DETERMINATION OF GROUNDWATER RECHARGE TO THE TRIASSIC BRUNSWICK FORMATION OF SOUTHEASTERN PENNSYLVANIA

A Thesis Submitted to the
Temple University Graduate Board
in Partial Fullfiment of the Requirement for the Degree

MASTER OF ARTS

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DEPARTMENT COPY

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RICHARD E. SACKS

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF MASTER OF ARTS IN GEOLOGY, COLLEGE OF ARTS
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APRIL 1986

John K. Adams
DR. JOHN K. ADAMS
ADVISOR

April 14, 1986
DATE

DEDICATION

This work is dedicated to my family, who provided the inspiration and encouragement to make it all possible.

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ABSTRACT

The Triassic Brunswick Formation is an important aquifer in southeastern Pennsylvania and northern and central New Jersey, an area where rapid development is producing increased groundwater use. In order to prevent groundwater mining, it is necessary to have knowledge of the rate of groundwater recharge. Based on streamflow data during periods of baseflow recession, Moody and Associates, Inc. (1975) estimated the average annual recharge rate for the Brunswick Formation to be between 300,000 and 400,000 gallons/day/square mile.

In this study the groundwater recharge rate for the Brunswick Formation was calculated by the baseflow recession and hydrologic budget methods using streamflow and climatic data from three small watersheds. The baseflow recession method yielded annual groundwater recharge rates which ranged from 441,000 gallons/day/square mile to 663,000 gallons/day/square mile. Annual groundwater recharge rates calculated using the hydrologic budget method ranged from 321,000 gallons/day/square mile to 424,000 gallons/day/square mile. Based on the results of both methods, the average annual recharge rate is 447,000 gallons/day/square mile.

Although the baseflow recession method yielded reasonable annual recharge rates, it does not produce accurate results for shorter time periods. Monthly groundwater recharge rates calculated using the hydrologic budget are much more representative of actual seasonal variations than those calculated using the baseflow recession method. The primary advantage of the baseflow recession method is that it is simpler to use and requires much less data.

The results of this study illustrate that groundwater recharge is controlled by both the hydraulic characteristics of the aquifer and climatic conditions. During the winter months, when there is a precipitation excess, the hydraulic characteristics of the aquifer determine the maximum potential recharge rate. However, during the summer months when there is less precipitation and greater evapotranspiration, the maximum potential recharge rate is not attained.

TABLE OF CONTENTS

APPENDICES

LIST OF TABLES

LIST OF FIGURES

1.0 INTRODUCTION

The Triassic Brunswick Formation, which occurs along a narrow zone extending from approximately the Schuylkill River through southeastern Pennsylvania and into central and northern New Jersey (Figure 1), is an important aquifer. Many industrial and domestic supply wells already tap this aquifer which underlies an area that is rapidly being developed. Increased pumping of groundwater to supply the growing needs of society makes it necessary to have a knowledge of the rate of groundwater recharge in order to prevent groundwater mining and aquifer depletion.

Typically, groundwater recharge is estimated from streamflow data during periods of baseflow recession. When using this method the assumption is made that baseflow, which by definition represents discharge from the groundwater reservoir, must be equal to groundwater recharge if there is no significant change in groundwater storage. It must also be assumed that surface water and groundwater drainage divides coincide.

Groundwater recharge may also be calculated through the use of a hydrologic budget, as shown by the equation:

$$R = P - ET - Q$$

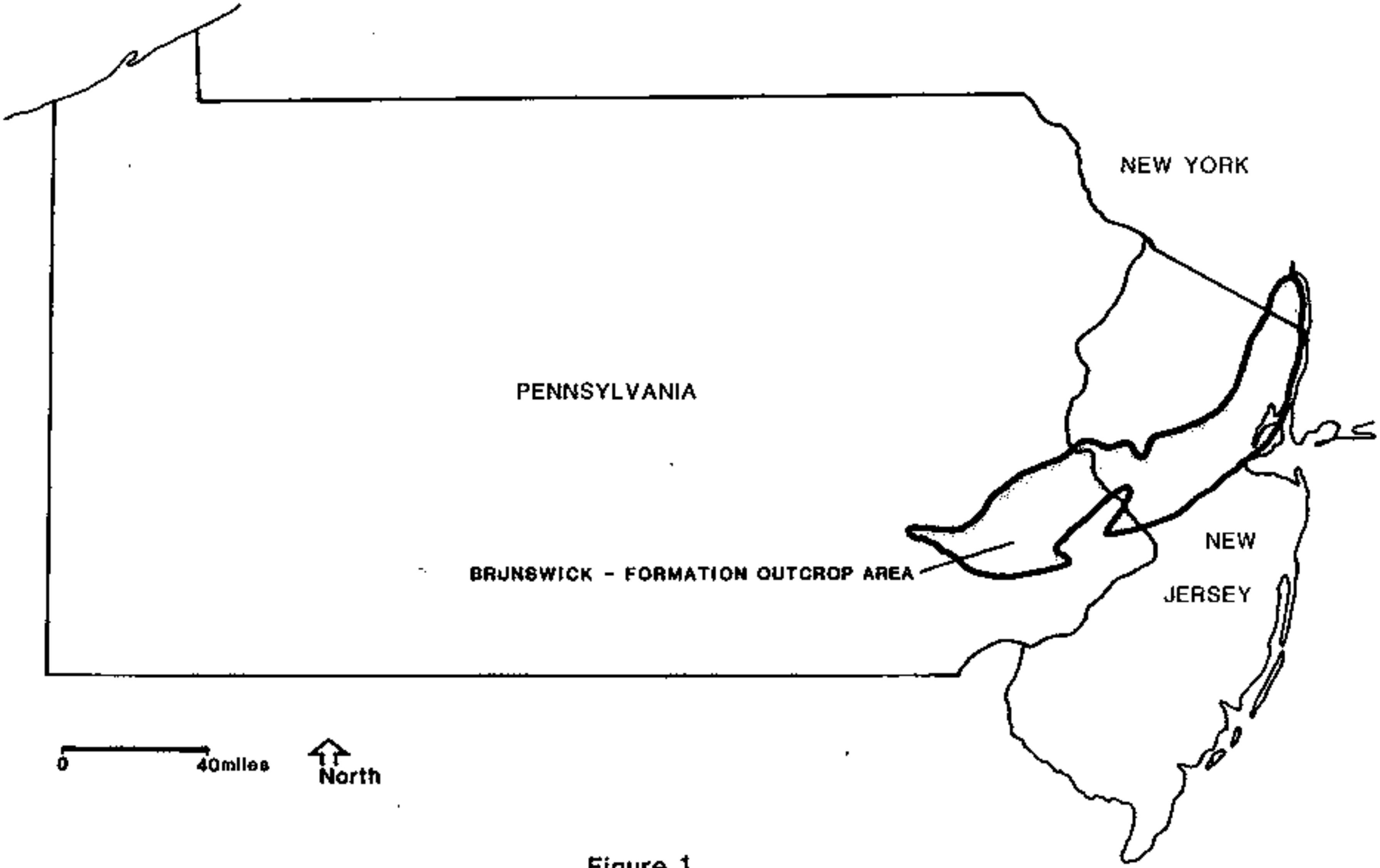


Figure 1

Geographic Occurrence of the Triassic Brunswick Formation

where R is groundwater recharge, P is precipitation, ET is evapotranspiration and Q is storm runoff. As in the baseflow recession method, it is assumed that there is no significant change in groundwater storage, and that surface water and groundwater divides coincide.

Numerous papers have been written that discuss the groundwater resources of the Brunswick formation. However, very few studies have been performed which provide detailed information on groundwater recharge.

Moody and Associates, Inc. (1975) estimated the range of average annual recharge to the Brunswick Formation to be between 300,000 and 400,000 gallons per day per square mile. This was calculated by the baseflow method, using streamflow data from United Stated Geological Survey (USGS) gauging stations for the 1970 hydrologic year. Watersheds gauged by USGS stations are relatively large however, and usually include more than one aquifer. This requires that the baseflow contributions from each of the various aquifers must be estimated in order to determine the recharge to the respective aquifers.

The purposes of this study are to:

1. Compare the baseflow recession and hydrologic budget methods for calculating groundwater recharge.

2. Assess the accuracy of the published recharge rates for the Brunswick Formation.

3. Determine if there is significant areal variation in recharge to the Brunswick Formation.

2.0 GEOLOGY

The Brunswick Formation, along with the underlying Lockatong and Stockton Formations of southeastern Pennsylvania and central and northern New Jersey, is a member of the Newark Group. Between the Schuylkill River and the Maryland border, stratigraphically equivalent rocks are subdivided into the Gettysburg, Hammer Creek and New Oxford Formations, as shown in Table 1. These rocks, which paleontologic data indicate are of Late Triassic age, were deposited in a portion of a downfaulted basin which has a northeast-southwest trend and extends from southeastern New York to northern Virginia. Numerous basins of this type exist within the area between Nova Scotia and North Carolina. The Newark Group unconformably overlies Paleozoic and Precambrian rocks and in New Jersey is uncomformably overlain by Cretaceous rocks.

The Brunswick Formation consists predominantly of reddish-brown shale, mudstone and siltstone. According to Van Houten (1960), the dominant minerals in the Brunswick are feldspar, illite, chlorite, quartz, and calcite. In some locations the Brunswick Formation includes very thin beds of green shale and brown shale which can be traced for distances of up to 1 mile. Near the base of the

TABLE 1

SUMMARY OF STRATIGRAPHIC INFORMATION

Dauphin-Lebanon County Line to Maryland Border	Schuylkill River to Dauphin-Lebanon County Line	Schuylkill River to Western New Jersey
	(modified from Glaeser, 1966)	
GETTYSBURG FORMATION 15,500 feet thick Red, medium- to fine-grained sandstone and shale. Conglomerate in upper part. Sandstone is more abundant in the eastern part of the area. Heidlersburg (middle) Member is re,d, green, and gray shale and argillite and minor gray to white sandstone	HAMMER CREEK FORMATION 9,400 to 12,200 feet thick Conglomerate, coarse sandstone, and minor shale.	BRUNSWICK FORMATION 9,000 to 16,000 feet thick Red shale, siltstone, and sandstone. Conglomerate and coarse sandstone in upper part. Some gray shale and argillite near base.
		LOCKATONG FORMATION 1,500 to 4,000 feet thick Upper part-alternating red and gray argillite and shale. Lower part -dark-gray shale and argillite; siltstone and sandstone near base. Lenses out west of Schuylkill River.
NEW OXFORD FORMATION 4,800 to 6,900 feet thick Arkose, conglomerate and red sandstone, siltstone, and shale. Unconformable upon lower Paleozoic and Precambrian rocks.	NEW OXFORD FORMATION (in western part) 500 to 4,800 feet thick STOCKTON FORMATION (in eastern part) 2,300 to 6,000 feet thick	STOCKTON FORMATION 2,300 to 6,000 feet thick Arkose, conglomerate and red sandstone, siltstone, and shale. Unconformable upon lower Paleozoic and Precambrian rocks. Top gradational with overlying Lockatong Formation.

Source: Wood (1980)

Brunswick much of the rock is massive red argillite which is interbedded with dark gray argillite of the Lockatong Formation. At the northern border of the Triassic basin the shales and other typical rock types of the Brunswick Formation are interbedded with and grade laterally into sandstone and fanglomerate. These fanglomerates were deposited in the form of alluvial fans at the mouths of streams flowing into the basin from the north. They consist of angular quartz, limestone or other lithic fragments in a reddish brown, sandy-to-argillaceous matrix (Longwill and Wood 1965).

Generally the Brunswick and Lockatong Formations dip approximately 20° or less to the north and northwest. Superimposed upon this homoclinal structure are several broad anticlines and synclines with axes trending approximately N60°W (Longwill and Wood 1965).

Numerous fractures are present in the Brunswick Formation, including very narrow fractures which parallel the bedding planes, vertical joint sets and faults. Three distinct sets of joints, striking N30°E, N45°W and N75°E have been observed in the Brunswick Formation. The latter two joint sets are not as well developed as the first. Spacing of the joints averages approximately 6 inches but varies between several inches and several feet. Jointing is best developed in the massive, more competent beds. Faults, which are relatively common in the Brunswick Formation, are primarily normal; however, in some locations there have been lateral movements (Longwill and Wood 1965).

Within the study area, the Brunswick Formation has been intruded by diabase dikes and sills. The sills are generally thicker than the dikes, with some greater than 1,000 feet thick (Longwill and Wood 1965). Contact metamorphism of the Brunswick Formation in close proximity to the intrusives has changed its physical properties considerably. The reddish-brown shales have been altered to a very hard, dark, hornfels which closely resembles the dark gray argillite of the Lockatong Formation. In the less severely baked zones, the color has changed from reddish-brown to purplish red. These altered zones vary in width, usually proportionally to the size of the intrusive body. Near small dikes the altered zone is usually between 40 and 100 feet wide, whereas in the vicinity of the larger intrusives, the altered zone may be greater than 1 mile wide. In some cases the joints and other fractures in the baked shale have increased the void space of the rock thereby increasing the hydraulic conductivity of the aquifer, and probably the recharge characteristics.

3.0 HYDROGEOLOGY

Due to the fact that the rocks of the Brunswick Formation are very fine grained, the permeability associated with the primary porosity is very low. Groundwater movement through these rocks is facilitated by the secondary porosity, due to the numerous fractures which are of post depositional origin.

The fractures, which are coplaner with the bedding planes, are usually very narrow and probably contribute little to the permeability (Longwill and Wood 1965). Nearly vertical joint sets provide interconnected channels for groundwater flow and thus greatly increase the permeability of the Brunswick Formation. Faults also increase the porosity and permeability, providing conduits for significant amounts of groundwater flow. It is possible that, in some cases, faults permit interbasin groundwater transfer.

Due to the anisotropy of the Brunswick Formation, its hydraulic characteristics may vary greatly with location and direction. Longwill and Wood (1965) reported a transmissivity range of 100 gallons per day per foot to 180,000 gallons per day per foot for the Brunswick Formation, based on pumping test data. The median transmissivity was 4,000 gallons per day per foot. However, these results were considered questionable by Longwill and Wood (1965) due to the fact that the Brunswick Formation does not behave as an ideal aquifer. Observation wells located along strike from the pumping wells exhibited greater drawdown and therefore yielded lower transmissivity values than those wells normal to the strike. The apparently lower transmissivity along the strike was caused by the fact that those observation wells were hydraulically connected with the pumping well whereas those normal to strike were not.

Storage coefficients, which were also highly variable ranged from $3x10^{-5}$ to $3x10^{-2}$ with a median value of $1x10^{-4}$. The storage coefficient of an aquifer is equivalent to the volume of water released from or taken into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface. Storage coefficients for artesian aquifers are usually signficantly lower than those for water table aquifers, ranging from 1×10^{-4} to 1×10^{-3} and from 5×10^{-2} to 3×10^{-1} respectively (Longwill and Wood 1965). This is due to the fact that water released from storage under water table conditions is derived from drainage of a portion of the aquifer whereas under artesian conditions it is derived from compression of the voids within the aquifer.

The Brunswick Formation exhibits both water table and artesian conditions. Near the surface, the Brunswick Formation is a water table aquifer. However, at greater depths it is under artesian conditions. This may result from weathering processes which clog fractures with clay to depths of approximately 200 feet, creating a partially confining layer (Longwill and Wood 1965).

Groundwater recharge is controlled by a number of factors in addition to the hydraulic characteristics of the aquifer, including rainfall intensity, rainfall volume, evapotranspiration and infiltration rate. The infiltration rate is dependent upon soil type, antecedent moisture content in the unsaturated zone, basin morphology and land use.

4.0 INVESTIGATION METHODOLOGY

4.1 Basin Selection

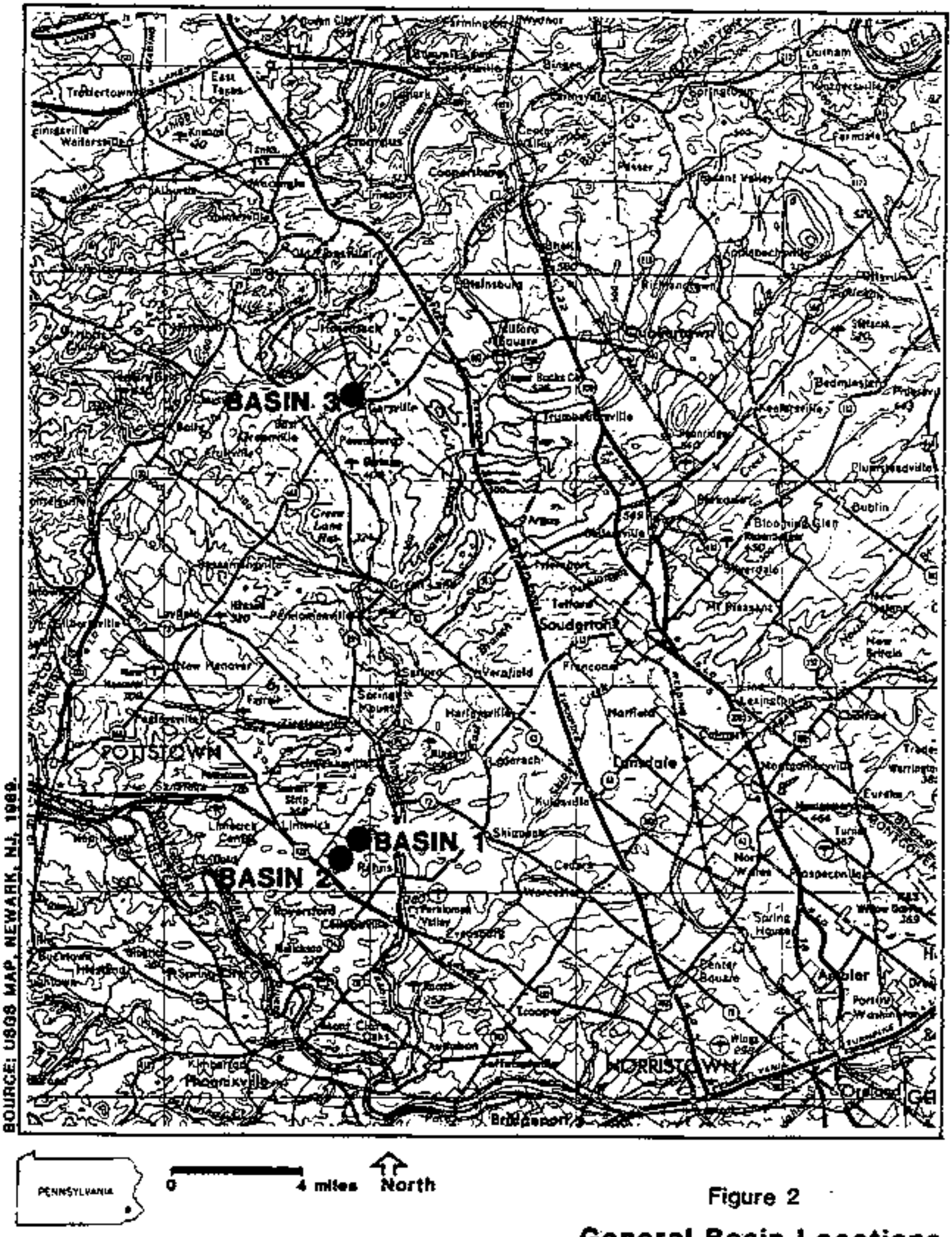
Groundwater recharge to the Brunswick Formation was calculated using both the baseflow recession method and a hydrologic budget with stream discharge data from three small watersheds. Data from a greater number of watersheds would have enhanced this study, however, the work involved in the installation and maintenance of the stream gauges and the data collection precluded the use of more than three. Difficulty in locating suitable watersheds was also a limiting factor.

It was necessary for each watershed to be underlain entirely or almost entirely by the Brunswick Formation and to have a drainage area which would produce flows within the capacity of the stream gauge except during severe storm events. A location where the stream was narrow, with relatively high banks was necessary for installation of the stream gauge. The stream was required to have a low enough gradient to permit the proper ponding behind the stream gauge and also to have a bed which would allow it to be sealed in place such that underflow would be minimized. Access to the site had to be relatively easy for construction of the stream gauge and data collection, yet the location had to be far enough from structures to prevent damage from erosion during severe storm events. Methods used for limiting erosion will be discussesd later in this section. Another prerequisite for use of a basin was a low population density so as to minimize the effects of groundwater pumping, and changes of the ground surface such as regrading, paving, and construction.

Three small watersheds from northern Montgomery County, Pennsylvania which possessed these characteristics were selected for this study (Figure 2). Basins 1 and 2 with areas of 0.2 square miles (126 acres; 0.52 Sq. Km.) and 0.62 square miles (396 acres; 1.61 Sq. Km.) respectively, are drained by two branches of Schoolhouse Run. As shown in Figures 3 and 4 these basins are located approximately 1/2 mile (0.87 Km) northwest of Trappe, Pennsylvania. Basin 3 which is located 1 mile (1.6 Km) northeast of Pennsburg, Pennsylvania is drained by the Macoby Creek and has an area of 1.09 square miles (698 acres; 2.82 Sq. Km.). The location of this basin is shown in Figure 5.

4.2 Weir Installation

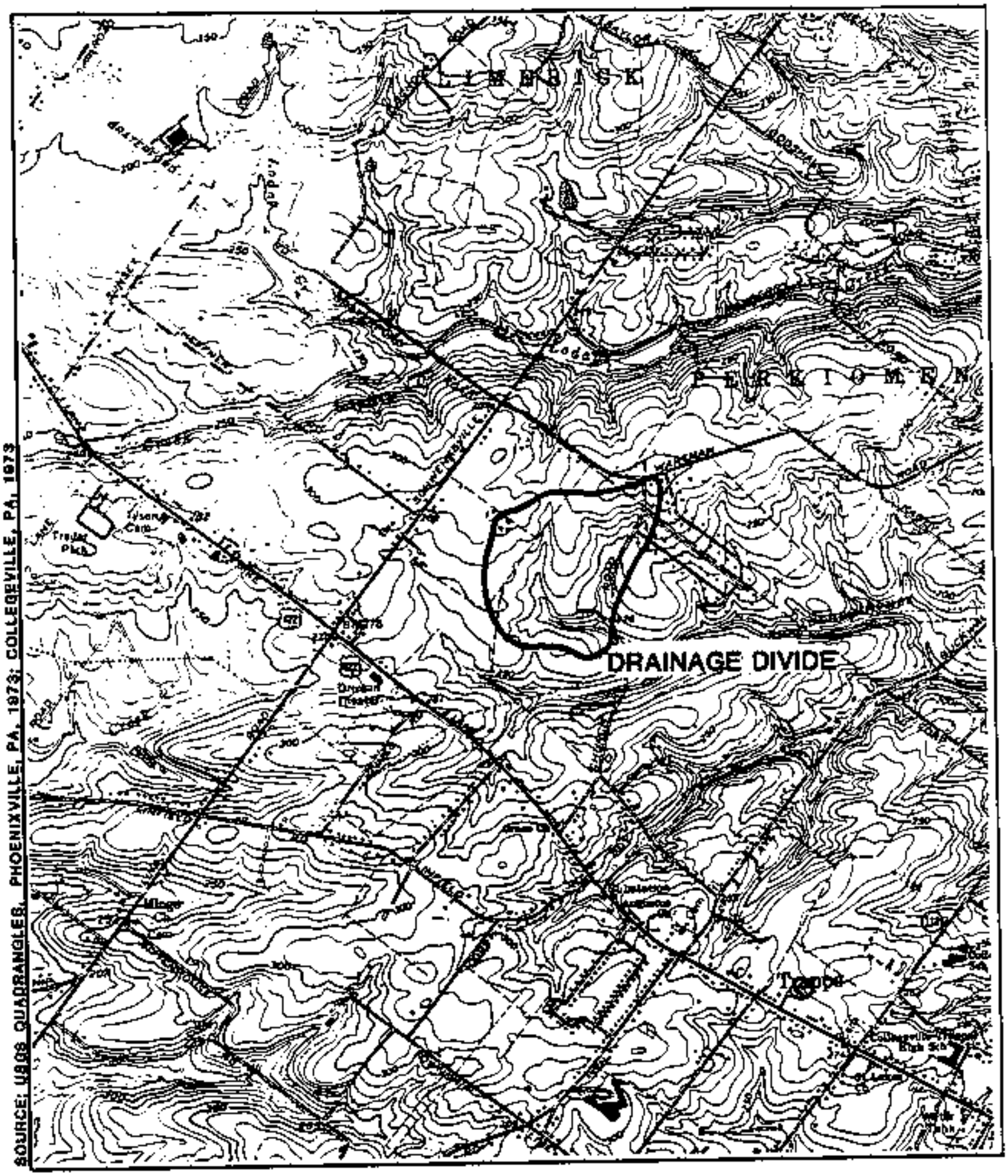
Stream flow data is required for calculating recharge by both the baseflow and hydrologic budget methods. Ninety degree, sharp crested triangular weirs were used for measuring stream flow. The weirs consisted of a 3 foot by 5 foot by 1/4 inch steel plate with a 1.5 foot notch cut out from the center of the 5 foot side as shown



SOURCE: USGS MAP, NEWARK, NJ, 1969.

Figure 2

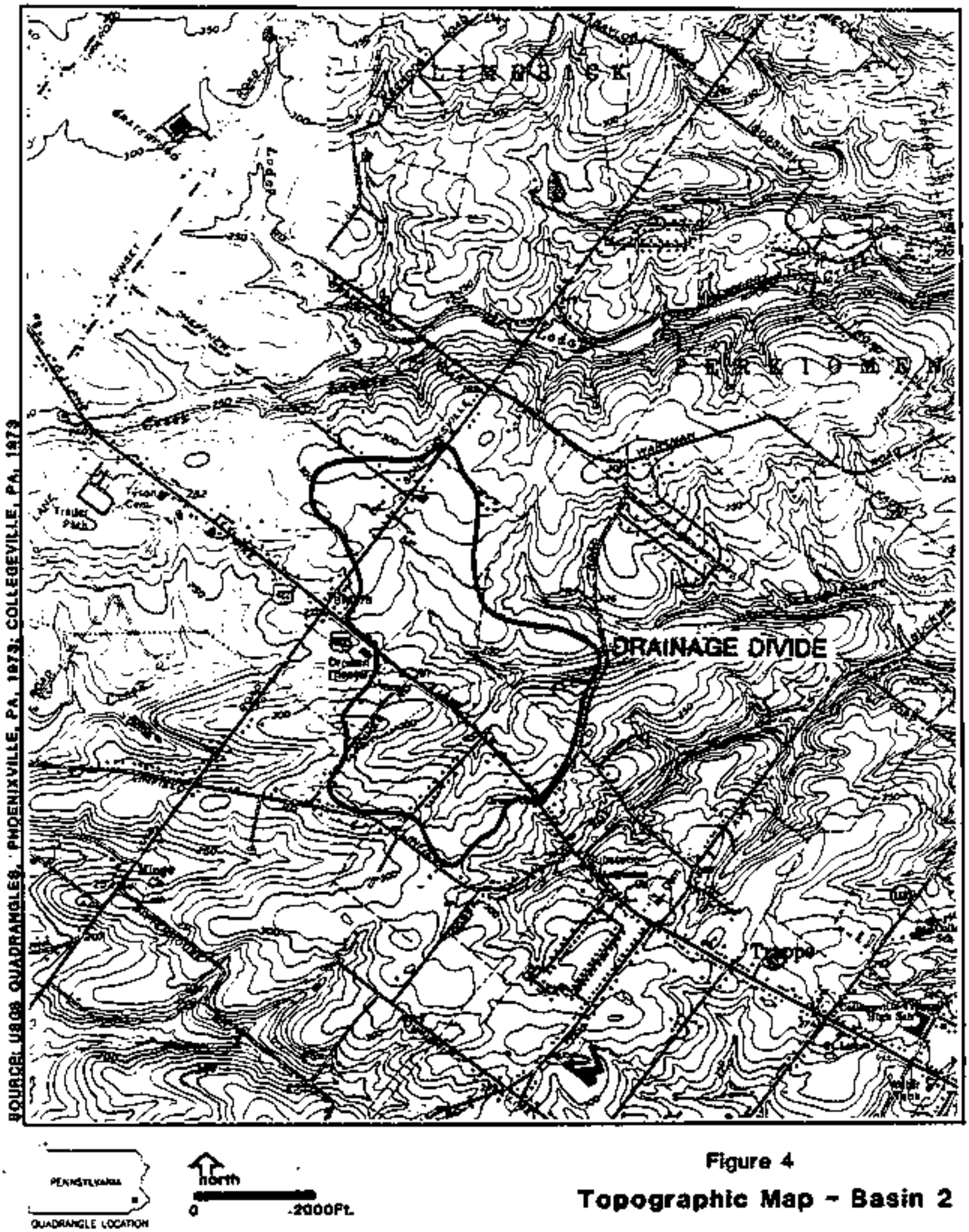
General Basin Locations



SOURCE: USGS QUADRANGLES, PHOENIXVILLE, PA. 1973; COLLEGEVILLE, PA. 1973

Figure 3

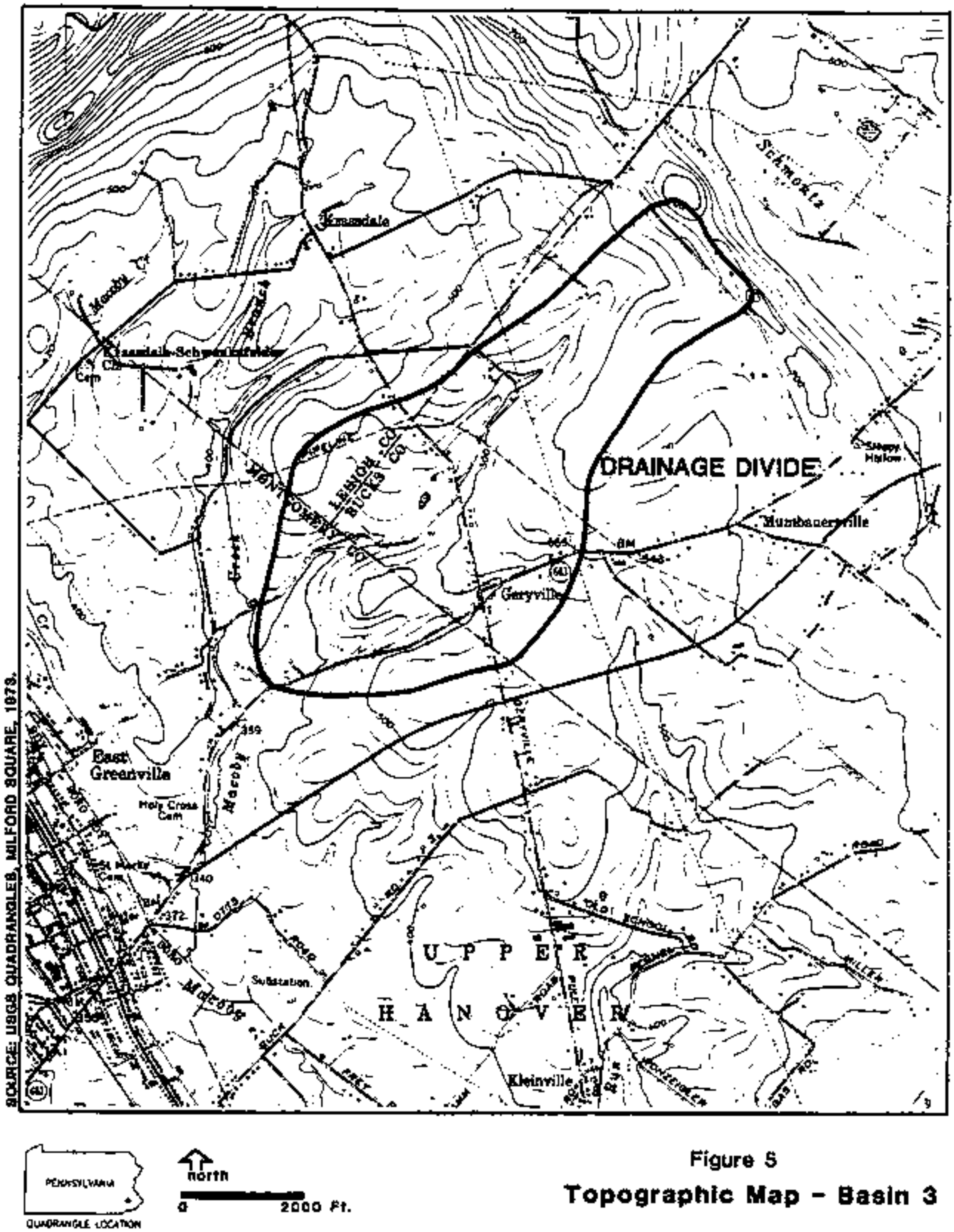
Topographic Map - Basin 1



SOURCE: USGS QUADRANGLES, PHOENIXVILLE, PA. 1973; COLLEGEVILLE, PA. 1973

Figure 4

Topographic Map - Basin 2



SOURCE: USGS QUADRANGLES, MILFORD SQUARE, 1973.

Figure 5

Topographic Map – Basin 3

on Figure 6. Crests of the weirs were beveled 30 degrees from horizontal in the downstream direction. Maximum capacity of this size and type of weir is 6.81 cubic feet per second. At stages less than 2 feet this type of weir has an accuracy level of approximately 98 percent (Gray; 1973).

Proper installation of the weir is essential for accurate flow measurements. Straight segments of streams must be used for weir placement so that water flow is directed toward the notch and turbulence is minimized. The weir must be perfectly vertical and leveled across the stream. The weir must be installed such that the base of the notch is located high enough above the streambed to permit free flow of water over the crest. The approach pool which results from the elevation of the notch must extend far enough upstream to prevent turbulence at the weir.

Initially the dams used for channelling water through the weirs were constructed using rocks, clay and plastic sheets as illustrated in Figures 7, 8 and 9. This however, proved inadequate except for short term monitoring of low flows. Final construction of the stream gauges consisted of a rock and concrete wall extending into the stream bed and several feet into each bank, with the weir plate cemented into place at the center of the channel. Photographs showing the final construction of the weirs in Basins 1, 2 and 3 are

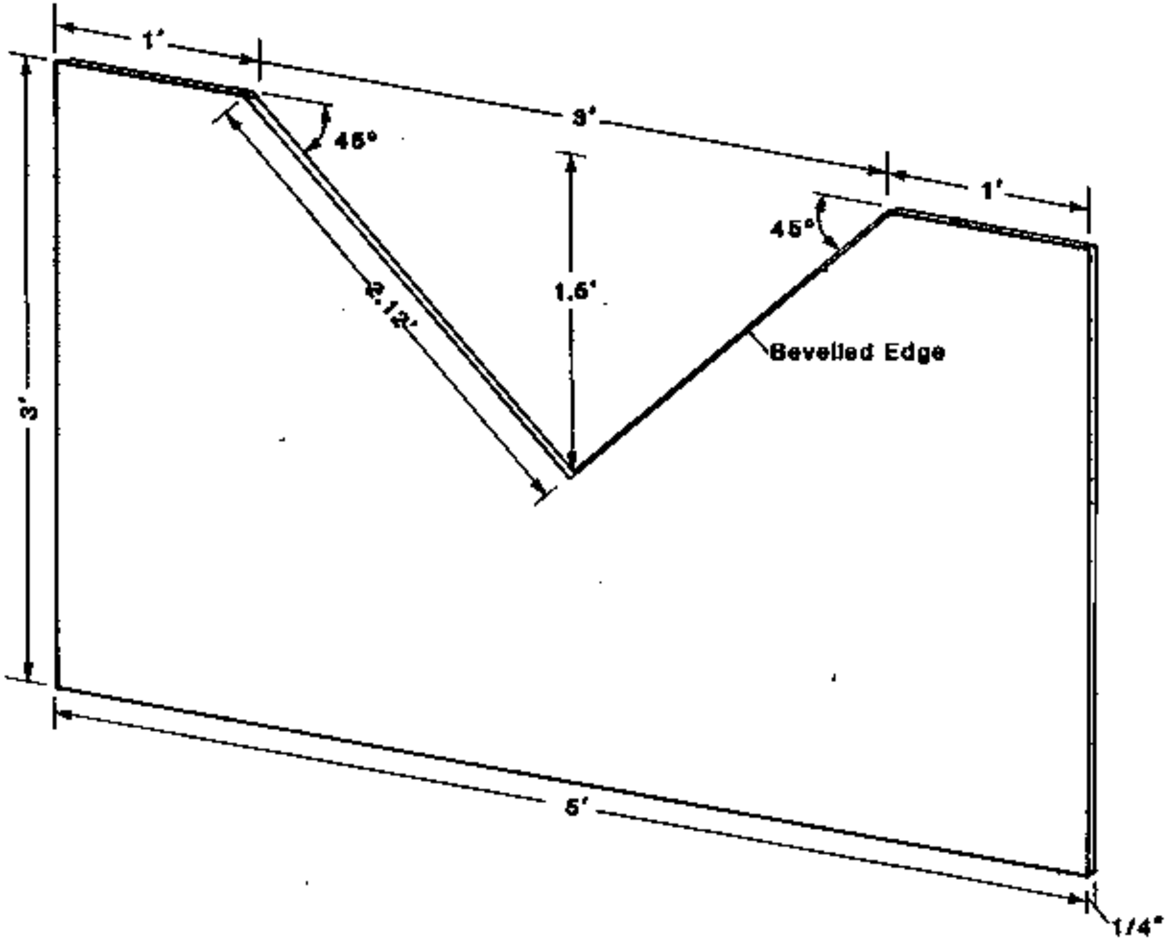


Figure 6

Dimensions: Ninety Degree, Sharp Crested Triangular Weir

Figure 7

Initial Weir Construction

Basin 1

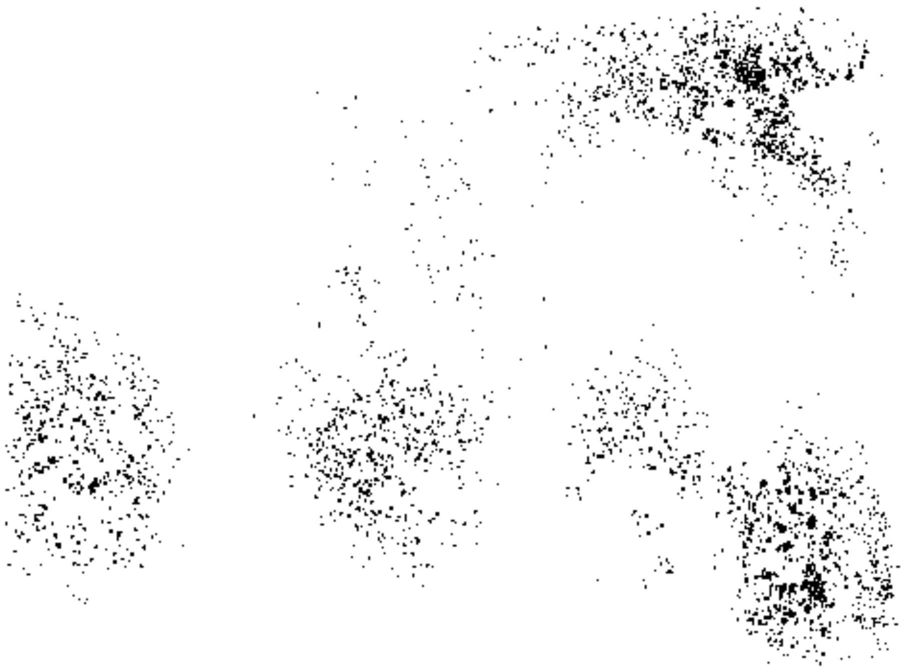


Figure 8

Initial Weir Construction

Basin 2

Figure 9

Initial Weir Construction

Basin 3

presented as figures 10, 11 and 12, respectively. Construction was begun by digging the necessary distance into both banks of the stream and stream bed. A concrete foundation was then laid on both sides of the stream, upon which a wall was built up to the elevation where the top of the weir would be when completed. When the wall was completed there was just enough space to slide the weir plate into position at the center of the channel. The weir plate was driven at least 6 inches into the stream bed, which was composed mostly of clay at the three locations used for this study. Once it was in place any gaps around the weir plate were sealed with cement (Figure 13). A staff which was graduated in inches and millimeters was placed towards one side of the stream, 3 to 5 feet upstream from the weir. Large rocks were placed in the streambed below the notch and along the banks beneath the containing walls to prevent erosion caused by water flowing over the weir and overflow during major storm events.

Stage height on each of the weirs was recorded as often as possible for a period of one year. The stage height readings were then converted to discharge rates using the equation for a ninety degree triangular weir:

$$Q = 2.5\ H^{5/2}$$

where Q is the discharge rate in cubic feet per second and H is the stage height in feet. Hydrographs were constructed by plotting

Figure 10

Final Weir Construction

Basin 1

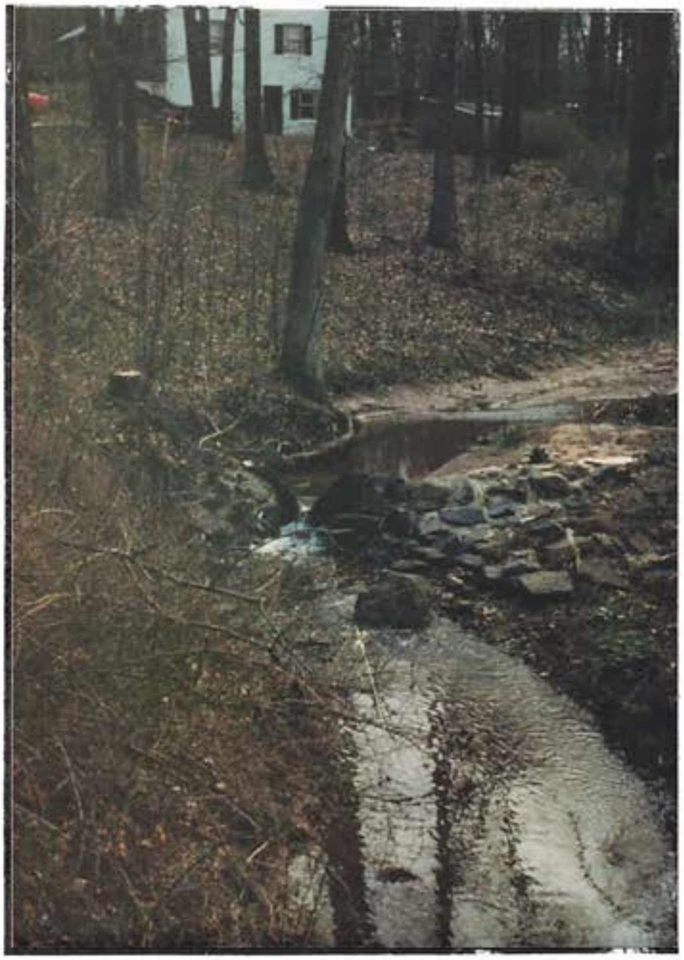


Figure 11

Final Weir Construction

Basin 2

Figure 12

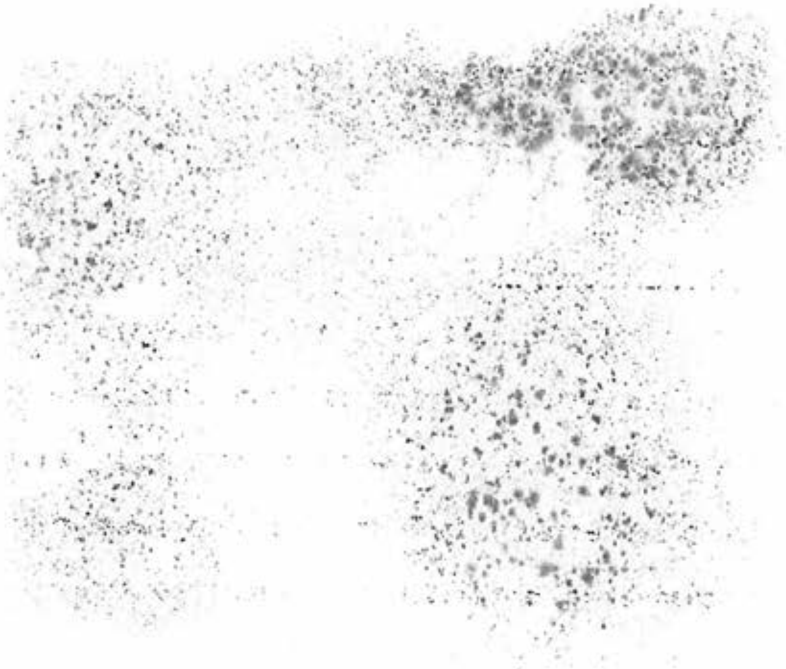
Final Weir Construction

Basin 3

Figure 13

Close-Up View of Weir Construction

Basin 1



discharge versus time on arithmetic graph paper. Streamflow hydrographs for each of the basins are presented in Appendix A. For storm events where the actual data was insufficient to plot the discharge, peak flow rates were calculated using the rational equation:

$$Q = CIA$$

where Q is the peak discharge in cubic feet per second, C is the runoff coefficient, I is the rainfall intensity in inches per hour and A is the drainage area in acres. The runoff coefficient (C) was estimated from Table 14-1 in Chow (1964).

4.3 Baseflow Recession Method

When calculating recharge by the baseflow recession method, the portion of streamflow which is derived from groundwater discharge (baseflow) for a given period of time is assumed to be equivalent to the recharge for that period. It must also be assumed that there is no significant change in groundwater storage and that the surface water and groundwater divides coincide. In actuality there would be a chronological offset equivalent to the residence time of the water in the aquifer. The discharge hydrograph was separated into baseflow and overland flow by extending the baseflow recession to a point beneath each storm peak. A line was then drawn from that point to the point on the curve where direct runoff ceased. The point at which direct runoff ceased was determined using both a judgment of the curve and the following equation:

$$N = A^{0.2}$$

where N is the number of days after peak that direct runoff ended and A is the drainage area in square miles. After separation of the hydrograph, the volume of baseflow was determined by planimetering the area under the curve. Baseflow in gallons/day was divided by the area of the basin to give gallons/day/square mile which is then equated to recharge.

4.4 Hydrologic Budget Method

A hydrologic budget which is expressed by the equation:

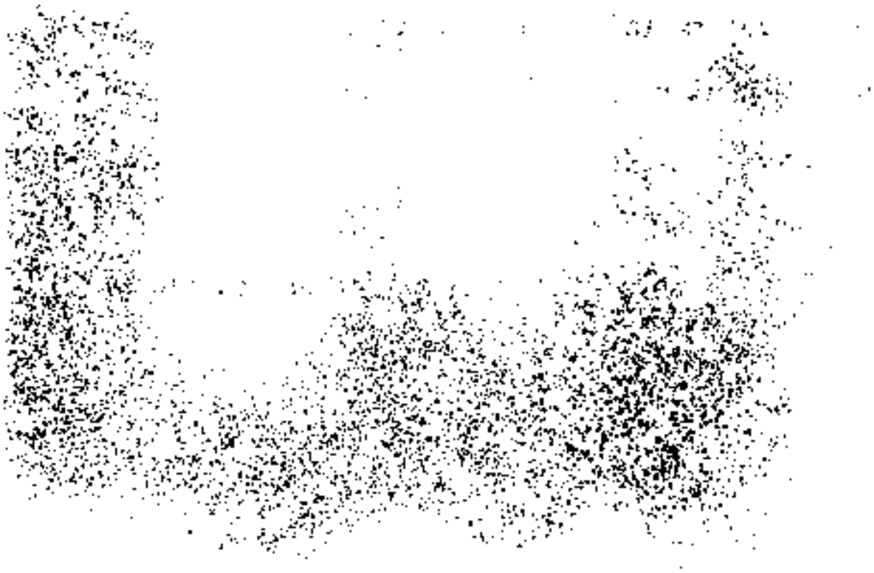
$$R = P-ET-Q$$

was also used to calculate the groundwater recharge. In this equation R is the groundwater recharge, P is precipitation, ET is evapotranspiration and Q is storm or surface runoff. It is assumed that there is no significant change in groundwater storage and that the surface water and groundwater divides coincide. Precipitation was measured in the field using rain gauges. Wedge type rain gauges were installed at Basins 2 and 3 (Figure 14). Due to the close proximity of Basins 1 and 2 a rain gauge was not necessary at Basin 1. Evapotranspiration was calculated using the methods of Thornthwaite (1948) and Eagleman (1967). Temperature and relative humidity data used in the evapotranspiration calculations were obtained from the Upper Perkiomen Valley Park, Montgomery County, Pennsylvania and the National Oceanographic and Atmospheric Administration (NOAA) stations in Philadelphia and Allentown, Pennsylvania, respectively.

Figure 14

Wedge Type Rain Gauge

Basin 3



The Thornthwaite (1948) method of calculating the potential evapotranspiration uses the following group of equations:

$$e = 1.6\ (10\ t\ /\ I)^{a}$$

$$i = (t/5)^{1.514};\ t > 0^{\circ}\mathrm{C}$$

$$I = \quad i$$

$$a = 6.75 \times 10^{-7}\ I^{3} - 7.71 \times 10^{-5}\ I^{2} + 0.01792\ I + 0.49239$$

where e is the monthly evapotranspiration in centimeters, t is the mean monthly temperature (°C), i is the monthly heat index and I and a are as shown.

Eagleman (1967) developed the following equations for calculating potential evapotranspiration:

$$E_T = C\ (0.035\ e_s)\ (100\text{-RH})^{1/2}$$

$$C = 0.20 + 0.0133\ t$$

where E_T is the monthly evapotranspiration rate in inches, e_s is the saturation vapor pressure in millibars, RH is the mean monthly percent relative humidity, t is the mean monthly temperature (°F) and C is a coefficient. If monthly temperatures are less than 30°F, C is equal to a constant value of 0.6. At temperatures greater than 70°F, the value of C remains constant at 1.13. The saturation vapor pressure e_s was determined from Figure 6.2 in Petterssen (1969).

Potential evapotranspiration calculated by six different methods was plotted against measured potential evapotranspiration by Eagleman. This graph which is included as Figure 15 indicates that the Eagleman method is more accurate than both the Thornthwaite (1948) and Blaney and Criddle (1962) methods. Although the methods of McIlroy (1964), Budyko (1956) and Penman (1956) were more accurate than Eagleman's, they require much more detailed meteorological data, such as measured soil moisture content and wind speeds at several heights above the ground.

Based upon Eagleman (1967) actual evapotranspiration is equal to approximately 72 percent of the potential evapotranspiration. An equation was derived by Eagleman (1976) to more accurately calculate the actual evapotranspiration. Use of this equation, however, was beyond the scope of this study due to the data required for the calculation. Annual actual evapotranspiration for the United States calculated by Eagleman (1976) using this method is shown in Figure 16.

Storm or surface runoff (Q) was determined by separating the hydrograph into its components as described in the previous section. That portion of the hydrograph which was attributed to storm runoff was then planimetered to determine the volume for each month.

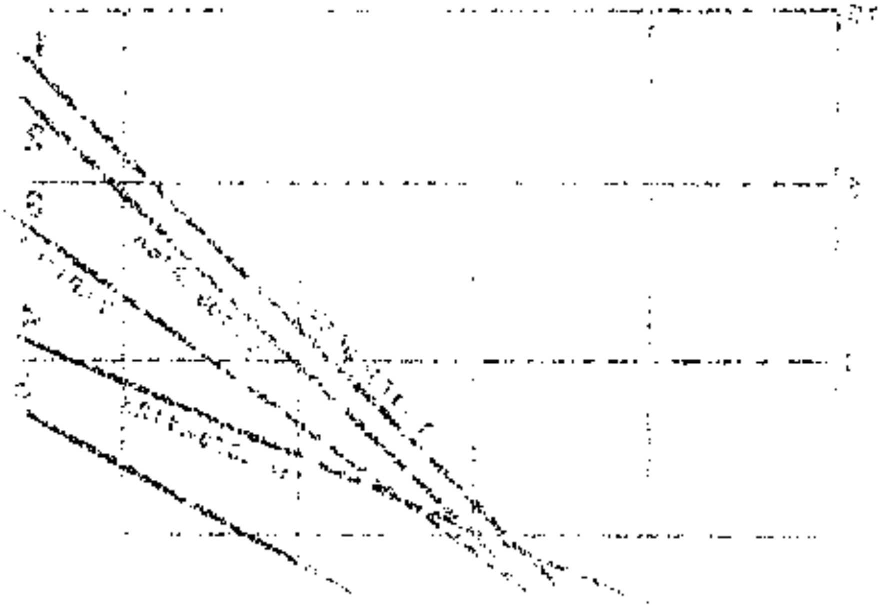
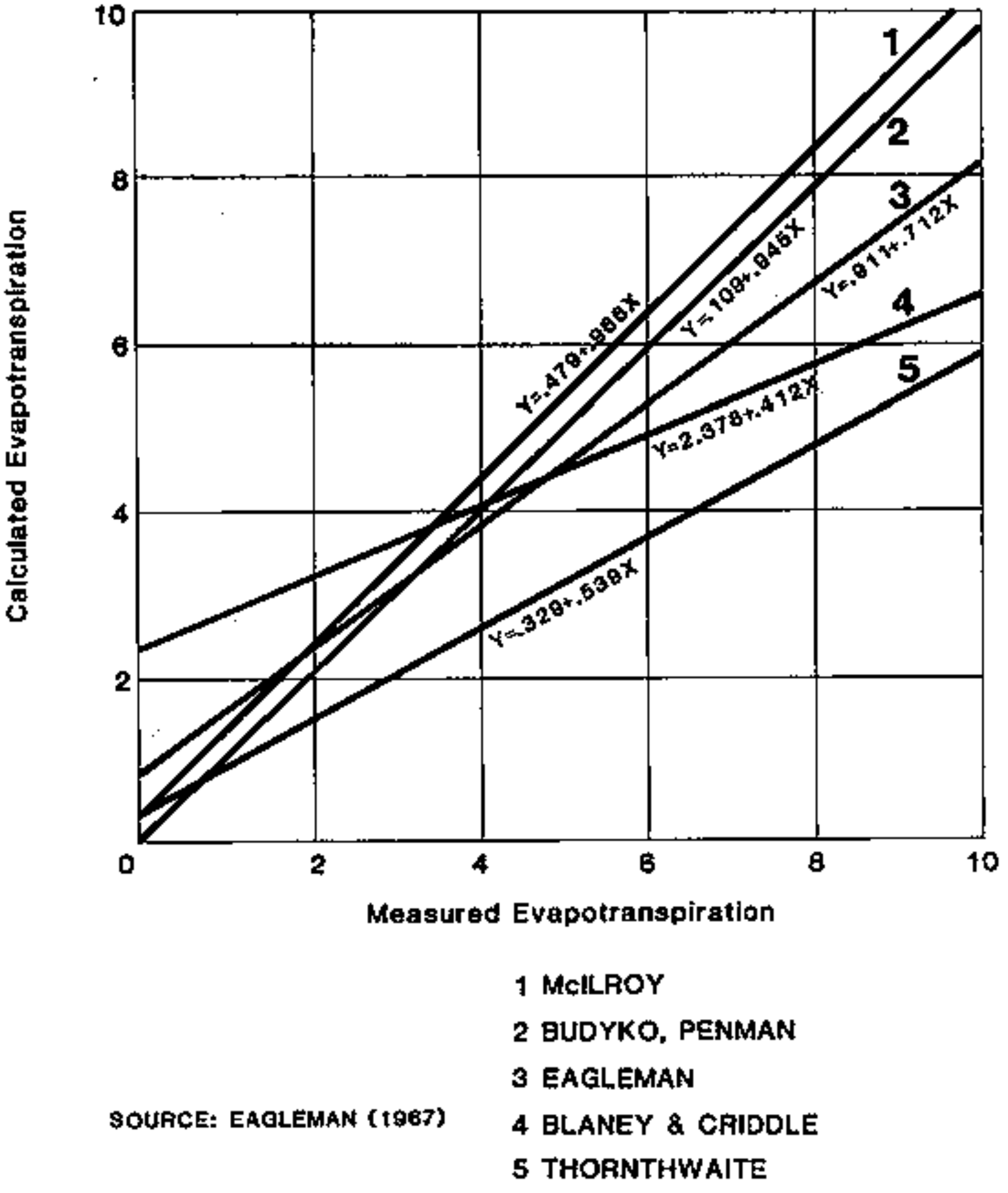


Figure 15

Comparison of Methods for Calculating Evapotranspiration



SOURCE: EAGLEMAN (1967)

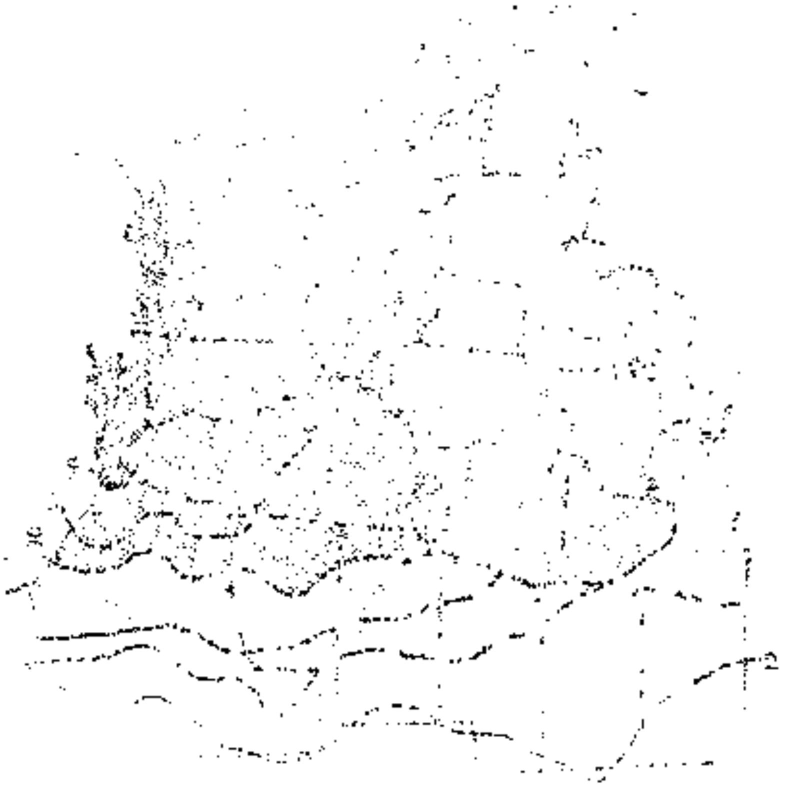
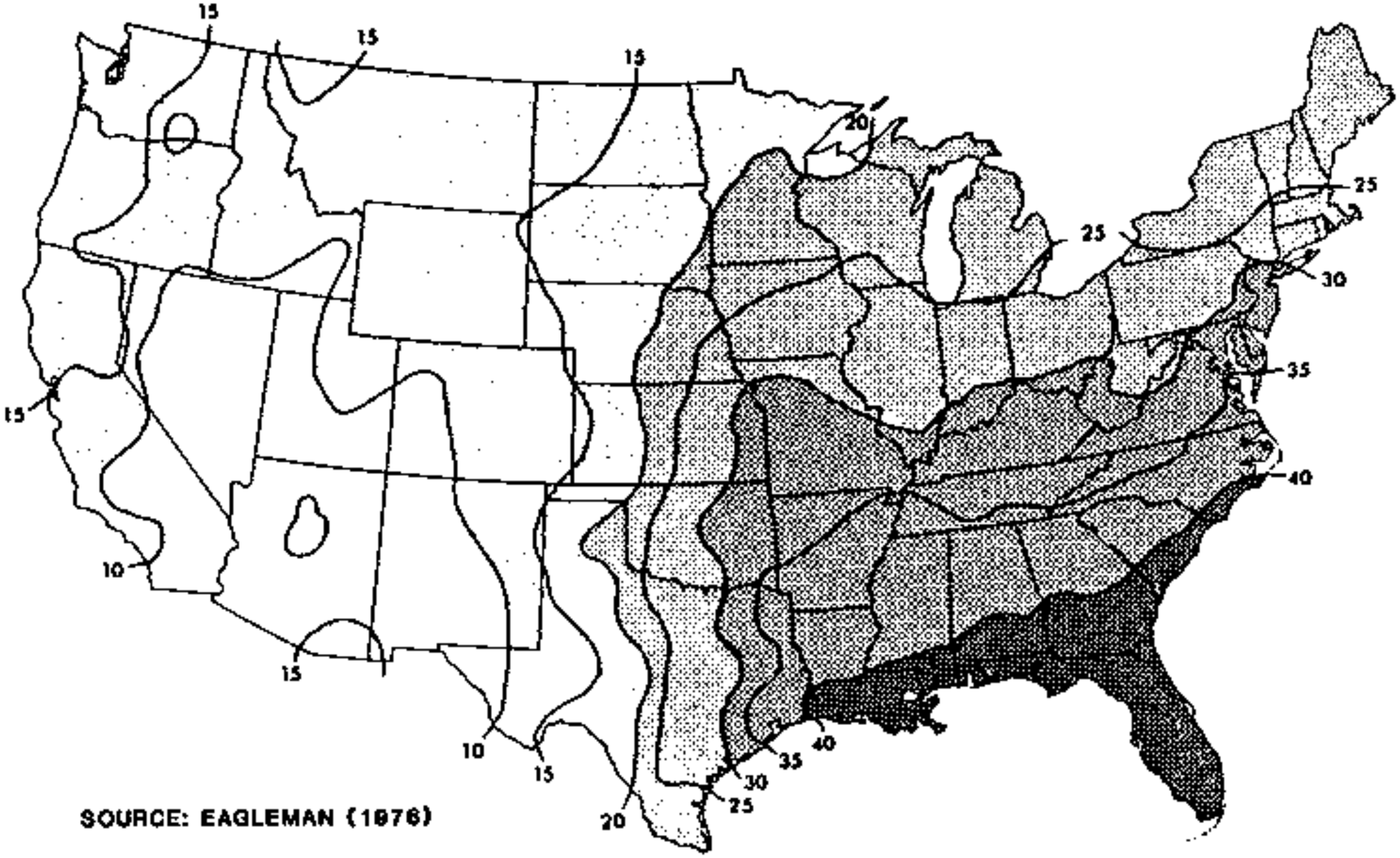


Figure 16

Annual Actual Evapotranspiration in the United States
(Inches)



SOURCE: EAGLEMAN (1976)

All data was collected for a period of one year, from December 1982 to November 1983. Groundwater recharge rates were calculated monthly for this period.

5.0 BASIN CHARACTERISTICS AND MORPHOLOGY

Climate, geology and basin morphalogy are the primary factors affecting groundwater recharge. Due to the proximity of the three basins used in this study, climatic conditions are nearly the same in each. General characteristics of the basins, including geology, morphalogy, soils and land use are described in this section. This information provides a basis for possible variations in groundwater recharge.

5.1 Basin 1

Basin 1 with a drainage area of 0.20 square miles (126 acres; 0.52 Sq. Km.) is located approximately 1 mile (1.6 Km.) northwest of Trappe, Pennsylvania (Figure 3). A small branch of Schoolhouse Run drains the basin. The length of the basin, which is actually the distance between the basin outlet and the most remote point as measured along the watercourse is approximately 3,000 feet. The basins rise which is the difference in elevation between the highest point in the basin and the lowest (basin outlet) is 70 feet. The rise is equivalent to the relief of the basin. Thus, the slope of the basin is 0.023.

Time of concentration for the basin is the time it takes for surface runoff to flow from the farthest point in the basin to the basin outlet. The time of concentration for Basin 1 was calculated to be 0.27 hours, using the following equation which was developed by Kirpich (1940):

5.0 BASIN CHARACTERISTICS AND MORPHOLOGY

Climate, geology and basin morphalogy are the primary factors affecting groundwater recharge. Due to the proximity of the three basins used in this study, climatic conditions are nearly the same in each. General characteristics of the basins, including geology, morphalogy, soils and land use are described in this section. This information provides a basis for possible variations in groundwater recharge.

5.1 Basin 1

Basin 1 with a drainage area of 0.20 square miles (126 acres; 0.52 Sq. Km.) is located approximately 1 mile (1.6 Km.) northwest of Trappe, Pennsylvania (Figure 3). A small branch of Schoolhouse Run drains the basin. The length of the basin, which is actually the distance between the basin outlet and the most remote point as measured along the watercourse is approximately 3,000 feet. The basins rise which is the difference in elevation between the highest point in the basin and the lowest (basin outlet) is 70 feet. The rise is equivalent to the relief of the basin. Thus, the slope of the basin is 0.023.

Time of concentration for the basin is the time it takes for surface runoff to flow from the farthest point in the basin to the basin outlet. The time of concentration for Basin 1 was calculated to be 0.27 hours, using the following equation which was developed by Kirpich (1940):

$$(1) \qquad t_c = \frac{0.00013 \times L^{0.77}}{S^{0.385}}$$

where t_c is the time of concentration in hours, L is length of the basin in feet and S is the ratio, of the basin rise to the basin length in feet, or approximately the average slope of the basin. Equation (1) for Basin 1 becomes:

$$tc = 0.00013 \times \frac{3{,}000^{0.77}}{0.02333^{0.385}} = 0.27 \text{ hrs}$$

Mockus (1957) developed the following equation for calculation of time of peak:

$$(2) \qquad Pr = tc + 0.60\ tc$$

where Pr is the time of peak or the time from the beginning of runoff to the time of peak runoff in hours, and tc is the time of concentration in hours. Basin characteristics are summarized in Table 2. Equation (2) for basin 1 becomes:

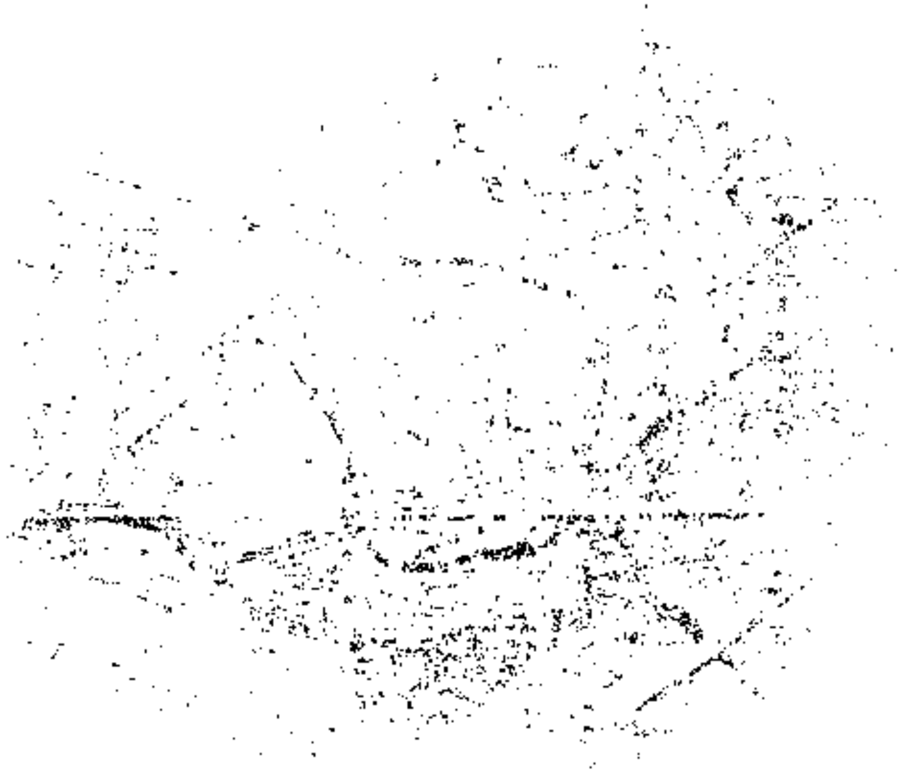
$$Pr = 0.52 + (0.60 \times 0.27) = 0.68 \text{ hrs}$$

Soils present in Basin 1 are primarily of the Reaville Series (Figure 17). These soils are moderately deep, moderately well drained to somewhat poorly drained reddish shaley silt loams. They have a relatively low permeability and moderate to low available moisture content. Members of other soil series also present in the basin include the Penn silt loam which has a moderate to high permeability, the Rowland silt loam with a moderate permeability,

TABLE 2

BASIN CHARACTERISTICS

Basin Characteristics	Basin 1	Basin 2	Basin 3
Basin Area	0.20 sq.mi. 0.52 sq.km.	0.62 sq.mi. 1.61 sq.km.	1.09 sq.mi. 2.82 sq.km.
Basin Length	3,000 feet 914 meters	6,200 feet 1,890 meters	11,400 feet 3,475 meters
Basin Rise	70 feet 21 meters	90 feet 27 meters	165 feet 50 meters
Average Slope	0.023	0.015	0.014
Time of Concentration	16 minutes	33 minutes	53 minutes
Time of Peak	41 minutes	64 minutes	90 minutes



SOURCE: SOIL CONSERVATION SERVICE, SOIL SURVEY, MONTGOMERY COUNTY, PA, APRIL 1967

NOTE: LEGEND IS ON FOLLOWING PAGE

Figure 17

Soils Map - Basin 1

FIGURE 17 (Continued)

LEGEND

AbA - Abbottstown silt loam, 0 to 3 percent slopes

AbB2 - Abbottstown silt loam, 3 to 8 percent slopes

CrA - Croton silt loam, 0 to 3 percent slopes

KsC3 - Klinesville very shaly silt loam, 8 to 15 percent slopes, severely eroded

PeB3 - Penn silt loam, 3 to 8 percent slopes, severely eroded

ReB2 - Readington silt loam, 3 to 8 percent slopes, moderately eroded

RsA2 - Reaville shale silt loam, 0 to 3 percent slopes, moderately eroded

RsB2 - Reaville shaly silt loam, 3 to 8 percent slopes, moderately eroded

RsB3 - Reaville shaly silt loam, 3 to 8 percent slopes, severely eroded

RsC3 - Reaville shaly silt loam, 8 to 15 percent slopes, severely eroded

Rt - Rowland silt loam

the Readington silt loam with a moderate to low permeability, the Croton silt loam with a low permeability and the Abbottstown silt loam with a very low permeability. The areas directly adjacent to the stream channel are occupied exclusively by the Rowland silt loam (Soil Conservation Service 1967). Bedrock is relatively shallow, in most areas less than 5 feet below grade.

Land use in Basin 1 had been primarily agricultural in the past, however, within a few years previous to this study, no crops have been planted and the dominant vegetation consists of low grasses. Most of the area along the watercourse is wooded. Two small ponds are present on the watercourse towards the lower end of the basin. Only eight houses are present in the basin, with the majority clustered near the northeast corner. Therefore, domestic activity has practically no impact on the natural recharge.

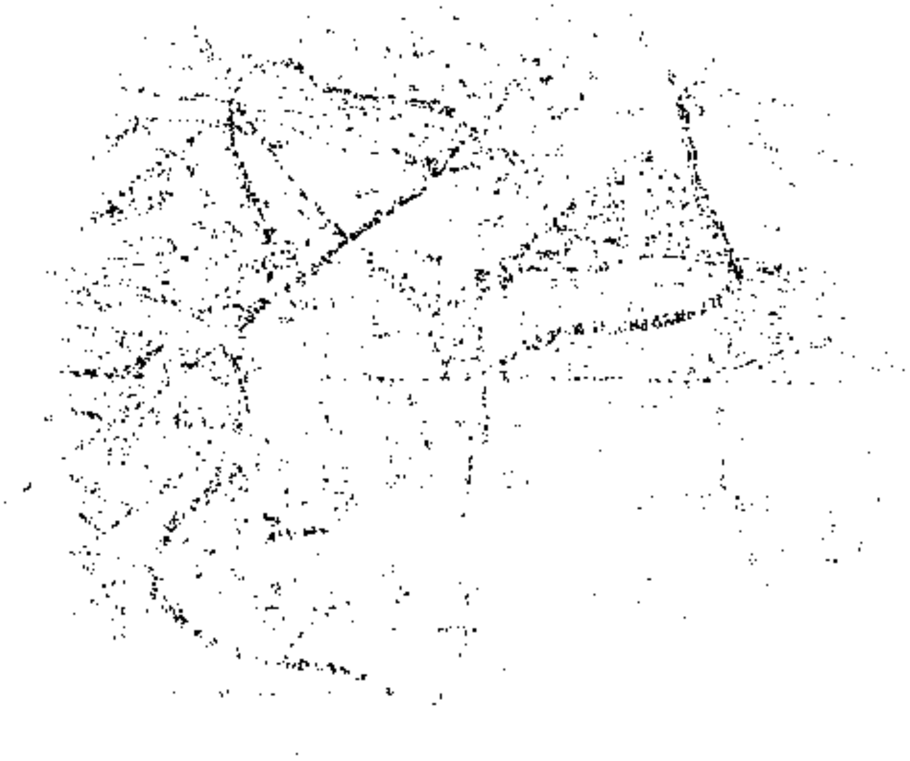
5.2 Basin 2

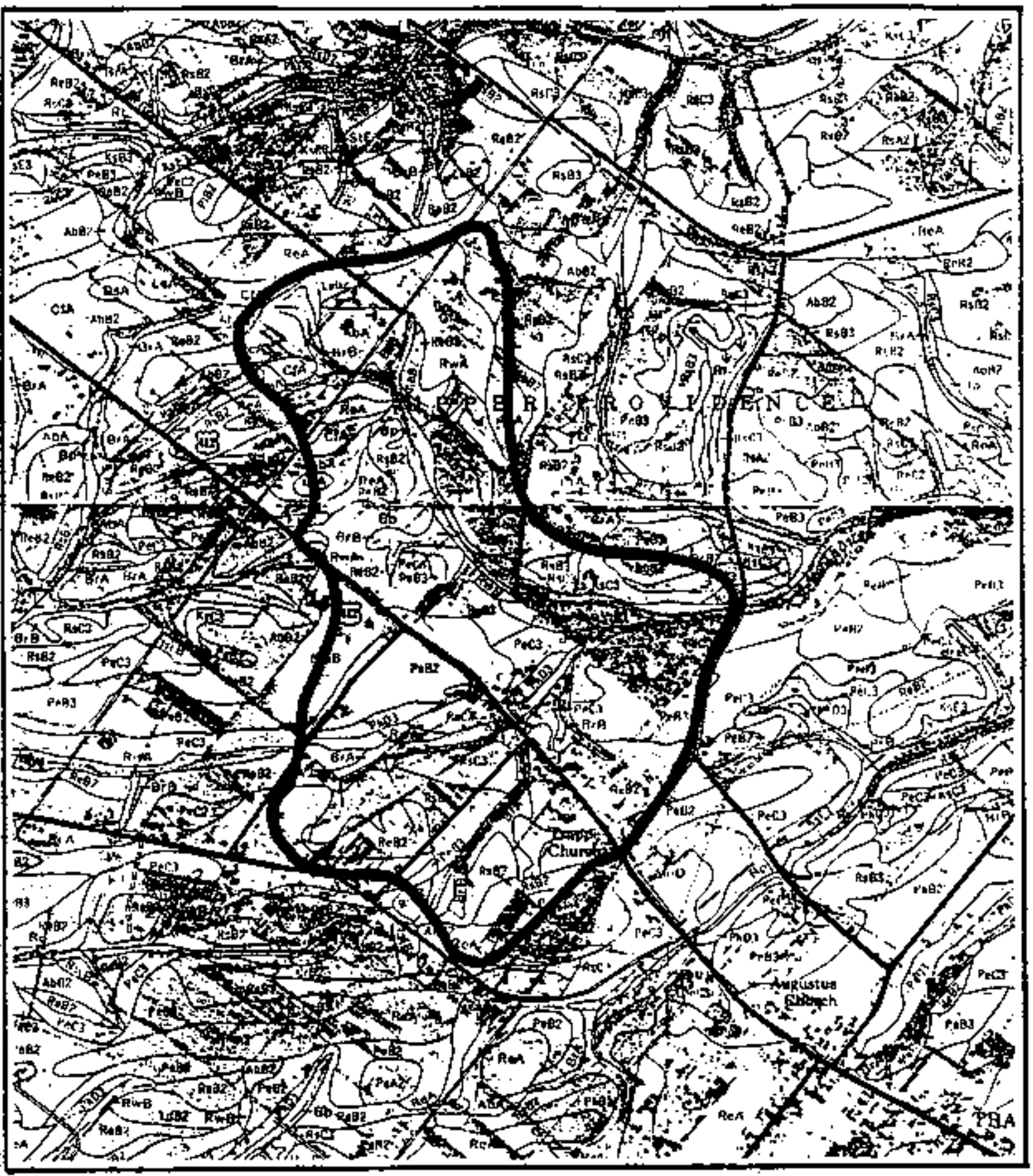
Basin 2 which borders the western and southern edges of Basin 1 (Figure 4) has a drainage area of 0.62 square miles (396 acres; 1.6 Sq. Km.). The basin, which is drained by a branch of Schoolhouse Run has a length of approximately 6,200 feet. This length is measured along the watercourse from the most remote point to the basin outlet. The basin rise which is the difference in elevation between the highest point in the basin and the lowest (basin outlet) is 90 feet. Based upon this length and rise, the basin slope is 0.015.

Using the methods described in the previous section on Basin 1, the time of concentration for Basin 2 was calculated to be 0.55 hours. Time of concentration is the time it takes for surface runoff to flow from the farthest point in the basin to the basin outlet. The time of peak which was also discussed in the previous section was calculated to be 1.07 hours for basin 2. Time of peak is the time from the beginning of surface runoff to the time of peak runoff. Basin characteristics for Basin 2 are summarized in Table 2.

The dominant soils in Basin 2 are members of the Penn, Reaville and Readington Series (Figure 18). Members of the Penn series are moderately deep to shallow reddish brown silt loams which are well drained. These soils have moderately high permeability and low to moderate available moisture capacity. Soils of the Reaville series are moderately deep, moderately well drained or somewhat poorly drained, reddish shaley silt loams. These soils have a relatively low permeability and moderate to low available moisture capacity. Readington series soils are deep, moderately well drained silt loams with moderately low permeability and moderate to high available moisture capacity.

Other soil types present in the basin include the Penn-Klinesville very shaley silt loams, Rowland silt loam, Bowmansville silt loam (local alluvium), Croton silt loam, Klinesville very shaley silt





SOURCE: SOIL CONSERVATION SERVICE, SOIL SURVEY, MONTGOMERY COUNTY, PA, APRIL 1967

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Figure 18

Soils Map - Basin 2

FIGURE 18 (Continued)

LEGEND

AbA - Abbottstown silt loam, 0 to 3 percent slopes

AbB2 - Abbottstown silt loam, 3 to 8 percent slopes, moderately eroded

BrA - Bowmansville silt loam - local alluvium, 0 to 3 percent slopes

BrB - Bowmansville silt loam - local alluvium, 3 to 8 percent slopes

CrA - Croton silt loam, 0 to 3 percent slopes

KsC3 - Klinesville very shaly silt loam, 8 to 15 percent slopes, severely eroded

LeB2 - Lawrencevile silt loam, 3 to 8 percent slopes, moderately eroded

PeB2 - Penn silt loam, 3 to 8 percent slopes, moderately eroded

PeB3 - Penn silt loam, 3 to 8 percent slopes, severely eroded

PeC3 - Penn silt loam, 8 to 15 percent slopes, severely eroded

PkD3 - Penn-Klinesville very shaly silt loam, 15 to 25 percent slopes, severely eroded

ReA - Readington silt loam, 0 to 3 percent slopes

ReB2 - Readington silt loam, 3 to 8 percent slopes, moderately eroded

RsB2 - Reaville shaly silt loam, 3 to 8 percent slopes, moderately eroded

RsB3 - Reaville shaly silt loam, 3 to 8 percent slopes, severely eroded

RsC3 - Reaville shaly silt loam, 8 to 15 percent slopes, severely eroded

Rt - Rowland silt loam

RwA - Rowland silt loam - local alluvium, 0 to 3 percent slopes

RwB - Rowland silt loam - local alluvium, 3 to 8 percent slopes loam, Abbottstown silt loam and the Lawrenceville silt loam. Permeability of these soils ranges from moderate in the Rowland, Bowmansville, Klinesville and Lawrenceville to low and very low in the Croton and Abbottstown, respectively (Soil Conservation Service 1967). Bedrock is relatively shallow, less than 5 feet below grade in most areas.

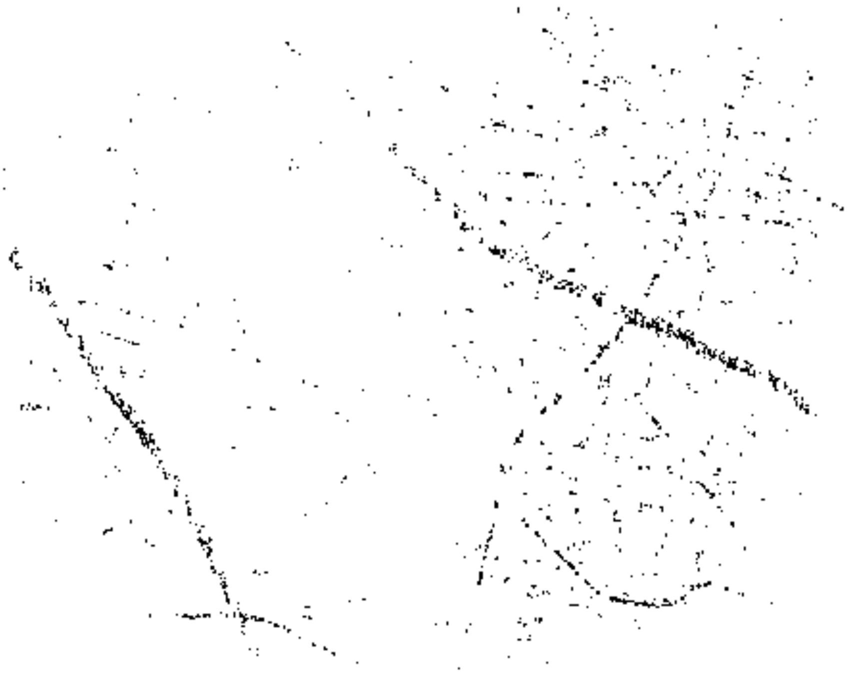
Approximately 10 percent of Basin 2 is wooded. The remainder of the basin consists of low density residential areas, agricultural areas used primarily for growing corn and former agricultural areas which have reverted to grasslands. There are approximately 75 houses in the basin with the majority clustered near the northern and southern ends of the basin. Although the Collegeville-Trappe Joint Water Authority operates several high volume water supply wells in the vicinity of Basin 2, they are not close enough to have significant impact on the basin. The geologic characteristics, soil conditions and land use in Basin 2 are similar to those in Basin 1 thus recharge characteristics would be expected to be similar.

5.3 Basin 3

Basin 3 is located approximately 1 mile (1.6 Km.) northeast of Pennsburg, Pennsylvania as shown on Figure 5, and has a drainage area of 1.09 square miles (698 acres; 2.8 Sq. Km.). the basin is drained by a branch of the Macoby Creek. Length of the basin as measured along the watercourse from the most remote point to the basin outlet, is approximately 11,400 feet. The basin rise which is the difference in elevation between the highest point in the basin and the lowest (basin outlet) is 165 feet. Based upon the basin rise and basin length, the slope was calculated to be 0.015.

The methods described in the section on Basin 1 were used to calculate the time of concentration and time of peak for Basin 3. Time of concentration which is the time it takes for surface runoff to flow from the farthest point in the basin to the basin outlet was determined to be 0.88 hours. The time from the beginning of runoff to the peak runoff, known as the time of peak, is 1.5 hours for this basin. Basin characteristics for Basin 3 are summarized in Table 2.

Soils in Basin 3 are primarily members of the Lehigh, Doylestown, Mount Lucas and Penn series (Figure 19). The Lehigh series consists of deep, light to dark gray silt loams which are moderately well to somewhat poorly drained. These soils have a low permeability and a moderate available moisture capacity. Doylestown series soils are deep, poorly draining grayish brown to brown silt loams with moderate available soil moisture and low permeability. Soils of the Mount Lucas series are deep, moderately well drained and somewhat poorly drainaged grayish-brown to brown to reddish-yellow silt loams. They have a high available moisture capacity yet a low permeability. Members of the Penn series are moderately deep to



SOURCES: SOIL CONSERVATION SERVICE. SOIL SURVEY, MONTGOMERY COUNTY, PA. APRIL 1967
SOIL SURVEY LEHIGH COUNTY, PA. NOVEMBER 1963.
SOIL SURVEY OF BUCKS & PHILADELPHIA COUNTIES, PA. JULY 1975

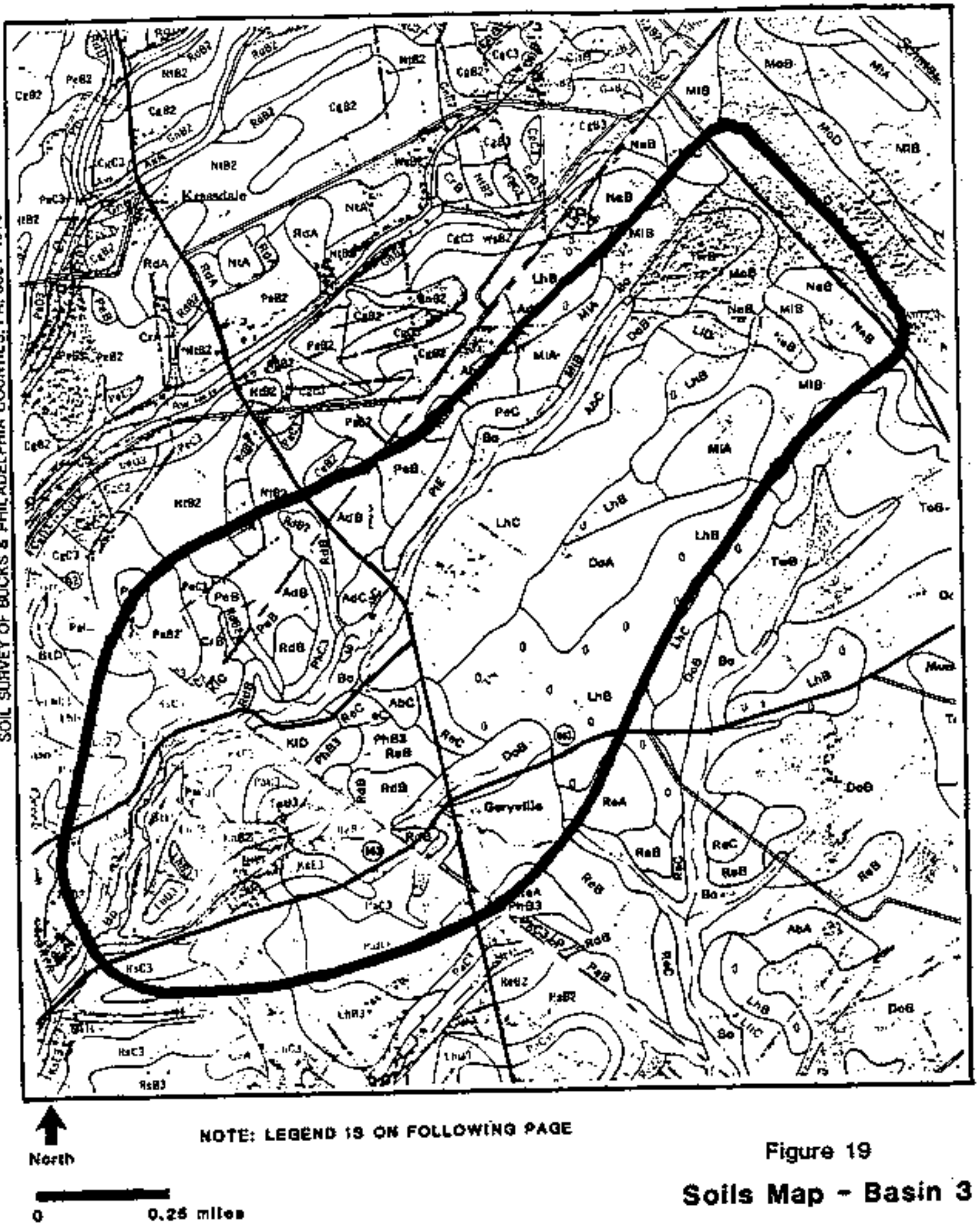


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Figure 19

Soils Map - Basin 3

FIGURE 19 (Continued)

LEGEND

AbB2 - Abbottstown silt loam, 3 to 8 percent slopes, moderately eroded

AbC - Abbottstown silt loam, 8 to 15 percent slopes

AdB - Allenwood gravelly silt loam, 3 to 8 percent slopes

AdC - Allenwood gravelly silt loam, 8 to 15 percent slopes

Bo - Bowmansville silt loam

Bp - Bowmansville silt loam

BtD - Brecknock soils, very channery subsoil variant, 15 to 25 percent slopes

CrB - Croton silt loam, 3 to 8 percent slopes

CrB2 - Croton silt loam, 3 to 8 percent slopes, moderately eroded

DoA - Doylestown silt loamm 0 to 3 percent slopes

DoB - Doylestown silt loam, 3 to 8 percent slopes

KlB2 - Klinesville shaly silt loam, 3 to 8 percent slopes, moderately eroded

KlC - Klinesville very shaly silt loam, 8 to 15 percent slopes

KlD - Klinesville very shaly silt loam, 15 to 25 percent slopes

KsC3 - Klinesville very shaly silt loam, 8 to 15 perent slopes, severely eroded

KsE3 - Klinesville very shaly silt loam, 15 to 35 percent slopes, severely eroded

LhB - Lehigh channery silt loam, 3 to 8 percent slopes

LhB2 - Lehigh channery silt loam, 3 to 8 percent slopes moderately eroded

LhB3 - Lehigh channery silt loam, 3 to 8 percent slopes severely eroded

LhC - Lehigh channery silt loam, 8 to 18 percent slopes

LEGEND (Continued)

LhC3 - Lehigh channery silt loam, 8 to 15 percent slopes, severely eroded

LlD - Lehigh extremely stoney silt loam, 8 to 25 percent slopes

MlA - Mount Lucas silt loam, 0 to 3 percent slopes

MlB - Mount Lucas silt loam, 3 to 8 percent slopes

MOB - Mount Lucas extremely stoney silt loam, 0 to 8 percent slopes

NeB - Neshaminy channery silt loam, 3 to 8 percent slopes

PaB2 - Penn shaly silt loam, neutral substratum, 3 to 8 percent slopes, moderately eroded

PaB3 - Penn shaly silt loam, neutral substratum, 3 to 8 percent slopes, severely eroded

PaC3 - Penn shaly silt loam, neutral substratum, 8 to 15 percent slopes, severely eroded

PeB - Penn silt loam, 3 to 8 percent slopes

PeB2 - Penn silt loam, 3 to 8 percent slopes, moderately eroded

PeC3 - Penn silt loam, 8 to 15 percent slopes, severely eroded

PhB3 - Penn-Klinesville shaly silt loams, 3 to 8 percent slopes, eroded

PlE - Penn-Klinesville extremely stoney silt loams 25 to 50 percent slopes

PkC3 - Penn-Klinesville complex, 8 to 15 percent slopes, eroded

RdB - Readington silt loam, 3 to 8 percent slopes

RdB2 - Readington silt loam, 3 to 8 percent slopes, moderately eroded

ReB2 - Readington silt loam, 3 to 8 percent slopes, moderately eroded

ReB - Reaville shaly silt loam, 3 to 8 percent slopes

ReC - Reaville shaly silt loam, 8 to 15 percent slopes

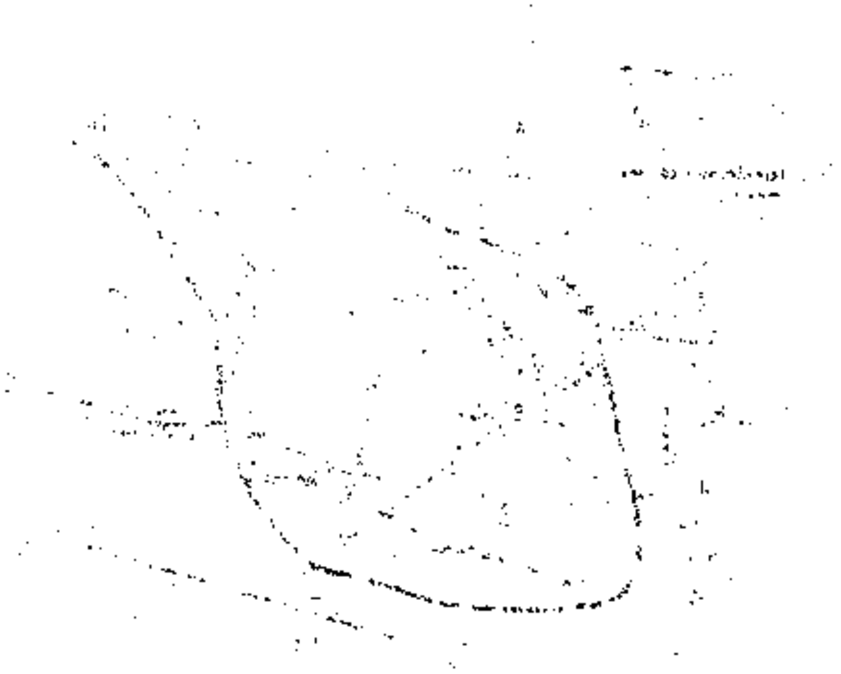
RsC3 - Reaville shaly silt loam, 8 to 15 percent slopes, severely eroded

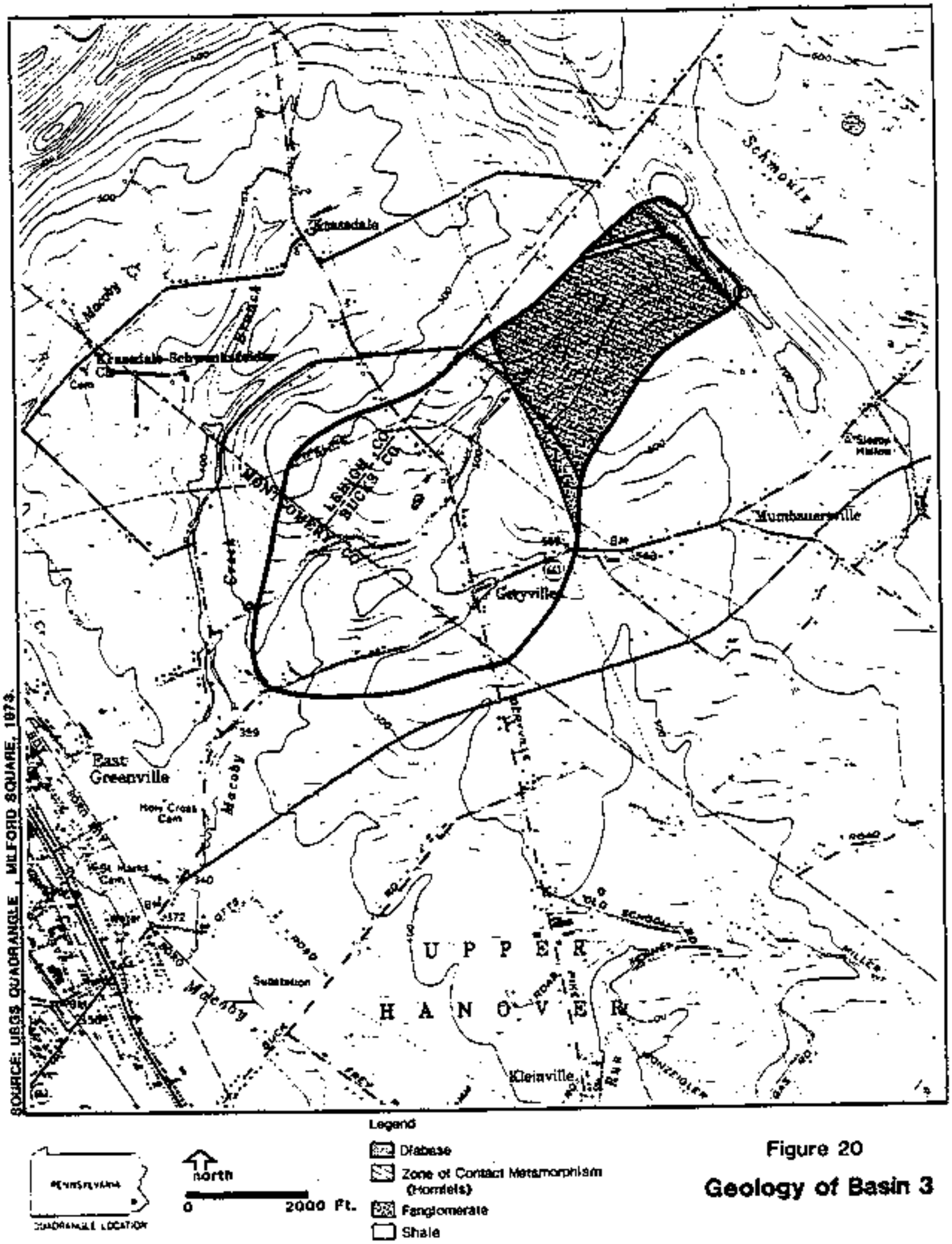
TwB - Towhee extremely stoney silt loam, 0 to 8 percent slopes shallow, reddish brown silt loams which are well drained. Moderately high permeability and low to moderate available moisture capacity are characteristic of these soils.

Members of ten other soil series are also found the Basin 3. These include the Abbottstown, Allenwood, Bowmansville, Brecknock, Croton, Klinesville, Norton, Neshaminy, Readington and Towhee series. Bedrock is relatively shallow, less than 5 feet below grade in most areas.

Land use in the basin is primarily for agricultural purposes. Some areas which are no longer cultivated have reverted to grasslands. Approximately 20% of the basin is wooded, most of which is in the northeastern or upstream section. Population density is low as indicated by the fact that there are only approximately 50 houses within the basin. The majority of these houses are clustered along the Geryville Pike which bisects the basin in a north-south direction.

Basin 3 differs geologically from Basins 1 and 2 in several respects. As shown in Figure 20, approximately 2 percent of the basin, near the northeast divide is underlain by diabase. The aureole associated with the diabase intrusives extends over approximately 1/3 of the basin. Within this area the Brunswick shale has





SOURCE: USGS QUADRANGLE, MILFORD SQUARE, 1973.

Figure 20

Geology of Basin 3

undergone varying degrees of contact metamorphism as discussed in Section 2.0. According to Kammerer (1953) the Brunswick Formation consists primarily of limestone fanglomerate in Basin 3. Field mapping conducted for this study indicated that approximately one-third of the basin is underlain by Fanglomerate.

6.0 RESULTS

6.1 Baseflow Recession Method

Groundwater recharge was calculated monthly for the period from December 1982 through November 1983 using the baseflow recession method. Examples of the recharge calculations are presented in Appendix B. The average monthly flow rates during periods of baseflow recession for each of the basins are presented in Table 3. Basins 1 and 2 each exhibited periods of zero stream flow during the warmer months whereas streamflow in Basin 3 never dropped below approximately 8 gallons per minute (see Figures 21, 22 and 23). The lowest average monthly streamflow for Basin 3, 47 gallons per minute occurred in August 1983. Maximum average monthly flow rates were 213 gpm, 617 gpm and 1,604 gpm for Basins 1, 2 and 3 respectively. The maximum flows occurred during March in Basins 1 and 2 and April in Basin 3. Photographs illustrating near capacity flow at each of the weirs are presented as Figures 24, 25 and 26. During many storm events, the capacity of the weirs was greatly exceeded.

Calculated monthly groundwater recharge rates are listed in Table 4 and presented graphically as Figures 27, 28, and 29. The monthly groundwater recharge rates calculated for Basin 1 ranged from zero to 1,556,000 gallons/day/square mile with an average annual recharge rate of 441,000 gallons/day/square mile. Basin 2 had average

TABLE 3

AVERAGE MONTHLY FLOW RATE DURING PERIODS OF BASEFLOW RECESSION (GALLONS PER MINUTE)

Month		Basin #1	Basin #2	Basin #3
December	1982	43	169	307
January	1983	60	200	583
February	1983	151	395	905
March	1983	213	617	1,244
April	1983	112	557	1,604
May	1983	49	148	571*
June	1983	11	49	258*
July	1983	0	0	134*
August	1983	0	0	47*
September	1983	0	0	53
October	1983	0	24	76
November	1983	32	154	237

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* Estimated

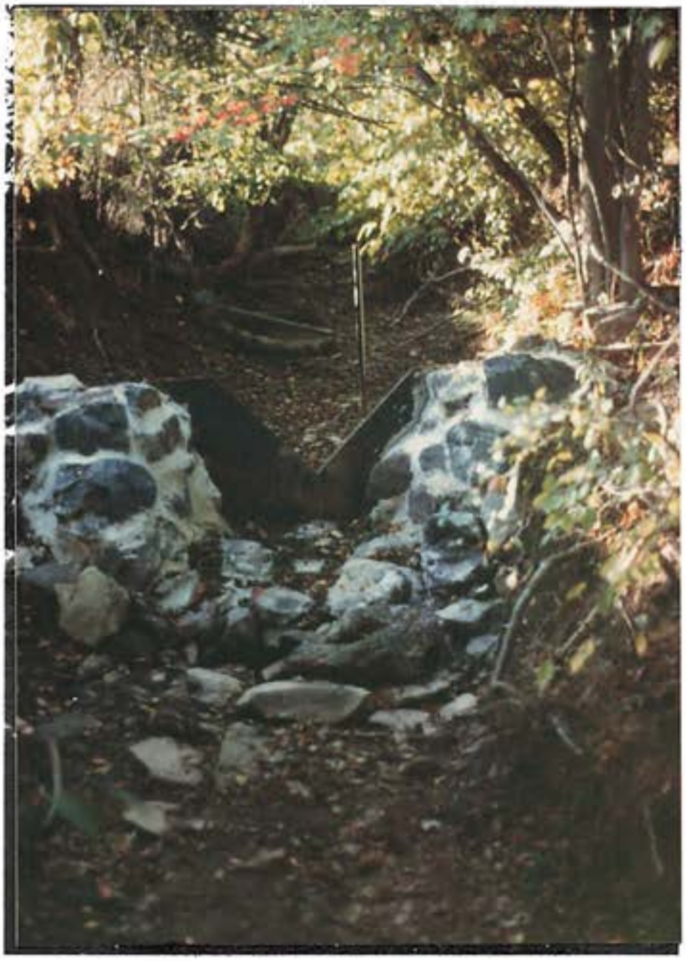

Figure 21

Low Flow Basin 1

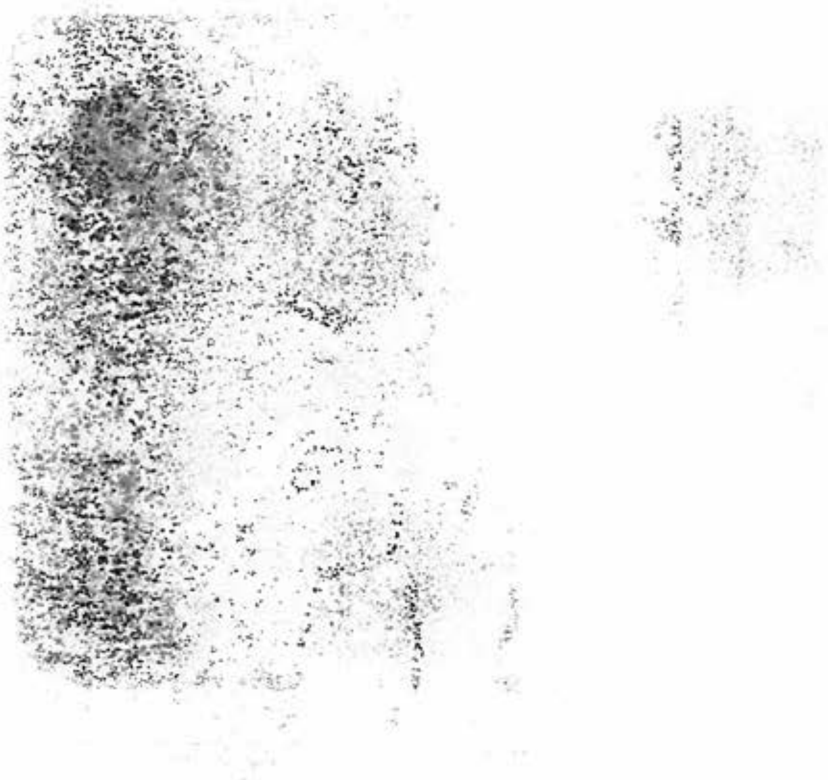

Figure 22

Low Flow - Basin 2

Figure 23

Low Flow - Basin 3

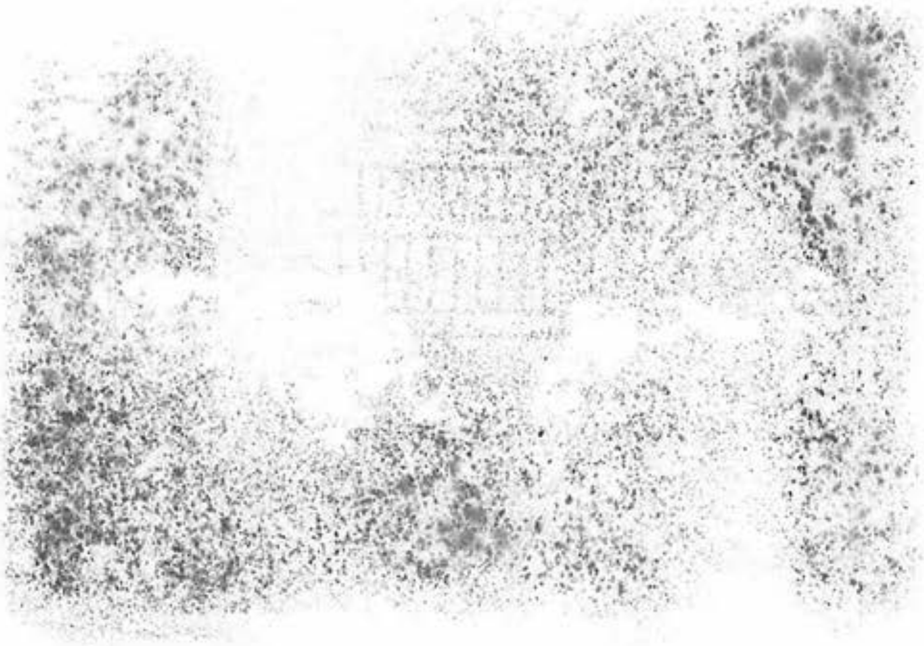

Figure 24

Storm Runoff - Basin 1