GROUNDWATER PROBLEMS IN THE MID-ATLANTIC FALL LINE CITIES

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ACKNOWLEDGMENT

In the course of a discussion about D.C. water resource problems, Mr. William Johnson, then-Director of the Department of Environmental Services, suggested a study to look at the impact of the construction industry on the groundwater of the District of Columbia. This project was formulated from this idea. The principal investigators would like to express their gratitude to Mr. William Johnson for his suggestion and support of the Water Research Center's activities. We would also like to express our gratitude to Mr. Kwaku Mensa Nunuye (Saudi Arabian Dames and Moore) for his involvement during the initial stages of the project formulation. We would like to thank all the individuals who have been involved in either answering our questions, providing reference materials or suggesting solutions to issues that concerned the project. Special thanks to the following: Richard Brillantine and David Loveland (D.C. Regulatory and Consumer Affairs, DCRA), Herbert T. Hopkins (U.S. Geological Survey in Richmond, Virginia), Donald Jackson (Geraghty and Miller, Inc.), Brian Beard (Schnabel), Robert Bryant (Bryant and Bryant Architects), Robert R. Jordan, State Geologist, and Philip J. Cherry, Hydrogeologist (State of Delaware), W. Jerrold Samford, Chief Regional Geologist (State Water Control Board, Commonwealth of Virginia), Bob Ford, Peggy Fleming, James Patterson, Richard Hammerschlag and Robert Cooke (National Park Service), and finally. Col. Audette, Real Estate Broker (Georgetown).

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DISCLAIMER

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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 near 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 (flopped quarries or pits)
   ost recharge area
   groundwater basins

III. Construction Dilemmas
   dewatering - add watering
   water in-fill (bathtub 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 insectides, 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>
<thead>
<tr>
<th>Decade</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1890's</td>
<td>Public Industrial Supply, Health and Disease (N.H. Darton logged the chemistry and geology of numerous fall line wells)</td>
</tr>
<tr>
<td>1930's</td>
<td>Drought Conditions of the East Coast</td>
</tr>
<tr>
<td>1940's</td>
<td>Baltimore Industrial Survey</td>
</tr>
<tr>
<td>1950's</td>
<td>Housing after WW II – state planning and zoning reports</td>
</tr>
<tr>
<td>1965</td>
<td>Urban Renewal and Water in the Urban Environment – resource and hazard reports</td>
</tr>
<tr>
<td>1960</td>
<td>Environmental Movement and Clean and Safe Water Acts</td>
</tr>
<tr>
<td>1970's</td>
<td>Clean-up Programs and Transit Programs, Role of Contamination and Construction Impacts</td>
</tr>
<tr>
<td>1980's</td>
<td>Groundwater Basin Science Reports and Regulations</td>
</tr>
</tbody>
</table>
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).

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 that 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..Papadopulus and Associates,. Inc. - Rockville, Maryland
7. Dames and Moore, Ltd. - Bethesda, Maryland
9. Cather De Leuw (Metro Subway)
11. Bryant and Bryant, Architects - Washington, D.C.
13. U.S. Geological Survey - Maryland-Delaware-D.C. - Towson, 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)
20. State Water Resources Research Center - Virginia - VPI (Blacksburg)
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).

<table>
<thead>
<tr>
<th>Changes in land or water use</th>
<th>Possible hydrologic effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transition from pre-urban to early urban stage:</td>
<td>Decrease in transpiration and increase in storm flow. Increased sedimentation of streams.</td>
</tr>
<tr>
<td>Removal of trees or vegetation ---</td>
<td>Some lowering of water table.</td>
</tr>
<tr>
<td>Construction of scattered city-type houses and limited water and sewage facilities.</td>
<td>Some increase in soil moisture and perhaps a rise in water table. Perhaps</td>
</tr>
<tr>
<td>Drilling of wells ----------------------------</td>
<td>some waterlogging of land and contamination of nearby wells or streams</td>
</tr>
<tr>
<td>Construction of septic tanks and sanitary drains.</td>
<td>from overloaded sanitary drain system.</td>
</tr>
<tr>
<td>Transition from early-urban to middle-urban stage:</td>
<td>Accelerated land erosion and stream sedimentation and aggradation. Increased flood flows.</td>
</tr>
<tr>
<td>Building of land for mass housing, some topsoil removed, farm ponds filled in.</td>
<td>Elimination of smallest streams.</td>
</tr>
<tr>
<td>Mass construction of houses, paving of streets, building of culverts.</td>
<td>Decreased infiltration, resulting in increased flood flows and lowered</td>
</tr>
<tr>
<td></td>
<td>ground-water levels. Occasional flooding at channel constrictions (culverts) on</td>
</tr>
<tr>
<td></td>
<td>remaining small streams. Occasional over-topping or undermining of banks of</td>
</tr>
<tr>
<td></td>
<td>artificial channels on small streams.</td>
</tr>
<tr>
<td>Discontinued use and abandonment of some shallow wells.</td>
<td>Rise in water table.</td>
</tr>
<tr>
<td>Diversion of nearby streams for public water supply.</td>
<td>Decrease in runoff between points of diversion and disposal.</td>
</tr>
<tr>
<td>Untreated or inadequately treated sewage discharged into streams or disposal wells.</td>
<td>Pollution of stream or wells. Death of fish and other aquatic life. Inferior</td>
</tr>
<tr>
<td></td>
<td>quality of water available for supply and recreation at downstream populated areas.</td>
</tr>
<tr>
<td>Transition from middle-urban to late-urban stage:</td>
<td>Reduced infiltration and lowered water table. Streets and gutters act as storm drains</td>
</tr>
<tr>
<td>Urbanization of area completed by addition of more houses and streets, and of public,</td>
<td>creating higher flood peaks and lower base flow of local streams.</td>
</tr>
<tr>
<td>commercial, and industrial buildings.</td>
<td>Increased pollution of streams and concurrent increased loss of aquatic life. Additional</td>
</tr>
<tr>
<td></td>
<td>degradation of water available to downstream users.</td>
</tr>
<tr>
<td>Larger quantities of untreated waste discharged into local streams.</td>
<td>Rise in water table.</td>
</tr>
<tr>
<td>Abandonment of remaining shallow wells because of pollution.</td>
<td>Increase in local streamflow if supply is from outside basin.</td>
</tr>
<tr>
<td>Increase in population requires establishment of new water supply and distribution systems,</td>
<td></td>
</tr>
<tr>
<td>construction of distant reservoirs diverting water from upstream sources within or outside</td>
<td></td>
</tr>
<tr>
<td>basin.</td>
<td></td>
</tr>
<tr>
<td>Channels of streams restricted at least in part to artificial channels and tunnels.</td>
<td></td>
</tr>
<tr>
<td>Transition from middle-urban to late-urban stage - Continued</td>
<td></td>
</tr>
<tr>
<td>Construction of sanitary drainage system and treatment plant for</td>
<td>Increased flood damage (higher stage for a given flow). Changes in channel geometry and</td>
</tr>
<tr>
<td>sewage.</td>
<td>sediment load.</td>
</tr>
<tr>
<td>Improvement of storm drainage system.</td>
<td>Aggradation.</td>
</tr>
<tr>
<td>Drilling of deeper, large-capacity industrial wells.</td>
<td>Removal of additional water from the area, further reducing infiltration and recharge of</td>
</tr>
<tr>
<td></td>
<td>aquifer.</td>
</tr>
<tr>
<td></td>
<td>Lowered water-pressure surface of artesian aquifer; perhaps some local overdrafts</td>
</tr>
</tbody>
</table>
|                                                                                           | (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.                                                                       |
| Increased use of water for air conditioning.                                                |                                                                                          |
| Drilling of recharge wells ------------------                                             |                                                                                          |
| Waste-water reclamation and utilization.                                                    |                                                                                          |
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 around 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 Trio-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
Figure 5. Comparison of precipitation and fluctuation of the water table in the Fall Zone (O'Connor 1984).
<table>
<thead>
<tr>
<th>Problem</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>2. Pipe failures (frozen ground)</td>
<td>Newspapers (ref. Washington Post)</td>
</tr>
<tr>
<td>3. Buried landforms (rivers, swamps, marshes)</td>
<td>Tiber Creek; U.S. Naval Observatory: Mayflower Hotel Swamp</td>
</tr>
<tr>
<td>4. Cat clays (sulphur rich)</td>
<td>Anne Arundel County, Rt. 50, B.W. Parkw. Soil surveys (ref. Prince George's)</td>
</tr>
<tr>
<td>5. Seasonal high water tables</td>
<td>Montgomery &amp; Fairfax Counties, or N.W. Washington, D.C. Subway Construction in N.W. Zoo</td>
</tr>
<tr>
<td>6. Saprolite sponge</td>
<td>N.E. and S.E. D.C.</td>
</tr>
<tr>
<td>7. Rock Fracture System (Piedmont)</td>
<td></td>
</tr>
<tr>
<td>8. Endangered species</td>
<td></td>
</tr>
<tr>
<td>9. Perched water tables</td>
<td></td>
</tr>
<tr>
<td>10 a. Springs (historic)</td>
<td></td>
</tr>
<tr>
<td>b. (active)</td>
<td></td>
</tr>
<tr>
<td>11. Saltwater Intrusion</td>
<td>Pierce Mill, Capital Hill</td>
</tr>
<tr>
<td>12. Septic Systems discharge</td>
<td>FBI buildings, Zoo, River Road</td>
</tr>
<tr>
<td>13. Street salting/abrasives</td>
<td>Baltimore Inner Harbor</td>
</tr>
<tr>
<td>(open)</td>
<td>Arlington County Treatment Plant</td>
</tr>
<tr>
<td>16. Leakage from water/sewerage pipes</td>
<td>Kenilworth, Oxon Cove</td>
</tr>
<tr>
<td>17. Water In-filling (bath tub effect)</td>
<td>Prince William County Government records</td>
</tr>
<tr>
<td>18. Dewatering (wooden piles)</td>
<td>(Infiltration Study D.C., Phil.)</td>
</tr>
<tr>
<td>19. Cement mattress</td>
<td>Cherry Trees: Tidal Basin area</td>
</tr>
<tr>
<td>20. Change of flow direction</td>
<td>Gallery Place</td>
</tr>
<tr>
<td>21. Carbonate build-up (stalactites/stalagmites)</td>
<td>Construction at Van Ness St. (south sick Lincoln Memorial and U.D.C. Garage Level C</td>
</tr>
<tr>
<td>22. Mineral resource operations</td>
<td>Sylvan Dell Quarry, Savage Quarry</td>
</tr>
<tr>
<td>23. Dredged soils</td>
<td>Masonville</td>
</tr>
<tr>
<td>25. Hazardous - arsenic</td>
<td>Alexandria Waterfront</td>
</tr>
<tr>
<td></td>
<td>God's Dump 28th St. S.E.</td>
</tr>
<tr>
<td>27. Illegal disposal site</td>
<td>Fort Myer Military Base (Arlington)</td>
</tr>
<tr>
<td>28. Injection wells</td>
<td>Impervious land use change</td>
</tr>
<tr>
<td>29. Lost recharge area</td>
<td>UDC campus - Van Ness</td>
</tr>
<tr>
<td>30. Subsidence (fill)</td>
<td>Ohio Drive S.W. (Hairs Pt.)</td>
</tr>
<tr>
<td>31. Groundwater laws per state</td>
<td>Mont. Co., MD, well casing regulations</td>
</tr>
</tbody>
</table>
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>
<thead>
<tr>
<th>Source</th>
<th>Joint Set</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Fellow's (1950)</td>
<td>S:N42°E</td>
<td>S:N40°W</td>
<td>S:N72°W</td>
<td>S:← Strike</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D:68°SE</td>
<td>D:60°NE</td>
<td>D:Vertical</td>
<td>D:← Dip</td>
<td></td>
</tr>
<tr>
<td>Johnston (1964)</td>
<td>S:N-S</td>
<td>S:N30° to 50°E</td>
<td>D:35° to 65°SE</td>
<td>S:N70°W</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D:60°W to</td>
<td>Vertical</td>
<td>(Lineation)</td>
<td>N70°E</td>
<td>D:Vertical to 60°</td>
</tr>
<tr>
<td>Cloos (1964)</td>
<td>S:N20°E</td>
<td>S:N70°W</td>
<td></td>
<td>D:70°NE</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D:60°SE</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>D:55°W</td>
<td>D:44°SE</td>
<td>D:53°NE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MRWJ, A-9 (1973)</td>
<td>S:N5° to 10°W</td>
<td>S:N50°E</td>
<td></td>
<td>S:N60°W</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D:60° to 75°W</td>
<td>D:50° to 70°SE</td>
<td></td>
<td>D:70° to 90°N</td>
<td></td>
</tr>
<tr>
<td>MRWJ, Beth. Station</td>
<td>S:N5° to 10°W</td>
<td>S:N40°E</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1974)</td>
<td>D:40° to 70°W</td>
<td>D:30° to 65°SE</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(also foliation)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MRWJ, Medical Center Station</td>
<td>Horizontal jointing and indistinct</td>
<td></td>
<td>S:N60° to 90°W</td>
<td>S:N5°W</td>
<td></td>
</tr>
<tr>
<td>(1974)</td>
<td>foliation are characteristic</td>
<td></td>
<td>D:65° to 75°NE</td>
<td>D:50° to 75°E (Primary)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D:60° to 80°W</td>
<td>D:70° to 80°S</td>
<td>D:50° to 80°E</td>
<td>D:65°NE</td>
<td></td>
</tr>
</tbody>
</table>
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.

<table>
<thead>
<tr>
<th>SOIL TYPES</th>
<th>PERCENTS</th>
<th>AREA (ACRES)</th>
<th>YEARLY GROUNDWATER RECHARGE (x 10^7 gal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ashe</td>
<td>0.4</td>
<td>174</td>
<td></td>
</tr>
<tr>
<td>Brandywine</td>
<td>1.2</td>
<td>353</td>
<td></td>
</tr>
<tr>
<td>Glenelg (v)</td>
<td>0.2</td>
<td>81</td>
<td></td>
</tr>
<tr>
<td>Glenelg (r)</td>
<td>0.6</td>
<td>304</td>
<td></td>
</tr>
<tr>
<td>Manor</td>
<td>3.2</td>
<td>1,430</td>
<td></td>
</tr>
<tr>
<td>Neshaminy</td>
<td>0.4</td>
<td>172</td>
<td></td>
</tr>
<tr>
<td><strong>SUBTOTAL</strong></td>
<td><strong>6.0</strong></td>
<td><strong>2,514</strong></td>
<td><strong>731</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Soil Types</th>
<th>PERCENTS</th>
<th>AREA (ACRES)</th>
<th>YEARLY GROUNDWATER RECHARGE (x 10^7 gal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Christiana</td>
<td>1.3</td>
<td>534</td>
<td></td>
</tr>
<tr>
<td>Croom</td>
<td>0.9</td>
<td>358</td>
<td></td>
</tr>
<tr>
<td>Chillum</td>
<td>0.7</td>
<td>321</td>
<td></td>
</tr>
<tr>
<td>Joppa</td>
<td>0.5</td>
<td>250</td>
<td></td>
</tr>
<tr>
<td>Keyport</td>
<td>0.4</td>
<td>158</td>
<td></td>
</tr>
<tr>
<td>Matapeake</td>
<td>0.1</td>
<td>42</td>
<td></td>
</tr>
<tr>
<td>Sassafiras</td>
<td>1.6</td>
<td>710</td>
<td></td>
</tr>
<tr>
<td>Sunnyside</td>
<td>0.5</td>
<td>257</td>
<td></td>
</tr>
<tr>
<td>Rumford</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Galestown</td>
<td>0.2</td>
<td>116</td>
<td></td>
</tr>
<tr>
<td>Beltsville</td>
<td>0.1</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>Fallsington</td>
<td>0.1</td>
<td>37</td>
<td></td>
</tr>
<tr>
<td>Bourne</td>
<td>0.2</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>Woodstown</td>
<td>0.4</td>
<td>174</td>
<td></td>
</tr>
<tr>
<td>Muirkirk</td>
<td>1.9</td>
<td>797</td>
<td></td>
</tr>
<tr>
<td><strong>SUBTOTAL</strong></td>
<td><strong>7.9</strong></td>
<td><strong>3,896</strong></td>
<td><strong>1,164</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Soil Types</th>
<th>PERCENTS</th>
<th>AREA (ACRES)</th>
<th>YEARLY GROUNDWATER RECHARGE (x 10^7 gal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Codorus</td>
<td>0.4</td>
<td>191</td>
<td></td>
</tr>
<tr>
<td>Iuka</td>
<td>0.6</td>
<td>273</td>
<td></td>
</tr>
<tr>
<td>Bibb</td>
<td>0.4</td>
<td>174</td>
<td></td>
</tr>
<tr>
<td>Lindsale</td>
<td>0.3</td>
<td>219</td>
<td></td>
</tr>
<tr>
<td>Melvin</td>
<td>0.3</td>
<td>117</td>
<td></td>
</tr>
<tr>
<td>Dunning</td>
<td>0.1</td>
<td>51</td>
<td></td>
</tr>
<tr>
<td>Udifluvents</td>
<td>0.1</td>
<td>52</td>
<td></td>
</tr>
<tr>
<td>Fluvaquents</td>
<td>0.4</td>
<td>183</td>
<td></td>
</tr>
<tr>
<td>Udorthents</td>
<td>10.5</td>
<td>4,336</td>
<td></td>
</tr>
<tr>
<td><strong>SUBTOTAL</strong></td>
<td><strong>12.3</strong></td>
<td><strong>5,646</strong></td>
<td><strong>1,686</strong></td>
</tr>
</tbody>
</table>

| 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).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>B-19</th>
<th>Piedmont Borings B-11 (60ft)</th>
<th>B-9 (97ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chloride in ppm cl</td>
<td>42.4</td>
<td>38.0</td>
<td>41.0</td>
</tr>
<tr>
<td>Sulfide in ppm</td>
<td>0.66</td>
<td>0.28</td>
<td>0.0</td>
</tr>
<tr>
<td>Sulfate in ppm</td>
<td>127.5</td>
<td>250.0</td>
<td>57.5</td>
</tr>
<tr>
<td>pH</td>
<td>6.3</td>
<td>6.65</td>
<td>6.7</td>
</tr>
<tr>
<td>Conductivity in micromhos/cm</td>
<td>420.0</td>
<td>550.0</td>
<td>330.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>resistivity in ohm/cm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2381</td>
<td>1818</td>
<td>3030</td>
</tr>
<tr>
<td>Hardness in mg/l CaCO₃</td>
<td>116.0</td>
<td>164.0</td>
<td>174.2</td>
</tr>
<tr>
<td>Acidity in mg/l CaCO₃</td>
<td>5.0</td>
<td>21.0</td>
<td>28.4</td>
</tr>
<tr>
<td>Alkalinity in mg/l CaCO₃</td>
<td>91.3</td>
<td>87.0</td>
<td>117.2</td>
</tr>
</tbody>
</table>

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

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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)

<table>
<thead>
<tr>
<th>Buildings</th>
<th>No. of Sump</th>
<th>Estimated Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dept. of Justice</td>
<td>15</td>
<td>178,495</td>
</tr>
<tr>
<td>IRS</td>
<td>10</td>
<td>32,387</td>
</tr>
<tr>
<td>New Post Office</td>
<td>16</td>
<td>30,631</td>
</tr>
<tr>
<td>U.S. Customs and ICC</td>
<td>13</td>
<td>48,792</td>
</tr>
<tr>
<td>Dept. of Commerce</td>
<td>22</td>
<td>238,469</td>
</tr>
<tr>
<td>Museum of History &amp; Technology</td>
<td>8</td>
<td>21,552</td>
</tr>
<tr>
<td>Steam Tunnel</td>
<td></td>
<td>622,723</td>
</tr>
<tr>
<td>TOTAL</td>
<td>90</td>
<td>573,055</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Estimated pumping rate (gallon per minute per lineal foot)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravel and sand with 10-20% silt and clay</td>
<td>5-10</td>
</tr>
<tr>
<td>Sand with little or no silt and clay</td>
<td>1-5</td>
</tr>
<tr>
<td>Sand or gravel with some above 20% silt or clay</td>
<td>1-5</td>
</tr>
<tr>
<td>Clayed sands, clayed grounds, silty sand, silt gravel</td>
<td>1-5</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>ROCK</th>
<th>PERMEABILITY (feet per min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coastal Plain</td>
<td></td>
</tr>
<tr>
<td>- Pleistocene sand &amp; gravelly sands</td>
<td>5 x 10^-4</td>
</tr>
<tr>
<td>- Cretaceous and &amp; gravelly sands</td>
<td>3 x 10^-4</td>
</tr>
<tr>
<td>Piedmont</td>
<td></td>
</tr>
<tr>
<td>- decomposed rock (saprolite)</td>
<td>1 x 10^-4</td>
</tr>
<tr>
<td>- bedrock</td>
<td>4 x 10^-5</td>
</tr>
</tbody>
</table>
- 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 subaqueous 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.
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   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 baseline 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
   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.

   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.


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


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


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.


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.
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.

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.

"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.
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.

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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.

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.

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.

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.

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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


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 it impact on the exporting and/or importing region are critical factors. Assessing the groundwater feasibly 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.
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.


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.


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.
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.

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.

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
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26. Todd, David Keith, 1980
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.
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.

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