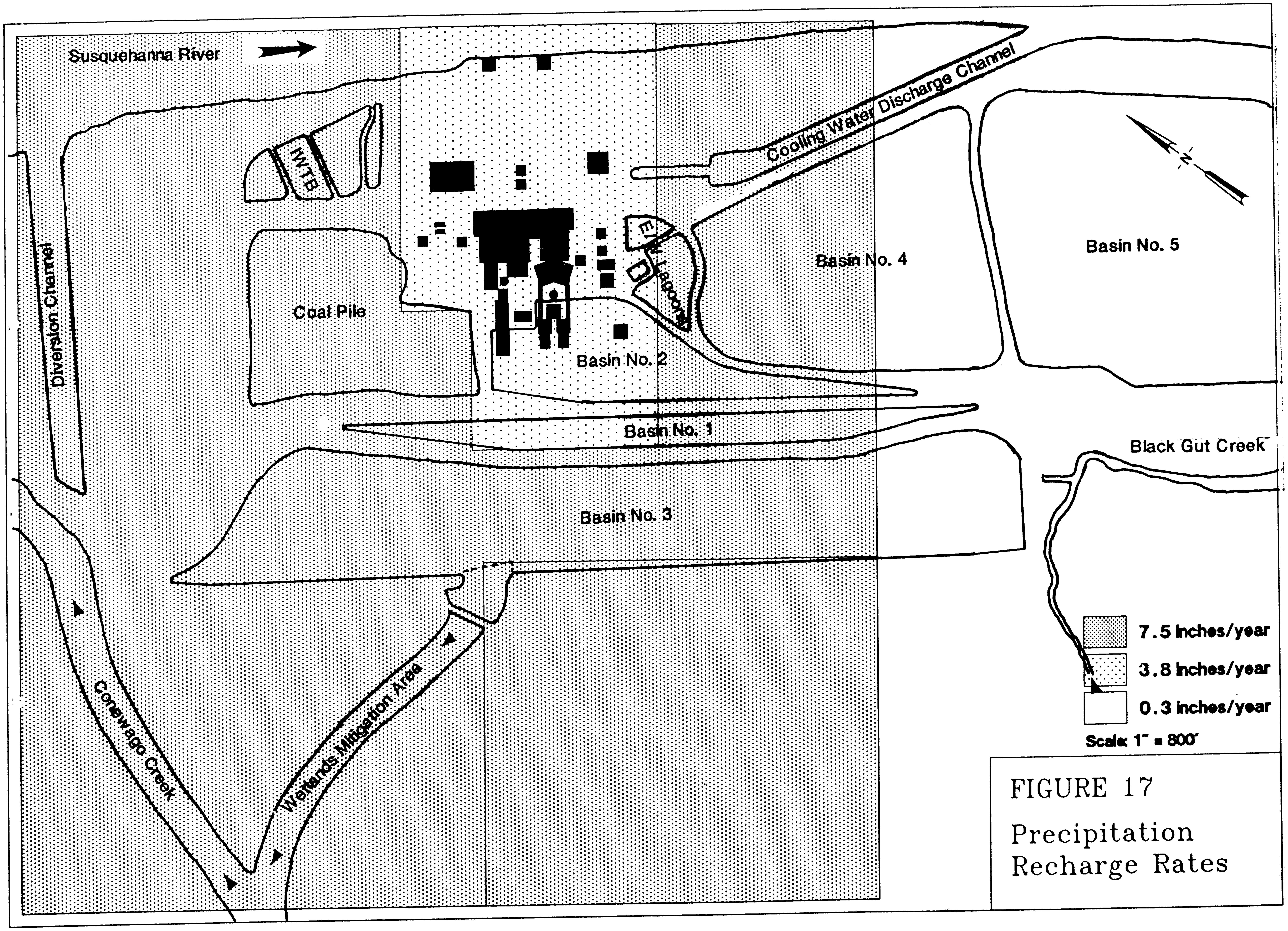
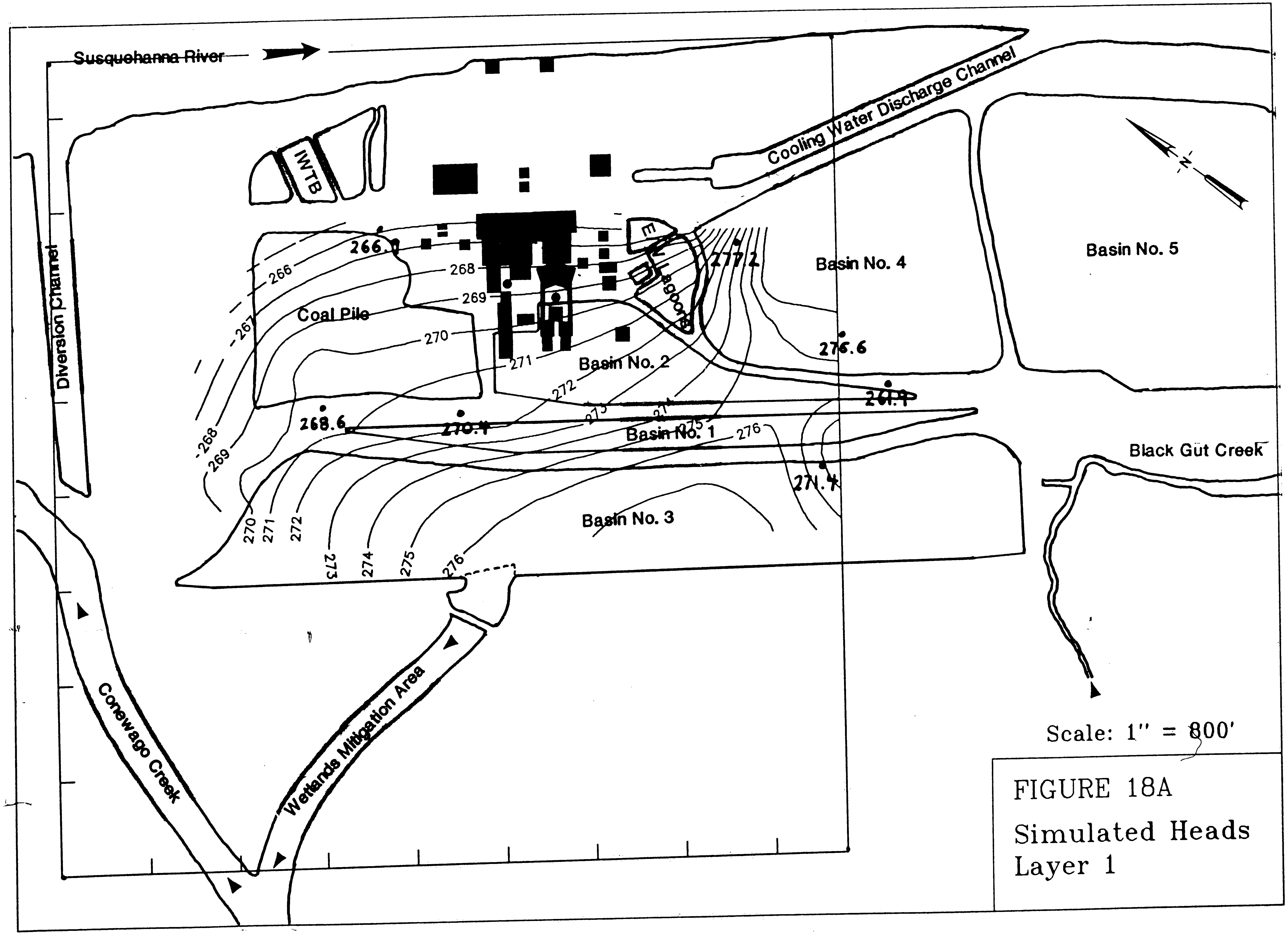
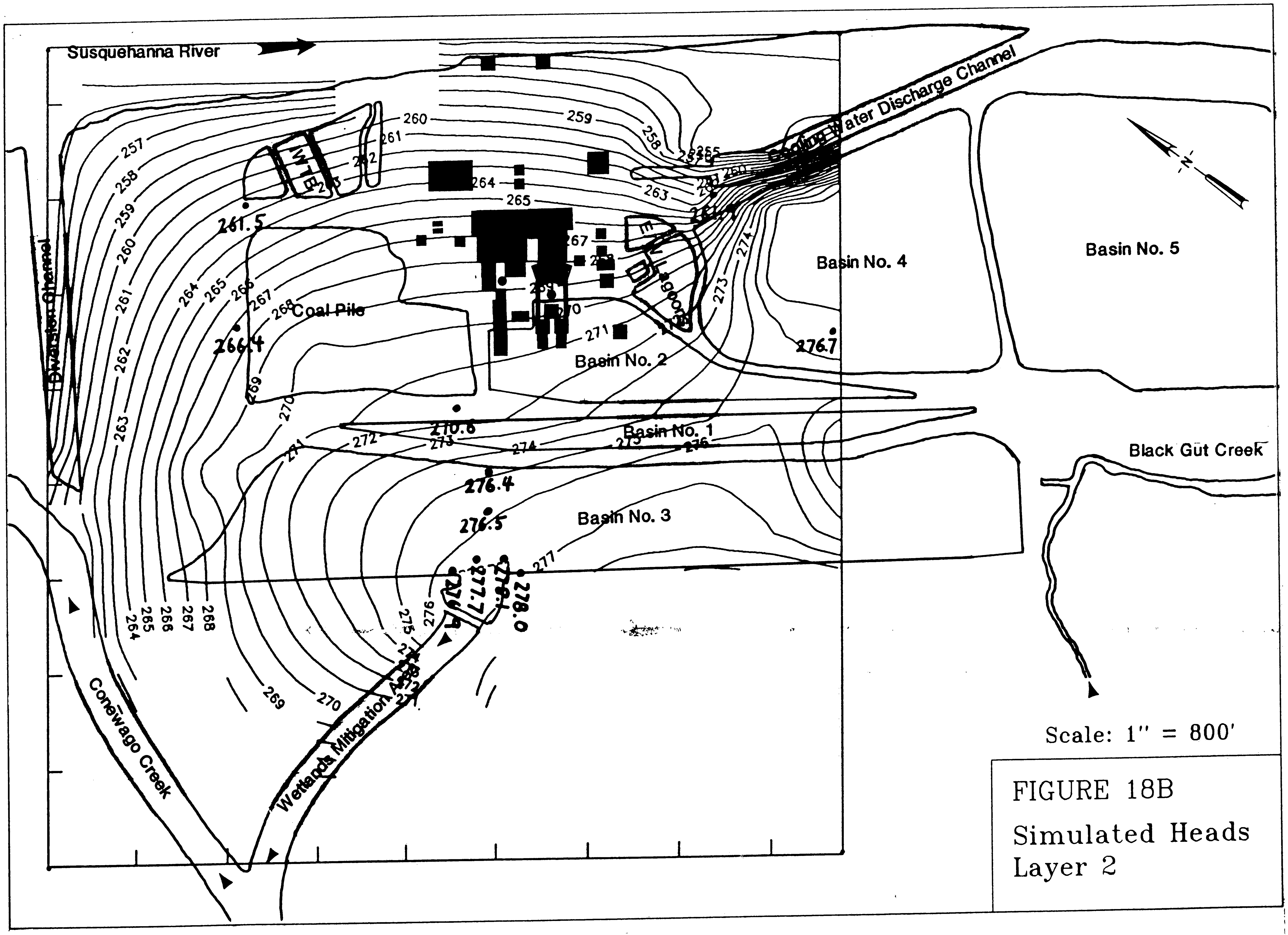


FIGURE 17
Precipitation
Recharge Rates



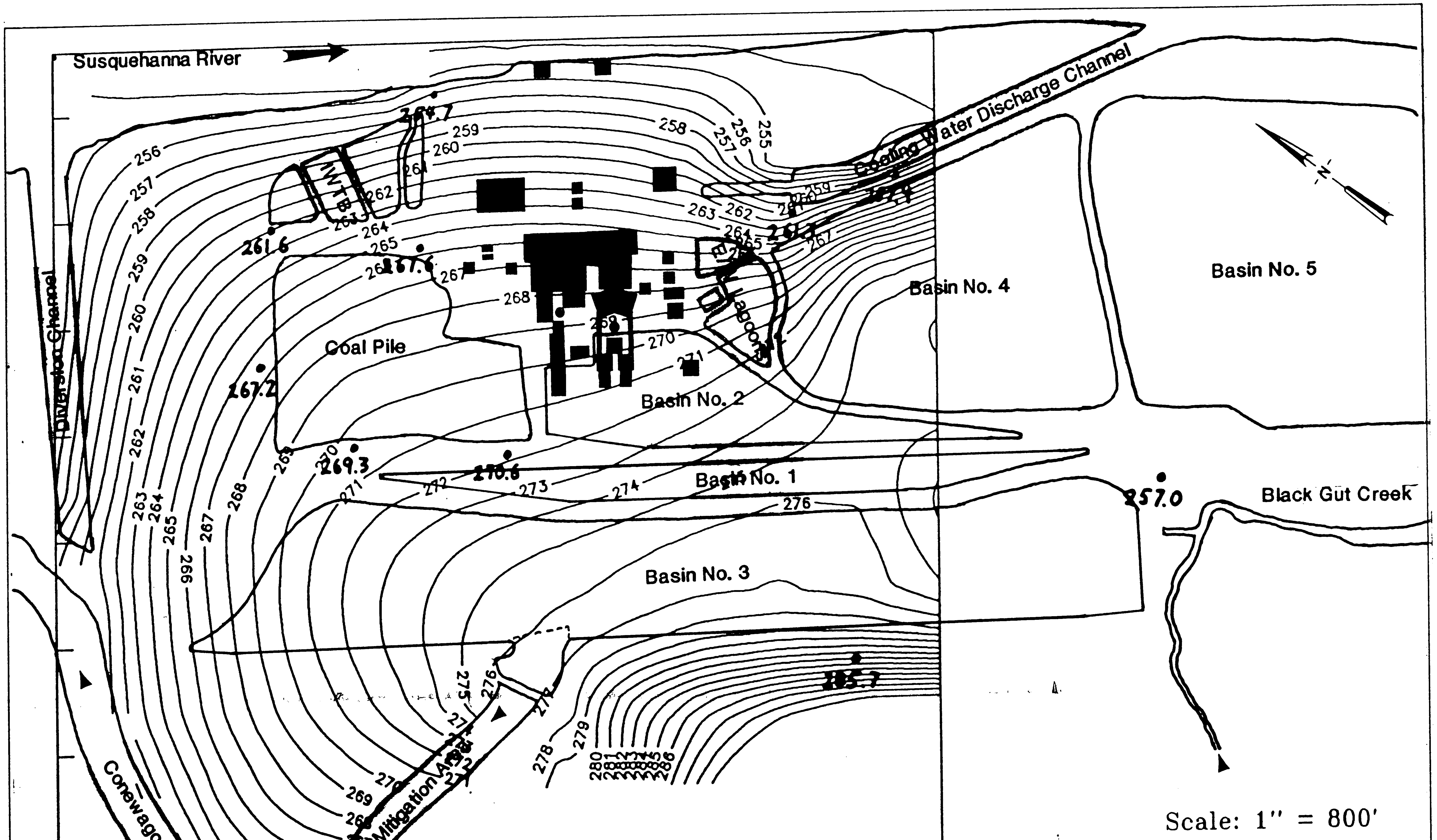
Scale: 1" = 800'

FIGURE 18A
Simulated Heads
Layer 1



Scale: 1" = 800'

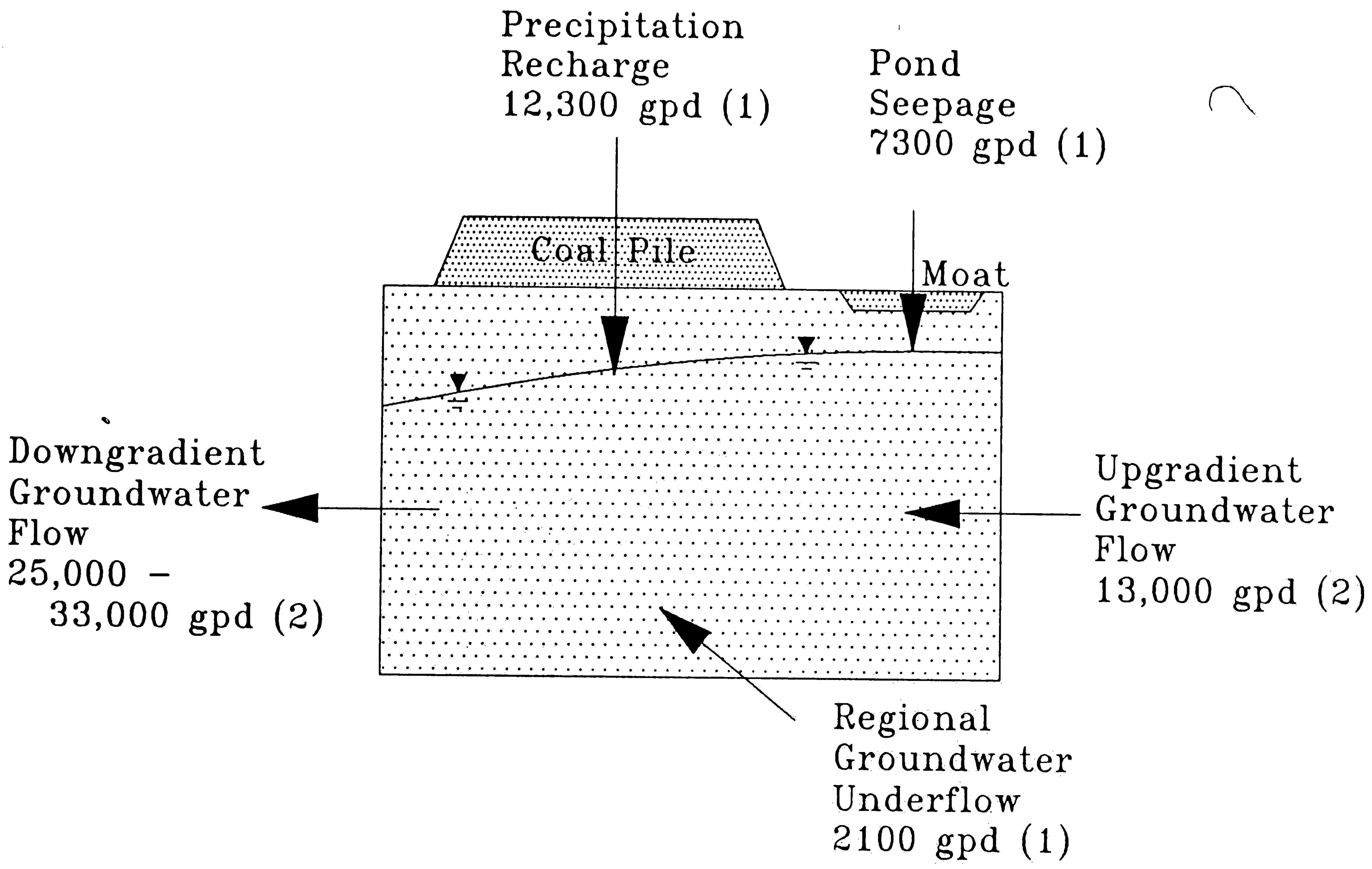
FIGURE 18B
Simulated Heads
Layer 2



Scale: 1" = 800'

FIGURE 18C

Simulated Heads Layer 3



Net Addition of Water to Aquifer Across the Coal Pile

1. Model Predictions:
   Recharge – 12,300 gpd
   Seepage – 7,300 gpd
   Underflow – 2,100 gpd
   TOTAL 21,700 gpd

2. Predicted Using Darcy's Law:
   Upgradient Flow Entering – 13,000 gpd
   Downgradient Flow Exiting – 25,000 to 33,000 gpd
   NET 12,000 to 20,000 gpd
   (Average 16,000 gpd)

Notes:

(1) Model–predicted volumes

(2) Calculated using Darcy's Law and observed conditions upgradient/downgradient of coal pile

FIGURE 19

Coal Pile Water Budget

Governing Equation: Q = (Kv*A/d)(Hr−H)

Where:
Q = Seepage Rate
Kv = Vertical Hydraulic Conductivity
A = Area of Surface Water
d = Thickness of "Riverbed"
Hr = River Stage
H = Head in Aquifer

Relationship:

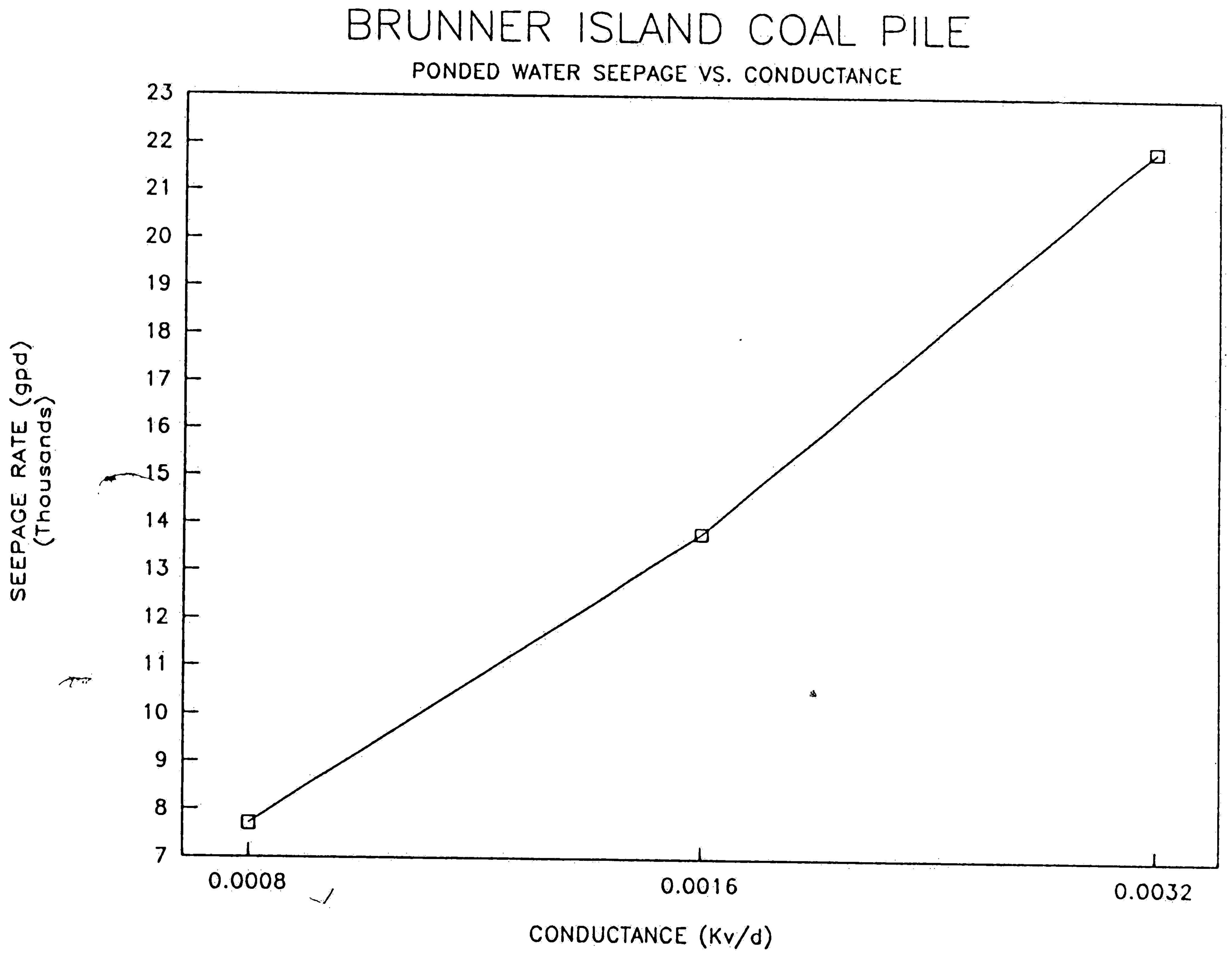


FIGURE 20

Seepage Rates and Conductance

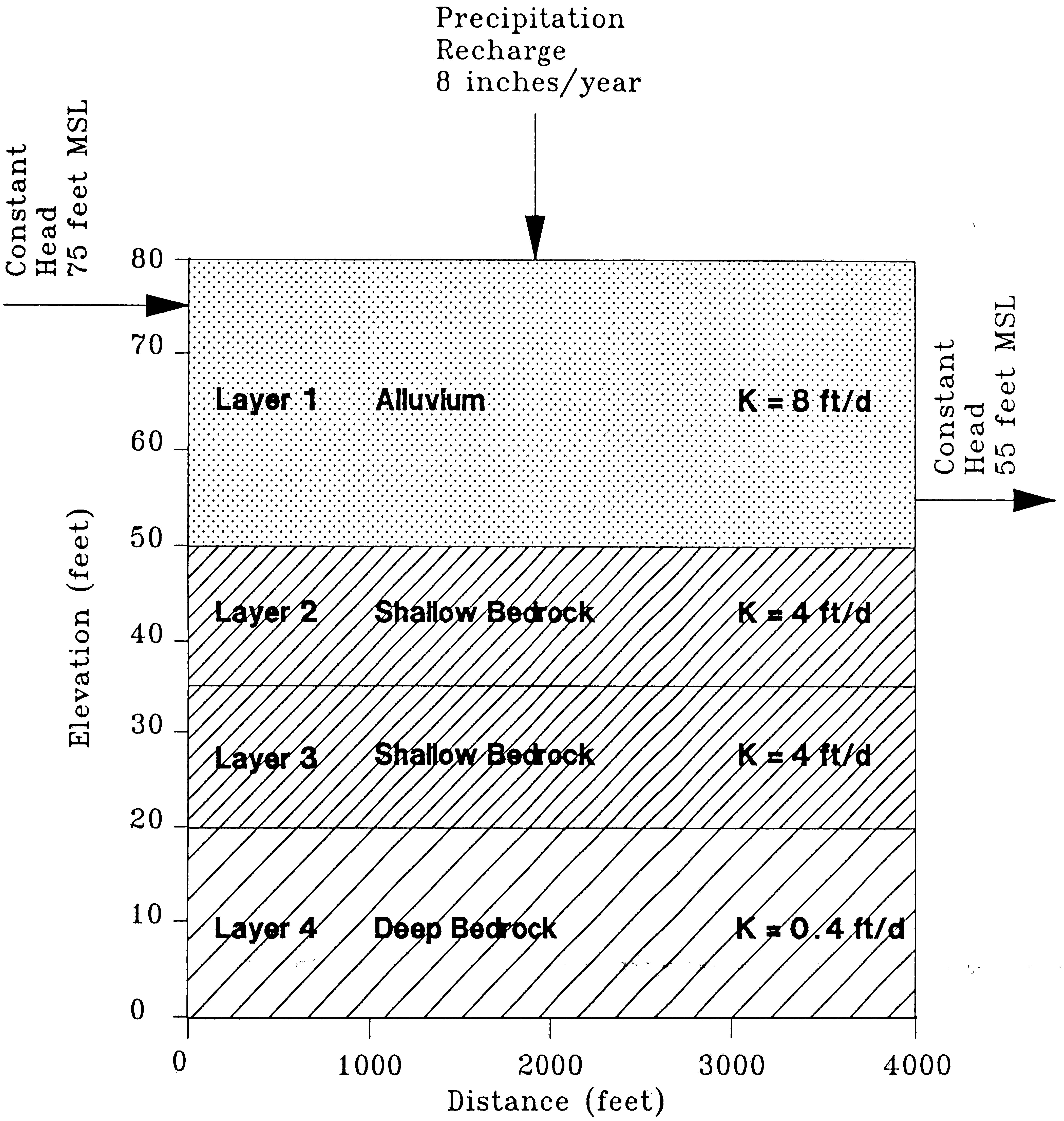


FIGURE 21
3-D Test Case
Conceptual
Diagram

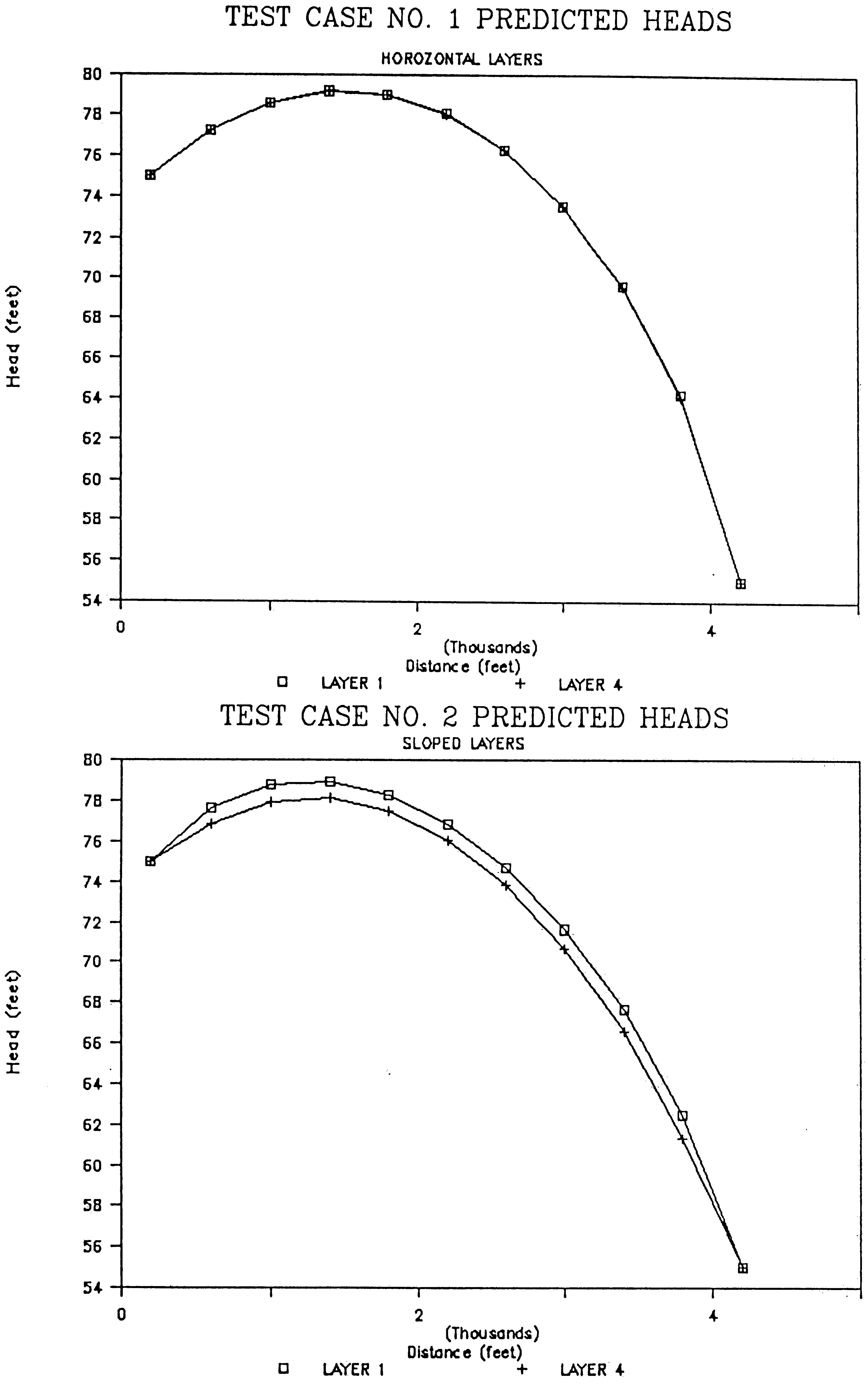
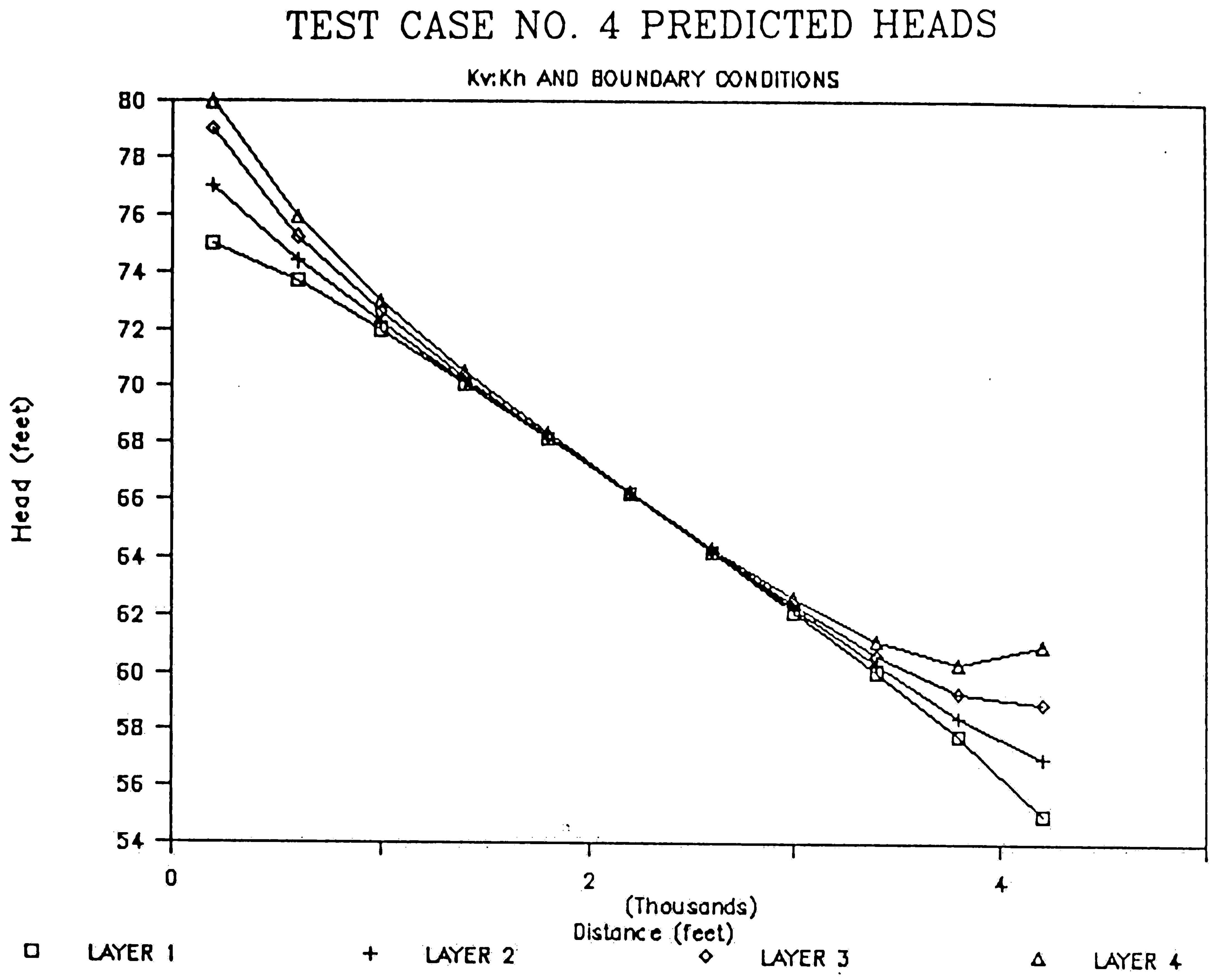
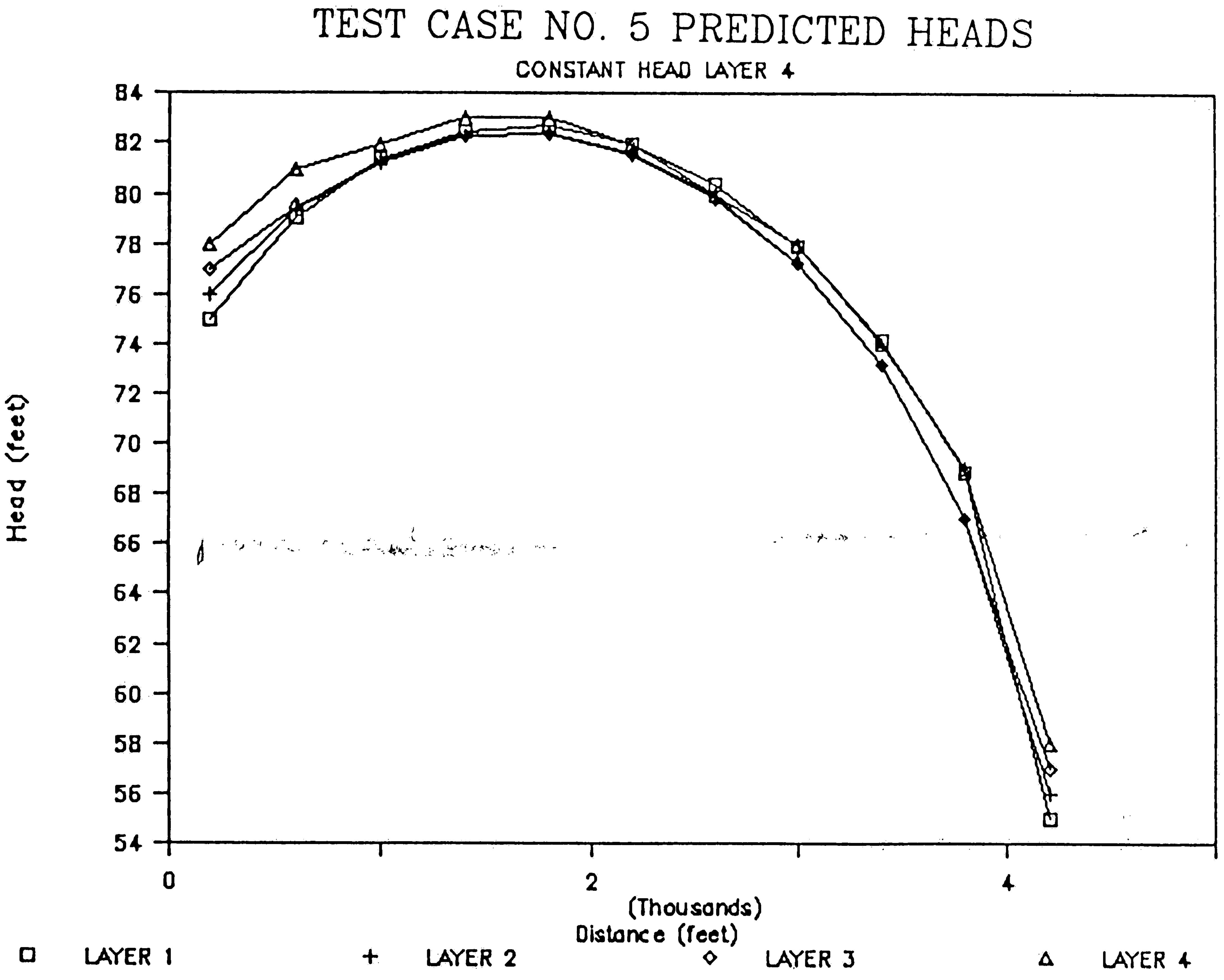


FIGURE 22A
Test Cases 1 & 2
Predicted Heads


TEST CASE NO. 4 PREDICTED HEADS

Kv:Kh AND BOUNDARY CONDITIONS


TEST CASE NO. 5 PREDICTED HEADS

CONSTANT HEAD LAYER 4

FIGURE 22B
Test Cases 4 & 5
Predicted Heads

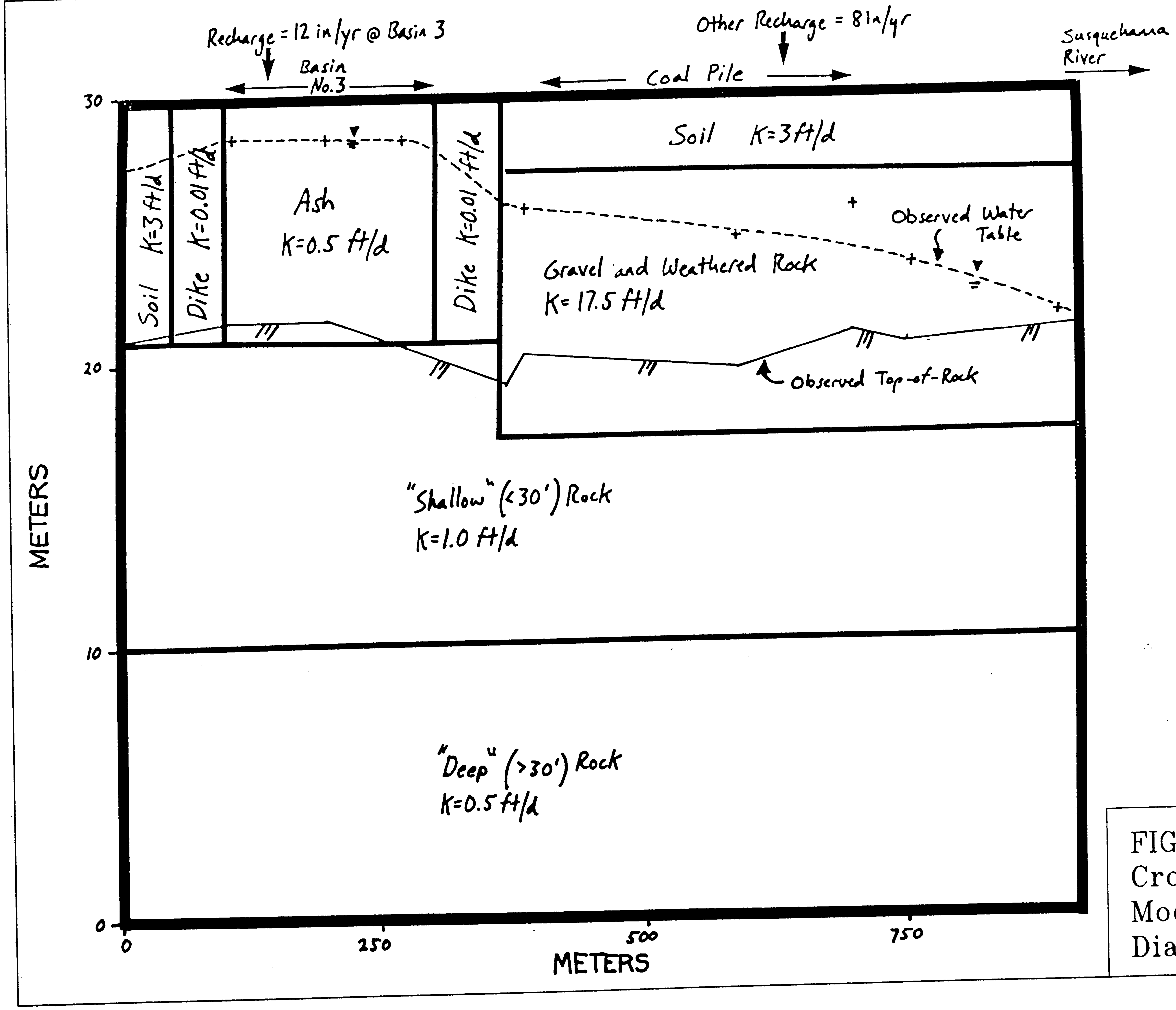


FIGURE 23
Cross–Sectional
Model Conceptual
Diagram

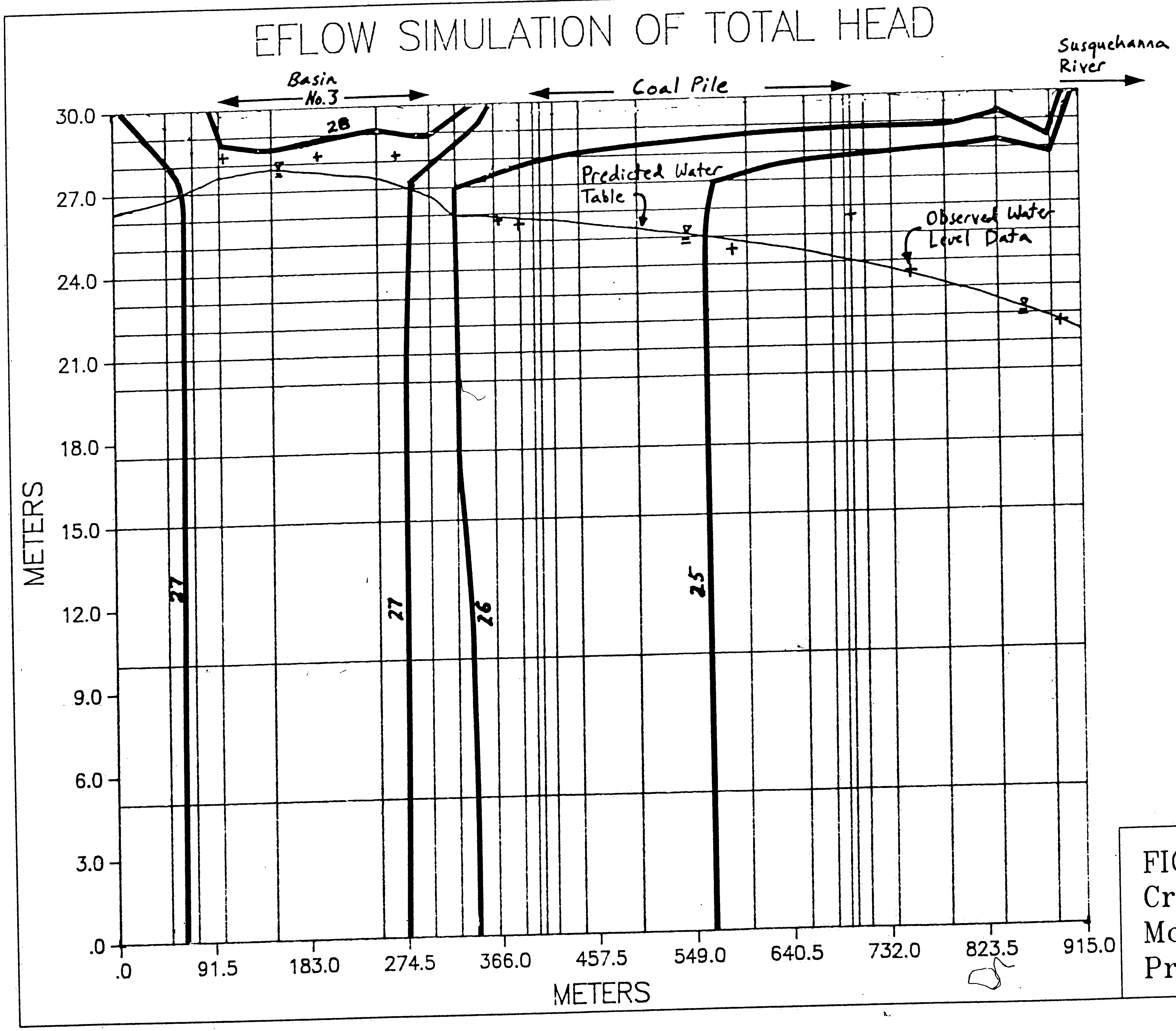


FIGURE 24
Cross-Sectional
Model
Predicted Heads

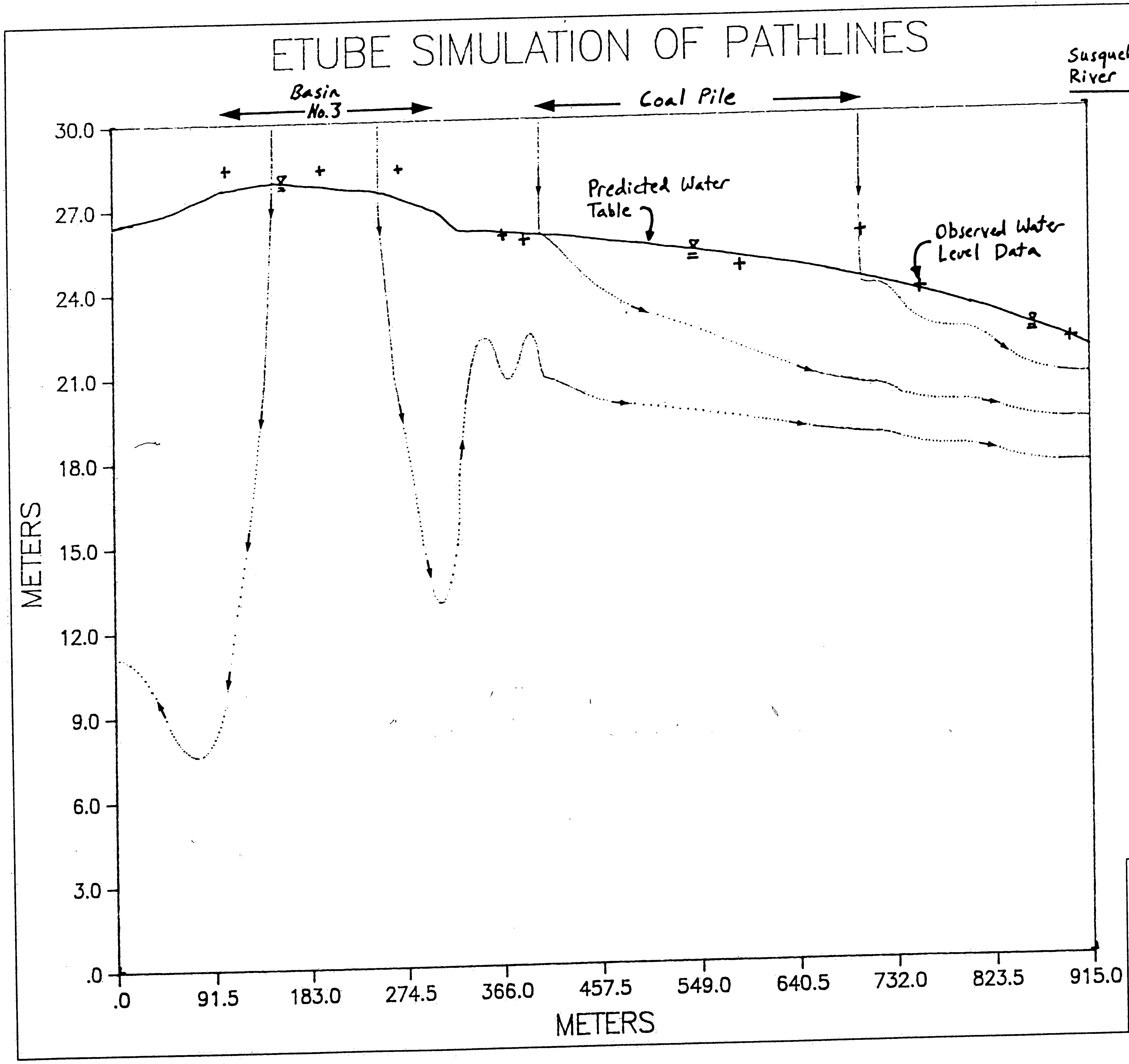


FIGURE 25
Cross-Sectional
Model Groundwater
Pathlines

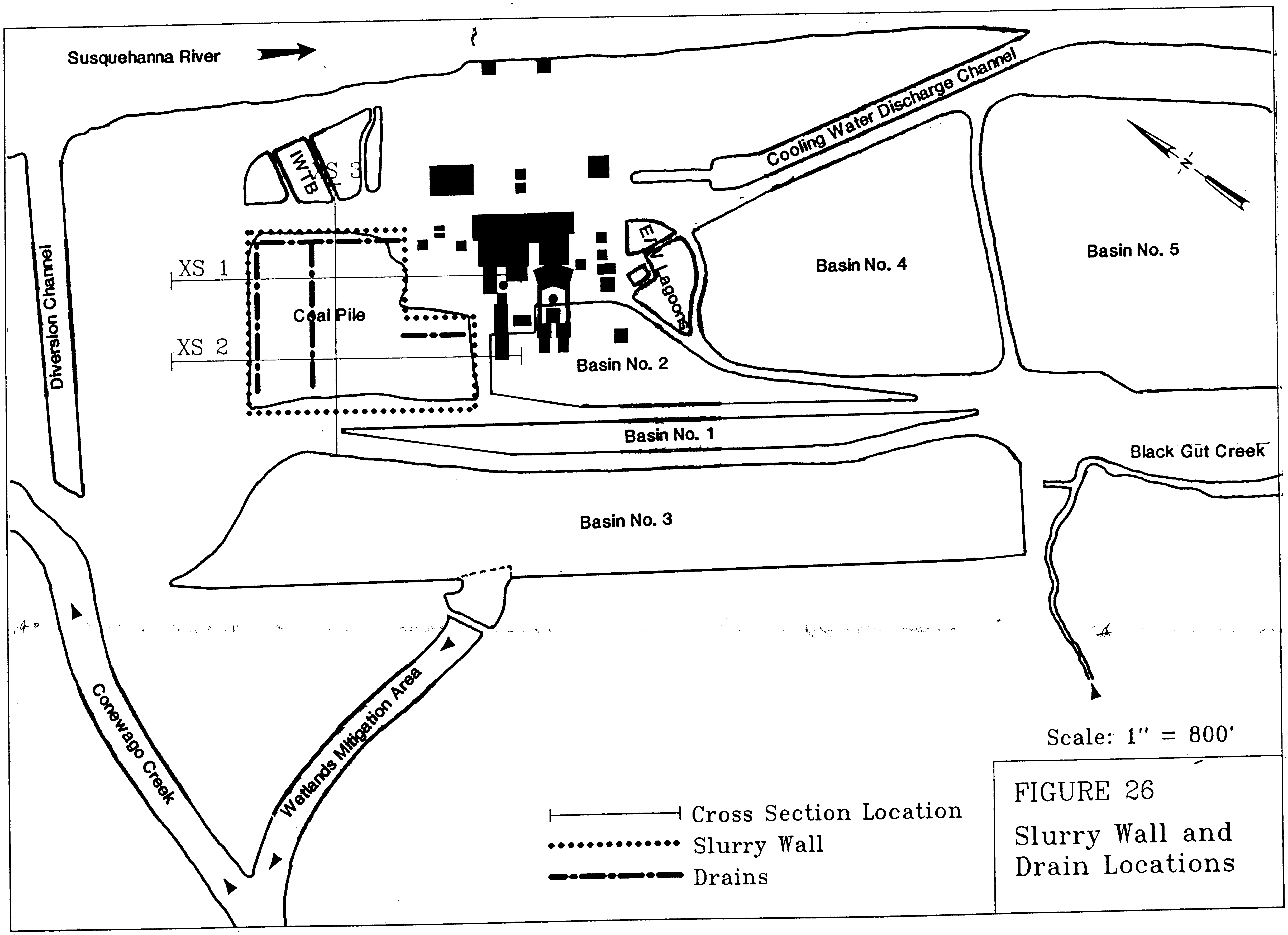


FIGURE 26

Slurry Wall and Drain Locations

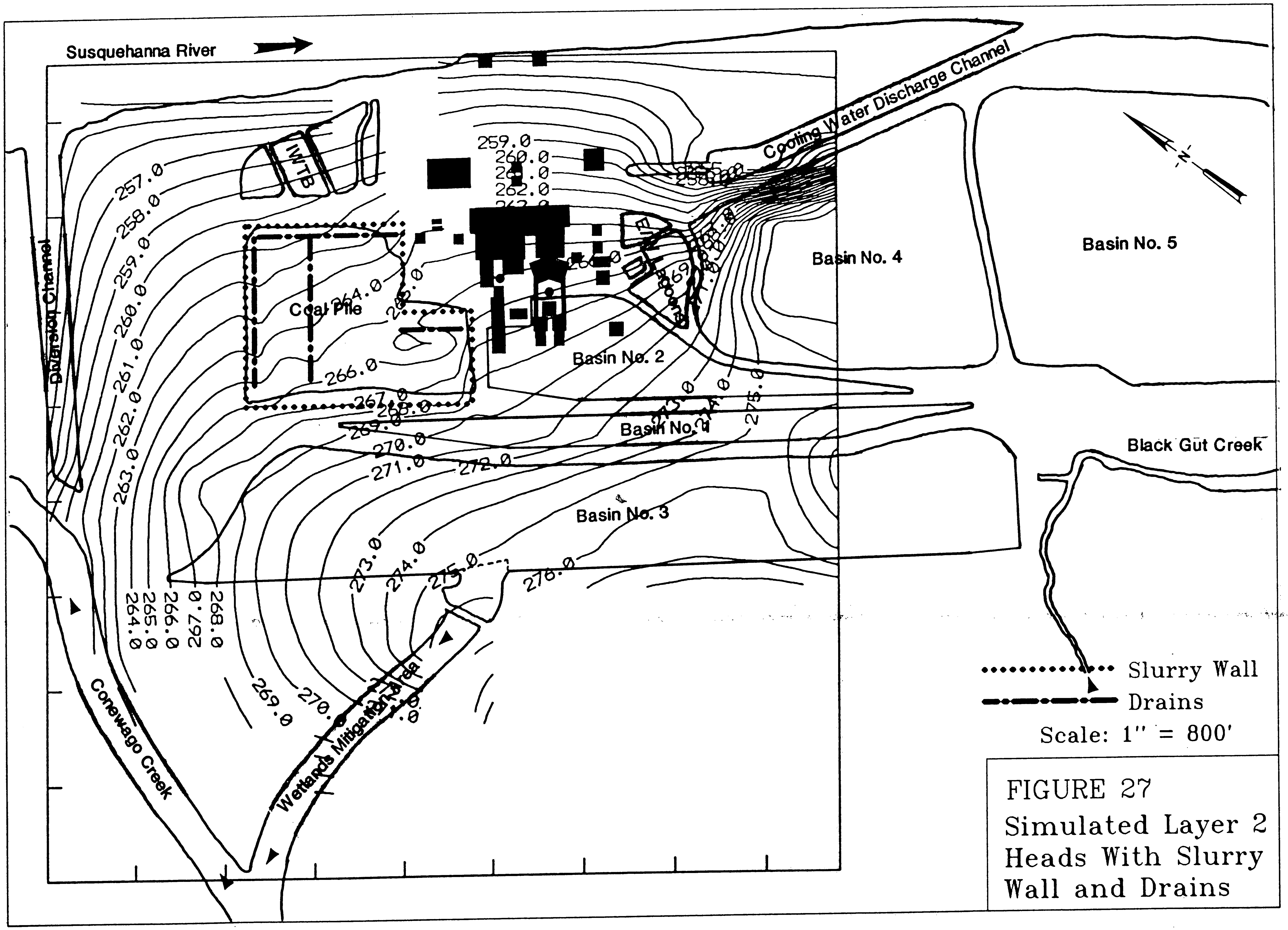
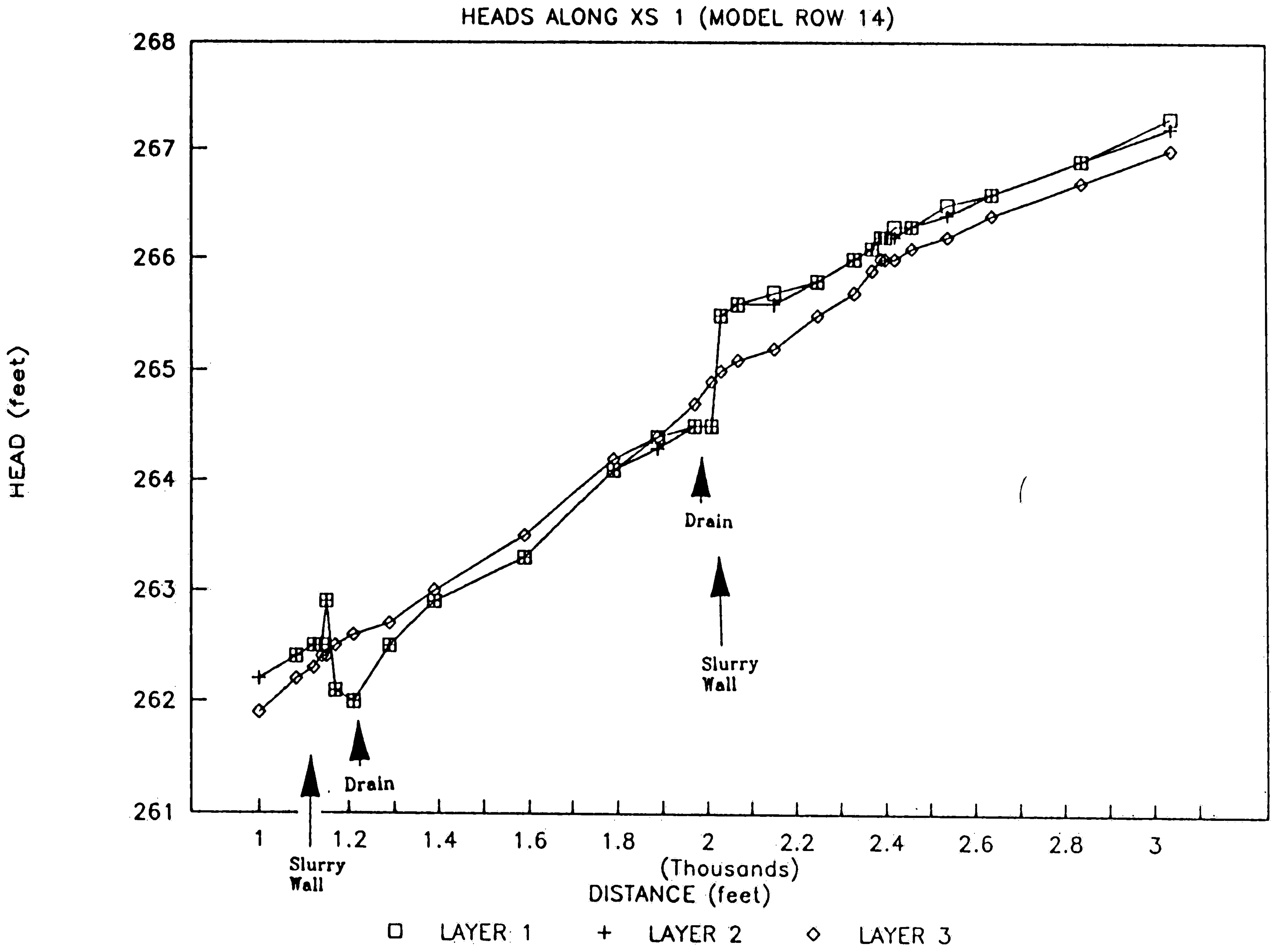


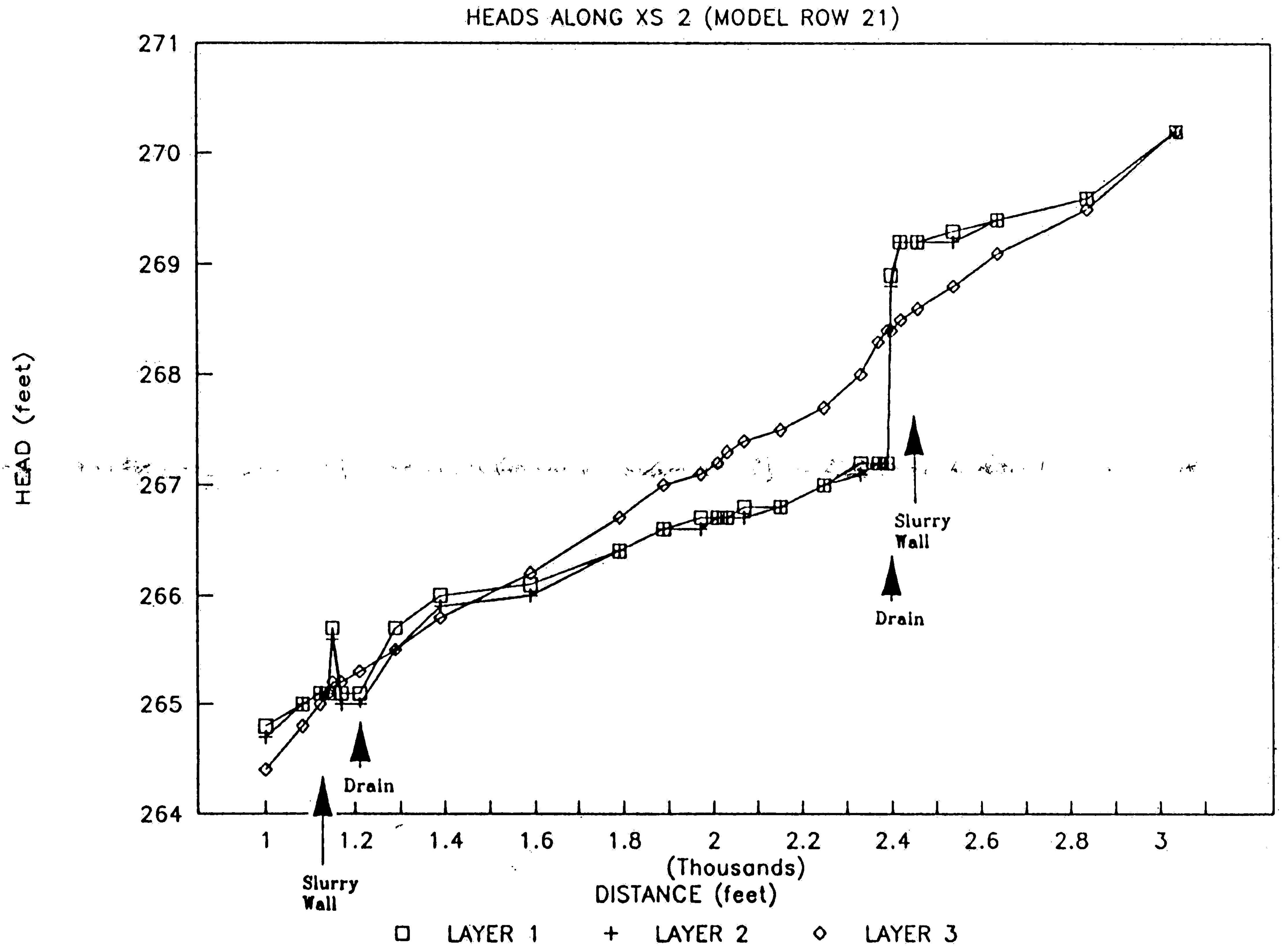
FIGURE 27
Simulated Layer 2 Heads With Slurry Wall and Drains

FIGURE 28A



HEADS ALONG XS 1 (MODEL ROW 14)

FIGURE 28B



HEADS ALONG XS 2 (MODEL ROW 21)

FIGURES 28A, 28B
Layers 1, 2, and 3
Heads With Slurry
Wall and Drain

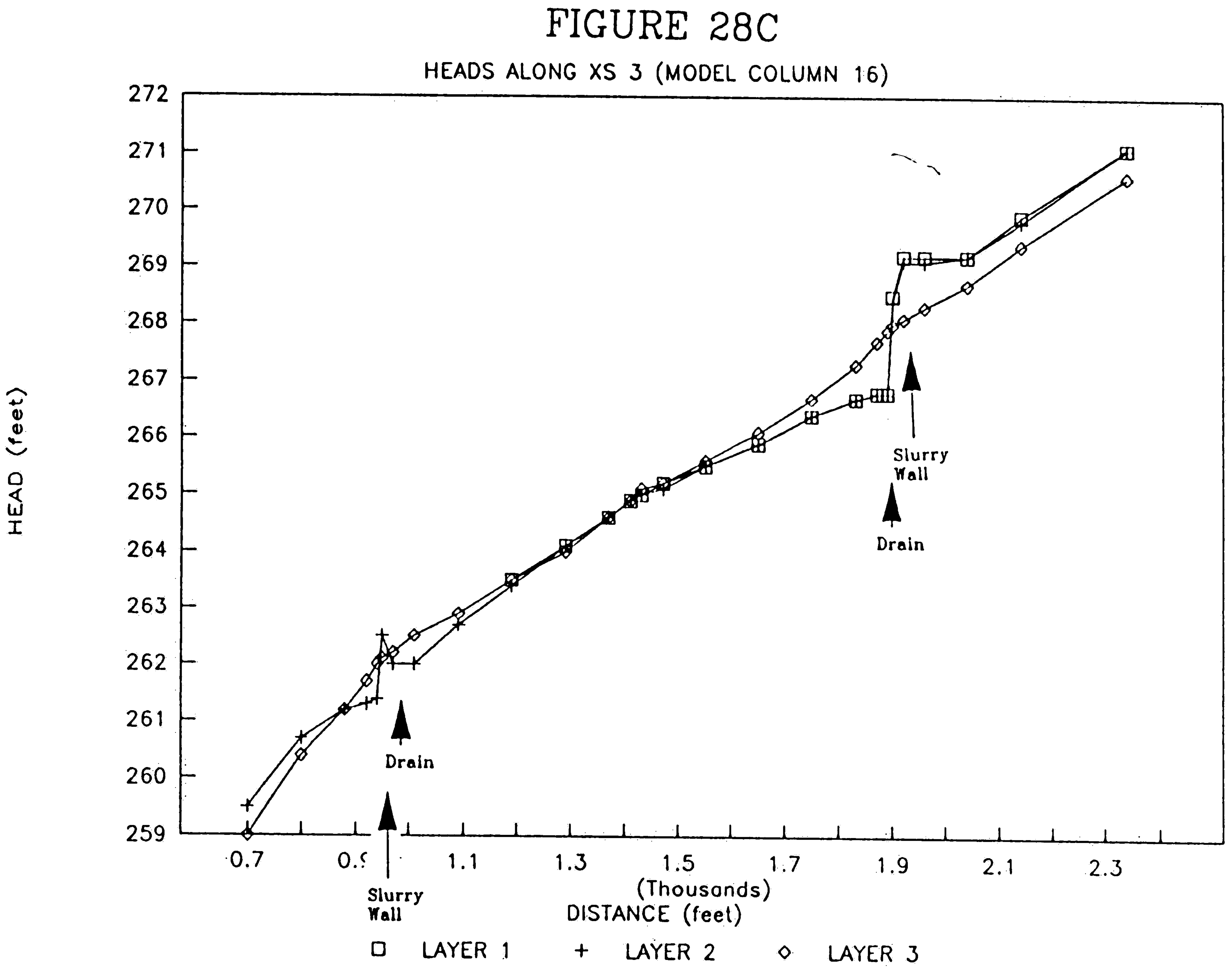


FIGURE 28C

HEADS ALONG XS 3 (MODEL COLUMN 16)

FIGURE 28C
Layers 1, 2, and 3
Heads With Slurry
Wall and Drain

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# APPENDIX 1 - Aquifer Data Summary

BRUNNER ISLAND SES HYDRAULIC CONDUCTIVITY DATA
All values in ft/day

1. Recovery and Slug Test Data From Monitoring Wells

| NOTES | WELL NO. | SOIL | SOIL/BR | BEDROCK (Depth Into Rock) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 0-5' | 5-10' | 10-15' | 15-20' | 20-25' | 25-30' | 30-35' | 35-40' | 40-50' |
| [4] | 1 | | | 2.7 | 2.7 | | | | | | | |
| | 2 | | 0.7 | | | | | | | | | |
| | 3 | | 0.2 | | | | | | | | | |
| | 4A/B | | 2.4 | | | | | 7.6 | 7.6 | | | |
| | 5 | | | | 0.3 | 0.3 | | | | | | |
| | 6 | | 6.2 | | | | | | | | | |
| | 7 | | 5.9 | | | | | | | | | |
| | 8 | | | | 10.0 | 10.0 | | | | | | |
| | 8A | | | | 3.1 | 3.1 | | | | | | |
| | 9 | | | | | | | | | | | 0.1 |
| | 10 | 21.0 | | | | | | | | | | |
| | 11 | 2.5 | | | | | | | | | | |
| | 12 | 1.7 | | | | | | | | | | |
| | 13 | | | 1.8 | 1.8 | | | | | | | |
| | 14 | | | 3.2 | 3.2 | | | | | | | |
| | 15 | | | | | | | | | | | |
| | 16 | | | | | | | | | | | |
| | 17 | | | | | | | | | | | |
| | 18 | 0.2 | | | | | | | | | | |
| | 18A | 0.5 | | | | | | | | | | |
| | 19 | | | | | | | 0.2 | 0.2 | 0.2 | 0.2 | |
| | CL1A | | | 4.7 | 4.7 | | | | | | | |
| | CL1B | | | | | | | 0.5 | 0.5 | | | |
| | CL1C | | | | | | | | | | | 0.0 |
| | CL2A | | 3.6 | | | | | | | | | |
| | CL2B | | | | | | 9.6 | 9.6 | | | | |
| | CL2C | | | | | | | | | | | 1.1 |
| | CL3A | | 11.0 | | | | | | | | | |
| | CL3B | | | | | 0.0 | 0.0 | | | | | |
| | CL3C | | | | | | | | | 0.0 | | |
| | CL7A | 9.5 | | | | | | | | | | |
| | CL7B | | | | | | 2.0 | 2.0 | | | | |
| | CL8A | 1.6 | | | | | | | | | | |
| | CL8B | | 2.8 | | | | | | | | | |
| | CL8C | | | | | | 8.2 | 8.2 | | | | |
| | CL9A | 5.2 | | | | | | | | | | |
| | CL9B | | | 0.9 | 0.9 | | | | | | | |
| | CL9C | | | | | | | 11.0 | 11.0 | | | |
| | CL10A | | 3.0 | | | | | | | | | |
| | CL10B | | | | | 4.9 | 4.9 | | | | | |

2. Bedrock Pressure (Packer) Tests

| | | | | 0-5' | 5-10' | 10-15' | 15-20' | 20-25' | 25-30' | 30-35' | 35-40' | 40-50' |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cluster Wells<br>[1,4] | CL1 | | | 6.3 | 6.0 | | 0.2 | 1.5 | 4.3 | 0.0 | | 1.0 |
| | CL2 | | | | 4.7 | 2.3 | 1.4 | 4.5 | 4.9 | 0.1 | 0.8 | 5.0 |
| | CL3 | | | | 1.6 | | 2.9 | 0.4 | 0.0 | 0.0 | 0.0 | |
| | CL7 | | | 0.3 | 0.3 | 1.3 | 1.3 | 1.1 | 1.1 | | | |

|  |  |  |  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | CL8 |  |  | 1.9 | 1.9 | 2.4 | 2.4 | 2.9 | 2.9 | 1.1 | 1.1 | 0.7 |
|  | CL9 |  |  |  | 1.2 | 1.0 | 1.0 | 3.2 | 3.2 | 3.1 | 3.1 | 0.1 |
|  | CL10 |  |  | 1.7 | 1.7 | 3.5 | 3.5 | 0.0 | 0.0 |  |  |  |
| Siting Study | 3-001 | 4.1 |  | 0.6 | 0.7 | 1.1 |  |  |  |  |  |  |
| [2,3] | 3-002 | 1.3 |  |  |  | 0.6 | 0.8 |  |  |  |  |  |
|  | 3-003 | 1.9 |  | 1.9 | 2.0 | 0.5 |  |  |  |  |  |  |
| Basin 7 Study | TB-3 |  |  | 0.1 |  | 2.6 | 0.2 |  |  |  |  |  |
| by DGC | TB-4 |  |  | 0.6 | 2.6 | 1.6 | 0.0 |  |  |  |  |  |
| [2] | TB-5 |  |  |  | 8.5 | 11.3 | 0.9 | 1.8 |  |  |  |  |
|  | TB-6 |  |  | 4.5 | 2.0 | 2.0 | 16.4 |  |  |  |  |  |
|  | TB-7 |  |  |  | 15.6 | 7.1 | 16.4 | 0.8 |  |  |  |  |
|  | TB-8 |  |  |  | 3.7 | 1.6 | 0.3 | 0.8 |  |  |  |  |
|  | TB-9 |  |  |  | 19.3 | 20.1 | 19.3 |  |  |  |  |  |
|  | TB-10 |  |  | 15.0 |  | 0.1 | 0.0 | 0.0 |  |  |  |  |

3. Slug Tests Performed on Open & Cased Auger Holes

|  |  |  |  |  |
|---|---|---|---|---|
| Basin 6 and 7 | 77-A | 10.0 |  |  |
| Studies | 77-B | 1.0 |  |  |
|  | 77-C | 0.1 |  |  |
|  | 77-D | 0.5 |  |  |
|  | 77-E | 1.9 |  |  |
|  | 77-F | 7.1 |  |  |
|  | 77-G | 0.2 |  |  |
|  | 77-H |  | 7.0 |  |
|  | 77-I | 10.0 |  |  |
|  | 77-J |  |  | 0.5 |
|  | 77-K |  | 0.7 |  |
|  | 77-L |  |  | 0.1 |
|  | 77-1 | 0.8 |  |  |
|  | 77-2 | 0.7 |  |  |
|  | 77-3 | 0.6 |  |  |
|  | 77-4 | 0.1 |  |  |
|  | 77-5 | 0.1 |  |  |
|  | 77-6 | 0.1 |  | 0.2 |
|  | 77-7 | 0.1 |  |  |
|  | 77-8 | 0.3 |  |  |
|  | 77-9 |  |  | 0.3 |
|  | 77-10 | 1.8 |  |  |
|  | 77-11 | 2.6 |  |  |
|  | 77-12 | 0.5 |  | 2.1 |
|  | 77-13 | 1.0 |  |  |
|  | 77-14 | 0.5 |  |  |
|  | 77-15 | 0.4 |  |  |
|  | 77-16 | 0.5 |  |  |
|  | 77-17 | 0.1 |  |  |
|  | 77-19 | 2.0 |  |  |
|  | 77-21 | 10.0 |  |  |
|  | 77-22 | 10.0 |  |  |

4. Slug Tests Conducted on Wells in Basin 4

|  |  |  |
|---|---|---|
| Ash | CL4A | 4.9 |
| Ash | CL4B | 1.0 |

|  |  |  |
|---|---|---|
| Ash | CL4C | 0.2 |
| Ash | CL5A | 0.5 |
| Ash | CL5B | 2.3 |
| Ash | CL5C | 0.2 |
| Ash | CL6A | 0.8 |

NOTES:

[1] Double Packer Pressure Tests
[2] Single Packer Pressure Test to Bottom of Hole
[3] Soil Slug Test Data, Rock Pressure Test Data
[4] Double/multiple values reflect testing over 10' intervals

DATA SUMMARY:

|  | Log Avg | Median | No. of Tests | Used in Initial Model |
|---|---|---|---|---|
| SOIL |  |  |  |  |
| #all data | 0.9 | 0.9 | 34 |  |
| #central island | 2.2 | 1.9 | 11 | 2 |
| #coal pile | 4.3 | 5.2 | 3 |  |
| SOIL/BEDROCK INTERFACE |  |  |  |  |
| #all data | 2.4 | 3.6 | 11 |  |
| #central island | 2.5 | 3.0 | 9 | 3 |
| #coal pile | 3.0 | 3.0 | 3 |  |
| BEDROCK |  |  |  |  |
| Central Island |  |  |  |  |
| #tests < 30' | 1.6 | 1.9 | 51 | 2 |
| #tests > 30' | 0.3 | 0.2 | 16 | 0 |
| #cp < 30' |  | 1.7 |  |  |
| #cp > 30' |  | 0.5- |  |  |
| Central Island < 30' |  |  |  |  |
| #slug/recov tst | 2.1 | 3.1 | 17 |  |
| #press tests | 1.3 | 2.0 | 36 |  |
| Entire Island |  |  |  |  |
| #all tests | 1.6 | n.d. | 65 |  |
| ASH | 0.8 | 0.7 | 7 | 1 |

# APPENDIX 2 - Water Level Data

## FEBRUARY 1989 VS. AVERAGE WATER LEVELS

| MODEL LAYER AND LOCATION | FEB 1989 OBSERVED WATER LEVE (FT MSL) | AVG 1984-89 OBSERVED WATER LEVEL (FT MSL) |
|---|---|---|
| LAYER 1 | | |
| CL-8A | 270.4 | 270.6 |
| LAYERS 1&2 | | |
| CL-4B | 277.2 | 277.0 |
| CL-5A | 275.4 | 275.8 |
| CL-5B | 276.6 | 276.9 |
| CL-7A | 268.6 | 268.2 |
| CL-9A | 266.9 | 266.4 |
| MW-11 | 274.1 | 274.0 |
| LAYER 2 | | |
| CL-2A | 261.9 | 261.4 |
| CL-3A | 261.5 | 261.3 |
| CL-5C | 276.7 | 276.4 |
| CL-8B | 270.6 | 270.7 |
| CL-10A | 266.4 | 266.2 |
| MW-12 | 276.4 | 275.4 |
| TB-1 | 276.5 | |
| WC-1 | 278.0 | |
| WC-2 | 278.1 | |
| WC-3 | 277.7 | |
| WC-4 | 276.9 | |
| LAYER 3 | | |
| CL-2B | 261.3 | 261.2 |
| CL-2C | 261.6 | 261.3 |
| CL-3B | 261.6 | 261.5 |
| CL-3C | 261.7 | 261.5 |
| CL-7B | 269.3 | 269.0 |
| CL-8C | 270.6 | 270.2 |
| CL-9B | 267.6 | 267.5 |
| CL-9C | 267.9 | 267.7 |
| CL-10B | 267.2 | 267.0 |
| MW-8 | 257.4 | 258.9 |
| MW-14 | 254.7 | 254.4 |
| MW-19 | 285.7 | 286.1 |

BRUNNER ISLAND SURFACE WATER ELEVATIONS

| INFORMATION LOCATION: | | --------------Information Source------------- | | | | -------Surface Water Elevation---- | | |
|---|---|---|---|---|---|---|---|---|
| | | Drawing No. E-201048 | '86 Baker Modeling | Survey 10/86 | Survey 1/89 | 11/21/88 | 12/20/88 | 02/08/89 |
| SUSQ. RIVER @: | Plant Guage | <256.0 | 253.0 | 251.0 | | | | |
| | Conewago | | | 252.7 | 255.6 | | | |
| | Diversion Channel | | | | 255.0 | | | |
| | Below CWDC * | | | | | 253.82 | 251.57 | 252.07 |
| | Basin No. 6 Dsch. | | | 251.6 | 252.0 | | | |
| CONEWAGO CR. @: | Access Bridge N | | | | 259.0 | | | |
| | Railroad Trestle * | | 258.0 | 255.2 | 261.7 | 262.37 | 260.27 | 260.37 |
| | Split at Wetlands | | 262.0 | 259.8 | 261.8 | | | |
| RED POND @: | Old Red Pond | | 274.0 | 277.0 | | | | |
| | Wetland @ Pond Disch * | | 262.0 | | 271.7 | 272.17 | 272.27 | 272.17 |
| | Filled Ground Elev | | | | 277.8 | | | |
| DIV. CHANNEL @: | Conewago Creek | | 256.0 | | 254.8 | | | |
| | River | | 253.0 | 252.7 | 255.0 | | | |
| | Center * | | | | | | | |
| IWTB's | * | 266.0 | | | 267.0 | 266.84 | 266.74 | 266.64 |
| SWAMP NW OF CP | * | 276.4 | 273.0 | | 275.9 | 276.97 | 276.72 | 276.97 |
| CWDC @: | Plant Above Falls | 259.0 | | | 261.5 | | | |
| | Plant Below Falls * | 253.8 | 254.0 | 253.2 | | 254.3 | 253.7 | 254.2 |
| | River | | 253.0 | 251.3 | 252.5 | | | |
| E/W LAGOONS | * | 275.0 | | | 275.6 | 277.3 | 277.15 | 277.4 |
| BASIN NO. 4 | * | 275.8 | 280.0 | 276.5 | 276.4 | | | 276.72 |
| BLACK GUT @: | Railroad Trestle * | | 256.0 | | 259.2 | 259.57 | 259.27 | 259.37 |
| | Basin No. 3 Disch. | | 256.0 | 253.7 | | | | |
| | Midway Basin No. 5 * | | | | 252.9 | | | |
| | Near Susq. River | | | | 251.2 | | | |
| BASIN NO. 6 | * | 279.0 | | | 284.7 | | | |
| MISCELLANOUS: | CP Runoff Ditch | | | | 272.4 | | | |
| | Swamp N of IWTB | | | | 260.0 | | | |
| | B#7 Standing Water | | | | 257.4 | | | |
| | B#5 Reclam. Area | | | | 273.6 | | | |

NOTES:
------
* Indicates Staff Gauge Location

# APPENDIX 3 - 3-D Flow Model Data Listings

Model input data sets for all model runs presented in this thesis are on file with:

Dr. Gerard P. Lennon
Associate Professor of Civil Engineering
Fritz Engineering Laboratory No. 13
Lehigh University
Bethlehem, PA 18015
(215) 758-3558

Data files on both hardcopies and floppy disks are available.

# VITA

David A. Stoner is currently a Project Development Manager with Westmoreland Energy, Inc. in Charlottesville, VA. His responsibilities there include environmental licensing and project development activities in support of Westmoreland's coal-fired independent power and cogeneration projects. Prior to joining Westmoreland in 1990, David was employed as an Environmental Engineer for Hydrosystems, Inc. in Charlottesville, where he conducted hydrogeological and remedial investigations. Prior to joining Hydrosystems in 1989, David was employed as a Consultant and Environmental Scientist in several positions with the Pennsylvania Power and Light Company (PP&L) from 1983 to 1988. He initiated this master's program on a part-time basis while at PP&L in 1986. David earned a B.S. in Environmental Resource Management from the Pennsylvania State University in 1983.