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WATER QUALITY ISSUES AT FOSSIL FUEL PLANTS

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sponsored by the Energy Division of the
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Edited by William G. Dinchak and Michael J. Mathis

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FOREWORD

In the United States, more electricity is generated by fossil-fueled steam power plants than by any other single type of power plant. It is expected that this will continue to be the case for the foreseeable future. Most of these plants depend on the availability of high volumes of water for uses such as condenser cooling, boiler make-up, ash sluicing, and house service. An assured supply of water of reasonable quality is essential for their efficient operation.

Being high volume users of water has placed special responsibilities on fossil power plants to safeguard the waters upon which they and other industries, businesses, and individuals depend. Regulations promulgated by the United States Environmental Protection Agency, in response to the mandates of the Federal Clean Water Act, recognize steam electric power plants as a distinct point source category, with unique water uses and special wastewater characteristics. Over the past decade, significant efforts and expenditures have been committed by the owners of fossil power plants to meet the mandates of the Clean Water Act.

While the Clean Water Act focuses on point source discharges to surface waters, increasing attention has recently been focused on protection of the nation's ground water. Once again, special attention has focused on fossil, and particularly coal-fired power plants. Largely as a result of regulatory initiatives at the state level, many coal-fired power plants are taking special measures to protect ground water from the effects of leachate from overlying coal piles.

The Energy Division of ASCE considered it appropriate, in light of concerns for protection of water quality, to sponsor a symposium on the topic of water quality considerations at fossil power plants in conjunction with the ASCE Fall, 1985 convention in Detroit, Michigan, a city located in the heart of the Great Lakes Basin. This symposium, and its proceedings, seeks to explore the relationship of fossil power plants to the water resources upon which they depend. Of concern are noteworthy approaches to the supply and treatment of water for power plant use, and measures taken to protect surface and groundwater near power plants. The proceedings volume contains ten papers presented at the symposium.

Appreciation is extended to the broad spectrum of experts whose papers appear in this publication and who are responsible for the quality of programs. Thanks go to the Environmental Effects Committee and the Fossil Power Committee of the Energy Division of ASCE for co-sponsoring the sessions. The co-authors of the papers are commended for sharing their experience in print with the Civil Engineering profession.

Each of the papers included in the proceedings has been accepted for publication by the proceedings editors. All papers are eligible for discussion in the Journal of the Energy Division. All papers are eligible for ASCE awards.

William G. Dinchak
Michael J. Mathis

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COAL ASH DISPOSAL AND WATER QUALITY:
A CASE STUDY

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Abstract

Duke Power Company's Belews Creek Steam Station is a 2280 megawatt, coal-fired steam electric generating plant which began generating power in 1974-1975. The station is located on Belews Lake, a 3863-acre (1563 ha) reservoir which supplies condenser cooling and general service water. Belews Creek was designed with a wet fly and bottom ash sluicing system. Ash disposal was to a 300-acre mixed fly and bottom ash settling pond, from which sludge water was returned to Belews Lake.

After approximately one year of full-power operation, a drastic decline in Belews Lake fish populations was found to be associated with the discharge of dissolved selenium and arsenic to the reservoir in the ash sludge water return. By 1977, selenium concentrations as high as 20 µg/l (ppb) or more consistently exceeded the North Carolina water quality standard of 10 µg/l (ppb), and this element was bioaccumulated to high levels by biota of the reservoir, resulting in fish mortality. Although the Belews Lake selenium problem was relatively unique at the time it was first recognized, selenium problems with adverse impacts on fish and wildlife have since been recognized in other impoundments in North Carolina, South Carolina, Texas, and California.

Several solutions to this problem were considered. The most promising options were 1) chemical treatment of the ash sluicing system with acid and ferric iron to remove dissolved selenium and arsenic from the sludge water discharge, 2) re-routing of the ash sludge water discharge to the nearby Dan River, in combination with the chemical treatment above, and 3) conversion to a dry fly ash handling system, with land-filling of the dry ash within the existing ash settling pond drainage basin.

Field testing and economic evaluations resulted in adoption of the dry fly ash handling conversion option. The dry ash handling system was installed under contract by an outside vendor, and became operational in January 1985. Experience with the new system has been satisfactory to date.

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Introduction

This paper presents a brief case history of operating experiences and water quality impacts experienced at Duke Power Company's Belews Creek Steam Station. The discussion will proceed from a description of the facilities and the environmental impact problems which were encountered as a result of their operation through the adoption of corrective actions designed to mitigate adverse effects of power plant ash basin effluent discharges to Belews Lake.

The Belews Creek Steam Station is a Duke Power Company coal-fired steam-electric generating station which consists of two units of 1140 MWe each (Fig. 1). The station is located in north-central North Carolina approximately 15 miles (24 km) northeast of the city of Winston-Salem (1,2). The first unit was placed in service in August 1974, the second in December 1975. Belews Creek burns low-sulfur Appalachian bituminous coal from eastern Kentucky and from West Virginia. Coal entering the station is distributed randomly between Units 1 and 2. Condenser cooling water for each unit is provided from the adjacent 3863-acre (1563 ha) Belews Lake impoundment at a maximum rate of 1170 cfs (33.1 m³/sec).

The Belews Creek station is equipped with cold-side electrostatic precipitators to remove fly ash from flue gases before they are released from the stacks. Fly ash collected by the precipitators was mixed with Belews Lake water to form a slurry which flowed at a total rate of

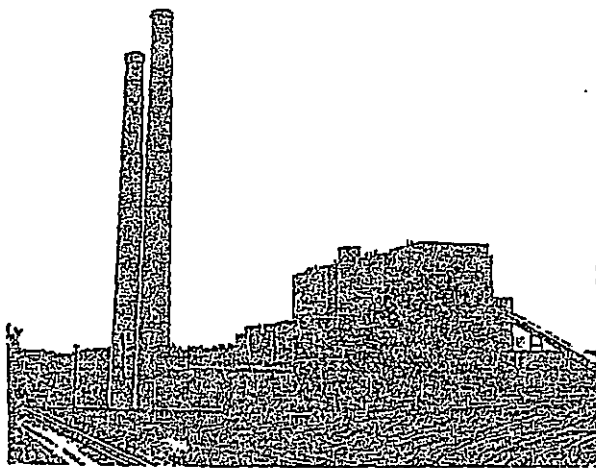


Figure 1. Duke Power Company's 2280 MWe Belews Creek Steam Station near Winston-Salem, North Carolina.

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approximately 8 cfs ($0.23 \text{ m}^3/\text{sec}$) in separate pipelines for each unit to an ash basin, where ash particulates were removed by settling (Fig. 2). The effluent from which ash had been separated was discharged back to Belews Lake beginning in early 1975 and continuing to spring 1985. Each unit also discharged bottom ash slurry (approximately 8 cfs, $0.23 \text{ m}^3/\text{sec}$) to the ash basin by separate pipelines, and station sump water was carried by a fifth pipeline. Thus, five separate waste streams entered the Belews Creek ash basin via the piping system, while one effluent stream (total flow rate 20-23 cfs, $0.57\text{-}0.65 \text{ m}^3/\text{sec}$) left at the ash pond discharge structure and returned to Belews Lake. Intermittent coal yard drainage also entered the ash basin independently of the piping system by a surface drain, as did treated metal cleaning waste.

Ash Basin Effluent Characteristics

During the period June 1976 (when NPDES monitoring began) through February 1978, the Belews Creek ash basin effluent contained Se and As at concentrations of approximately 150 to 200 $\mu\text{g/l}$ (ppb) (1,2). The coal burned at Belews Creek produced an alkaline reaction when sluiced in water, with an initial pH of 9 to 11. Under these conditions in oxygenated waters, both Se and As are highly soluble, and were discharged to the lake in dissolved form. The ash basin effluent was also monitored for eight other metals (Fe, Cu, Cr, Cd, Ni, Pb, Hg, and Zn) during this period, but concentrations were low and generated no concerns or observed impacts in Belews Lake (1,2,10).

In 1977, an SO_2 fly ash conditioning system was installed at Belews Creek to improve precipitator performance by increasing surface conductivity of fly ash particles (2). The SO_2 injection system initially

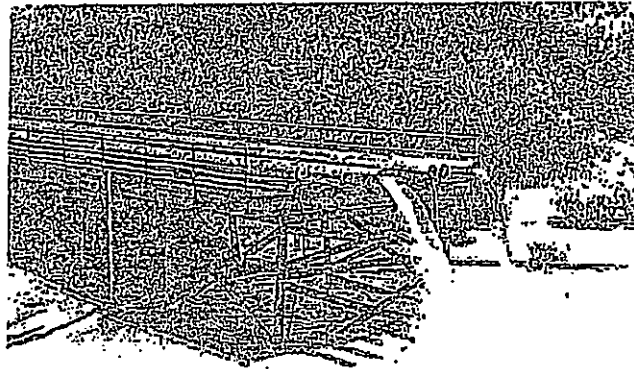


Figure 2. Wet fly and bottom ash sluice piping system flowing to the mixed fly and bottom ash settling pond.

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reduced the pH of the ash slurry from pH 9-11 to pH 4-7. At the lower slurry pH, solubility of Se decreased, while solubility of certain acid-soluble metals increased (Fe, Cu, Cr, Zn). However, in the ash pond, pH was moderated by neutralizing effects of ash and the CO₂-bicarbonate system, so that the net effect on the basin effluent was to reduce pH slightly to about pH 8. Effluent Se concentrations fell to 100-130 µg/l (ppb), and As fell to 50-100 µg/l (ppb).

Ash Effluent Discharge Impacts

Water quality in Belews Lake and its tributaries was monitored by Duke Power and its contractors since impoundment in 1970 (1,10). Soon after ash basin effluent began to be discharged to Belews Lake, it was found that Se concentrations in the lake water had increased, to peak levels of 12 µg/l (ppb) in 1976, and 22 µg/l (ppb) in 1977 (1). Background for Se in natural waters in the region was less than 1 µg/l (ppb). Elevated Se levels were also found in Belews Lake sediments (3).

In 1976, and continuing to present, it was found that fish populations in Belews Lake were declining drastically from pre-1976 levels, and that reproduction had ceased for almost all fish species in the main reservoir (1,4,5). Accompanying these responses was a strong bioaccumulation of Se in muscle, liver, ovary, and other tissues of Belews Lake fishes (1,4). Concentrations of 20 to 70 µg/g (ppm, wet basis) were commonly detected, compared to normal background of 1-2 µg/g (ppm). Mortality and lack of reproduction in Belews Lake fishes was ascribed to toxic effects of Se residues (1,4,6,9).

Corrective Actions

In cooperation with the North Carolina Division of Environmental Management (NCDEM), Duke Power Company evaluated corrective actions to deal with the Belews Lake ash basin effluent/Se problem, including conventional water treatment, in-basin treatment of ash sluice water by an acid/ferric iron process (7), relocation of the treated discharge to the nearby Dan River, conversion to dry fly ash handling, or some combination of these alternatives.

Following a trial acid treatment that provided encouraging results, discussions occurred with NCDEM on a proposed rerouting of the ash pond effluent to the Dan River while treating the ash basin. An application for a permit for this discharge was submitted in 1981. While permit review proceeded, Duke Power received a proposal at the end of 1982 from Monier Resources, Inc. to expand an existing dry fly ash sales pilot plant on site by constructing three added silos of 1500 tons (1.36 x 10⁶ kg) capacity each, and to construct and operate a flyash landfill within the ash pond drainage basin. The steel silos (Fig. 3) would be cone-bottomed and equipped with sufficient baghouse venting capacity to receive fly ash from all four precipitator sections. Two of the silos would be equipped with pre-wetter systems and ash conditioners for direct loading of ash with 15 percent moisture into dump trucks for land filling. One silo for sales would allow loading of dry fly ash into tankers.

Because the contractor would pay all capital expenses, this option was attractive, and a contract was signed with Monier in 1983. An agreement

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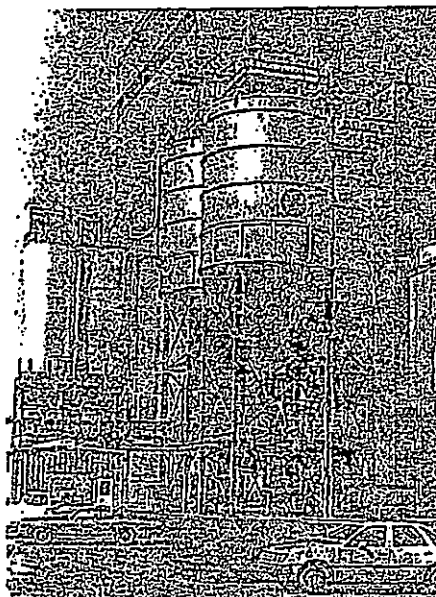
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was also reached with NCDEM on a biological monitoring program for the Dan River and on interim acid treatment in the ash pond during conversion to the dry fly ash system. Acid addition occurred from January to early April 1984. Sulfuric acid was added at the slurry influent point when the discharge tower pH exceeded 7.0, and ceased when the pH reached 6.5. This achieved a reduction of 50 percent in the Se concentration in the effluent (Table 1) from the December 1983 level. The new discharge permit was issued in September 1984, with a daily mass limit of 1.9 kg (4.19 lb) total Se to the Dan River from the ash pond and the Belews Lake spillway, combined.

The ash landfill permit was issued in December 1984, with the dry ash handling system becoming fully operational during February 1985. The ash is unloaded at the landfill and spread and compacted with a bulldozer (Fig. 4). This achieves greater than 90 percent of standard Proctor density. Silt fencing, drainage ditches, and a sedimentation pond control runoff from the site. Two feet (0.6 m) of soil cover are provided at the completion of each lift. A total of 178,000 tons (1.6 x 10⁶ kg) of fly ash had been landfilled through June 1985. As shown in Table 1, Se concentration in the ash pond effluent had decreased by 75 percent since the dry fly ash system began full operation.

The discharge to the Dan River consists of a new overflow tower with sluice gate and stoplogs and a skimmer collar to retain floating ash. The effluent is then routed to a stilling basin and through a Parshall flume to a riprapped effluent channel to the Dan River. With the combined Se concentration in the ash pond effluent and in the lake spillway well below the permit limit, the new discharge began operation after the pond water level was raised to allow dike integrity tests. The old discharge tower will be permanently closed with a standpipe.

Figure 3. Dry fly ash collection silos installed at the Belews Creek Steam Station, July, 1985. Three 1500 ton wet loading silos to right, smaller dry-loading silos to left.



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Table 1. Selenium concentrations in Belews Creek Steam Station ash pond effluent and Belews Lake spillway, 1983-1985.

Date	Effluent Se, ppb	Spillway Se, ppb	Total Se, kg/day
12/06/83	139.8	(not measured)	(not measured)
1/05/84	90.0	"	"
2/07/84	73.0	"	"
3/06/84	75.9	"	"
4/03/84	65.0	"	"
1/09/85	68.0	"	"
2/05/85	76.0	6.9	4.1
3/05/85	49.0	3.3	0.4
4/02/85	27.8	2.0	0.8
5/07/85	18.7	2.5	0.2

Conclusion

Duke Power Company's experiences with the Belews Creek ash basin effluent illustrate some of the demanding problems and questions with which engineers, scientists, and resource managers must deal as facility development and increases in sophistication regarding potential water quality impacts of industrial facilities continue in our society (8). This case history confirms that careful planning and effective interdisciplinary studies will be required to prevent or to control and correct adverse environmental impacts associated with industrial facilities which must be built to satisfy the needs of the nation.

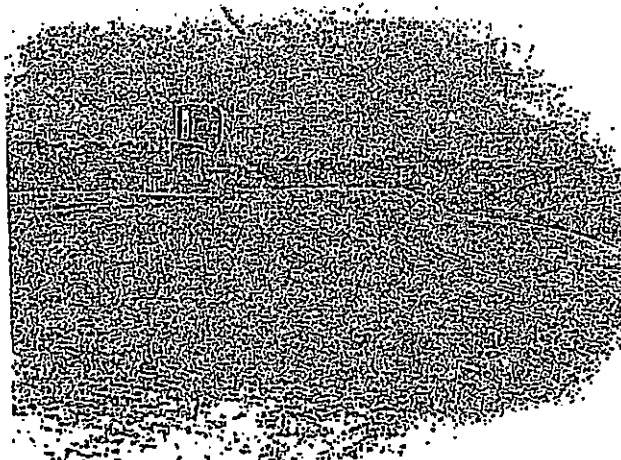


Figure 4. Dry fly ash landfill in the existing Belews Creek Steam Station ash settling pond drainage basin, July 1985. The settling pond continues to receive bottom ash sluice water, runoff, treated metals cleaning waste, and coal yard runoff.

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**EVALUATION OF THE EFFECT OF ASH DISPOSAL
AT THE RIVERBEND PLANT OF
DUKE POWER COMPANY ON
GROUNDWATER AND SURFACE-WATER QUALITY**

Prepared for
Duke Power Company

Prepared by
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Report No. I308-12/7/87-01F

EXECUTIVE SUMMARY

In April 1985, Duke Power Company applied for a permit to construct a basin at its Riverbend Plant in Gaston County, North Carolina, in which ash dredged from its settling pond would be placed for drying. The North Carolina Division of Environmental Management (DEM) prepared a permit in response to the Company's request, (1) requiring an assessment to determine the existing groundwater quality in the immediate vicinity of the dredge pond, (2) to determine the effect of the groundwater discharge from the ash ponds upon the Catawba River, and (3) a proposal for a monitoring well network sufficient to detect any contaminants which could reach the river.

On the basis of three independent investigations at the Allen Plant and studies conducted by the EPA and other agencies at other coal-fired plants, Duke Power does not believe a groundwater monitoring program is needed at the Riverbend Plant. Kilkelly Environmental Associates conducted a comparative hydrogeologic study of the Allen and Riverbend plants to estimate the input of ash trace elements to the Catawba River both through surface runoff and groundwater, and to make a preliminary assessment of the risk posed to health and the environment by groundwater contaminants from the Riverbend ash pond reaching the Catawba River. The major findings of this study are listed below:

- The Allen and Riverbend coal-fired, electric-generating plants of Duke Power Company are located 12 miles apart on the west bank of the Catawba River in Gaston County, North Carolina.
- Both plant sites are underlain by bedrock composed of granite and diorite of the Charlotte Belt and by saprolite derived from the chemical and physical breakdown of these rocks. Diorite, which forms an especially clay-rich saprolite, appears to be somewhat more prevalent at the Allen Plant than at the Riverbend Plant. However, the bedrock, and the saprolite derived from it are similar enough in mineral composition at both sites to permit hydrologic and chemical data collected at either plant to be used in conjunction with hydrogeologic data from the other plant.

- Three intensive hydrogeologic and geochemical studies were conducted at the Allen Plant in the early 1980's to determine the extent to which seepage from its inactive and active ash ponds was affecting groundwater quality. Relying on the similarity in the hydrogeologic conditions at the plants, geochemical data from the Allen Plant was used in this report, in conjunction with hydrogeologic data from the Riverbend Plant, to determine the effect of ash-pond effluent on groundwater quality at the Riverbend Plant.
- Chemical analyses of water samples, both from ash and from saprolite at the Allen Plant, show that metals, which are present in large concentrations in the ash, are relatively insoluble with the result that ash pond effluent contains only very small concentrations of most metals.
- The saprolite at both the Allen and Riverbend Plants has a large capacity, through ion exchange and precipitation, to immobilize the metals contained in the ash effluent. At Allen, calcium and strontium, which are among the more mobile of the metal constituents in the effluent, move through the upper, clay-rich part of the saprolite at a rate of only about 0.3 ft/yr. The rate of movement at Riverbend may be somewhat faster, due to the smaller percentage of clay in the saprolite at that site, but is believed to be substantially less than 1 ft/yr. Thus, in the 30 years of operation of the Riverbend ash pond the more mobile metals are not believed to have moved as much as 15 to 20 feet into the saprolite.
- Boring data at the Riverbend Plant indicate that the thickness of saprolite beneath the ash pond ranges in thickness from about 60 ft to about 100 ft. Thus the "advancing fronts" of the most mobile metals derived from the ash are still well above the bedrock surface.
- Relative to the effect of ash-pond effluent on the quality of the Catawba River, analysis of streamflow records show an average flow past the Riverbend Plant of about 2866 cfs. Effluent from the pond reaches the river both through surface outflow and through the groundwater system. The rate of surface outflow averages about 7.1 cfs and the rate of groundwater outflow is estimated to be about 0.7 cfs, or one-tenth the rate of surface outflow. Thus, the average flow of the river is about 400 times the rate of surface outflow from the pond and about 370 times the combined surface and groundwater rate.
- Although the velocity of the Catawba River is relatively slow past the Riverbend site, modeling using conservative mixing coefficients suggests that complete transverse mixing of the pond effluent occurs within about three miles of the ash pond. Due to the small concentration of metals in the surface outflow from the pond, and the large dilution factor, metals contained in the effluent do not cause a detectable increase in concentration once complete mixing has occurred.
- Relative to the effect of groundwater seepage on stream quality, modeling of flow through the groundwater system using a retardation factor only 1/3 of the value estimated at the Allen Plant shows that no measurable concentration of the metals that are subject to ion exchange and other delaying reaction will reach the Catawba within the next 50 years (by 2037).

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1. INTRODUCTION

At the time of issuance of permits for new ash-disposal facilities, or at the time of renewal of permits, the North Carolina Division of Environmental Management (DEM) may require electric utilities to institute monitoring programs to determine the effect of ash-disposal operations on groundwater quality.

In April 1985, Duke Power Company applied for a permit to construct a basin at its coal-fired Riverbend Plant in Gaston County, NC, in which ash dredged from its settling pond would be placed for drying. The permit prepared by DEM in response to the Company's request requires that:

"S. An assessment shall be made of the existing groundwater quality in the immediate vicinity of the dredge pond. If contaminants are encountered at or below a depth of 20 ft, the vertical and horizontal extent of those contaminants should be established. This assessment should be made prior to use of the dredge pond in order that background groundwater quality can be established."

"T. A similar assessment shall be made to establish groundwater quality around the periphery of the existing ash ponds. Since groundwater in the vicinity of the ponds will ultimately discharge into the Catawba River, discovery of any contaminants in the GA zone would lead to a determination of which areas, at what depths, and in what concentrations those contaminants are entering the river. The permittee shall, within 90 days of permit issuance, submit to the Department for approval a proposed plan to assess groundwater quality at the existing fly ash basins. The plan should include (a) a schedule for completion of each phase of the investigation and (b) a proposed monitoring well network sufficient to detect any contaminants which could reach the river."

Intensive studies on the effect of ash disposal have been conducted at the Allen Plant, which is also located in Gaston County about 12 miles south of the Riverbend Plant. These studies show that groundwater quality has not been significantly degraded by seepage from the Allen plant ash ponds. In connection with this conclusion, it is important to note the agencies that conducted the studies: Duke Power Company (Roche, Gniska and Harwood, Dec. 1984); Arthur D. Little, Inc., (June 1985) under

contract with the U.S. Environmental Protection Agency and Tetra Tech, Inc., under contract with the Electric Power Research Institute (July 1985).

On the basis of these three independent investigations at the Allen Plant and studies conducted by the EPA and other agencies at other coal-fired plants, Duke Power does not believe a groundwater monitoring program is needed at the Riverbend Plant. In an effort to determine if this is, in fact, the case, Duke Power requested Kilkelly Environmental Associates (KEA) to conduct a comparative hydrogeologic study of the Allen and Riverbend Plants, to estimate the input of ash trace elements to the Catawba River both through surface runoff and groundwater, and to make a preliminary assessment of the risk posed to health and the environment by groundwater contaminants from the Riverbend ash pond reaching the Catawba River.

2. HYDROGEOLOGIC CONDITIONS AT ALLEN AND RIVERBEND PLANTS

The intensive studies conducted at the Allen Plant clearly demonstrate the following:

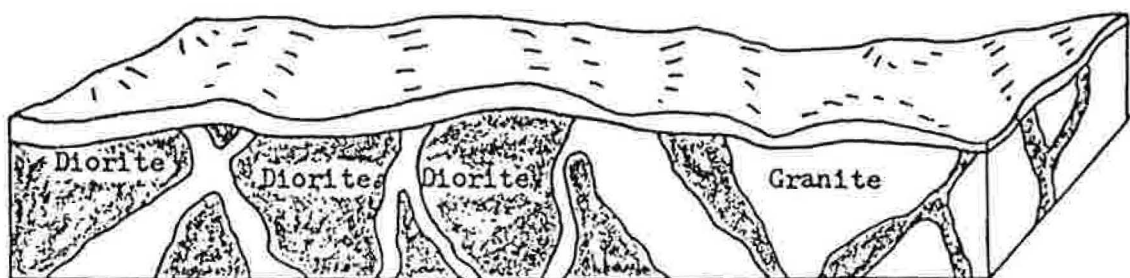
1. The residual (saprolite) and alluvial materials underlying and adjacent to the ash ponds have a very small hydraulic conductivity, resulting in a slow rate of movement of water through the materials.
2. The residual and alluvial materials have a very large capacity to immobilize metals through ion exchange, which, together with the slow rate of movement, results in negligible groundwater pollution.

Both of these findings are consistent with the hydrogeologic conditions at the Allen Plant. Before discussing the specific conditions at the Riverbend Plant, it will be useful to review the general hydrogeologic conditions in the area.

2.1 GENERAL HYDROGEOLOGIC CONDITIONS

The rocks underlying both the Allen and Riverbend sites have considerable similarities. Both sites are underlain by igneous rocks of the Charlotte Belt. They may be referred to as "granite-diorite complex" because the light-colored granite is closely interspersed with dark-colored diorite. The rocks are not bedded or layered but appear locally as discrete cross-cutting dikes (see Figure 1). In some outcrops and well cores, the granite appears to cut across, as dikes, the more predominant diorite, whereas in other places the diorite appears to form dikes in granite.

There appears to be no pattern of orientation or directional trend along the discrete granite and diorite boundaries. There is a slight tendency for the rock boundaries to be more fractured than the large separate bodies of granite and diorite, at least in the deeper fresh rock. In the saprolite, however, the spaces between the different rocks



Diagrammatic sketch showing the relation between
diorite and granite in the Charlotte Belt.
Conditions typical of the Allen Plant site are on
the left and those at Riverbend are on the right.
(Modified from LeGrand, 1952, fig.3.)

FIGURE 1

appear to be closed by the swelling of the decomposed minerals, such as feldspars and hornblende. The fracture system in the bedrock is difficult to determine. From present knowledge, it can be deduced that some fractures are along the granite and diorite boundaries but most are not. The overall yields of wells in the Charlotte Belt are about average for the entire Piedmont region — certainly not above average.

The statements that follow apply to the Piedmont region generally and form a basis for a conceptual model of specific sites. In these respects, both the Allen and Riverbend sites are similar, and much of the knowledge gained from the Allen site can be applied readily to the Riverbend site.

1. The gross groundwater system in the region is not an extensive continuum, as is the case in most regions. Instead, the region is composed of countless relatively small groundwater units, each unit almost confined to each small surface drainage basin in which a perennial stream occurs.
2. The region is underlain by igneous and metamorphic rocks; the rocks range in chemical composition between that of granite (mainly silica and silicates of aluminum and potassium) and that of diorite (chiefly silicates of aluminum, iron, magnesium, and calcium).
3. A layer of saprolite lies on the fresh rock in most places; the thickness of the saprolite ranges from a feather edge to slightly more than 100 feet.
4. Water occurs in two types of media: (a) clayey granular weathered material and (b) underlying fractures and other linear openings in bedrock.
5. A close network of streams prevails and, in few places, the distance to a perennial stream is more than one-half mile. A hill-and-dale topography occurs, commonly with gentle slopes.
6. A continuous flow of groundwater occurs toward each stream. Some of the overflowing groundwater is consumed as evapotranspiration in valleys; the remainder discharges as small springs and as bank and channel seepage into streams.
7. Because all the perennial streams receive groundwater from adjacent interstream areas, streams are linear sinks in the water table. This part of the water table is directly observable. The topography of the water table is similar to that of the land surface, but its relief is less. Thus, it is easy to construct synthetic water-table maps and to predetermine the general direction of the natural movement of groundwater.

8. The path of natural movement of groundwater is relatively short and is almost invariably restricted to the zone underlying the gross topographic slope extending from the land-surface divide to the stream.
9. From a point source of infiltration, water, or waste that might be with it, extends as a narrow fan or expansive trail down-gradient toward the nearest perennial stream; its dispersal depends on the kind and degree of permeability, on the hydraulic gradient, and on the distance to the stream.
10. Almost all recharges and discharges are through porous granular material (clayey soil or floodplain deposits), but much of the intermediate flow between the recharge and discharge areas is through bedrock openings.
11. The saturated zone is not simple to define. Its top boundary is the water table, which lies in the clayey weathered material more often than not, but which becomes discontinuous where it lies in fractured bedrock. The lower boundary is irregular and indistinct; it is represented by the base of the zone in which interconnecting fractures exist. The saturated zone is absent where unfractured rocks crop out, but it is commonly 50 to 300 ft thick. Water-yielding capacity within the zone ranges through several orders of magnitude; commonly it is less near the base of the saturated zone than near the top.
12. The water table is near land surface in valleys and as much as 20 to 70 ft below land surface beneath hills. The range of seasonal fluctuation of the water table is as little as 3 ft in valleys and as much as 8 ft beneath hills.
13. Bedrock fractures tend to decrease in size and number with depth, and in most places there is an insignificant storage and circulation of groundwater below a depth of 400 ft.
14. Many fractures underlie "draws" or linear sags in the surface topography. These draws, representing zones of relatively high permeability in the bedrock, are sites for the best-producing wells.
15. The yields of wells range from less than 1 gallon per minute to as much as 200 gallons per minute; the sustained yield of most wells is less than 100 but more than 6 gallons per minute. The cone of pumping depression of a domestic well does not generally extend to the cone of another pumping well a few hundred ft away.
16. Two distinctive chemical types of groundwater are present. The first includes soft, slightly acidic water low in dissolved mineral constituents; water of this type comes from light-colored rocks resembling granite in composition, and includes granite, granite gneiss, mica schist, slate, and rhyolite flows and tuffs. The second includes a hard, slightly alkaline water relatively high in dissolved solids; water of this type comes from dark rocks, such as diorite, gabbro, hornblende gneiss, and andesite flows and tuffs.

Without detailed field observations of the geologic conditions at the two sites, there is a risk in pointing out specific similarities and differences. Some probable slight differences might be inferred as follows:

- A. Granite appears to be predominant at Riverbend, whereas diorite is predominant at Allen.
- B. The saprolite at Allen is probably thinner and more clay-rich than the saprolite at Riverbend.
- C. The groundwater in the bedrock at Allen may be more alkaline or slightly less acid than the water in the bedrock at Riverbend.

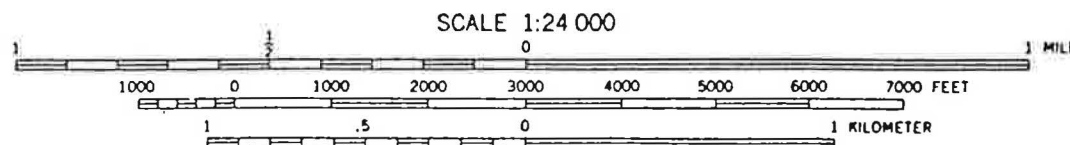
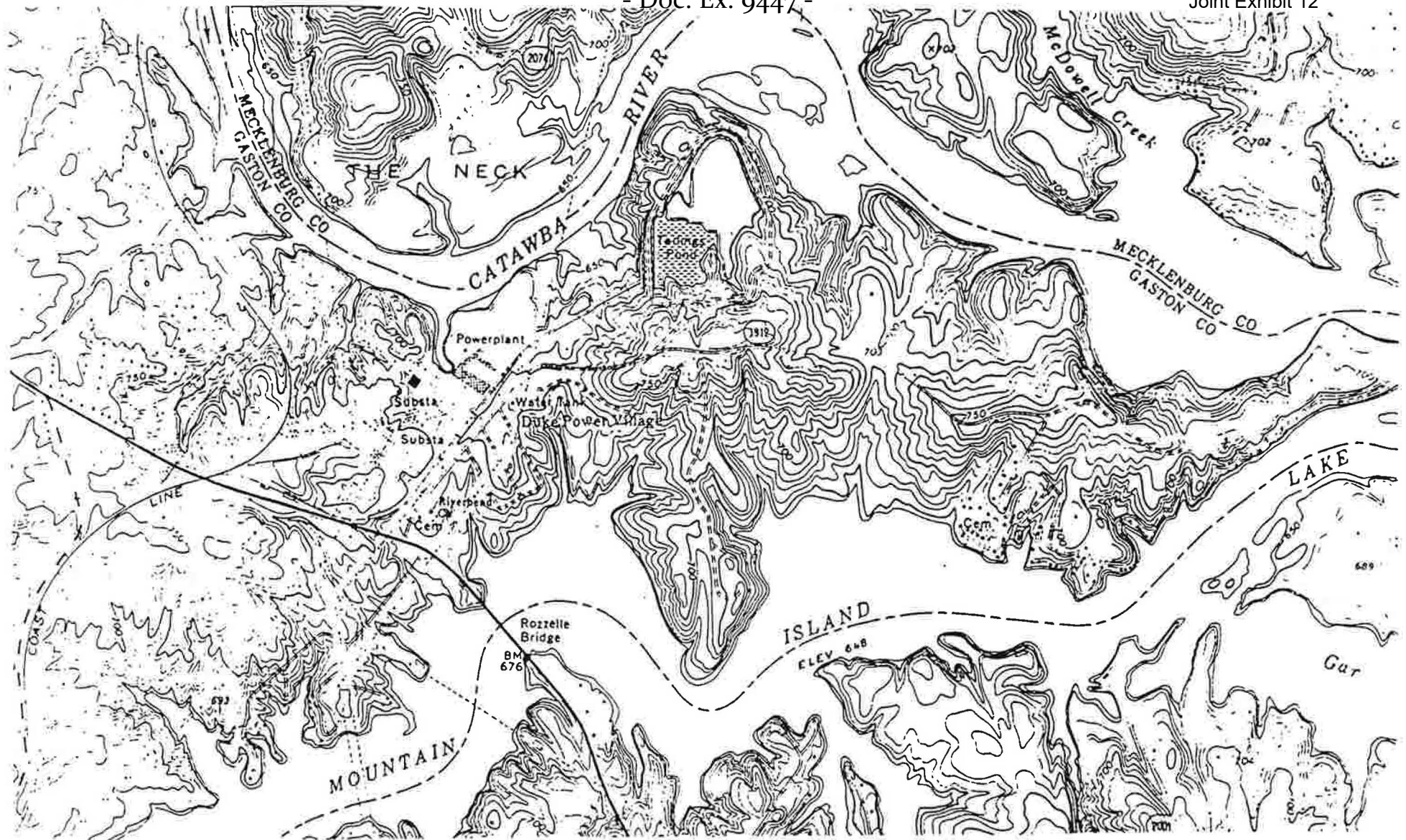
2.2 HYDROGEOLOGIC CONDITIONS AT RIVERBEND PLANT

The Riverbend Plant, as the name implies, is located on a peninsula about 2.5 miles long and generally less than a mile wide formed by a great eastward bend in the Catawba River (Figure 2). The power plant is located near the narrow neck at the western end of the peninsula, and the ash pond is to the east on a northward bulge in the peninsula.

A topographic divide runs in a generally east-west direction down the center of the peninsula. It is consistent with our understanding of the hydrogeology of the Piedmont to assume that the water-table divide is coincident with the topographic divide. The southern edge of the ash pond is about 800 ft north of the topographic divide, and the dredge pond (ash-basin) is centered about 700 ft north of the divide.

Test borings were constructed in the area occupied by the ash pond, both in connection with the excavation of material used in dike construction and to determine the foundation conditions at the dikes. These borings generally penetrated only 20 to 40 ft in sandy, clayey, silty saprolite and thus ended well above the bedrock surface. A relatively dense network of borings exists in the area immediately to the south and southeast of the pond, which provides more complete geologic data from land surface to

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CONTOUR INTERVAL 10 FEET
DATUM IS MEAN SEA LEVEL

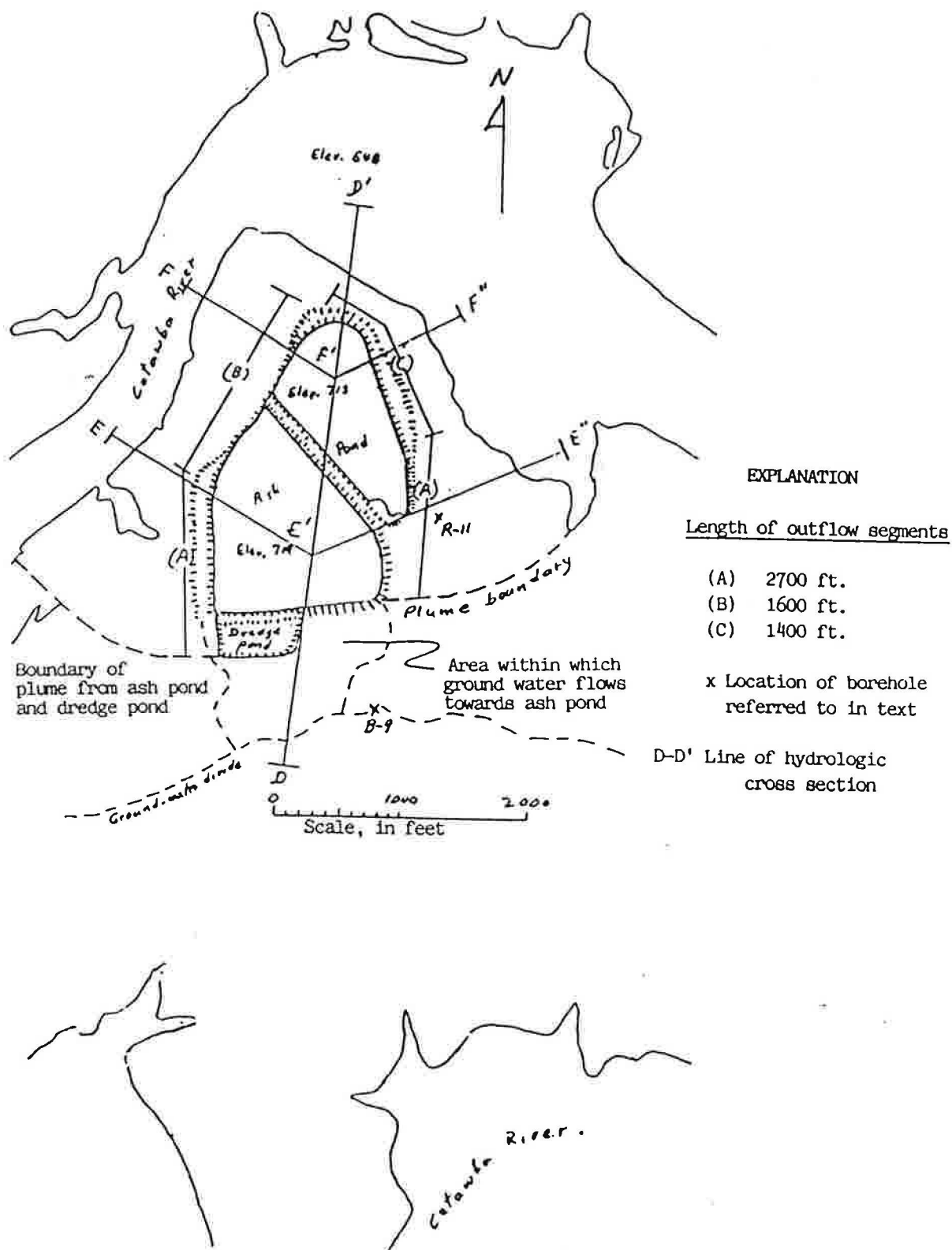
Location and Topography of the Riverbend Ash Pond Area

the top of bedrock. Data from these borings can be used to infer the geology of the ash pond site. Driller's logs of borings B-9 and R-11 are given below. The locations of these borings in relation to the dredge pond and the ash pond are shown in Figure 3. Note that Boring B-9 is located along the topographic (and water table) divide, and boring R-11 is about 300 ft east of the ash pond and about midway between the topographic divide and the Catawba River.

Driller's Log for Boring B-9, Duke Power Co. Riverbend Plant

Depth (ft)	Material
0 - 5	Red to orange, fine to coarse sandy, gravelly clay
5 - 10	Red, slightly micaceous, fine to coarse sandy, gravelly clay
10 - 15	Red to orange, fine to coarse sandy, gravelly, silty clay
15 - 20	No sample
20 - 25	Pink to orange, slightly micaceous, fine to medium sandy silt
25 - 30	Tan to orange, fine to medium sandy silt
30 - 35	Micaceous, fine to medium sandy silt
35 - 40	Tan to orange, micaceous, fine to medium sandy silt
40 - 45	Micaceous, fine to medium, sandy silt
45 - 50	Tan to orange, slightly micaceous, fine to medium slightly sandy silt
50 - 66	Fine to medium slightly sandy silt

Elevation of land surface 788 ft. Hole dry.



Map of Riverbend Ash Pond Area Showing Segments Used to Calculate Ground-water Outflow from Pond, Ground-water Divides, Locations of Hydrogeologic Cross Sections and Boundary of Outflow Plume.

FIGURE 3

Driller's Log for Boring R-11, Duke Power Co. Riverbend Plant

Depth (ft)	Material
0 - 5	No sample
5 - 10	Orange, clayey silt
10 - 15	Orange, slightly micaceous, fine to medium slightly sandy, slightly clayey silt
15 - 20	Tan to red, micaceous, fine to medium sandy silt
20 - 30	Red to orange, micaceous, fine to medium slightly sandy, silty clay
30 - 55	Brown to orange, fine to medium slightly sandy, clayey silt
55 - 60	No sample
60 - 95	Brown to orange, slightly micaceous, fine to coarse sandy silt
95 - 120	Tan to brown, micaceous, fine to coarse sandy silt (Groundwater freely entered the hole in this section)

Elevation of land surface 720 ft. Depth to water level about 55 ft below land surface after 24 hours.

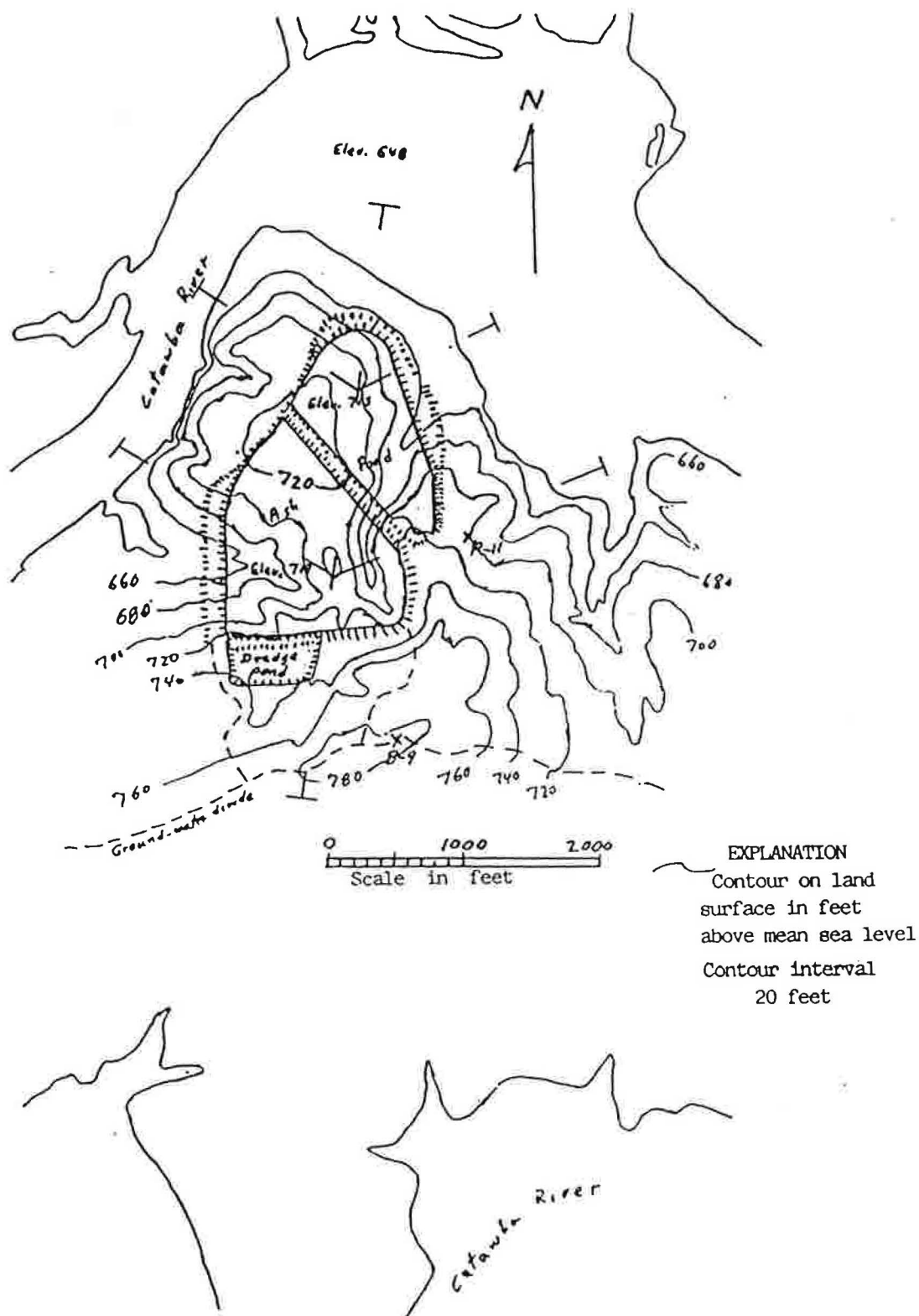
The logs of these borings, which are typical of many others in the area, show that the upper part of the saprolite tends to contain significant clay because of the chemical breakdown of feldspar present in the granitic rocks. Downward, toward the unweathered rock, the material becomes silty with sand-size fragments of quartz.

Field logs of 17 test borings in the area east and south of the ash pond were analyzed to determine the characteristics and thickness of the saprolite. The borings were constructed both with a power auger and with a rotary drill, with water as the circulating fluid. None of the borings penetrated bedrock, but an effort was made during drilling, through the use of standard penetration resistance tests, to ensure that the borings were near the bedrock surface.

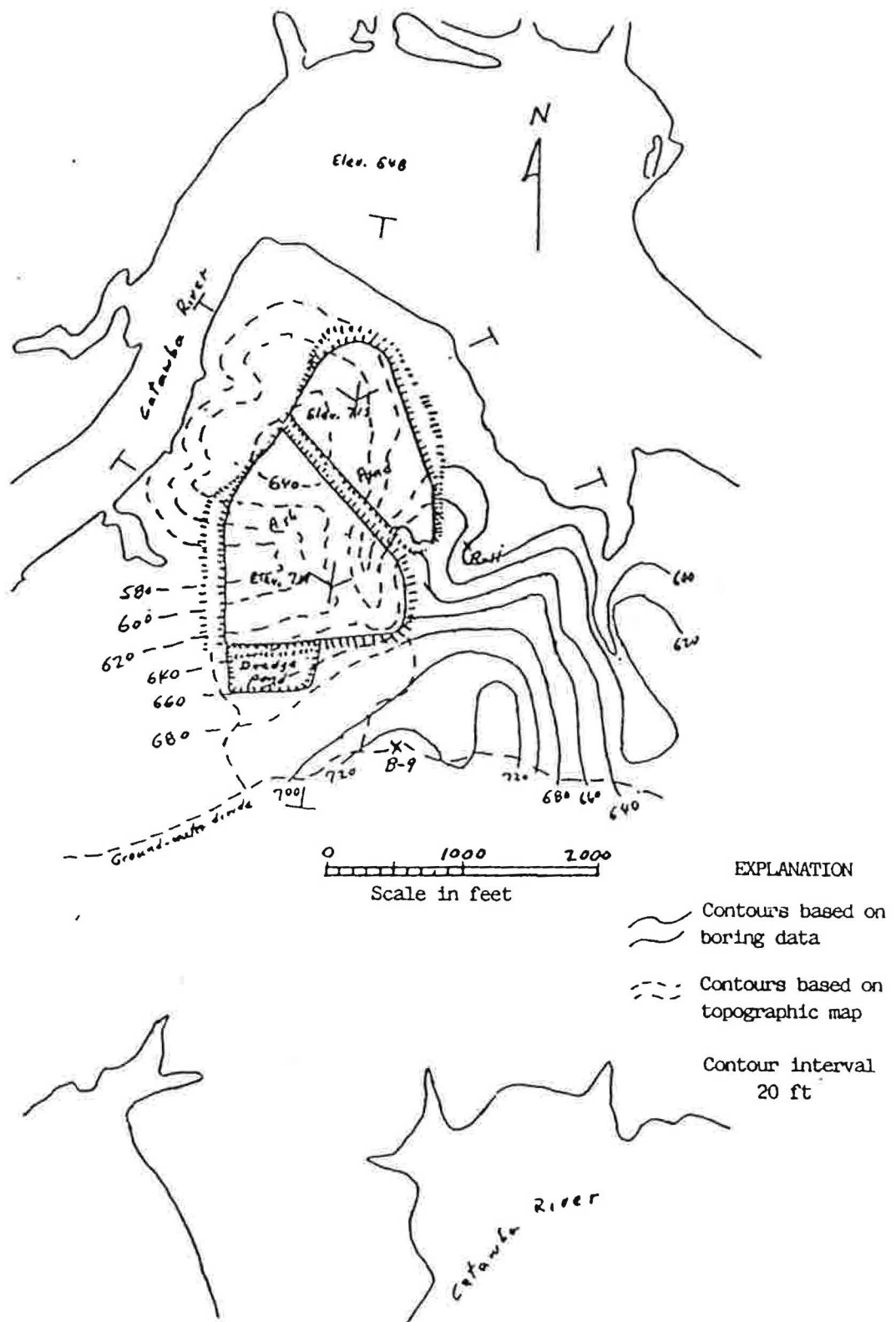
Figure 4 shows the altitude of the land surface, based on a topographic map of the ash pond area with a 2-ft contour interval prepared by Duke Power Co. Figure 5 is a map of the ash pond area showing the configuration of the bedrock surface based on the total depth of the test borings. It is important to note that because none of the borings actually penetrated bedrock, the altitudes of the bedrock surface are somewhat less than those shown in Figure 5. The contours on the top of the bedrock were extended into the site of the ash pond on the basis of the relations between land-surface topography and depth to bedrock that exist in the area in which boring data were obtained.

The approximate thickness of the saprolite can be determined from the difference in the altitudes in Figures 4 and 5. The approximate thickness of the saprolite is shown in Figure 6 in the area for which boring data were obtained. As shown on this figure, the thickness of saprolite ranges from about 20 ft to more than 120 ft and averages between 60 and 80 ft in the area. Review of the penetration-resistance tests suggests that the borings in the area where the saprolite appears to be relatively thin were terminated well above the bedrock surface.

It is apparent from the preceding discussion that the specific data from the borings provide key information about (1) the depth to the bedrock (and thickness of the saprolite) and (2) depth to the water table (and thickness of the unsaturated zone). Interpolation between data points (the placement of contours) that was necessary to prepare Figures 4, 5 and 7 is based partly on hydrogeologic experience, especially on the relation of land-surface topography to depth to bedrock and depth to the water table. Thus, the contour maps and the cross-sections are believed to represent usefully close approximations but are not necessarily exact representations of conditions at all points.

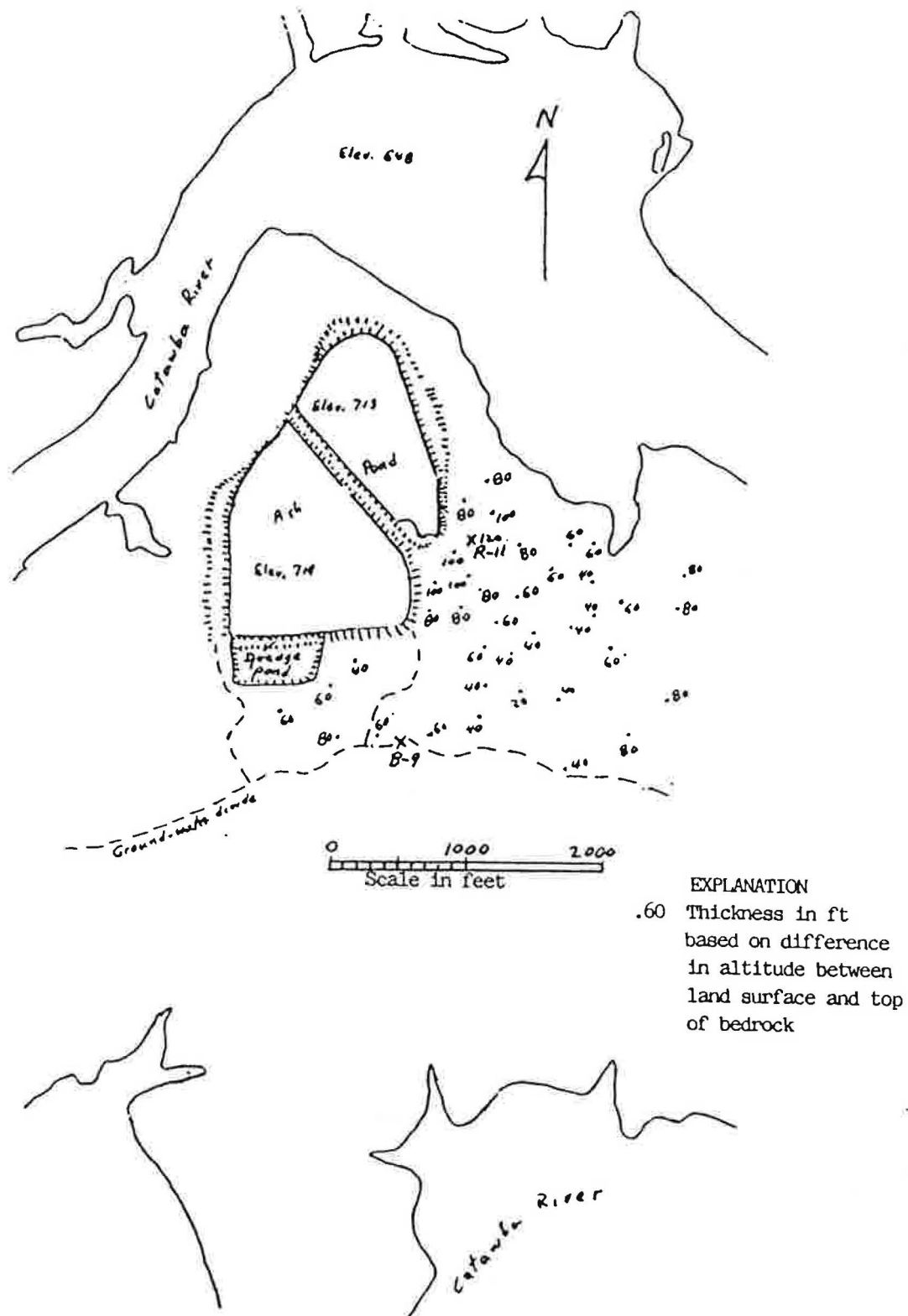


Map of Riverbend Ash Pond Area Showing Land-Surface Topography Prior to Development of Ash Pond



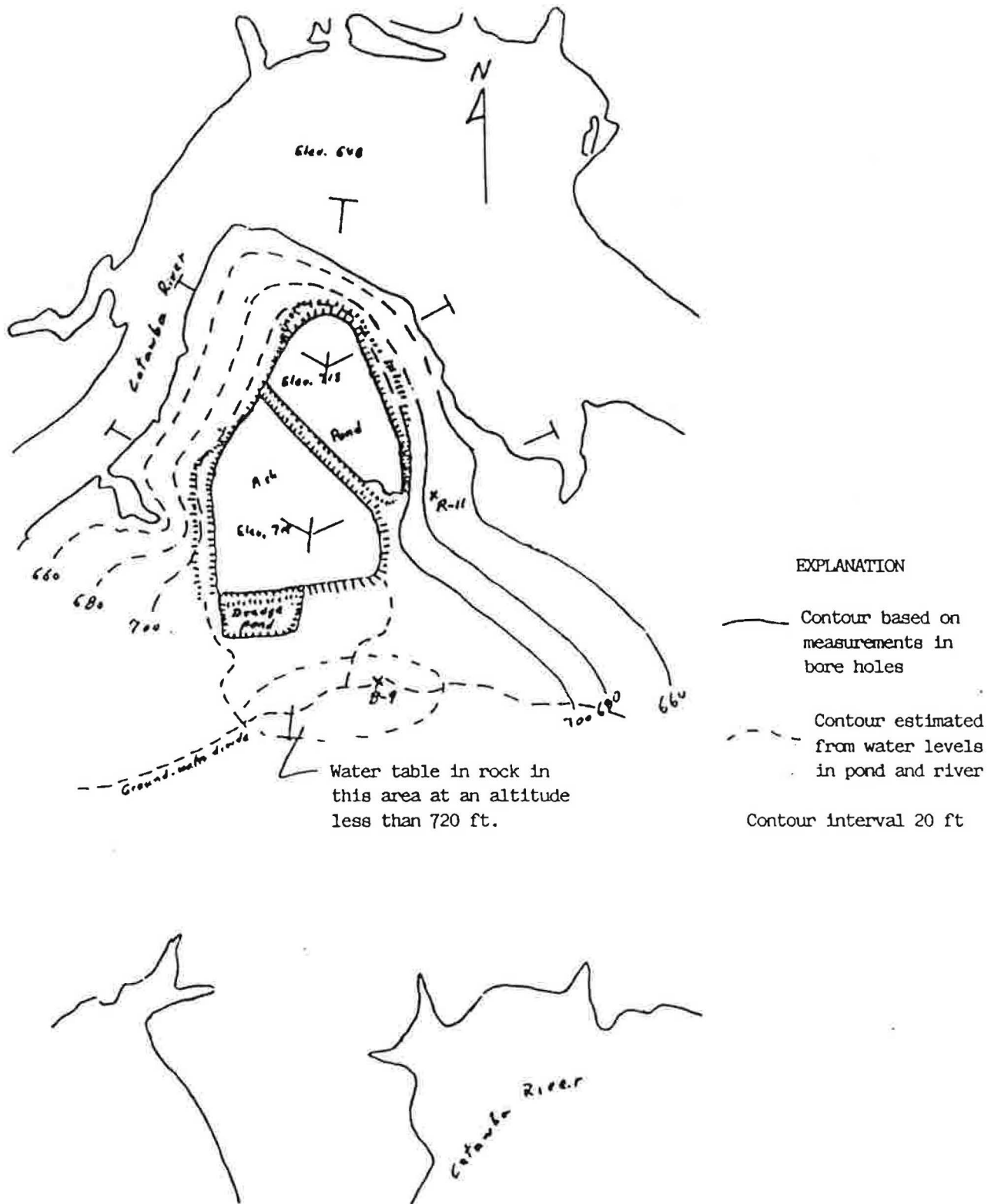
Map of Riverbend Ash Pond Area Showing the Approximate Configuration of the Bedrock Surface

FIGURE 5



Map of Riverbend Ash Pond Area Showing Estimated Thickness of Saprolite Based on Boring Data Supplied by Duke Power Co.

FIGURE 6



Map of Riverbend Ash Pond Area Showing the Approximate
Altitude of the Water Table in the Saprolite and Dikes

FIGURE 7

3. EFFECT OF RIVERBEND ASH POND ON GROUNDWATER

The Riverbend ash pond is divided, by a dike, into two cells. The water surface is maintained at a level of about 719 ft above sea level in the southern cell and at a level of about 713 ft in the northern cell. During periods when ash slurry is being added to the pond, excess water is discharged from the lower (northern) cell directly to the Catawba River.

The Catawba River stage is maintained at an average level about 648 ft above sea level by the Mountain Island Dam, which is 8 miles downstream. Because the river stage is below that of the pond, there is a hydraulic gradient between the pond and the river through the groundwater system. As a result, an important consideration related to the operation of the ash pond is its effect on groundwater quality and, ultimately, the effect of groundwater derived from the pond on the quality of the river.

The effect of the ash pond on groundwater depends primarily on

- the vertical hydraulic conductivity (K) of the ash and the saprolite,
- the transmissivity (T) of the saprolite and bedrock,
- the hydraulic gradients in the saprolite and bedrock, and
- the ion-exchange capacity of the saprolite.

The groundwater system at Riverbend, as at the Allen Plant and other places in the Piedmont, consists of two distinctly different parts: (1) the granular surficial layer of saprolite that forms during the chemical and physical breakdown of bedrock, in the process referred to as "weathering," and (2) the unweathered bedrock. Water occurs in and moves through the saprolite in the pore spaces between rock particles and through

the bedrock in sheet-like openings that develop along fractures. Because of significant differences in the hydraulic properties of saprolite and bedrock, it is necessary to treat the groundwater system at Riverbend as a two-part system.

Water in the ash pond moves vertically downward across the ash layers into the saprolite and also laterally through the dikes and surrounding saprolite. Most of the water that enters the saprolite beneath the pond moves through the saprolite toward the Catawba River; the remainder seeps downward into the bedrock and then laterally to the Catawba River. Because the stages of the pond and river are maintained at relatively constant levels, the movement of water from the ash pond to the river through the groundwater system can be analyzed with steady-state equations that involve only the water-transmitting characteristics of the ash, saprolite, and bedrock.

3.1 HYDRAULIC CONDUCTIVITY OF ASH AND SAPROLITE

No determination of hydraulic conductivity (K) of the ash and saprolite have been made on samples from Riverbend. However, the report on the Allen Plant prepared by Arthur D. Little, Inc. (ADL) contains results of laboratory determinations of the K of ash, and the report prepared by Tetra Tech contains data on the saprolite. The data from these reports are summarized in Table 1.

TABLE 1
Hydraulic Conductivity Data from the Allen Plant

Material	Hydraulic Conductivity (K) (ft/d)	Source
Ash	$2.8 \times 10^{-4} - 5.6 \times 10^{-1}$ (avg. of 4 samples = 1.6×10^{-1})	A.D. Little, Table 5-2
Saprolite	1.05 - 2.8 (avg. of 9 samples = 1.34)	Tetra Tech, Table 4-18

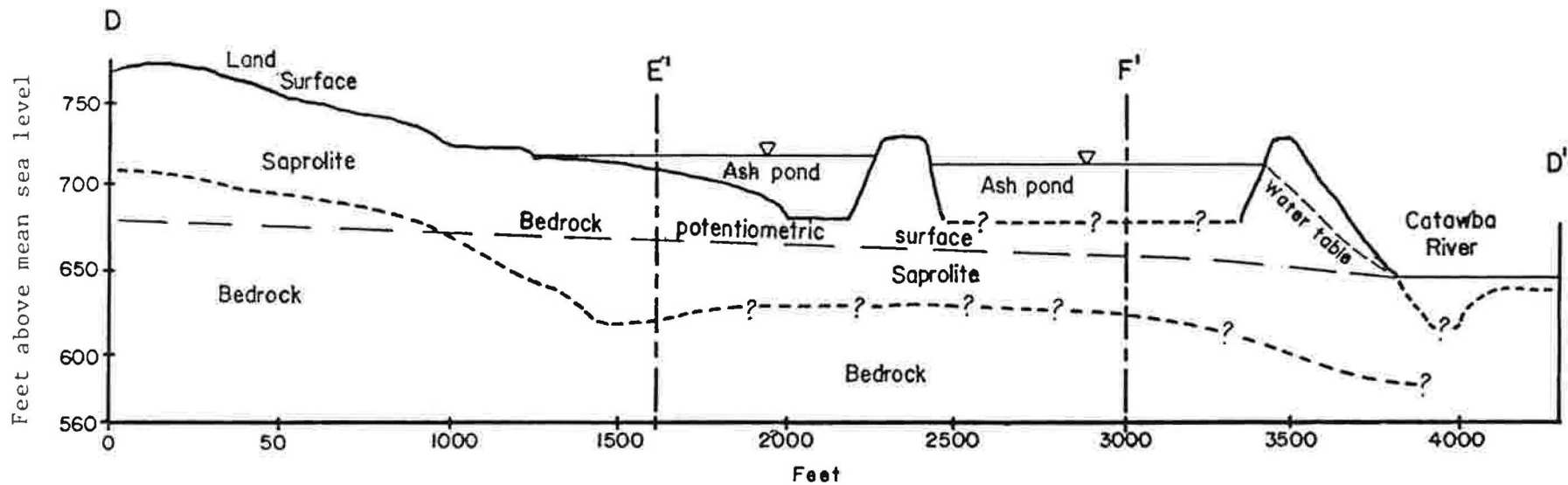
The hydraulic conductivity of ash depends on the physical characteristics and thickness of the ash and on the length of time it has compacted. As a result of compaction, the bottom layers of ash in ponds are generally the least permeable, and it is these layers that control the rate at which water seeps from ponds. However, for purposes of computations at Riverbend that require the K of ash, the average value of 1.6×10^{-1} given in Table 1 will be used.

Relative to hydraulic conductivity of the saprolite, values for 9 samples from the Allen Plant averaged 1.34 ft/d and ranged from 1.05 to 2.8 ft/d. Recognizing that the saprolite at Riverbend may be somewhat more permeable than that at Allen, an average value of 2 ft/d will be used in calculations for Riverbend.

3.2 TRANSMISSIVITY OF THE SAPROLITE AND BEDROCK

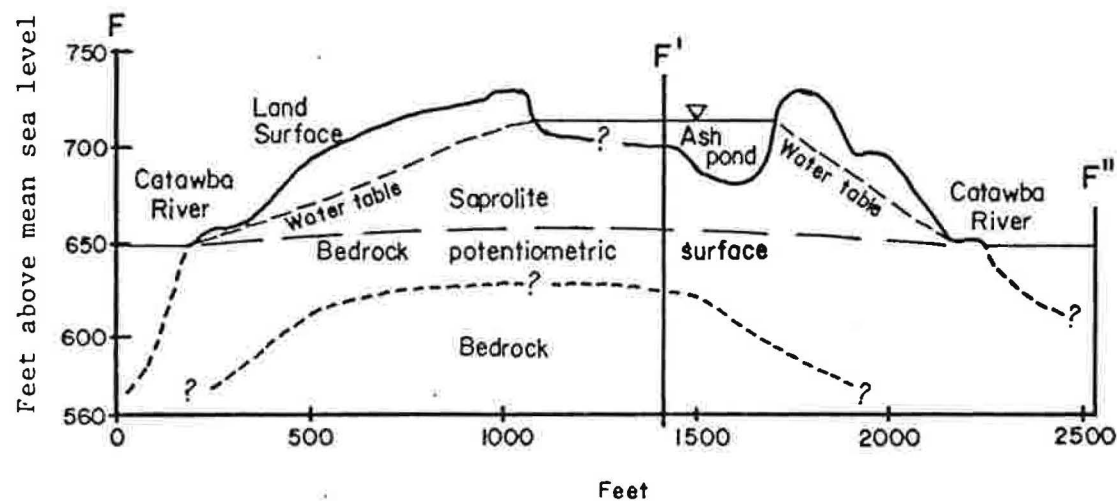
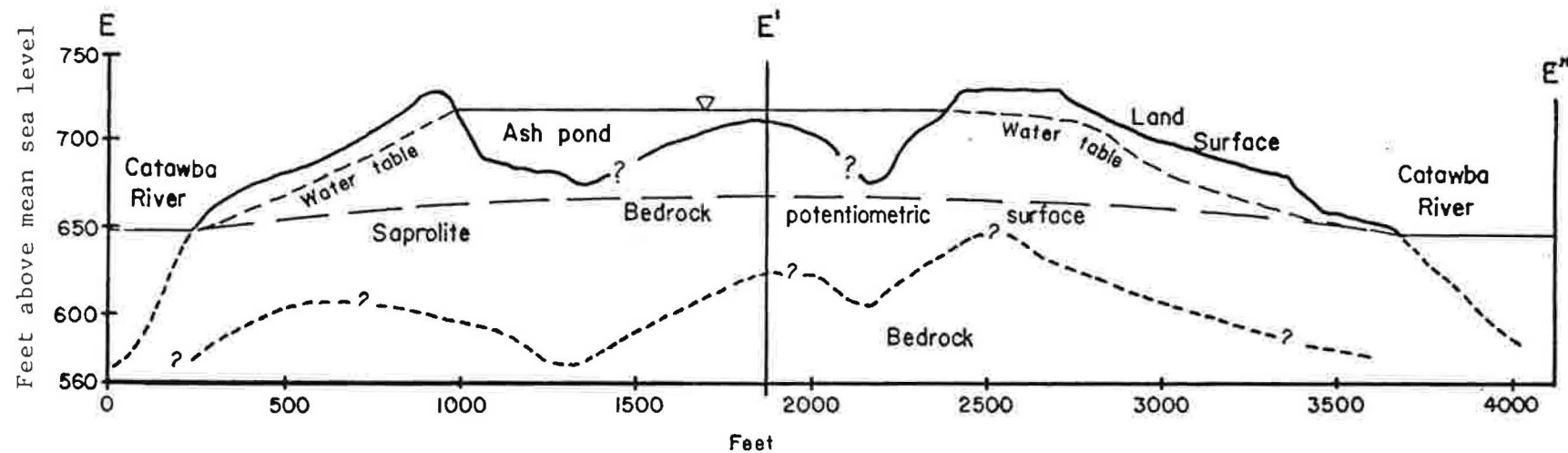
The quantity of water moving between the pond and the river depends on, among other factors, the water-transmitting capacity of both the saprolite and the bedrock. This capacity is referred to as transmissivity (T), which is equal to the hydraulic conductivity (K) times the thickness (b) of the zone through which movement occurs ($T = Kb$).

The transmissivity of the saprolite at Riverbend can be estimated by multiplying the hydraulic conductivity discussed in the previous section by the thickness of saprolite through which water moves. Estimates of this thickness can be obtained from the difference in the altitude of the bedrock surface (Figure 5) and the altitude of the water table (Figure 7). However, for the purpose of this analysis, equally satisfactory values for saprolite thickness can be obtained from the difference in altitude between the water table and the bedrock surface on the hydrogeologic sections shown in Figures 8 and 9.



Hydrogeologic Cross Section Along Line D-D' in Figure 3

Figure 8



Hydrogeologic Cross Sections Along Lines E-E'' and F-F'' in Figure 3.

Figure 9

The lines of these sections are shown on Figure 3, together with the segments that will be used in calculating groundwater outflow from the pond to the river. The water-transmitting thickness of saprolite for each of the outflow segments is shown in Table 2.

TABLE 2
Thickness and Transmissivity of the Saprolite for the Outflow Segments
Shown in Figure 3

Outflow Segment	Hydrogeologic Section	Saprolite Thickness ^{1/} (ft)	Transmissivity (ft ² /d)
A	E - E"	70	140
B	F - F'	60	120
C	F' - D'	90	200 ^{2/}
	F' - F"	110	

^{1/} Average thickness midway between pond and river.

^{2/} Based on average thickness of 100 ft.

No data on hydraulic conductivity and transmissivity of the bedrock are available for either the Allen or Riverbend Plant areas. Water-bearing fractures in the bedrock are very irregular in occurrence, as discussed in Section 2.1. This fact, together with large differences in water-transmitting capacity between different fractures and even at different places along the same fracture, causes the hydraulic conductivity to range from essentially zero in some parts of the bedrock to as much as 10 ft/d in narrow, densely fractured zones.

However, to estimate the effect of the ash pond on groundwater, it is necessary to estimate the transmissivity of the bedrock. The first consideration in this process is the thickness (b) of the water-transmitting zone in the bedrock beneath the peninsula on which the ash pond is located. The Catawba River is a groundwater discharge zone of regional impact so that all groundwater in the bedrock beneath the peninsula is derived from recharge on the peninsula. Because of the narrow width of the peninsula, the

longest possible groundwater flow lines are less than one-half mile in length. In view of this, it is doubtful that there is any significant movement of groundwater below a depth of 50 ft below the bedrock surface. Using this value for thickness and 1 ft/d for hydraulic conductivity, the transmissivity of the bedrock is estimated to be 50 ft²/d.

3.3 HYDRAULIC GRADIENTS IN THE SAPROLITE AND BEDROCK

As noted previously, the difference in the water levels between the pond and river provides the condition necessary for the development of a hydraulic gradient between the pond and river through the groundwater system.

The estimated altitude of the water table in the dikes and saprolite is shown in Figure 7. The altitudes on this figure were used to draw the water-table profiles in Figures 8 and 9. It should be noted that the water-table profiles in Figures 8 and 9 are drawn to connect the water surfaces of the pond and river. However, it is important to also note that the hydraulic gradient represented by the water table is not the "effective" hydraulic gradient in the saprolite between the pond and the river.

To understand this fact, note that the potentiometric surface of the bedrock is also shown in Figures 8 and 9. This surface, which shows the height to which water would stand in wells that are cased through the saprolite and finished as open holes in the bedrock, is substantially below the pond levels and the water table. This is to be expected because, for water to move downward across the ash in the pond and across the saprolite to the bedrock, there must be a gradient between the pond surface and the bedrock. The magnitude of this gradient (i.e., the difference in level between the pond and the potentiometric surface) reflects the head loss as water moves across the ash and saprolite.

The average effective hydraulic gradient that controls flow from the pond to the river through the saprolite is much flatter than the water table but somewhat steeper than the potentiometric surface of the bedrock. This conclusion is based on the boring logs, which indicate that the lower part of the saprolite is the most permeable. As a result, water from the pond will tend to move vertically downward across the upper part of the saprolite and then laterally to the river through the lower part. Thus, the effective, lateral hydraulic gradient in the saprolite, as stated above, will be much flatter than the water table. However, in the absence of additional data, the average effective lateral hydraulic gradient in the saprolite will be assumed, for purposes of outflow computations, to be the average of the water table and bedrock gradients along each of the outflow segments. These gradients are shown in Table 3.

TABLE 3
Hydraulic Gradients for Saprolite and Bedrock for the Outflow Segments
Shown in Figure 3

Hydrogeologic Unit	Outflow Segment	Hydrogeologic Section	Hydraulic Gradient (ft/ft)	Average Gradient for Segment (ft/ft)
Saprolite (and dikes)	A	E - E'	.07	
		E' - E''	.05	.06
	B	F - F'	.05	.05
	C	F' - D'	.09	
		F' - F''	.07	.08
Bedrock	A	E - E'	.025	
		E' - E''	.02	.02
	B	F - F'	.01	.01
	C	F' - D'	.013	
		F' - F''	.012	.01

Relative to the potentiometric surface of the bedrock, it was noted previously that none of the bore holes penetrated the bedrock. Therefore, no data are available on the bedrock potentiometric surface. However, boring B-9, along the water-table divide, was dry at a depth of 66 ft or at a bottom altitude of 722 ft (see Section 2.2). To estimate

the altitude of the water level in bedrock, the Jacob equation for the profile of the water table was solved for a peninsula 1 mile wide, with a bedrock transmissivity of 50 ft²/d and a recharge rate of 100,000 gpd/mi². The solution shows a height of the water table 31 ft above the controlling water level at the discharging boundary (the Catawba River). This places the water table in the bedrock at the divide south of the Riverbend ash pond at an altitude of about 679 ft (648 + 31), the position shown on Figure 8.

From this altitude on the divide, the bedrock potentiometric surface was sketched to the river surface. The potentiometric surface, as sketched, probably results in a steeper hydraulic gradient and, therefore, a larger outflow through the bedrock than actually exists, because sediment on the bottom of the river hampers the discharge of water from the bedrock, causing the potentiometric surface (static head) in the bedrock to be above the river level beneath the river. The hydraulic gradient for the bedrock, based on the profiles of the potentiometric surface shown in Figures 8 and 9, are also shown in Table 3.

3.4 GROUNDWATER OUTFLOW FROM THE ASH POND

Sections 3.1 through 3.3 provide the data necessary to calculate the rate of flow of water from the ash pond to the Catawba River through the groundwater system.

Darcy's law applies to the steady-state condition that exists in the area and is, therefore, used to calculate the rate of flow. Darcy's law, expressed as an equation, is

$$Q = Tw \, dh/dl$$

where:

Q is rate of flow in ft³/d,
T is transmissivity in ft²/d,
w is width of the outflow segment in ft, and
dh/dl is the hydraulic gradient in ft/ft.

The values used for items in the above equation and the calculated outflow through each of the segments shown in Figure 3 are given in Table 4.

TABLE 4
Groundwater Outflow from the Ash Pond

Outflow Segment	Length of Segment	Hydrogeologic Unit	Transmissivity (ft ² /d)	Hydraulic Gradient (ft/ft)	Rate of Outflow (ft ³ /d)
A	2700	Saprolite	140	.06	22,680
		Bedrock	50	.02	2,700
B	1600	Saprolite	120	.05	9,600
		Bedrock	50	.01	800
C	1400	Saprolite	200	.08	22,400
		Bedrock	50	.01	700
TOTAL					58,900

As shown in Table 4, the estimated outflow from the ash pond to the Catawba River through the groundwater system is 58,900 ft³/d or about 0.7 cfs or 440,000 gpd. For comparative purposes, a water-budget analysis in the ADL report on the ash ponds at the Allen Plant shows an outflow from the ponds through the dikes and the groundwater system of about 71,000 ft³/d (533,000 gpd).

It may also be of interest to compare the total outflow shown in Table 4, of 0.7 cfs, with the flow of the Catawba River. The average flow of the river at the Riverbend Plant is estimated to be 2600 cfs, so the inflow from the ash pond added through groundwater to the river represents only about 1/3700 of the average flow of the river.

The computations in Table 4 show a rate of outflow through the bedrock of 4200 ft³/d (31,000 gpd). This quantity includes both water originating in the pond and water that reaches the bedrock in the area between the water-table divide and the south side of the

pond (see Figure 3). This area is estimated to include about 19 acres or about .03 square mile. If the recharge to the bedrock in this area is about 100,000 gpd/mi², as estimated in Section 3.3, the rate of movement of water from this area toward the pond is about 400 ft³/d (3,000 gpd). This water moves through the bedrock beneath the pond and is, therefore, a part of the bedrock outflow calculated in Table 4. Subtracting the 400 ft³/d from the 4200 ft³/d moving into the river from the bedrock leaves 3800 ft³/d reaching the bedrock from the ash pond.

The boundaries of the zone through which water originating in the ash pond and dredge pond may be reaching the river are shown in Figure 3. It is important to note that the maximum extent of the plume, as predicted in Figure 3, is entirely on property owned by Duke Power Company.

3.5 GROUNDWATER VELOCITIES AND TIME OF TRAVEL

The rate at which water from the pond moves through the groundwater system to the river is also of interest in connection with the effect of the pond effluent on groundwater and river quality. It is well known, at least among hydrogeologists, that groundwater moves slowly - compared, say, to the rate of movement of water in streams. The rate of movement of groundwater in the vicinity of the Riverbend ash pond was calculated for both the saprolite and the bedrock.

The equation used in these calculations is Darcy's Law which, in terms of velocity, is:

$$v = \frac{K dh}{n dl}$$

where:

v is velocity in ft/d

K is hydraulic conductivity in ft/d

n is "effective" porosity and is dimensionless, and

dh/dl is hydraulic gradient in ft/ft.

The values used in solving the equation and the results are shown in Table 5.

TABLE 5
Estimated Groundwater Velocities in Saprolite and Bedrock in the Riverbend Ash Pond Area

Material	Hydraulic Conductivity (ft/d)	Effective Porosity	Hydraulic Gradient (ft/ft)	Estimated Velocity	
				(ft/d)	(ft/yr)
Saprolite					
Vertical	0.2	0.2	0.5	0.5	180
Horizontal	2	0.2			
E - E'			0.06	0.6	220
E' - E''			0.06	0.6	220
F - F'			0.05	0.5	180
F' - F''			0.08	0.8	290
E' - D'			0.02	0.2	70
Bedrock	1	0.001			
E' - D'			0.007	7	2500
F' - D'			0.01	10	3600

Relative to Table 5, it should be noted that because the upper part of the saprolite tends to be less permeable than the lower part, the value of hydraulic conductivity used in calculating vertical velocity is 1/10 the value used in calculating horizontal velocities.

The calculated velocity of groundwater movement through the bedrock seems too large. If this is, in fact, the case, it suggests that either the porosity is too small or the hydraulic conductivity or hydraulic gradient are too large.

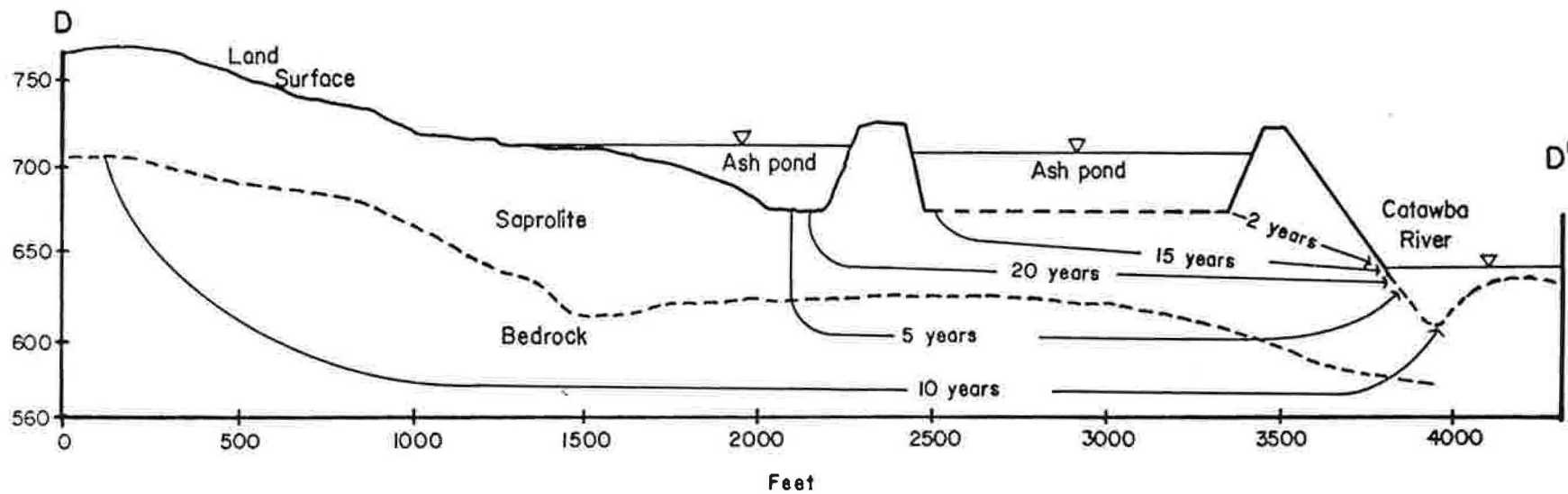
In any case, it is clear from the rounded values of velocity shown in the last column of Table 5 that sufficient time has elapsed since the Riverbend ash pond was placed in operation in 1957 for water to move from the pond to the river. This is also apparent from Figure 10 which shows the estimated times of travel for water originating in the ash pond to reach the Catawba River. The effect of "apparently" faster velocity in the bedrock is clearly evident in the figure.

3.6 EFFECT OF POND SEEPAGE ON GROUNDWATER QUALITY

One of the primary concerns of the North Carolina Division of Environmental Management is the effect of seepage from the Riverbend ash pond on groundwater quality. This was also the major concern of the three studies conducted at the Allen Plant that are referred to in the introduction to this report.

The materials disposed of in the Riverbend ash pond include fly ash, bottom ash, and boiler cleaning wastes. These are the same types of materials disposed of in the Allen Plant ash ponds so that the results of the intensive chemical analyses and studies conducted at the Allen Plant are also generally applicable to Riverbend.

The similarity in the chemical composition of ponded ash at the Allen and Riverbend Plants is shown in Table 6 which contains the results of leachate extraction studies conducted by Duke Power Company on samples collected at both plants in 1980. The leachate was generated through the application of the Environmental Protection Agency Extraction Procedure which is described by Roche, Gnilka, and Harwood (1984, p.2).



Estimated Times of Travel in Years Along Hypothetical Flowlines
From the Riverbend Ash Pond to the Catawba River

Figure 10

TABLE 6
Concentration of Selected Metals in Leachate Extracted From
Ash Samples Through the Use of the EPA Extraction Procedure
and EPA Toxicity Criterion Limits for Solid Wastes Under the
Resource Conservation and Recovery Act. (From Roche, Gniska,
and Harwood, 1984, Table 1 and p. 3). (All concentrations in
parts per billion.)

Constituent	<u>2L</u> ppb	Riverbend			EPA Toxicity Criterion
		Allen	Cell 1	Cell 2	
Arsenic	10	51	82	75	5000
Barium	2000	1200	1100	1300	1000
Cadmium	5	<25	<25	<25	100,000
Chromium	50	10	20	60	1000
Lead	15	<500	<500	<500	5000
Mercury	1.1	0.11	<0.1	<0.1	5000
Selenium	50	<6	<6	<6	200
Silver	18	150	30	40	5000

Coal, and ash derived from its combustion, contains a large number of metals in trace concentrations. However, the results in Table 6 suggest that most of the metals in the ash are not readily soluble. In this regard, it should be noted that the EPA extraction procedure involves pH adjustment to 5.0 in the leachate-extraction process.

The studies conducted at the Allen Plant by the Arthur D. Little Co. included trace metal analyses of soils, ash solids, ponded ash, and of samples of groundwater upgradient from the ash pond, beneath the inactive and active ponds, and down gradient from the ponds. Unfortunately, the metals in the ADL analyses included only arsenic from among the metals listed in Table 6. The analyses made during the ADL study were also

subjected to an intensive analysis in the Tetra Tech report, including an averaging of the analyses from groups of wells reflecting conditions in different parts of the effluent plume. (See Tetra Tech, Inc., 1985, Tables 4-18 and 4-19.)

Table 7 contains analyses from the ADL report, that show the concentration of selected constituents in the soil and ponded ash, in the native groundwater (upgradient), and the well in saprolite beneath the active ash pond that should contain the largest concentration of metals derived from the ash. The locations of wells and other features of the Allen ash ponds are shown in Figure 11. Two values are shown for several of the constituents in some of the analyses in Table 7. The significance of these values are not explained in the ADL report but are assumed to represent the minimum and maximum values of a series of samples obtained from the wells that were sampled.

The data in Table 7 support the conclusion that the metals in ash are not readily soluble. The most obvious exceptions to this are iron and manganese which occur in much larger concentrations in the well in the plume than in the up gradient well and also in larger concentrations than those allowed by EPA and North Carolina standards. Fortunately, the concentrations of iron and manganese allowed by the standards are based on taste and the discoloration of laundry, bathroom and other fixtures rather than public-health considerations. In view of the fact that the maximum possible area that could be occupied by the plume from the Riverbend ash pond is on property owned by Duke Power Company (Figure 3) the concentrations of iron and manganese in excess of the standards are of relatively little significance. In fact, it is possible that some or all of the additional iron and manganese in ground water from the plume is due to the ion exchange of metals in the pond effluent for iron and manganese that occurs naturally in the saprolite.

TABLE 7
Selected Chemical Analyses From the Allen Plant Related to Ash-pond Seepage. (From Arthur D. Little, Inc., 1985, Table 5.3.) (All constituents in mg/l except arsenic which is in µg/l.)

Constituent	Saprolite (Well 3-4)	Ash solids (Wells 3-2, 3-3)	Groundwater up Gradient (Well 3-4B)	Groundwater in Plume (Well 3-2)	EPA Drinking Water Standards ^{1/}
Calcium	471-4056	2251-4578	9.95-10.9	15.8-17	
Sulfate			2.1	1.4	250
Arsenic <i>ug/L</i>	0.6-1.41	16.2-57.1	< 0.2-7.0	0.057-0.76	50
Boron			< 0.005-0.016	< 0.15-1.6	0.75 ^{2/}
Copper	952-17.6	20.8-45.1	< 0.008	< 0.008	1
Iron	11,164-16,558	11,700-29,491	< 0.01	25.9	0.3
Manganese	155-303	83-171	< 0.01-0.07	6.44-14	0.05
Nickel	4.48-10.8	5.3-26.0	< 0.05	< 0.05	
Strontium	8.85-33.1	112-239	0.141-0.166	0.241-0.274	
Vanadium	28.1-49.1	22.2-41.5	<0.005-0.016	<0.005	
Zinc	22.8-36-2	18.5-45.7	<0.05	<0.05	5

^{1/} North Carolina underground water quality standards are the same as those of EPA for arsenic, iron, and manganese. No standards are specified for the other constituents listed.

^{2/} EPA criterion for protection of sensitive crops.

The very low concentration of metals derived from the ash in the water samples obtained from the well in the plume is not surprising. This is due, in the first place, and as mentioned above, to the fact that the metals in the ash are not readily soluble. It is due in the second place, and even more importantly, to the well-known capacity of saprolite to immobilize metals through the process of ion exchange - that is, by the process whereby metals dissolved from the ash and carried in solution in the effluent from the pond are exchanged, upon reaching the saprolite, for other metals which are natural constituents of the saprolite.

The ADL study included analyses of the ion-exchange capacity of alluvial materials and of saprolite at the Allen Plant. The results of these studies are contained in Table 5.4 of the ADL report and show a wide range in the capacity of the different materials that were tested to tie up metals contained in the pond effluent. It is not possible, without a detailed analysis of the basic data (which are not included in the report), to identify the reason for the wide range.

However, it is suspected that the samples which show the smallest ion-exchange capacity were from parts of the plume where much of the ion-exchange capacity had already been depleted. If this is the case, the largest exchange capacities are the ones of greatest importance to the context of this discussion. These show that the saprolite and other materials have the capacity to remove metals, such as arsenic, copper, and selenium, equal to 1,000 to nearly 10,000 times the concentration present in the pond effluent. These numbers mean, in effect, that unit volumes of the saprolite and other materials have the capacity to remove the metals from 1,000 to 10,000 unit volumes of the effluent.

The large ion-exchange capacity of the residual soils (saprolite) in the Piedmont area is obviously an important factor in the lack of significant groundwater pollution problems in the vicinity of ash-disposal ponds. With this in mind, it is important to call attention again to the thickness of saprolite in the Riverbend ash pond area which, as shown in Figure 6, ranges from about 20 to 120 ft. The exact thickness beneath the pond is not known but is believed to range from about 60 to possibly more than 100 ft.

The Tetra Tech report contains an analysis of the vertical attenuation of chemical constituents based on analyses of water samples from wells in the ash pond at the Allen Plant. This analysis confirms the results of the ADL analyses and also shows a large ion-exchange capacity still remaining at a depth of only 8 ft. below the ash in 1981 and 1982, about nine years after use of the "active" ash pond began. (See Table 4-20 in the Tetra Tech report.) In other words, the rate of seepage and the concentration of metals in the effluent are such that the ion-exchange capacity of the saprolite is being depleted ("used up") at a rate considerably less than 1 ft/yr. Assuming that the ion-exchange capacity of the saprolite at Riverbend is similar to that at Allen, as appears to be the case based on the similarity of the hydrogeology of the two sites, it appears likely that metals derived from the Riverbend ash pond have not only not yet reached the Catawba but have not yet reached the bedrock.

The effect of ash pond seepage, both on groundwater and, ultimately, on the Catawba River involves both hydrogeologic and geochemical factors. The preceding discussion in this section has dealt with some of the results of previous studies, including the effect of ion exchange on the concentration of metals contained in the seepage. With the background of that discussion, it will be useful at this point to deal somewhat more comprehensively with the hydrogeologic and geochemical factors. These factors include:

1. Differences in the mineral composition of the saprolite^{1/} from place to place resulting from differences in mineral composition of the granite-diorite complex that forms the bedrock at both the Allen and Riverbend sites. These differences affect both the "background" groundwater quality and cation-exchange capacity of the saprolite.
2. Lateral and vertical differences in mineral composition of the ash resulting from the discharge to the pond at different times of bottom ash, fly ash, and boiler-cleaning wastes. These differences affect both the rate of movement of water through the ash and its chemical composition as it enters the saprolite.
3. Differences in the "attractive force" between the saprolite and the different metals dissolved in the pond effluent. It is this "force" that determines the ion-exchange capacity.

Relative to the first factor, all of the materials through which the effluent moves are capable of ion exchange; the amount depending on mineral composition and grain size of the materials (Davis and De Wiest, 1966, p. 88-92). Because the saprolite tends to be finer grained and more clay-rich with increasing distance above the bedrock, the upper part of the saprolite has the largest ion-exchange capacity.

Relative to the third factor, the attractive force between ions and the surface of the rock particles is different for different metals with the result that those that are most strongly attracted will displace those that are weakly held. Freeze and Cherry (1979, p. 133) show that the normal order of preference for some monovalent and divalent cations for most clays is

Affinity For Adsorption

Monovalent ions

Cs > Rb > K > Na > Li

Stronger → Weaker

Divalent ions

Ba > Sr > Ca > Mg

^{1/} For convenience in this discussion, all of the earth materials between land surface and the top of bedrock will be referred to as saprolite. However, it should be noted that they include not only saprolite but also the materials used to construct the enclosing dikes and, near the river, thin alluvial deposits.

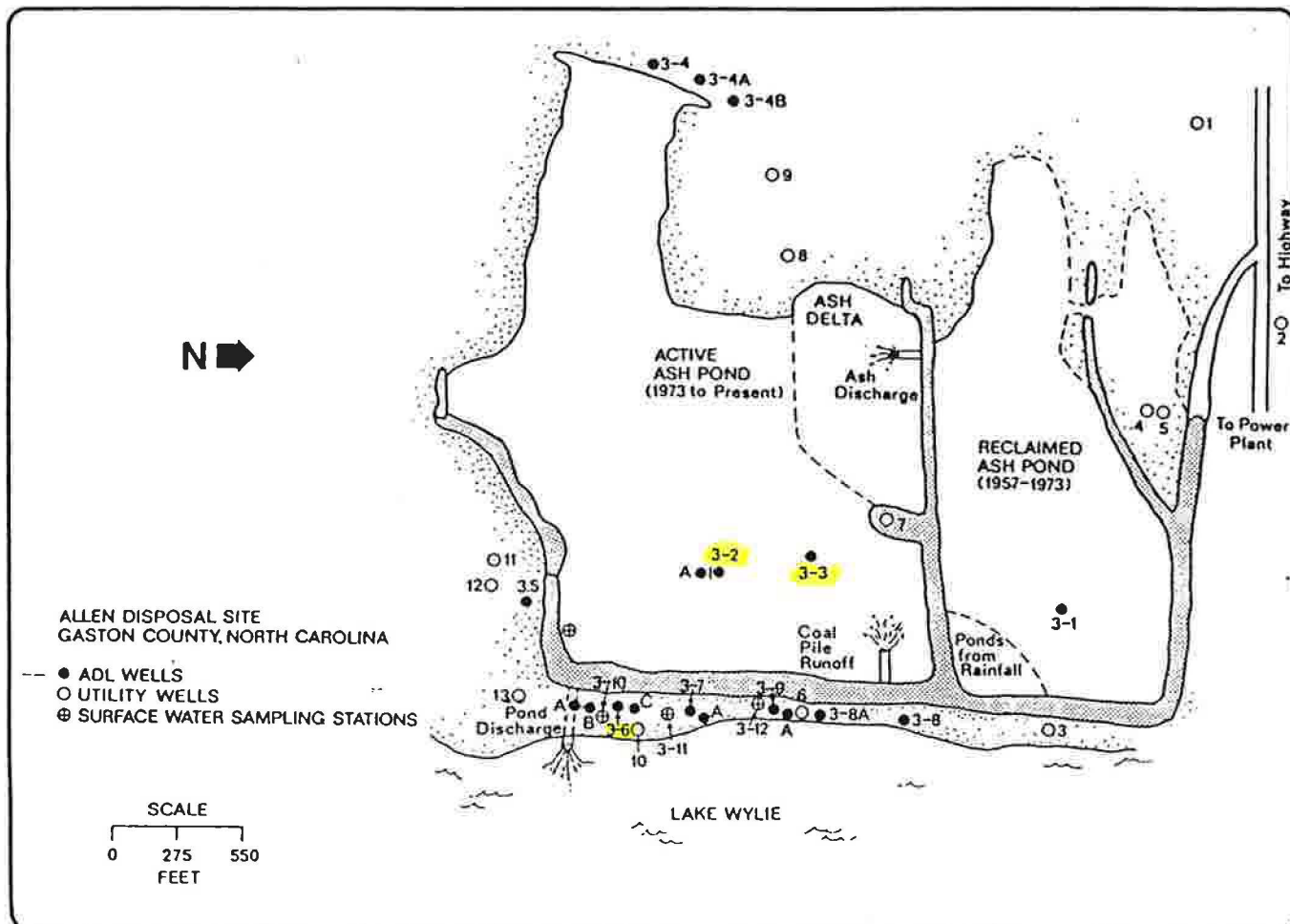
The divalent ions are normally held more strongly than the monovalent ions.

Differences in the attractive force not only result in replacement of ions that are natural constituents of the rocks with ions in solution in the effluent but also result in a "partitioning" of the metals in the effluent along flowlines. Thus, referring to the above diagram, calcium should advance through the saprolite more rapidly than strontium and strontium should advance more rapidly than barium.

Other factors that affect the rate of movement of metals from the ash pond include pH and temperature. However, the preceding discussion is sufficient to show that chemical analyses of water samples from wells at different depths in the saprolite and at different distances from the pond should not be expected to show a perfectly consistent pattern radially away from the pond.

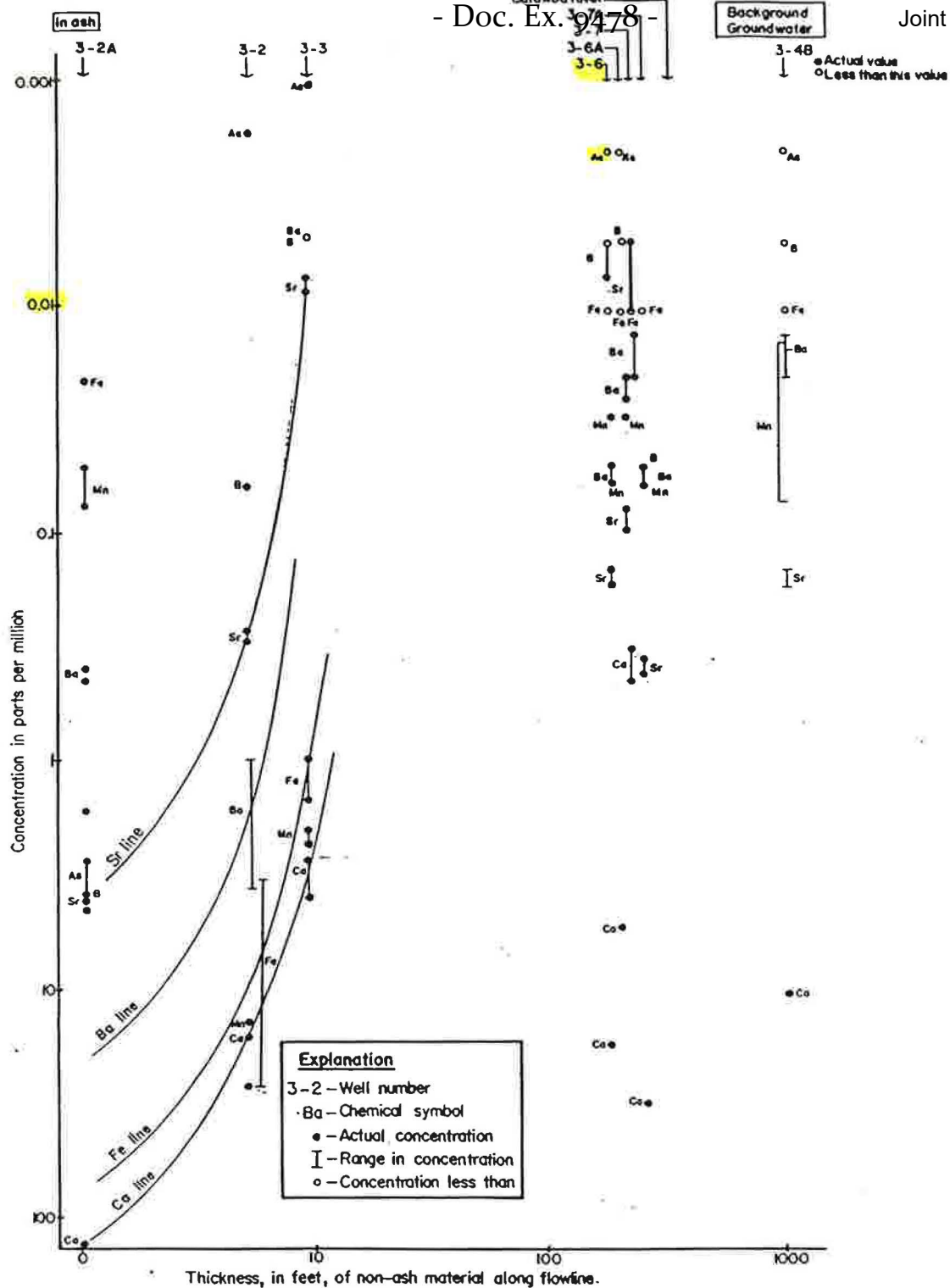
In an effort to evaluate the effect of the factors discussed above on the movement of metals from the pond to the river, the concentration of selected constituents for wells screened in the saprolite at different depths beneath the ash in the active Allen pond and at different distances from the pond were plotted on Figure 12. The locations of the wells are shown on Figure 11 and their positions with respect to the pond are shown on Figures 13 and 14. It should be noted that the large range in chemical concentrations required the use of a logarithmic scale in the preparation of Figure 12. The thickness of non-ash material between the wells and the pond was also plotted on a logarithmic scale in order to expand the separation of the wells in the ash pond.

The concentrations of the different constituents plotted on Figure 12 represent samples collected from the wells on two different dates, one in late February and one in late



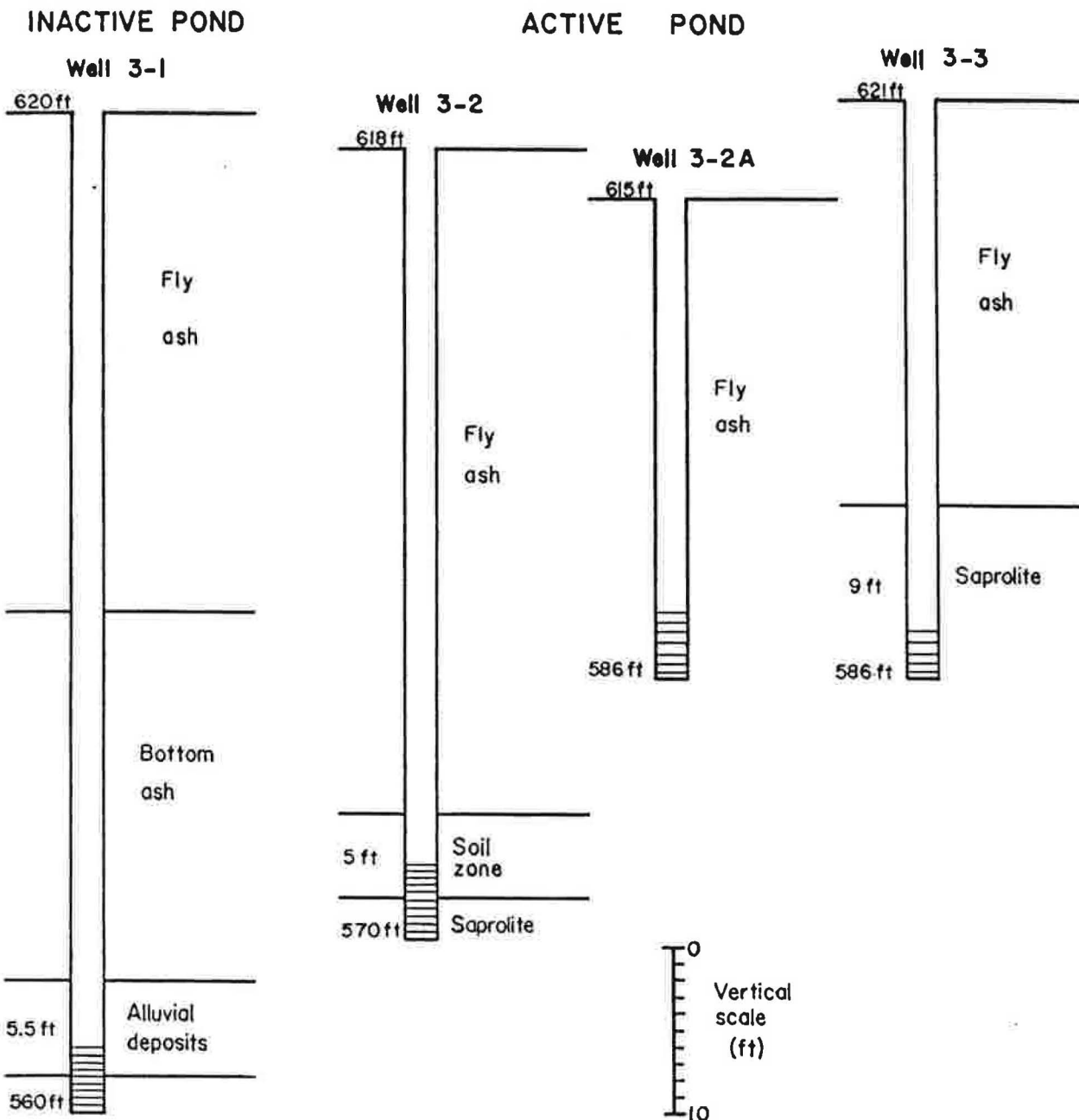
Map of the Ash Pond Area at the Allen Plant of Duke Power Company Showing the Locations of Water-Quality Sampling Wells and Other Features (from Tetrattech, Inc., 1985, Fig. 4-48).

Figure 11



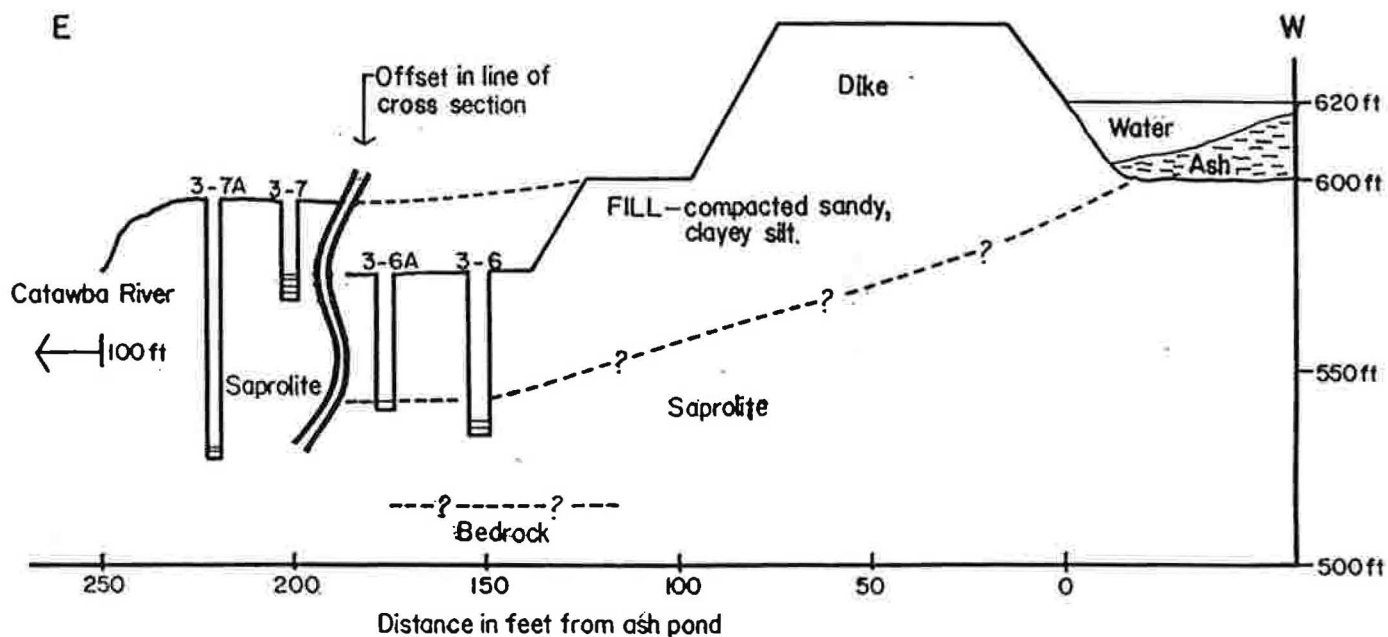
Concentrations of Selected Metals Versus Length of Flowlines in Saprolite at the Active Allen Powerplant Ash Pond of Duke Power Company. The Dashed Lines Show the Decrease in Concentration With Distance Beneath the Ash for Selected Metals.

Figure 12



Sections Showing Materials Penetrated and Positions of Screens in Water-Quality Sampling Wells Drilled Through the Ash in Both the Inactive and Active Ash Ponds at the Allen Powerplant of Duke Power Company.

Figure 13



Length of flowlines from ash pond to well screens.
(Based on the shortest straightline distance.)

Well no.	Distance (ft)
3-6	175'
3-6A	200'
3-7	220'
3-7A	250'

Geologic Section Extending from the Active Ash Pond at the Allen Powerplant of Duke Power Company to the Catawba River (Lake Wylie). Relative Locations and Screened Intervals of Wells Used in Figure 12 are Shown on the Section.

Figure 14

March 1981. Differences in concentration on the different dates are shown as vertical bars. It is not possible, from the available data, to determine the cause of the differences in concentration between the sampling dates. However, it is suspected that much, if not all, of the differences are due to inaccuracies in the analytical procedures and to differences in sampling procedures. (This statement is not intended as a criticism of either the analysts or the sample collectors, but is made to call attention to the unavoidable difficulties in determining the concentration of substances that are present in only fractions of a part per million.)

In reviewing Figure 12, it is important to note that the values plotted along the left-hand side of the graph are of analyses of water samples obtained from the ash and which thus show the concentrations in the effluent that reaches the saprolite. Referring back to the second factor listed above, it probably should not be assumed that these analyses show the composition of the effluent at all points in the pond.

Note also in Figure 12 that the values plotted along the right-hand side of the graph are of analyses of water samples from a well upgradient from the pond which were collected to show the "natural" quality of the groundwater. Again, referring back to the first factor listed above, it probably should not be assumed that these analyses show the composition of unpolluted groundwater at all points in the area.

It is evident from the left-hand side of Figure 12 that metals from the active ash pond at the Allen plant have moved into the upper several feet of the saprolite - that is, much of the cation-exchange capacity has been utilized to this depth. It is also evident from the right-hand side of the figure that none of the metals had reached the nearest wells downgradient from the pond by 1981. In this regard, note that the concentrations of the different metals in wells 3-6, 3-6A, 3-7, and 3-7A coincide closely to the

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concentrations in well 3-4B, the "background" well. The scatter in the data are believed to reflect the effect of the factors discussed above plus analytical and sampling problems. The effect of the second factor seems to be especially evident from a comparison of the values for barium, iron, and manganese in well 3-2A with the higher values in wells 3-2 and 3-3. It is believed that the higher values in wells 3-2 and 3-3 show the effect of differences in effluent quality from time to time and from place to place in the pond.

No wells were constructed that would permit samples to be obtained from the zone between 9 ft and 175 ft. Nevertheless, the trend lines on Figure 12 are believed to show the change in concentration with depth of several of the metals. The slope of the lines indicate that the different "metal fronts" had advanced into the saprolite in the eight years prior to 1981 to a distance of only a few feet. This distance gives a "rate of advance" of less than 1 ft/yr. This number, if in error, is too large because (1) the center of the screens were used in determining the thickness of non-ash material at wells 3-2 and 3-3, rather than the depth to the upper part of the screen and sand pack, and (2) "pumping" of the wells to obtain samples may have resulted in downward movement of water from zones above the screened interval. Relative to the rate of advance, studies by Gibb and Cartwright (1982) of the migration of zinc, cadmium, copper, and lead through geologic materials at zinc smelter sites in Illinois show rates of advance of a few tenths of a foot per year.

In an effort to confirm the rate of advance discussed above and, if possible, to obtain a more precise answer, an analysis was made of only the data obtained from the wells in the ash and in the saprolite beneath the ash ponds at the Allen plant. It was desirable in this analysis to be able to combine the data from both the active and inactive ponds.

Figure 15 is a graph showing the concentrations of calcium and strontium versus years per foot in samples obtained in late February and late March 1981 from the wells listed in Table 8. The factor of years per foot was obtained for each well by dividing the years

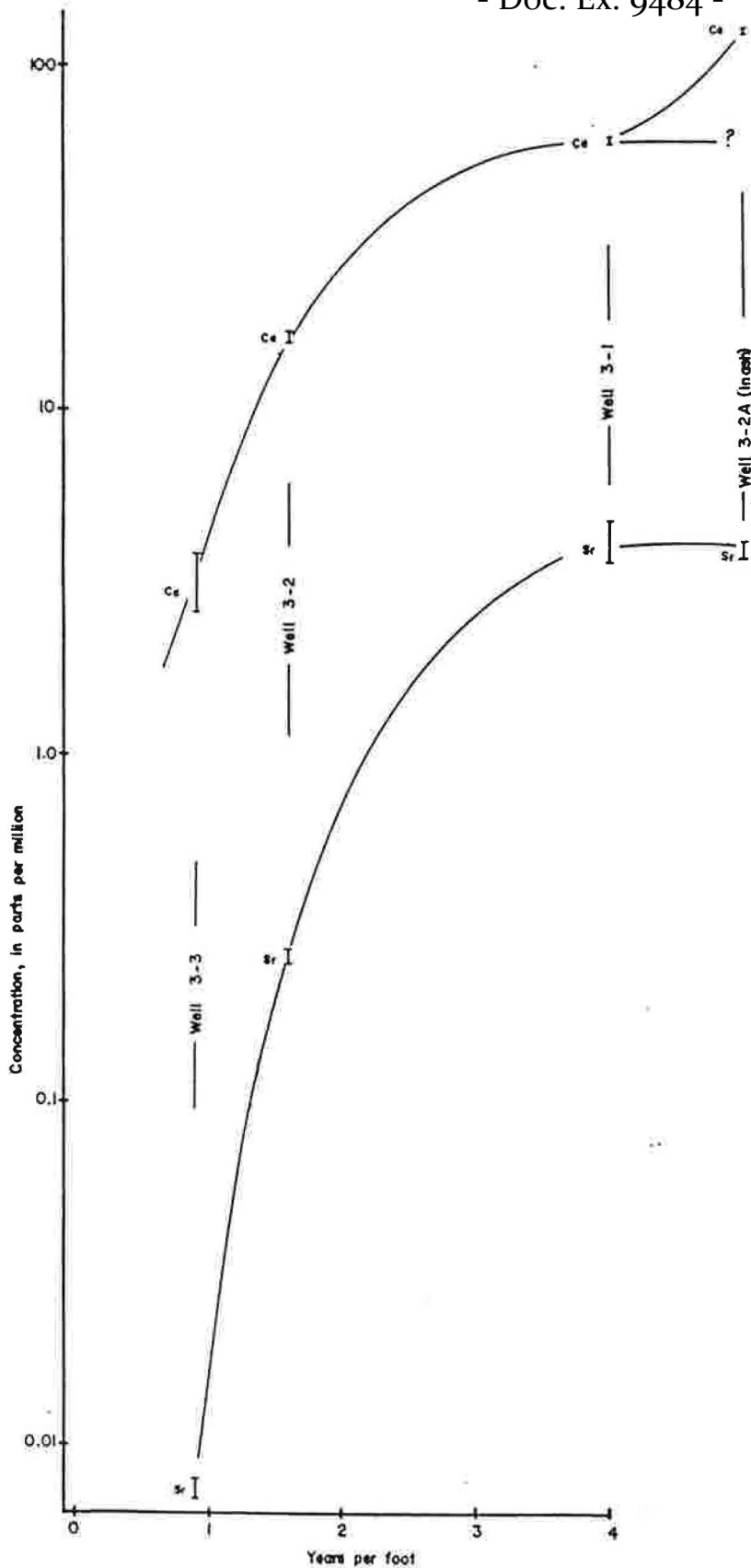
TABLE 8
Basic Data Used in the Preparation of Figure 15

Well No	Depth Below Ash (ft)	Time of Travel (years)	Years/ft	Calcium (ppm)	Strontium (ppm)
3-2A	In ash	—	—	126-129	3.7-4.13
3-1	5.5	24	4	59.5-60.7	3.6-4.7
3-2	5	8	1.6	15.8-17	0.25-0.274
3-3	9	8	0.9	2.5-377	0.007-0.008

since each pond began receiving ash by the distance between the bottom of each pond and the center of the well screens. Data used in preparing the figure are shown in Table 8.

The range in each constituent for the two analyses for each well are shown as a bar. The trend lines drawn through the bars are believed to show the decrease in concentration of calcium and strontium as the effluent moves from the pond through the saprolite. The tendency of these lines to approach the horizontal at the higher concentrations suggests that three to four years is required to essentially "use up" the cation-exchange capacity of each foot of saprolite. Or, in other words, the "metal front" moves at a rate of a few tenths of a foot per year.

It is important to note here that this rate applies only to the upper, clay-rich, part of the saprolite. Because the clay content of the lower part is less than that of the upper part, the ion-exchange capacity of the lower part is smaller and the metal front, once it



Concentrations of Calcium and Strontium Versus Years Per Foot for Wells Open to Ash and to Saprolite Beneath the Ash Ponds at the Allen Powerplant of Duke Power Company

Figure 15

moves into the lower part of the saprolite, will move faster. How much faster is not known but it might be as much as a foot per year.

It has been noted previously that the saprolite at Riverbend appears to contain a smaller content of clay than the saprolite at Allen. This would result in a somewhat faster rate of movement of the metal front at Riverbend. However, it is highly doubtful that the metal front at Riverbend has advanced as much as 15 to 20 ft into the saprolite in the 30 years the pond has been in use. Thus, it is believed that the front is still well above the bedrock surface and, as far as lateral movement in the saprolite is concerned, is still a considerable distance from the river.

In concluding this discussion, it is important to note that the locations of both the Allen and Riverbend ash ponds closely conform to the criteria listed by Heath and Lehr (1987) for solid-waste disposal sites. The ash ponds at both sites are underlain by thick sections of clay-rich saprolite having sufficient cation-exchange capacity to immobilize the metals in the ash effluent from many decades of operation. The ash ponds are also adjacent to a major stream that has a very large dilution capacity. Based on Figure 15, it appears unlikely that the Riverbend ash pond will remain active long enough for metals derived from the ash to reach the river. However, one of the objectives of this study was to determine what effect unmodified ash effluent reaching the Catawba through the groundwater system would have on the quality of the river. This topic is discussed in Section 6.

4. General Surface Water Quantity and Quality

The location of flow and water quality monitoring stations along the reaches of the Catawba River/Mountain Island Lake is shown in Figures 16 and 17 (the latter indicating river miles and the location of the Charlotte water intake). The Riverbend ash basin discharges near Mile 7 (see Figure 17).

A statistical summary of the flows through Cowans Ford and Mountain Island dams is presented in Table 9. Such data were independently verified by direct communication with U.S.G.S. staff and direct access to computerized HISARS records. The 12-year Duke Power Company record (1973-1985) yields a mean flow of about 2866 cfs. Earlier estimates were from 2600 cfs (41-year HISARS record) to 2800 cfs, depending upon mean flow values reported for Rock Hill, South Carolina (4251 cfs or 4495 cfs). The lower figure incorporates flows of pre-impoundment years (which would tend to lower the mean. STORET water quality files were accessed for : (1) Station 2142648 (just downstream from Lake Norman, Catawba River at N.C. Hwy 73 near Hicks, Lat: 35 25 38 and Long: 80 57 24, record length 1968 to 1987) ; and Station 2142808 (same latitude as northern Charlotte city limits, Catawba River at N.C. Hwy 27 near Thrift, Lat: 35 17 53 and Long: 81 00 14, record length 1968 to 1987). Duke Power supplied water quality records at : Station 288 (about 1 mile upstream of the Riverbend ash basin), Station 277 (about 3 miles downstream from the ash basin discharge), and at the Riverbend ash basin outfall. The data provide a reasonable profile of water quality along the Catawba. Statistical summaries are presented in Tables 10 through 15.

In the figures that follow, some distortion of the actual profiles is **built-in** due to unequal time intervals in the

recorded data (but most have been properly adjusted). It is nevertheless useful to view the magnitude of the observed iron concentrations along the river, as well as the values of other parameters at the ash basin outfall. The iron limit is 1.0 mg/l (N.C. Administrative Code, 1985): iron concentrations at the Riverbend ash basin effluent are below this number and would be further diluted by a 1:400 ratio (from a mean effluent discharge of 7.1 cfs and mean river flow of 2866 cfs). A **dilution ratio** of about 394 was calculated 5 miles downstream for a continuous discharge at the source (later section). Iron concentrations at the STORET station near Hicks (just downstream from Lake Norman) reached 2.4 mg/l once (probably during anoxic conditions in Lake Norman from late August to November), and 1.5 mg/l at Thrift (near Charlotte latitude). The **mean iron concentrations** in downstream order are : **0.32**, 0.76, 0.23 (ash basin effluent partially mixed with Catawba River), 0.35 and 0.41 mg/l (see Table 15). The profile is illustrated in Figure 18. It should be noted that the mean iron concentrations are higher upstream of the ash basin. The mean effluent flow of 6.63 cfs (Table 12) is the result of sampling at equal time intervals : the 7.1 cfs value represents the average of all reported observations, and it was used in the transport model because it yields a more conservative prediction (less dilution).

Figures 19 to 31 depict all other known flow and water quality data related to the Riverbend Site. Most of the variation in dissolved oxygen at both Duke Power stations 278 and 277 (river miles 6 and 10.5 approximately) seems to be explained largely by the temperature variation (see regression analysis below).

Regression Output:

Constant	12.45
Std Err of Y Est	0.68
R Squared	0.89
No. of Observations	150.00
Degrees of Freedom	148.00
X Coefficient(s)	-0.20
Std Err of Coef.	0.01

Tables 11 and 13 and Figure 22 reveal a slight increase in pH downstream from the ash basin (from 6.8 upstream to 7.04 downstream). Water quality is well within established State standards throughout these reaches.

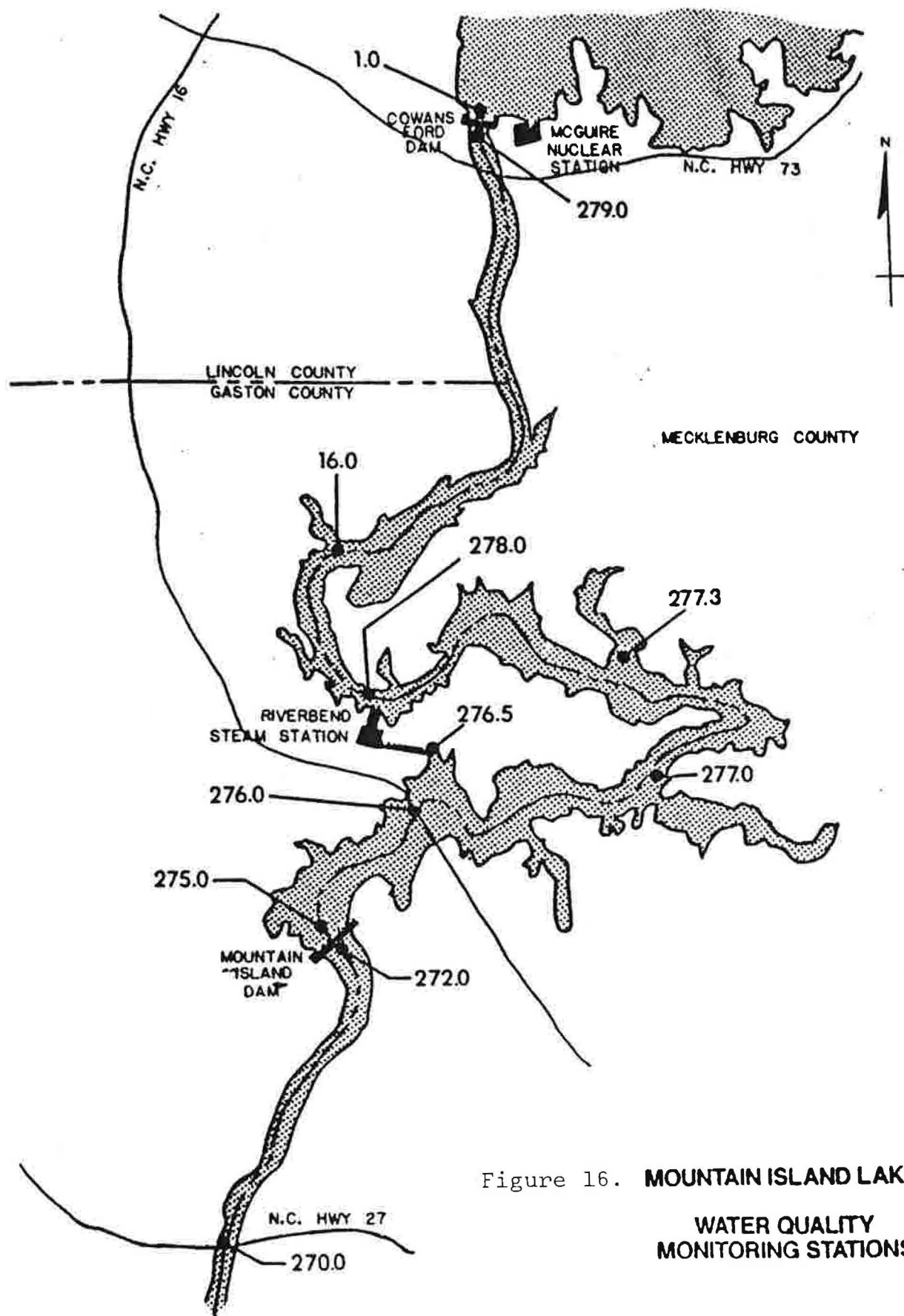


Figure 16. **MOUNTAIN ISLAND LAKE**
WATER QUALITY
MONITORING STATIONS

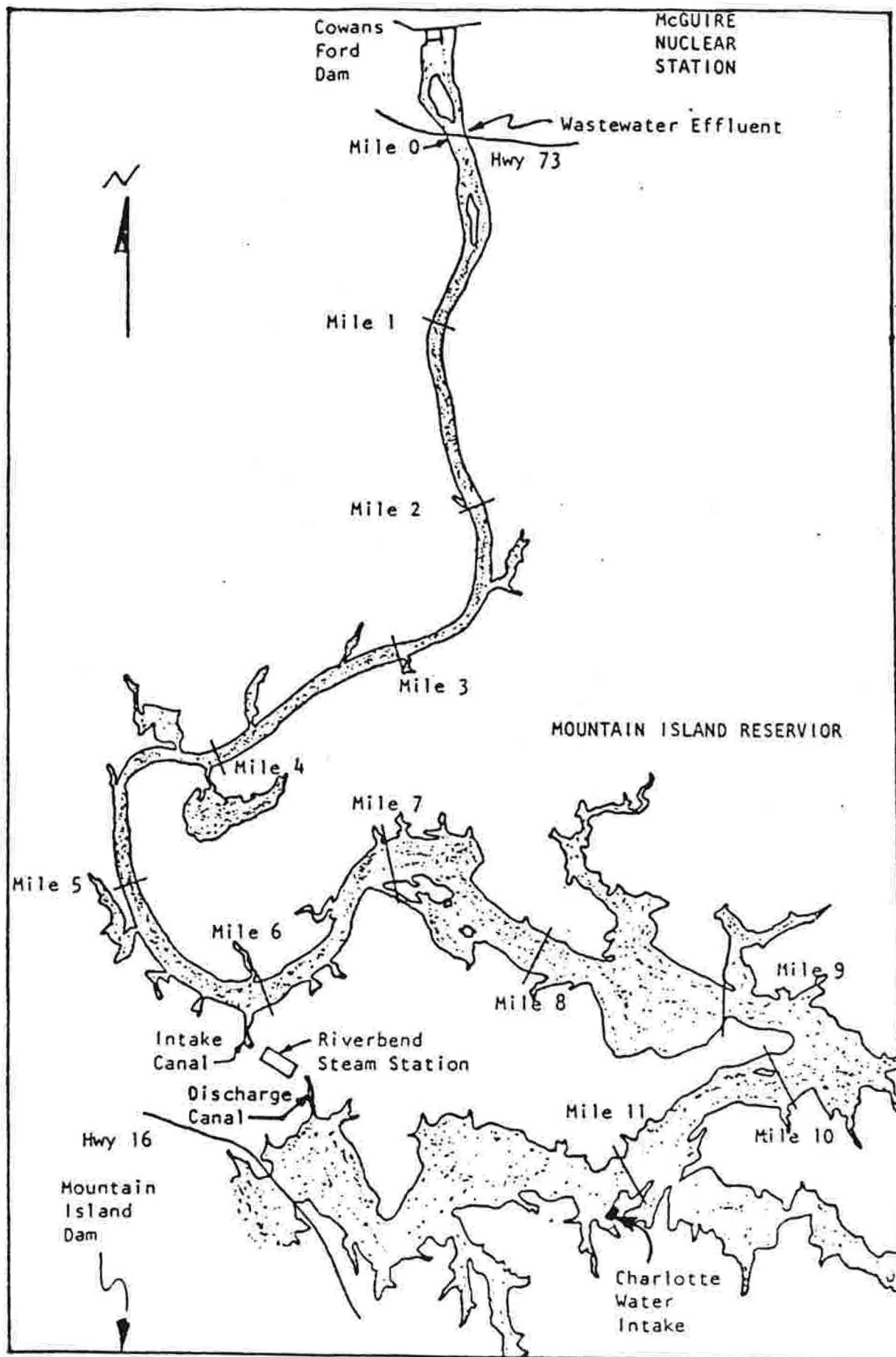


Figure 17. Map of Mountain Island Reservoir study area.

TABLE 9. Statistical Summary of Flows
Through Cowans Ford and Mtn.
Island Dams

Statistic	Cowans Ford Dam (cfs)	Mtn. Island Dam (cfs)
Sample size	4639	4636
Average	2845.98	2885.74
Median	2092	2267.5
Mode	80	80
Geometric mean		
Variance	7.80655E6	6.62877E6
Standard deviation	2794.02	2574.64
Standard error	41.022	37.8133
Minimum	0	0
Maximum	28954	11981
Range	28954	11981
Lower quartile	419	417.5
Upper quartile	4688	4810
Interquartile range	4269	4392.5
Skewness	1.35048	0.766127
Standardized skewness	37.5512	21.296
Kurtosis	3.95845	-0.325744
Standardized kurtosis	55.0341	-4.52733

TABLE 10. Statistical Summary of Catawba River
Water Quality at Hicks, N. C.,
STORET Station No. 2142648

Statistic	Temperature (deg. C)	pH (std units)	Arsenic (µg/l)
Sample size	210	185	68
Average	17.3895	6.85189	10.1471
Median	18.5	6.8	10
Mode	26	6.9	10
Geometric mean	15.7503	6.83951	10.1025
Variance	47.2315	0.170988	1.47059
Standard deviation	6.87252	0.413507	1.21268
Standard error	0.474249	0.0304017	0.147059
Minimum	3	6	10
Maximum	29	7.9	20
Range	26	1.9	10
Lower quartile	11	6.5	10
Upper quartile	24	7.2	10
Interquartile range	13	0.7	0
Skewness	-0.193008	0.139583	8.24621
Standardized skewness	-1.14185	0.775076	27.7609
Kurtosis	-1.22982	-0.703723	68
Standardized kurtosis	-3.63785	-1.95381	114.461

Statistic	Cadmium (µg/l)	Lead (µg/l)	Mercury (µg/l)
Sample size	78	78	64
Average	37.7692	86.4103	0.89375
Median	50	100	0.5
Mode	50	100	0.5
Geometric mean	27.7473	73.3362	0.464913
Variance	387.842	922.011	6.84091
Standard deviation	19.6937	30.3646	2.61551
Standard error	2.22987	3.43812	0.326939
Minimum	2	10	0.2
Maximum	100	100	21
Range	98	90	20.8
Lower quartile	20	100	0.2
Upper quartile	50	100	0.5
Interquartile range	30	0	0.3
Skewness	-0.382606	-1.94997	7.45485
Standardized skewness	-1.3795	-7.03072	24.3474
Kurtosis	0.0137749	2.12744	57.8397
Standardized kurtosis	0.024833	3.8353	94.4519

TABLE 11. Statistical Summary of Catawba River
Water Quality at Station 278, Upstream
of Duke Power Riverbend Site

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Statistic	Temperature (deg C)	Dissolved Oxygen (mg/l)	pH (std units)
Sample size	19	19	19
Average	16.7316	8.98421	6.82105
Median	17.6	8.9	6.9
Mode	25.8	6.5	6.7
Geometric mean	13.5942	8.73557	6.81463
Variance	83.4001	4.63029	0.0895322
Standard deviation	9.13236	2.15181	0.299219
Standard error	2.09511	0.493659	0.0686456
Minimum	3	5.4	6.1
Maximum	28.5	12.4	7.2
Range	25.5	7	1.1
Lower quartile	6.8	7.3	6.7
Upper quartile	26	11.5	7.1
Interquartile range	19.2	4.2	0.4
Skewness	-0.190007	0.133655	-1.15878
Standardized skewness	-0.33812	0.237841	-2.06206
Kurtosis	-1.53364	-1.1858	1.05092
Standardized kurtosis	-1.36457	-1.05507	0.935061

Statistic	Manganese (mg/l)	Chromium (µg/l)	Copper (µg/l)
Sample size	12	4	4
Average	0.0483333	28.8	52.7
Median	0.05	2.5	4
Mode	0.05	0.2	2.8
Geometric mean	0.0420671	3.41194	9.63041
Variance	8.87879E-4	2931.65	9643.99
Standard deviation	0.0297973	54.1447	98.2038
Standard error	8.60174E-3	27.0724	49.1019
Minimum	0.02	0.2	2.8
Maximum	0.13	110	200
Range	0.11	109.8	197.2
Lower quartile	0.03	1.2	3
Upper quartile	0.05	56.4	102.4
Interquartile range	0.02	55.2	99.4
Skewness	2.02414	1.99746	1.99954
Standardized skewness	2.86257	1.63092	1.63261
Kurtosis	5.22732	3.99167	3.99844
Standardized kurtosis	3.69628	1.62959	1.63236

TABLE 11. Statistical Summary of Catawba River
Water Quality at Station 278, Upstream
of Duke Power Riverbend Site (Cont.)

Statistic	Lead ($\mu\text{g/l}$)	Zinc ($\mu\text{g/l}$)
Sample size	4	4
Average	15.15	50.15
Median	2.3	30.3
Mode	1	10
Geometric mean	4.12221	32.9004
Variance	706.19	2936.57
Standard deviation	26.5742	54.1901
Standard error	13.2871	27.0951
Minimum	1	10
Maximum	55	130
Range	54	120
Lower quartile	1.55	18.1
Upper quartile	28.75	82.2
Interquartile range	27.2	64.1
Skewness	1.99657	1.78784
Standardized skewness	1.63019	1.45977
Kurtosis	3.98875	3.36984
Standardized kurtosis	1.6284	1.37573

TABLE 12. Statistical Summary of Ash Basin
Effluent Water Quantity and Quality,
Duke Power Riverbend Site

Statistic	Flow (cfs)	Iron (mg/l)	Arsenic (mg/l)
Sample size	97	155	121
Average	6.62875	0.235935	0.12119
Median	7.5814	0.19	0.057
Mode	9.4384	0.1	0.045
Geometric mean	5.183	0.190631	0.0585635
Variance	12.9126	0.031397	0.29332
Standard deviation	3.59342	0.177192	0.54159
Standard error	0.364856	0.0142324	0.0492355
Minimum	0.15472	0.01	4E-3
Maximum	16.555	1.15	6
Range	16.4003	1.14	5.996
Lower quartile	3.4038	0.11	0.035
Upper quartile	9.4384	0.29	0.094
Interquartile range	6.0346	0.18	0.059
Skewness	-0.0463643	2.3268	10.8355
Standardized skewness	-0.186421	11.8263	48.6592
Kurtosis	-0.871952	6.95531	118.546
Standardized kurtosis	-1.75296	17.6757	266.178

Statistic	Selenium (µg/l)	Chromium (µg/l)	Mercury (µg/l)
Sample size	121	88	88
Average	4.62066	9.34886	1.19773
Median	5	2.3	0.1
Mode	5	50	0.1
Geometric mean	3.92827	2.98314	0.383448
Variance	7.55599	291.757	4.19976
Standard deviation	2.74882	17.0809	2.04933
Standard error	0.249892	1.82083	0.21846
Minimum	0.2	0.5	0.1
Maximum	20	50	13.4
Range	19.8	49.5	13.3
Lower quartile	2	1.2	0.1
Upper quartile	5	4.1	2
Interquartile range	3	2.9	1.9
Skewness	1.99863	1.99099	3.86023
Standardized skewness	8.97532	7.6249	14.7836
Kurtosis	7.5056	2.06318	18.4327
Standardized kurtosis	16.8528	3.9507	35.2959

TABLE 12. Statistical Summary of Ash Basin
Effluent Water Quality,
Duke Power Riverbend Site (Cont.)

Statistic	pH (std units)	Temperature (deg C)	Copper (mg/l)
Sample size	155	91	155
Average	7.67935	17.8352	0.0445419
Median	7.5	18.3	0.05
Mode	7.5	20	0.05
Geometric mean	7.65732	15.745	0.0295483
Variance	0.348532	61.4376	1.14893E-3
Standard deviation	0.590366	7.83822	0.0338958
Standard error	0.0474193	0.821668	2.72258E-3
Minimum	6.2	2.8	1E-3
Maximum	9.5	30	0.125
Range	3.3	27.2	0.124
Lower quartile	7.3	11	0.012
Upper quartile	8	25	0.05
Interquartile range	0.7	14	0.038
Skewness	0.59465	-0.121861	0.583951
Standardized skewness	3.0224	-0.474579	2.96802
Kurtosis	0.172883	-1.27452	-0.844369
Standardized kurtosis	0.439353	-2.48178	-2.14582

Statistic	Cadmium (µg/l)	Nickel (µg/l)	Lead (µg/l)
Sample size	88	88	88
Average	3.53295	22.8443	25.0557
Median	0.3	8.15	1
Mode	0.2	5	1
Geometric mean	0.545998	11.344	2.57906
Variance	53.5491	1092.74	3620.05
Standard deviation	7.31773	33.0566	60.1668
Standard error	0.780072	3.52385	6.41381
Minimum	0.1	1	1
Maximum	23	100	200
Range	22.9	99	199
Lower quartile	0.2	5.25	1
Upper quartile	0.7	14.8	2.35
Interquartile range	0.5	9.55	1.35
Skewness	1.8904	1.86027	2.37291
Standardized skewness	7.23968	7.1243	9.08756
Kurtosis	1.64984	1.69603	4.10615
Standardized kurtosis	3.15921	3.24765	7.86269

TABLE 12. Statistical Summary of Ash Basin
Effluent Water Quality,
Duke Power Riverbend Site (Cont.)

Statistic	Zinc ($\mu\text{g/l}$)
Sample size	88
Average	12.8932
Median	10.1
Mode	10
Geometric mean	9.16569
Variance	94.4503
Standard deviation	9.71855
Standard error	1.036
Minimum	1
Maximum	57
Range	56
Lower quartile	5.05
Upper quartile	18.35
Interquartile range	13.3
Skewness	1.45091
Standardized skewness	5.55655
Kurtosis	3.90366
Standardized kurtosis	7.47494

TABLE 13. Statistical Summary of Catawba River
Water Quality at Station 277, Downstream
from Duke Power Riverbend Site

Statistic	Temperature (deg. C)	Dissolved Oxygen (mg/l)	pH (std units)
Sample size	29	29	29
Average	18.1448	9.37931	7.04483
Median	17.9	8.8	7.1
Mode	6.9	11.5	6.9
Geometric mean	14.5869	9.14392	7.04014
Variance	109.605	4.8067	0.0675616
Standard deviation	10.4693	2.19242	0.259926
Standard error	1.94409	0.407122	0.0482671
Minimum	3.5	6.6	6.3
Maximum	31.5	15	7.5
Range	28	8.4	1.2
Lower quartile	7.3	7.6	6.9
Upper quartile	28.4	11.5	7.2
Interquartile range	21.1	3.9	0.3
Skewness	-0.0479907	0.616404	-0.428173
Standardized skewness	-0.105507	1.35515	-0.941332
Kurtosis	-1.76087	-0.384441	1.14615
Standardized kurtosis	-1.93562	-0.422593	1.2599

Statistic	Manganese (mg/l)	Chromium (µg/l)	Copper (µg/l)
Sample size	22	4	4
Average	0.0354545	6.975	3.375
Median	0.03	3.3	4.15
Mode	0.02	0.3	0.4
Geometric mean	0.0310165	2.7945	2.39722
Variance	3.78355E-4	90.2292	4.0425
Standard deviation	0.0194513	9.4989	2.0106
Standard error	4.14704E-3	4.74945	1.0053
Minimum	0.01	0.3	0.4
Maximum	0.09	21	4.8
Range	0.08	20.7	4.4
Lower quartile	0.02	1.25	2.2
Upper quartile	0.05	12.7	4.55
Interquartile range	0.03	11.45	2.35
Skewness	1.22714	1.81654	-1.83742
Standardized skewness	2.3498	1.4832	-1.50025
Kurtosis	1.55931	3.38517	3.49969
Standardized kurtosis	1.49292	1.38199	1.42874

TABLE 13. Statistical Summary of Catawba River
Water Quality at Station 277, Downstream
from Duke Power Riverbend Site (Cont.)

Statistic	Lead ($\mu\text{g/l}$)	Zinc ($\mu\text{g/l}$)
Sample size	4	4
Average	3.225	19.475
Median	2.45	10.95
Mode	1	10
Geometric mean	2.5329	15.2959
Variance	6.8825	313.502
Standard deviation	2.62345	17.706
Standard error	1.31173	8.853
Minimum	1	10
Maximum	7	46
Range	6	36
Lower quartile	1.55	10
Upper quartile	4.9	28.95
Interquartile range	3.35	18.95
Skewness	1.52417	1.98484
Standardized skewness	1.24448	1.62062
Kurtosis	2.63041	3.94711
Standardized kurtosis	1.07386	1.6114

TABLE 14. Statistical Summary of Catawba River
Water Quality at Thrift, N. C.,
STORET Station No. 2142808

Statistic	Temperature (deg. C)	pH (std units)	Arsenic ($\mu\text{g/l}$)
Sample size	236	208	56
Average	18.7657	6.7899	10.7143
Median	20	6.8	10
Mode	27	6.8	10
Geometric mean	16.7718	6.77513	10.4537
Variance	56.1885	0.195695	10.3896
Standard deviation	7.4959	0.442374	3.22329
Standard error	0.487941	0.0306731	0.43073
Minimum	2	5.1	10
Maximum	30	7.8	30
Range	28	2.7	20
Lower quartile	12	6.5	10
Upper quartile	25	7.1	10
Interquartile range	13	0.6	0
Skewness	-0.371736	-0.517578	4.9294
Standardized skewness	-2.33139	-3.04742	15.0596
Kurtosis	-1.0807	0.909028	25.6132
Standardized kurtosis	-3.38886	2.67611	39.1248

Statistic	Cadmium ($\mu\text{g/l}$)	Lead ($\mu\text{g/l}$)	Mercury ($\mu\text{g/l}$)
Sample size	66	71	63
Average	34.9394	87.0423	0.601587
Median	50	100	0.5
Mode	50	100	0.5
Geometric mean	24.9299	74.1933	0.407864
Variance	359.412	898.27	0.804352
Standard deviation	18.9582	29.9711	0.896857
Standard error	2.33359	3.55692	0.112993
Minimum	2	10	0.2
Maximum	50	100	6.3
Range	48	90	6.1
Lower quartile	20	100	0.2
Upper quartile	50	100	0.5
Interquartile range	30	0	0.3
Skewness	-0.616447	-2.03838	4.84899
Standardized skewness	-2.04452	-7.01195	15.7125
Kurtosis	-1.35167	2.48096	27.3782
Standardized kurtosis	-2.2415	4.2672	44.3578

TABLE 15. Statistical Summary of Catawba River
Iron Concentrations In Downstream Order

Statistic	@ Hicks ($\mu\text{g/l}$)	@ Sta. 278 (mg/l)	Ash Basin Effluent (mg/l)
Sample size	38	12	155
Average	320.813	0.766667	0.235935
Median	220	0.3	0.19
Mode	100	0.3	0.1
Geometric mean	195.836	0.36504	0.190631
Variance	161203	1.60424	0.031397
Standard deviation	401.501	1.26659	0.177192
Standard error	65.132	0.365632	0.0142324
Minimum	0.9	0.1	0.01
Maximum	2400	4.5	1.15
Range	2399.1	4.4	1.14
Lower quartile	100	0.2	0.11
Upper quartile	400	0.6	0.29
Interquartile range	300	0.4	0.18
Skewness	4.05073	2.77276	2.3268
Standardized skewness	10.1941	3.92128	11.8263
Kurtosis	19.946	7.98366	6.95531
Standardized kurtosis	25.0982	5.6453	17.6757

Statistic	@ Sta. 277 (mg/l)	@ Thrift ($\mu\text{g/l}$)
Sample size	23	38
Average	0.356522	405.789
Median	0.2	300
Mode	0.1	300
Geometric mean		316.519
Variance	0.240751	110717
Standard deviation	0.490664	332.742
Standard error	0.10231	53.9778
Minimum	0	100
Maximum	1.9	1500
Range	1.9	1400
Lower quartile	0.1	200
Upper quartile	0.3	400
Interquartile range	0.2	200
Skewness	2.29041	1.90865
Standardized skewness	4.48436	4.80333
Kurtosis	4.49326	3.2099
Standardized kurtosis	4.39865	4.03903

DUKE POWER CO. RIVERBEND SITE

CATAWBA RIVER , HICKS TO THRIFT

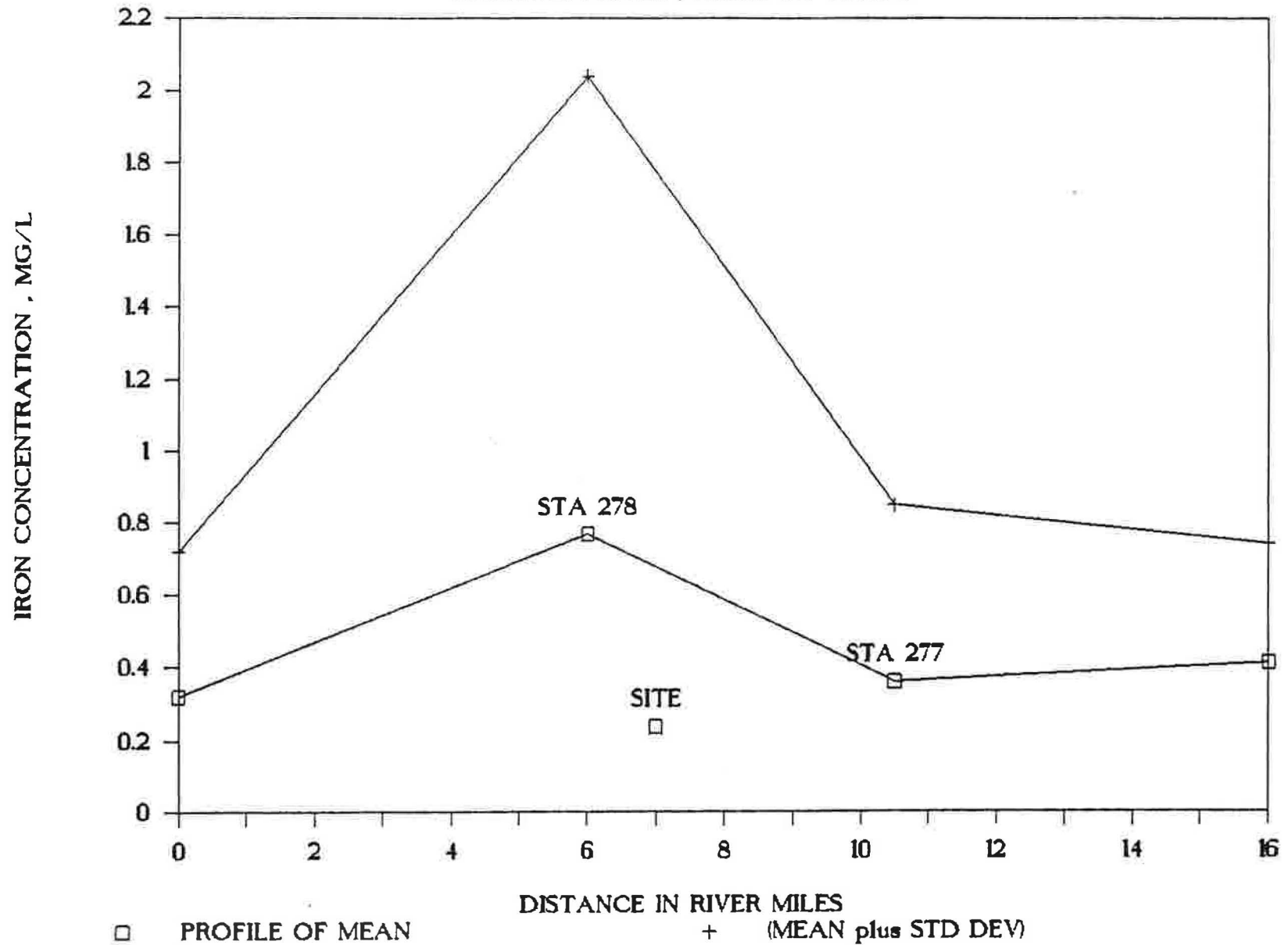


Figure 18. Profile of Iron Concentrations In Catawba River

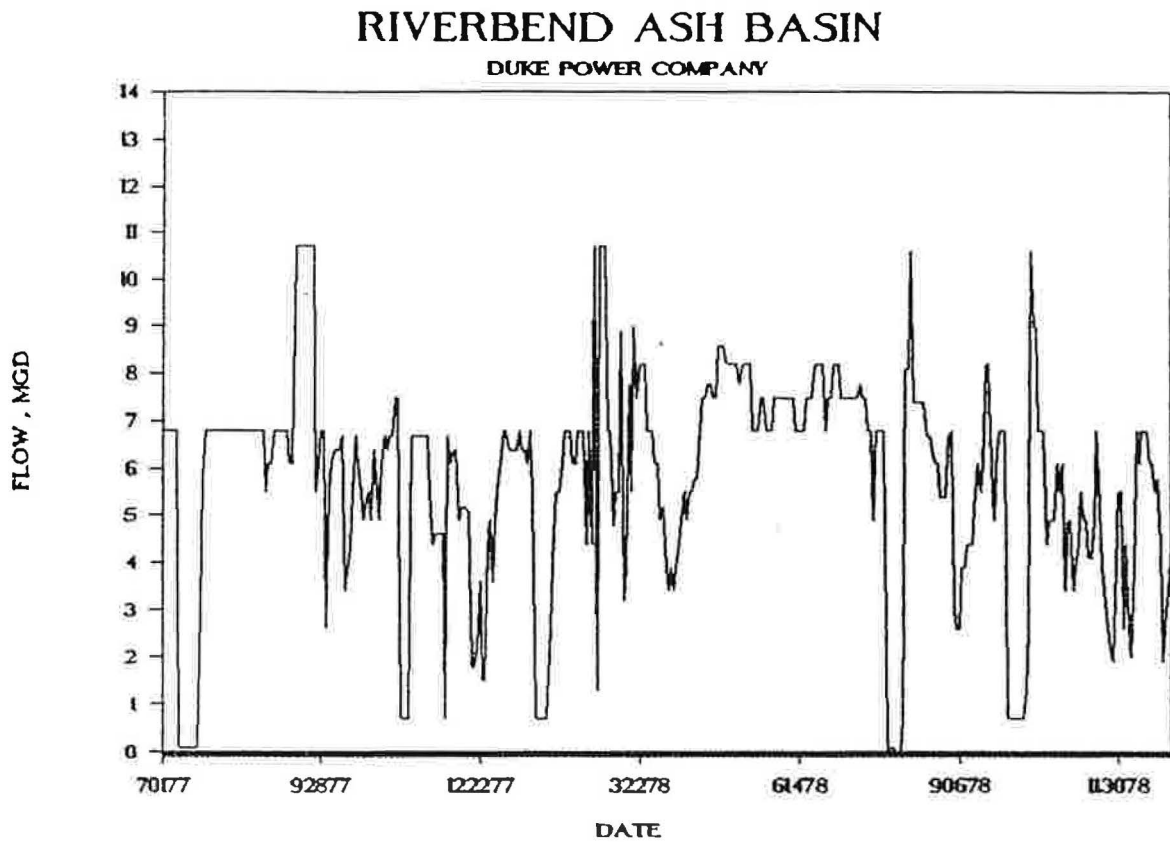
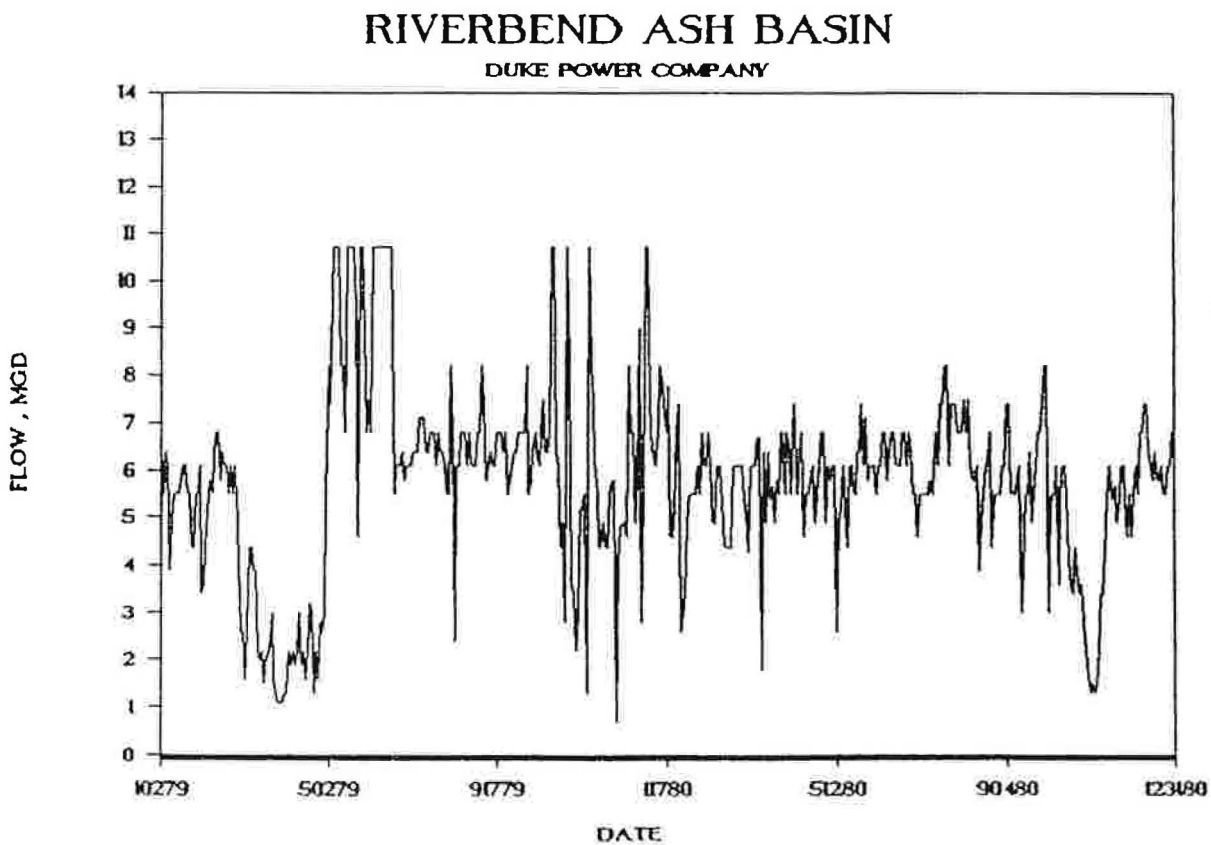


Figure 19. Ash Basin Flow



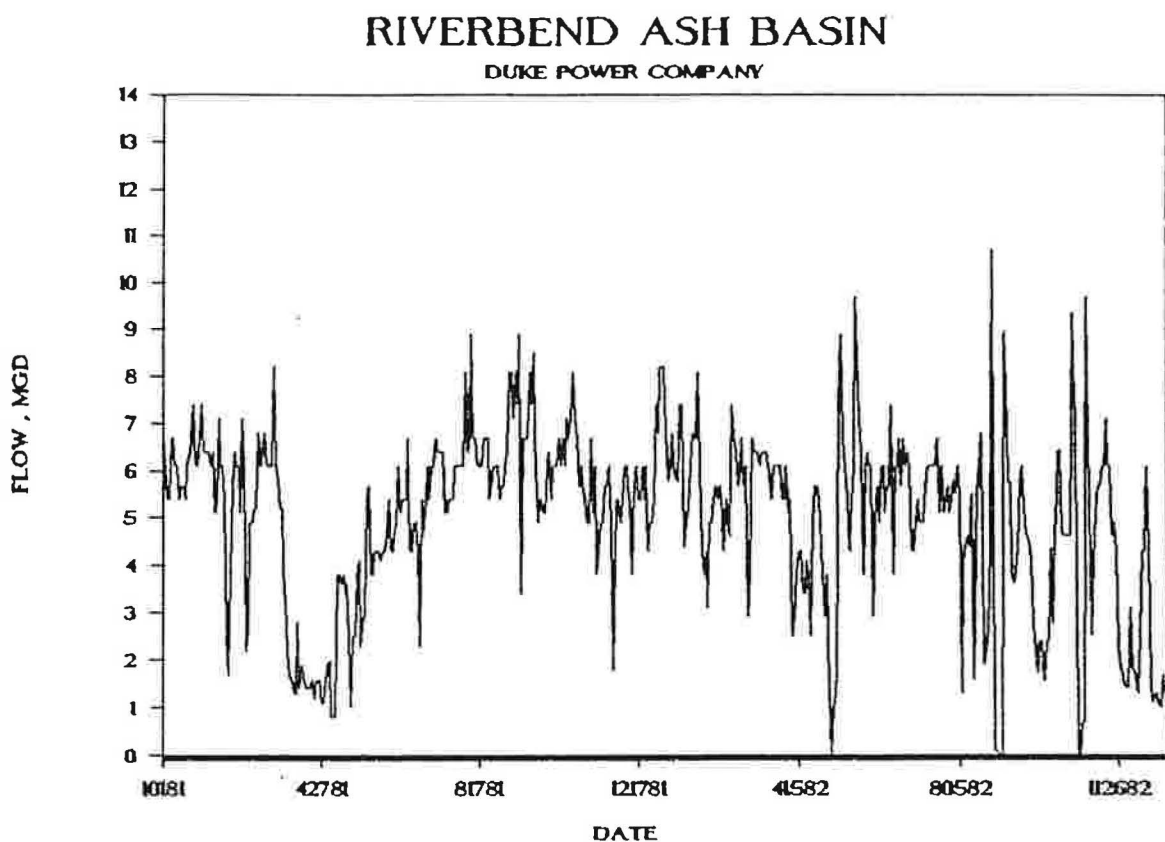
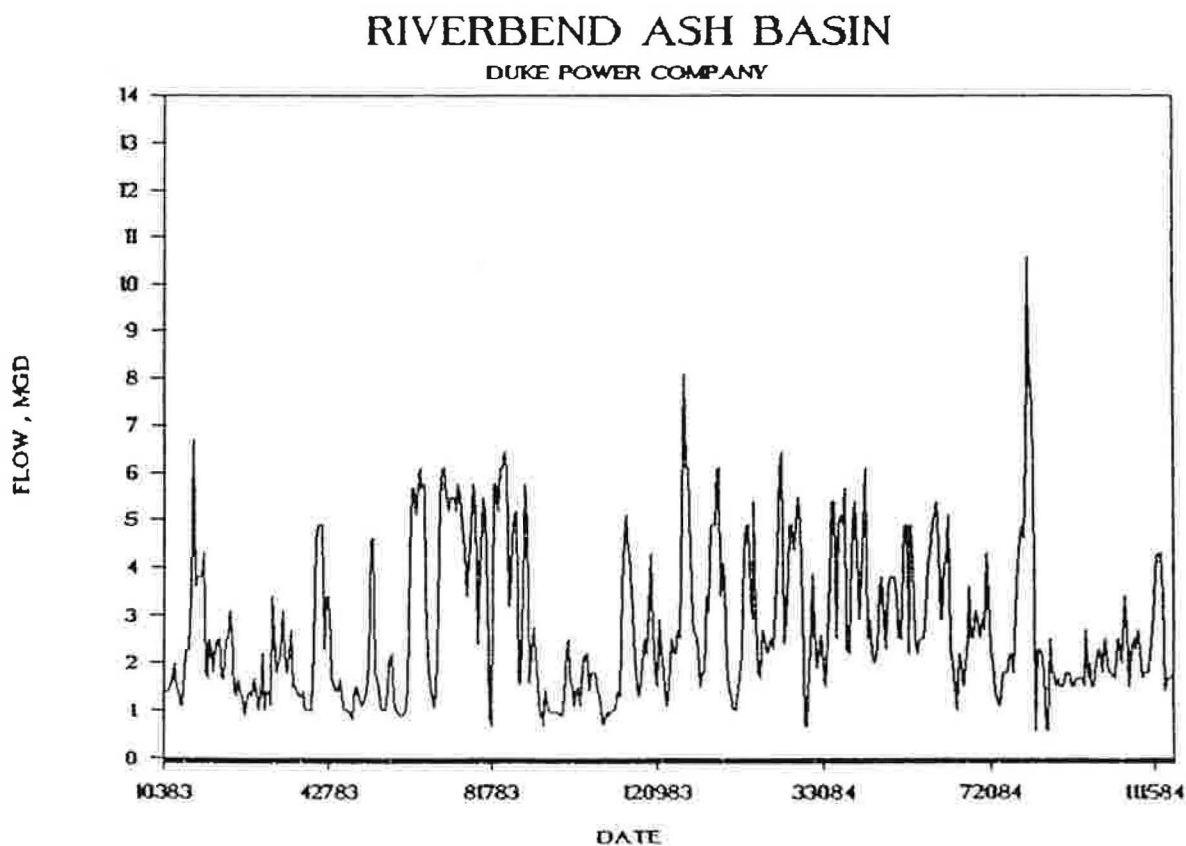


Figure 19. Ash Basin Flow (Cont.)



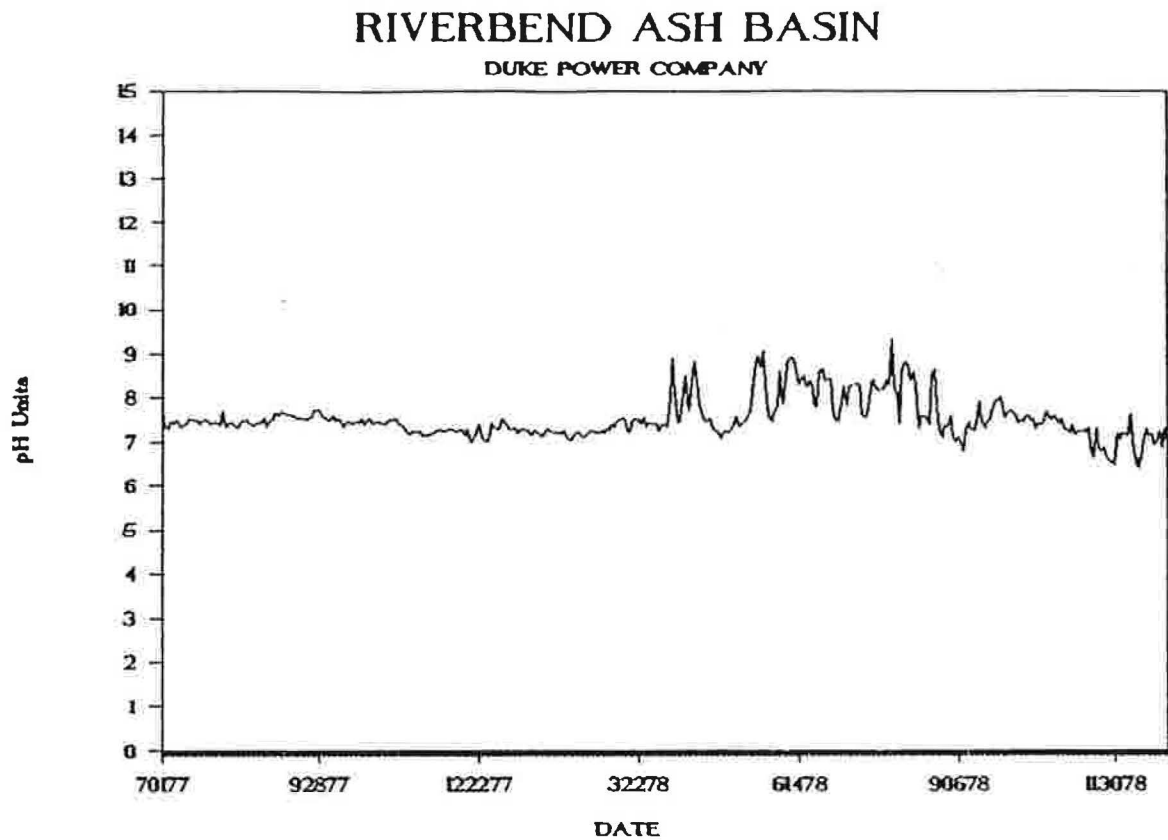
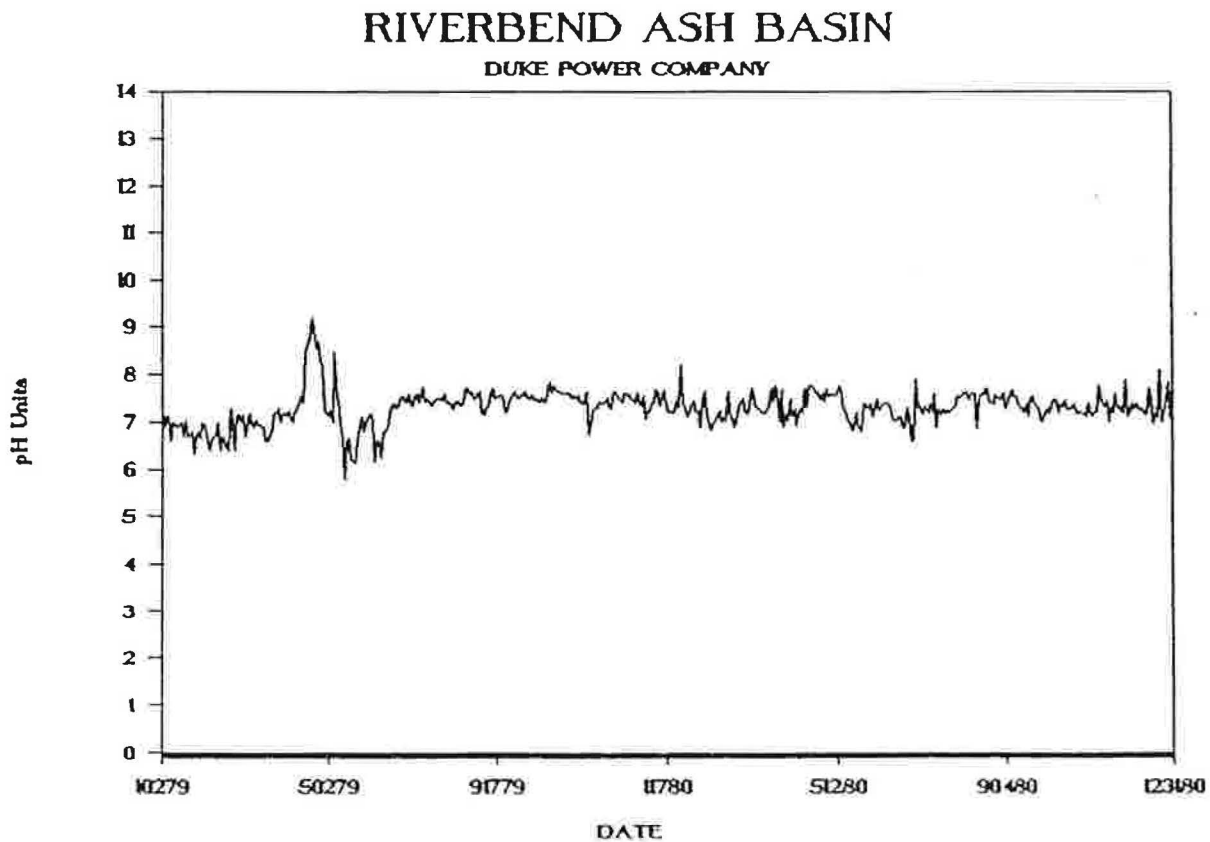


Figure 20. Time History of Effluent pH



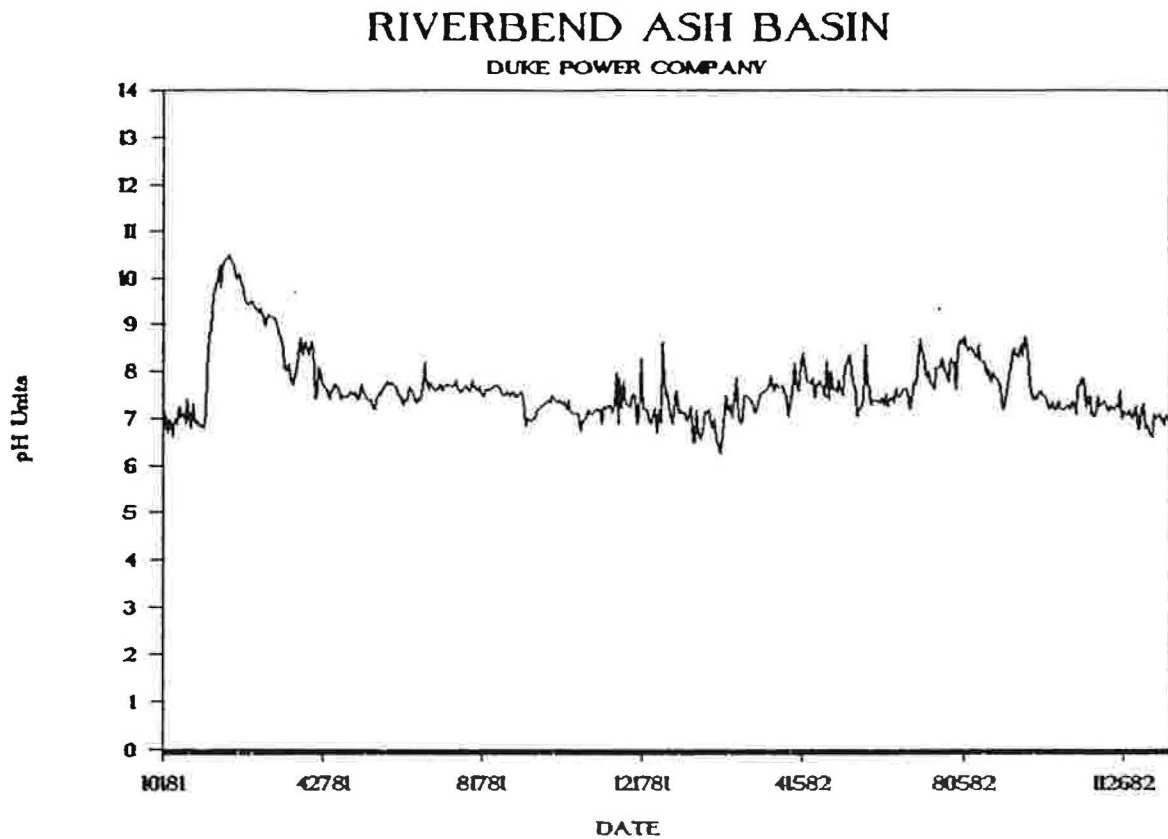
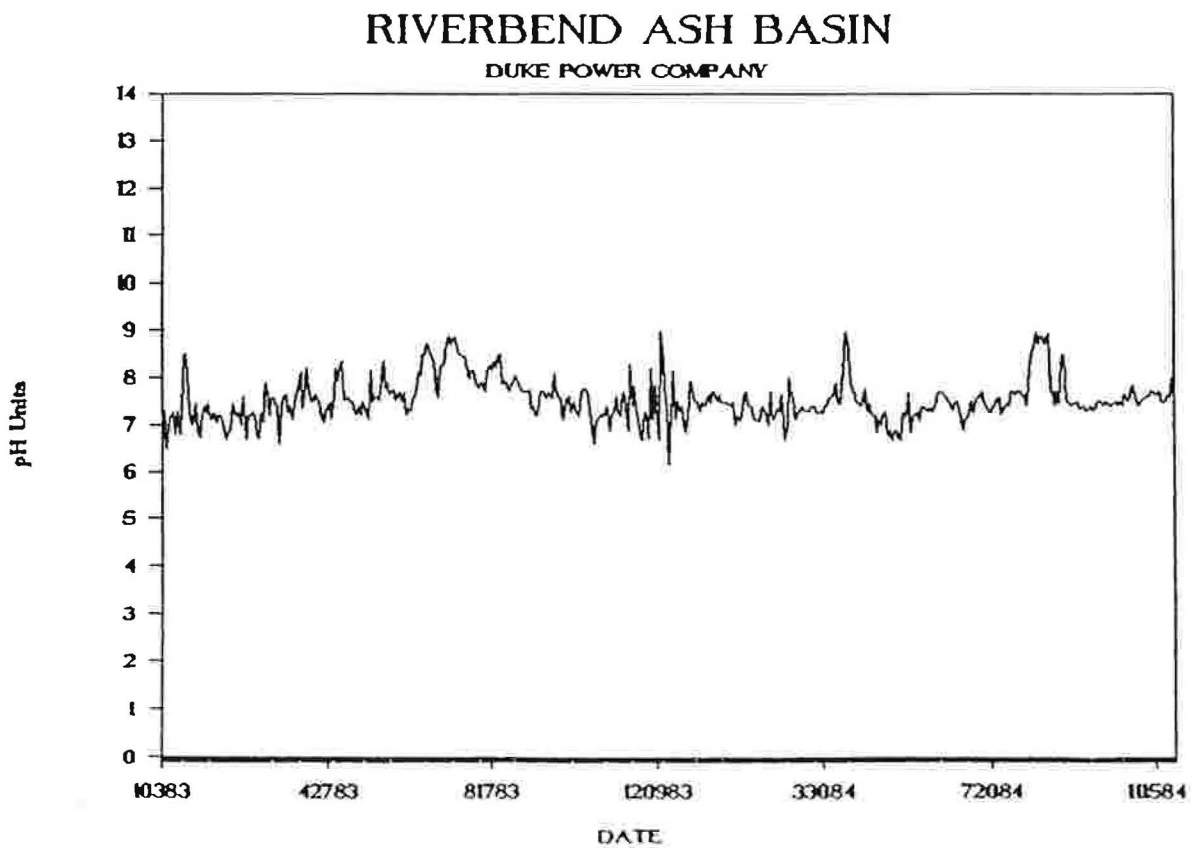


Figure 20. Time History of Effluent pH (Cont.)



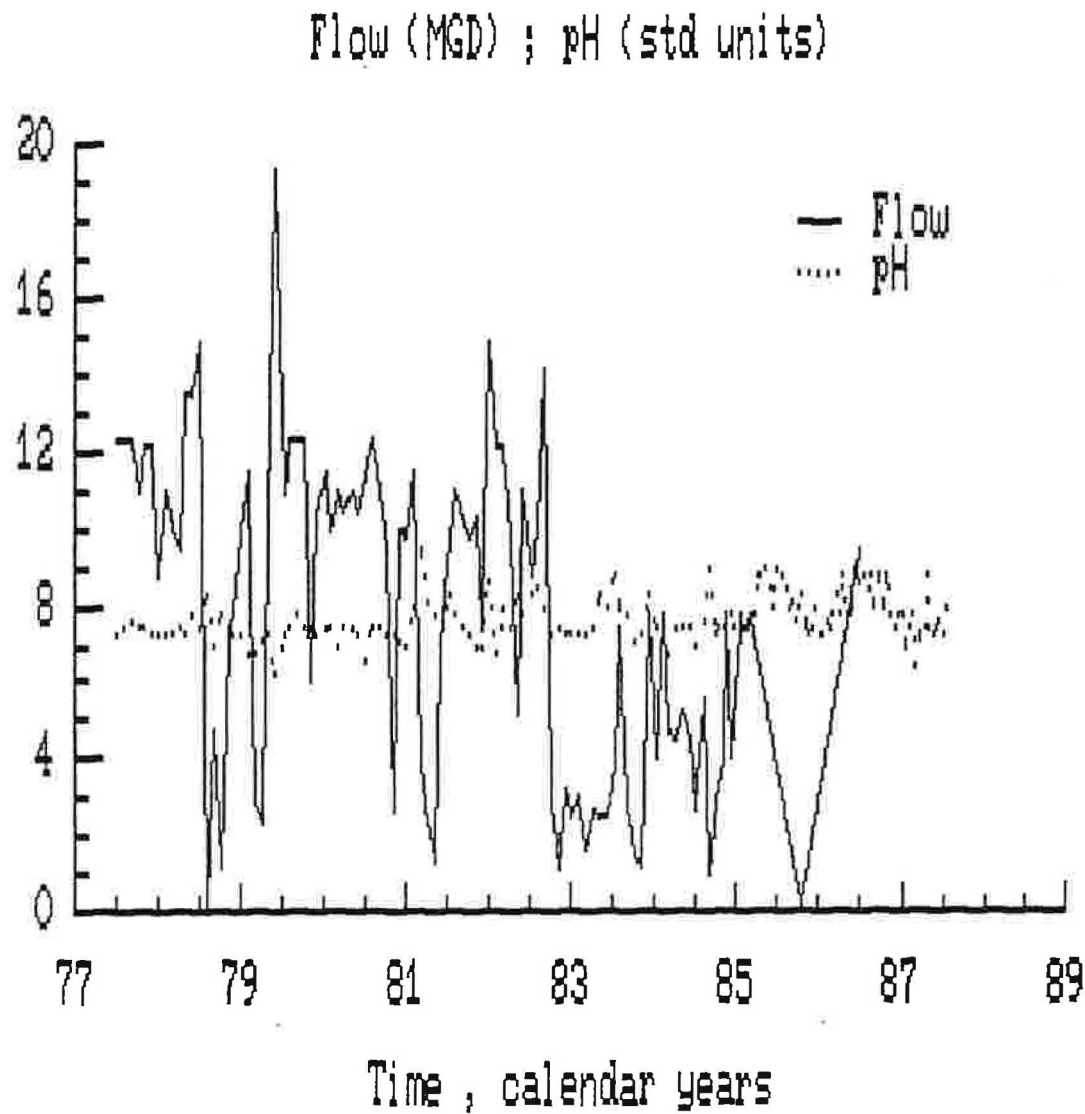


Figure 21. Ash Basin Flow Versus pH

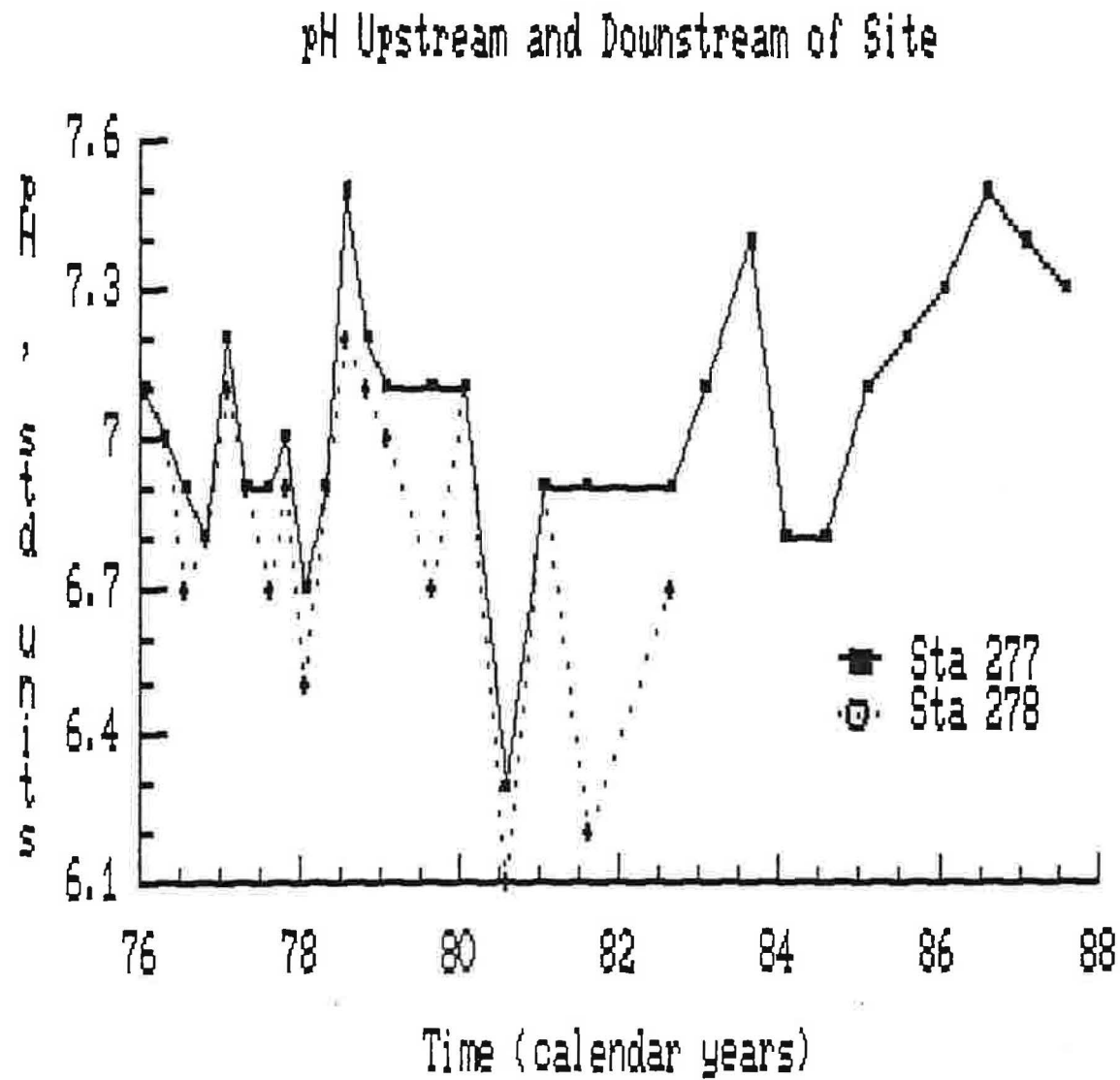


Figure 22. Time History of pH Upstream and Downstream of Site

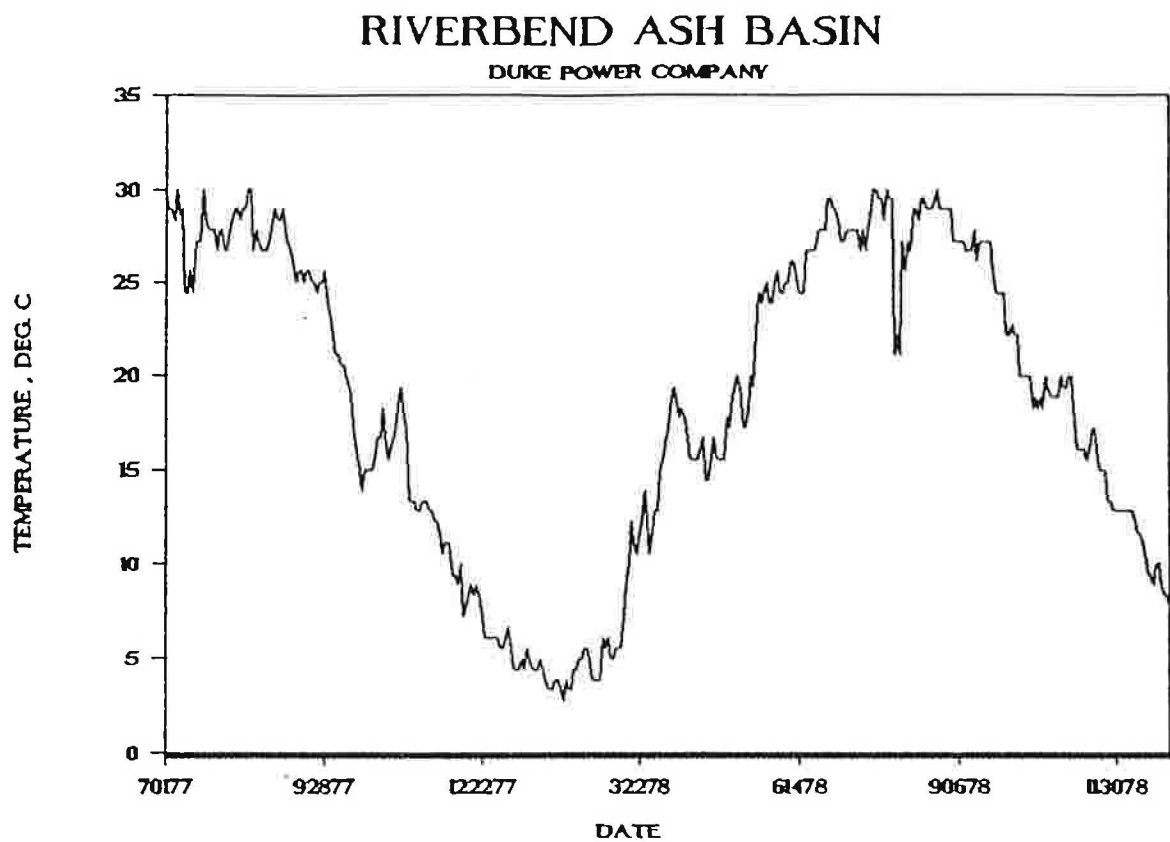
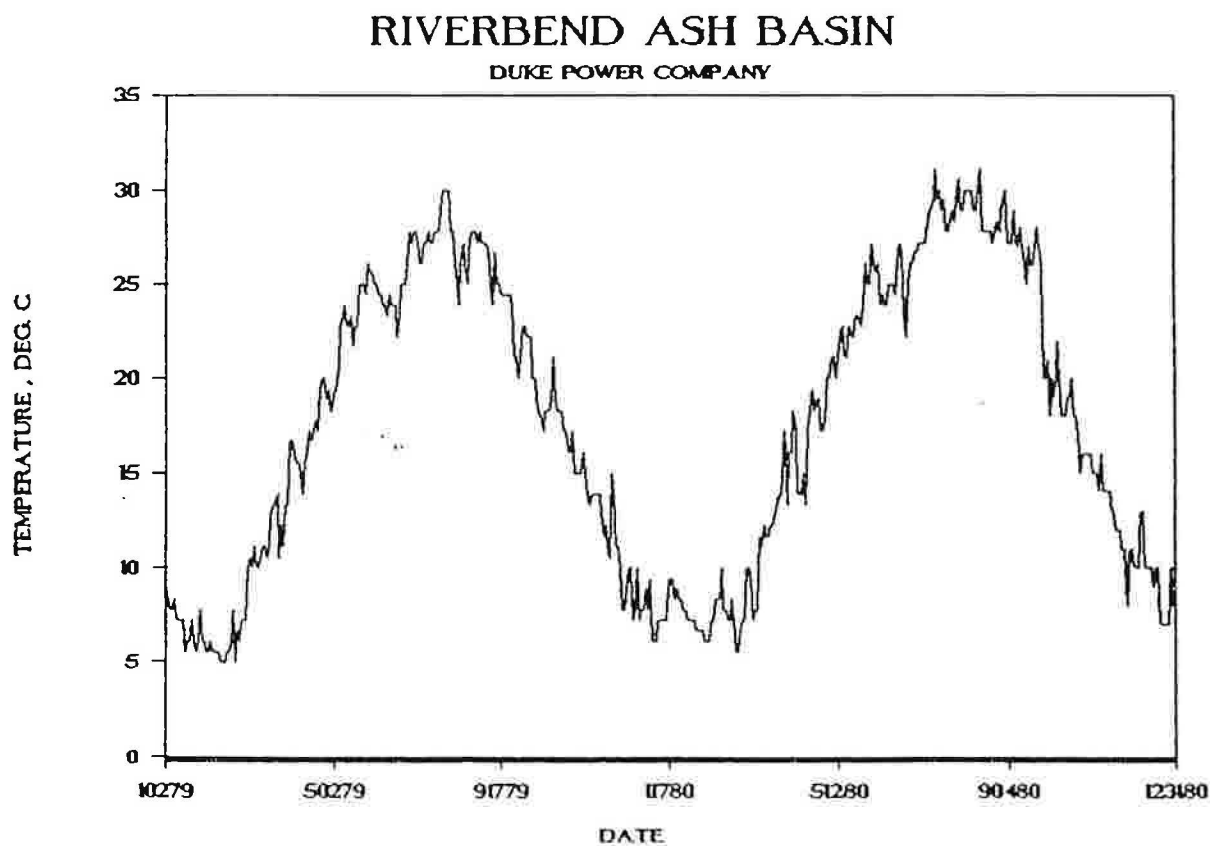


Figure 23. Time History of Effluent Temperature



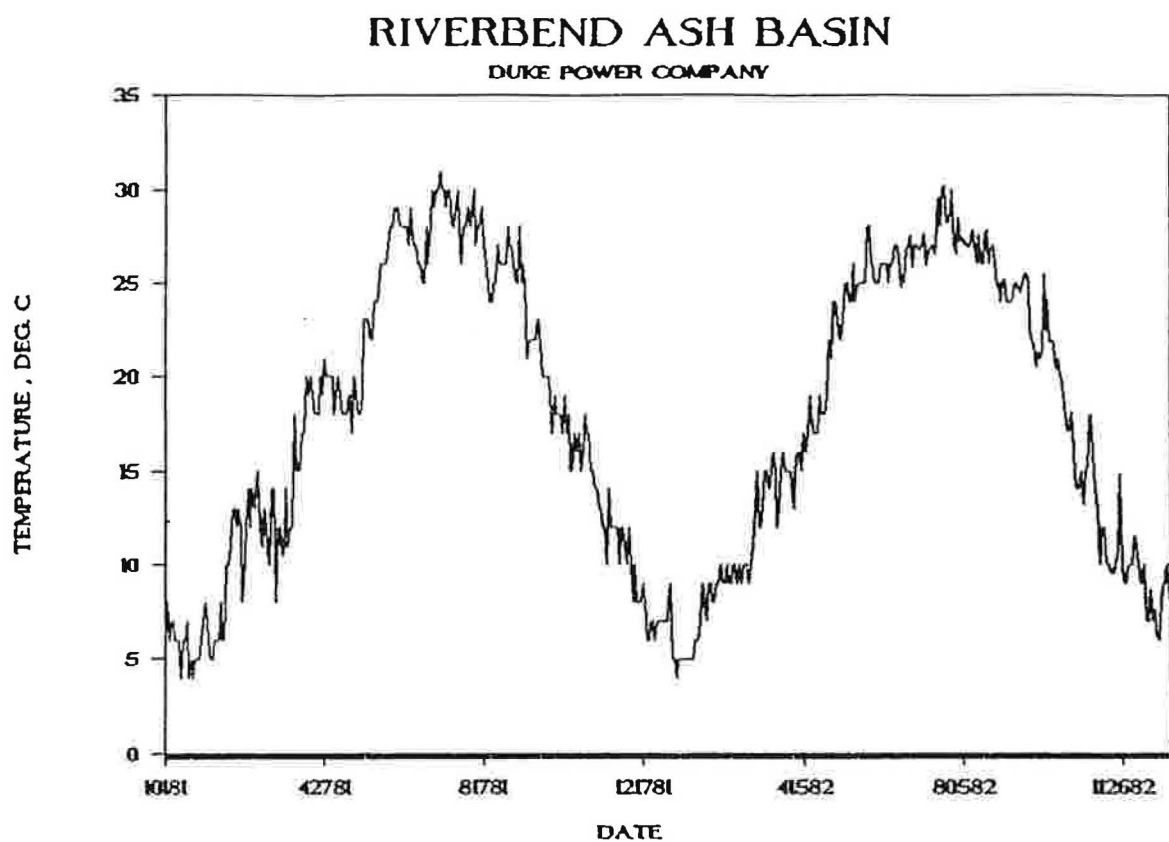
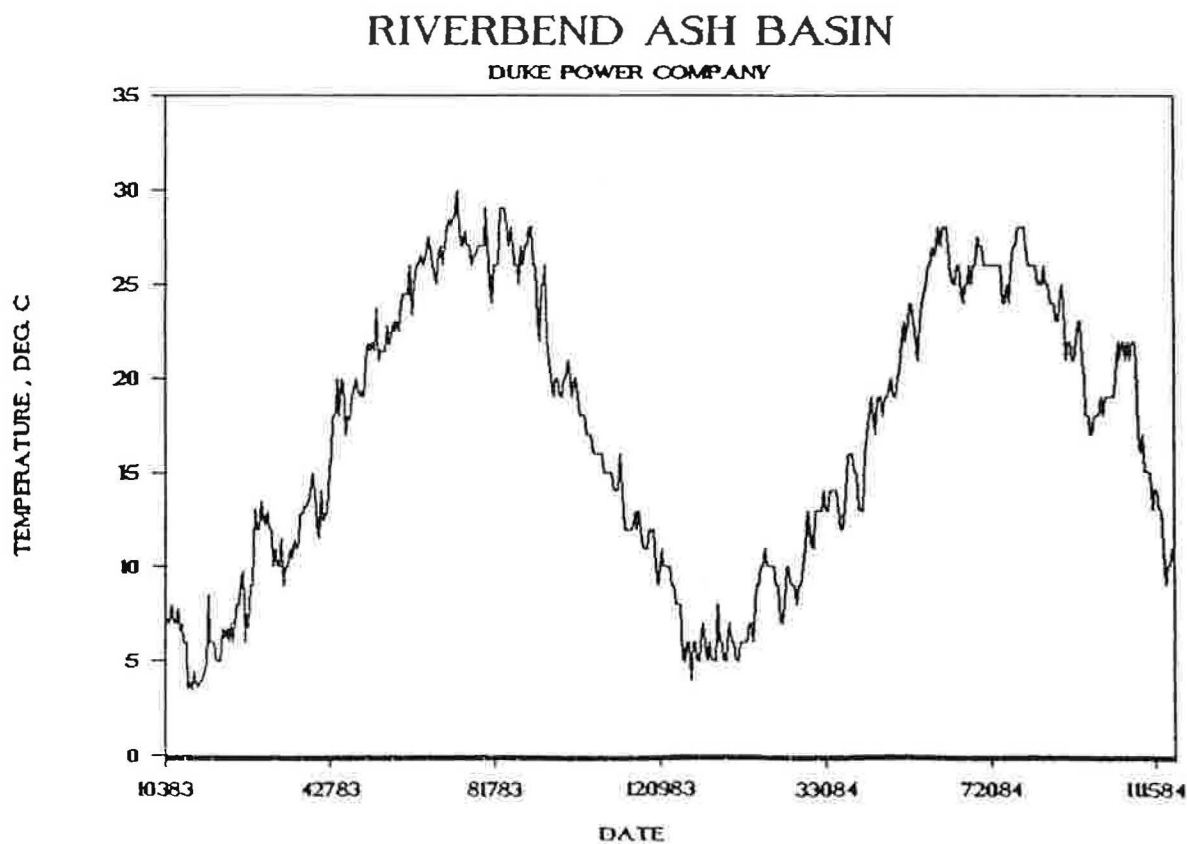


Figure 23. Time History of Effluent Temperature (Cont.)



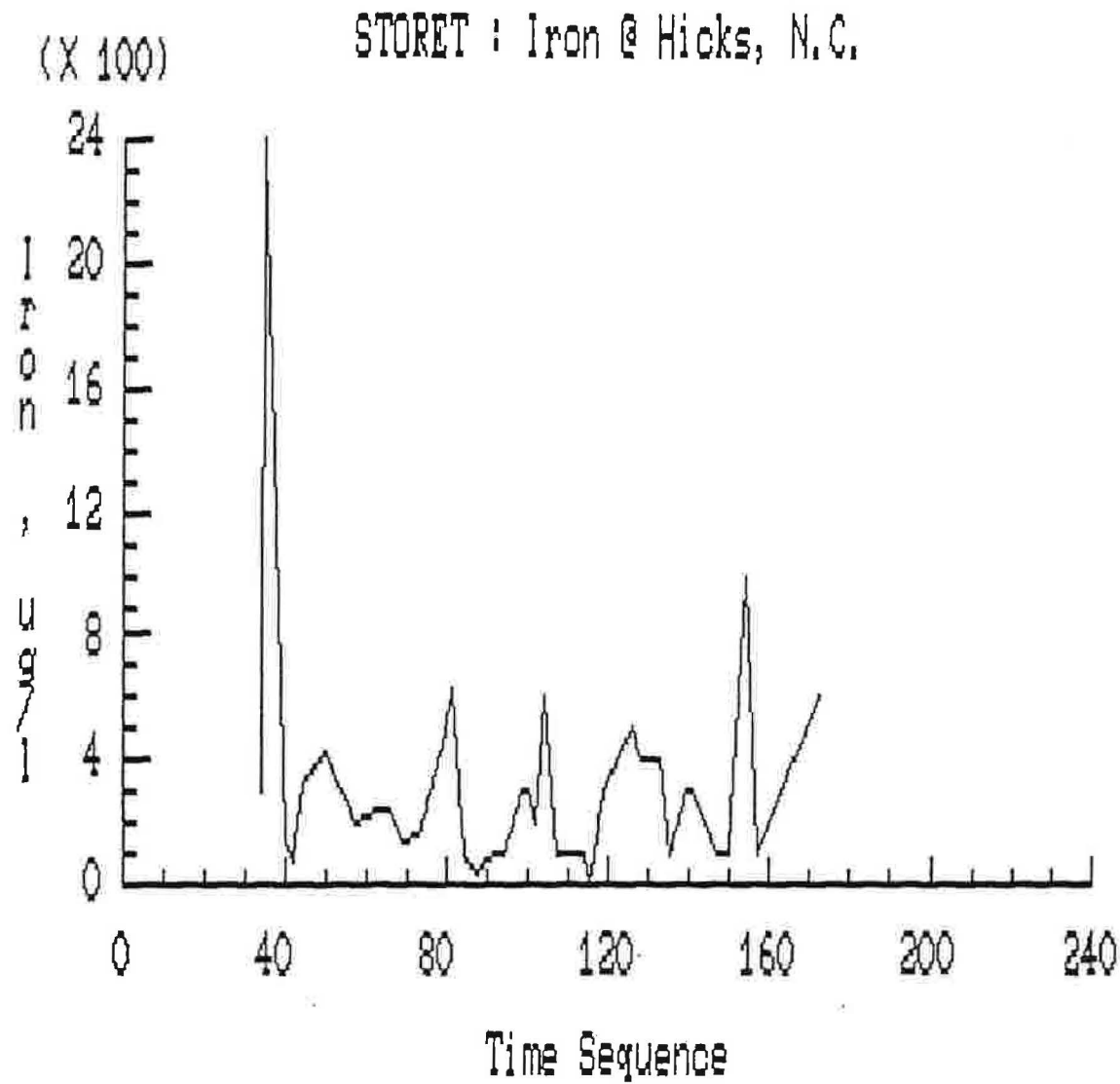


Figure 24. Iron Concentrations At Hicks, N.C.

Iron Upstream and Downstream of Site

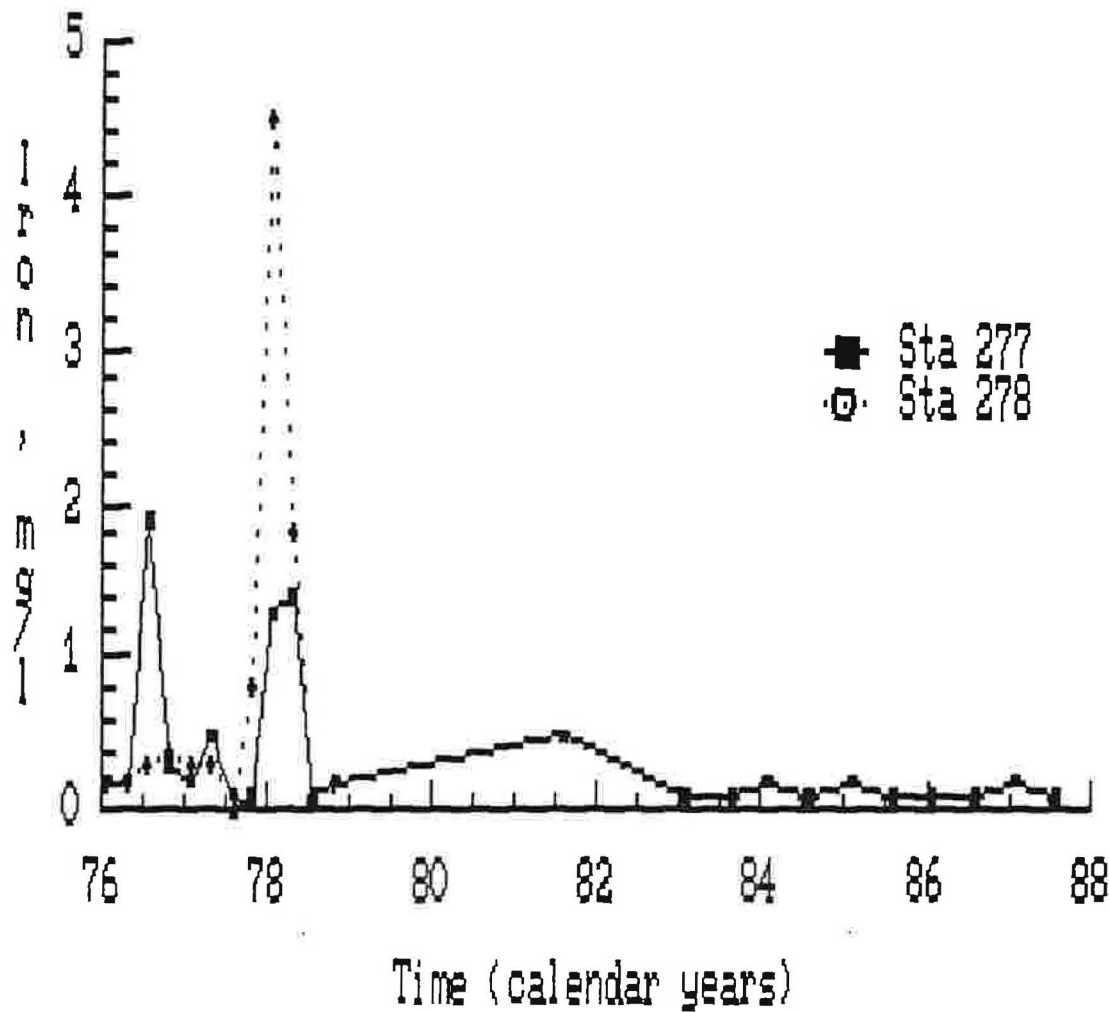


Figure 25. Iron Concentrations Upstream and Downstream of Site

Riverbend Ash Basin Iron Concentrations

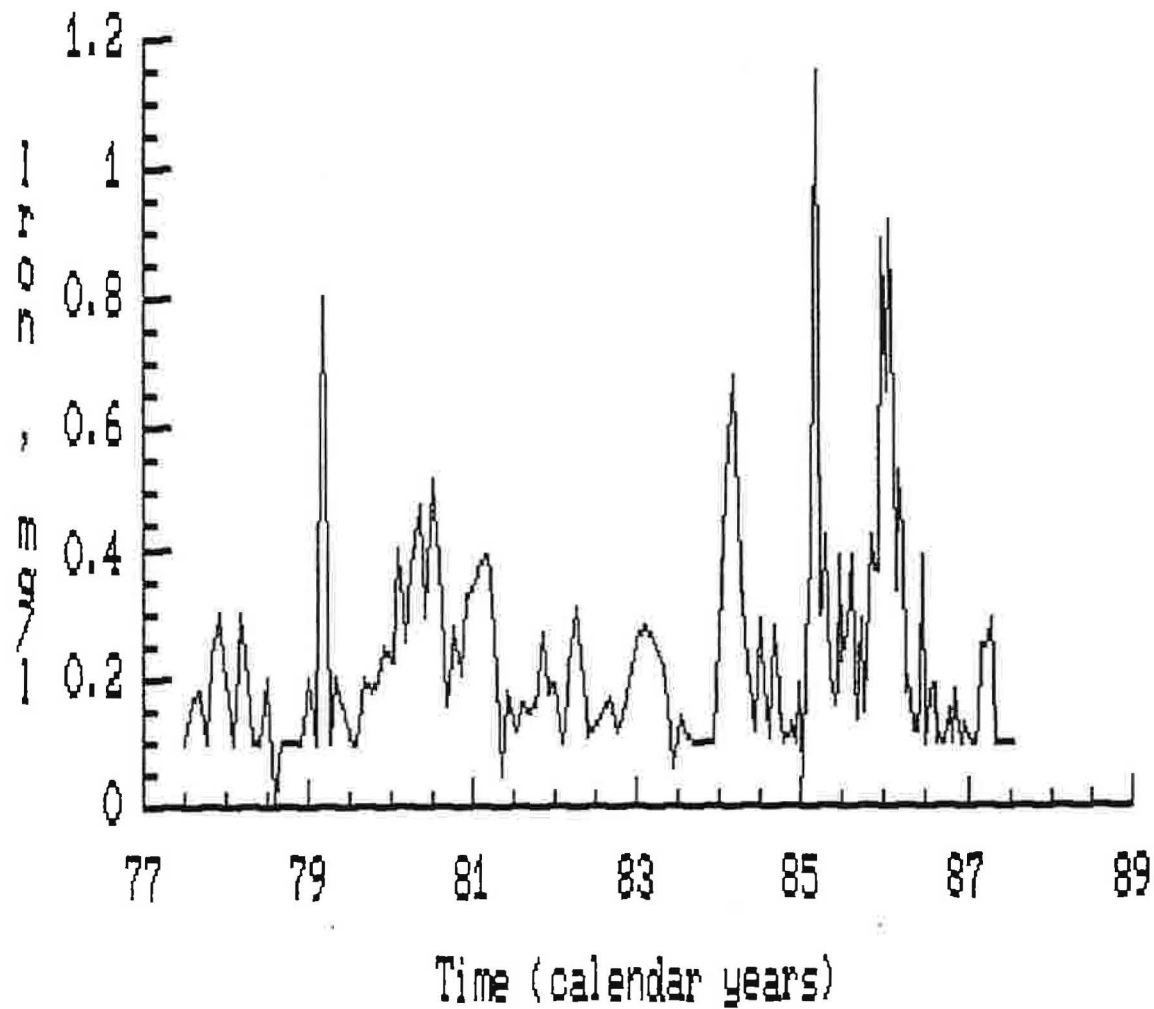


Figure 26. Time History of Effluent Iron Concentrations

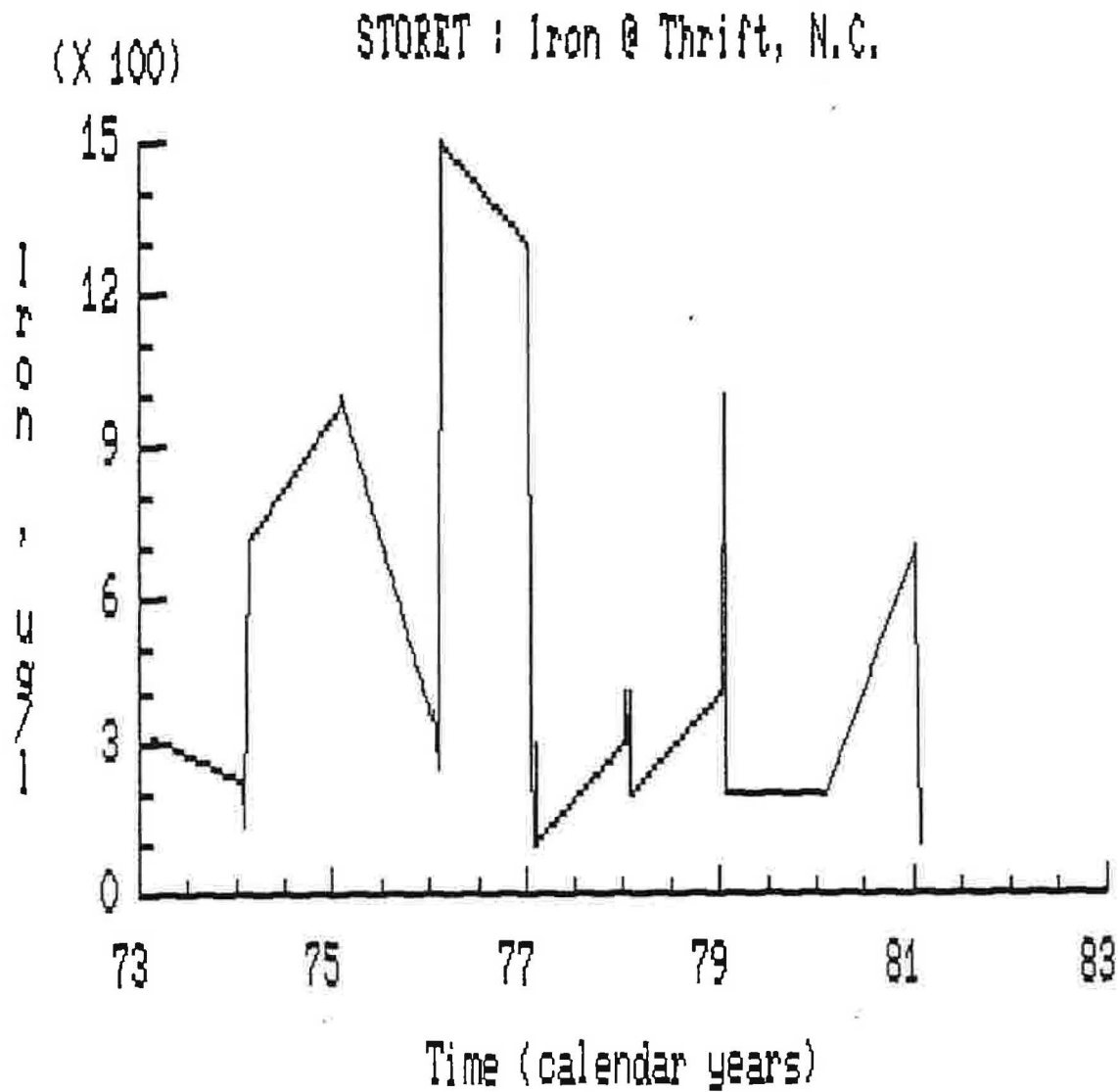


Figure 27. Iron Concentration At Thrift, N.C.

Manganese Upstream and Downstream

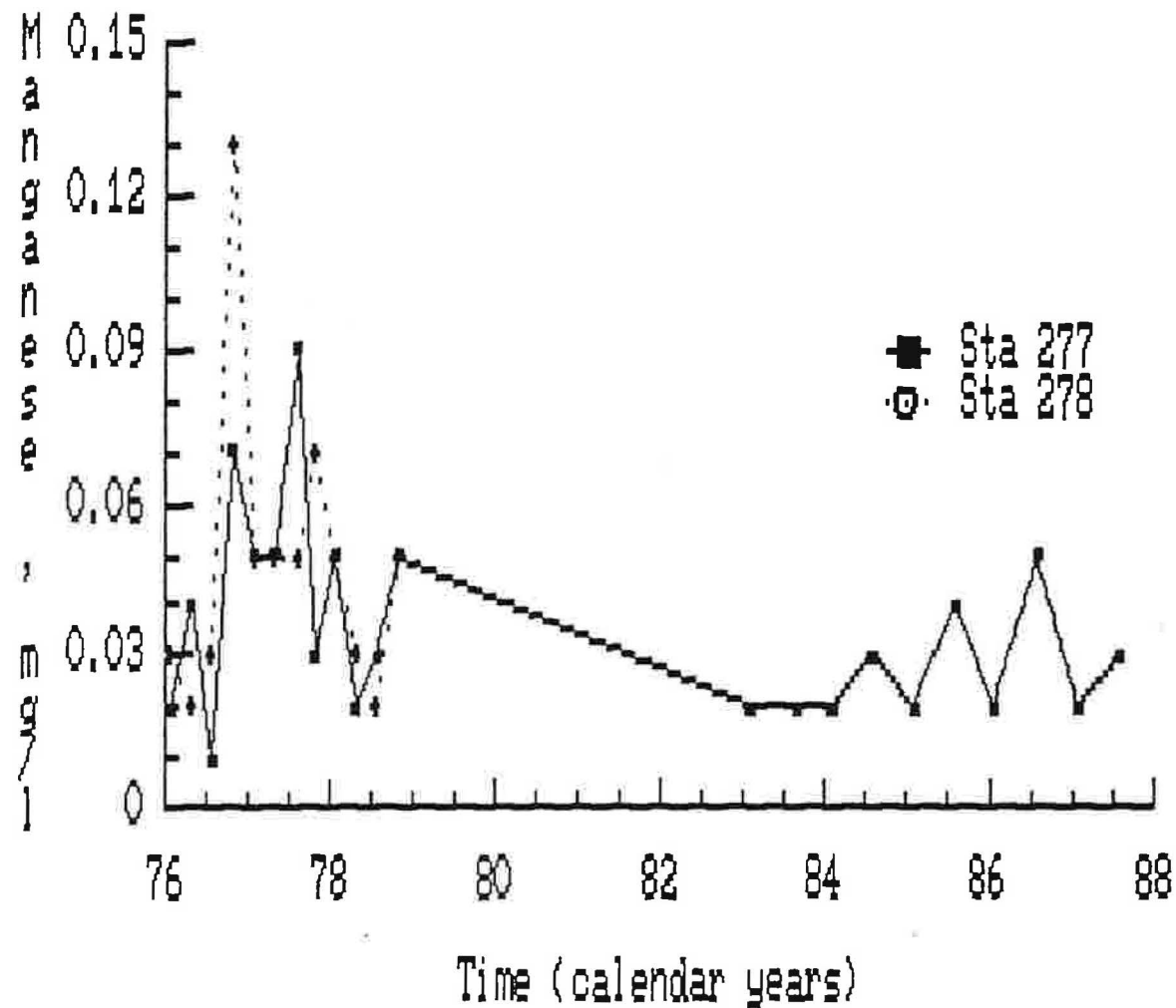


Figure 28. Manganese Concentrations Upstream (Sta 278) and Downstream (Sta 277) of Site

RIVERBEND Ash Basin Zinc

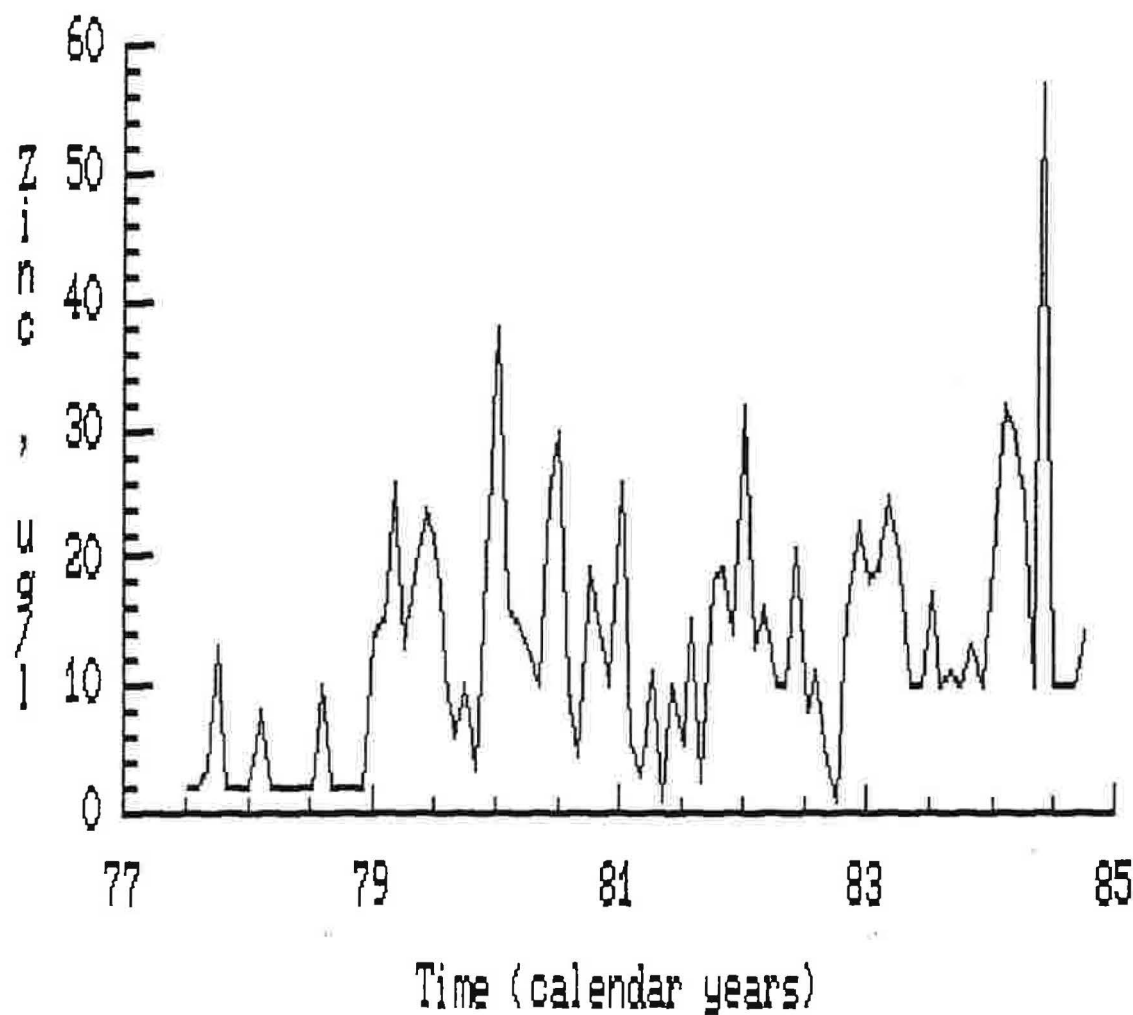


Figure 29. Time History of Effluent Zinc Concentrations

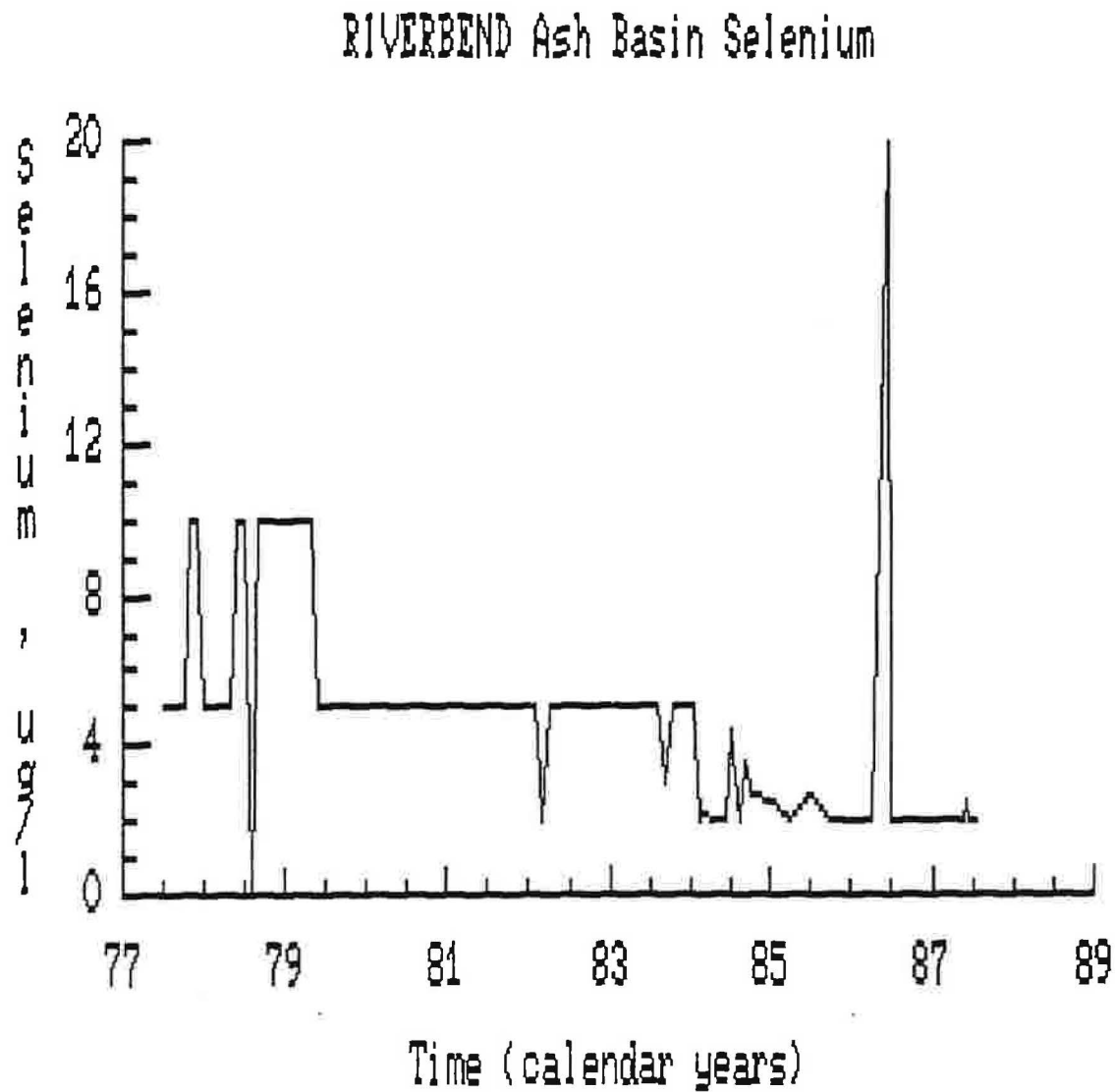


Figure 30. Time Series of Effluent Selenium Concentrations

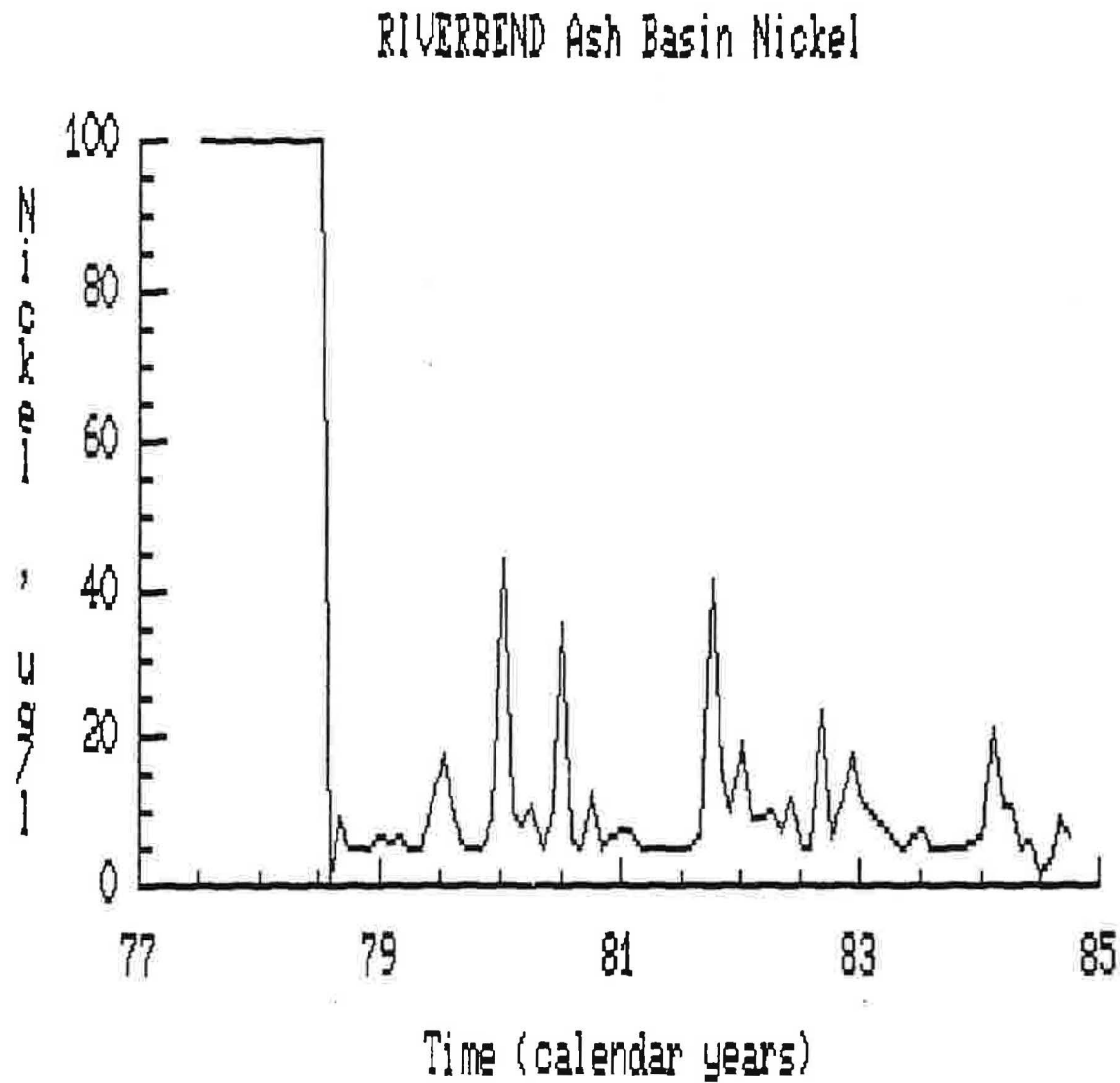


Figure 31. Time Series of Effluent Nickel Concentrations

5. Analysis of Potential Surface Water Impacts

As noted earlier, the mean effluent flow rate of the Riverbend Ash Basin is 7.1 cfs. The mean river flow was estimated at 2600 cfs for a 41-year record including pre-impoundment flows, and 2866 cfs for a shorter (12-year) more recent record. These values immediately suggest a dilution ratio from 1/366 to 1/404. A detailed examination of mixing phenomena in the Catawba River, including a two-dimensional transport model, is presented in the next sections.

5.1 Vertical and Transverse Mixing

From the river cross-sections supplied by Duke Power, an average cross-sectional area of flow between reaches 7 through 11 of 1388 meters squared (14,940 square feet) is obtained (see Figures 32 through 34) :

$$u_{avg} = Q_{avg} / A_{avg} = 0.19 \text{ ft/sec} \quad (\text{very sluggish})$$

Using only the average flow area between reaches 7 and 8,

$$u_{avg} = 2800 \text{ cfs} / 6566 \text{ sq ft} = 0.43 \text{ ft/sec} \quad (\text{still slow})$$

The vertical mixing (diffusion) coefficient may be estimated by :

$$\epsilon_v = 0.067 d u_*$$

where d = stream depth (about 1 meter roughly
at Mile 7)

$$u_* = \text{shear velocity}$$

$$= (g d S)^{\frac{1}{2}}$$

g = gravitational constant
 S = river bed slope (approx. 0.001 from
 the cross-sections)

With $u_* = 0.324$ fps,

$$\epsilon_v = 0.071 \text{ ft}^2/\text{sec}$$

The transverse mixing (diffusion) coefficient may be estimated by :

$$\epsilon_t = 1.5 d u_*^2 = 4.5 \text{ ft}^2/\text{sec}$$

(1.5 for sharp bends, irregular channels)
 (d about 2 meters average for reaches)
 (shear velocity = 0.46 fps for d = 2 m)

and the distance downstream from the contaminant source for complete mixing by :

$$L = 0.4 u_{\text{avg}} W^2 / \epsilon_t$$

where W = stream width average (approx. 297 meters, or 974 feet for reaches 7 through 11). Therefore,

$$L \approx 0.4 (0.19) (974)^2 / 4.5 (5280)$$

$$= 3.03 \text{ miles}$$

Because of the tremendous bend between Mile 9 and 10, it is very likely that the ash basin discharge has mixed in the cross-section by the time the plume reaches the Charlotte water intake (slightly over 4 miles downstream from the ash basin outfall) as predicted above.

A longitudinal dispersion coefficient can be estimated (in the absence of dye experiments) by :

$$E_L = 0.011 (u_{avg})^2 W^2 / (d u_*)$$

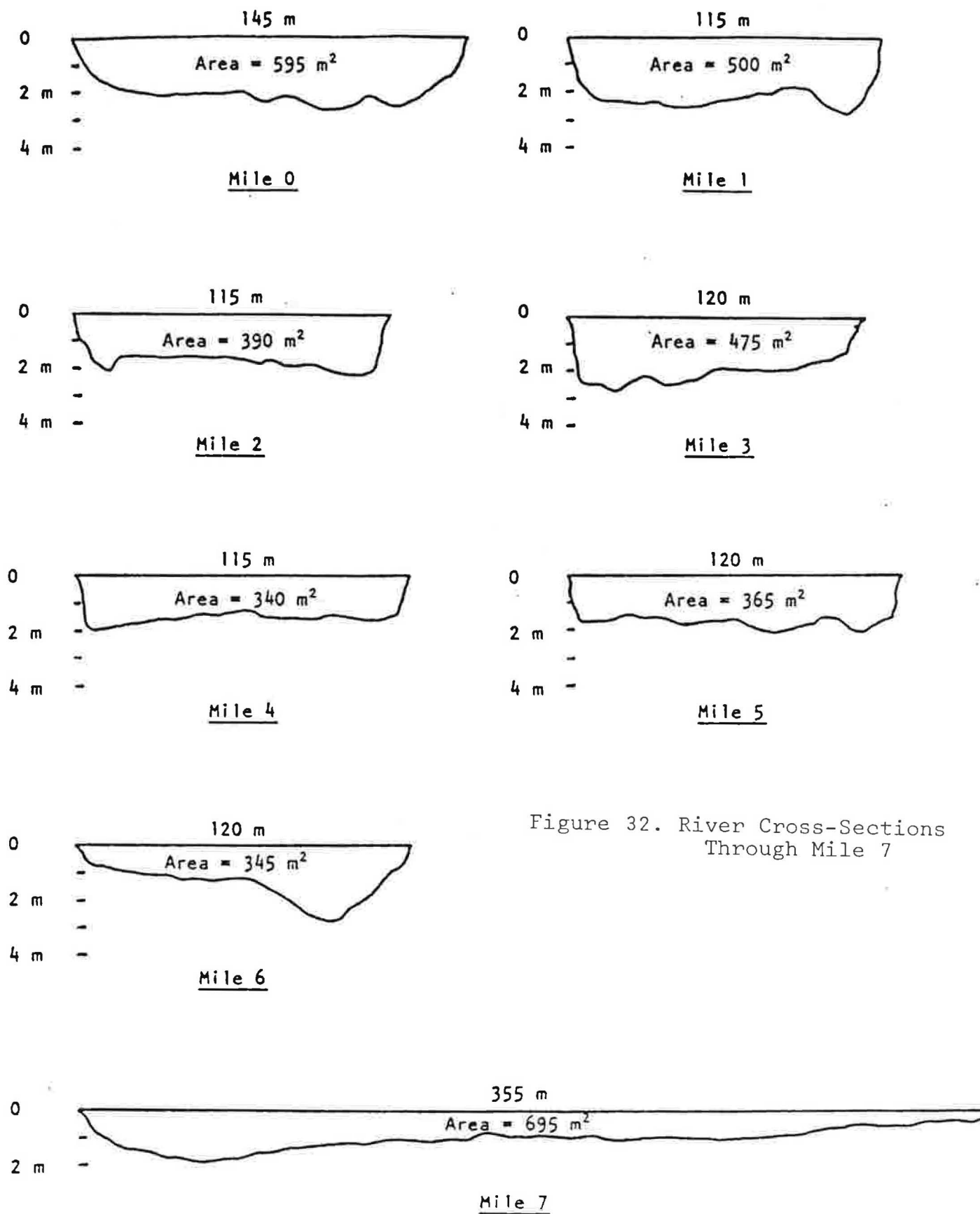
$$E_L \approx 125 \text{ ft}^2/\text{sec}$$

which is used later in applying the advective-dispersive equations to predict pollutant transport. The mixing time is proportional to the square of the average length traversed divided by the mixing coefficient. For our case, the transverse mixing time is :

$$(W/d)^2 / (\epsilon_t / \epsilon_v) = (297/2)^2 / (4.5/0.071)$$

$$\approx 348$$

times the vertical mixing time. In other words, complete vertical mixing would occur within 50 feet of the outfall.



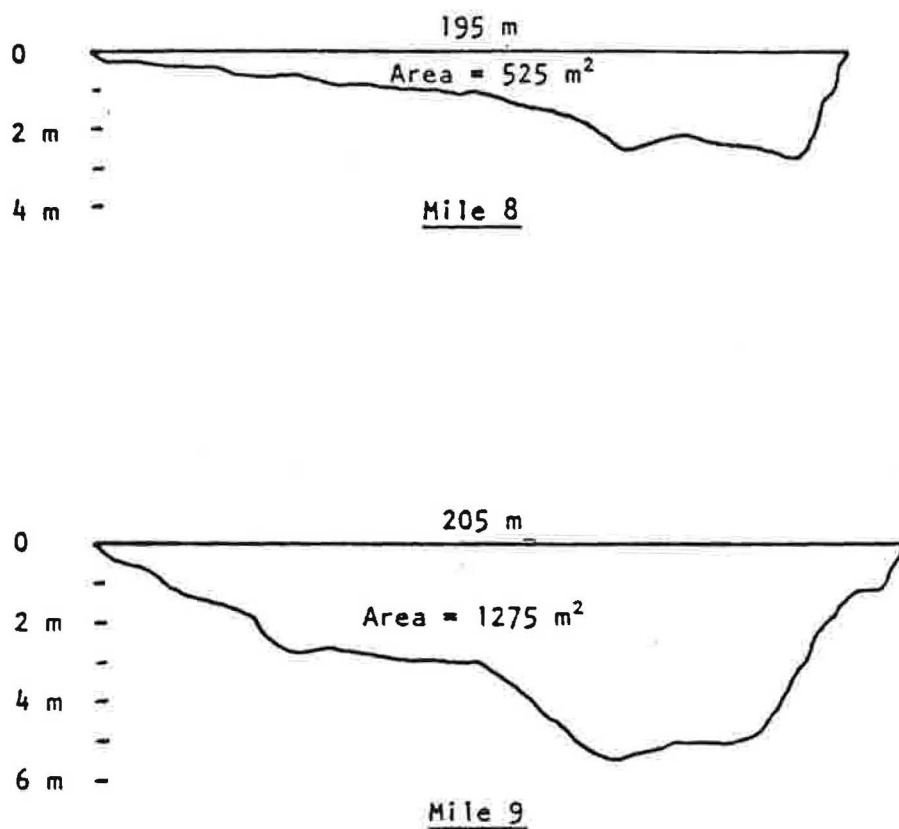


Figure 33. River Cross-Sections
at Miles 8 and 9

Note: Cross sections looking downstream.

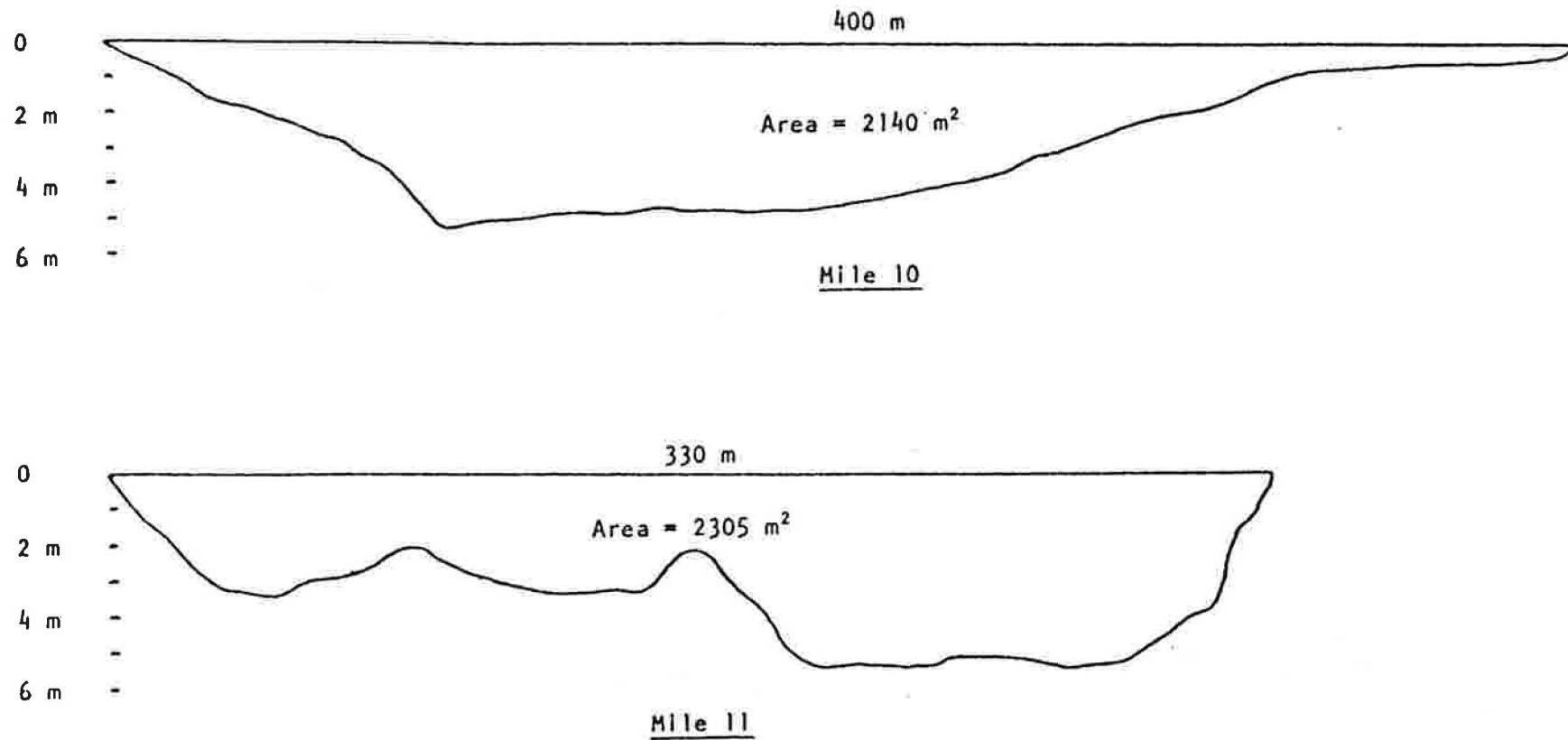


Figure 34. River Cross-Sections at
Miles 10 and 11

Note: Cross sections looking downstream.

5.2 ANALYTICAL, STEADY-STATE, CONTINUOUS TWO-DIMENSIONAL (VERTICAL LINE SOURCE) MODEL, SSCLS

The two dimensional advective-dispersive equation for a continuous vertical line source is a parabolic partial differential equation given by :

$$E_x \frac{\delta^2 C}{\delta x^2} + E_y \frac{\delta^2 C}{\delta y^2} - U \frac{\delta C}{\delta x} - KC = \frac{\delta C}{\delta t}$$

The time derivative goes to zero at steady-state, and the above equation reduces to a second order ordinary differential equation :

$$E_x \frac{d^2 C}{dx^2} + E_y \frac{d^2 C}{dy^2} - U \frac{dC}{dx} - KC = 0$$

The solution, in terms of the modified Bessel function of the second kind of order zero, for a side discharge is :

$$C(x,y) = \frac{q \exp\left(\frac{xU}{2E_x}\right)}{\pi \rho d_{avg} \sqrt{E_x E_y}} K_0(2\beta_2)$$

where

$$\beta_2 = \frac{\sqrt{(E_y x^2 + E_x y^2) (U^2 E_y + 4KE_x E_y)}}{4 E_x E_y}$$

and

$$q = \rho C_i Q_i$$

and $K_0(2\beta_2)$ is computed using polynomial approximations given by Abramowitz and Stegun (NBS Handbook of Mathematical Functions, 1964).

A dilution ratio may be computed at any point across and along the stream (y,x) by normalizing the predicted concentration with the input concentration : C/C_1 . A computer program was developed (SSCLS) and results were checked with a hand-held electronic calculator. If $2\beta_2$ is much greater than 1, the Bessel function can be approximated by an exponential function. Therefore,

$$K_0(2\beta_2) = \sqrt{\frac{\pi}{4\beta_2}} \exp(-2\beta_2)$$

and

$$C(x,y) = \frac{q \exp\left(\frac{xU}{2E_x}\right)}{\pi \rho d_{avg} \sqrt{E_x E_y}} \sqrt{\frac{\pi}{4\beta_2}} \exp(-2\beta_2)$$

or

$$\frac{C(x,y)}{C_1} = \frac{Q_1 \exp\left(\frac{xU}{2E_x}\right)}{\pi d_{avg} \sqrt{E_x E_y}} \sqrt{\frac{\pi}{4\beta_2}} \exp(-2\beta_2)$$

Thus, for a depth averaged across the stream cross-section at the source (Mile 7, $d_{avg} = 9.432$ feet), for $y = 487$ feet (stream width averaged over 5-mile stretch), zero decay, and for the transverse and longitudinal mixing values calculated earlier :

$$u_{avg} = 0.19 \text{ ft/sec}$$

$$E_x = 125 \text{ ft}^2/\text{sec} \approx E_L$$

$$E_y = 4.5 \text{ ft}^2/\text{sec} \approx \epsilon_t$$

$$x = 26,400 \text{ feet} = 5.0 \text{ miles}$$

$$Q_i = 7.1 \text{ cfs}$$

the concentration ratio is

$$C(x,y=487)/C_i = 0.002534 = 1 / 394.568$$

or about a 1:400 dilution ratio near the Charlotte water intake. The dimensionless concentration profile at the stream centerline is presented in Figure 35. Although the pollutants reach the stream centerline about 0.75 miles downstream, complete mixing across the entire river width occurs at 3.03 miles and beyond. The computed profile is presented in Figure 36. The concentration of any pollutant at the source (in any units) would simply be multiplied by the concentration ratio at the corresponding distance downstream. For example, on October 19, 1987 samples taken from the Riverbend effluent weir were analyzed for copper, iron, arsenic and selenium content, their concentrations 5 miles downstream would be as follows :

Concentration At Source (Ash Basin)	Concentration Ratio	Concentration 5 Miles Downstream
Cu, < 0.1 mg/l	0.002534	< 0.0002534 mg/l
Fe, < 0.1 mg/l	0.002534	< 0.0002534 mg/l
As, 131 µg/l	0.002534	0.331954 µg/l
Se, < 2 µg/l	0.002534	< 0.005068 µg/l

These constitute conservative estimates since sinks such as precipitation due to oxidation (which could be approximated in the decay coefficient K) have been set to zero.

DUKE POWER CO. RIVERBEND SITE Concentration X 1000

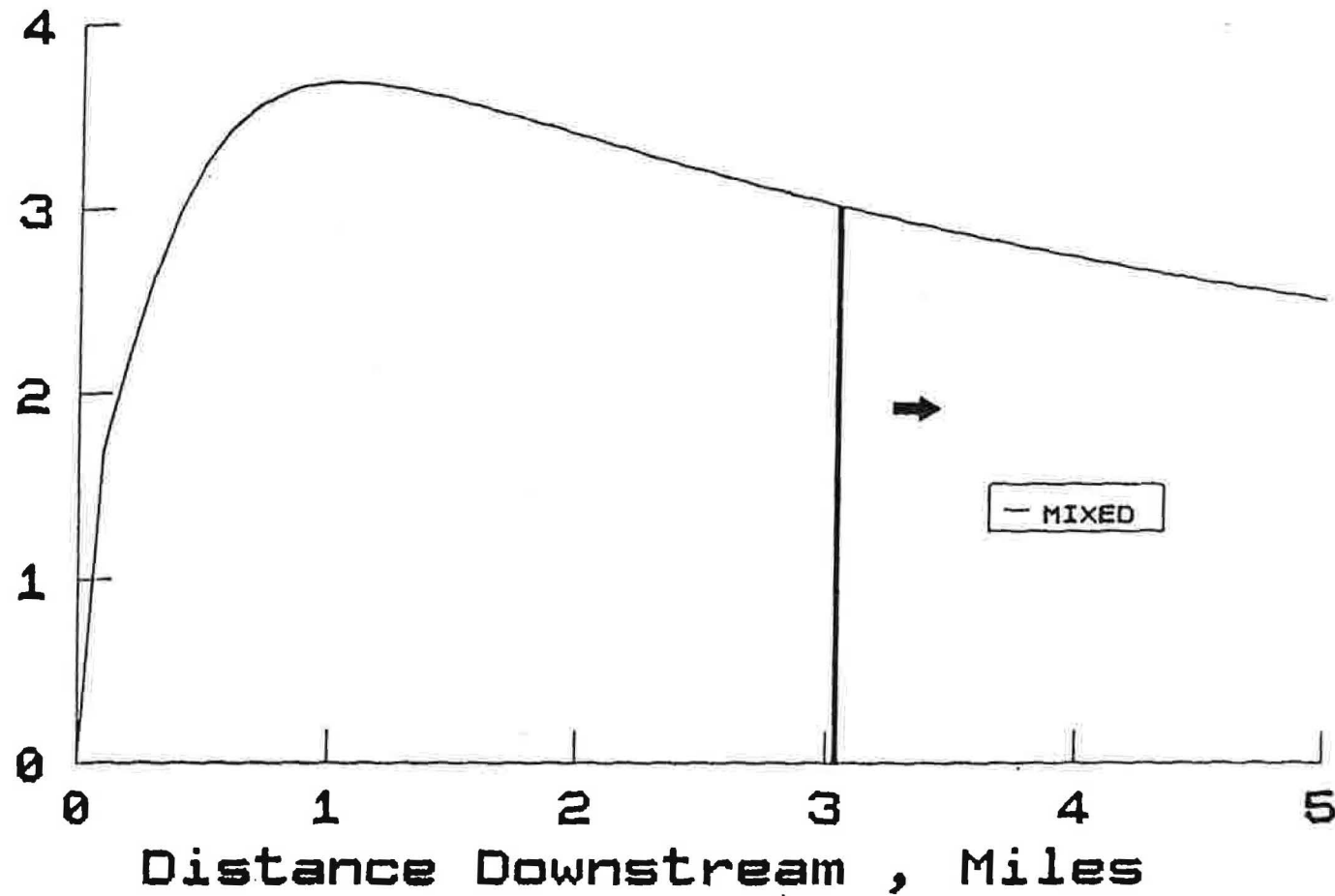


Figure 35. Concentration Ratio Profile Downstream from Site

Figure 36. Computed Profile of Concentration
Ratio, Downstream of Ash Basin

DUKE POWER COMPANY RIVERBEND PROJECT

DILUTION RATIO BELOW SOURCE
FOR PRISTINE RIVER = 404.662000

Concentration Ratio At 5.0 MILES = .002534

Dilution Ratio At Same Distance = 1 TO 394.568100

DISTANCE =	.0000 MILES	CONC. =	.000000
DISTANCE =	.1000 MILES	CONC. =	.001700
DISTANCE =	.2000 MILES	CONC. =	.002205
DISTANCE =	.3000 MILES	CONC. =	.002646
DISTANCE =	.4000 MILES	CONC. =	.002996
DISTANCE =	.5000 MILES	CONC. =	.003255
DISTANCE =	.6000 MILES	CONC. =	.003437
DISTANCE =	.7000 MILES	CONC. =	.003558
DISTANCE =	.8000 MILES	CONC. =	.003634
DISTANCE =	.9000 MILES	CONC. =	.003676
DISTANCE =	1.0000 MILES	CONC. =	.003694
DISTANCE =	1.1000 MILES	CONC. =	.003694
DISTANCE =	1.2000 MILES	CONC. =	.003682
DISTANCE =	1.3000 MILES	CONC. =	.003661
DISTANCE =	1.4000 MILES	CONC. =	.003633
DISTANCE =	1.5000 MILES	CONC. =	.003601
DISTANCE =	1.6000 MILES	CONC. =	.003566
DISTANCE =	1.7000 MILES	CONC. =	.003529
DISTANCE =	1.8000 MILES	CONC. =	.003491
DISTANCE =	1.9000 MILES	CONC. =	.003452
DISTANCE =	2.0000 MILES	CONC. =	.003412
DISTANCE =	2.1000 MILES	CONC. =	.003373
DISTANCE =	2.2000 MILES	CONC. =	.003334
DISTANCE =	2.3000 MILES	CONC. =	.003296
DISTANCE =	2.4000 MILES	CONC. =	.003258
DISTANCE =	2.5000 MILES	CONC. =	.003221
DISTANCE =	2.6000 MILES	CONC. =	.003185
DISTANCE =	2.7000 MILES	CONC. =	.003149
DISTANCE =	2.8000 MILES	CONC. =	.003115
DISTANCE =	2.9000 MILES	CONC. =	.003081
DISTANCE =	3.0000 MILES	CONC. =	.003048
DISTANCE =	3.1000 MILES	CONC. =	.003016
DISTANCE =	3.2000 MILES	CONC. =	.002984
DISTANCE =	3.3000 MILES	CONC. =	.002953
DISTANCE =	3.4000 MILES	CONC. =	.002924
DISTANCE =	3.5000 MILES	CONC. =	.002894
DISTANCE =	3.6000 MILES	CONC. =	.002866
DISTANCE =	3.7000 MILES	CONC. =	.002838
DISTANCE =	3.8000 MILES	CONC. =	.002811
DISTANCE =	3.9000 MILES	CONC. =	.002785
DISTANCE =	4.0000 MILES	CONC. =	.002759
DISTANCE =	4.1000 MILES	CONC. =	.002734
DISTANCE =	4.2000 MILES	CONC. =	.002710
DISTANCE =	4.3000 MILES	CONC. =	.002686
DISTANCE =	4.4000 MILES	CONC. =	.002663
DISTANCE =	4.5000 MILES	CONC. =	.002640
DISTANCE =	4.6000 MILES	CONC. =	.002618
DISTANCE =	4.7000 MILES	CONC. =	.002596
DISTANCE =	4.8000 MILES	CONC. =	.002575
DISTANCE =	4.9000 MILES	CONC. =	.002555
DISTANCE =	5.0000 MILES	CONC. =	.002534

6. Analysis of Potential Groundwater Contributions

Scarce data are available on actual groundwater quality conditions at the Riverbend Plant. However, the relevant hydro-geologic conditions are likely to be very similar to those at Plant Allen, which have been extensively studied. The ash introduced into the settling basins contains many metal constituents, some of them in fairly high concentrations. However, the majority of this material appears to remain in insoluble form, and the dewatered ash will eventually be removed from the settling basin and landfilled. The important questions are whether leaching from this ash will adversely affect groundwater downgradient from the basin, and, if this occurs, whether surface water conditions will be adversely impacted in the Catawba River.

The analysis thus naturally divides into three parts:

- 1) Potential impact on groundwater near the basin.
- 2) Potential groundwater contribution of contaminants to Catawba River/Mountain Island Lake.
- 3) Comparison of potential groundwater contribution to permitted surface discharges from the ash basin.

6.1 Potential Impact on Groundwater

The potential impact on groundwater must be considered in two sections. We first consider the trace metals, which include toxic contaminants. The naturally dominant metals iron and manganese must be considered separately.

Trace Metals

The trace metals examined in the ash include barium, cadmium, chromium, copper, arsenic, selenium, mercury and lead. Arsenic is apparently of particular concern. It should first be noted that monitoring at Plant Allen shows no instances of violation of groundwater standards for these constituents either underneath the ash basins or downgradient, despite the fact that several of these metals (arsenic, selenium, barium, cadmium, chromium) are found in relatively high concentrations in dry

fly ash. Based on the Plant Allen experience, it is thus expected that these trace metals will not pose any significant hazard to groundwater.

The concentrations of any trace metals which do reach groundwater are expected to be reduced by two processes: precipitation reactions, resulting in insoluble compounds (which may be of particular importance for arsenic in the presence of iron), and reversible adsorption to the clay particles of the saprolite. It appears that the adsorptive capacity of the saprolite is by itself sufficient to prevent contamination problems from these trace metals, which seems to be borne out by the experience at Plant Allen.

Where adsorption can be described by a linear, reversible isotherm, adsorption can be readily accounted for in a groundwater transport model by use of a retardation coefficient (R), which describes the reduced apparent velocity of the adsorbed contaminant relative to the movement of the groundwater:

$$R = V/V_c$$

where V is the velocity of the groundwater, and V_c the apparent velocity of the contaminant. For fast reversible adsorption described by a linear isotherm, Freeze and Cherry (1979) provide an approximation for R in terms of the soil-water distribution coefficient, K_d :

$$(1 + 4K_d) \leq R \leq (1 + 10K_d)$$

where K_d , expressed in units of ml/g, is the rate of change of the adsorbed mass per unit mass of soil (S) divided by the rate of change of solute concentration (C):

$$K_d = dS/dC$$

Unfortunately, the behavior of most metal ions is not

accurately described by a linear isotherm. Instead, adsorptive behavior for these constituents is more accurately described by the nonlinear Langmuir isotherm (EPRI, "Chemical Attenuation Rates..."):

$$S = (K_L A_m C) / (1 + K_L C)$$

where:

S = moles adsorbed at equilibrium per gram of solid

A_m = maximum adsorptive capacity of the soil

K_L = Langmuir adsorption constant

C = total concentration in solution at equilibrium.

From this relationship,

$$dS/dC = K_L A_m / (1 + K_L C)^2$$

This value will be approximately linear for concentrations which are small relative to the adsorptive capacity of the soil, which appears to hold for all the trace metals under consideration. Further, the rate of adsorption will be greater at lower concentrations.

The EPA report on Plant Allen gives estimates of the adsorptive capacity of several types of native soil found at the plant for various trace metals (as l/g), analyzed at varying solution concentrations (Table 5.4, EPA, 1985). These allow computation of an approximate linear soil-water distribution coefficient over the concentration range of the metals found beneath the plant. Taking the minimum reported values from these tests, and applying the relationship given by Freeze and Cherry we can estimate minimum approximate values for the retardation coefficients, as follows:

	Minimum K_d (ml/g)	Minimum R
Arsenic	13600	54401
Selenium	510	2041
Cadmium	240	961
Copper	830	3321
Nickel	140	561
Vanadium	140	561

These values would indicate that these metals would be nearly immobile in the groundwater. It is possible that the estimates may be high and the observed reductions may include precipitation as well as adsorption. However, coefficients for Langmuir type adsorption for arsenic given in EPRI, "Chemical Attenuation Rates..." (1986), suggest that the value of K_d for arsenic in the range of observed concentrations should be somewhat greater than 2000 ml/g, which is still quite high.

From the data presented in Figure 15 and Table 8, Section 3.6, a rate of contaminant migration (V_c) of 0.3 feet per year for the trace metals was estimated. From Table 5, Section 3.6, a groundwater velocity of 180 feet per year (≈ 0.5 ft/day) is obtained. Thus, the resulting retardation coefficient is 600. It is interesting to note that this value is slightly above the minimum values reported above for nickel and vanadium. This R value was then used in a two-dimensional analytical contaminant transport model (TDAST, Javandel et al., 1984) within a groundwater quality advisory system (Medina, et al., 1987). The Riverbend Plant has currently been in operation for 30 years, and the minimum distance from the ash basin to the Catawba River is about 500 feet. Since the clay content of the saprolite at Riverbend appears to be slightly smaller than at Allen, the R value was also reduced by a factor of 3 (very conservative) to $R = 200$. At the reduced retardation coefficient, breakthrough of contaminants to the river along the shortest flowline would still require over 1600 years !

For a conservative, worst case analysis the following values were used :

$V = 0.493$ ft/day (180 ft/yr)	Table 5, Section 3.5
$E_L = 9.3 \times 10^{-2}$ ft ² /day	Figure 9.4, Freeze and Cherry (1979)

$E_T = 9.3 \times 10^{-3}$ ft ² /day	1/10 of E_L value
$R = 200 \quad \text{---> } (600/3)$	Table 5, Table 8
$H_L = 1250$ ft. (half-length of the basin profile parallel to the river, see Figures 8 and 9, Sections 2.2 and 3.2 respectively)	

Output of the transport model, given these parameters, follows, giving predictions of percent of under-site concentrations at years 1987, 2007 and 2037. These results indicate that no measurable concentration of the retarded contaminants will reach the river along the shortest flowlines even in the next 50 years. It is expected that the ash basin will have been removed from service long before this date, and the residual ash landfilled, so that the input concentrations will be decreasing well before this date is reached.

ANALYTICAL TWO-DIMENSIONAL CONTAMINANT TRANSPORT MODEL, TDAST

The model TDAST provides an analytical solution to steady state flow in a two-dimensional Cartesian coordinate system, and is documented in Javandel et al. (1984). If the flow is coincident with the x axis, and the longitudinal and transverse components of the dispersion tensor are assumed independent of position and designated by D_L and D_T , the general governing equation for a confined, homogeneous, isotropic aquifer can be written as:

$$D_L \frac{\partial^2 C}{\partial x^2} + D_T \frac{\partial^2 C}{\partial y^2} - v \frac{\partial C}{\partial x} - \lambda RC = R \frac{\partial C}{\partial t}$$

where lambda represents decay and R is the retardation coefficient.

For a particular solution we first assume that the medium is initially free of the solute, and that at a certain time a strip type source of length 2a, orthogonal to the flow direction, is introduced along the y axis. If the source concentration diminishes exponentially with time, the initial and boundary conditions are:

$$C(0,y,t) = C_0 e^{-\alpha t} \quad -a \leq y \leq a$$

$$C(0,y,t) = 0 \quad |y| > a$$

$$\lim_{y \rightarrow \pm\infty} \frac{\delta C}{\delta y} = 0$$

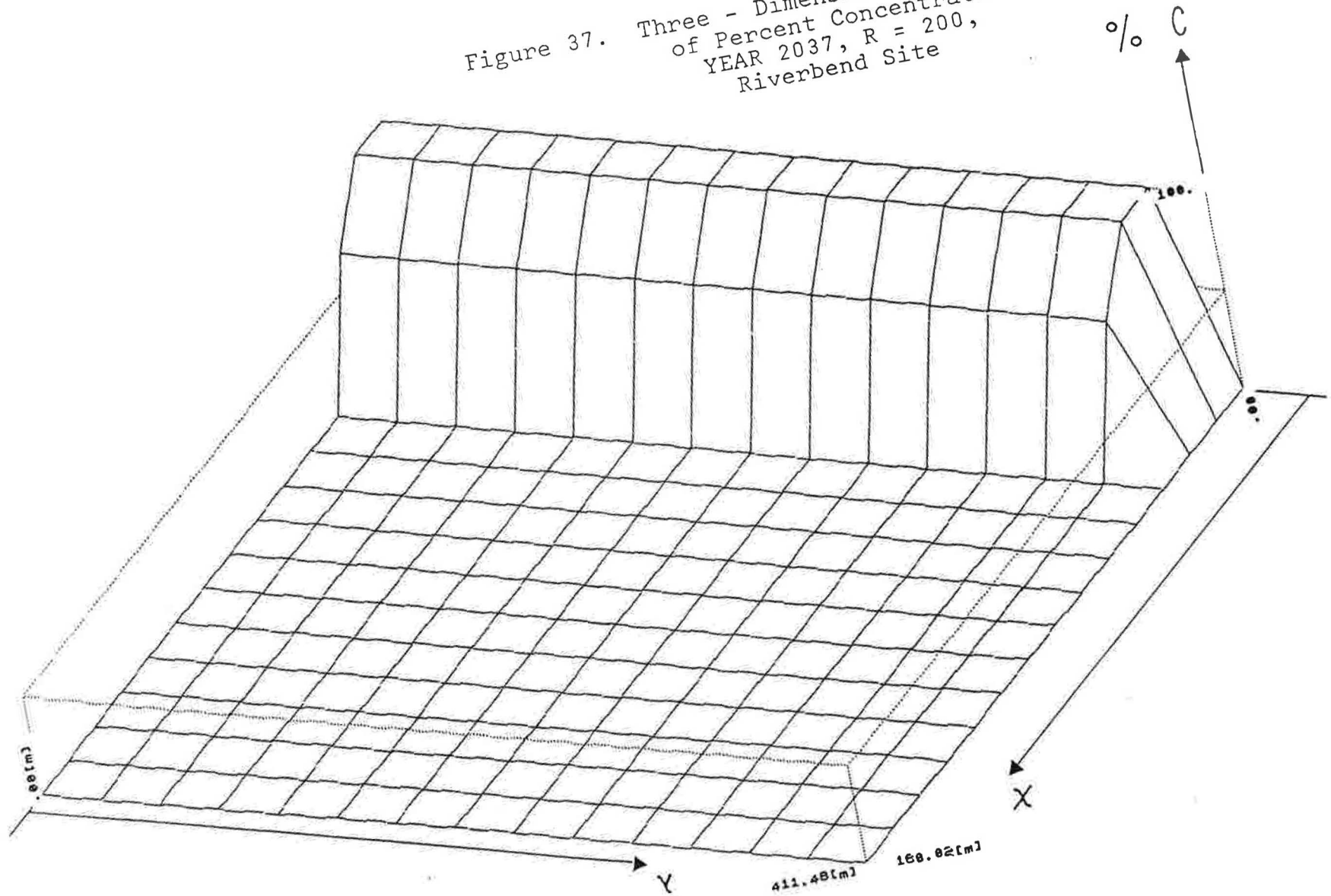
$$\lim_{x \rightarrow \infty} \frac{\delta C}{\delta x} = 0$$

Where the source "strip" is arranged orthogonal to the direction of flow, an analytical (but not closed form) solution is presented by Cleary and Ungs (1978) as:

$$C(x,y,t) = \frac{C_0 x}{4\sqrt{\pi D_L}} \exp \left[\frac{vx}{2D_L} - \alpha t \right] \\ \cdot \int_0^{t/R} \exp \left[- \left(\lambda R - \alpha R + \frac{v^2}{4D_L} \right) \tau - \frac{x^2}{4D_L \tau} \right] \tau^{-3/2} \\ \cdot \left[\operatorname{erf} \left(\frac{a-y}{2\sqrt{D_T \tau}} \right) + \operatorname{erf} \left(\frac{a+y}{2\sqrt{D_T \tau}} \right) \right] \delta \tau$$

The results of applying TDAST to the Riverbend Site are presented in Figures 37 and 38. Even for the year 2037, no measurable pollutant concentrations are reaching the river ($x = 500$ feet, 152 meters). Figure 37 represents a three-dimensional view of the contaminant plume for the year 2037 (80 years in operation) for $R = 200$: the pollutant concentrations (in percent, 100 percent at the source) are measurable at 21.3 meters (70 feet), with another 430 feet to go to reach the river, across a 1260 foot front (y -axis is parallel to the river). The computed output file is presented in Figure 38 for the years 1987, 2007 and 2037. The contaminants are immobile through the year 2007, showing some movement by 2037.

Figure 37. Three - Dimensional View
of Percent Concentration,
YEAR 2037, R = 200,
Riverbend Site



**Figure 38. State of North Carolina Groundwater
Advisory System, Output File**

SITE NAME: Riverbend

SITID = RIVRBN FILES= A:RIVRBN.OUT A:RIVRBN.SIT

Application of analytical model TDAST

Run # 1

YEAR 1987

Time = 10958. days (30 years)
 HALF LENGTH OF SOURCE: 381.00
 SOURCE CONC.: 100.00 %
 LONG. DISPERSIVITY: .86400E-02 (m2/d)
 TRANS. DISPERSIVITY: .86400E-03 (m2/d)
 X VELOCITY: .15033 (m/day)
 RETARDATION COEF: 600.00
 DECAY FACTOR OF SOURCE: .00000 (1/day)
 DECAY FACTOR OF SOLUTE: .00000 (1/day)
 Aquifer concentration at source input directly,
 not calculated from leaching

CONCENTRATION RESULTS (percent)

X	Y AXIS (PERPENDICULAR TO FLOW) (meters)				
	.000	27.4	54.9	82.3	110.
.000	100.	100.	100.	100.	100.
10.7	.140E-42	.140E-42	.140E-42	.140E-42	.140E-42
21.3	.000	.000	.000	.000	.000
32.0	.000	.000	.000	.000	.000
42.7	.000	.000	.000	.000	.000
53.3	.000	.000	.000	.000	.000
64.0	.000	.000	.000	.000	.000
74.7	.000	.000	.000	.000	.000
85.3	.000	.000	.000	.000	.000
96.0	.000	.000	.000	.000	.000
107.	.000	.000	.000	.000	.000
117.	.000	.000	.000	.000	.000
128.	.000	.000	.000	.000	.000
139.	.000	.000	.000	.000	.000
149.	.000	.000	.000	.000	.000

Figure 38. State of North Carolina Groundwater
Advisory System, Output File (Cont.)

	137.	165.	192.	219.	247.
X	-----				
.000	100.	100.	100.	100.	100.
10.7	.140E-42	.140E-42	.140E-42	.140E-42	.140E-42
21.3	.000	.000	.000	.000	.000
32.0	.000	.000	.000	.000	.000
42.7	.000	.000	.000	.000	.000
53.3	.000	.000	.000	.000	.000
64.0	.000	.000	.000	.000	.000
74.7	.000	.000	.000	.000	.000
85.3	.000	.000	.000	.000	.000
96.0	.000	.000	.000	.000	.000
107.	.000	.000	.000	.000	.000
117.	.000	.000	.000	.000	.000
128.	.000	.000	.000	.000	.000
139.	.000	.000	.000	.000	.000
149.	.000	.000	.000	.000	.000

	274.	302.	329.	357.	384.
X	-----				
.000	100.	100.	100.	100.	.000
10.7	.140E-42	.140E-42	.140E-42	.140E-42	.000
21.3	.000	.000	.000	.000	.000
32.0	.000	.000	.000	.000	.000
42.7	.000	.000	.000	.000	.000
53.3	.000	.000	.000	.000	.000
64.0	.000	.000	.000	.000	.000
74.7	.000	.000	.000	.000	.000
85.3	.000	.000	.000	.000	.000
96.0	.000	.000	.000	.000	.000
107.	.000	.000	.000	.000	.000
117.	.000	.000	.000	.000	.000
128.	.000	.000	.000	.000	.000
139.	.000	.000	.000	.000	.000
149.	.000	.000	.000	.000	.000

Figure 38. State of North Carolina Groundwater
Advisory System, Output File (Cont.)

YEAR 2007

Time = 18263. days
RETARDATION COEF: 600.00

CONCENTRATION RESULTS

X	Y AXIS (PERPENDICULAR TO FLOW) (meters)				
	.000	27.4	54.9	82.3	110.
.000	100.	100.	100.	100.	100.
10.7	.298E-14	.298E-14	.298E-14	.298E-14	.298E-14
21.3	.000	.000	.000	.000	.000
32.0	.000	.000	.000	.000	.000
42.7	.000	.000	.000	.000	.000
53.3	.000	.000	.000	.000	.000
64.0	.000	.000	.000	.000	.000
74.7	.000	.000	.000	.000	.000
85.3	.000	.000	.000	.000	.000
96.0	.000	.000	.000	.000	.000
107.	.000	.000	.000	.000	.000
117.	.000	.000	.000	.000	.000
128.	.000	.000	.000	.000	.000
139.	.000	.000	.000	.000	.000
149.	.000	.000	.000	.000	.000

X	Y AXIS (PERPENDICULAR TO FLOW) (meters)				
	137.	165.	192.	219.	247.
.000	100.	100.	100.	100.	100.
10.7	.298E-14	.298E-14	.298E-14	.298E-14	.298E-14
21.3	.000	.000	.000	.000	.000
32.0	.000	.000	.000	.000	.000
42.7	.000	.000	.000	.000	.000
53.3	.000	.000	.000	.000	.000
64.0	.000	.000	.000	.000	.000
74.7	.000	.000	.000	.000	.000
85.3	.000	.000	.000	.000	.000
96.0	.000	.000	.000	.000	.000
107.	.000	.000	.000	.000	.000
117.	.000	.000	.000	.000	.000
128.	.000	.000	.000	.000	.000
139.	.000	.000	.000	.000	.000
149.	.000	.000	.000	.000	.000

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Figure 38. State of North Carolina Groundwater
Advisory System, Output File (Cont.)

	274.	302.	329.	357.	384.
X	-----				
.000	100.	100.	100.	100.	.000
10.7	.298E-14	.298E-14	.298E-14	.298E-14	.000
21.3	.000	.000	.000	.000	.000
32.0	.000	.000	.000	.000	.000
42.7	.000	.000	.000	.000	.000
53.3	.000	.000	.000	.000	.000
64.0	.000	.000	.000	.000	.000
74.7	.000	.000	.000	.000	.000
85.3	.000	.000	.000	.000	.000
96.0	.000	.000	.000	.000	.000
107.	.000	.000	.000	.000	.000
117.	.000	.000	.000	.000	.000
128.	.000	.000	.000	.000	.000
139.	.000	.000	.000	.000	.000
149.	.000	.000	.000	.000	.000

YEAR 2037

Time = 29200. days
 SOURCE CONC.: 100.00 %
 LONG. DISPERSIVITY: .86400E-02 (m²/d)
 TRANS. DISPERSIVITY: .86400E-03 (m²/d)
 X VELOCITY: .15033 (m/day)
 RETARDATION COEF: 200.00

CONCENTRATION RESULTS

	Y AXIS (PERPENDICULAR TO FLOW) (meters)				
	.000	27.4	54.9	82.3	110.
X	-----				
.000	100.	100.	100.	100.	100.
10.7	100.	100.	100.	100.	100.
21.3	66.4	66.4	66.4	66.4	66.4
32.0	.129E-07	.129E-07	.129E-07	.129E-07	.129E-07
42.7	.116E-36	.116E-36	.116E-36	.116E-36	.116E-36
53.3	.000	.000	.000	.000	.000
64.0	.000	.000	.000	.000	.000
74.7	.000	.000	.000	.000	.000
85.3	.000	.000	.000	.000	.000
96.0	.000	.000	.000	.000	.000
107.	.000	.000	.000	.000	.000
117.	.000	.000	.000	.000	.000
128.	.000	.000	.000	.000	.000
139.	.000	.000	.000	.000	.000
149.	.000	.000	.000	.000	.000

Figure 38. State of North Carolina Groundwater
Advisory System, Output File (Cont.)

	137.	165.	192.	219.	247.
X					
.000	100.	100.	100.	100.	100.
10.7	100.	100.	100.	100.	100.
21.3	66.4	66.4	66.4	66.4	66.4
32.0	.129E-07	.129E-07	.129E-07	.129E-07	.129E-07
42.7	.116E-36	.116E-36	.116E-36	.116E-36	.116E-36
53.3	.000	.000	.000	.000	.000
64.0	.000	.000	.000	.000	.000
74.7	.000	.000	.000	.000	.000
85.3	.000	.000	.000	.000	.000
96.0	.000	.000	.000	.000	.000
107.	.000	.000	.000	.000	.000
117.	.000	.000	.000	.000	.000
128.	.000	.000	.000	.000	.000
139.	.000	.000	.000	.000	.000
149.	.000	.000	.000	.000	.000

	274.	302.	329.	357.	384.
X					
.000	100.	100.	100.	100.	.000
10.7	100.	100.	100.	100.	.345E-13
21.3	66.4	66.4	66.4	66.4	.154E-07
32.0	.129E-07	.129E-07	.129E-07	.129E-07	.646E-17
42.7	.116E-36	.116E-36	.116E-36	.116E-36	.000
53.3	.000	.000	.000	.000	.000
64.0	.000	.000	.000	.000	.000
74.7	.000	.000	.000	.000	.000
85.3	.000	.000	.000	.000	.000
96.0	.000	.000	.000	.000	.000
107.	.000	.000	.000	.000	.000
117.	.000	.000	.000	.000	.000
128.	.000	.000	.000	.000	.000
139.	.000	.000	.000	.000	.000
149.	.000	.000	.000	.000	.000

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Iron and Manganese

Analysis of the impact on iron and manganese concentrations requires somewhat different assumptions. This is primarily due to the fact that these are among the dominant metal ions in the native saprolite. Further, these two metals are found in large quantities in the ash, and these are the only constituents for which violations of the groundwater standards were noted beneath Plant Allen.

Because the saprolite may contain large concentrations of iron and manganese (depending on the parent material), it is to be expected that the residual capacity to adsorb these ions may be reduced. The data available on adsorption rates are not conclusive, largely dealing with artificial substrates, but measured rate constants suggest that the marginal rate of adsorption for these metals may be rather low at the higher observed concentrations beneath Plant Allen (EPRI, 1986). Instead, the dominant factors controlling concentrations of these metals are likely precipitation/ dissolution reactions. For instance, metastable ferrosic hydroxide [$\text{Fe}_3(\text{OH})_8$] will control maximum iron concentrations under most redox conditions. Similarly, MnCO_3 (rhodochrosite) and various Mn oxides are suspected to control solubility of manganese, although the data are less conclusive here. It is suspected that a substantial proportion of both the Mn and Fe which enters the groundwater system will be immobilized by precipitation reactions, thus reducing the concentrations away from the site.

For a conservative analysis, it may be assumed that a substantial proportion of the manganese and iron which reaches the groundwater will be transported with the groundwater, with little retardation of apparent velocity.

The Riverbend site has been in operation for 30 years. If

little retardation occurs, and precipitation of the metals is not considered, flow rates are such that it must then be assumed that these metals will be present along the groundwater flowlines between the site and the river at essentially the same concentrations as beneath the site. (However, we should emphasize that we suspect that concentrations will actually be reduced by precipitation reactions).

6.2 Potential Groundwater Contribution of Contaminants to Catawba River/Mountain Island Lake

The analysis presented in Section 6.1 suggests that the only metal contaminants likely to be of concern downgradient from the site will be iron and manganese. This contention is supported by surface water quality monitoring downstream from the site (Duke Power station 277, USGS/EPA station Thrift, No. 02142808), which does not show violation of standards for the trace metals. A few violations of iron standards have been noted downstream. However, iron is ubiquitous in the region, and it is of interest to note that iron concentrations are on average higher upstream from the site.

In any case, it is instructive to consider the potential contribution of these metals due to groundwater flow from the ash basin to the river, given no attenuation. The rate of flow from the ash basin to the river is estimated at about 5.85×10^4 ft³/day. In comparison, the river flow is estimated to average 2.476×10^8 ft³/day : a 1/4200 dilution factor.

The highest concentrations observed in the groundwater beneath the Plant Allen basin are:

Fe	25.9 mg/l
Mn	14.0 mg/l

From the analysis presented earlier, dilution on reaching the river will be about 1/400. For both metals, this dilution would be

sufficient to reduce the metal concentrations well below the surface water standards. It should further be noted that the bottom waters in the river adjacent to the site are generally not anoxic, and thus further precipitation of these metals should be expected when groundwater enters the river.

6.3 Comparison of Groundwater and Surface Contributions

The average surface discharge is $6.13 \times 10^5 \text{ ft}^3/\text{day}$, an order of magnitude greater than the estimated groundwater flow from the basin. The relative contribution of the groundwater will depend on the degree to which contaminants are attenuated before reaching the river. For the worst case scenario with iron, no attenuation, the relative contributions would be:

Surface:	$4.10 \times 10^6 \text{ mg/day}$
Groundwater:	$4.29 \times 10^7 \text{ mg/day}$

Thus the groundwater contribution of iron could range up to 10 times the surface contribution, but this is likely an overestimation. The 1:400 dilution upon reaching the river and flowing down to the Charlotte water intake would still result in concentrations below the permitted surface discharge.

By comparison, the worst case scenario for arsenic, with no adsorption or precipitation, gives the following contributions:

Surface:	$2.06 \times 10^6 \text{ }^{\mu}\text{g/day}$
Groundwater:	$2.65 \times 10^6 \text{ }^{\mu}\text{g/day}$

Thus for arsenic the maximum potential contribution of the groundwater would be close to the average surface contribution. Further, the sum of these contributions would still be considerably less than the permitted surface discharge. It is

even more likely that the groundwater contribution of arsenic will be undetectable.

6.4 CONCLUSION

It appears highly unlikely that any subsurface or surface-water quality problems exist as a result of the ash pond as demonstrated by the absence of a detectable increase in any metals downstream from the Riverbend Plant. Relative to the effect of ash-pond effluent on the quality of the Catawba River, analysis of streamflow records past the Riverbend Plant indicates that the average flow of the river is about 400 times the rate of surface outflow from the pond and about 370 times the combined surface and groundwater rate. Although the velocity of the Catawba River is relatively slow past the Riverbend site, modeling using conservative mixing coefficients suggests that complete transverse mixing of the pond effluent occurs within about three miles of the ash pond. Due to the small concentration of metals in the surface outflow from the pond, and the large dilution factor, metals contained in the effluent do not cause a detectable increase in concentration once complete mixing has occurred.

The effect of groundwater seepage on stream quality was determined by modeling the flow through the groundwater system using a retardation factor only 1/3 of the value estimated at the Allen Plant. Results indicate that no measurable concentration of the metals that are subject to ion exchange and other delaying reaction will reach the Catawba within the next 50 years (by 2037).

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Appendix I. Source Code Listing for Model SSCLS,
Steady-State Continuous Line Source

```

      PROGRAM SSCLS
C.....Steady State Continuous Line Source
C... Boundary Source (Soln X 2):
C...
C...       $q' \exp(XU/2Ex)$ 
C...       $C = \frac{q' \exp(XU/2Ex)}{\pi \delta \sqrt{ExEy}} \quad KO(2\beta)$ 
C...
C.....
C... Dr. M. A. Medina , Duke University
C.....
      REAL*8 KO,IO
      REAL*4 K,XAXIS(51),YAXIS(51)
      REAL XC,YC
      CHARACTER*7 FMT
      CHARACTER*1 TITLE(75)
      INTEGER*4 SIZE, INTARY(4000)
      CHARACTER*30 LABL,LABLY,LABLX
      CHARACTER*6 NAMEL
      CHARACTER*1 NUL,ESC,BEL
      COMMON LABL,LABLY,LABLX,NAMEL,XC,YC
      COMMON /GRACOM/ SIZE, INTARY

      CALL FILES(IN)
      CALL FILES(IOUT)

      FMT = '(/1X,A)'
      RHO = 1.94
      PI = 4. * ATAN(1.)
      SIZE = 4000

      WRITE(*,FMT) 'TITLE : '
      READ(IN,1) TITLE
1  FORMAT(75A1)
      WRITE(IOUT,3) TITLE
3  FORMAT(//5X,75A1)
      WRITE(*,3) TITLE
      WRITE(*,FMT) 'U,X,Y,K,Ex,Ey : '
      WRITE(*,FMT)
      . '1.....2.....3.....4.....5.....6.....| '
      READ(IN,5) U,X,Y,K,Ex,Ey
5  FORMAT(3F10.0,E10.0,2F10.0)
      WRITE(*,111) U,X,Y,K,Ex,Ey
111 FORMAT(3F10.2,E10.2,2F10.2)
      WRITE(*,FMT) 'Havg,Qavg,Cavg,Qriv : '
      WRITE(*,FMT)
      . '1.....2.....3.....4.....| '
      READ(IN,7) Havg,Qavg,Cavg,Qriv
7  FORMAT(4F10.0)
      WRITE(*,113) Havg,Qavg,Cavg,Qriv
113 FORMAT(4F10.2)

```

XX=X/5280.

C.... Dilution Ratio at Source

DR0 = Cavg / ((Qavg * Cavg)/(Qavg + Qriv))

WRITE(IOUT,11) DR0

11 FORMAT(/5X,'DILUTION RATIO BELOW SOURCE '/
 . 5X,'FOR PRISTINE RIVER '=',F15.6)

BETA2 = SQRT((Ey*X*X + Ex*Y*Y)*(U*U*Ey + 4.*Ex*Ey*K))

BETA2 = BETA2/(4.*Ex*Ey)

C... Dilution Ratio Downstream End ... C/Cavg

q = RHO * Cavg * Qavg

CC0 = EXP(X*U / (2.* Ex)) * K0(2.* BETA2) * (q / Havg)

CC0 = CC0 / (PI * RHO * SQRT(Ex * Ey)) / Cavg

DR = 1./CC0

WRITE(IOUT,13) XX,CC0,DR

13 FORMAT(/5X,'Concentration Ratio At ',F5.1,' MILES =',F11.6/
 . /5X,'Dilution Ratio At Same Distance = 1 TO',F15.6/)

C... CONCENTRATION PROFILE ...

WRITE(*,FMT) 'Computing Profile ...'

DX = X / 50.

X = 0.

DO 50 I=1,51

IF (X.EQ.0.) THEN

IF (Y.EQ.0.) CXY = Cavg / DR0

IF (Y.GT.0.) CXY = 0.

ELSE

BETA2 = SQRT((Ey*X*X + Ex*Y*Y)*(U*U*Ey + 4.*Ex*Ey*K))

BETA2 = BETA2/(4.*Ex*Ey)

CXY = EXP(X*U / (2.* Ex)) * K0(2.* BETA2) * (q / Havg)

CXY = CXY / (PI * RHO * SQRT(Ex * Ey))

ENDIF

XAXIS(I) = X / 5280.

YAXIS(I) = CXY * 1000.

WRITE(IOUT,51) XAXIS(I),CXY

X = X + DX

50 CONTINUE

51 FORMAT(10X,'DISTANCE =',F10.4,' MILES',2X,'CONC. =',F10.6)

CLOSE(IN)

CLOSE(IOUT)

WRITE(*,FMT) 'Closing Input,Output Files ...'

WRITE(*,FMT) 'ENTER TITLE ... A30 :'

READ(*,91) LABL

91 FORMAT(A)

WRITE(*,FMT) 'ENTER Y-AXIS LABEL ... A30 :'

READ(*,91) LABLY

```

WRITE(*,FMT) 'ENTER X-AXIS LABEL ... A30 :'
READ(*,91) LABLX
WRITE(*,FMT) 'ENTER LEGEND LABEL ... A6 :'
READ(*,91) NAMEL
WRITE(*,FMT) 'ENTER LEGEND X,Y COORD. (%) ...:'
WRITE(*,FMT) '1....2....'
READ(*,93) XC,YC
WRITE(*,FMT) 'ENTER MIXING DISTANCE, MILES ... XL,XR :'
WRITE(*,FMT) '1....2....'
READ(*,93) XL,XR
93 FORMAT(2F5.0)
WRITE(*,FMT) 'Plotting ...'

CALL PLOTS(XAXIS,YAXIS,51,XL,XR)

```

```

C-----
C   RESET MODE TO 80x25
C-----
      NUL = CHAR(0)
      ESC = CHAR(27)
      BEL = CHAR(7)
      READ(*,*)
      WRITE(*,19) NUL,ESC,BEL
19 FORMAT(2A1,['=3h',A1)
C-----

```

```

STOP
END

```

```

REAL*8 FUNCTION KO(X)
C.... Modified Bessel Function of Order Zero, Second Kind
C.... Polynomial Approximation
C.... Ref.: Abramowitz and Stegun, p. 379.
REAL*8 IO
IF (X.GT.0. .AND. X.LE.2.) THEN
  X2 = X/2.
  KO = - ALOG(X2) * IO(X) - 0.57721566
  KO = KO + 0.42278420 * X2 ** 2 + 0.23069756 * X2 ** 4
  KO = KO + 0.03488590 * X2 ** 6 + 0.00262698 * X2 ** 8
  KO = KO + 0.00010750 * X2 ** 10
  KO = KO + 0.00000740 * X2 ** 12
  RETURN
ENDIF
  XX2 = 2. / X
  KO = 1.25331414 - 0.07832358 * XX2 + 0.02189568 * XX2 ** 2
  KO = KO - 0.01062446 * XX2 ** 3 + 0.00587872 * XX2 ** 4
  KO = KO - 0.00251540 * XX2 ** 5 + 0.00053208 * XX2 ** 6
  KO = KO / SQRT(X) / EXP(X)
RETURN
END

```

```

      REAL*8 FUNCTION IO(X)
C.... Modified Bessel Function of Order Zero, First Kind
C.... Polynomial Approximation
C.... Ref: Abramowitz and Stegun, p. 378
      T = X/3.75
      IF (X.GE.(-3.75) .OR. X.LT.3.75) THEN
        IO = 1. + 3.5156229 * T * T + 3.0899424 * T ** 4
        IO = IO + 1.2067492 * T ** 6 + 0.2659732 * T ** 8
        IO = IO + 0.0360768 * T ** 10 + 0.0045813 * T ** 12
        RETURN
      ENDIF
      IO = 0.39894228 + 0.01328592 / T + 0.00225319 / T ** 2
      IO = IO - 0.00157565 / T ** 3 + 0.00916281 / T ** 4
      IO = IO - 0.02057706 / T ** 5 + 0.02635537 / T ** 6
      IO = IO - 0.01647633 / T ** 7 + 0.00392377 / T ** 8
      IO = IO / SQRT(X) * EXP(X)
      RETURN
      END

```

```

      SUBROUTINE FILES(IO)
C.....
C..... TO OPEN FILE FILIO AS I/O FILE IO .....
C.....
      CHARACTER*20 FILIO,NAME*3
      WRITE(*,'(//A\)' ) ' ENTER NAME OF I/O FILE : '
      READ (*,'(A\)' ) FILIO
      WRITE(*,'(A\)' ) ' ENTER I/O FILE UNIT NUMBER (I2) : '
      READ (*,'(BN,I2\)' ) IO
      WRITE(*,'(A,I2\)' ) ' FORMATTED I/O FILE UNIT NUMBER = ',IO
      WRITE(*,'(A\)' ) ' ENTER FILE STATUS (1=NEW,0=OLD) : '
      READ (*,'(BN,I1\)' ) IS
      IF(IS.EQ.1) THEN
        OPEN (IO,FILE=FILIO,STATUS='NEW')
        NAME = 'NEW'
        WRITE(*,11) FILIO,NAME
      ENDIF
      IF(IS.EQ.0) THEN
        OPEN (IO,FILE=FILIO,STATUS='OLD')
        NAME = 'OLD'
        WRITE(*,11) FILIO,NAME
      ENDIF
11 FORMAT(1X,'FILE ==> ',A,' IS ',A)
      RETURN
      END

```

SUBROUTINE PLOTS(X,Y,N,XL,XR)

implicit integer*2 (a-z)

integer*2 status

REAL X(N),Y(N),XL,XR,XC,YC

REAL XD(2),YD(2)

CHARACTER*1 TITL1(30),TITLY(30),TITLX(30),NAME(6)

COMMON TITL1,TITLY,TITLX,NAME,XC,YC

C Dummy curve to fill-in bottom area.

XD(1)=XL

XD(2)=XR

YD(1)=0.0

YD(2)=0.0

C PLOT: Open Plotting System

status = popnps()

C PLOT: Assign Plotting System Output Device

status = ppsots(7,'DISPLAY')

C Define TWO data sets (dummy = 2)

C PLOT: Define X/Y data set.

status = pdsxy(1,N,X,Y)

status = pdsxy(2,2,XD,YD)

C Define all data sets to be line charts.

C PLOT: Define data set chart type to be line.

DO 100 i=1,2

status = pline(i)

100 CONTINUE

C-----PLOT: Set existence and location of legend.

status = plloc(1,1,XC,YC)

C Set legend alignment

status = plalin(2,2)

C Set legend font (Complex Roman Font).

status = pltfnt(102)

C Set legend height.

status = plthgt(2)

C Name data set for legend.

status = pdsnms(1,6,NAME)

C-----
C Set to fill region between data sets 1 and 2 (dummy).

C PLOT: Fill between two data sets.

status = pdspar(2,1)

C Set the color of the dummy to be color index 4.

```
C      PLOT: Set output primitive color for data set.
      status = pdsclr(2,4)

C      PLOT: Set output primitive style for data set.
C      status = pdsstl(2,5)

C      PLOT: Set visibility of data set (hide dummy).
      status = pdsvis(2,0)

C      Set color index 4 to be blue-green (75%,25%).
C      PLOT: Set color representation.
      status = pscrep(4,0.0,25.0,75.0)

C      PLOT: Define axis title string.
      status = ptaxs(1,30,TITLX)
      status = ptaxs(2,30,TITLY)

C      PLOT: Define title string.
      status = pthds(30,TITL1)

C      PLOT: Output the currently defined chart.
C      THIS DRAWS THE CHART.
      status = ppltit()
C-----
C      PLOT: Close output device.
      status = pclios(7,'DISPLAY')

C      PLOT: Close plotting system.
      status = pclsps()

      RETURN
      END
```