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**water resources  
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WASHINGTON, DISTRICT OF COLUMBIA

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**GROUNDWATER  
PROBLEMS IN THE  
MID-ATLANTIC  
FALL LINE  
CITIES**

**By**

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**September 1984**

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The D.C. Water Resources Research Center

The University of the District of Columbia

Washington, D.C.

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## I. ABSTRACT

In recent years, researchers and managers in the North Eastern U.S. have focused most of their efforts on groundwater problems such as contamination and overdraft. However, little attention has been given to the groundwater regime of the major cities of the Fall Zone. The Fall Zone is a dividing zone between the Piedmont province and the Atlantic Coastal Plain province in the East Coast of the United States. The Fall Zone extends from New York to Georgia. The cities that lie along the Fall Zone are referred to as fall line cities (e.g., Philadelphia, Wilmington, Baltimore, Washington, and Richmond).

There are a number of problems related to groundwater underlying urban areas. These are related to construction, tunneling, and the history of land use activities.

What makes the study of such a problem more difficult is the fact that the ecological and economic impacts of these land uses are compounded with the geologic complexity of the Fall Zone. To study the groundwater along the fall line requires an understanding of groundwater flow behavior in three systems: the crystalline rock products of the Piedmont, the consolidated-unconsolidated sedimentary units of the Coastal plain, and the Urban cover itself. Urban cover meaning all the man-made or man imposed cover on top of the natural soil and bedrock.

Furthermore, most of the groundwater data that exists for the fall line cities concerns pre-urban development. In 1965, as a result of urban sprawl, and renewal of the core cities by high rise construction, tunneling and a host of other excavation and paving activities, the groundwater picture of the fall line cities became significantly modified.

The purpose of this project is to develop an understanding of the groundwater situation of the fall line cities. The project examines groundwater quantity and quality of these cities. The impact of urbanization as well as institutional problems related to groundwater is discussed. Special emphasis was placed on the study of the District of Columbia's groundwater problems as they relate to construction, tunneling, and other urban activities.

## II. STATEMENT OF PURPOSE

Until surface water supply becomes critical, research on, and development of groundwater for drinking and industrial uses for the fall line cities will be limited. Additionally, conjunctive use of surface and groundwater resources for these cities is not seen as forthcoming in the rear future. However, as the cities continue to develop, and attempts are made to attract more industries and businesses, significant impacts resulting from construction, tunneling, and other activities would be made on the groundwater. The subsequent ecological and

economic impacts would force urban planners and decision makers to critically assess the situation of the groundwater underlying these cities.

In light of the remarks mentioned above, groundwater problems may be divided into two major categories; these being the problems associated with the natural system, and those associated with human activities. The natural system involves climatology and regional geology of the city, while the human activities include historical inheritance, land use changes, construction dilemmas, man-made contamination, and legal aspects. Table 1 provides these categorical divisions. It is therefore essential to understand the complex mechanisms involved with the groundwater of these cities and the interaction between the natural and the man made systems.

The purpose of this study is to evaluate the interaction between the groundwater and urbanization. The specific objectives are to: 1) increase the understanding of the history and the sciences of the local groundwater regime under the cities; 2) gather information on groundwater charges with urbanization; 3) evaluate recent urban activities and their impact on the groundwater situation.

Table 1: GROUNDWATER PROBLEMS IN THE FALL LINE CITIES

I. Historical Inheritance

- dredge and fill material behavior
- springs and wells
- subsidence
- buried land forms
- salt intrusion of natural waters
- cemeteries

II. Land Use Changes

- infiltration rates and % imperviousness
- % urbanization vs. open space
- mineral resource operations (flooded quarries or pits)
- lost recharge area
- groundwater basins

III. Construction Dilemmas

- dewatering - add watering
- water in-fill (bath tub effect)
- flow direction change
- floating pressure (cement mattress)
- blasting and fractures
- porous pavements
- buildup of carbonates
- injection wells - well drilling

IV. Types of Man-Made Contamination

- leaks from water supply pipes
- sewer pipes
- storage tanks (gasoline, etc.)
- sanitary landfill leachates
- injection of waste (industrial or agri or domestic)
- infiltration and/or percolation of insecticides, fertilizers, pesticides or herbicides, etc. (domestic vs. agri)
- high and low levels of radioactive waste toxic waste, hazardous waste
- acid waters
- septic tanks and other bacterial organisms-disease and health
- street de-icing

V. Legal Aspects

- permits and well documentation by state, federal, etc.
- amounts and levels (cone of depression)
- change of quality
- interstate*, interbasin, groundwater basins

VI. Climatic Fact

- wet-dry conditions (ordinary to extremes)
- change of state (freezing-thawing)
- seasonal water table
- gravity-transfer (slides, slumps, creep)
- pipe failure (frozen ground)

VII. Regional Geology

- natural chemistry
- fracture systems
- aquifer-aquitards units
- soils and saprolite (cut clays)

### III. DISCUSSION SIGN AND METHODS

#### 3.1 Background Information

A number of studies have been conducted for groundwater assessment of fall line cities in the eastern United States. These studies were commissioned by historical events related to climate, or zoning and planning problems. It is remarkable that most of these studies were conducted before the urban renewal programs created under President Johnson's "Great Society." Table 2 shows the chronology of events.

Public health and diseases carried enough weight to bring about the first in-depth analysis of the Mid-Atlantic subterranean water supply. Each city in the study zone was assessed in 1896 (N. H. Darton). This was a detailed study of the chemistry and hydrogeology of the fall line cities from Philadelphia to Richmond (Dayton 1896 and 1904).

The drought conditions of the early 1930's put immense pressure on East Coast well systems. Most shallow wells went dry and many small towns or cities switched to deeper wells or surface supplies. Correlation of well water levels to precipitation provided the basis for scientific research of that period. These conditions led to early groundwater forecasting studies conducted by Cady (1933), Hoyt (1936), and Meinzer (1944).

The Baltimore Industrial Survey (Geyer, 1946) was another major breakthrough in organizing groundwater records, standardizing the city record system, and obtaining the complete coopera-

Table 2: CHRONOLOGY OF GROUNDWATER STUDIES

1890's	Public Industrial Supply, Health and Disease (N.H. Darton logged the chemistry and geology of numerous fall line wells)
1930's	Drought Conditions of the East Coast
1940's	Baltimore Industrial Survey
1950's	Housing after WW II - state planning and zoning reports
1965	Urban Renewal and Water in the Urban Environment - resource and hazard reports
1960	Environmental Movement and Clean and Safe Water Acts
1970's	Clean-up Programs and Transit Programs, Role of Contamination and Construction Impacts
1980's	Groundwater Basin Science Reports and Regulations

tion of the private sector to assess, monitor, and manage the local groundwater.

State planning and zoning initiatives required the knowledge of the local groundwater base and potential for supply reserves. Most states called on cooperative agreements with the local U.S.G.S. water office to undertake and assess the water potential. The bulk of these reports were published in the early sixties with fieldwork in the late fifties. Reports were prepared either on a county or a city basis (Otton, 1964; O'Bryan, 1966; Dingman, 1954; and Rasmussen, 1957). While most of these reports are available and contain large amounts of data, they do not reflect the current state of urbanization and have become therefore historical logs of what was before 1965.

The mid-sixties mark the era of urban renewal and the movement to revitalize decaying core cities. The U.S.G.S. undertook the "Urban Area Study. Project" to supply data on city environments in different climate zones. The Baltimore/Washington Corridor was one of the few urban areas selected for this detailed study. Numerous reports, maps and information resulted from the project (Froelich, USGS Cir. 806).

On the national scene, the U.S. Geological Survey published a comprehensive series of publications called "Water in the Urban Environment Series" (Circular 601 A-L). A few of these excellent booklets dealt with groundwater in the cities (Circular 601 E,H,I).

The late sixties and seventies ushered in the numerous federal laws associated with the "Clean Water Act". For example, the U.S. Water Resources Council conducted an assessment of the groundwater in the country (Mack, 1971). A variety of ground water regions were outlined based on major river basins. The Mid-Atlantic groundwater region was reviewed in USGS P.P #813-I (1978). However, more recently the groundwater regions were reclassified by geologic characteristics and another regional system based on geomorphic provinces was published in USGS Water Supply Paper 2242 (1983).

Public concerns about quality of groundwater led to the U.S. Environmental Protection Agency's (EPA) involvement. Many good studies now exist on the reassessment of the local, county, or city sanitary landfills (Otton, 1972). The most recent studies deal with computer models for aquifers (USGS Cir 737). Numerous reports are available for certain aquifers. Currently the USGS is investigating the Atlantic Coastal Plain aquifers as part of the national "Regional Aquifer Study" program to assess and model regional aquifers (Harsh, 1983).

At the local level, T.V. studies for the District of Columbia Blue Plains Treatment Plant have yielded data on pipe and on water leaks, flow volumes into and out of the system, all the fall line table for pipe laying. General construction in cities provides information on depth, configuration of bedrock,

and dewatering. Engineering reports such as the reports for the D.C. Metro Subway (Mueser and Rutledge, 1967, 1969) contain initial scientific data as well as data on all the individual building projects.

Background information and engineering reports on urban construction projects, for this study, were not easy to find. It was essential to cover a broad range of sources to be able to obtain significant results. Furthermore, most of the old publications pertaining to this study were out of print or not available for distribution. The city or government libraries did not have many of the reports or articles one would expect for this project. Therefore, the literature survey covered a broad range of activities: review of county and city reports; engineering construction reports; field conference guides, measurement techniques and models, text books and other technical references.

However, direct contacts and interviews with specialized agencies and individuals provided more pertinent information than the literature itself, because most of the information was neither centralized nor incorporated in the reports. The investigators were able to identify a number of problems from these individuals. A list of sources of information is provided in Table 3.

Table 3: SOURCES OF INFORMATION

1. National Park Service - National Capital Region - Ecology Services Labs
2. Schnabel Engineering Associates - Bethesda, Maryland
3. Geraghty and Miller, Inc. - Annapolis, Maryland
4. Woodward - Clyde Consultants - Rockville, Maryland
5. Otton and Associates - Towson, Maryland
6. S. S. Papadopoulos and Associates, Inc. - Rockville, Maryland
7. Dames and Moore, Ltd. - Bethesda, Maryland
8. U.S.G.S. Northeast Water Research Section - Reston, Virginia
9. Cather De Leuw (Metro Subway)
10. Metro - Engineering Office - Washington, D.C.
11. Bryant and Bryant, Architects - Washington, D.C.
12. U.S. Geological Survey - Virginia State Office - Richmond, Virginia
13. U.S. Geological Survey - Maryland-Delaware-D.C. - Towson, Maryland
14. State Geological Surveys - Maryland Geological Survey - Baltimore, Maryland
15. State Geological Surveys - Delaware Geological Survey - Newark
16. State Geological Surveys - District (Dept. of Environmental Science-UDC)
17. State Geological Surveys - Virginia Department of Mineral Resources (Charlottesville)
18. State Geological Surveys - New Jersey ( Dept. of Environmental Protection)
19. State Geological Surveys - Pa. Bureau of Topography and Geological Survey
20. State Water Resources Research Center - Virginia - VPI (Blacks<sup>b</sup>burg)
21. State Water Resources Research Center - D.C. - UDC (Van Ness)
22. State Water Resources Research Center - Md. - Univ. of Md. at College Park
23. State Water Resources Research Center - Pa. - Pennsylvania State University (Harrisburg)
24. State Water Resources Research Center - Delaware - University of Delaware
25. State Water Resources Research Center - New Jersey - Rutgers University (Trenton)
26. USDA - Soil Conservation Service: College Park
27. Virginia State Water Control Board (Alexandria) (Richmond)
28. Maryland Department of Natural Resources (Annapolis)
29. Delaware Department of Environmental Protection (Wilmington)
30. General Services Administration - Federal (D.C.)
31. D.C. Department of Public Works (formerly DES)
32. D.C. Department of Consumer and Regulatory Affairs (D.C.)
33. U.S. Environmental Protection Agency - regional offices - Philadelphia
34. National Zoological Park Construction Manager
35. National Park Service - Rock Creek Park Environmental Manager

### 3.2 Urbanization

Native Americans plying the Chesapeake and Delaware tidewaters were the first to recognize and utilize the economic benefits of this scenic zone as they established settlements or camps at the base of the falls along the East Coast.

Numerous Indian camps, established at the end of tidewater on each major river (Potomac, Susquehanna, James) were the seeds from which sprang the major seaports of early colonial time (1600-1800). Just as the dugout canoes could not traverse the falls, the European sailing vessels were stopped by the protruding Piedmont rocks. The road to navigation gave way to the embryo of urbanization; as for example Tohoga became Georgetown. Many other native American settlements turned into commercial dock cities like Baltimore's Inner Harbor and Fells Point. The history of the development of some cities, i.e., Baltimore and Washington, and the downfall of other cities, i.e., Laurel and Savage along the Fall Zone, is a fascinating subject in itself, but outside the scope of this report.

The urbanscape of each major city in the study area is a complex mesh of four hundred years of social history plunked and cemented to 500 million years of dynamic geologic history.

The new wave of urban awareness since 1965 has resulted in socioeconomic aspects, which have direct impact on the groundwater. They are:

- trends in population growth;

- size and extent of urban sprawl;
- need for economic revival;
- urban transportation revitalization;
- high-rise construction; and
- expansion of public services.

Urbanization may be described in many ways as creeping of the core city outwards, as putting more and more people in less and less space, or as 'creating an asphalt and concrete jungle. Whatever the definition, the urbanization process changing from slab foundation to high-rise construction involves vast amounts of ground disturbances.

The roots of urban survival, namely the utility pipelines, are underground. To that are added other urban segments, such as road fill and roadbeds, root systems, dumps, granite curbs, storage tanks, cut and fill buried valleys, reclaimed or filled mining areas. Urbanization, then, is an evolution of a constantly changing subterranean ecology of covering and uncovering. *H. E. Thomas* in 1951 pointed out the initial problems of construction and groundwater, using New York City, Philadelphia and Baltimore as examples, where recharge areas were covered and aquifer storage lost. Currently the new FBI building in D.C. is a good urban groundwater impact example where ancient springs were reactivated when the century-old fill was removed for deep basement garage construction.

The best understanding of what happens to the hydrologic systems in general when urban growth takes place is summarized in USGS Water Supply Paper 1591-A (1962).

Table 4 relates the general cause and effect of land use changes. It must be emphasized that there is great concern over loss of groundwater, especially through loss of recharge areas, but equal concern has to be given to artificial recharge through urban means such as domestic irrigation (lawn watering), downspouts, and broken pipe infiltration.

Urbanization impacts the groundwater sources both quantitatively and qualitatively. A host of urban activities can significantly alter the groundwater levels. The construction industry uses the sewer systems for dewatering discharges. The sewer pipelines made of bricks or tiles can sometimes be damaged by excessive quantities of water. In cities where a combined sewer system exists, such as Washington, D.C., the discharges may further reduce the sewer capacity or compete with the sanitary sewer during high flows. The dewatering flow in this case becomes an added cost to the treatment plant. In addition, the dewatered discharges contain sediment, which might be deposited in the sewer system.

Suspended solids may also be added to the water in the sewers. Dewatering discharges sometimes contain obnoxious substances which can be a nuisance or harmful to the environment. Additionally, the acidity of these discharges has a serious impact on the ground structures and on

Table 4. Hydrologic effects of urban growth (Source: USGS WSP #1591-A).

Changes in land or water use	Possible hydrologic effect
<p>Transition from pre-urban to early urban stage:                      Removal of trees or vegetation ---                      Construction of scattered city-type houses and limited water and sewage facilities.                      Drilling of wells -----                      Construction of septic tanks and sanitary drains.</p>	<p>Decrease in transpiration and increase in storm flow. Increased sedimentation of streams.                       Some lowering of water table.                      Some increase in soil moisture and perhaps a rise in water table. Perhaps some waterlogging of land and contamination of nearby wells or streams from overloaded sanitary drain system.</p>
<p>Transition from early-urban to middle-urban stage:                      Bulldozing of land for mass housing, some topsoil removed, farm ponds filled in.                       Mass construction of houses, paving of streets, building of culverts.                        Discontinued use and abandonment of some shallow wells.                      Diversion of nearby streams for public water supply.                      Untreated or inadequately treated sewage discharged into streams or disposal wells.</p>	<p>Accelerated land erosion and stream sedimentation and aggradation. Increased flood flows. Elimination of smallest streams.                      Decreased infiltration, resulting in increased flood flows and lowered ground-water levels. Occasional flooding at channel constrictions (culverts) on remaining small streams. Occasional over-topping or undermining of banks of artificial channels on small streams.                      Rise in water table.                       Decrease in runoff between points of diversion and disposal.                      Pollution of stream or wells. Death of fish and other aquatic life. Inferior quality of water available for supply and recreation at downstream populated areas.</p>
<p>Transition from middle-urban to late-urban stage:                      Urbanization of area completed by addition of more houses and streets, and of public, commercial, and industrial buildings.                       Larger quantities of untreated waste discharged into local streams.                       Abandonment of remaining shallow wells because of pollution.                      Increase in population requires establishment of new water supply and distribution systems, construction of distant reservoirs diverting water from upstream sources within or outside basin.                      Channels of streams restricted at least in part to artificial channels and tunnels.</p>	<p>Reduced infiltration and lowered water table. Streets and gutters act as storm drains creating higher flood peaks and lower base flow of local streams.                      Increased pollution of streams and concurrent increased loss of aquatic life. Additional degradation of water available to downstream users.                      Rise in water table.                       Increase in local streamflow if supply is from outside basin.                       Increased flood damage (higher stage for a given flow). Changes in channel geometry and sediment load. Aggradation.</p>
<p>Transition from middle-urban to late-urban stage - Continued                      Construction of sanitary drainage system and treatment plant for sewage.                      Improvement of storm drainage system.                      Drilling of deeper, large-capacity industrial wells.                        Increased use of water for air conditioning.                        Drilling of recharge wells -----                      Waste-water reclamation and utilization</p>	<p>Removal of additional water from the area, further reducing infiltration and recharge of aquifer.                       Lowered water-pressure surface of artesian aquifer; perhaps some local overdrafts (withdrawal from storage) and land subsidence. Overdraft of aquifer may result in salt-water encroachment in coastal areas and in pollution or contamination by inferior or brackish waters.                      Overloading of sewers and other drainage facilities. Possibly some recharge to water table, owing to leakage of disposal lines.                      Raising of water-pressure surface.                      Recharge to ground-water aquifers.                      More efficient use of water resources.</p>

receiving streams. Activities that might alter the groundwater table are: tunneling; deep foundations; alteration of the urban landscape, change of slopes and vegetation; and especially increase of impervious surfaces. As indicated in Figure 1, the increase of impermeable paved surfaces increases runoff and decreases infiltration.

### 3.3 Natural Groundwater Systems

To assess the status of the groundwater underlying the fall line cities, it is important to understand the fundamental principles and basic mechanisms of groundwater hydrology.

Groundwater is an integral part of the hydrologic cycle. This cycle can be expressed mathematically as  $P=ET+R+G$ , where P is precipitation, ET is evapotranspiration, R is runoff and G is groundwater changes.

An understanding of the groundwater systems requires complete knowledge of the climatology. The Mid-Atlantic region yields between 35 and 50 inches (889-1270 mm) of precipitation per year with an average monthly precipitation of 2 1/2 inches (63.5 mm). Snowfall is about 17 inches (431.8 mm) per season from November to March and the ground freezes to a shallow depth averaging 6 to 12 inches (152.4 to 304.8 mm) for short periods. There is, however, a considerable daily freeze-thaw in the spring months (January to April). Climate statistics vary slightly from Richmond to Philadelphia. Calculations obtained

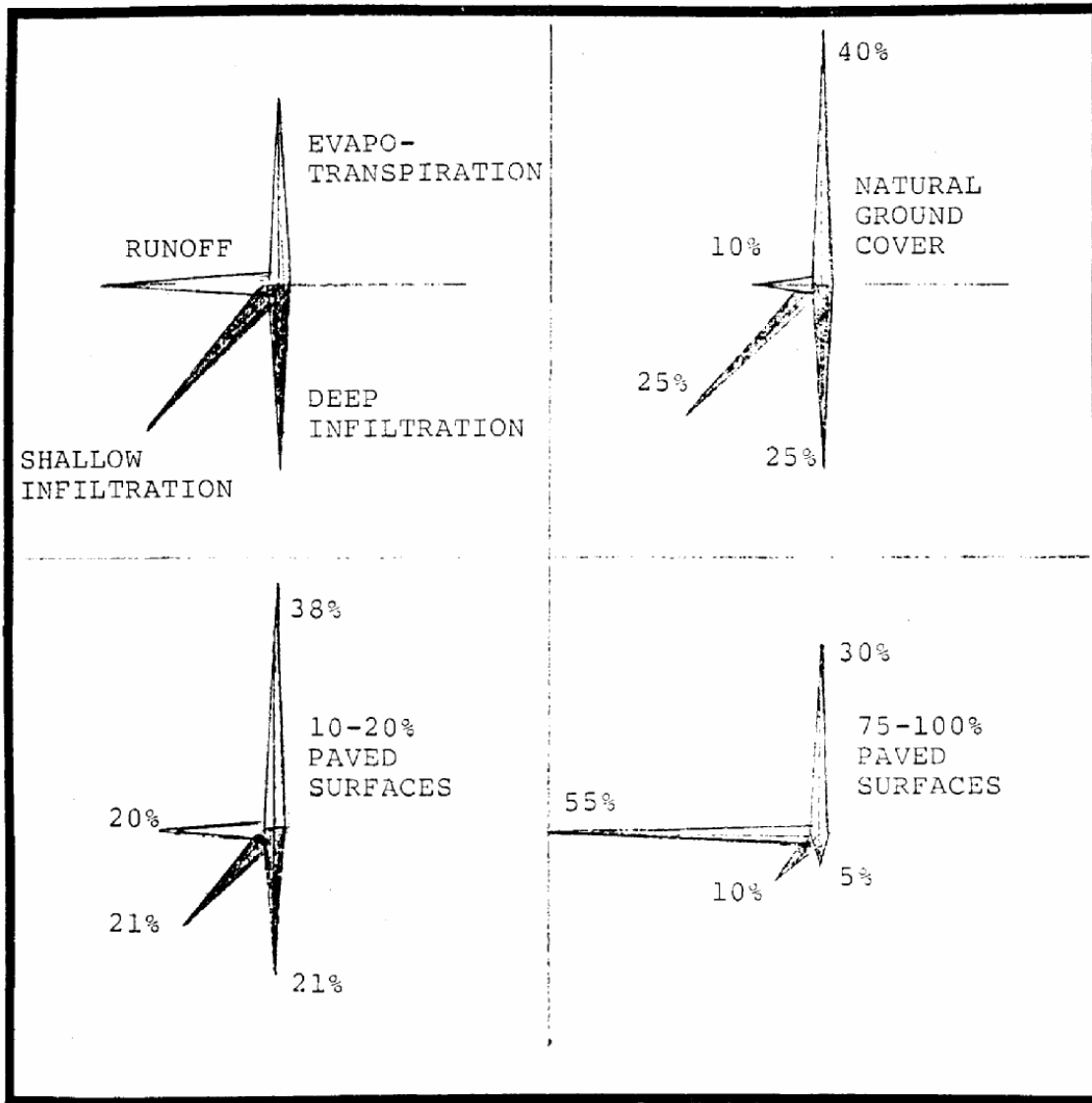


Figure 1. Effect of paved surfaces on groundwater.

for groundwater led to average values ranging between 11 and 14 inches (279.4 to 355.6 mm) per year. (See Figure 2)

There are a variety of waters underground. A general groundwater environment is divided up into two zones separated by pressure differences. The pressure boundary is known as the water table and it fluctuates generally on a daily and seasonal basis. A common view is that groundwater is all liquid below the water table and many scientists will treat that behavior only.

But the zone above the water table has important implications for vegetation, infiltration, soil, construction engineering, and basin characteristics.

Groundwater basins or sheds need to be outlined especially if they are to be protected and managed. It is not only important to know the life cycle of a spring or the flow of a natural system, but it is also essential to calculate or measure amount of depression or drawdown of recharge; infiltration of outside capacity; transmissibility; and per unit.

the following parameters: each well; rate of natural sources; yield or specific meability of each geologic

### 3.4 Description of the Study Area

The famous American geomorphologist William Morris Davis (1904) coined the term Fall Line for the sharp boundary between the Appalachian Piedmont Province and the Atlantic Coastal Plain Province. The Fall Zone marks a series of waterfalls and rapids

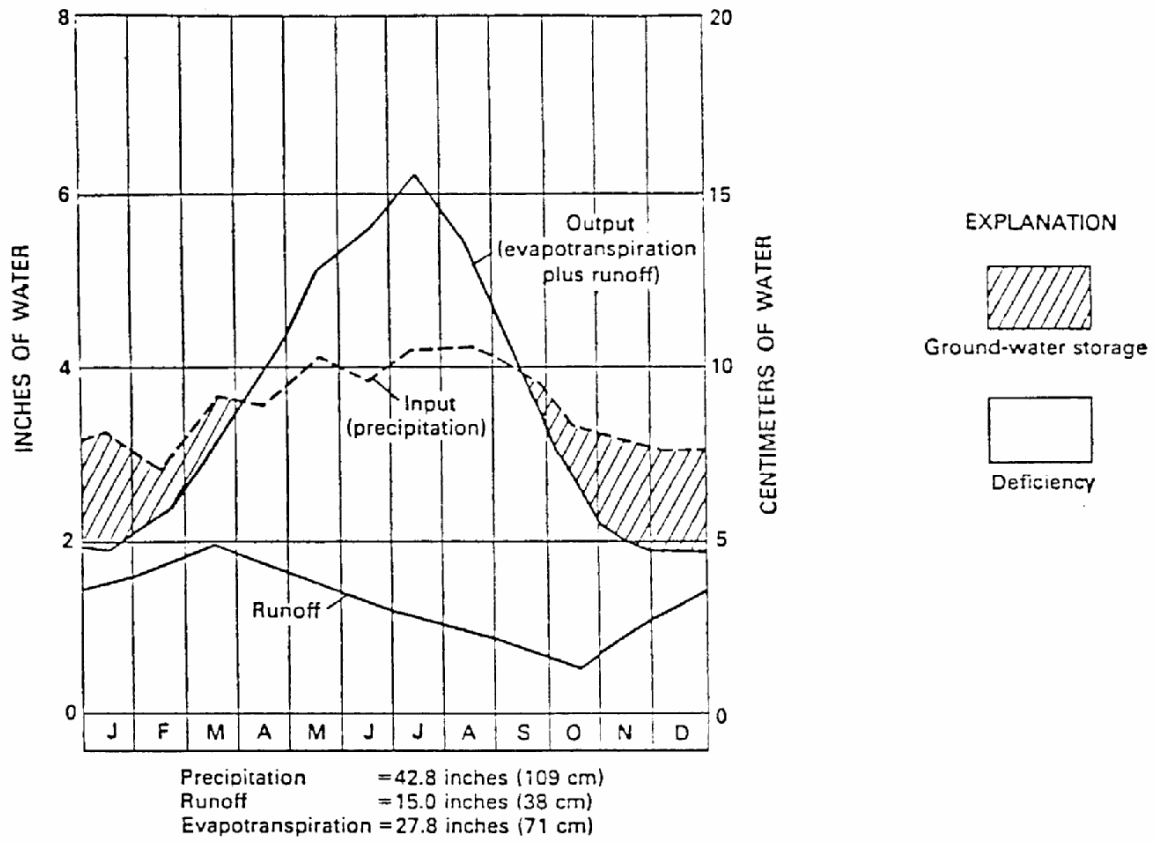


Figure 2. Water budget for the Patuxent River basin above the Unity gaging station (USGS Cir. 806).

on all streams that cross it. The Fall Line is the eastern limit of this zone and is characterized by a line drawn on a map connecting falls from New York City to Macon, Georgia (Fig. 3). The Fall Zone boundary marks a major hiatus in geologic time uncomfortably separating the ancient meta-igneous and meta-sedimentary crystalline rocks of the Piedmont from the much younger soft erodible sands, clays, and gravels of the Atlantic Coastal Plain.

Piedmont rock must be judged by its suspect terrane history of plate tectonics. A linear mafic belt of gabbroic plutons, soapstone and serpentinites through each city (Fredericksburg north) affect the natural chemistry of the fracture system groundwater. Two varieties of carbonates occur in complicated regional structures: marbles in the domes of metro Baltimore and limestone-dolostones of Chester Valley of Philadelphia. Sinkholes are associated with the sedimentary carbonates while heavy quarrying still occurs in the Baltimore marble district. The granite plutons from Richmond to Wilmington decay at the

edges and contribute by chemical weathering to the water chemistry but the fracture systems are the key to secondary permeability. Richmond has the most interesting adjunct geology with a special Triassic age coal basin. This area called the Gayton Coal Fields has been urbanized recently and some subsidence problems have occurred. Philadelphia has a small sliver

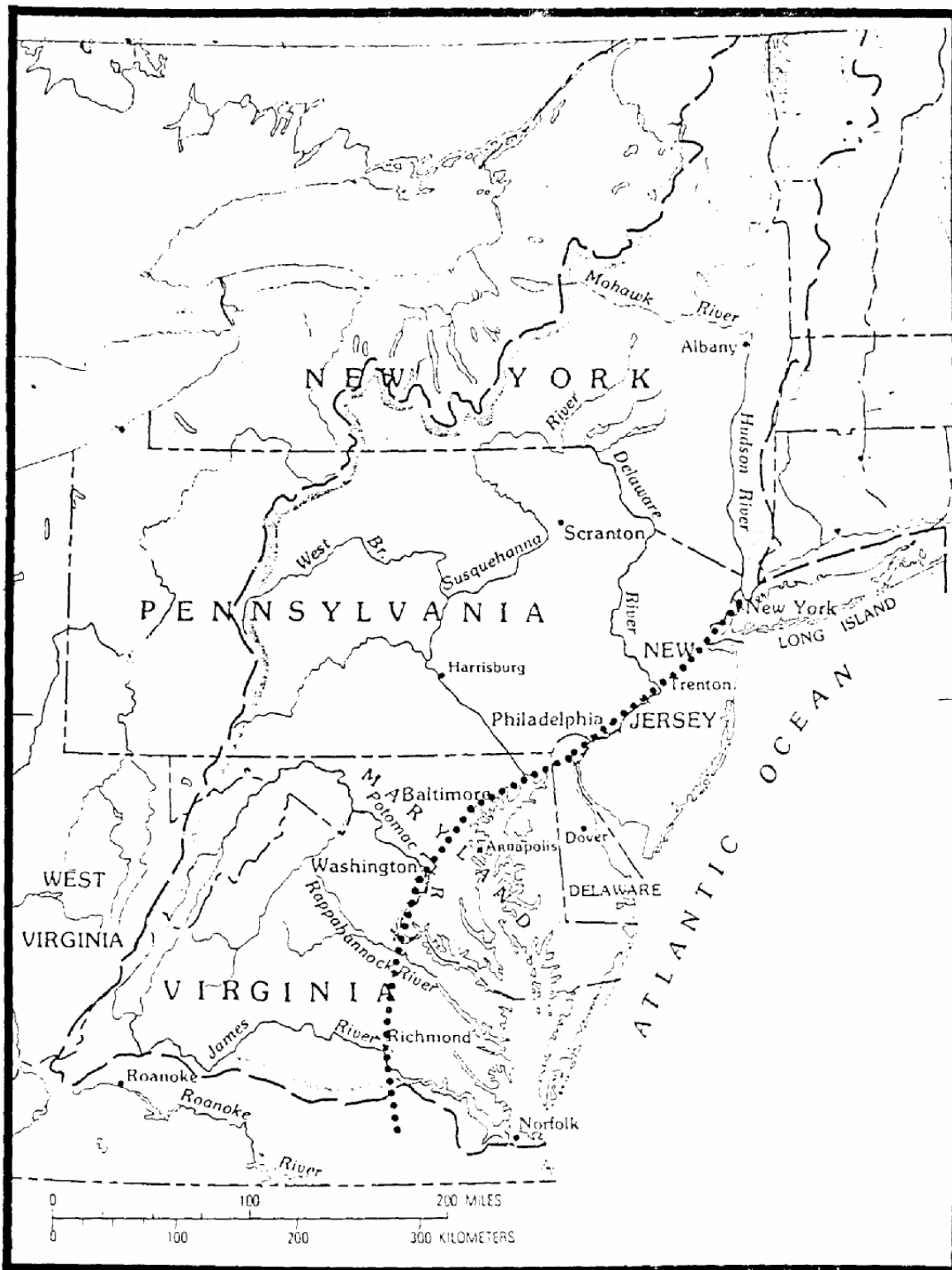


Figure 3. The Fall Line (.....) in the Mid-Atlantic Region (USGS Prof. Paper 813-I).

the Piedmont lowlands but restricted mainly to the Cambrian carbonates. Over time Philadelphia has progressed or sprawled to the Triassic-Jurassic Newark basin of red sandstones and diabase (igneous) rock. The report of Chester County, Pa. (McGreevey, 1977) is the most comprehensive on the geohydrology statistics of the whole suite of Piedmont rocks. In the Piedmont groundwater usually occurs in the fracture system or the saprolite zone.

Coastal Plain consolidated or unconsolidated sediments need to be qualified by their depositional sedimentary history. One hundred million years of stream alluvium, deltas, estuarine and floodplain deposits are the keepers of the groundwater. The

Potomac Group (Cretaceous Age) is the only true aquifer found in the Fall Zone area. The outcrop belt for this group is found in the Fall Line cities. Its general dip is gently to the southeast, but cross-bedding of many strata allow for drainage.in many directions. Drill holes do not always catch this structure which is only encountered when exposed. The weight, pressure, and flow regime within the Potomac Group may cause creep, slumps or slides on moderate or slopes greater than 8 percent. Change in the clay mineral percentage from montmorillonite to illite occurs in Washington for this North-south belt. Montmorillonite clays are the swelling or accordion clays dependent on wet/dry periods. In the western Coastal Plain most of the groundwater occurs in the Patuxent and Patapsco formations of the Potomac Group, or the younger Magothy and Aquia sand aquifers (Figure 4).

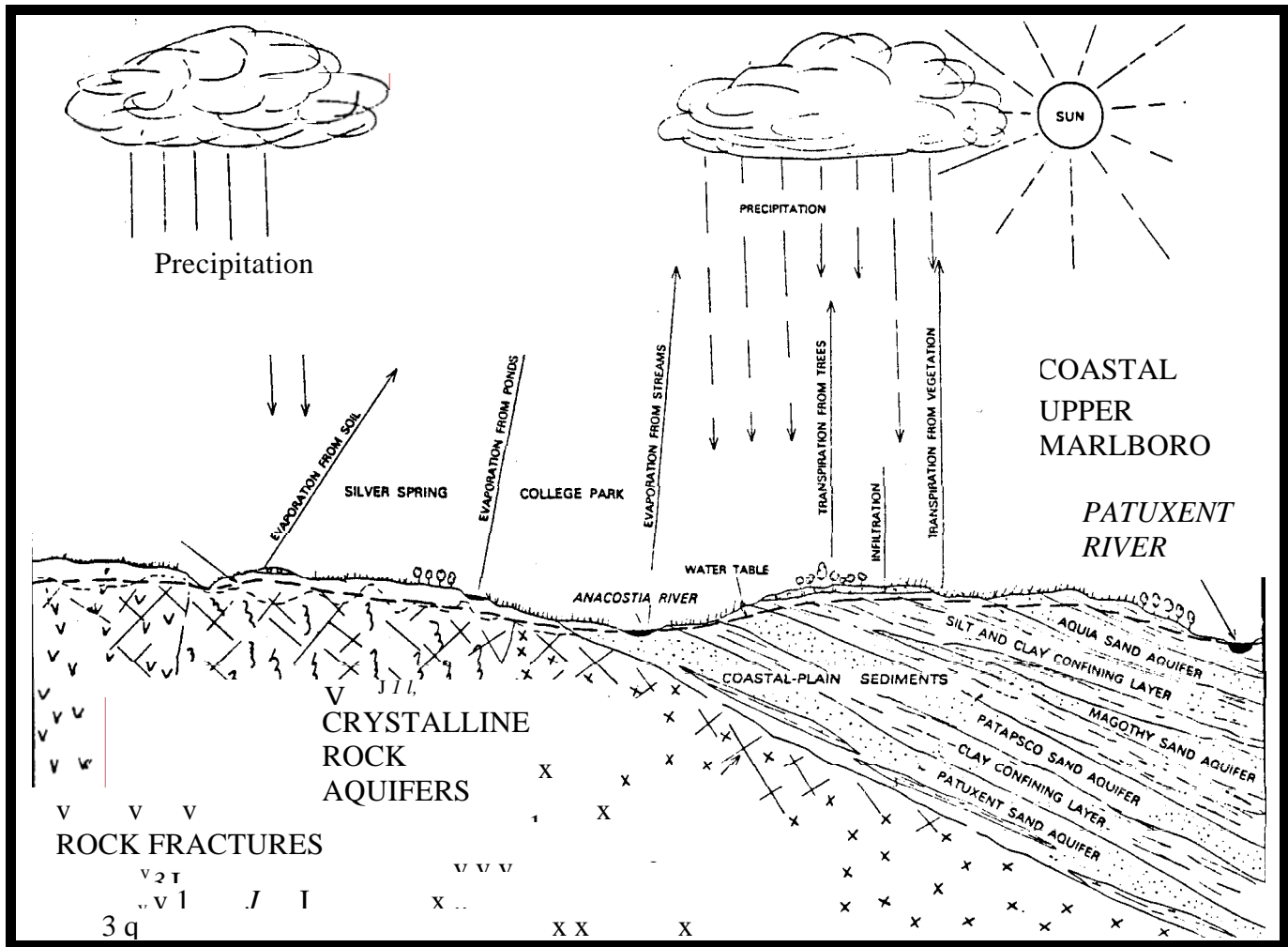


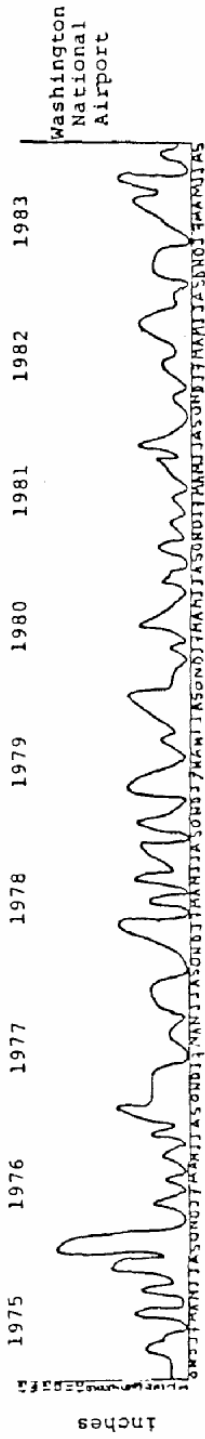
Figure 4. Major hydrogeologic features of the Fall Zone (USGS Cir. 806).

### 3.5 Data Analysis

A few agencies take time to collect or monitor groundwater as cities develop. The data available is kept by the agency or the construction company that acquired it. There is no central location where all the data are gathered for a given city. Even at the state level, most of the data collected is for the rural areas or the suburban counties but rarely for the city proper, except for Philadelphia (Wood, C., personal communication).

A series of analyses dealing both with the old and new records for a variety of locations were conducted. These analyses ranged from examination of well records to the well site investigation and well numbering systems. The well records reviewed provided a relationship for the precipitation and water table fluctuation between the Coastal Plain and Piedmont (see Figure 5). The review of various sites allowed for the tabulation of special problems and their specific impact on the groundwater (see Table 5). Each state uses a special numbering system to locate and identify individual wells. A review of the Piedmont fracture systems yielded many insights. Assessment of urban soils and their properties through soil surveys in each of the 28 counties within the study area, provided data on acidity, permeability, porosity, soil type, horizontal and vertical distribution, land use, infiltration rate, percentage of impervious vegetative cover and evapotranspiration. Additionally, selected

PRECIPITATION



WATER LEVEL OF WELLS

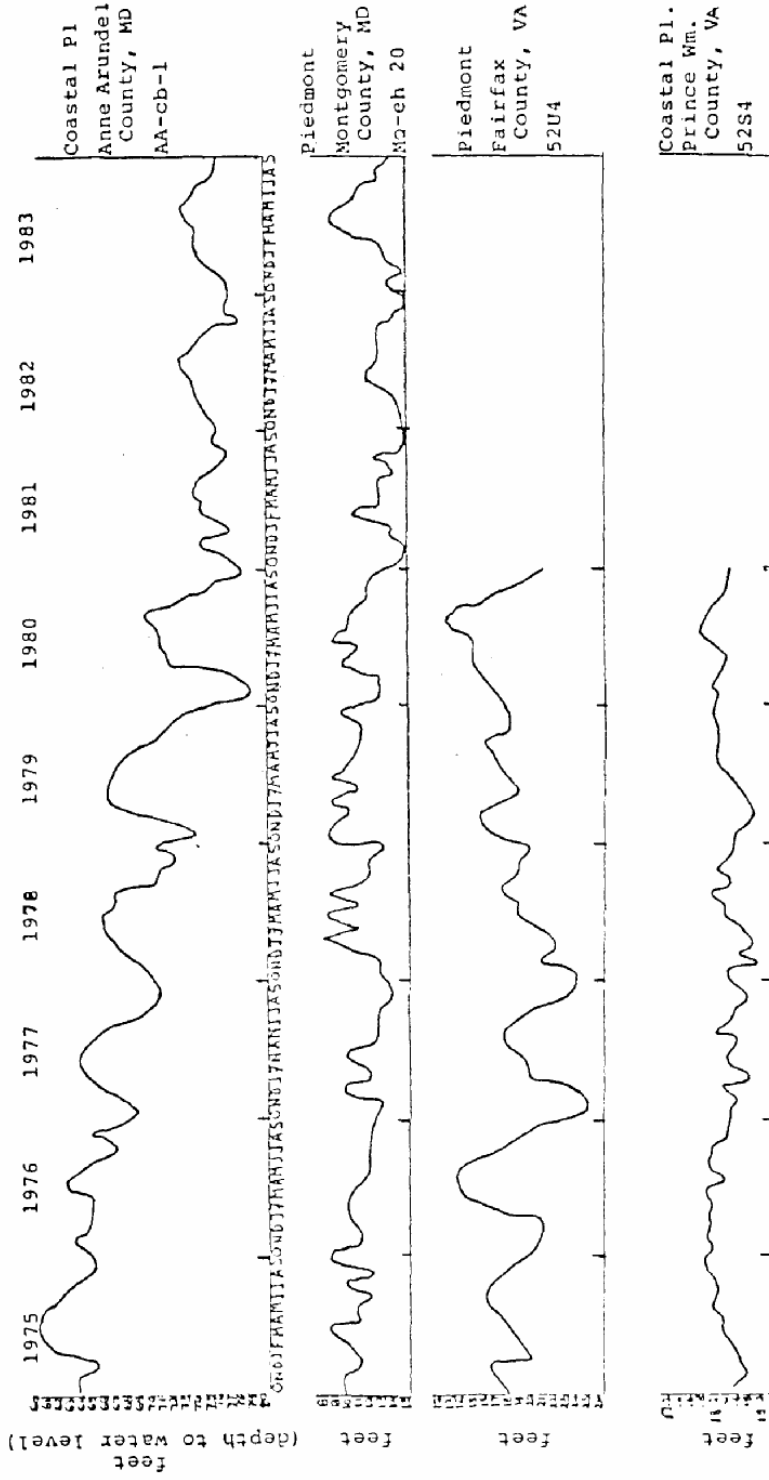


Figure 5. Comparison of precipitation and fluctuation of the water table in the Fall Zone (O'Connor 1984).

Table 5: GROUNDWATER PROBLEMS:

MID-ATLANTIC FALL ZONE

PROBLEM	EXAMPLES
1. Slumps/landslides	O St. S.E., Montana Ave. RI Ave. Metro
2. Pipe failures (frozen ground)	Newspapers (ref. Washington Post)
3. Buried landforms (rivers, swamps, marshes)	Tiber Creek; U.S. Naval Observatory: Mayflower Hotel Swamp
4. Cat clays (sulphur rich)	Anne Arundel County, Rt. 50, B.W. Parkway.
5. Seasonal high water tables	Soil surveys (ref. Prince George's)
6. Saprolite sponge	Montgomery & Fairfax Counties, or N.W. Washington, D.C.
7. Rock Fracture System (Piedmont)	Subway Construction in N.W.
8. Endangered species	Zoo
9. Perched water tables	N.E. and S.E. D.C.
10 a. Springs (historic) b. (active)	Pierce Mill, Capital Hill FBI buildings, Zoo, River Road
11. Saltwater Intrusion	Baltimore Inner Harbor
12. Septic Systems discharge	Southern Prince George's
13. Street salting/abrasives	Washington, D.C.
14. Underground storage tanks/leaks	Newspapers (ref. Washington Post) Arlington County Treatment Plant
15a. Sanitary landfills (closed) (open)	Kenilworth, Oxon Cove Prince William County
16. Leakage from water/sewerage pipes	Government records (Infiltration Study D.C., Phil.)
17. Water In-filling (bath tub effect)	Cherry Trees: Tidal Basin area
18. Dewatering (wooden piles)	Gallery Place
19. Cement mattress	12th and H Streets, N.W.
20. Change of flow direction	Construction at Van Ness St. (south side)
21. Carbonate build-up (stalactites/ stalagmites)	Lincoln Memorial and U.D.C. Garage Level C
22. Mineral resource operations	Sylvan Dell Quarry, Savage Quarry
23. Dredged soils	Masonville
24. Toxic substance - chrome	Hawkins Pt.
25. Hazardous - arsenic	Alexandria Waterfront
26. Hazardous - cleaning fluid perchloroethylene	4400 MacArthur Blvd., N.W.
27. Illegal disposal site	God's Dump 28th St. S.E.
28. Injection wells	Fort Myer Military Base (Arlington)
29. Lost recharge area	Impervious land use change UDC campus - Van Ness
30. Subsidence (fill)	Ohio Drive S.W. (Hairs Pt.)
31. Groundwater laws per state	Mont. Co., MD, well casing regulations

maps were reviewed to be integrated in the overall analysis of the project.

#### IV. FINDINGS

##### 4.1 Groundwater in the Fall Zone

The following section describes briefly the availability, the quantity and the quality of groundwater in the Fall Zone. To understand the mechanisms that control groundwater in the Fall Line, it is important to highlight the geologic features of the region.

Basically, the Coastal Plain lies at the east of the Fall Line and extends from Virginia through Maryland, Delaware, Pennsylvania, New Jersey and Long Island. The Coastal Plain is underlain by unconsolidated deposits. The surface deposits of the Coastal Plain are largely permeable consolidated sand and gravel or slightly to non-permeable clay. To the other side of the Fall Line is the Piedmont province. The Piedmont province is a plateau of hills and locally extensive lowlands. The province is underlain by weathered crystalline metamorphic and igneous rocks.

One of the major problems in the Piedmont Zone is the permeability and porosity that are controlled by the cracks in the numerous sedimentary and metamorphic rocks associated with the ancient rock structure (i.e. folds and faults). Rock fractures may be joints (no movement) or faults (movements). Metro subway

studies summarized these regional joint systems from their research and previous work (see Table 6). There are fracture systems inherent in each rock type and those superimposed from the rock structure (Lopez, R., personal communication). The local faults are high angle reverse faults. These faults usually come in clusters (O'Connor, J., 1982). These are most evident near the National Zoological Park in Northwest Washington, D.C. These faults have displaced Piedmont rocks over the Coastal Plain. It is also important to notice that blasting during construction creates new fracture systems. The fracture systems provide new avenues for water to infiltrate. The other important characteristic is permeability. The permeability of a rock or soil defines its ability to transmit a fluid. Infiltration and porosity are the most important aspects of permeability.

In the Piedmont, the groundwater is generally slow and has a small yield based on the size of the fractures. In the Coastal Plain, the unconfined flow is based on the local surface streams and subject to influent-effluent seepage. Confined groundwater in the Coastal Plain flows to the East (See Figure 6). It is important to note that the construction industry has a major impact on the direction and damming of groundwater flows.

#### 4.2 Groundwater Quantity

Large yields may occur in the Coastal Plain surface deposits which are low permeable clays and permeable consolidated sands

Table 6. Bedrock Joints in Washington, D.C. and Montgomery County, MD (Mathews 1982).

Source	Joint Set			
	1	2	3	3-4
Fellows (1950)		S:N42°E D:68°SE	S:N40°W D:68°NE	S:N72°W D:Vertical
Johnston (1964)	S:N-S D:60°W to Vertical (Lineation)	S:N30° to 50°E D:35° to 65°SE		S:N70°W N70°E D:Vertical to 60°
Cloos (1964)		S:N20°E D:68°SE		S:N70°W D:70°NE
MRWJ, A-6 (1967)	S:N7°W D:55°W	S:N20°E D:44°SE		S:N73°W D:53°NE
MRWJ, A-9 (1973)	S:N5° to 10°W D:60° to 75°W	S:N50°E D:50° to 70°SE		S:N60°W D:70° to 90°N
MRWJ, Beth. Station (1974)	S:N5° to 10°W D:40° to 70°W (also foliation)	S:N40°E D:30° to 65°SE		
MRWJ, Medical Center Station (1974)	Horizontal jointing and indistinct foliation are characteristic			S:N60° to 90°W D:65° to 75°NE (Primary)
Cording, et al Van Ness (1974)	S:N2°W to N5°E D:60° to 80°W	S:N85°E D:70° to 80°S	S:N5° to 20°W D:50° to 80°E	S:N5°W D:50° to 75°E (Secondary)

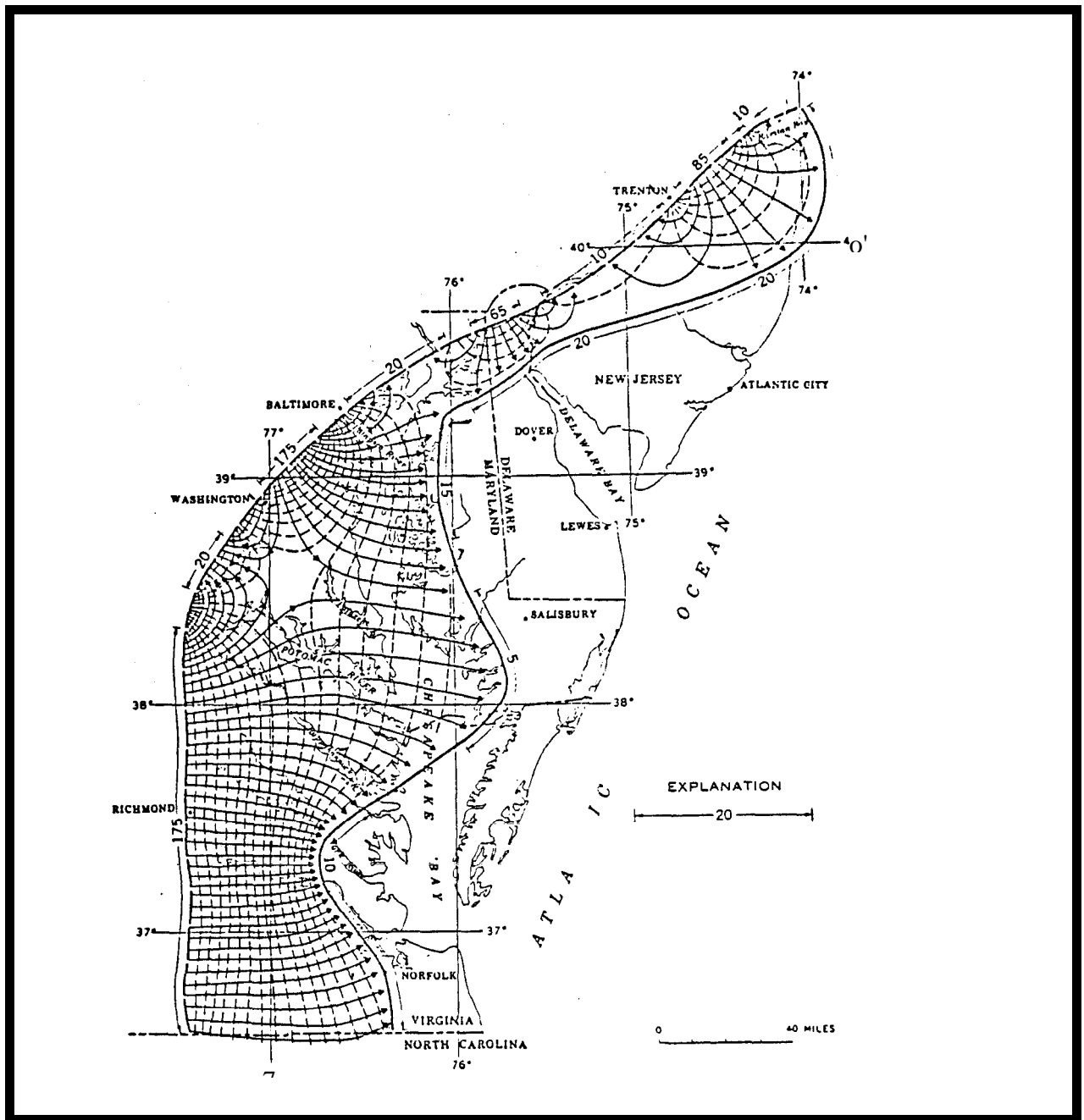


Figure 6. General pattern of groundwater flow in the Fall Line and the Coastal Plain (USGS Prof. Paper 498-A).

and gravels. Generally the wells are less than 100 feet deep and can yield as much as 100 gallons per minute. The deeper artesian aquifers in the Coastal Plain are more productive, however. Under the present hydrologic conditions, the groundwater in the Coastal Plain is estimated at about 9 billion gallons per day. In the Piedmont province, the most dependable groundwater wells are in the crystalline rock areas. In that zone, wells yield about 15 gallons per minute, however, as much as 400 gallons per minute have been reported. The occurrence of groundwater and well yields is the function of soil and rock types.

Piedmont igneous and metamorphic rocks are poor to fair aquifers depending on the siting of the well. Careful selection of the well site by fracture zones will significantly increase yields (Nutter, 1974, McGreevey, 1977, Richardson, 1982). Most water bearing fractures in Piedmont rocks occur in the upper 150 feet' (45.73 m) and few exist below 350 feet (106.7 m) because of the confining pressure of the overburden sealing of the cracks. Piedmont well yields are generally in the 15 gpm for the schist or granite (most common rocks) and tend to have highs around 100 gpm. The static water levels range from 555 feet (1.52-11.67 m) below the land surface. Coastal Plain areas contain both artesian (confined) and water table (unconfined) aquifers: The unconsolidated sand beds are good aquifers but the best yields are at 200-300 feet (60.98-91.46 m) below sea level down the southeast of the strata. This places

the high yields outside the city boundaries in most cases, but the recharge area is in the cities. Southern New Jersey and the eastern urban segments of Baltimore, Washington and Richmond do use this water source. Yields vary between 100-300 gpm. The static level of the water table ranges from 4-45 feet (1.22-13.72 m) below the surface.

Terrace gravels and river alluvium drain quickly and are not a good continuous source to rely on. Normal fluctuation of the water table is related to climate and is 20 feet (6 m) over the thirty-year normal record period.

For example, groundwater in the Washington, D.C., area is obtained from both consolidated crystalline rock (Piedmont) and unconsolidated sedimentary rocks (Coastal Plain). The exposures of these two rock types are divided by the Fall Line running diagonally from roughly the northeast to the southwest (See Fig. 7). Combining the tabulation of pervious areas for the District of Columbia (see Table 7), with the U.S. Geological Survey's estimate of 11 inches for infiltration in the District, the yearly groundwater availability has been theoretically computed and shown in the same table.

#### 4.3 Groundwater Quality

In the Mid-Atlantic region, the quality of groundwater differs from location to location in accordance with the hydrogeology. Generally, the Coastal Plain's outcrop area contains

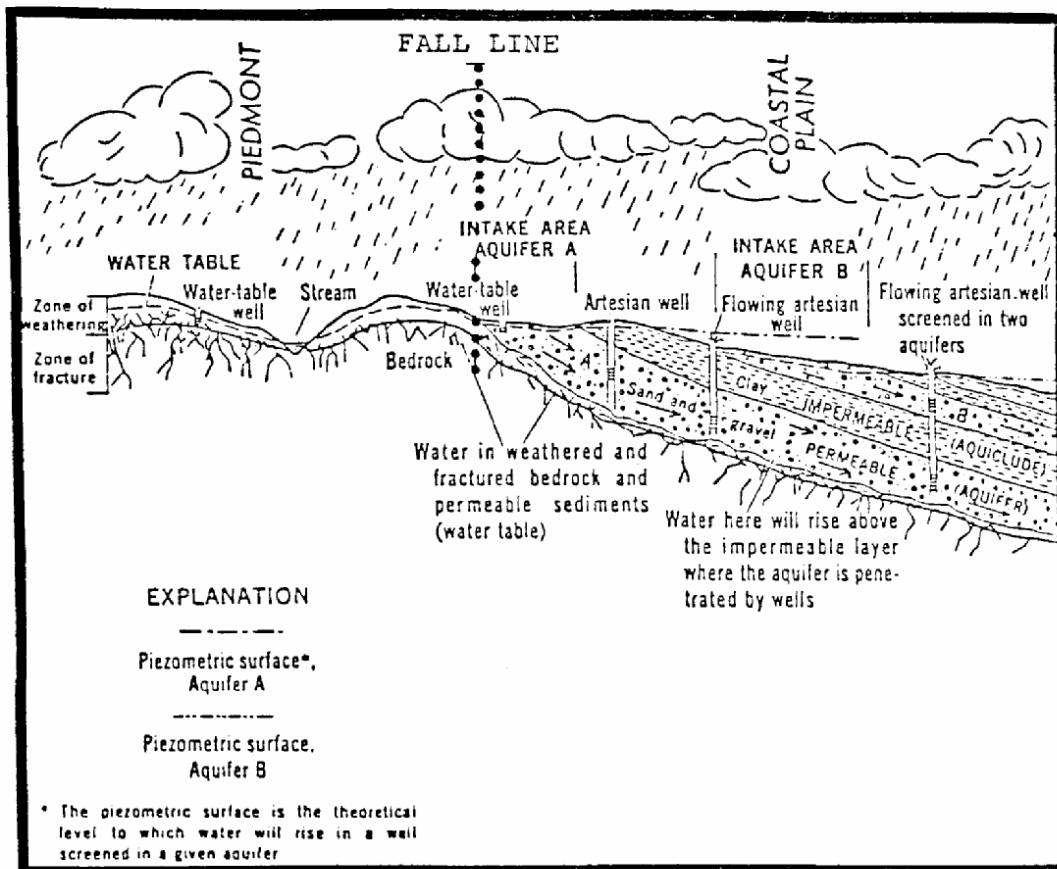


Figure 7. Hydrogeology of Washington, D.C. area (USGS WSP 1776).

Table 7. Pervious areas in Washington, D.C.

	SOIL TYPES	PERCENTS	AREA (ACRES)	YEARLY GROUND- WATER RECHARGE (X 10 <sup>6</sup> gal)
Piedmont	Ashe	0.4	174	
	Brandywine	1.2	353	
	Glenelg (v)	0.2	81	
	Glenelg (r)	0.6	304	
	Manor	3.2	1,430	
	Neshaminy	0.4	172	
SUBTOTAL		6.0	2,514	751
Coastal Plain	Christiana	1.3	534	
	Croom	0.9	358	
	Chillum	0.7	321	
	Joppa	0.5	250	
	Keyport	0.4	158	
	Matapeake	0.1	42	
	Sassafras	1.6	710	
	Sunnyside	0.5	257	
	Rumford	-	-	
	Galestown	0.2	116	
	Beltsville	0.1	52	
	Fallsington	0.1	37	
	Bourne	0.2	90	
	Woodstown	0.4	174	
Muirkirk	1.9	797		
SUBTOTAL		7.9	3,896	1164
Flood Plains Uplands Terraces	Codorus	0.4	191	
	Iuka	0.6	273	
	Bibb	0.4	174	
	Lindside	0.5	219	
	Melvin	0.3	117	
	Dunning	0.1	51	
	Udfluvents	0.1	52	
	Fluvaquents Udorthents	0.4 10.5	183 4,386	
SUBTOTAL		13.3	5,646	1686
TOTAL		27.2	12,056	3601

soft and slightly acidic groundwater with local excessive amounts of iron and total dissolved solids.

There are a number of groundwater quality problems in the Fall Zone. Some of these are due to natural processes; others result from man's activities. High iron concentration along with salinity and hardness are the most prevalent in the region. Hardness is commonly thought of in terms of the soap consuming property of the water and is attributable chiefly to the presence of calcium and magnesium; but free acid, heavy metals and other alkaline-earth metals also affect the hardness. Table 8 summarizes field determination of pH, hardness and specific conductance, etc., of groundwater in Washington, D.C. In Washington, D.C., the water from most aquifers is soft to moderately hard, ranging from 2-175 ppm. Water in the Piedmont zone is *dominant* in calcium bicarbonate, while water in the Coastal Plain zone is dominant in calcium magnesium bicarbonate with dissolved solids ranging from 23 to 801 ppm and averaging 87 ppm. The concentration of iron has been found to exceed the permissible U.S. Public Health Service standard of 0.3 ppm. Zinc, salts of chloride and sulfates are also present in the groundwater (See Figure 8).

Other quality problems induced by nature, but have lesser importance is: excessive amounts of fluoride, presence of hydrogen sulfide and methane gases, and oil contaminations.

Table 8. Groundwater chemical analyses at Cross-town Water Main Tunnel, Georgetown, D.C. (Mathews 1982).

Parameter	B-19	Piedmont Borings	
		B-11 (60ft) *	B-9 (97ft)
1. Chloride in ppm cl	42.4	38.0	41.0
2. Sulfide in ppm	0.66	0.28	0.0
3. Sulfate in ppm	127.5	250.0	57.5
4. pH	6.3	6.65	6.7
5. Conductivity in micromhos/cm	420.0	550.0	330.0
resistivity in ohm/cm	2381	1818	3030
6. Hardness in mg/l CaCO <sub>3</sub>	116.0	164.0	174.2
7. Acidity in mg/l CaCO <sub>3</sub>	5.0	21.0	28.4
8. Alkalinity in mg/l CaCO <sub>3</sub>	91.3	87.0	117.2

\* Number in parentheses is depth from which samples were obtained.

LEGEND : DESCRIPTION OF WELLS

Mississippian Formations

1. R-Ca-9 = albite-chlorite facies, depth 110 ft. (Rockville)
2. K-Bc-24 = oligoclase-mica facies, depth 109 ft. (Kensington)
3. FC-Ca-12 = undifferentiated, depth 138 ft. (Falls Church)
4. FC-ac-3 = gneiss, depth 135 ft. (Falls Church)
5. BT-Ca-1 = gneiss, depth 40 ft. (Beltsville)

Granite

6. AN-Ab-2 = depth 84 ft. (Annandale)

Mafic Rocks

7. FC-Ac-10 = depth 135 ft. (Falls Church)

Serpentine

8. R-Ba-4 = depth 35 ft. (Rockville)

Potomac Group

9. AX-Bb-9 = dug well (Alexandria)
10. WW-Bb-2 = Spring (Washington West)
11. AN-Bb-7 = dug well (Annandale)

Quaternary Terrace

12. Ax-Aa-18 = dug well (Alexandria)

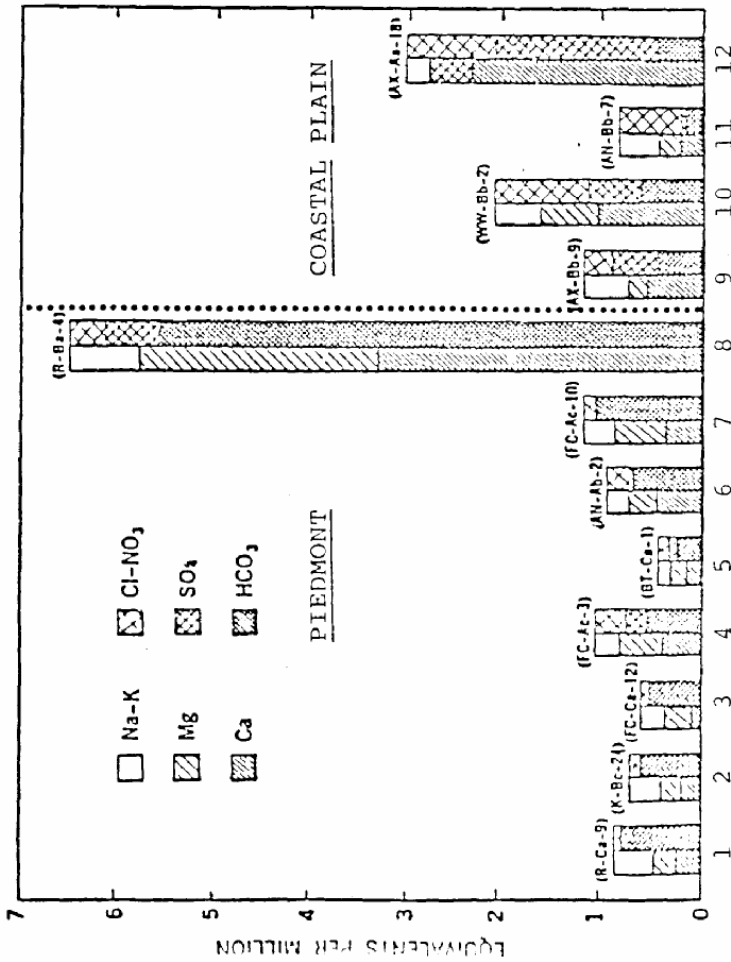


Figure 8. Chemical analyses from selected wells in the Washington Metropolitan area (adapted from Johnston 1964).

Groundwater pollution caused by human activities in the Fall Zone manifests itself in a variety of ways. Acid mine drainage affects mostly surface water, however in coal mining areas of Pennsylvania, Maryland, Virginia and West Virginia, it may also be a source of groundwater contamination. Aquifer contamination is the most serious. Pumping of wells near sources of contamination may induce directly or indirectly aquifer contamination. Such problems have been cited in

Long Island, N.Y. and in Atlantic City, N.J. Also, high nitrate concentrations have been identified in wells affected by cesspools, septic tanks, and fertilizers from agricultural lands. However in the Fall Line cities, the most serious groundwater contaminations are due to the following: salts from winter road deicing, leachates from dumpsites and landfills, accidental or intentional disposal of hazardous and industrial wastes, and a variety of leaks. In Washington, D.C., winter deicing may be the cause of foundation structure problems in the public monuments, such as Lincoln monument.

Conversely, groundwater can have corrosive effects on concrete or metallic structures, under certain conditions. Chloride, sulfide and sulfate in groundwater increase corrosion on concrete. A pH less than five will also have the same effect on concrete. Groundwater conductivity is a major factor in metal corrosion. The conductivity is usually between 300 and 550 micro-ohms per centimeter. When the conductivity is greater than

1000, a cathodic protection is required. It has been found in general that groundwater in the Washington, D.C., area does not attack steel or concrete used in pipelines unless the groundwater is already polluted or the soils contain chemical residues.

In general, the quality characteristics of the groundwater are measured not only through chemical analysis, but also through physical and biological analyses. The chemical analysis includes the determination of the concentration of inorganic constituents, and that of the organic and biological parameters. The physical analysis includes the temperature, color, turbidity, odor, taste, etc. Finally, the biological analysis includes tests to determine the presence of coliform bacteria. The detection of coliform organisms, which are normally found in the intestines of humans and animals, indicates the presence in groundwater of possible sewage leaks.

#### 4.4 Groundwater Contamination

As discussed earlier, contamination generated from oil and gas products, road salts, industrial sites, hazardous waste sites, and agricultural sites and from pesticides and herbicides are prevalent in most urban areas.

Some of the most serious sources of contamination are heating oil or gasoline leaks from underground storage tanks. Gasoline penetration to the groundwater from petroleum sources occurs in several ways. In hard rock shells, groundwater flow is

likely to be in feet per year range, and therefore the contamination is slow. But in carbonate areas where the groundwater flow is sometimes in feet per hour, pollution can spread quickly. A petroleum contamination plume is usually narrow in width and may not occur through the entire thickness of the aquifer. Large quantities of petroleum may leak through an aquifer over many years without being detected.

In urban areas, gasoline leaks must be controlled at the stations. Most underground storage tanks are made of unprotected carbon steel. The typical service station tank has the capacity of 4,000 gallons. Half of all the buried steel tanks leak after 15 years. According to a survey made by the American Petroleum Institute, 92.3% of all leaks from steel tanks are caused by corrosion. A number of factors speed up metal corrosion. Installation and operational practices as well as a variety of chemical reactions are leading causes. As a remedial measure, petroleum companies such as Exxon, Shell and Texaco are replacing unprotected steel tanks with fiberglass tanks or cathode protected steel tanks. Recently, in Washington, D.C., oil companies have been switching to fiberglass tanks.

#### 4.5 Groundwater impacts on Construction in the District of Columbia

The groundwater table is influenced by factors such as seasonal changes of infiltration, variation of river levels, presence of sewer systems and other pipelines, temporary or permanent pumping, and dewatering associated with construction activities. On the other hand, groundwater conditions in urban areas such as the District of Columbia have a significant impact on construction and tunneling.

Factors such as geologic boundaries, perched water tables, water table fluctuations, vertical mixing and the hydraulic gradient, all impact engineering construction. In excavations, exposure of soil and rock boundaries may lead to the creation of springs, seeps, and in fillings (the bath tub effect). The FBI Building and the new Intellsat complex in Washington, D.C. are recent examples. The perched water tables are usually found in sandy lenses in the impermeable clays. Because they are hard to map, perched water tables tend to cause unexpected construction problems. The metro tunneling in Washington, D.C. encountered a few of these perched water tables. The vertical mixing has a dual effect. One is to modify the porosity-permeability balance, which can create compaction and flow problems that result in construction delays and/or design changes. The other effect is the vertical chemical mixing which can cause corrosion or contamination.

Water table fluctuations may produce quick-state clays, when water is introduced, and dry compaction when water level is lowered. Finally, any kind of ground *construction* perpendicular to local groundwater flows will change the flow direction and velocity. The groundwater table in *Washington, D.C.* is typically 10 to 40 ft. below the ground surface. During underground *construction* for subways, utility pipelines and sewer systems, a series of engineering problems may be encountered. These problems include dewatering, add watering, erosion, deterioration of material or leaks caused by blasting due to air drying or softening in presence of water, settlement loosening or excavation. A few specific examples as related to *Washington, D.C.* are discussed below.

Certain projects in Washington, D.C. now being built or recently completed provide examples of foundation construction problems and solutions. An example of cut and cover construction is provided by the 1,000-foot center section of the mall tunnel of the Inner Loop Freeway, crossing, the mall between 2nd and 3rd Streets, N.W. Because this section intersects the former Tiber Creek Channel, many construction-dewatering difficulties were encountered. For this project, the groundwater level was approximately 25 ft. to 30 ft. above subgrade. The total amount of water pumped out during the dewatering process reached amounts close to 250 gallons per minute. Periodically it was necessary to flush the eductor system with water from city mains to

eliminate corrosive or clogging materials, which interfered with the eductor operation. A series of approximately 40 piezometers were placed near adjacent government buildings to monitor the draw down created.

In the District of Columbia, construction contracts such as the one previously described may contain a provision for *recharging* the groundwater to avoid consolidation settlements caused by draw down. Lowering the water table through pumping not only causes subsidence, but also may cause deterioration of foundation material. For many historical buildings, such as Gallery Place, Evening Star, and the Pavilion (old Post Office) which are built on wooden piles, water table must be maintained by add watering. It is interesting to note that buildings along Pennsylvania Ave., N.W. illustrate a conflicting use of groundwater regime, with regard to add watering on the north side and dewatering on the south side. Table 9 shows estimated flows of foundation dewatering in the Federal Triangle area bordering Pennsylvania Ave.

During the early phases of sewer tunnel construction between L and Half St., S.E., to Navy Yard, dewatering was accomplished by deep wells placed at a minimum spacing of 300 ft. While the pumped quantity was relatively small, it was reported that the use of wells significantly reduced sloughing of materials when clean cohesion less sand was encountered. In general, for some

locations, it may be necessary to use well point or grouting methods to cut down on or eliminate water flow during dewatering. Tables 10 and 11 give an estimation of pumping rates and rock permeability, respectively, for the District of Columbia.

#### 4.6 Legal, Institutional and Management Implications

Like surface water, groundwater is subject to various laws from Federal, State, Counties and Cities. These laws cover both quantity and quality and vary from location to location. The following sections will examine the groundwater laws as they pertain to cities in the fall-line region.

##### Federal Legislation

There are a number of Federal laws impacting environmental control with the focus on groundwater quality protection. These laws are administered by the Environmental Protection Agency and other Federal agencies. The major enabling legislations are listed below:

- The Comprehensive Environmental Response Compensation and Liability Act of 1980 (CERCLA) established as a trust fund (called the Superfund) to finance government responses to releases or threats of releases of hazardous substance that may harm public health or the environment.

- The Resource Conservation and Recovery Act of 1976, which provides cradle-to-grave management of hazardous waste. This Act also includes minimum requirements for permits for hazardous waste treatment, storage and disposal facilities.

Table 9. Federal Triangle Summary (Greeley and Hansen)

Buildings	No. of Sump	Estimated Flow
Dept. of Justice	15	178,495
IRS	10	32,387
New Post Office	16	30,631
U.S. Customs and ICC	13	48,792
Dept. of Commerce	22	238,469
Museum of History & Technology	8	21,552
Steam Tunnel		6 22,723
TOTAL	90	573,055

Table 10. Pumping rates from different geological formations in the District of Columbia (Dames and Moore 1963).

	Estimated pumping rate (gallon per minute per lineal foot of Soil Type)
Gravel and sand with 20 little or no silt and clay	10-
Sand with little or no silt and clay	5-10
Sand or gravel with some above 20% silt or clay	1-5
Clayed sands, clayed grounds, silty sand, silt gravel	1

Table 11. Rock permeability in the District of Columbia (Metro Subway Study 1976).

PERMEABILITY	
ROCK	(feet per min)
Coastal Plain	
- Pleistocene sand & gravelly sands	$5 \times 10^{-4}$
- Cretaceous and & gravelly sands	$3 \times 10^{-4}$
Piedmont	
- decomposed rock (saprolite)	$1 \times 10^{-4}$
- bedrock	$4 \times 10^{-5}$

- The Clean Water Act provides the management structure for state water quality programs including groundwater. Section 208 of the Act entitled "Area Wide Waste Treatment Management," designates within each state areas which as a result of urbanization have substantial water quality problems. The state agencies are required to effectively manage the waste treatment plants and to include in their management plans the protection and the enforcement of groundwater quality.

- The Federal insecticide, fungicide and Rodenticide Act (FIFRA) relate to the control of pesticide that might affect the groundwater.

- Finally, the Toxic Substances Control Act (TSCA) concerns the chemicals and the mixing of chemicals as they may affect humans and the environment, during their manufacture, processing and use. This Act limits the use of certain chemicals and mixtures that have the potential of contaminating the groundwater.

#### State Legislation.

In the Mid-Atlantic States, Riparian and Reasonable use doctrines are prevalent. Pennsylvania uses the first doctrine and the other states use the latter.

In general, the states operate their groundwater program through Federal regulations developed under the authority of various Federal acts such as those cited above. Most of the states' activities involving groundwater programs have laws that

are managed by state water control boards. One of the most important activities of the managing agencies is the administration of the National Pollutant Discharge Elimination System (NPDES). The NPDES specifies that no right exists to dispose of pollutants into a well except as authorized by a NPDES permit.

In addition to the general rules, some states in the Mid-Atlantic have established more specific controls on groundwater use. For example, Virginia requires owners of flowing wells to cap them, and records of commercial and industrial wells must be furnished to the state. New York requires that uncontaminated groundwater used for cooling purposes be returned to the ground through recharge wells. State laws address item such as permit, drilling, maintenance and requirements for use of public sub aqueous lands (e.g. dredging, filling, excavation and tunneling).

The state regulations also include limitations on withdrawals from aquifers, groundwater quality standards, and management of oil, gas and coalfields, and disposal of hazardous and solid waste. At the local level the most important issue is groundwater protection. The protection covers prevention of contamination before it happens and immediate action after it happens. This is accomplished through legal, direct action and/or persuasion. The legal activities are mainly through the zoning

ordinance. A local ordinance may relate to erosion control, runoff control, hazardous waste, oil spills . . . etc.

### Cities and Counties

The cities and counties link regulations with local planning and zoning. Therefore it is essential to aim groundwater resource management at the local level. At this level, the development proposals for compliance are reviewed by the planning commission, the zoning board, the municipal engineers, the soil and water conservation district, the neighborhood associations, various experts, and agencies. Where groundwater problems involve several jurisdictions or states, an interstate commission or intergovernmental commission is formed. Plans are necessary to coordinate local, state and federal water quality management efforts to ensure uniform enforcement and compliance with established standards. Specific regulations dealing with details such as well casing, well spacing, contamination, etc. . . . are considered at the local level. For example, the Montgomery County, Maryland has a 40 ft. well casing requirement. Also, Baltimore, Md., and Philadelphia., Pa., has their own well permit system.

### V. Conclusion:

This project addressed a large area namely the mid-Atlantic Fall Zone. However, it was limited in scope. The project focused on the fall line cities, specifically on the interaction

between urbanization and groundwater. As the cities developed, significant stress was placed on the quantity and quality of the groundwater. In these cities the most obvious impact of urbanization on groundwater is the reduction of recharge areas. Fluctuations of the water table by dewatering and add watering through building construction and tunneling activities, and modification of groundwater flow direction, are a few examples related to the impact of construction on the quantity of groundwater.

Qualitatively, groundwater in the fall zone is affected by natural and urban activities. Of all the contamination problems, oil and gasoline leaks to the groundwater, and leachates from dump sites and landfills are the most significant. Conversely, groundwater impacts the construction industry through foundation problems, settlement, seepages, and corrosion, etc.

Pollution from natural sources is not very well understood. Consequently there is a need for management to develop an understanding of the occurrence, the flow, and other basic mechanisms of groundwater. In urban areas detailed information on wells, and activities that directly or indirectly affect groundwater should be developed and centralized. Because of the site specificity of groundwater problems, management responsibilities should rest with local and city governments rather than with the Federal government. Even though groundwater use is presently limited in the fall line cities, it is necessary to develop management policies that would ensure future protection and wise utilization of this important resource.

## I. ANNOTATED BIBLIOGRAPHY: SELECTED REFERENCES

### 1. Back, William 1966

Hydrochemical Facies and Ground Water Flow Patterns in Northern Part of Atlantic Coastal Plain: USGS Professional Paper 498-A. 42 pp.

This classic report unveils the relationships between geology, hydrology and the chemical character of groundwater. The Mid-Atlantic Coastal Plain is the focus for this base line field model. Chemistry is controlled by the ground water flow pattern. Rock chemistry controls are centered on the clays, glauconitic sands and calcareous (shell) materials. Hydrochemical facies are defined and excellent regional maps abound.

### 2. Bennett, G.D.1976

Introduction to Ground-Water Hydraulics: USGS TWRI - Book 3 ch.B-2. 70 pp.

This is a self-instruction programmed text. This do-it-yourself booklet is divided into 8 chapters: concepts and definitions, Darcy's Law, Application of the Law, storage, flow, wells, finite difference methods and analog techniques. It is not a book to read but to do. Strong on math equation solutions and general problems.

### 3. Craul, Phillip J. (ed.) 1982

Urban Forest Soils: A Reference Workbook, SUNY-College of Env. Sci. and Forestry (Syracuse, N.Y.) 190 pp.

A timely symposium held at the U. of Md. and cosponsored by USDI-NPS. Seven chapters cover a wide range of new surface-subsurface interrelationships: Basic Soil Properties and Characteristics; Ecology of Tree Roots; Soil Compaction: Causes and Control; Soil Fertility for Urban Trees; Soil Drainage and Infiltration; Long Term Silviculture Implications in Urban Forestry; Methodology for soil on-site Soil Analysis. This text is full of new approaches and recognized problems. Very helpful to the general scientist in opening doors to interdisciplinary and urban applied science cooperation. Keys into the basic laws applied to an artificial system that buries the real urban nature.

4. Heath, R.C. 1983

Basic Ground-Water Hydrology: U.S.G.S. Water Supply Paper 2220 85 pp.

This government publication is a model textbook. It is informative and easy to read. Each concept or term is explained on a page with carefully chosen graphics and scientifically understandable English. Written as a technical report, it is a good review or beginning text for those who need to know the science and math of groundwater regime. A major *contribution* to having the educated citizens look at the facts of hydrology without a long formal course.

5. Heath, R.C.1984

Groundwater Regions of the U.S.: U.S.G.S. Water Supply Paper 2242. 78 pp.

A basic text on the general description of the 15 major ground-water regions of the U.S. An easy to read segment on the geologic background of concepts and terminology via diagrams is a key to the text. A series of references for each region is included. Discusses the history of establishing groundwater regions.

6. Lohman, S.W. 1972

Groundwater Hydraulics: U.S.G.S. Professional Paper 708. 70 pp.

Another classic report on the physics and math of the flow through permeable rock. It stresses the role of quantitative studies on; aquifers to store or transmit water. It enumerates on field tests of discharging wells and the derivation of equations for boundary *conditions*. Uses Baltimore for many of its problem examples (p. 48). Gives math foundation for all the flow concepts. Essential reading for those who will prepare computer models.

7. National Academy Press 1984

Groundwater Contamination: Studies in Geophysics - NAP. 79 pp.

A collection of research papers detailing the current scientific understanding of groundwater contaminant transport both in theory and by investigation of contaminated aquifers. The report bares the fundamental questions and uncertainties that require more research for the prediction of contaminant transport and control of groundwater contamination. Fourteen papers comprise the volume. Seven papers deal with case studies. The Delaware landfill site pertains to our study area.

8. Nutter, L.J. and Otton, E.G. 1969  
Groundwater Occurrence in the Maryland Piedmont, Md. Geo. Survey Report of Inv. #10. 56 pp.  
One of the earliest recent general reports to outline all the problems associated with theory and applications of squeezing water from the crystalline and sedimentary rocks of the Piedmont. A good summary of previous reports and their data. Gives many local examples with raw data as well as a good treatment of the geophysical methods just being applied to hydrology. Excellent background data on the science of the Piedmont system. Gives the quality and quantity of groundwater to be found and where. Maps and graphics are still valid.
9. Otton, E.G. , 1972  
Solid Waste Disposal in the Geohydrologic Environment of Maryland: MD.. Geo. Survey Report of Inv. #18. 59 pp.  
A summary report on the siting and evaluation of the state landfills. While this report is outdated and many of the sites are reclaimed or closed, it provides historical data on these areas. Gives a good treatment of the role of regional geology to landfills and their problems. Summarizes general data on what goes into a landfill. Uses data from case studies across the country. Good treatment of all the chemical problems from ordinary domestic waste.
10. Watt, M.H. and Sveinbjornsson, H., 1980  
"Notes on Water Supply Interconnections: Institutional Factors." DCWRRC Report No. 22, N.T.I.S., Springfield, Va. No. W81-02906. 49 p., 7 fig., 4 tab., 29 ref., 4 append. One way to increase water supply reliability in a given area is through the construction of water supply interconnections. Such an approach encompasses engineering, environmental, -legal and management factors; this report was focused mainly on institutional factors. Some comprehensive overview is provided on the potential benefits and problems associated with interconnections, with special reference to the Washington, D.C. Metropolitan Area (WMA). A brief description of basic features and historical examples of water supply interconnections is given, and recently proposed interconnections were analyzed.

11. Wyrick, G.G. and Borchers, J.W. 1981  
Hydrologic Effects of Stress-Relief Fracturing in an Appalachian valley: U.S.G.S. Water Supply Paper 2177. 51 pp.

An important case study on how fracture systems affect the occurrence and movement of groundwater. This study was made to determine how aquifer characteristics are related to fracture systems so that the relation could be applied to other valleys. The study was conducted primarily in the Appalachian Plateau Province. The geology is primarily for fractured horizontal beds.

ANNOTATED BIBLIOGRAPHY  
SELECTED GENERAL BACKGROUND  
REFERENCES

12. Baldwin, H.L. & Others, 1963

A Primer on Groundwater, USGS - Washington - GPO 26 p. Everything you wanted to know about groundwater in a simple straight-forward approach for the lay person. A series of simple but informative illustrations to carry the points of quantity and quality home to the reader.

13. Davis, G.H. & Others, 1983

Groundwater Issues and Answers: Am. Inst. of Prof. Geol., Arvada, Colorado. 24 p. A brief but current look at the major concerns about groundwater. Covers scientific, socio-economic, administration and legal aspects with pictures, tables, figures, and excellent short text. It informs and makes one think about our groundwater resources.

14. Froelich, A.J. & Others, 1980

Geologic and Hydrologic Nap Reports for Land-Use Planning in the Baltimore--Washington Urban Area: U.S.G.S. Circular 806. 12 p.

A summary of the data compiled for the Balt-Wash Urban area study. Geared to help the decision makers and land-use planners. It gives us our environmental meter stick to judge what impacts will take place for each option chosen. Gives a list of the general urban problems related to all land use. Groundwater is a part of the whole land use scheme. Excellent tables, figures and pictures of the fall line area are included.

15. Knapp, G.L. and Glasby, J.P., 1972

Urban Hydrology - A selected Bibliography with Abstracts: U.S.G.S. Water Resources Inv. 3-72.

This is a source document of 650 selected annotated references on the scientific and water-management needs. Has many early references to urban groundwater problems especially dealing with deicing. It concentrated on technical advances in the late sixties.

16. Mack, L. E. 1971 Groundwater Management in Development of a National Policy in Water: National Water Commission (Arlington, Va.) PB 201 536 NWC - EES - 71 - 004, 177 p.

This report is a readable overview of the role of groundwater, the fundamentals of groundwater hydrology, constraints on the optimum use of groundwater, and discussion of groundwater management. Thirteen conclusions and recommendations are given and are still quite important today. Excellent treatment of groundwater management as the application of four basic disciplines of which we must have communication and understanding. The four disciplines are engineering, socio-economic, administration, and law.

17. McGuinness, C.L. 1963

The Role of Groundwater in the National Water Situation: U.S.G.S. Water-Supply Paper 1800 1121 p.

A comprehensive federal report on the state of ground water resources in the early sixties. It includes a state-by-state description, which is now quite dated after twenty years. The ground regions defined by Thomas are now changed somewhat but the predictions of the Senate committee are still with us. Very interesting reading on our progression over the last twenty years and worth comparing to Water Supply Paper 2250 for the 1983 Summary of Water.

18. Nace, R.L. & Others 1957

Feasibility of Groundwater Features of the Alternate Plan for the Mountain Home Project Idaho: USGS W.S.P. 1376 121 p.

Water transfer projects are not new but this 50's plan to provide adequate supply is worth reviewing despite its basis in Idaho. Providing or exchanging water and its impact on the exporting and/or importing region are critical factors. Assessing the groundwater feasibility is a heavy step to using it as a substitute for surface supply lost or sold. This is a model study that could have many implications for our region very soon as in Richmond - Norfolk exchange. Aquifer test studies are quite useful.

19. Poland, J.F. & Others, 1972  
Glossary of Selected Terms Useful in Studies of the Mechanics of Aquifer Systems and Land Subsidence due to Fluid Withdrawal. USGS W.S.P. 2025 9 p.

Vocabulary in science is extremely difficult for citizens to comprehend. Hydrologic variation of usage by engineers, geologists, hydrologist and others made it necessary for glossaries to be written. A major groundwater hazard is land subsiding--the equations and concepts to prove failure are given. Both the math equations and English definitions are given for the necessary terms used in the physics of aquifer behavior in withdrawal of liquids.

20. Powers, J. Patrick 1981

Construction Dewatering, John Willey & Son, Inc. 484 p.

The dewatering study book is a summary of the theory, which involves the disciplines of soil mechanics, hydrology, geology, and fluid mechanics. New equipment and techniques for deep well construction developed for water supply wells are a more practical tool for dewatering. Dewatering studies include hydrologic analysis of dewatering system, piezometers, pumping test, groundwater chemistry and piping systems. On a practical impact, it concerns choosing a dewatering method, calculating dewatering cost, and designing dewatering specifications.

21. Rima, D.R. & Others, 1971

Subsurface Waste Disposal By Means of Wells - A Selective Annotated Bibliography: USGS Water Supply Paper 2020 305 p.

Reviews of literature are important steps to summarize what is known. The complications and desire to dispose of waste into the ground is still a current subject. Injection wells are currently a real problem since the Clean Stream Act of 1966. The references abstract include 692 items. Subject and geographic index included. All kinds of wastes are covered as well as legal and general reviews.

22. Robinson, G.P. and Speiken A.M. (ed) 1978  
Nature to be Commanded: U.S.G.S. Prof. Paper 950 95 p.

A unique Survey publication demonstrates the value of earth science maps applied to decision-making and management of different "urban settings. The groundwater problems of Long Island are covered in one chapter on the Atlantic Coastal Environment (p. 55) and the hydrological dilemmas of the coastal plain construction are covered in the next chapter (p. 69) for Fairfax County in Northern Va.Metro D.C. maps, cover topography, slope, landforms, geology, surface materials and depth cross-sections (suboutcrop) and stability.

23. Savini, J. & Kammerer, J.C., 1961

Urban Growth and the Water Regimen:USGS Water Supply Paper 1591 - A 43 p.

Part of a USGS series on the hydrologic effects of urban growth. Depicts the stages of urbanization and classifies the hydrologic effects. A good review of quality and quantity effects is standardized and dated, but worth reading. The second half deals mainly with surface water problems. Treats the population and urbanization of the 1950's.

24. Sinnott, A. & Cushing, E.M., 1978

Summary Appraisals of the Nation's Groundwater Resources - Mid-Atlantic Region: USGS Prof. Paper 813-I. 32 p.

The most recent regional federal survey of the study area is this report in the groundwater resources of the Mid-Atlantic. This report is of a series for the nation. Groundwater occurs in 3 broad geologic tennaves: Piedmont Coastal Plain, Glavated. Statistics on regional groundwater use and potential use are given maps and tables are regional basis.

25. Solley, W.B. & Others,1980

Estimated Use of Water in the U.S. in 1980: USGS Circular 1001 56 p.

Basic data and facts are always necessary and welcome to the researcher. Groundwater data is given on a state-by-state basis. Data is given in tables, maps, and figures for a variety of uses: public supply, irrigation and industry.

26. Todd, David Keith, 1980

Groundwater Hydrology, John Wiley & Son, Inc. 535 p.

Groundwater Hydrology presents the fundamentals of groundwater technology in a manner understandable to those most concerned topics include: occurrence of groundwater, groundwater movement, well hydraulics, levels and environmental influences, quality, pollution, modeling techniques, surface and subsurface investigations, artificial recharge, saline water intrusion and management of groundwater.

27. U.S.G.S. 1983 National Water Summary 1983  
Hydrologic Events and Issues: U.S.G.S. Water-Supply Paper 2250 243 p.

A refreshing new yearly water review that will continue. This data filled report summarized that Nation's State of their country's water. It describes major water issues state by state and the hydrologic impact. There is also a general overview of all the central public issues; hazardous waste, floods, acid rain, groundwater levels and public supply. There is a fair treatment of water quality issues. It has been the basis of many conferences and symposia this past year. Its calendar of events concerning hydrology during 82-83 is an eye-opener.

28. The D.C. Water Resources Research Center, 1980  
"DISTRICT OF COLUMBIA FIVE-YEAR WATER RESOURCES RESEARCH PROGRAM PLAN, 1982-1987", DCWRRC Report No. 24, NTIS Springfield, Va. No. W81-04306, 250 p., 35 Fig., 32 Table, 124 Ref.

The report describes the water resources situation in the District of Columbia. Research needs are identified; a 5-year research and development program plan for the D.C. Water Resources Research Center is presented. Geological, meteorological, biological and hydrological characteristics are described as well as surface and groundwater resources. Water resources problems are categorized and prioritized, and related agency activities are presented. The 5-year plan deals with water quantity and other related problems. Three-dimensional illustrations show details of physiography for the course of the Potomac River, physiographic provinces and geographic and geologic feature of the D.C. region, and cross sections of the Potomac River bed from 9 miles above Great Falls to the Atlantic Coastal plain.

29. Williams, Garnett P. 1977 Washington, D.C. - The Vanishing Springs and Waterways, U.S.G.S. Cir. 752 19 p.

The hydrologic history on any city is important to document. Urbanization is a stealer of both surface and subsurface waterways. The disappearance or reduction of DC springs and waterways is highlighted. Figures, pictures, tables, and historical clips related to the history of this city's lost rivers and favorite drinking sites.

SELECTED REFERENCES - CONSTRUCTION  
REPORTS

30. Greeley, Hansen, 1982, "Study Memorandum II - 4"  
  
Combined Sewer Overflow and Infiltration/Inflow Studies and Plans  
DCDES, Washington, DC.
31. Mathews, A.A., Inc., 1979, Crosstown Watermain: Alternative Alignment  
Study Vo. 1 - Design. Analysis Report Agreement: DCFA 156-DES  
DCDES, Washington, DC.
32. A.A. Mathews Div., 1982, CRS Group Engineers Division Crosstown  
Watermain Tunnel Section  
Geotechnical Report, DCDES, Washington, DC.
33. Mueser, Rutledge, Wentworth & Johnson, 1967, Final Report Subsurface  
Investigation  
Vol. 3 WMARTHA, B.S.: B&O Route
34. Mueser, et al., 1969,  
  
Final Report Subsurface Investigation  
  
Vol. 4 WMART Benning Route & Pentagon Route Contact TAC-2068-E,  
TAC 64-69-E Jan. 2, 1968
35. O'Brien and Gere, 1983,  
  
"Final Report" Combined Sewer Overflow Abatement Program, DCDES,  
Washington., DC.
36. Phillips, L.G. & Shadel, S.L., 1980,  
  
(Environmental Programs) Landfill Gas Testing Programs at  
Kenilworth and Oxon Cover Landfills. The Johns Hopkins University.  
Applied Physics Lab., 48 pp.
37. Reynolds, G. and Toto, J.V., 1963,  
  
Proposal for Subway Construction in Washington Dames  
& Moore, Rockville, Md.

## SELECT REFERENCES GUIDEBOOKS

38. Association of Engineering Geologists Field Trip Guide Book, 1976, Annual Meeting Association of Engineering Geologists, 105 pp.
39. Bally, A.W. & Others, 1981, Geology of Passive Continental Margins The American Association of Petroleum Geologists Eastern Section Meeting: Education Course Note Series #19
40. Crawford, W.A. & Crawford, M.L., 1974, Geology of the Piedmont of Southeastern Pennsylvania 39th Annual Meeting Pa. Geol. Field Conf. Bureau of Topographic & Geologic Survey - Penn. Department of Environmental Resources 104 pp.
41. Crowley, W.P. & Others, 1970, Guidebook for the 35th Annual Field Conference of Pennsylvania Geologists - New Interpretations of Eastern Piedmont Geology of Maryland or Granite and Gabbro or Graywacke and Greenstone: Maryland Geological Survey 60 pp.
42. Exline, J. (ed), 1981, Region I - Earth Science Field Guide: Three Sites Virginia Department of Education, Richmond 171 pp.
43. Fanning, D.S. & Others, 1983, Soils-Geomorphology Tour in Maryland Sponsored by S880 Committee of Soil Science Society of America 119 pp.
44. Johnson, G.H. & Others, 1983, Guidebook to the late Cenozoic Geology of the Lower York-James Peninsula Virginia 17th Annual Field Conference of the Atlantic Coastal Plain Geological Assoc. & 12 Annual Virginia Geo. Field Con. Department of Geology - The College of William & Mary 52 pp.
45. Mixon, R.B. & Newell, W.L., 1978, The Faulted Coastal Plain Margin at Fredericksburg, Virginia: 10th Annual Meeting Va. Geol. Field Conf. 50 pp.
46. O'Connor, J.V. & Others, 1974, A Guide to Theodore Roosevelt Island in the Potomac-Washington, D.C. Joint Project of Geol. Soc. of Washington & USGS-MPES Program. 10 p.

47. O'Connor, J.V., 1982, An Old Fashioned Geologic Excursion Through Rock Creek Valley, N.W., Washington, D.C., Un. of the District of Columbia Geoscience Guidebook 3 22 pp.
48. O'Connor, J.V. and Washington, C.F., 1977, Urban Geology of the Nation's Capital in Ridky, R.W. (ed) Guidebook for Field Trips in Maryland & The national Capital Area: Eastern Region of NAGT Annual Field Conf., University of Maryland.
49. O'Connor, J.V., 1984, Urban Geomorphology and Soils of the Nation's Capital in Am. Asso. Geog. Guidebook Annual Meeting, p. 100-105 plus maps.
50. O'Connor, J.V. & Marks, W.D., 1982, The Red Line: Landscape and Land Use Assessment UDC - Department of Earth and Life Science Geoscience Guidebook 9 p.
51. Olson, Carolyn G. (Ed), 1983, Soils and Land Use Tour Division S-5 American Society of Agronomy: Soil Science Society of America Annual Meeting - Washington
52. Owens, J.P. & Others, 1977, A Field Guide to Cretaceous and Lower Tertiary Beds of the Raritan & Salisbury Embayments, New Jersey, Delaware & Maryland AAPG & SEPM Annual Meeting (June, Washington, DC) 113 pp.
53. Ozol, M.A. (ed), 1978, Proceedings: 29th Annual Highway Geology Symposium at Annapolis, Md. 331 pp.
54. Patterson, J. & Others, 1981, Urban Forest Soils Field Tour - Urban Soil Conference University of Maryland, April 27, 1981 51 pp.

## SELECT REFERENCES - GEOGRAPHY

55. Cady, R.C., 1933, "Preliminary Report on Ground Water Resources of Northern Virginia: Virginia Geological Survey Bull. #41
56. Cady, J.L., 1938, Ground-Water Resources of Northern Virginia: Virginia Geological Survey. Bull. 50
57. Comer, C.D., 1976, "Prince William County Ground Water Present *Conditions* and Prospects. State Water Control Board, *Planning* Bull. 303
58. Darton, N.H., 1896, Artesian Well Prospects in the Atlantic Coastal Plain Region: U.S.G.S. Bull. #138
59. *Dingman, R.J.*, and Meyer, G., 1954, The Water Resources of Howard and Montgomery Counties - the Ground-Water Resources: Dept. of Geo., Mines and Water Resources Bull. 14
60. Greenman, David W., 1955, Ground Water Resources of Bucks County, *Pennsylvania*: Topographic and Geo. Survey Penn.
61. Greenman, D.W. and others, 1961, Ground Water Resources of the Coastal Plain Area of Southeastern Pennsylvania: Penn. Geo. Survey Bull. W13
62. Hahn, William F., 1977, Ground Water *Investigations* in the Delaware Piedmont for the city of Newark, 1976: Delaware Geo. Survey Rep. of Invest. #27
63. Halle, George M., 1973, Ground-Water in Southeastern Pennsylvania Geo. Survey Bull. W2
64. Johnston, P.M., 1962, Geology and Ground-Water Resources of the Fairfax Quadrangle Virginia: U.S. Geo. Survey Water Supply paper 1539-L
65. Johnston, P.M., 1964, Geology and Ground-Water Resources of Washington, D.C. and Vicinity: U.S. Geo. Survey Water Supply paper 1776
66. Lucas, Richard C., 1976, Anne Arundel County Ground Water *Information* Selected Well Records, Chemical Quality Data, Pumpage, Appropriation Data, and Selected Well Logs: Maryland Geo. Survey Water Res. Basic Data Rep. #8

67. Mack, Frederick K., 1966, Ground Water in Prince Georges County: Maryland Geo., Survey Bull. #29
68. McGreevey, L.J., and Sloto, R.A., 1977, Ground-Water Resources of Chester County, Pennsylvania: U.S.G.S. Water Resources Investigations 77-67 Open File Report
69. Nutter, L.J. and Otton, E.G., 1969, Ground Water Occurrence in the Maryland Piedmont: Maryland Geo. Survey Report of Investigation #10
70. Nutter, L.J. and Smigaj, M.J., 1975, Harford County GroundWater Information: Well Records, Chemical Quality Data, and Pumpage: Maryland Geo. Survey Water Res. Basic Data Rep. #7
71. Nutter, Larry J., 1977, Ground Water Resources of Harford County, Maryland: Maryland Geo. Sur. Bull. #32
72. O'Bryan, R.L. and McAvoy, R.L., 1966, Gunpowder Falls, Maryland: U.S. Geo. Sur. Water-Supply Paper 1815
73. Otton, E.G., Martin R.O.R. and Durum, W.A., 1964, Water Resources of the Baltimore Area, Maryland: U.S. Geo. Sur. Water-Supply Paper 1499
74. Rasmussen, W.C., and Andreasen, G.E., 1957, Hydrologic Budget of the Beaverdam Creek Basin Maryland: U.S. Geo. Survey Water-Supply Paper 1472
75. Richardson, C.A., 1982, Ground-Water in the Piedmont Upland of Central Maryland: U.S. Geo. Survey Water-Supply Paper 2077
76. Rosenau, J.C., and others, 1969, Geology and Ground-Water Resources of Salem County, New Jersey: U.S. Geo. Survey Special Report No. 33
77. Stuart, W.T., Schneider, W.J., and Crooks, J.W. 1967, Swatara Creek Basin of Southeastern Pennsylvania: U.S. Geo. Survey Water-Supply Paper 1829
78. Talley, John H., 1974, Hydrogeology of Selected Sites in the Greater Newark Areas, Delaware: Delaware Geo. Survey Rep. of Invest. #22

79. Tumpkins, Michael D., 1983, Prince Georges Co. Ground-Water Information: Well Records Chemical Quality Data, Pumpage, Appropriation Data, Observation Well Records and Well Logs: Maryland Geo. Sur. Water Res. Basic Data Rep. #13
  
80. Woodruff, K.D. 1972, Geology and Ground Water, University of Delaware, Newark, Delaware: Delaware Geo. Survey Rep. of Invest. #18

## SELECT REFERENCES – QUANTITY

81. Bennett, Robert R., 1945, Exploratory Test - Well Drilling in the Sparrows Point Area, MD: MD Dept. of Geo., Mines or Water Res. Maryland
82. Cederstrom, D.J. 1972, Evaluation of Fields of Walls in Consolidated Rocks, Virginia to Maine: U.S. Geological Survey Water Supply Paper 2021
83. Groot, J.J. and Demicco, P.M. and Cherry, P.J., 1983, Ground Water Availability in Southern New Castle County, Delaware: Delaware Geo. Survey Open file Report #27
84. Grossman, Max and Sherman, N., A.L., 1963, "Report" Present and prospective use of Water: The Manufacturing Industries New Jersey.
85. Hoyt, John C., 1936, Droughts of 1930 - 34: U.S.G.S. WaterSupply Paper #680
86. Johnston, P.M., 1960, Ground Water Supplies in Shale and Sandstone in Fairfax, Loudoun, and Prince William Counties, Virginia: U.S. Geo. Survey Circular #424
87. Meinzer, O.E. and Wenzel, L.K., 1944, Water Levels and Artesian Pressure in Observation Wells in the United States in 1942 Part 1. Northeastern States: U.S.G.S. Water Supply Paper.
88. Meinzer, O.E., and Wenzel, L.K. and others 1944, Water Levels and Artesian Pressure in Observation Wells in the United States in 1942 "Part 2." Southeastern State: U.S.G.S. Water Supply Paper #945
89. Nutter, L.J.:, 1974, Well Fields in the Bedrock Aquifer of Maryland, Maryland Geo. Survey Inf. Cir. #16
90. Popodopulus S.S. and other, 1974, Water from the Coastal Plain Aquifers in the Washington, D.C., :Metropolitan Area: U.S. Geo. Survey Circular #697
91. Sayse, A.N., 1954, Water Levels and Artesian Pressures in Observation= Wells in the United States in 1951 "Part I Northeastern States": U.S.G.S. Water-Supply Paper #1191

92. Sayse, A.N., 1954, Water Levels and Artesian Pressures in Observation Well in the United States in 1951 "Part II Southeastern States," U.S.G.S. W.S.P. #1192
93. Sinnott, A. and Cashing, E.M. 1978, Summary Appraisals of the Nation's Ground-Water Resources - Md. Atlantic Region: U.S. Geo. Survey Professional Paper 813 – I
94. Talley, John H. 1978, Ground-Water Levels in Delaware July, 1966 December, 1977: Del. Geo. Sur. Rep. of Invest. #30
95. Talley, John H. and Hahn, W.F., 1978, Well and Aquifer Tests, Laud Tract Well Field, Newark, Delaware: Delaware Geo. Survey Rep. of Invest. #28
96. Thelen, E. and Howe, L.F. 1978, Porous Pavement: Franklin Institute Press.
97. Woodruff, K.D. 1967, Ground-Water Levels in Delaware January, 1962 - June, 1966: Delaware Geo. Survey Rep. of Invest. #9

## SELECT REFERENCES – QUALITY

98. Back, W. and Barnes, I, 1965, Relation of Electrochemical Potentials and Iron Content to Ground-Water Flow Patterns: U.S. Geological Survey Professional Paper 498 - C, 16 p.
99. Biesecker, J.E., and Leifesfe, D.K., 1975, Part E - Water Quality of Hydrologic Bench Marks - An Indicator of Water Quality in the Natural Environment: U.S. Geo. Survey Circular, 460 – E
100. Cederstrom, D.J., 1943 Chloride in Ground Water in the Coastal Plain of Virginia: Virginia Geological Survey Bull. #58
101. Cedersdtrom, D.J., 1946, "Chemical Character of Ground Water in Coastal Plain of Virginia Geological Survey Bull. #68
102. Geyer, John C., 1945 Ground Water in the Baltimore Industrial Area: 17 D State Planning Commission 9-49
103. Groot, Johan J., 1983, Salinity Distribution and GroundWater Circulation beneath the Coastal Plain of Delaware and the Adjacent Continental Shelf: Delaware Geo. Survey Open File Report #26
104. Holsinger, John R., 1967, Systematics, Species and Distribution of the Subteranean Amphipod Genus Stygonectes (Gammaridea): U.S. Nat. Museum Bull. 259 Smithsonian Institution Press
105. Holsinger, John R., 1978, Systematics of the Subteranean Amphipod Genus Stygonectes Part II; Species of the Eastern United States.
106. Langmuir, D., 1969, Iron in Ground Waters of the Magothy and Raritan Foundations in Camden and Burlington Counties, New Jersey: N.J. Geo. Survey Water Resources Circular No. 19
107. Miller, John C., 1972 Nitrate Contamination of the Water Aquifers in Delaware: Delaware Geo. Survey Rep. of Invest. #20
108. Schaefer, F.L. and Walker, R.L., 1981, Saltwater Intrusion into the Old Bridge Aquifer in the Keyport - Union Beach Area of Monmouth County, New Jersey: U.S. Geo. Survey Water Supply Paper 2184

109. Schneider, N.J., 1970, Hydrologic Implication of SolidWaste Disposal: U.S. Geo. Survey Circular 601-F.
110. Spoljaric, N. and Crawford, W.A. 1979, Renewal of Metals from Laboratory Solutions and Landfill Leachete by Greensand filters: Delaware Geo. Survey Rep. of Invest. #32
111. Swenson, H.A. and Baldwin, H.L. 1965, A Primer on Water Quality: U.S. Geological Survey.
112. Talley, John H., 1981, Sinkholes, Hockessin Areas, Delaware: Delaware Geo. Survey Open File Report #14
113. Thomas, J.D. and Herdel, S.G. 1969, Chemical and Physical Character of Municipal Water Supplies in Maryland: Maryland Geo. Survey Rep. of Invest. #9
114. Turk, John T. 1983, An Evaluation of Trends in the Acidity of Precipitation and the Related Acidification of Surface Water in North America: U.S.G.S. Water Supply Paper 2249
115. Woll, Richards 1978, Maryland Ground Water Information: Chemical Quality Data: Maryland Geo. Survey Water Resources Basic-Data Rep. #10
116. Woodruff, K.D., 1969, The Occurrence of Saline Ground Water in Delaware Aquifers Delaware Geo. Survey Rep. of Invest. #3 or #13
117. Woodruff, K.D. 1970, General Ground-Water Quality in Rush Water Aquifers of Delaware: Del. Geo. Sur. Rep. of Invest. #15

SELECT REFERENCES -  
GENERAL

118. Calver, J.L., 1973, Geologic Studies, Coastal Plain of Virginia: Virginia Division of Mineral Resources Bull. 83 (Part 1 and 2)
119. Cederstrom, D.J., 1945, Geology and Ground-Water Resources of Coastal Plain in Southeastern Virginia: Virginia Geological Survey Bull. 63
120. Cleaves, Emery T., 1968, Piedmont and Coastal Plain Geology along the Susquehanna Aqueduct, Baltimore to Aberdeen, Maryland: Maryland Geologic Survey Report of Invest. #8
121. Darton, N.H., 1951, Structural Relations of Cretaceous and Tertiary Formation's in Part of Maryland and Virginia: Bulletin of the Geological Society of America Vol. 62
122. Glaser, J.D., 1969, Petrology and Origin of Potomac and Magothy Sediments, Middle Atlantic Coastal Plain: Maryland Geological Survey Report of Investigations No-11
123. Hansen, H.J., 1974, Sedimentary Facies of the Aqua Formation in the Subsurface of the Maryland Coastal Plain: Maryland Geo. Survey of Investigation No. 21
124. Hansen, H.J., 1978, Upper Cretaceous (SENONIAN) and Pleistocene (DANIAN) Pinchouts on the south flemko of the Salisbury Embayment, Maryland, and their Relationship to Antecedent Basement Structures: Maryland Geo. Survey Report of Investigations No. 29
125. Jordon, R.R., 1964, Columbia Sediments of Delaware: Delaware Geological Survey Bull. No. 12
126. Kraft, J.C. and Carey, W., 1980, Selected Papers on the Geology of Delaware: Delaware Academy of Science Vol. 7 1976
127. Rasmussen, W.C., O'Dell, J.W. and Beamer, N.H., 1966, Delaware Water: U.S. Geo. Survey Water-Supply Paper 1767
128. Association of Engineering Geologist and American Society of Civil Engineers, 1984, Geologic and Geotechnical Problem in Karstic Limestone of the Northeastern U.S. 1984 AEG/ASCE Symposium Sponsors

129. Schneider, W.J., Richard, D.A. and Spieker, A.M., 1978 Role of Water in Urban Planning and Management: U.S. Geo. Survey Circular 601-H
130. Spoljaric, Nonad 1967, Quantitative Lithofacies Analysis of Potomac Formation, Delaware: Delaware Geo. Survey, Report of Invest. #12
131. Spoljaric, Herad 1972, Geology of the Fall Zone in Delaware: Delaware Geo. Survey Rep. of Invest. #19
132. Thomas, H.E., and Schneider, W.J. 1970, Water as an Urban Resource and Nuisance: U.S. Geo. Sur. Cir. 601-D.

## SELECT REFERENCES - MODELS

133. Appel, C.A. and Bredhoe ft, J.D., 1976, Status of GroundWater Modeling in the U.S.Geological Survey: U. S. Geological Survey Circular #737
134. Hansen, H.J., 1972, A User's Guide for the Artesian Aquifer of the Maryland Coastal Plain - Part one: Introductory Definitions and Examples: Dept. of Natural Resources Maryland Geo. Survey
135. Hansen, H.J., 1972, A User's Guide for the Artesian Aquifer of the Maryland Coastal Plain - Part two: Aquifer Characteristics: Department of Natural Resources Maryland Geo. Survey
136. Johnston, Richard H., 1977, Digital Model of the unconfined Aquifer in Central and Southeastern Delaware: Delaware Geo. Survey Bull. #5
137. Kapple, G.W. and Hansen, H.J., 1976, A Digital Simulation Model of the Aquifer in Southeastern Maryland: Maryland Geo. Survey Inf or. Ar. #20
138. Leahy, P.P., 1979, Digital Model of the Piney Point Aquifer in Kent County, Delaware: Delaware Geo. Survey Rep. of Invest. #29
139. Leahy, Patrick P., 1982, Ground-Water Resources of the Piney Point and Cheswold Aquifers in Central Delaware as determined by a flow model: Del. Geo. Survey Bull. #16
140. Mack, Frederick K., 1974, In Evaluation of the Magothy Aquifer in the Annapolis Area, Maryland: Maryland Geo. Survey Rep. of Invest. #22
141. Mack, F.K., and Mandle, R.J., 1977, Digital Simulation and Prediction of Water Levels in the Magothy Aquifer in Southern Maryland: Maryland Geo. Sur. Rep. of Invest. #28

## SELECT REFERENCES - TECHNIQUES

142. Bentall, Ray 1963, Methods of Collecting and Interpreting Ground-Water Data: U.S. Geo. Survey Water-Supply Paper 1544-H
143. Bonini, William E., 1967, An Evaluation of the Resistivity and Seismic Refraction Techniques in the search for Pleistocene Channels in Delaware: Delaware Geological Survey Rep. of Invest. #11
144. DeBuchananne, G.D., 1977, Role of Earth Sciences in the Disposal of Radioactive waste: U.S. Geological Survey Reprint
145. Feth, J.H., 1973 Water Facts and Figures for Planners and Managers U.S. Geological Survey Circular 601-1
146. Le Grand, H.E., 1967, Ground Water of the Piedmont and Blue Ridge Provinces in the Southeastern States: U.S. Geo. Sur. Circular 538
147. Nace, R.L., West, S.W. and Mower, R.W., 1957, Feasibility of Ground-Water Features of the Alternate Plan for the Mountain Home Project Idaho: U.S. Geo. Sur. Water-Supply Paper 1376
148. Schnieder, Robert, 1962, An Application of Thermometry to the study of Ground-Water: U.S. Geo. Survey Water Supply Paper 1544-B
149. Snyder, D.M., 1983, Water Well Computer File - A Status Report "Geology Pennsylvania": Pennsylvania Geo. Survey vol. 14/5
150. Solley, W.B., Chase, E.B. and Mann III, W.B., 1980 Estimated Use of Water in the United States in 1980: U.S. Geo. Survey Circular 1001
151. Talley, John H., 1980, Effects of Earthquakes. and Earth Tides on Water Levels in Selected Wells in the Piedmont of Delaware: Del. Geo. Survey Open File Report #11
152. Woodruff, K.D., 1971, Application of Geophysics to Highway Design in the Piedmont of Delaware: Delaware Geo. Survey Rep. of Invest. #16

