EFFECTS OF GROUNDWATER PUMPING ON THE HYDROGEOLOGY OF THE PRIMROSE CREEK WATERSHED, NEW HOPE, PENNSYLVANIA

A Thesis

Submitted to

the Temple University Graduate Board

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MASTER OF ARTS

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by

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ABSTRACT

Pumping of 3.01 x 10^8 gallons per square mile (gal/mi^2) of groundwater from a carbonate aquifer near New Hope, Pa. changed the hydrogeologic system of a small watershed by inducing groundwater inflow and accelerating ground subsidence. A deficit in the annual water budget indicated that 1.7 x 10^8 gal/mi^2 of groundwater flowed into the Primrose Creek Watershed as inflow from adjacent drainage basins to supply the demand of the pumps in the New Hope Crushed Stone Company's (NHCS) quarry operation. Pumping accelerated sinkhole collapse by the following mechanisms: the loss of buoyant support as a result of a lowering of the water table, increased groundwater velocities caused by the steepening of hydraulic gradients, induced recharge in areas which previously rejected recharge.

ACKNOWLEDGEMENTS

I would like to thank the faculty of the Geology Department for their guidance and support. Thanks to my advisor Dr. John Adams and to Chuck Handschin for their technical support. Thanks to Dr. Mary Lou Hill and Dr. Pete Goodwin for their constructive comments. Also thanks to Jon Cawley for his help with slide preparation. I would also like to thank Fraser Hamilton, Jon Touchberry, and Chris Orzechowski for their field assistance. Thanks to Roy F. Weston, Inc. for help with the digitized maps. I dedicate this work to my parents, Joseph Hill and Elizabeth Hill.

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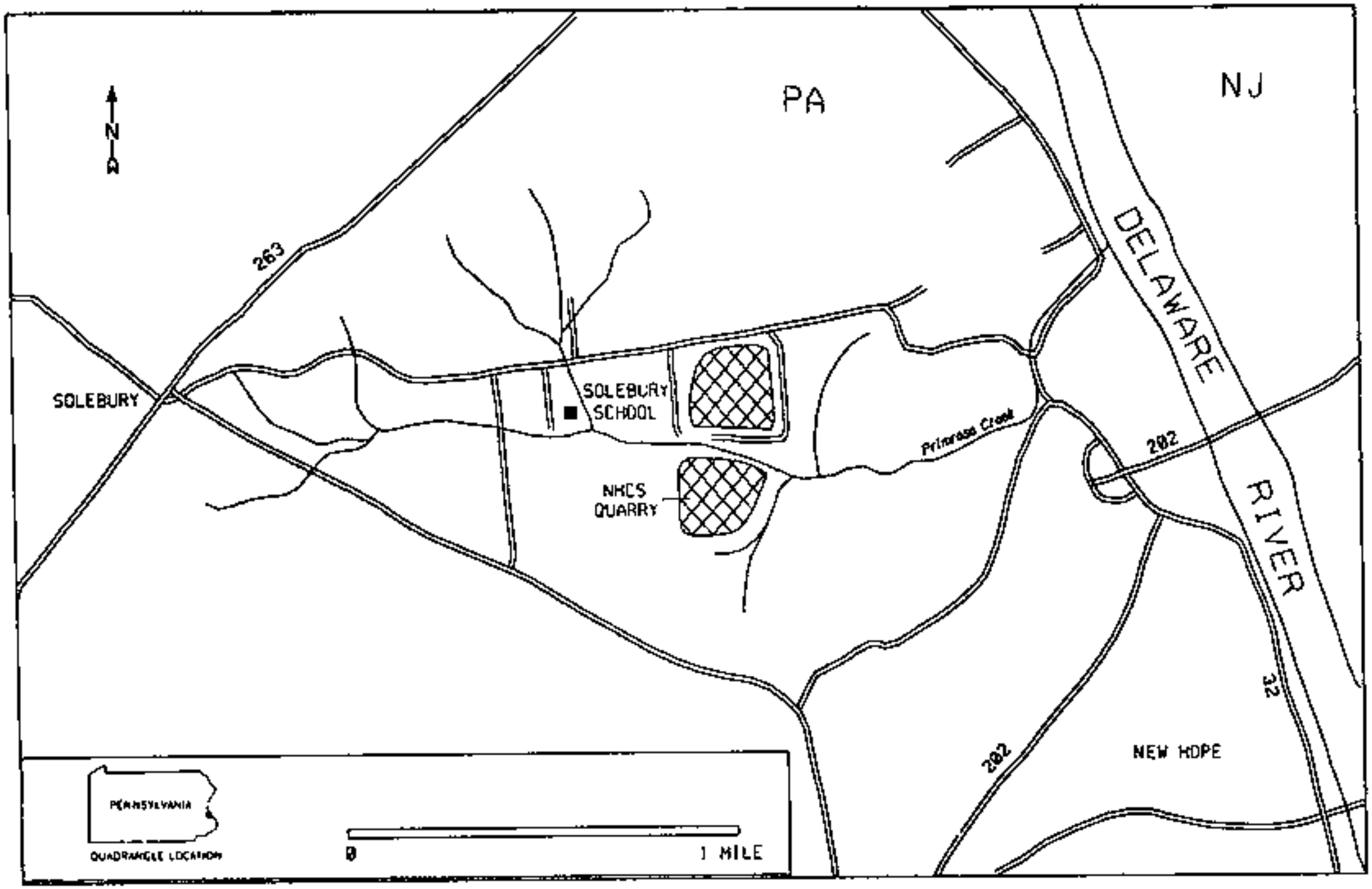
CHAPTER 1

INTRODUCTION

Primrose Creek is located in Bucks County in southeastern Pennsylvania about two miles northwest of New Hope at north latitude 42° 2' 30" and west longitude 75° 0' 0" (Figure 1). The creek, a small tributary to the Delaware River, drains an area of 2.8 square miles. Land within the drainage basin is mostly used as farmland, left as wooded areas, or developed into housing tracts. Farmland and wooded areas account for 70-80% of the basin area. However, farms are being sold and trees cut down as urbanization progresses. Houses and farms within the basin are scattered except for some clustering in the town of Solebury and along the southeastern drainage divide.

Near the center of the basin is a quarry operated by the New Hope Crushed Stone Company (NHCS quarry) which mines limestone and dolomite for sale as crushed stone. The quarry consists of two pits, the deepest reaching 140 feet below mean sea level; both pits are pumped continuously. Groundwater is pumped into Primrose Creek downstream from the quarry, sustaining flow in this section of the creek and making it perennial. Upstream of the quarry Primrose Creek is intermittent. Pumping in the quarry creates a cone of depression around the pits which affects the hydrology and geomorphology of the Primrose Creek Basin.

Figure 1. Location Map of the Primrose Creek Watershed.



Purpose and Scope

The objective of this study was two-fold: 1) to develop a hydrologic budget in order to quantify the flux of water through the study area and to determine annual recharge rates and 2) to document the effects of groundwater withdrawals on the hydrogeologic system of a small watershed. This study focused on the carbonate aquifer in the Primrose Creek Watershed because of the interesting opportunity to study the hydrogeologic effect of dewatering an excavation in a lithology which is prone to subsurface chemical erosion. Groundwater withdrawals from carbonate aquifers should be monitored and limited to prevent the chance of catastrophic sinkhole collapse and the depletion of water resources of adjacent drainage basins.

Methods of Investigation

Geologic and hydrologic data were collected for one year from February, 1988 to January, 1989. A geologic map of the Primrose Creek Watershed was prepared based on existing area maps and first-hand field observations. Measurements of strike and dip of bedding, joints, and fractures were recorded; the best exposure was observed in the NHCS quarry and along the Delaware River.

Hydrologic data stations included two stream gauging stations, a 90 degree v-notch weir to measure pump discharge, a rain gauge located at the National Oceanographic and Atmospheric Administration (NOAA) station in Lambertville, NJ, a rain gauge located at the NHCS quarry, and two observation wells fitted with Steven's Meters to measure depth to water continuously. Streamflow and pump discharge were measured concurrently once a week and the data were analyzed using the methods of Corbett et al. (1943) for streamflow and Fetter (1980) for discharge over the weir crest. Data collected at the (NOAA) rain gauge in Lambertville, NJ were used from February, 1988 to June, 1988 at which time the NHCS rain gauge was installed. From June, 1988 to January, 1989 data from the NHCS rain gauge were used.

Previous Work

Howell et al. (1950) worked on the subdivision and dating of the carbonate rocks in Bucks County. Geologic maps of the Buckingham Valley were prepared by Willard (1955) and Willard et al. (1959). Drake (1965) summarized changes in nomenclature of the carbonate formations in Buckingham Valley and in Lehigh County. Lessentine (1952) studied the structure of Buckingham Valley and Zietz and Gray (1960) conducted a geophysical study across the Furlong Fault. Greenman (1955) studied the water resources of Bucks County. Wood et al. (1972) studied the water resources of the same carbonate formations in Lehigh County and quantified streamflow losses and groundwater underflow. Foose (1953, 1969) documented sinkhole development due to groundwater dewatering in Hershey Valley, Pennsylvania which is hydrologically and geologically analogous to the Primrose Creek Watershed. Newton (1986) reported mechanisms of sinkhole development related to groundwater withdrawals along the east coast of North America.

CHAPTER 2

GEOLOGY

The Primrose Creek Watershed is located partly in the Triassic Newark-Gettysburg basin and partly in a structural window which exposes Precambrian and Lower Paleozoic rocks. Kummel (1897) subdivided the Triassic rocks into three formations. In ascending order they are the Stockton Formation, the Lockatong Formation, and the Brunswick Formation (also called the Passaic Formation, Olsen, 1990). Locally, small deposits of limestone conglomerate occur at the contact with Paleozoic limestones and appear to fill paleokarst features or old stream channels.

The stratigraphic sequence of the Paleozoic formations is: the Cambrian Hardyston Quartzite, Leithsville Limestone, and Allentown Limestone; the Early Ordovician Beekmantown Limestone (Figure 2). The Beekmantown Formation is the youngest Paleozoic formation in Bucks County; the Triassic Stockton Formation unconformably overlies the Paleozoic carbonate formations (Howell et al., 1950). The nomenclature used in this report for the carbonate rocks is consistent with the usage of the Pennsylvania Bureau of Topographic and Geologic Survey. For a review of changes in nomenclature see Table 1.

Diabase dikes, sills and basalt flows intrude and are interbedded with the clastic sediments. Large intrabasinal faults break the basin into a series of rhomb-shaped fault blocks with a regional dip toward the northwest (Manspeizer and Cousminer, 1988; Willard et al., 1959). One such fault is the Furlong Fault which brings Precambrian gneiss to the surface in Bucks County.

Figure 2. Stratigraphy of the Primrose Creek Watershed.

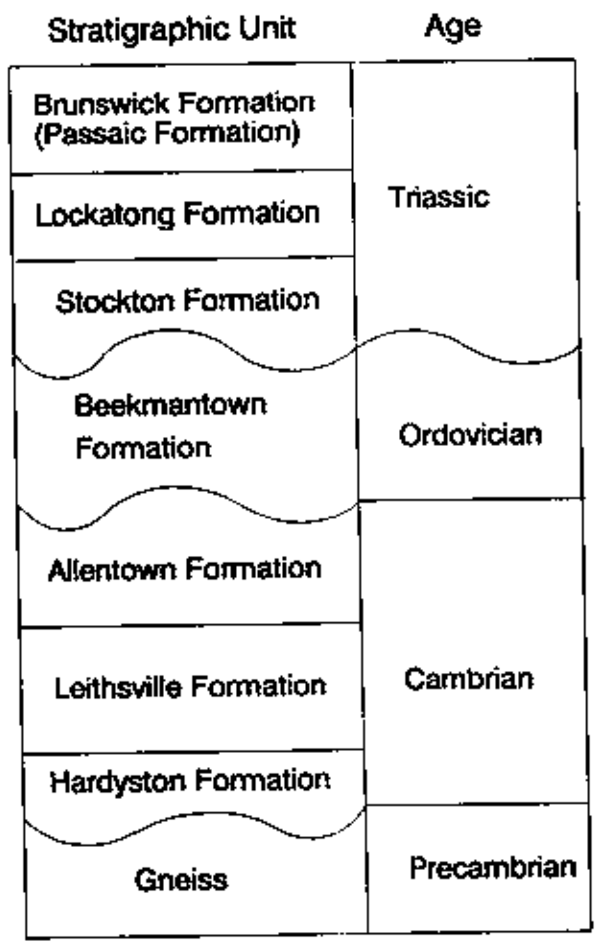
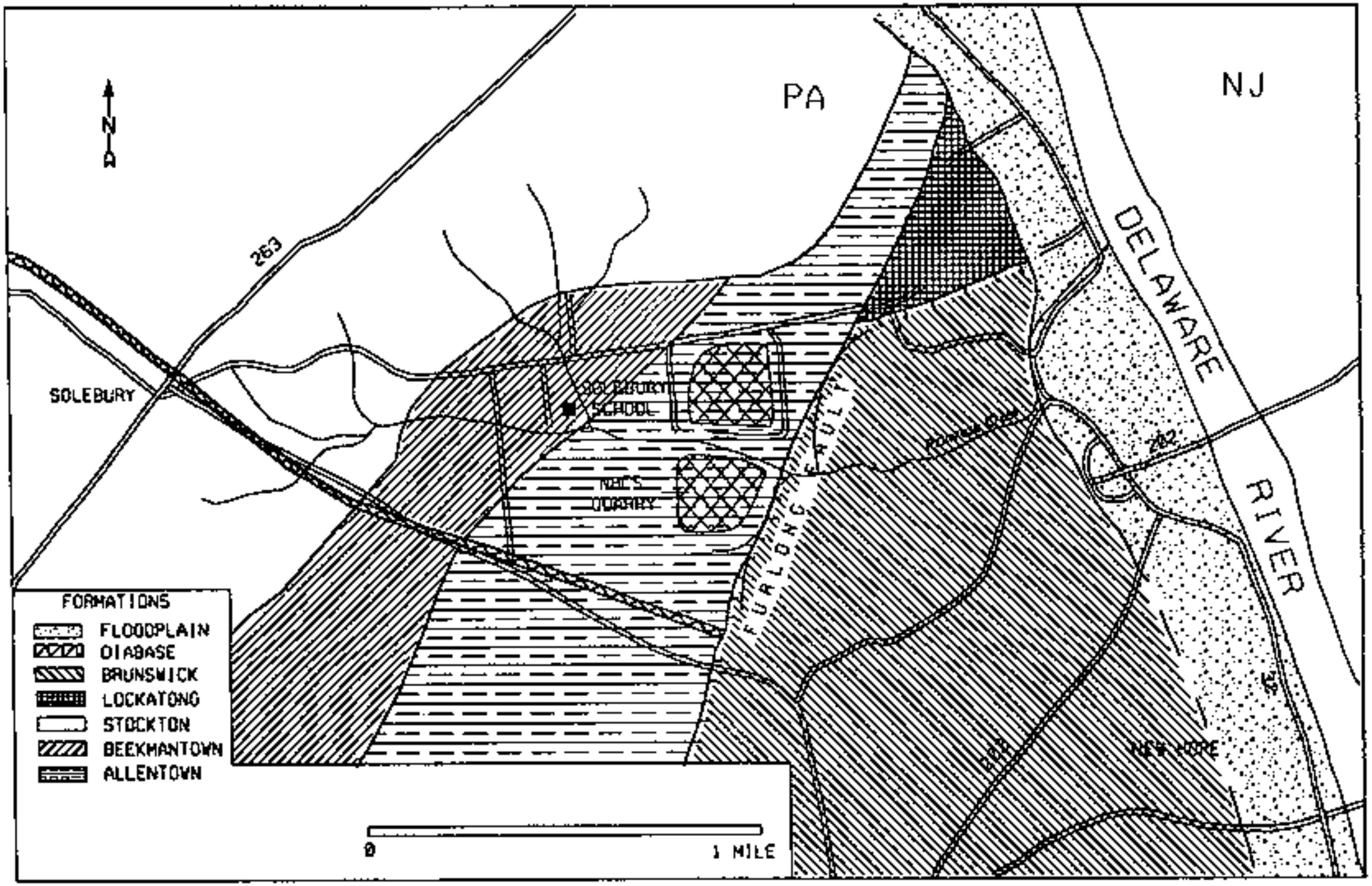


Table 1. Stratigraphic Nomenclature of Cambro–Ordovician Formations in Southeastern Pennsylvania Used by Previous Authors. Modified From Drake (1965).

Wherry (1909)	B. L. Miller and others (1939)	Howell, Roberts, and Willard (1950)	Drake (1965)	Age
Coplay Limestone	Beekmantown Formation	Beekmantown Formation	Epler Formation Rickenbach Dolomite	Ordovician
Allentown Limestone	Allentown Formation	Allentown Formation Limeport Formation	Allentown Dolomite	Cambrian
Leithsville Limestone	Tomstown Formation	Leithsville Formation	Leithsville Formation	
	Hardyston Formation	Hardyston Formation	Hardyston Quartzite	

Figure 3. Geologic Map of the Primrose Creek Watershed.



Local Geology

In the Primrose Creek Watershed three Triassic formations and two Cambro-Ordovician formations are exposed (Figure 3). The best exposure is of the Allentown Formation in the NHCS quarry pits in the center of the study area.

Allentown Formation

The Allentown Formation is dominated by light blue-grey to black carbonate interbedded with thin shaley layers. Bedding ranges from thin laminae to more massive beds 2-3 ft thick. Grain size varies considerably from very fine-grained micrite with conchoidal fracture to a highly crystalline, coarse-grained calcarenite. A stratigraphic column from the northern pit of the quarry reveals more detail of the Allentown Formation (Figure 4).

Cycles lower in the section can be defined by basal shaley beds grading upward into massive grey-black, fine-grained limestone which coarsens upward into grey-black limestone with wavy bedding. Higher in the section cycles are based on edgewise conglomerates or fine-grained, thinly bedded, black limestone grading upward into thinly laminated grey-black dolomitic limestone or a purple-buff dolomite. Such facies indicate a stratigraphic position in the middle of the Allentown Formation.

Several weathered outcrops of the Allentown Formation exhibit solution pits, grooves, and tunnels indicating some degree of chemical weathering. One outcrop in the old Limeport Quarry reveals two small tunnels formed along a bedding plane

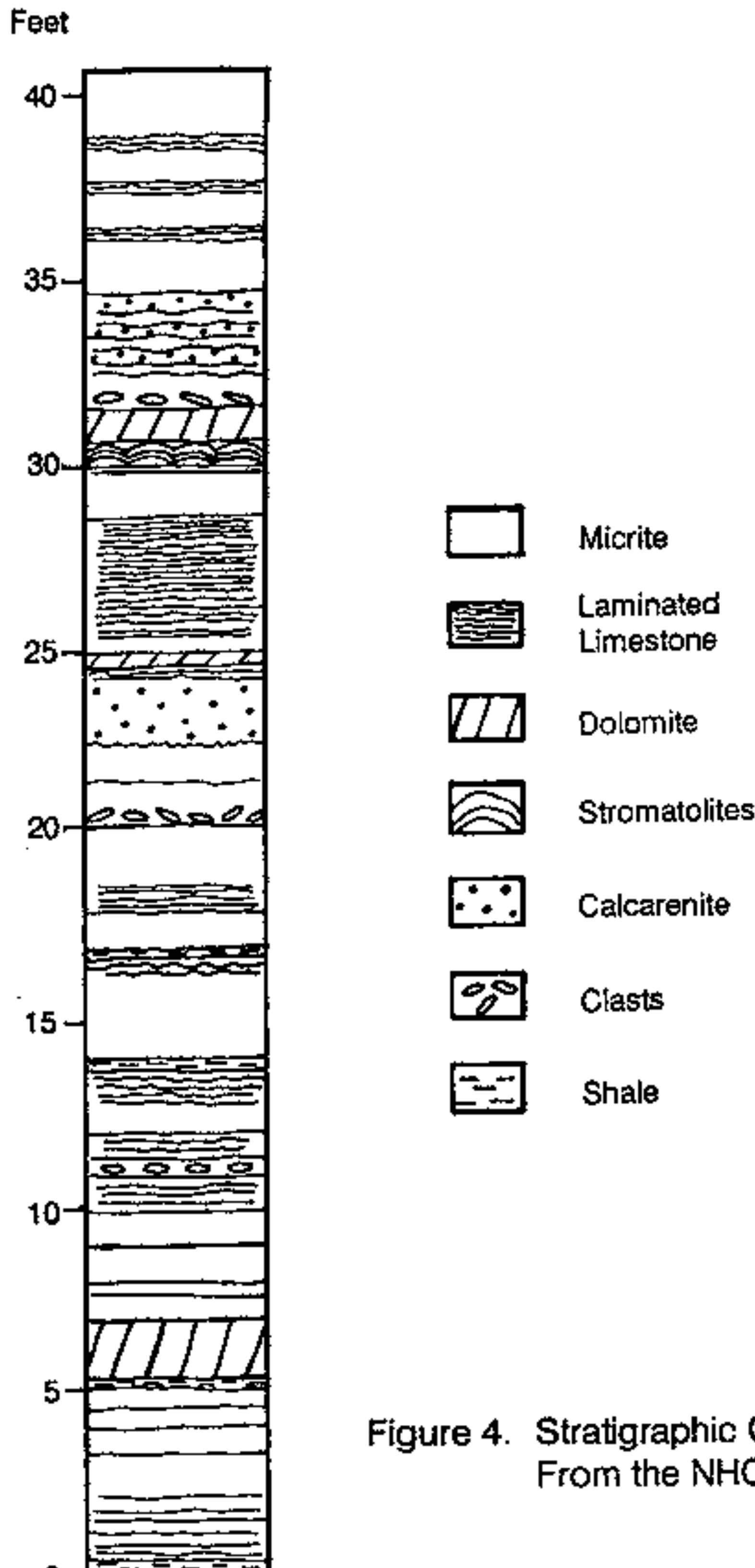


Figure 4. Stratigraphic Column From the NHCS Quarry.

Figure 5. Evidence of Chemical Weathering Along a Fracture and a Bedding Plane.

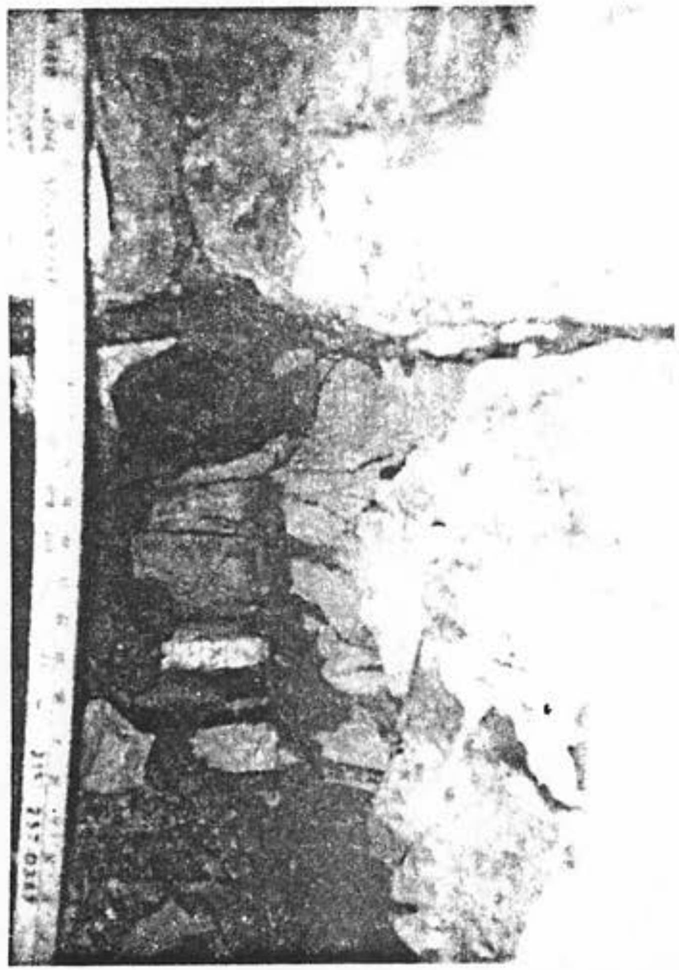


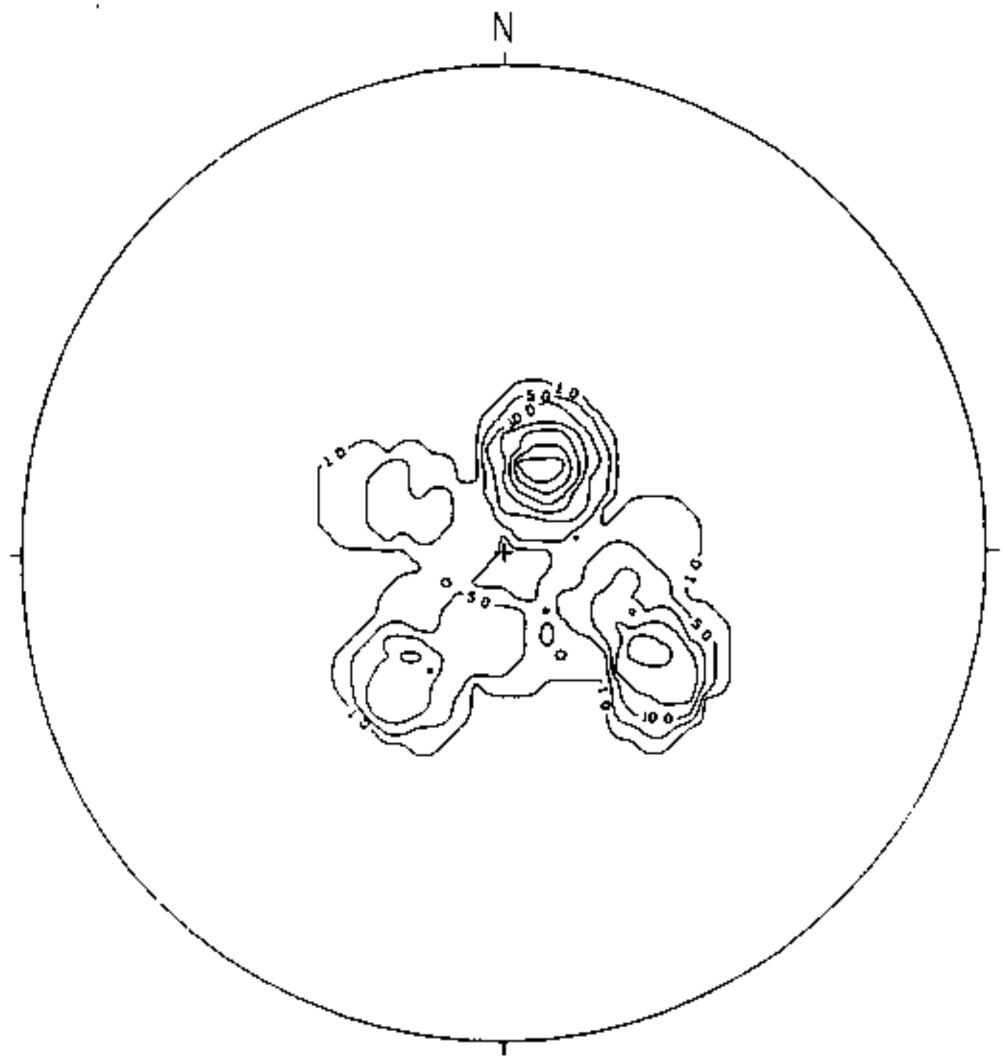
Figure 6. Closeup of a Solution Tunnel Along the Bedding Plane Shown in Figure 5.

with a fracture rising vertically from them (Figure 5 and 6). There is also evidence of paleokarst in the upper section of the NHCS quarry.

Beekmantown Formation

The second Paleozoic formation exposed in the Primrose Creek Basin is the Beekmantown Formation. The contact between the Beekmantown and Allentown Formations is believed to be disconformable as indicated by the local occurrence of a bed of red shale. This red shale bed was not observed in outcrop but pieces of red shale were observed in a farmer's field along Phillips Mill Road northwest of the NHCS quarry (Phillips Mill Road trends east-west and passes just north of the NHCS quarry). The location of this float is near the contact between the Beekmantown and Allentown Formations as mapped by Willard (1955).

There is one outcrop of the Beekmantown Formation located on the grounds of Solebury School along Phillips Mill Road. This outcrop is a pinnacle, a karst feature which forms between sinkholes. At this locality the lithology is a light grey, medium-grained carbonate with thin shaley layers interbedded with 2 foot thick limestone and dolomite beds. Here the Beekmantown Formation is similar to the Allentown Formation except for a conspicuous bed of nodular oolitic chert which is typical of the Beekmantown Formation. Small solution pits and grooves along the surface of an exposed bedding plane indicate chemical weathering. The carbonate rocks of the Allentown and Beekmantown Formations generally strike northeast-southwest with dips between 15 and 35 degrees but are gently warped and therefore strike and dip in a range of directions (Figure 7).



Schmidt Equal Area Net n = 31

Figure 7. Contour Plot of Poles to Bedding Surfaces in the Allentown Formation Measured in the NHCS Quarry.

Stockton Formation

In the northwestern part of the study area the Triassic Stockton Formation unconformably overlies the Ordovician Beekmantown Formation. The Stockton Formation consists of medium to coarse-grained arkose and arkosic conglomerate interbedded with red shale as indicated by chips of red shale in stream channels. Lithologies of the Stockton Formation strike northeast-southwest with beds dipping to the northwest at an average of 15 to 20 degrees.

Lockatong Formation

The triangular area between the Furlong Fault and a fault splay is underlain by a small patch of the Lockatong Formation. The Lockatong is a very fine-grained, grey to black, argillaceous shale which is resistant to weathering. There is no outcrop in this area except for blocky pieces of float which cover the hillside. Most pieces of float are very fine-grained with no apparent bedding which is typical of the massive beds of the Lockatong Formation. However, some float has very thin laminations or varves.

Brunswick Formation

Stratigraphically overlying the Lockatong Formation is the Brunswick Formation. Locally the shales of the Brunswick Formation are warped and extremely fractured due to extensive faulting. Near the intersection of Primrose Creek and Route 32 is a small outcrop of soft, red shale with a very fine-grained texture. Bedding surfaces are wavy and irregular ranging from a few millimeters to a few centimeters in thickness. The average strike at this locality is S28E with dips ranging from 12 to 29 degrees to the south and west. The strike is almost perpendicular to the general local strike of bedding possibly due to folding.

Floodplain Deposits

The youngest sediments in the study area are found along the Delaware River as Quaternary and modern floodplain deposits. These consist of well sorted, well rounded gravel composed of lithic fragments which were deposited as glacial outwash during the Pleistocene.

Diabase Dikes

Several small diabase dikes are exposed in the NHCS quarry. Contact metamorphism is indicated by the presence of pyrite, talc, and calcite along the margins of the diabase. The largest dike is continuous through both pits of the quarry while two smaller dikes seem to pinch out and are difficult to trace from wall to wall (Figure 8). Another dike in the study area is located along Sugan Road and crosscuts the Stockton, the Beekmantown, and the Allentown Formations but is cut off at the Furlong Fault (Sugan Road extends from Solebury towards New Hope). Within the Primrose Creek Basin this dike is observed only as float.

Structure

The Furlong Fault, a large normal fault dipping to the southeast at an approximate angle of 45 degrees and striking approx N30E brings the Paleozoic carbonates up into contact with the Triassic shales with an estimated throw of 10,000

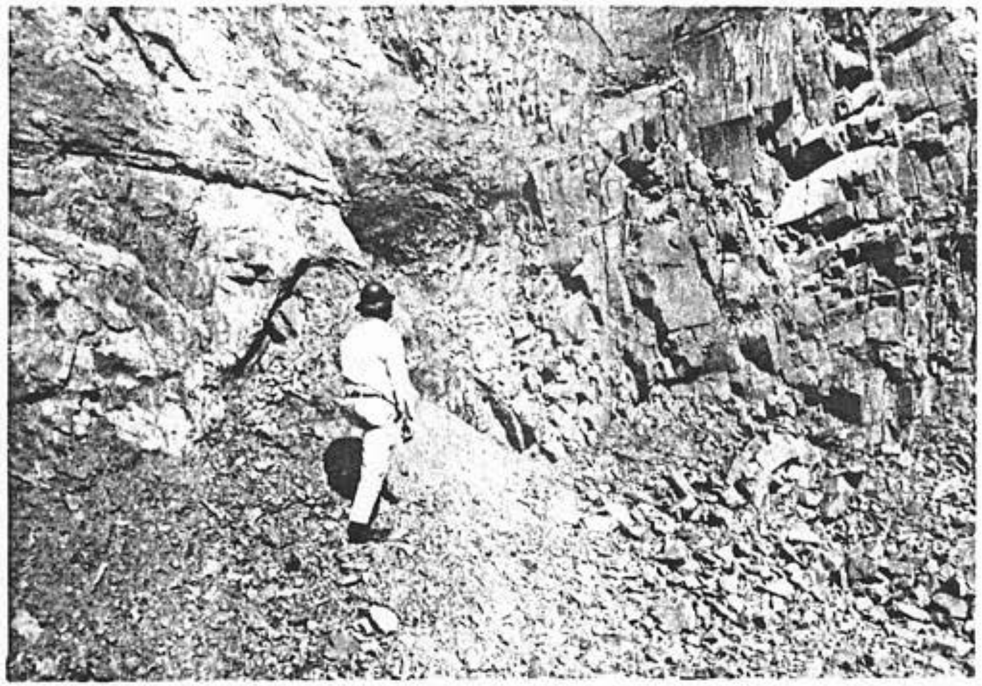


Figure 8. Diabase Dikes Crosscutting the Allentown Formation in the NHCS Quarry.

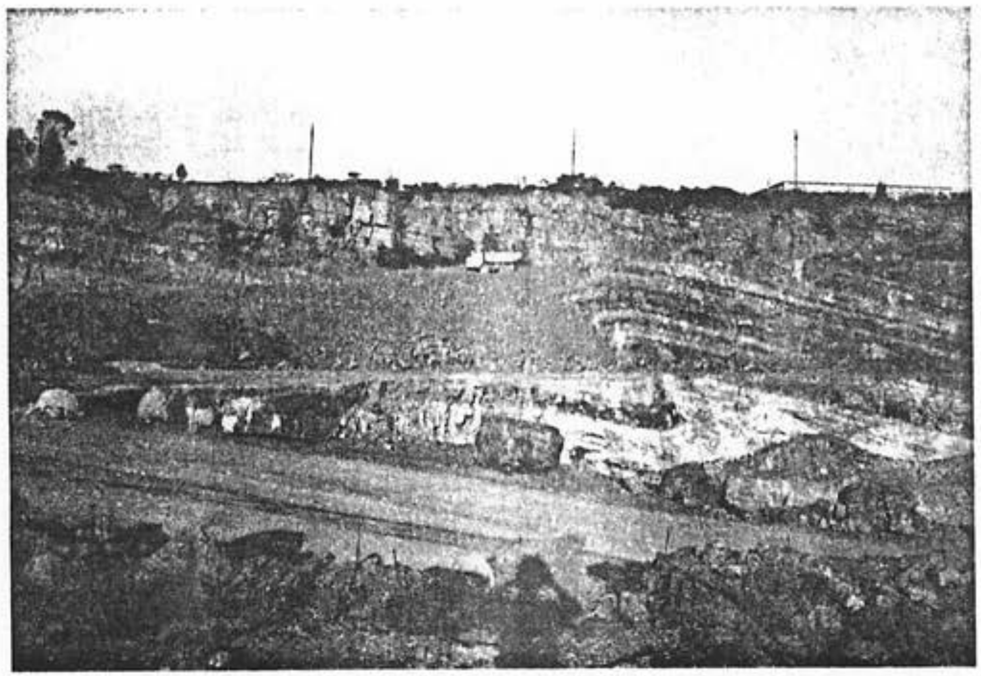


Figure 9. A Thrust Fault Exposed in the NHCS Quarry.

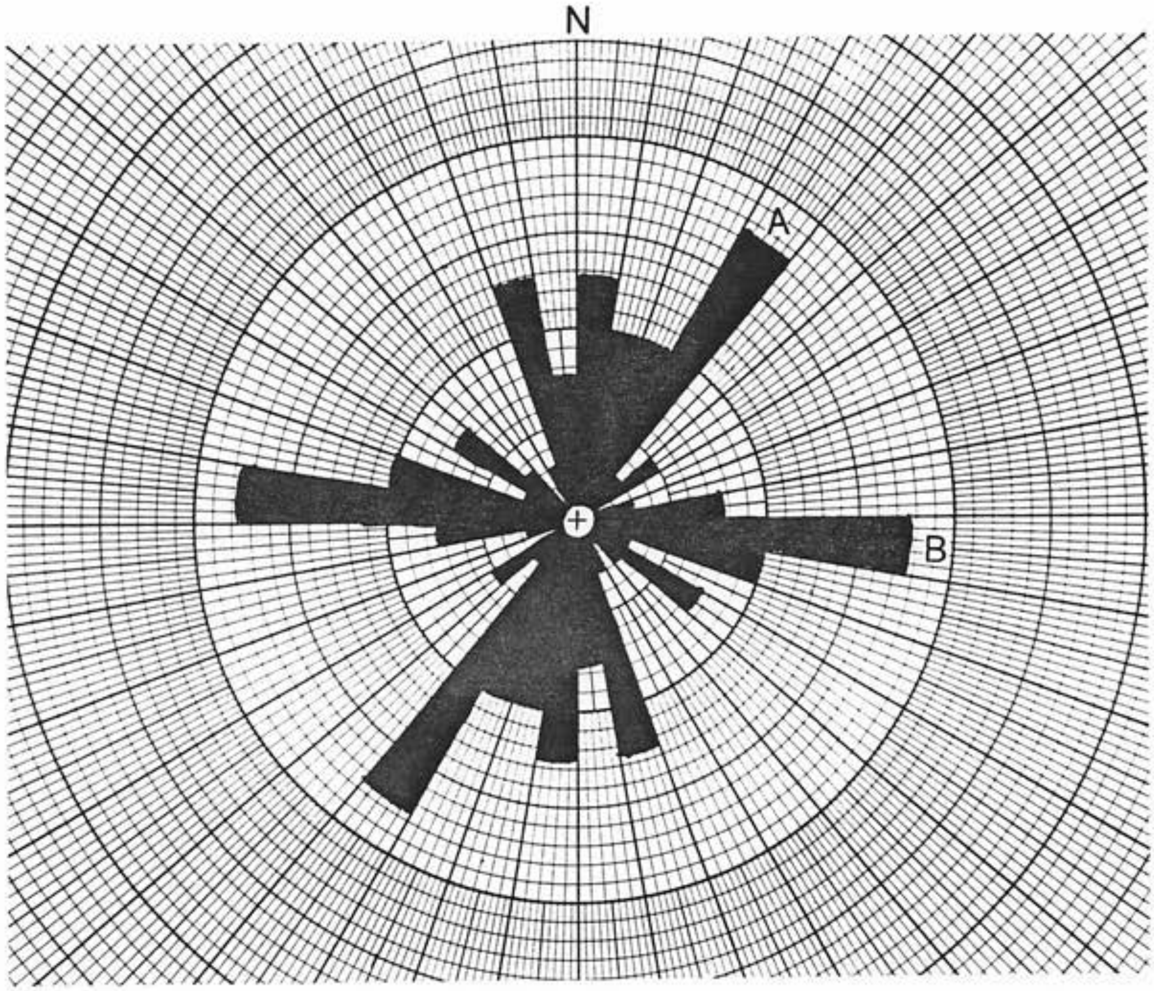
ft (Willard et al., 1959). This estimate was based on the total thickness of the Triassic rocks which may be penecontemporaneous; therefore the actual displacement across the fault may be much less (Zietz and Gray, 1960). A small splay from the Furlong Fault brings the Lockatong Formation into contact with the Brunswick Formation in the northeastern corner of the study area (Howell, 1950). A small thrust fault crosscuts the northern pit of the quarry with displacement of the southern hanging wall up about 20 ft (Figure 9).

An analysis of joint orientations observed in the NHCS quarry shows the existence of two major vertical joint sets and several minor vertical and sub-vertical joint sets (Figure 10). One major joint set (joint set A) trends approximately N30E which is parallel to the Furlong Fault while the other intersects the Fault at approximately 60 degrees (joint set B).

Geomorphology

In the Primrose Creek Watershed lithology and structural lineaments control the basin geomorphology. Major structural features include joints, bedding plane partings, folds, fractures, and faults. The major joint sets and the strike of bedding appear to exert the greatest structural influence on the geomorphology of the study area.

In general the sandstones form ridges parallel to the strike of bedding, the carbonates form valleys, and the shales form rolling hills. The headwaters of Primrose Creek form a dendritic pattern as they flow from the hills underlain by Stockton Formation sandstones. These streams converge near the Stockton



n = 49

Figure 10. Rose Diagram of Joint Orientations in the Allentown Formation Measured in the NHCS Quarry.

-Beekmantown contact to form the main stem of Primrose Creek which then flows from west to east parallel to joint set B. Downstream at the southeastern boundary of the NHCS quarry two tributaries seem to flow along strike of the Furlong Fault.

There are also two solution valleys which appear to be oriented sub-parallel to the two major joint sets. The sinkholes observed in the study area predominantly occur near or in the stream bed of Primrose Creek. It appears that the orientation of Primrose Creek and it's tributaries, solution valleys, and sinkholes are controlled by the two major joint sets but because the strike of bedding and of the Furlong Fault are similar to joint set A it is difficult to identify the structural feature which exerts the most influence on the geomorphology of this area.

CHAPTER 3

WATER BUDGET CALCULATIONS

The first objective of this study was to develop a yearly water budget which would be used to quantify the flux of water through the designated study area and determine recharge rates. A water budget models the volume of water coming into the system, flowing through the system, then leaving the system. Most of the variables in the equation can be measured or calculated empirically, but some such as underflow must be determined by the water budget equation which is:

$$P = R + ET + Sg + Ss + U + D$$

where P = precipitation
R = streamflow or runoff
ET = evapotranspiration
Sg = change in ground water storage
Ss = change in soil moisture
U = underflow
D = diversions by man

Change in soil moisture is assumed to be negligible over a period of one year but the other factors must be either measured directly, derived from empirical calculations, or determined by the budget.

Precipitation

Precipitation was assumed to be the only input into the system, although this cannot be confirmed until after the yearly water budget is completed and the value of underflow is determined. Precipitation data were collected at three rain gauging stations. For the period from February to March, 1988, data from the National

Oceanographic and Atmospheric Administration (NOAA) station in Lambertville, New Jersey, about 2 miles west of the study area were used. Data for the month of June were collected at Neshaminy Falls owing to a lack of data at the Lambertville station. A rain gauge installed at the New Hope Crushed Stone Company quarry (NHCS), near the center of the basin, supplied precipitation data from July, 1988 until January, 1989.

The NHCS gauging station and the Lambertville, NJ gauging station are less than 2 miles apart so they should record similar amounts of precipitation (Figure 11). However, during intense storms, Lambertville usually receives more precipitation. The largest discrepancy occurred in the last week of July, 1988 when Lambertville recorded 6.37 inches and the NHCS gauge recorded only 4.45 inches. In each month from July, 1988 to January, 1989, with the exception of December, Lambertville received more precipitation than the NHCS quarry. When rainfall is less than 2 inches between measurements (data were collected every 7 days) there is good agreement between the two stations. However, when there is more than 2 inches of rainfall, which is usually the case during intense storms, the correlation is less.

Use of data from Lambertville introduces little error into the water budget calculations for the months of March and April because precipitation never exceeded 2 inches between measurements. On the other hand, in the months of February and May, precipitation exceeded the 2 inch limit; some error may have been introduced in these monthly budgets. The data collected from February, 1988 to January, 1989 document a year of below normal precipitation. The annual volume of precipitation

Figure 11. Correlation of Rain Gauging Stations
1988 – 1989

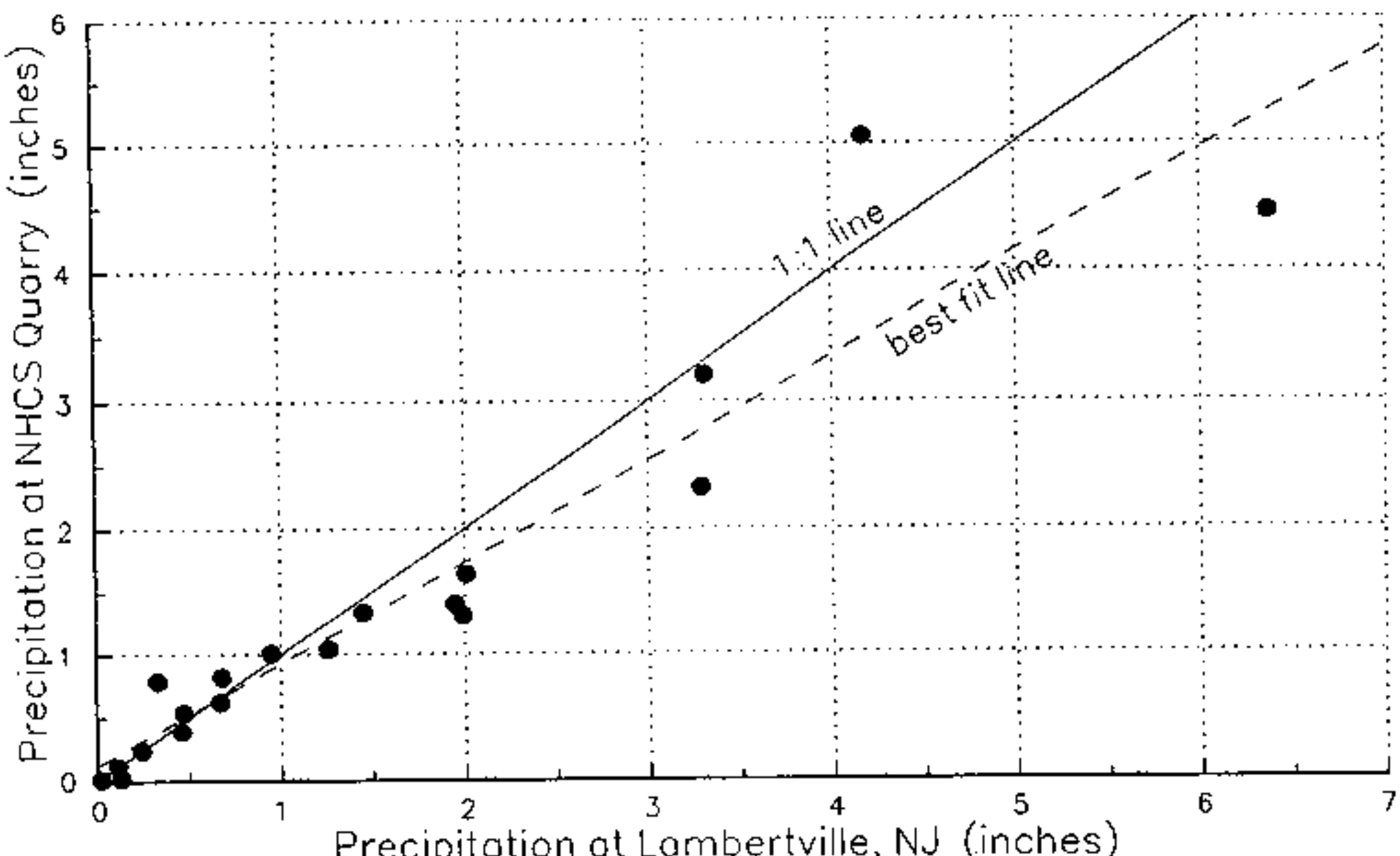


Table 2. Precipitation Recorded at Lambertville, NJ.

Month	Year			
	1986	1987	1988	1989
JAN	4.65	4.34	2.85	2.26
FEB	3.16	1.06	4.23	3.10
MAR	1.85	3.42	2.42	4.14
APR	5.38	6.28	2.71	2.54
MAY	1.55	1.81	5.68	8.19
JUN	0.69	5.72	1.71	9.37
JUL	4.44	8.72	10.88	4.99
AUG	5.08	2.70	3.88	7.27
SEP	1.55	4.15	2.54	9.39
OCT	2.14	3.91	2.66	4.87
NOV	7.98	3.96	7.25	2.51
DEC	6.77	1.65	1.07	0.63
Total	45.24	47.72	47.88	59.26
4−year average = 50.03				

Units are basin inches

used in this study was 43.83 inches compared to the four-year annual average of 50.03 inches (Table 2).

Streamflow

Water input to the system by precipitation that is not evaporated or transpired by plants, either runs off into Primrose Creek, or infiltrates through the soil and bedrock to replenish the groundwater reservoir. As the groundwater level rises, water in storage flows as baseflow toward a discharge area which is usually a stream. Thus streamflow is composed of storm runoff and baseflow. To separate these two components of streamflow a hydrograph of discharge vs. time was prepared for two locations along Primrose Creek (Figure 12). Data were collected by using a Pygmy-Price meter and calculations were performed as described by Corbett and others (1943). These Primrose Creek stations were gauged every week at the same time that pump discharge from the quarry was measured.

Station A gauged streamflow draining from a 1.55 square mile area labelled Basin 1 (Figure 13). Basin 1 is underlain by the arkoses and conglomerates of the Lower Member of the Stockton Formation, the carbonates of the Beekmantown and Allentown Formation, one major diabase dike and several smaller intrusives. The land cover is chiefly woods and farm lands with sparse to moderate development.

Station B gauged total streamflow output from the study area which includes Basin 1 plus a small 0.2 square mile area referred to as Basin 2. Streamflow at Station B included water draining from Basin 1 plus groundwater which was pumped from the NHCS quarry pits and discharged into Primrose Creek. Storm runoff has

Figure 12. Stream Discharge Hydrograph
1988–1989

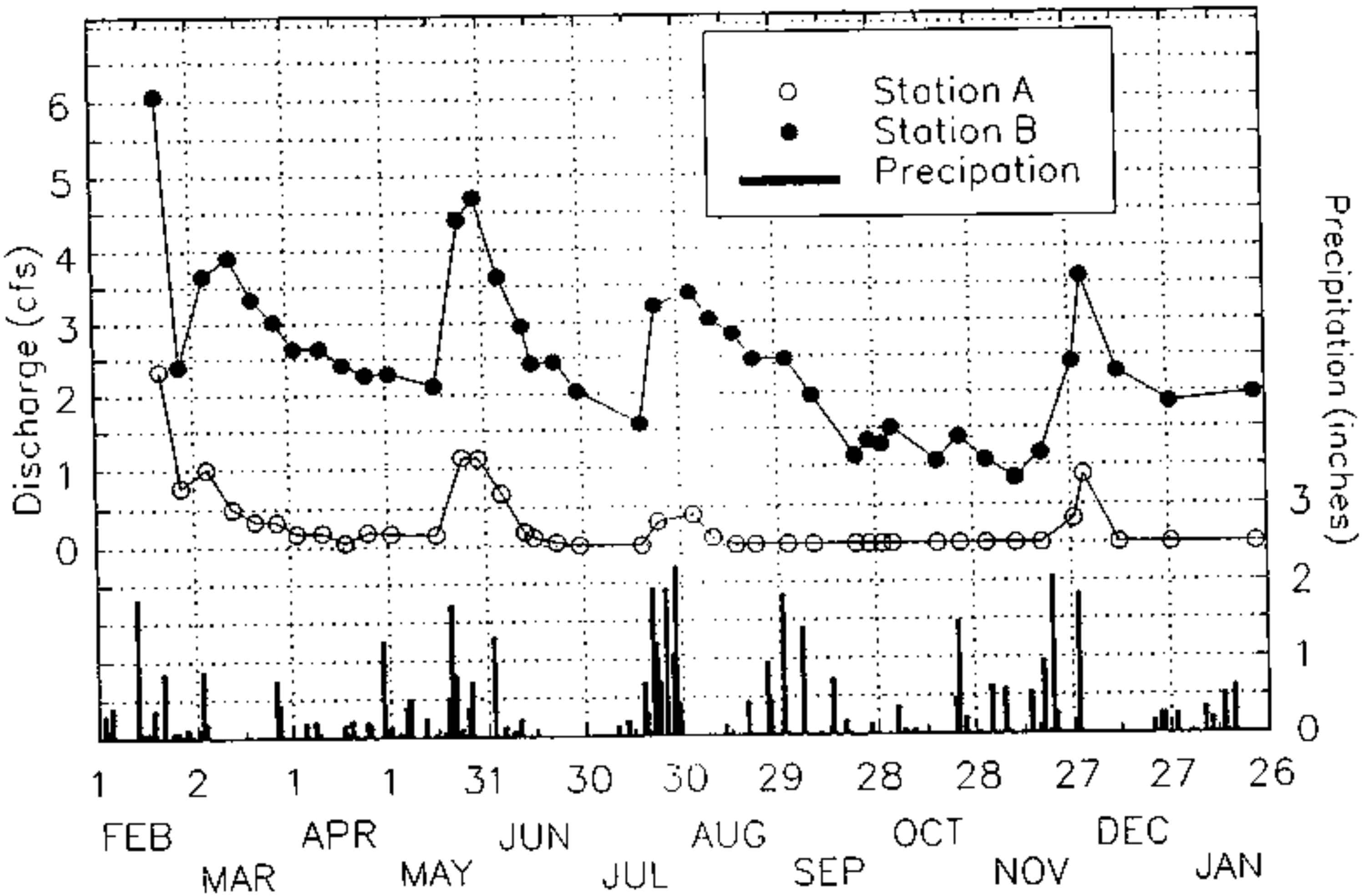
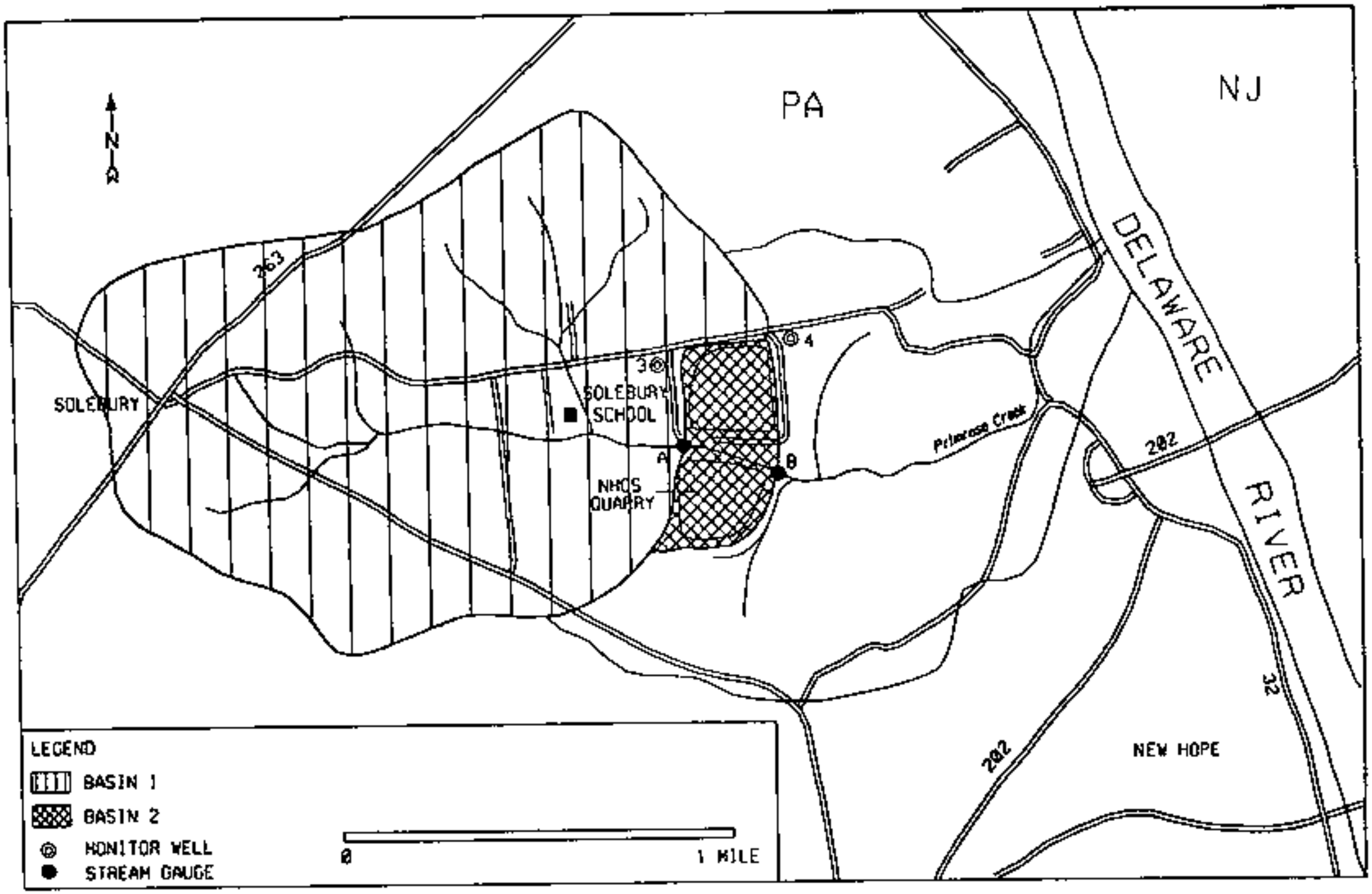


Figure 13. Basin 1 and Basin 2 of the Primrose Creek Watershed.



been observed from Basin 2 but was deemed negligible. The quarry itself comprises most of the 0.2 square mile area of Basin 2; therefore, almost all precipitation falls directly into the quarry pits then flows toward the pumps and is eventually recorded at Station B.

Because continuous recorders were unavailable for stream discharge, many flood peaks were missed. The volume of storm runoff was estimated using Soil Conservation Service (SCS) curves which are based on slope, ground cover, soil type, and antecedent precipitation (Mather, 1978).

In order to determine which set of curves to use, three steps were undertaken. First, based on SCS soil maps of the Primrose Creek area, the hydrologic soil group was determined to be in class C, moderately fine to fine textures with slow infiltration and water transmission rates (Soil Conservation Service, 1975). Secondly, the five-day antecedent moisture condition of the soil was determined for each precipitation event based on the precipitation record and the season of the year. During the growing season a high percentage of precipitation is either transpired by plants or evaporated. Therefore more intense precipitation is required to saturate the soil horizon and thus begin runoff. Finally, the volume of storm runoff for each precipitation event was estimated using SCS curves numbered 62/79/91 (Mather, 1978). Total streamflow for each month was the sum of measured discharge and the estimated volume of storm runoff (Tables 3 and 4).

Table 3. Streamflow Components for Basin 1.
1988–89

Month	Storm Runoff (Rs)	+ Base Flow (Rg)	= Total Streamflow (R)
FEB 88	0.55	1.08	1.63
MAR	0.00	0.41	0.41
APR	0.00	0.11	0.11
MAY	0.25	0.48	0.73
JUN	0.00	0.15	0.15
JUL	3.60	0.11	3.71
AUG	0.10	0.07	0.17
SEP	0.02	0.00	0.02
OCT	0.05	0.00	0.05
NOV	2.32	0.22	2.54
DEC	0.00	0.00	0.00
JAN 89	0.00	0.00	0.00
Total	6.89	2.63	9.52

Units are basin inches
One basin inch = 17,377,500 gallons per square mile
Area = 1.55 square miles

Table 4. Streamflow Components for Basins 1 + 2.
1988--89

Month	Storm Runoff (Rs)	+ Base Flow (Rg)	= Total Streamflow (R)
FEB 88	0.49	0.96	1.45
MAR	0.00	0.35	0.35
APR	0.00	0.11	0.11
MAY	0.22	0.44	0.66
JUN	0.00	0.13	0.13
JUL	3.19	0.11	3.30
AUG	0.09	0.06	0.15
SEP	0.02	0.00	0.02
OCT	0.04	0.00	0.04
NOV	2.05	0.19	2.24
DEC	0.00	0.00	0.00
JAN 89	0.00	0.00	0.00
Total	6.10	2.35	8.45

Units are basin inches
One basin inch = 17,377,500 gallons per square mile
Area = 1.75 square miles

Note: 8.45 basin inches (over 1.75 square miles for Basin 1 + 2) is the same volume of water as 9.52 basin inches (over 1.55 square miles for Basin 1)

Evapotranspiration

Precipitation that does not infiltrate to the water table or runoff to Primrose Creek may evaporate or be transpired by plants. Evapotranspiration may be measured directly by a lysimeter or it may be calculated based on numerous models (Viessman et al., 1989). In this study evapotranspiration was calculated by a procedure developed by Thornthwaite (1948) and modified by Mather (1978) which relates evapotranspiration to temperature and a sunlight factor based on latitude. Temperature data for this study were recorded at the Lambertville station in New Jersey (Table 5).

Change In Storage

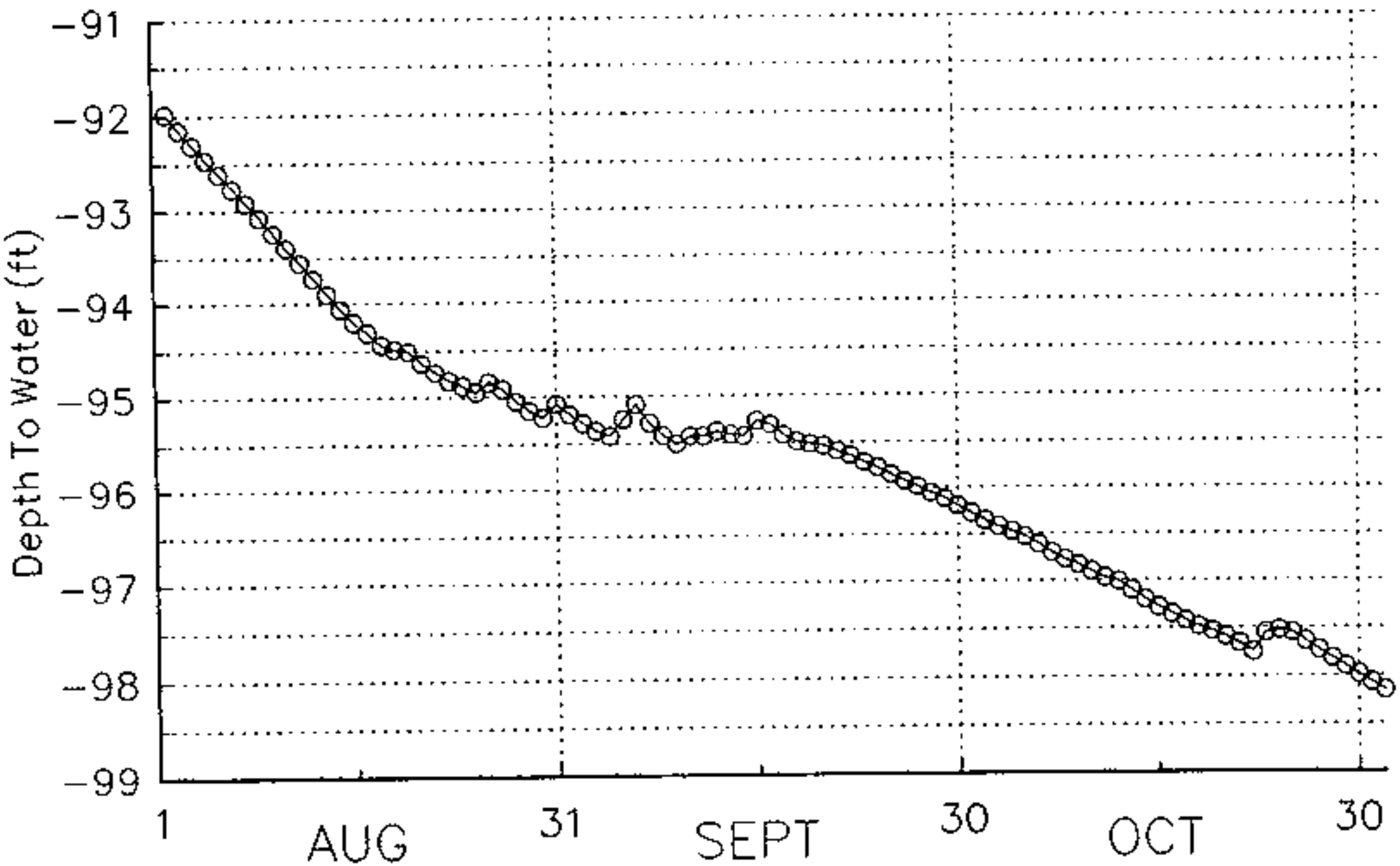
The volume of water stored in an aquifer is dependent on an aquifer characteristic known as storativity (S). In a confined aquifer the storativity results from the elasticity of the aquifer and the compressibility of the water. In an unconfined aquifer, such as the Primrose Creek system, the storativity is a measure of how much water the aquifer will store or yield and is therefore essentially the same as specific yield. Specific yield is defined as the volume of water released from storage per unit surface area of aquifer per unit decline in the water table (Freeze and Cherry, 1979). In this study specific yield was calculated by observing water level declines over a period of several months during which there is little or no recharge, while at the same time measuring the volume of water which is being withdrawn from the aquifer system (Wood et al., 1972).

Table 5. Evapotranspiration Calculations.
1988–89

Month	Temperature F	Temperature C	Latitude Factor	Monthly Index	Unadjusted ET	Adjusted ET
FEB 88	33.60	0.90	23.90	0.07	0.00	0.04
MAR	43.50	6.40	30.90	1.45	0.03	0.78
APR	50.80	10.40	33.30	3.05	0.05	1.65
MAY	62.90	17.20	37.20	6.47	0.10	3.65
JUN	70.40	21.30	37.50	8.99	0.13	4.96
JUL	78.70	25.90	38.10	12.10	0.17	6.58
AUG	77.10	25.10	35.40	11.47	0.16	5.83
SEP	65.20	18.40	31.20	7.22	0.11	3.38
OCT	50.40	10.20	28.80	2.95	0.05	1.39
NOV	46.20	7.90	24.90	1.99	0.03	0.84
DEC	33.90	1.10	24.30	0.09	0.00	0.05
JAN 89	35.50	1.90	25.20	0.24	0.00	0.12
						29.27

Annual Heat Index = 56.10
Value of A–Function = 1.37
Total Annual Evapotranspiration = 29.27 inches

Figure 14. Water Level in Well 3.
Aug 1–Nov 1, 1988



From the drop in groundwater level, as measured by continuous depth to water recorders, it is possible to calculate the change in volume (^V) of the dewatered part of the aquifer. The period from August 1 to November 1, 1988 was chosen because there was little recharge during this time (Figure 14). In this report the total amount of pumpage (D) from the quarry represents the volume of water being released from the aquifer system. The equation for specific yield (Sy) is:

$$Sy = D/\hat{\ }V$$

Calculated specific yields were 4.1% for well #4 and 4.8% for well #3. The value of 4.8% is more appropriate because most of the water which is pumped from the NHCS quarry comes from the area around well #3. Also there is some indication that the groundwater in the vicinity of well #4 flows away from the quarry. The degree of interconnection between the quarry and observation wells 3 and 4 will be discussed later in this report. The average specific yield of 4.4% was used for water budget calculations because this value is the same as the specific yield of 4.4% calculated by Wood et al. (1972) for the Beekmantown Formation in Allentown, Pa. It is also in good agreement with the 5% value determined by Meisler (1963) for the carbonate rocks in the Lebanon Valley, Pa. This value also confirms that the aquifer system in the study area is unconfined.

To calculate the change in storage for each month during the study period, the following formula was used:

$$\hat{\ }S = Sy \times A \times h$$

where: ^S = change in storage for that month
Sy = specific yield

A = area of the basin
h = change in head for that month

The monthly changes in storage are found in the water budget in Tables 6 and 7.

Diversions

Minor diversions of groundwater from the study area include withdrawal for domestic use and for irrigation purposes. There are no public supply wells in the area and most of the homes have their own wells. The farms in the area pump minor amounts of groundwater during the growing season to irrigate their crops. These diversions are negligible compared to the volume of water which is withdrawn by the New Hope Crushed Stone Company.

During the period of this study the quarry operation pumped water continuously from both pits directly into Primrose Creek between Station A and Station B. Some quantity of water may have seeped back down toward the pumps and was recycled, but most of the water flowed out of the study area toward the Delaware River. Discharge from the southern pit was pumped into a 90 degree V-notch weir where readings were taken once a week at the same time that stream gauge data were collected. Pump discharge through the weir was calculated by the following formula (Fetter, 1980):

$$Q = 2.5H^{(5/2)}$$

Where Q = discharge (cubic feet per second)
H = head of the backwater above the weir crest (feet)

The pump in the northern pit fed water into a small holding basin which drained into Primrose Creek between Station A and the weir. Knowing the amount of water flowing into the quarry area through Station A, the discharge of the southern pump (weir), and the total outflow as measured at Station B, it was possible to calculate the discharge of the northern pump (pump 2).

$$\text{Station A} + \text{Pump 2} + \text{Weir} = \text{Station B}$$

Figure 15 is a discharge hydrograph showing both pumps and their response to precipitation. The combined monthly output of both pumps is shown in the water budget for Basins 1+2 in Tables 6 and 7.

The total volume of water pumped by the quarry over the year was 17.21 basin inches over an area of 1.75 square miles. This value seems large when expressed in basin inches because more than half of this water may be flowing toward the pumps from areas outside of the Primrose Creek Basin. The cone of depression caused by the pumps in the quarry covers an area larger than the 1.75 square miles of the Primrose Creek Basin.

Underflow

Underflow is defined as the volume of groundwater which flows undetected into or out of the study area beneath the stream gauging stations (Wood et al., 1972). If all variables of the water budget equation are known, then underflow may be determined indirectly using the following formulae:

$$\text{Basin 1:} \quad U = P - (R + ET + Sg)$$

$$\text{Basin 1+2:} \quad U = P - (R + ET + Sg + D)$$

A positive number for underflow indicates a surplus of water within the study area which does not show up in increased storage so it must move toward the pumps

Figure 15. Pump Discharge Hydrograph.
1988-1989

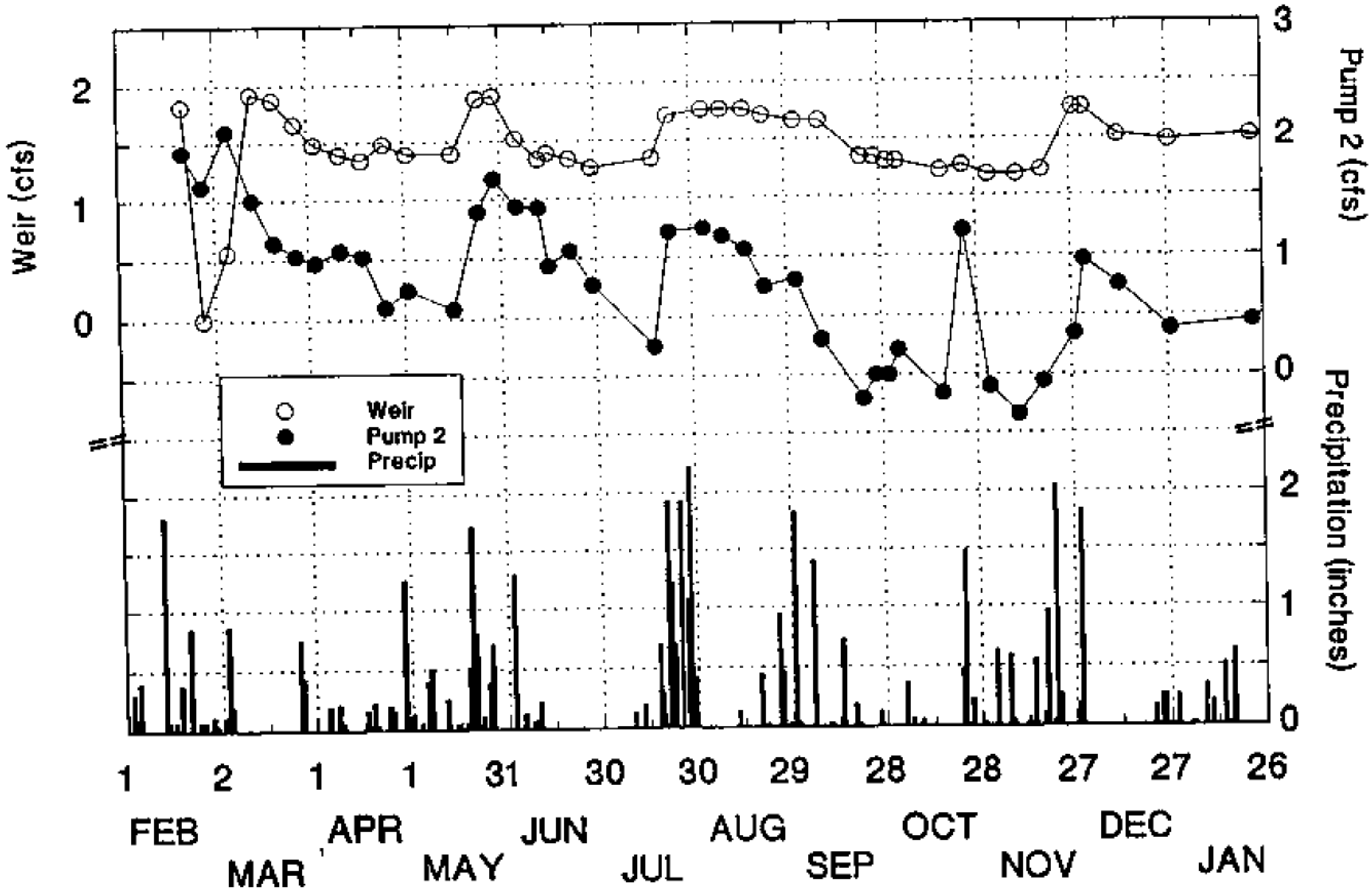


Table 6. Water Budget Basin 1.
1988–89

MONTH	P	= ET	+ R	+ S	+ U
FEB 88	4.23	0.04	1.63	1.12	1.44
MAR	2.42	0.78	0.41	–0.73	1.96
APR	2.71	1.65	0.11	–0.56	1.51
MAY	5.68	3.65	0.73	1.18	0.12
JUNE	1.71	4.96	0.15	–0.78	–2.62
JULY	10.30	6.58	3.71	1.39	–1.38
AUG	2.73	5.83	0.17	–1.60	–1.67
SEPT	2.47	3.38	0.02	–0.53	–0.40
OCT	2.18	1.39	0.05	–0.89	1.63
NOV	6.50	0.84	2.54	2.34	0.78
DEC	1.07	0.05	0.00	–1.12	2.14
JAN 89	1.83	0.12	0.00	–0.02	1.73
Total	43.83	29.27	9.52	–0.21	5.25

Units are basin inches
One basin inch = 17,377,500 gallons per square mile
Area = 1.55 square miles

Table 7. Water Budget Basins 1 + 2.
1988–89

MONTH	P	= ET	+ R	+ S	+ D	+ U
FEB 88	4.23	0.04	1.45	1.12	1.65	−0.03
MAR	2.42	0.78	0.35	−0.73	1.94	0.08
APR	2.71	1.65	0.11	−0.56	1.48	0.03
MAY	5.68	3.65	0.66	1.18	1.79	−1.60
JUN	1.71	4.96	0.13	−0.78	1.58	−4.18
JUL	10.30	6.58	3.30	1.39	1.48	−2.45
AUG	2.73	5.83	0.15	−1.60	1.80	−3.45
SEP	2.47	3.38	0.01	−0.53	0.92	−1.31
OCT	2.18	1.39	0.04	−0.89	0.83	0.81
NOV	6.50	0.84	2.24	2.34	1.08	0.00
DEC	1.07	0.05	0.00	−1.12	1.36	0.78
FEB 89	1.83	0.12	0.00	−0.02	1.30	0.43
Total	43.83	29.27	8.45	−0.21	17.21	−10.88

Units are basin inches
One basin inch = 17,377,500 gallons per square mile
Area = 1.75 square miles

as underflow (outflow) from within the surface divides. A negative number for underflow indicates a deficit within the study area that is not balanced by a decrease in storage. This deficit must be balanced by groundwater underflow (inflow) from adjacent drainage basins.

Underflow from Basin 1 was found to be +5.25 basin inches/yr (bi/yr); therefore Basin 1 lost 5.25 basin inches of groundwater as outflow to Basin 2. On the other hand, flow into the total area studied (Basins 1+2) was calculated to be -10.88 basin inches/yr. The negative sign suggests that the study area gained 10.88 basin inches of groundwater as inflow from adjacent groundwater basins. The difference between these two values is due to the volume of water (17.21 basin inches) which was withdrawn from Basin 2. This value was not included in the water budget for Basin 1 because the pumps are located in Basin 2.

If the total demand on the hydrologic system of the study area (Basins 1+2) is 17.21 bi/yr and inflow equals 10.88 bi/yr, then outflow equals the difference of 6.34 bi/yr (Table 8). This value represents the volume of groundwater from Basins 1+2 which flowed toward the quarry and was pumped out of the study area. Therefore 6.34 bi/yr includes the 5.25 bi/yr from Basin 1 plus some water from Basin 2.

Recharge

Recharge to the groundwater supply is usually calculated by two methods: the budget method and the baseflow method. The budget method was used in this study to calculate the volume of water which is available for recharge based on

Table 8. Underflow Calculations for Basins 1 + 2.

Total Pumpage	17.21 bi/yr
Inflow	−10.88 bi/yr
Outflow (from Basins 1 + 2)	6.34 bi/yr

Table 9. Recharge Calculations for Basin 1.
1988–89

Month	P	– ET	– Rs	= Recharge
FEB 88	4.23	0.04	0.55	3.64
MAR	2.42	0.78	0.00	1.64
APR	2.71	1.65	0.00	1.06
MAY	5.68	3.65	0.25	1.78
JUN	1.71	4.96	0.00	–3.25
JUL	10.30	6.58	3.60	0.12
AUG	2.73	5.83	0.10	–3.20
SEP	2.47	3.38	0.02	–0.93
OCT	2.18	1.39	0.05	0.74
NOV	6.50	0.84	2.32	3.34
DEC	1.07	0.05	0.00	1.02
JAN 89	1.83	0.12	0.00	1.71
Total	43.83	29.27	6.89	7.67

Units are basin inches
One basin inch = 17,377,500 gallons per square mile
Area = 1.55 square miles

Table 10. Recharge Calculations for Basins 1 + 2.
1988–89

Month	P	– ET	– Rs	= Recharge
FEB 88	4.23	0.04	0.49	3.70
MAR	2.42	0.78	0.00	1.64
APR	2.71	1.65	0.00	1.06
MAY	5.68	3.65	0.22	1.81
JUN	1.71	4.96	0.00	–3.25
JUL	10.30	6.58	3.19	0.53
AUG	2.73	5.83	0.09	–3.19
SEP	2.47	3.38	0.02	–0.93
OCT	2.18	1.39	0.04	0.75
NOV	6.50	0.84	2.05	3.61
DEC	1.07	0.05	0.00	1.02
JAN 89	1.83	0.12	0.00	1.71
Total	43.83	29.27	6.10	8.46

Units are basin inches
One basin inch = 17,377,500 gallons per square mile
Area = 1.75 square miles

precipitation (P), evapotranspiration (ET), and storm runoff (Rs). Any water which is not evaporated or transpired by plants, or discharged into streams as runoff is available to recharge the groundwater table as shown by the equation:

$$\text{Recharge} = P - ET - Rs$$

Using this method the annual recharge rate was found to be 8.46 bi/yr over a 1.75 square mile area (Tables 9 and 10).

The baseflow method is based on the measured amount of groundwater discharged to streams (baseflow, Rg) plus any change in groundwater storage (^S).

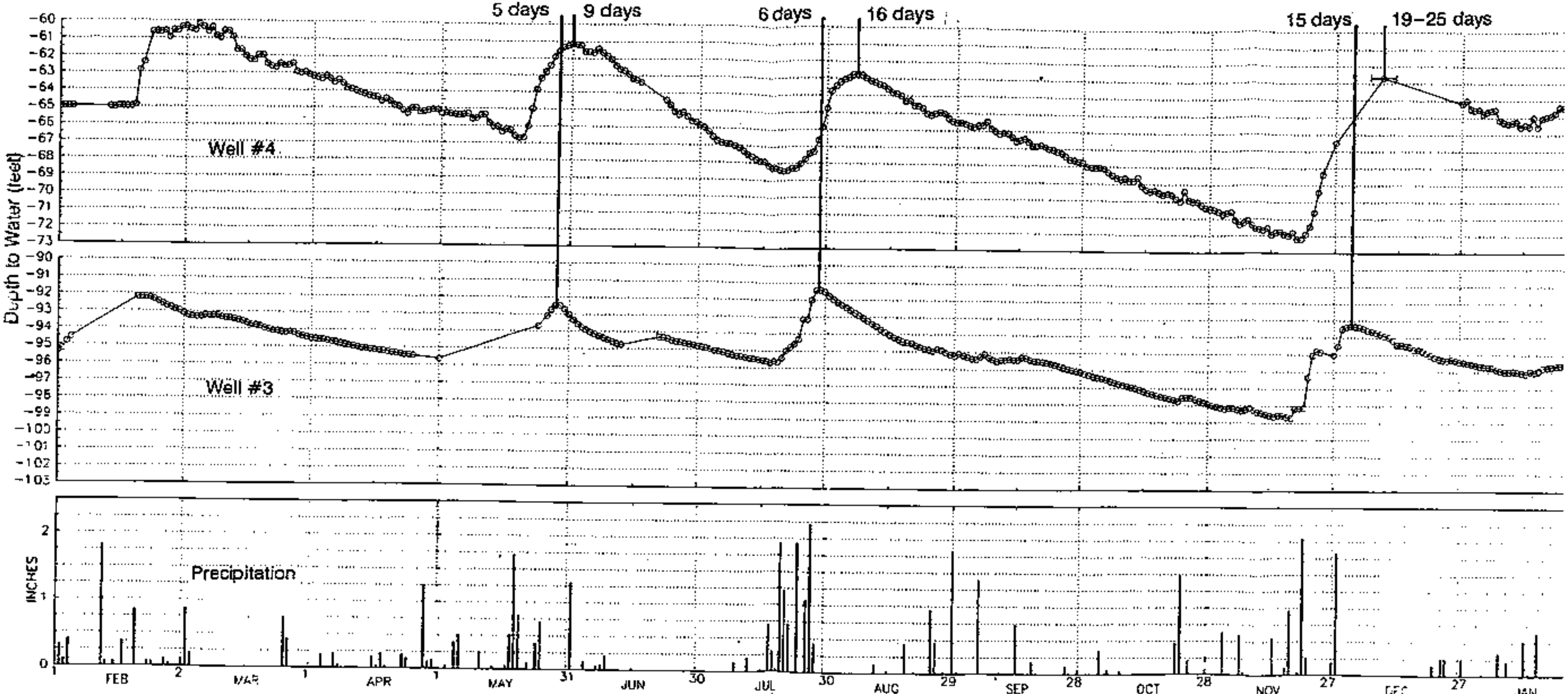
$$\text{Recharge} = Rg + \hat{}S$$

Recharge to the groundwater supply will be discharged as baseflow into streams over a yearly period so that equilibrium is maintained. The two methods should yield equivalent answers unless there is some outside stress affecting the system. In this study pumpage from the quarry stresses the system by creating a cone of depression that acts as a sink which steals baseflow from Primrose Creek so the baseflow method is unreliable. Also natural seepage from Primrose Creek may make measurements unreliable.

Discussion

It is postulated that there is another source providing water to the Primrose Creek Watershed in addition to precipitation. Underflow, or more precisely, inflow of 10.88 bi/yr of groundwater from adjacent watersheds is the additional source. Pumping of 1.4 mgd (17.21 bi/yr) from the NHCS quarry creates a deficit of 10.88 basin inches in the yearly water balance of the Primrose Creek Watershed. A water

Figure 20. Hydrograph of Water Levels in Observation Wells vs. Precipitation.



5 days = lag time from first increase in water level to peak water level

1988–89

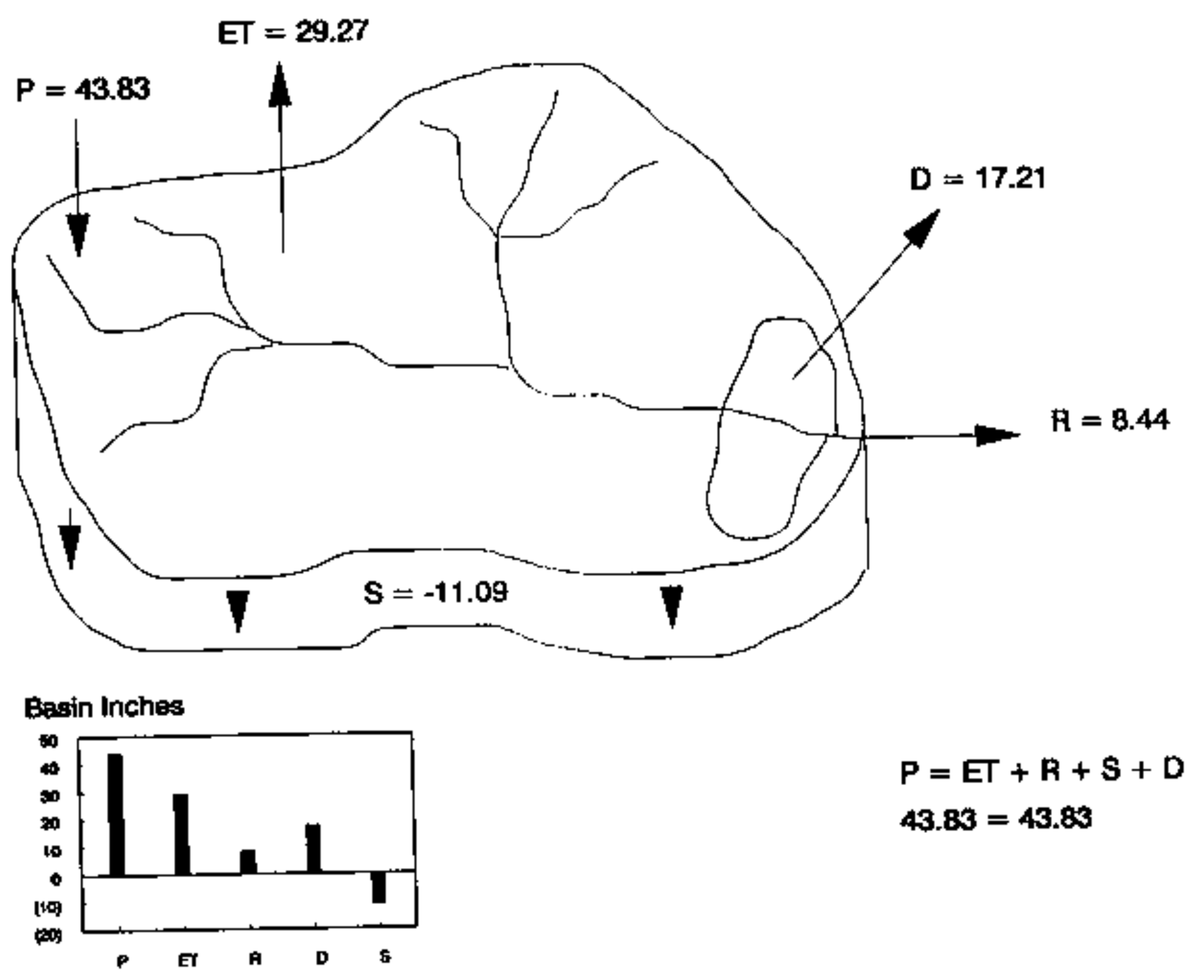


Figure 16. Predicted Case: Water Budget Balanced by Water From Storage.

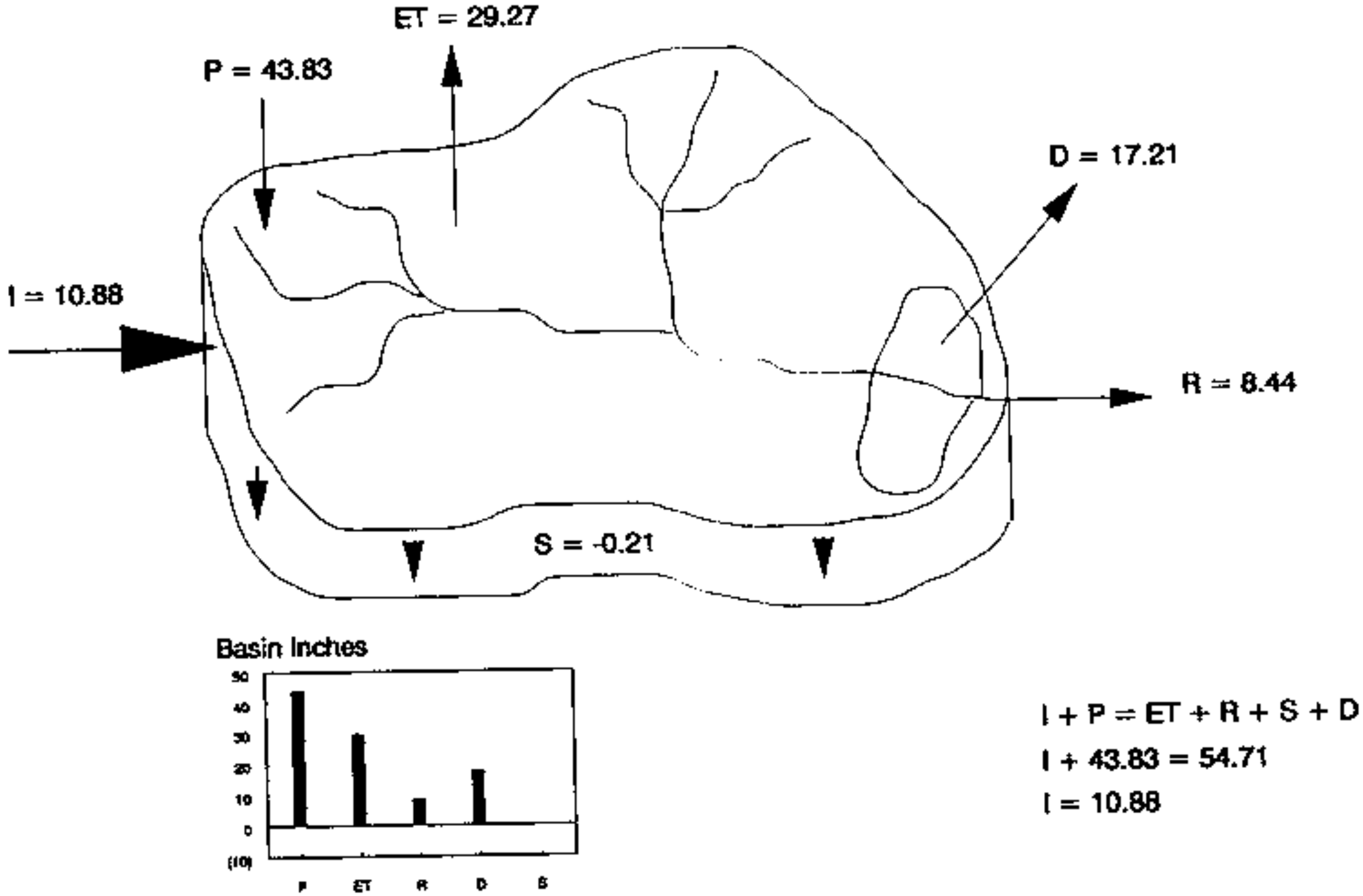


Figure 17. Observed Case: Water Budget Balanced by Groundwater Inflow.

deficit is usually accommodated by a decrease in the volume of water in storage but the measured change in storage for the year studied was only -0.21 basin inches, insufficient to account for this deficit. The volume of groundwater released from storage that would be required to balance the water budget of the Primrose Creek Watershed was calculated to be -11.09 bi/yr (Figure 16). Because this drop in storage was not observed, another source or inflow of groundwater may be recharging the carbonate aquifer in the watershed, particularly during the summer months (Figure 17 and Table 7).

Inflow is greatest in the summer months because to excessive water loss as a result of high temperatures and growing plant life combined with pumping creates a larger cone of depression and steeper hydraulic gradients. In this study 67% of precipitation was lost to evapotranspiration, most of which occurred during the growing season. This percentage of water loss is close to the value of 70% reported by Viessman et al. (1989) as a yearly average for the United States.

As a result of this water loss during the summer months the cone of depression created by the NHCS quarry pumps may have covered an area larger than the Primrose Creek Basin. Indirect evidence for this effect is the observation that springs north of the quarry dried up during the summer months in 1988. As the cone of depression extended beneath the surface divides of the Primrose Creek Watershed, hydraulic gradients were changed, and groundwater flowed into the study area. This inflow of groundwater was necessary to offset the volume of water pumped from the Primrose Creek Watershed.

Primrose Creek is an influent stream upgradient from Station A. Spring-fed tributaries originating near the contact between the Stockton and Beekmantown Formations north of the NHCS quarry flowed year round except for June/July, 1988. However, the creek was dry at Station A during five months (except for storm events) in the summer and fall of 1988 (Table 3). Some of the spring water infiltrated through the stream bed of Primrose Creek and some water flowed directly into sinkholes. This water was eventually recorded as pump discharge from the NHCS quarry. There is also some water seepage through the bed of Primrose Creek between gauging stations A and B.

During the study period there were four baseflow recessions in response to four major recharge events. Inspection of Figures 18 and 19 reveals a lag time of one month between recharge months and a corresponding increase in pumpage at the NHCS quarry. It is further evident that the greatest loss of groundwater from storage occurred one month after these recharge months, coincident with the increased pumpage.

Figure 18. Water Budget Basin 1.
1988 – 1989

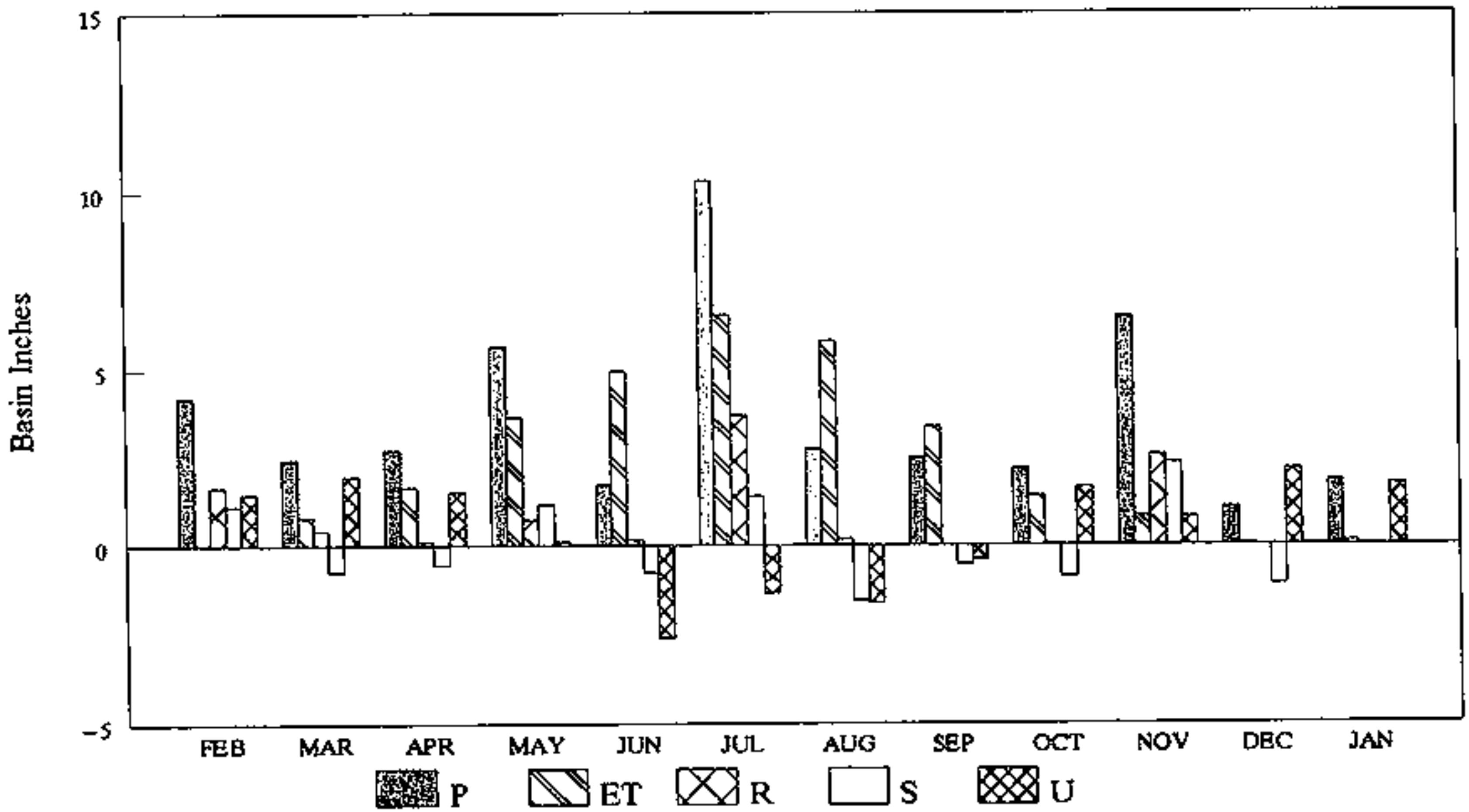
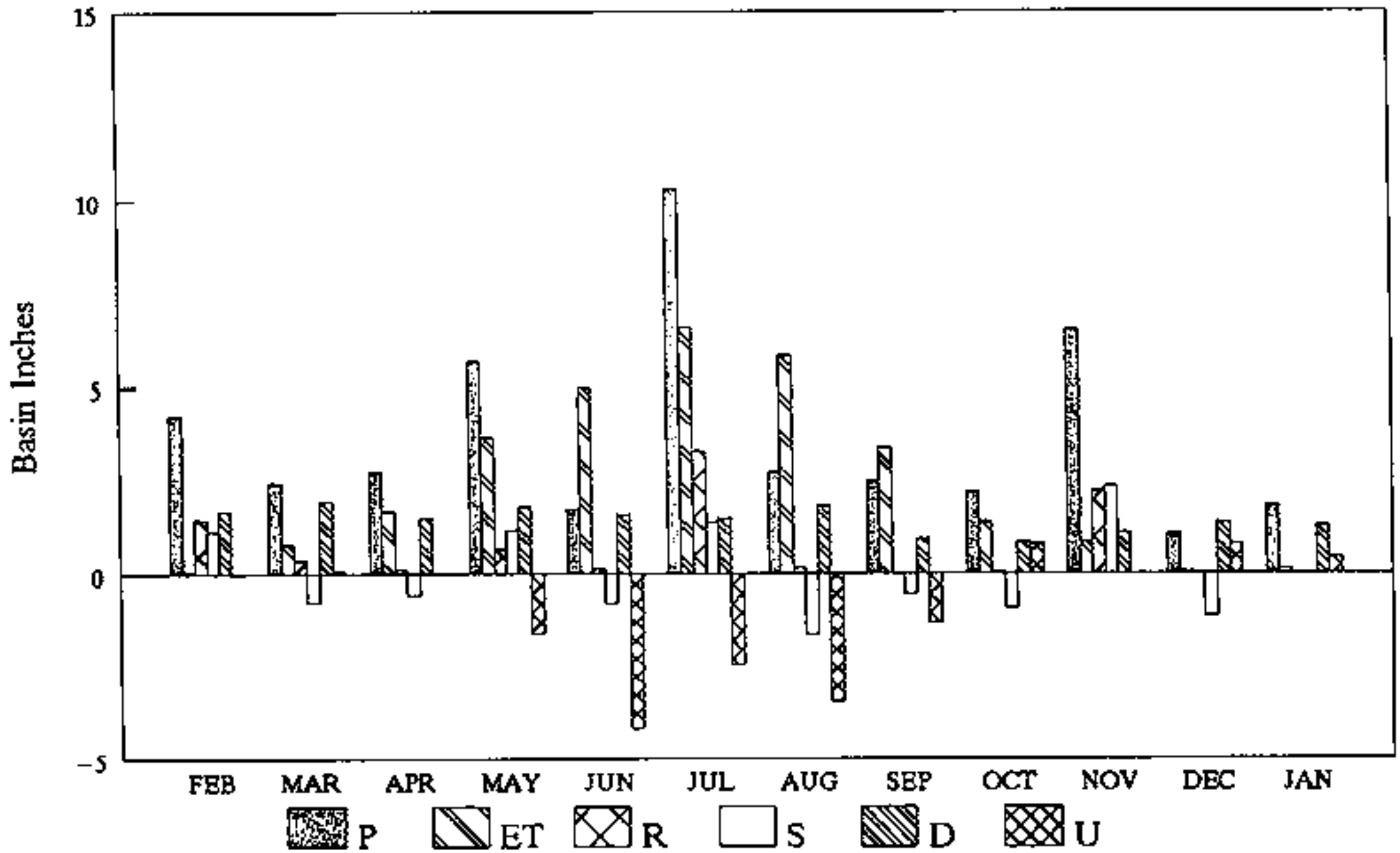


Figure 19. Water Budget Basins 1 + 2.
1988 – 1989



CHAPTER 4

AQUIFER CHARACTERISTICS

Aquifer Yield

The rate of discharge of the pumps in the quarry is similar to the yields of supply wells in the Allentown Formation in Lehigh County. The average pumping rate at the quarry in 1988-89 was 995 gpm. This is similar to the median potential yield of wells installed in the Allentown Formation in Lehigh County, reported as 750 gpm (Wood et al., 1972). Wood et al. (1972) also estimated that about 50% of the industrial or public supply wells would yield over 1,500 gpm. Comparing pump discharge from an open pit to the yield of supply wells is not an orthodox procedure but is done here to show a hydrologic similarity between Cambro-Ordovician carbonates in Buckingham Valley and those in Lehigh County.

Two observation wells in the carbonate aquifer were monitored by continuous recorders and were used to calculate aquifer characteristics to document spatial variations within the aquifer. Well #3 was completed in a highly karstified part of the Allentown Formation. This well is adjacent to a solution valley located near the northwest corner of the NHCS quarry. Well #4 was completed in an area of the Allentown Formation which is less porous. Specific yields were calculated as described in chapter 3 to be 4.8% and 4.1% for well #3 and well #4 respectively. Confidence in the value of 4.8% for the area around well #3 is much greater than the value of 4.1% for the area around well #4.

The specific yield is approximately equal to the porosity of the carbonates because most of the groundwater is stored within secondary fractures, bedding plane partings, and solution openings. When groundwater is released by gravity drainage only a small amount of water remains in the fractures as specific retention held by the forces of surface tension (Wood et al., 1972). Primary porosity of the carbonates in the Primrose Creek Watershed is negligible due to diagenetic changes such as crystallization; therefore the secondary porosity, estimated to be 4.4%, is the total porosity.

Comparison of Observation Wells

The two observation wells in this study are approximately 1600 feet apart but penetrate aquifers with different hydrologic characteristics such as porosity and degree of connection to the NHCS quarry. The different responses of the water table to precipitation was further evidence of the difference between the hydrologic properties of the carbonate rocks near each well (Figure 20). Depending on the intensity of precipitation each well records a different increase in head and a different lag time from event to peak water level. Compared with well #4, well #3 records a dampened response to minor precipitation events (a minor precipitation event is defined as <1.5 inches/day). One possible explanation for this stoic response to precipitation in well #3 is that the water table averages 90 ft below the top of well casing (TOC) compared with 60 ft TOC in well #4. Recharging water will take longer to infiltrate to the water table. Another possible explanation is that the volume of void space near the water table is sufficiently large such that minor amounts of precipitation have no effect on the water table. The best examples of the dampened response to precipitation in well #3 versus well #4 were reactions to the storm event around October 20 and minor precipitation events in March, April, and January. Each of the observation wells showed a response to the event but the shape of the response was different.

In response to major precipitation events (> 1.5 inches/day) well #3 recorded a shorter lag time from event to peak water level than well #4 (Figure 20 and Table 11). The shorter lag time appears to be the result of point sources of recharge through sinkholes. Most sinkholes occur in existing drainage channels where storm runoff is concentrated. During major precipitation events storm runoff infiltrates to the water table quickly via these sinkholes causing the short lag time observed in the hydrograph of well #3. The best example is the recharge event in July during which 10.83 inches of rain were recorded at the quarry. It was estimated that over 50% of this precipitation was lost to storm runoff during a one week period. Some of this runoff flowed directly into sinkholes, quickly recharging the groundwater reservoir in the vicinity of well #3 but not near well #4 because well #4 is not hydraulically connected to a sinkhole system. The water table as measured in well #3 rose to a yearly high of 91.5 ft (TOC) even though it was the middle of the summer. Well #4 did not record a yearly water table high resulting from the late July storms.

Although well #3 recorded a yearly water table high on July 28, 1988, the magnitude of change in water level was still less than that recorded in well #4. In other words, well #3 recorded less rise in water level than well #4 after major

Table 11. Differences Between Well #3 and Well #4.

Recharge Event	Lag Time* (days)		Change in Water Level (feet)	
	Well #3	Well #4	Well #3	Well #4
May 24–June 1, 1988	5	9	1.2	2.2
July 22–Aug 16, 1988	6	16	3.5	5.6
Nov 17–Dec 9, 1988	15	19–25	5.4	9.8

*Lag Time = Time from first increase in water level to peak water level

Table 12. Summary of Linear Regression Calculations.

Variables	Goodness of Fit
Well #3 vs. Weir	0.82
Well #3 vs. Pump #2	0.80
Well #4 vs. Pump #2	0.77
Well #4 vs. Weir	0.71

precipitation events. This difference may be due to a greater volume of void space of the aquifer in the vicinity of well #3. Possibly, the volume of void space is so large that even during major precipitation events more water is needed around well #3 to cause the same rise in water level recorded in well #4. A greater volume of void space near well #3 also suggests in a qualitative sense that specific yield must be greater around well #3 than well #4. The difference between well #3 and well #4 is evident in the recharge months of February, July, and November.

Quarry Connection

Well #3 is hydraulically connected to the quarry pumping to a greater degree than is well #4 as indicated by different hydraulic gradients, observation of groundwater seepage through the quarry walls, statistical analysis, and a blasting event which resulted in flooding of the northern pit of the quarry on April 10, 1989. The drawdown caused by pumping is greater in well #3 in which the water table is an average of 60 feet above sea level than in well #4 in which the water table is an average of 114 ft above sea level. The pump in the northern pit is located 15 feet above sea level. Both wells are approximately the same distance from the pump (925 ft) yet the hydraulic gradient from well #4 to the pump is twice that from well #3 to the pump. This suggests that there may be an impermeable boundary between the pump and well #4 or alternatively that the area between the pump and well #3 is significantly (two times) more conductive.

Observations of seepage in the quarry support the idea that well #3 is more affected by the quarry pumps than well #4. Well #3 is to the northwest of the

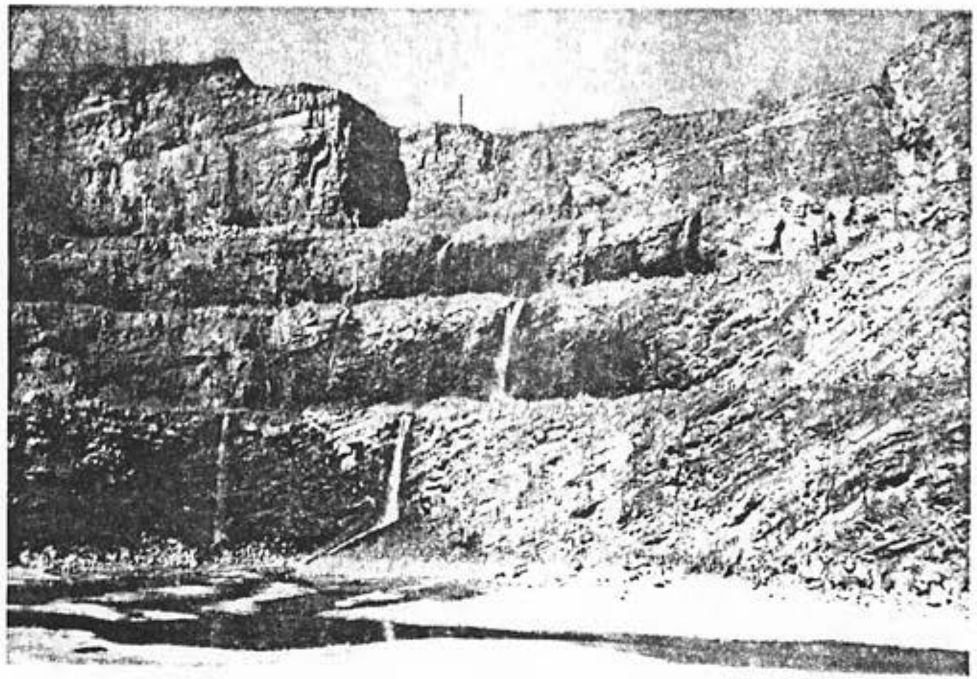


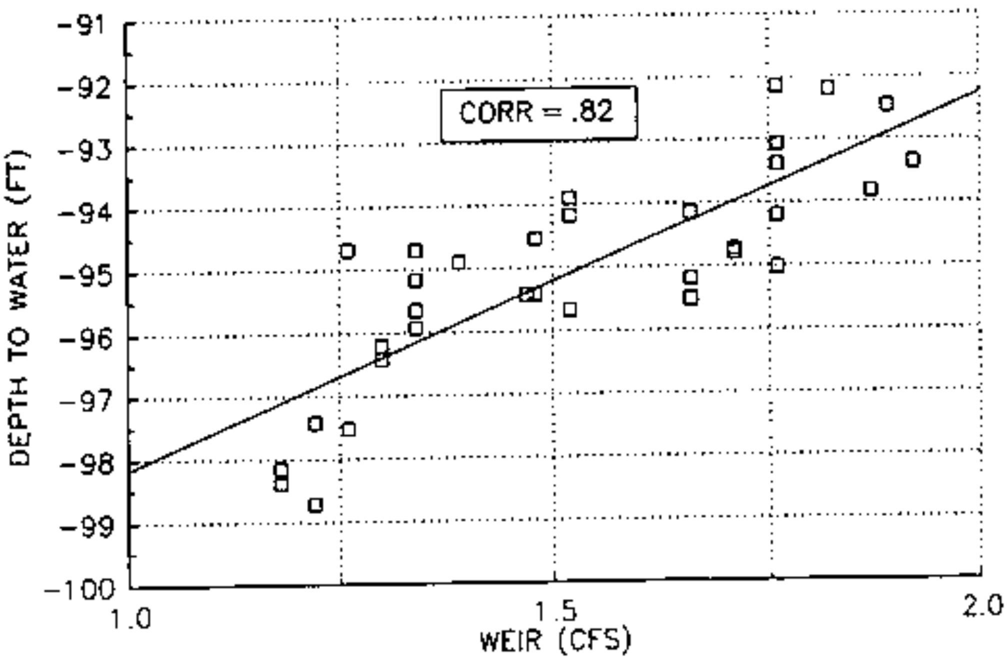
Figure 21. Water Falls From the Southern Pit of the NHCS Quarry.

quarry and most of the wet areas in the quarry are on the northwestern walls. On the northern wall of the southern pit water falls all year long from a fracture zone which trends northwest-southeast (Figure 21). This fracture zone intersects a solution valley which passes close to well #3. In the northern pit the wettest area has always been the northwestern wall which is adjacent to this solution valley; today water can be seen gushing from two or three voids. Well #4 is northeast of the quarry; there is a small area on the northeast wall which is wet year round but it is evident that the volume of water seeping through the wall is less than that seeping through the northwestern wall.

Linear regression calculations revealed a correlation between the wells and the pumps in the quarry (Figures 22 and 23); the best correlation was between the weir (southern pit) and well #3 (Table 12). These data suggest that well #3 is more closely connected to the quarry pumping than well #4.

On April 10, 1989, the quarry blasted in the northwest corner of the northern pit and opened or exposed several voids which were connected to well #3. The next day water was observed gushing from the voids and the floor of the quarry was flooded within a few days as the depth to water in well #3 dropped 10 feet in 8 days (Figure 24); water level in well #4 was not affected. At this time, discharge from pump #2 increased from 1 cfs to 4.5 cfs. This event along with the other evidence strongly suggests that well #3 is hydraulically connected to the quarry pumping to a greater degree than is well #4.

Figure 22. Correlation of Well 3 vs. Weir.
1988–1989



Correlation of Well 3 vs. Pump 2
1988–1989

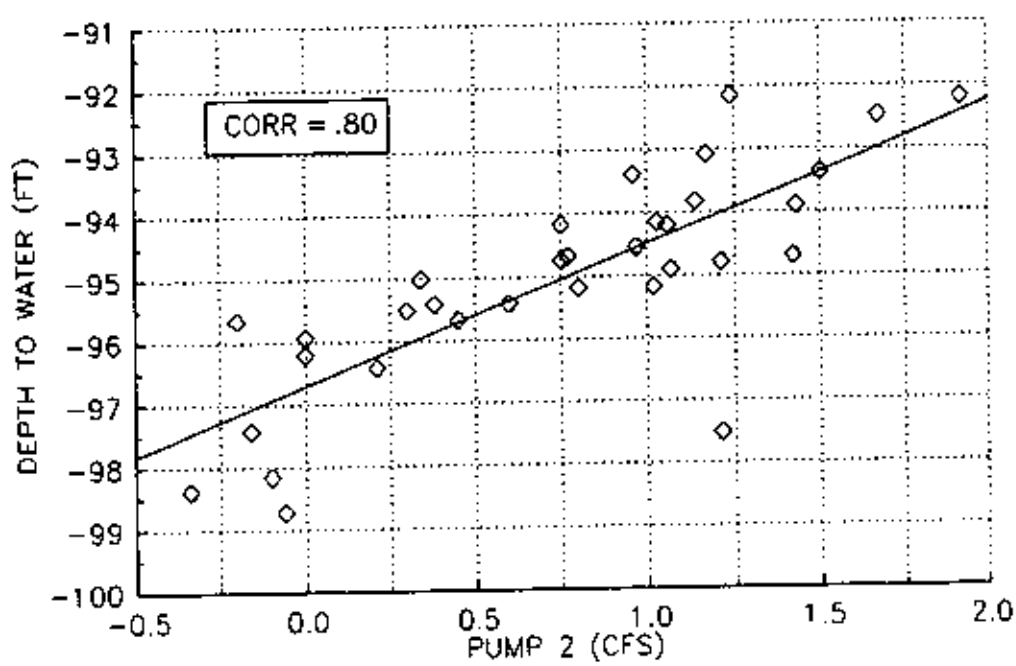
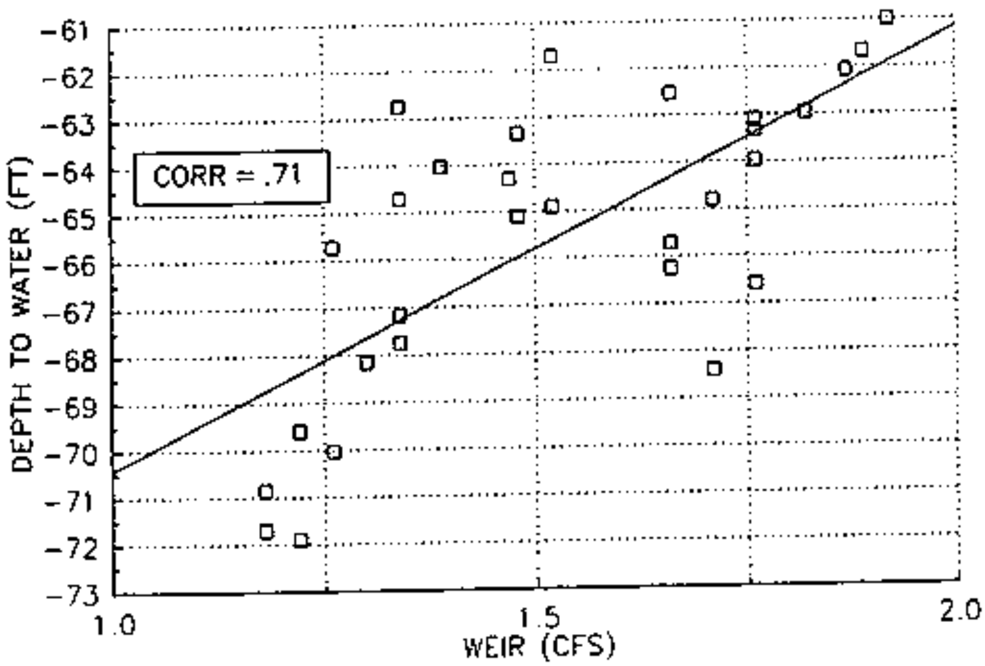


Figure 23. Correlation of Well 4 vs. Weir.
1988–1989



Correlation of Well 4 vs. Pump 2
1988–1989

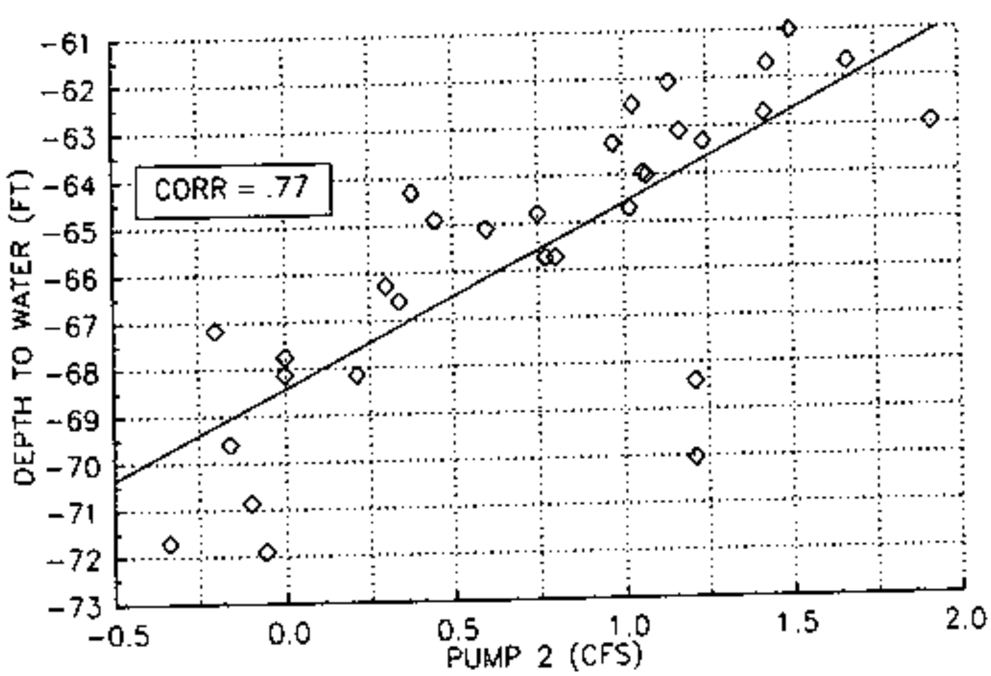
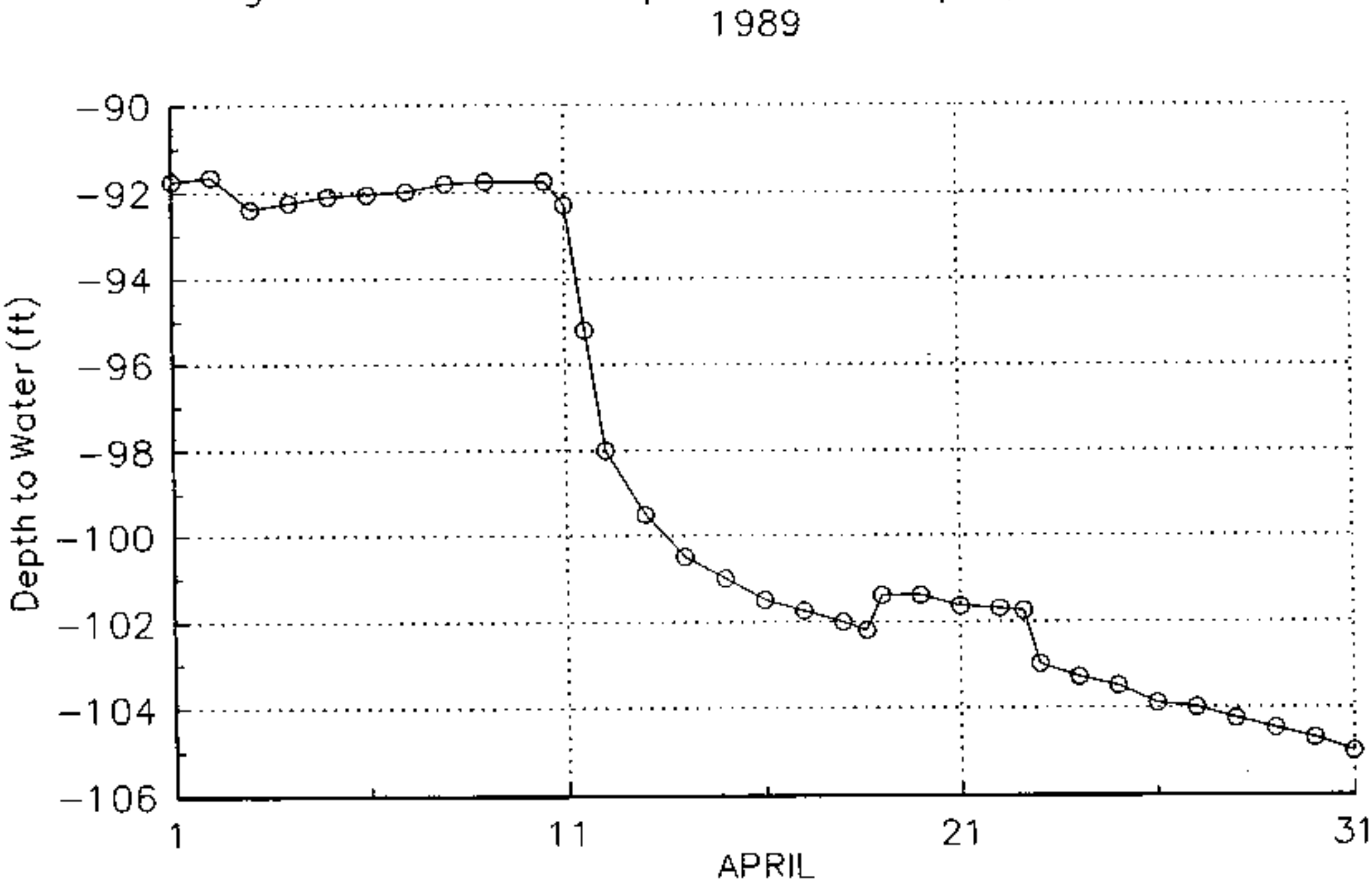


Figure 24. Well 3 Response to the April, 1989 Event.



As a result of this event some residential wells (not including well #4) to the north of the quarry went dry and water levels in others dropped to such an extent that the wells had to be drilled deeper or new deeper wells had to be installed to ensure an adequate supply of water. Residents to the southeast of the quarry across the Furlong Fault were not affected by this event. The quarry built a dam across half of the northern pit allowing water levels to rise to a static level. An environmental consulting firm which was called in to develop a plan to alleviate the problem, decided to drill holes and inject concrete to create a grout curtain which would seal most of the voids in the carbonates and allow the groundwater to rise to previous levels. As of this writing the plan has not been successful.

Discussion

The hydrologic characteristics of the carbonate aquifer in the Primrose Creek Watershed are similar to reported values for the same formations in east-central Pennsylvania. Specific yield (and porosity) ranged from 4.1% to 4.8% when calculated by the method described by Wood et al. (1972). Because the area around well #4 does not contribute much water to the quarry pumps, a better value for specific yield is 4.8%.

Observation well #3 is drilled in an area with a high degree of karst development; as a result data from this well record the higher values of transmissivity. The hydrographs of wells #3 and #4 versus precipitation reveal that well #3 records a shorter lag time from event to peak water level and less rise in the water table than does well #4. The shorter lag time suggests that well #3 intersects a system of conduits which are connected to sinkholes that act as sources of direct groundwater recharge. Well #3 may record less rise in the water table because the volume of void space in the aquifer is significantly larger near well #3 than near well #4.

CHAPTER 5

SINKHOLE DEVELOPMENT

That part of the Primrose Creek Watershed underlain by carbonate rocks exhibits typical karst topography such as pinnacles, sinkholes, solution valleys, losing streams, and disappearing streams. The carbonate rocks are Cambrian to Ordovician age and have been exposed to many cycles of chemical weathering. Evidence of past karst activity includes paleosinkholes in-filled with sandstones and shales along the Cambrian/Ordovician-Triassic unconformity (Willard et al., 1959).

Dissolution rates of carbonates range from 8-130 mm/1000 yrs (Jennings, 1985). Natural sinkholes take hundreds of thousands of years to develop but induced sinkholes, those caused by human's influence, can form in a few years; most sinkholes in the United States have formed in the last 50 - 100 years (Newton, 1986).

Mechanisms

Mechanisms involved in the formation of induced sinkholes are as follows (Newton, 1986):

a) loss of buoyant support

b) increase in velocity of ground-water movement

c) movement of water from the land surface to openings in bedrock where recharge had previously been largely rejected.

d) increase in magnitude of water-level fluctuations

At least three of these mechanisms are operative in the study area. The NHCS quarry operation is causing increased sinkhole development by pumping almost 1000 gpm from the carbonate aquifer creating a cone of depression and lowering water levels. As the water table declines, pore pressure decreases and there is a loss of buoyant support. Soils near existing solution features become compacted due to the dewatering of void space and eventually collapse by the process of stoping. Evidence for this process is the morphology of newly formed sinkholes within the study area. Foose (1953) states that sinkholes with steep walls and cylindrical shapes indicate a sudden lowering of the water table and a loss of support. In 1988 a sinkhole appeared in a corn field between Solebury School and Sugan Road. Its dimensions were approximately 30 feet in diameter and about 15 feet in depth with steep walls indicating a sudden loss of support from beneath. A smaller sinkhole in a field across Phillips Mill Road from Solebury School exhibited steep walls and was cylindrical in shape (Figures 25 and 26).

A second result of the pumping is the steepening of hydraulic gradients which causes an increase in groundwater velocity (v). According to Darcy's Law if the hydraulic gradient (dh/dl) increases while area (A) and hydraulic conductivity (K) remain constant then the velocity (v) must increase:

$$v = Q/A = K(dh/dl)$$

The accelerated flow of groundwater may flush sediment-filled conduits leaving the unconsolidated deposits above unsupported. Thirdly, induced recharge through newly created sinkholes may accelerate carbonate dissolution rates by providing a source

Figure 25. Cylindrical Sinkhole With Steep Walls (Spring, 1988).

Figure 26. The Same Sinkhole as Shown in Figure 25 (Fall, 1988).

Figure 27. Induced Recharge Through a Sinkhole.

of carbon dioxide-rich water to the subsurface (Figure 27). Water with a high concentration of dissolved carbon dioxide will aggressively react with the carbonates. This recharging water may also flush sediment from conduits via turbulent flow as suggested by the quick response of well #3 to precipitation events. The fourth mechanism involved in the formation of induced sinkholes is an increase in the magnitude of water level fluctuations (Newton, 1986). This may also be occurring in the study area but there are insufficient data to document it.

Another factor in the formation of induced sinkholes in the study area is blasting. Blasting may cause settling or disturb the sediment filling the solution cavities. In one case in August, 1991, the water level in well #4 decreased instantaneously by about 0.5 ft following a blast event indicating some effect on the groundwater system. While these mechanisms are probably accelerating sinkhole development in the Primrose Creek Watershed, it should be remembered that sinkhole development is a natural process. Paleokarst features buried under Triassic rocks in southeastern Pennsylvania document that these carbonates have been affected by this process more than once in the last 200 million years.

CHAPTER 6

CONCLUSIONS

Pumping of 17.21 bi/yr (3.01 x 10^8 gal/square mile) from the carbonate aquifer in the Primrose Creek Watershed created a deficit in the annual water budget of 10.88 bi/yr (1.7 x 10^8 gal/square mile). Precipitation alone was not enough to supply the water demands on the Primrose Creek Watershed. It is concluded that this demand was met by an annual inflow of approximately 10.88 bi/yr of groundwater from adjacent drainage basins. This number may be a high estimate of inflow because it does not take into account water which seeped through Primrose Creek's streambed.

Pumping groundwater from the carbonate aquifer also may have accelerated sinkhole development in the Primrose Creek Watershed. Four of Newton's (1986) mechanisms of sinkhole development appear to have been active during this study. They are as follows:

-The loss of buoyant support as a result of lowering the water table within the cone of depression.

-Groundwater velocity increases due to steepening hydraulic gradients caused by pumping.

-Induced recharge in areas which previously rejected recharge.

-Vibrations caused by blasting in the quarry.

REFERENCES

Corbett, D. M., et. al., 1943. Stream-Gauging Procedure: U. S. Geological Survey Water-Supply Paper 888, 245 p.

Drake, Avery Ala, Jr., 1965. Carbonate Rocks of Cambrian and Ordovician Age, Northampton and Bucks Counties, Eastern Pennsylvania, and Warren and Hunterdon Counties, Western New Jersey: U.S. Geological Survey Bulletin # 20 p. L1-L7.

Fetter, C. W., Jr., 1980. Applied Hydrogeology: Columbus, Ohio, Charles E. Merril Publishing Company, 488 p.

Foose, R. M., 1953. Ground-Water Behavior in the Hershey Valley, Pennsylvania: Bulletin of the Geologic Society of America, v. 64, p. 623-646.

__________, 1969. Sinkhole Formation by Ground-Water withdrawal, Far West Rand, South Africa: Science, v. 157, p. 1045-1048.

Freeze, R. Allen, and John A. Cherry, 1979. Groundwater: Englewood Cliffs, New Jersey, Prentice-Hall, Inc., 604 p.

Greenman, David W., 1955. Ground-Water Resources of Bucks County, Pennsylvania: Pennsylvania Geological Survey, 4th Series, Bulletin W-11, 67 p.

Howell, B. F., Henry Roberts, and Bradford Willard, 1950. Subdivision and Dating of the Cambrian of Eastern Pennsylvania: Bulletin of the Geological Society of America, v. 61, p. 1355-1368.

Jennings, J. N., 1985. Karst Geomorphology: Oxford, B. H. Blackwell, 293 p.

Kummel, H. B., 1897. Annual Report of the State Geologist for the Year 1896: New Jersey Geological Survey, pp. 25-88.

Lessentine, R. H., 1952. Areal and Structural Geology of Buckingham Valley, Pennsylvania, unpublished master's thesis: Bethlehem, Pennsylvania, Lehigh University, 80 p.

Manspeizer, W. and H. L. Cousminer, 1988. Late Triassic-Early Jurassic Synrift Basins of the U.S. Atlatic Margin: in Sheridan, R. E. and J. A. Grow, eds., The Geology of North America, v. I-2, The Atlantic Continental Margin, U.S.: Geological Society of America, p. 197-216.

Mather, J. R., 1978. The Climatic Water Budget in Environmental Analysis: Lexington, Massachusetts, Heath Company, 239 p.

Meisler, Harold, 1963. Hydrogeology of the Carbonate Rocks of the Lebanon Valley, Pennsylvania: Pennsylvania Geological Survey, 4th Series, Water Resource Report 18, 81p.

Miller, B. L., 1939. Guidebook to Places of Geologic Interest in the Lehigh Valley: Pennsylvania Geological Survey, 4th Series, Bulletin G-16, 47 p.

Newton, J. G., 1986. Development of Sinkholes Resulting From Man's Activities in the Eastern United States: U.S. Geological Survey Circular 968, 54 p.

Olsen, Paul E. and Dennis V. Kent, 1990, Continental Coring of the Newark Rift: EOS, Transactions, American Geophysical Union, 71 (15), p. 385,394.

Soil Conservation Service, 1975. Soil Survey of Bucks and Philadelphia Counties: U.S. Deparatment of Agriculture, 130 p.

Thornthwaite, C. W., 1948. An Approach Toward a Rational Classification of Climate: Geographical Review, v. 38. pp. 55-94.

Viessman, Jr., W., G. L. Lewis and J. W. Knapp, 1989. Introduction to Hydrology: New York, Harper and Row, 780 p.

Wherry, E. T., 1909. The Early Paleozoic of the Lehigh Valley District, Pennsylvania: Sci. new ser., v. 30, # 769, 416 p.

Willard, Bradford., 1955. Cambrian Contacts in Eastern Pennsylvania: Bulletin of the Geological Society of America, v. 66, p. 819-833.

Willard, Bradford, Jacob Freedman, D. B. McLaughlin, J. Donald Ryan, Edgar T. Wherry, L. C. Peltier, H. R. Gault, 1959. Geology and Mineral Resources of Bucks County, Pennsylvania: Pennsylvania Geological Survey Bulletin C-9, 4th Series, 243 p.

Wood, C. R., H. N. Flippo, Jr., J. B. Lescinsky, and J. L. Barker, 1972. Water Resources of Lehigh County: Pennsylvania Geological Survey, 4th Series, Water Resource Report 31, 263 p.

Zietz, Isidore, and Carlyle Gray, 1960. Geophysical and Geological Interpretation of a Triassic Structure in Eastern Pennsylvania: Professional Paper-U.S. Geological Survey, # 20, p. 10-29.

APPENDIX

DATA TABLES

Table A–1. Measured Precipitation From February, 1988 to January, 1989.

Date 1988–89	Lambertville, New Jersey (inches)	Weekly Total (inches)	NHCS Quarry Rain Gauge (inches)
FEB 2	0.31		
3	0.10		
4	0.40		
12	1.82		
13	0.07		
15	0.07		
17	0.38		
20	0.85	3.15	NA
23	0.07		
24	0.07		
26	0.00	0.99	
27	0.11		
28	0.04		
MAR 2	0.11		
3	0.87		
4	0.20		
5	0.00	1.33	
13	0.00	0.00	NA
20	0.00	0.00	
26	0.75		
27	0.43	0.75	
APR 2	0.00	0.43	
4	0.19		
7	0.21		
8	0.05		
10	0.00	0.45	NA
16	0.10		
17	0.03	0.10	
18	0.22		
19	0.03		
23	0.20		
24	0.15	0.48	
28	1.26		
29	0.10		
30	0.13		
MAY 1	0.00	1.64	

	3	0.05		
	5	0.40		
	6	0.51		
	11	0.25		
	14	0.04		
	15		1.25	NA
	17	0.05		
	18	0.52		
	19	1.72		
	20	0.81		
	21	0.02		
	22	0.10		
	23	0.00	3.22	
	24	0.39		
	25	0.71		
	28	0.00	1.10	
JUN	1	1.30		
	4	0.12	1.42	
	8	0.07		
	9	0.22		
	11	0.00	0.29	
	14	0.00	0.00	NA
	21	0.00	0.00	
	28	0.00	0.00	
JUL	9	0.13		
	12	0.20		
	17	0.70	0.33	0.79
	18	0.30		
	19	0.03		
	20	1.93		
	21	1.22		
	22	0.71	4.18	5.06
	24	1.93		
	26	1.08		
	27	2.22		
	28	0.43		
AUG	2	0.00	6.37	4.45
	8	0.00	0.00	0.00
	11	0.13		
	15	0.00	0.13	0.02
	18	0.44		
	20	0.02		
	21	0.00	0.46	0.39

24	0.95		
25	0.46		
27	0.02		
29	1.83		
30	0.03		
31	0.00	3.29	2.32
SEP 4	1.40		
5	0.06		
8	0.00	1.45	1.34
9	0.02		
13	0.73		
17	0.18		
18	0.02		
21	0.00	0.95	1.01
25	0.12	0.11	0.11
26	0.01		
29	0.00	0.02	0.01
OCT 2	0.00	0.00	0.00
3	0.36		
5	0.06		
8	0.05		
16	0.00	0.47	0.54
21	0.47		
22	1.48		
23	0.00	1.95	1.40
24	0.22		
28	0.02		
31	0.00	0.24	0.24
NOV 1	0.63		
5	0.59		
6	0.04		
9	0.00	1.26	1.04
11	0.02		
13	0.55		
16	0.10		
17	0.96	0.67	0.62
19	0.04		
20	2.05		
21	0.26		
27	0.18	3.31	3.20
28	1.83		
30	0.00	2.01	1.64

DEC	11	0.00	0.00	0.00
	21	0.16		
	23	0.26		
	24	0.26		
	27	0.00	0.68	0.82
	28	0.25		
JAN	2	0.02		
	6	0.34		
	8	0.21		
	12	0.52		
	13	0.02		
	15	0.63		
	22	0.00	1.99	1.31
	26	0.08		
	27	0.04		
	29	0.40		

Table A–2. Measured Streamflow of Primrose Creek at Station A.

Date 1988–89		Discharge (cfs)	Avg Daily Discharge (cfs)	Monthly Discharge (basin inches)
FEB	20	2.33		
	26	0.77	1.55	1.08
MAR	5	1.00		
	13	0.49		
	20	0.34		
	27	0.32	0.54	0.41
APR	2	0.17		
	10	0.18		
	17	0.05		
	24	0.19	0.15	0.11
MAY	1	0.16		
	15	0.15		
	23	1.14		
	28	1.13	0.65	0.48
JUN	4	0.68		
	11	0.18		
	14	0.11		
	21	0.04		
	28	0.00	0.20	0.15
JUL	17	0.00		
	22	0.31	0.15	0.11
AUG	2	0.40		
	8	0.10		
	15	0.00		
	21	0.00		
	31	0.00	0.10	0.07
SEP	8	0.00		
	21	0.00		
	25	0.00		
	29	0.00	0.00	0.00
OCT	2	0.00		

	16	0.00		
	23	0.00		
	31	0.00	0.00	0.00
NOV	9	0.00		
	17	0.00		
	27	0.31		
	30	0.88	0.59	0.22
DEC	11	0.00		
	27	0.00	0.00	0.00
JAN	22	0.00	0.00	0.00

Table A–3. Measured Streamflow of Primrose Creek at Station B. *

Date 1988–89		Discharge (cfs)	Avg Daily Discharge (cfs)	Monthly Discharge (basin inches)
FEB	20	6.07		
	26	2.39	4.23	2.61
MAR	5	3.66		
	13	3.91		
	20	3.34		
	27	3.02	3.48	2.29
APR	2	2.64		
	10	2.64		
	17	2.42		
	24	2.27	2.49	1.59
MAY	1	2.29		
	15	2.12		
	23	4.4		
	28	4.69	3.38	2.23
JUN	4	3.63		
	11	2.94		
	14	2.43		
	21	2.44		
	28	2.03	2.69	1.71
JUL	17	1.59		
	22	3.22	2.41	1.59
AUG	2	3.4		
	8	3.03		
	15	2.82		
	21	2.46		
	31	2.46	2.83	1.86
SEP	8	1.96		
	21	1.13		
	25	1.34		
	29	1.29	1.43	0.91
OCT	2	1.51		

	16	1.06		
	23	1.38		
	31	1.08	1.26	0.83
NOV	9	0.84		
	17	1.16		
	27	2.41		
	30	3.59	2.00	1.27
DEC	11	2.27		
	27	1.85	2.01	1.32
JAN	22	1.97	1.97	1.30

*Discharge at Station B consists of flow through Station A plus groundwater pumped from the NHCS quarry.

Table A–4. Measured Discharge Over the Weir Crest of Water Pumped From the NHCS Quarry.

Date 1988–89		Discharge (cfs)	Avg Daily Discharge (cfs)	Monthly Discharge (basin inches)
FEB	20	1.82		
	26	0.00	0.91	0.56
MAR	5	0.56		
	13	1.92		
	20	1.87		
	27	1.66	1.50	0.99
APR	2	1.48		
	10	1.39		
	17	1.34		
	24	1.48	1.42	0.90
MAY	1	1.39		
	15	1.39		
	23	1.87		
	28	1.89	1.63	1.07
JUN	4	1.52		
	11	1.34		
	14	1.39		
	21	1.34		
	28	1.26	1.37	0.87
JUL	17	1.34		
	22	1.71	1.52	1.00
AUG	2	1.76		
	8	1.76		
	15	1.76		
	21	1.71		
	31	1.66	1.73	1.14
SEP	8	1.66		
	21	1.34		
	25	1.34		
	29	1.30	1.41	0.90
OCT	2	1.30		

16	1.22		
23	1.26		
31	1.18	1.24	0.82
NOV 9	1.18		
17	1.22		
27	1.76		
30	1.76	1.48	0.94
DEC 11	1.52		
27	1.47	1.50	0.99
JAN 22	1.52	1.52	1.00

Table A-5. Calculated Discharge of Water Pumped From Pump 2 in the NHCS Quarry.

Date 1988-89		Discharge (cfs)	Avg Daily Discharge (cfs)	Monthly Discharge (basin inches)
FEB	20	1.92		
	26	1.62	1.77	1.09
MAR	5	2.10		
	13	1.50		
	20	1.14		
	27	1.03	1.44	0.95
APR	2	0.97		
	10	1.07		
	17	1.02		
	24	0.60	0.91	0.58
MAY	1	0.74		
	15	0.58		
	23	1.39		
	28	1.67	1.09	0.72
JUN	4	1.43		
	11	1.42		
	14	0.93		
	21	1.06		
	28	0.77	1.12	0.71
JUL	17	0.25		
	22	1.21	0.73	0.48
AUG	2	1.24		
	8	1.17		
	15	1.06		
	21	0.75		
	31	0.80	1.00	0.66
SEP	8	0.30		
	21	−0.20		
	25	0.00		
	29	0.00	0.03	0.02
OCT	2	0.21		
	16	−0.16		

	23	1.21		
	31	−0.10	0.02	0.01
NOV	9	−0.34		
	17	−0.06		
	27	0.34		
	30	0.96	0.22	0.14
DEC	11	0.75		
	27	0.38	0.56	0.37
JAN	22	0.45	0.45	0.30