Ground-Water Availability, Hockessin, Delaware

by Paul M. Williams[a]

ABSTRACT

A four-year case study evaluation of the ground-water availability in a small multiaquifer basin in northern Delaware has been performed to determine the hydrologic conditions when pumpage approaches the expected long-term basin-wide rate of ground-water recharge. The basin is located in the Piedmont physiographic province and includes rocks of the Cockeysville marble and Wissahickon schist.

Only about one-third of the basin (the marble area) contains favorable geologic conditions for large production well development (≈ 1 MGD/well); however, the entire basin serves as a recharge area for the marble sector. The *manageable* storage area is limited to the marble area; consequently, accurate ground-water recharge and storage characteristics of this basin are critical to maximizing the long-term yield while minimizing adverse impacts of pumpage. The analysis was performed using the Thornthwaite-Mather water balance accounting procedure to determine the long-term significance of the exported pumpage.

INTRODUCTION

The use and manipulation of ground-water reservoirs as storage vessels are currently being debated as a means of overcoming a variety of water problems (Ambroggi, 1977). While this has much to recommend it, the hydrologic uncertainties which water managers may have in ground-water storage manipulation must be adequately dealt with for the idea to be reasonably applied.

If the measurement of ground-water reservoir storage characteristics and recharge were as simple to measure as storage and inflow in surface reservoirs, the development of aquifers as storage vessels by means of mass inflow-outflow diagrams as Helweg (1978) suggests, would have taken place before now to a much greater extent. In many cases the storage characteristics and recharge (inflow) of an aquifer are not the same in terms of time and area. This is contrary to the need to minimize runoff (the "spill") while simultaneously maintaining an adequate storage volume for drought protection.

Using a significant portion of an aquifer for the withdrawal and storage of "extra" or "excess" water implies that potentially large changes in the hydrologic balance of an area will accompany the storage manipulation and that significant water level fluctuations may result.

The intention of this paper is to show what has happened hydrologically to a small ground-water basin in northern Delaware which has been pumped at a rate approaching the long-term ground-water recharge rate. This aquifer has been managed to produce the maximum amount of water to supply distribution systems when it is needed and not to *minimize* the natural ground-water runoff from streams. In effect this has meant that higher pumping rates have occurred in the Summer when demand is greatest, but also when stream flow and ground-water recharge are normally lowest.

This paper also demonstrates some of the complexities of adequately understanding the storage properties of a small multiaquifer basin.

PART I – GEOHYDROLOGY

The Town of Hockessin in northern Delaware lies within a small basin (approximately 3.8 mi^2) in the head waters of Mill Creek which is a tributary to White Clay Creek. The area is within the Piedmont physiographic province and is underlain by rocks of the Cockeysville marble and rocks of the Wissahickon formation (Figures 1 and 2). The area underlain by marble (1.3 mi^2) forms a broad flat valley whereas the area underlain by nonmarble rocks consists of rolling hills. Due to the favorable water-yielding characteristics of the marble, it has been developed by a water company in stages over the past 15 years to the current average level of water withdrawal (1.9 MGD). The Wissahickon formation, on the other hand, has relatively poor water-yielding characteristics and usually only yields several gallons per minute to wells. All of

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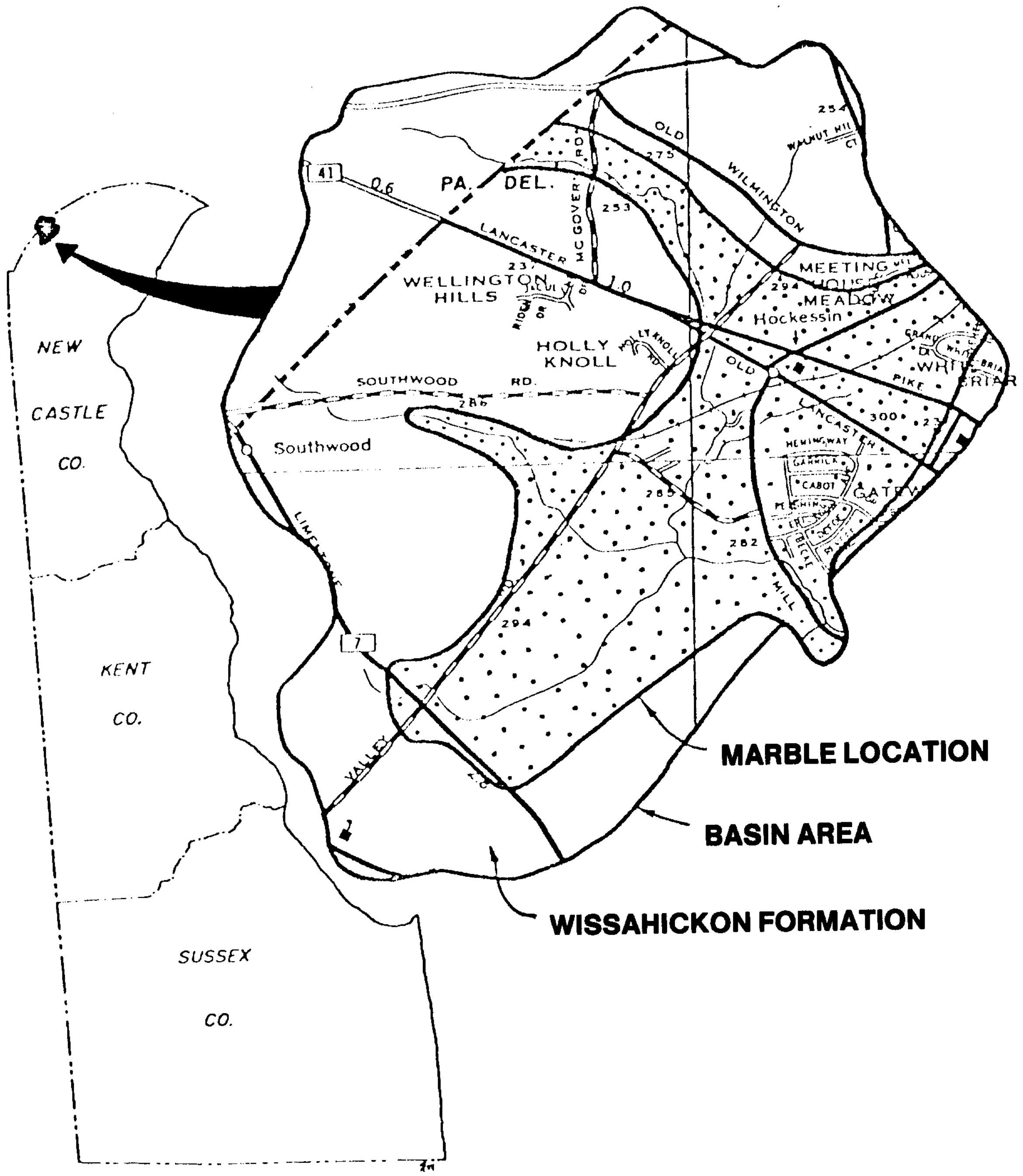

Fig. 1. Map of Delaware showing location of Hockessin basin.

the pumped water leaves the basin through water transmission mains or public sewers.

Figure 3 is a generalized diagram of the relative positions of the geologic units underlying the Hockessin basin. The contact between the marble and other rock types (nonmarble) appears to be sharp in some places and gradational in others. The actual boundaries of the marble, particularly in Pennsylvania, are not clearly determined.

Head changes in the marble are not transmitted very far into the nonmarble rock due primarily to significant differences in the hydraulic conductivities of the two formations. Pumping tests in the marble have indicated transmissivity values of 10,000-40,000 gallons per day per foot (gpd/ft) or 5 to 40 times greater than the Wissahickon formation (Talley and Hahn, 1978).

Saprolite or weathered material overlies both of the consolidated formations throughout the basin. As Figure 3 illustrates, this unit is thickest in the central portion of the basin where it overlies the marble and thins as the topography steepens on the flanks of the valley. The thickness of saprolite reported overlying the marble varies considerably from 30 to 100 feet or more and averages 50 to 75 feet. The thickness of the saprolite overlying the Wissahickon formation has not been mapped; however, data from well logs suggest the average to be half that reported for the marble.

The saprolite is composed of layers and lenses of sand, silt and clay. In many locations the hydraulic conductivity of the saprolite is sufficiently great to supply water to wells, both large-diameter dug wells and some 4- to 6-inch drilled and screened wells. The saprolite appears to be the most homogeneous unit in the basin in terms of hydraulic properties.

The following relationships appear to exist between the three units mentioned:

1. The saprolite receives water from precipitation and induced streamflow infiltration, and provides storage for most of the water in the basin.

2. The saprolite promotes (a) recharge to the Wissahickon schist and Cockeysville marble by leakage, and (b) base flow to the streams.

3. The schist and marble are poorly connected hydraulically.

4. The marble receives virtually all

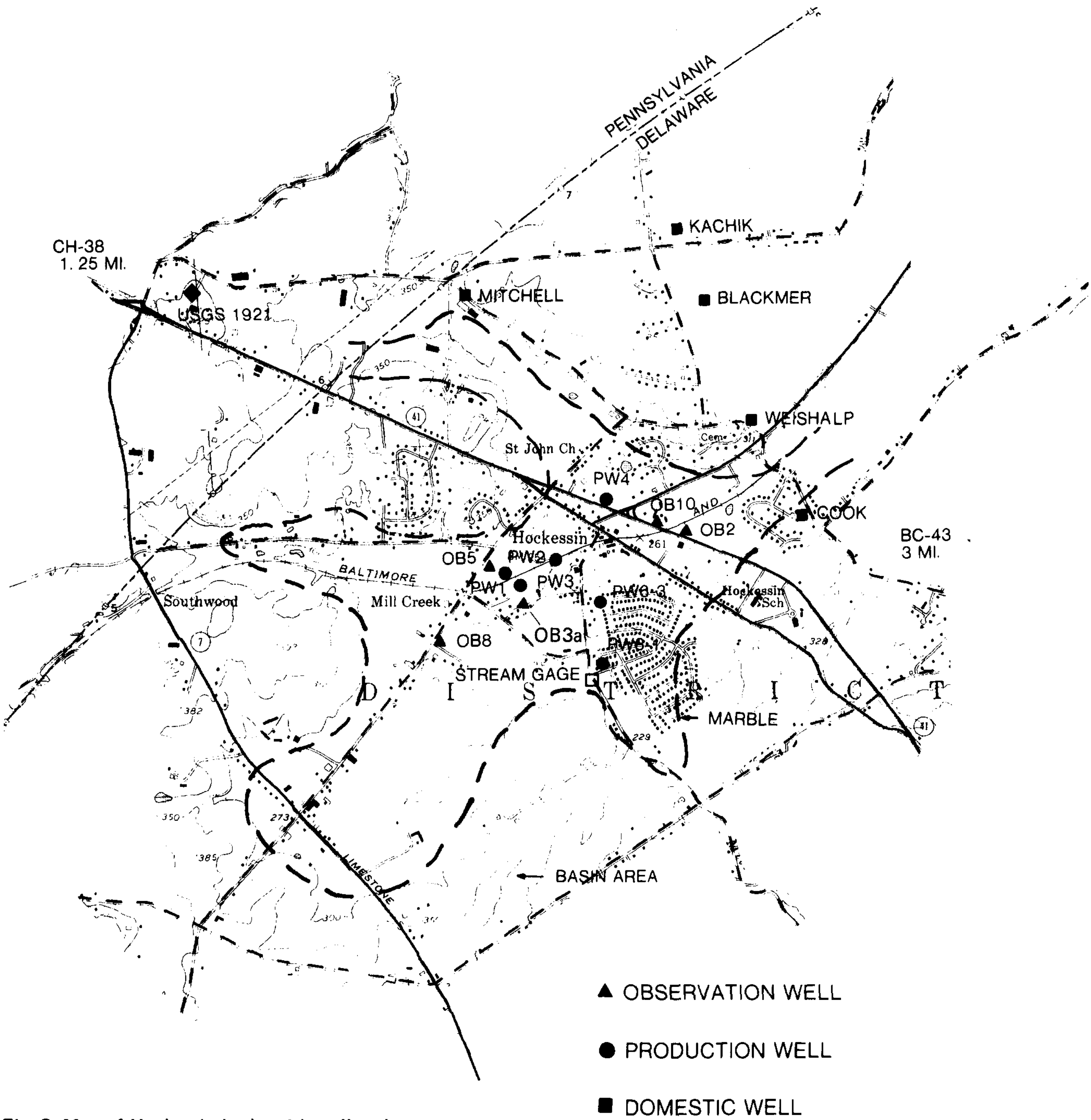

Fig. 2. Map of Hockessin basin with well and stream gage locations.

Fig. 3. Schematic block diagram of the Hockessin basin showing the general spatial relationship and weathering characteristics of the Wissahickon schist and the Cockeysville marble.

recharge from the overlying saprolite and feeds water to the production wells.

PART II – WATER BUDGET

The generalized hydrologic budget of the Hockessin basin is represented by the following:

$$P - O.F. - E.T. = W.P. + B.F. + \Delta S$$

where

- P is precipitation,
- O.F. is overland or direct stream flow,
- E.T. is evapotranspiration,
- W.P. is water production (pumpage),
- B.F. is stream base flow (ground-water runoff), and
- ΔS is change in ground-water storage.

Not included in this representation is inter-basin underflow either into or out of the basin. Although other small marble basins exist within several miles of Hockessin, as yet no evidence exists to suggest either subsurface connections with these other marble areas or that hydrologic head gradients at the basin boundaries have changed sufficiently to import any significant quantity of water.

This basin is within the head-water area of Mill Creek and as such all of the water available to meet the stream flow and ground-water components of the budget are from precipitation. Figure 4 is a monthly tabulation of each component of the hydrologic budget. A discussion of the significance of each budget component follows.

Precipitation

The average yearly precipitation in the Hockessin basin for the four years studied was 49.6 inches (Figure 4). The data came primarily from a station one mile north of the basin; however, other data within the basin were also used. The variation encountered in the average yearly values from these stations was less than .5 inches per year.

No long-term precipitation data exist for the Hockessin basin and in order to judge how representative these four years are of the long-term precipitation average, the short-term Hockessin data must be compared with data from nearby long-term stations.

The following data are presented for comparison:

1. Wilmington Weather Station long-term average 1894 to 1976–*43.5 inches* (10 miles southeast of Hockessin).

2. Wilmington Weather Station, May 1974 to April 1978 average–*42.1 inches.*

3. West Grove, Pennsylvania, 1931-1960 average–*45.0 inches* (7 miles northwest of Hockessin).

An extensive analysis of this data is beyond the scope of this paper; however, it does appear probable that the long-term average yearly precipitation in the Hockessin basin is *at least* 2-3 inches greater than that which has been recorded in Wilmington.

Month	*Precipitation*	*Overland stream flow*	*Actual evapotranspiration*	*Recharge*	*Water production*	*Base flow*	*Storage change*	*Cumulative feet of storage change*
May 1974	307	25	226	54	54	50	−50	−2.
June	356	11	313	31	48	21	−38	−3.5
July	155	11	359	0	58	14	−72	−6.4
August	402	10	360	0	42	11	−53	−8.5
September	320	12	227	0	39	15	−54	−10.70
October	149	14	107	0	48	14	−62	−13.20
November	110	8	56	0	45	13	−58	−15.50
December	362	34	20	276	59	26	191	−7.8
January 1975	318	45	15	189	55	27	107	−3.6
February	208	52	9	83	44	22	17	−2.9
March	350	82	34	294	45	35	214	+5.7
April	222	22	81	141	47	39	55	7.9
May	297	100	244	0	63	60	−123	3.0
June	550	40	318	169	65	42	62	5.4
July	667	143	375	246	57	45	144	11.2
August	107	16	320	0	61	48	−109	6.8
September	451	25	208	0	49	35	−84	3.5
October	245	61	148	22	55	35	−68	−.8
November	249	11	73	165	42	42	81	+4.
December	153	32	8	113	28	70	15	+4.6
January 1976	343	43	0	300	41	100	160	11.0
February	135	71	25	39	45	66	−72	8.1
March	125	23	60	42	44	65	−67	5.4
April	140	21	126	0	32	45	−77	2.3
May	320	37	203	100	54	39	7	2.6
June	188	24	321	0	40	27	−67	0
July	374	23	360	0	58	19	−77	−3.2
August	262	16	312	0	58	28	−86	−6.6
September	110	27	178	0	49	3	−52	−8.7
October	426	36	104	0	47	19	66	−11.3
November	36	4	28	0	56	14	−70	−14.1
December	101	34	0	68	49	23	−4	−14.3
January 1977	137	58	0	79	52	45	−18	−15.0
February	94	60	0	34	49	45	−60	−17.4
March	349	55	75	218	55	19	144	−11.6
April	295	40	136	119	59	14	46	−9.8
May	74	6	225	0	66	11	−77	−12.9
June	322	1	298	0	63	4	−67	−15.6
July	97	1	303	0	70	1	−71	−18.4
August	341	2	347	0	72	3	−75	−21.4
September	211	1	234	0	65	4	−69	−24.2
October	238	15	109	0	57	5	−62	−26.6
November	395	42	57	107	44	8	55	−24.4
December	414	124	2	288	42	18	228	−15.3
January 1978	610	216	0	463	47	37	379	−.2
February	89	99	0	0	43	29	−72	−3.0
March	353	83	19	251	56	51	144	2.72
April	131	14	102	0	57	68	−125	−2.3
Total	12688	1930	7125	3891	2474	1474		−2.3
Yearly avg., MG	3172	482	1781	973	618	369		38.
Yearly avg., inches	49.6	7.5	27.8	15.0*	9.7	5.8		.6

(* Includes .6-inch total soil depletion at end of study period.)

Fig. 4. Hockessin water balance (all amounts are in million gallons).

Evapotranspiration

A Thornthwaite-Mather (1957) water-balance accounting was performed using precipitation and temperature data. This procedure is an empirical technique which gives fairly accurate results over a period of years using monthly data. A modification of Thornthwaite-Mather was used (where overland stream flow is subtracted from precipitation prior to calculating evapotranspiration loss) which produced a more accurate estimation of storage change for the Hockessin basin.

For the four years studied, the average yearly calculated evapotranspiration loss is 27.8 inches. This value is approximately 1.8 inches greater than a long-term evapotranspiration average of 26.0 inches determined for the Wilmington area by Mather (1969).

Pumpage in the Hockessin Basin

Water pumped in the Hockessin basin has been recorded since the early to mid-60's when the first production wells were installed. The yearly pumpage was steadily increased until 1977 when it reached a maximum withdrawal rate of 1.9 million gallons per day (MGD). During the four years studied, pumpage averaged 1.7 MGD and was maintained at the desired levels despite periods of reduced ground-water recharge. Of all the components of the hydrologic budget, pumpage is the most accurate value determined (9.7 inches per year average or .46 MGD/mi²).

Stream Flow

Stream flow from the basin (Figure 5) has been recorded since April 1974. For the first three years, the gaging station consisted of a staff gage read once daily. Since May 1977, a continuous recorder has been in operation at the same site.

In spite of some uncertainties with the stream flow data, total runoff was calculated and separated into the base flow and overland flow components. The results of this analysis are as follows:

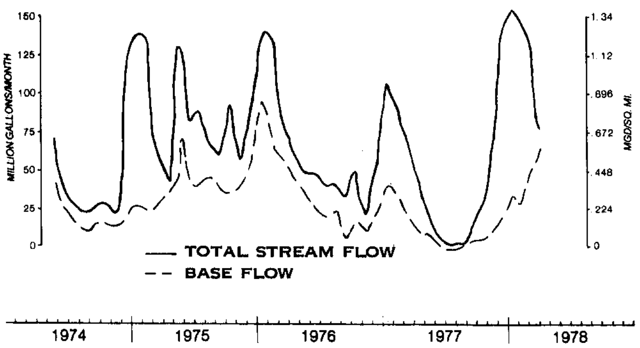

Fig. 5. Stream flow from the Hockessin basin.

Table 1. Stream Flow Values for Chester County, PA (McGreevy and Sloto, 1977)

	Total (MGD/mi²)	*Base Flow (MGD/mi²)*	*Overland Flow (MGD/mi²)*
1966-Dry Year	.5	.3	.2
1968-Normal Year	.8	.5	.3
1973-Wet Year	1.4	.8	.6

1. Total stream flow equalled 13.1 inches per year average (0.62 MGD/mi²).

2. Base flow averaged 5.8 inches per year (.28 MGD/mi²).

3. Overland flow averaged 7.5 inches per year (.35 MGD/mi²).

For the purpose of comparison, see Table 1 which shows stream flow values as determined for Chester County, Pennsylvania (McGreevy and Sloto, 1977).

On the basis of precipitation, the four years evaluated in the Hockessin basin are "wet;" however, total stream flow and base flow indicate that the Hockessin basin was dry by comparison to normal Chester County runoff. A similar comparison with the two streams which drain land surrounding this basin for the same four-year period as the study indicates a similar conclusion. Mill Creek, draining the Hockessin basin, is deficient in total stream flow. Of the two primary stream flow components, only overland flow was in the "expected" range. If the Hockessin basin *pumpage* (.46 MGD/mi²) is added to the tabulated stream base flows, all of the stream flow values not only compare favorably with the normal to wet year values determined for Chester County but compare favorably on a per square mile basis with the other streams in the area. On a long-term basis, pumpage appears to be at the direct expense of stream base flow.

Storage

Periodically during the four years of record, high rates of water outflow (pumpage, evapotranspiration and stream flow) coupled with average or below average precipitation have resulted in a decline in water stored in the basin. This is a normal seasonal occurrence which is lengthened by the pumping of wells. During these periods, all of the outflow above the available recharge is taken from ground-water storage.

The evaluation of the storage properties of the Hockessin basin is based primarily on the earlier water balance equation, rearranged such that ΔS is the only unknown. All of the other components of the water balance equation (except evapotranspiration) have been measured and are accurate within some small margin of error. The accuracy of the Thornthwaite-Mather evapotranspiration calculation has been demonstrated in this geographic area in other publications.

For the purpose of evaluating the basin performance under drought conditions, only an average specific yield is necessary as long as it is reasonable to assume that the average specific yield will not decline in a drought as dewatering takes place. For basins which are large in comparison to their pumpage and demonstrate reasonable homogeneity, the assumption is reasonable. Consequently, matching water level changes as observed in wells throughout this basin with the calculated changes of storage volume might be expected to give a reasonable estimation of the over-all specific yield. However, for basins such as Hockessin, which are small, heavily pumped and nonhomogeneous (horizontally and vertically), changes in the specific yield with respect to time should be anticipated. In Hockessin there are basically two reasons why storage yield may be expected to change in time.

First, the storage release within the marble is controlled by the head change within the marble which is transmitted upward into the saprolite (where most basin storage takes place). These head changes are caused by the differences between total ground-water outflow and ground-water recharge. However, the storage changes in the schist portions of this basin are not significantly controlled by pumpage as the hydraulic head communication across the boundary is poor. Storage release in the Wissahickon is by natural ground-water runoff only and may be expected to decline in a manner typical of base flow recessions of this area. The significance of this is that decreasing runoff from the schist area in a drought period will be available in the streams for induced infiltration as they cross the marble.

Secondly, portions of the marble area saprolite have been dewatered in the central portion of the basin. As this proceeds in a long-term drought situation the specific yield of the marble area will increasingly reflect the specific yield of the marble and not the overlying saprolite. Briefly, the storage characteristics of the basin for the four years studied were determined as follows:

Olmsted and Hely (1962) reported the specific yield of the saprolite of the Wissahickon schist to be between 8% and 10% (approximately 16.7 Mgal/ft/mi^2). The schist occupies an area of 2.4 square miles; thus storage release is approximately 41 Mgal/ft of water level decline, assuming the specific yield determined by Olmsted and Hely is applicable to Hockessin. Water levels in wells finished in the schist declined an average of 1.5 to 2 feet between June 1 and September 15, 1977 (Figures 6, 7, and 8), indicating a release from storage between 62 and 82 million gallons of water for the nonmarble portion of the basin. During this same time period, total basinwide water storage decline equalled 250 million gallons, calculated (Figure 4). Subtracting the amount which was contributed by the schist area, the remainder divided by the average water level decline in the marble area ($\approx$ 10. feet, Figure 9) gives a reasonable value of storage release from the marble area. This equals 17.8 Mgal/ft of water level decline.

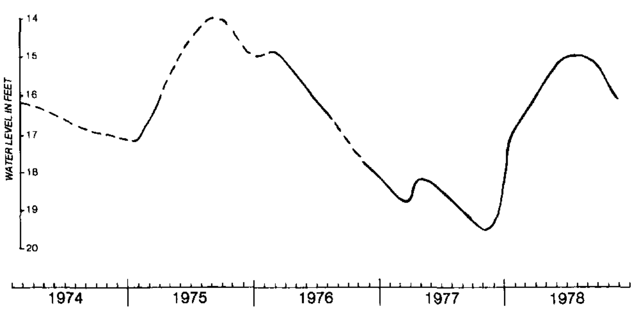

Fig. 6. Hydrograph of Blackmer domestic well in the Wissahickon schist.

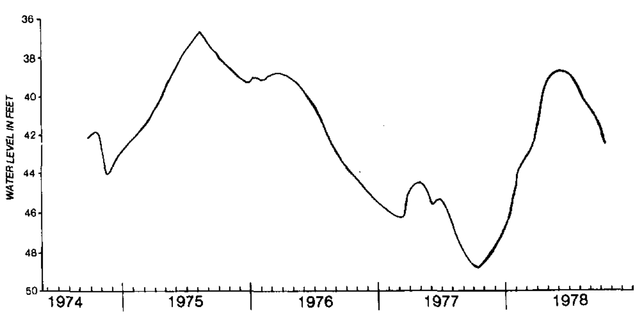

Fig. 7. Hydrograph of observation well CH-1921.

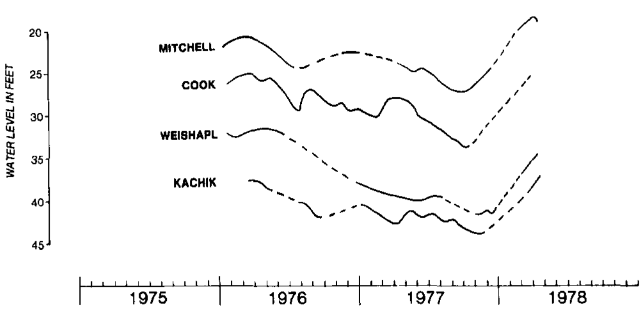

Fig. 8. Hydrographs of nonmarble domestic observation wells.

Converting to specific yield, marble area storage coefficient equals 6.5%.

This value is supported by the observation that water levels in the basin indicate that approximately one-third of the saprolite in the marble area was substantially dewatered prior to the four years of record. Thus, the specific yield may have been lowered because water levels are within the less weathered (less porous) portions of the marble bedrock. There is not sufficient background data to quantify the exact amount of specific yield reduction; however, as much as 2-4% is likely.

The greatest decline in storage took place between January 1976 and November 1977 when the water level in observation well 3a dropped 37.5 feet. Evaluating these storage declines with respect to the marble and schist area components, the total basin yield during these 21 months was as follows:

1. Marble area — Water level declines in observation well 3a = 37.5 feet. 37.5 feet × 17.8 Mgal/ft = 667 million gallons.

2. Schist area — Average water level decline in four wells = 6.68 feet. 6.68 feet × 41 Mgal/ft = 273 million gallons.

3. Total basin storage yield = 940 million gallons.

The only long-term observation well within this basin is well 3a. Although it is located within 300-400 feet of three production wells, hydrographs do seem to reflect the over-all storage conditions within the basin. Consequently, to evaluate any long-term storage changes within the basin for the four years studied it is necessary to use this well as a key to indicate over-all storage change.

Figure 9 is the hydrograph from well 3a for the period studied. Also included is a synthetic

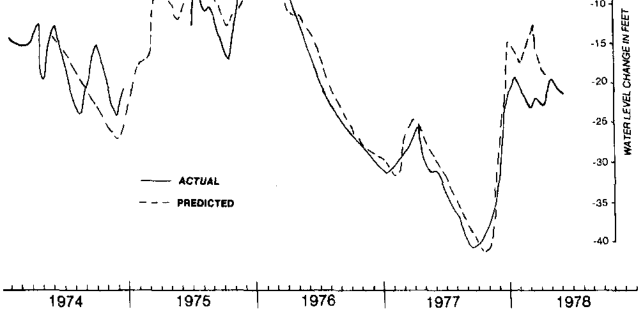

Fig. 9. Actual and predicted (calculated) water level change, observation well 3a in the Cockeysville marble.

hydrograph (calculated line) computed from the hydrologic budget assuming that for each 25 million gallons of storage change computed, there will be an associated one-foot change in observation well 3a water level (average basin specific yield = 3%). For this relationship to remain consistent throughout the period studied, the size and relative shape of the over-all water level pumping depression must remain unchanged. The indication has declined approximately 2.5 feet at well 3a (65 million gallons) since early 1974, seeking a new equilibrium (with stream-water levels) in response to increasing pumpage during the period studied.

Recharge Analysis

As developed in the previous sections, the following average values appear to be valid for each of the four years studied.

Precipitation = 49.6 inches measured (3174 Mgal).

E.T. (12-inch Storage) = −27.8 inches calculated (1773 Mgal).

Overland Streamflow = − 7.5 inches measured (480 Mgal).

Ground-Water Recharge = 15.0 inches per year (960 Mgal/yr).

Ground-Water Recharge = 2.6 million gallons per day (.680 MGD/mi^2).

Because it appears probable that precipitation was 10% higher during the period of study than during a "normal" year, the recharge value can be reduced to reflect the normal expected recharge. This would be about 13 inches per year or 2.3 MGD (.600 MGD/mi^2).

During the four years of record, pumpage accounted for 75% of the normally expected basin ground-water yield. However, the total basin allocated pumpage of 1.9 MGD equals approximately 85% of the normal long-term expected rate of ground-water availability.

Although the "average" recharge rate during the four years studied was .68 MGD/mi^2, there was considerable recharge variation during this time.

During 1976 and 1977 (Jan. 1976-Nov. 1977), a 21-month period occurred when the average recharge (precipitation minus overland stream flow and evapotranspiration) was .29 MGD/mi^2, which included 12 months of no recharge at all. However, these 21 months were preceded by a 14-month period of substantially higher than average recharge (1.2 MGD/mi^2). Due to stream base flow increases during this high recharge period (and pumpage continuation), only about one-half of the "extra" recharge was stored and available for stream and well output during the 21-month period of relative drought.

SUMMARY AND CONCLUSIONS

1. For the 3.8-square mile Hockessin basin, the water budget P – O.F. – E.T. = B.F. + W.P. + S is balanced for the four years studied without significant evapotranspiration reductions or interbasin inflow to accurately account for the water.

2. During the period studied, pumpage was maintained at the rates desired by the water company even during 21 months of about one-half of normal ground-water recharge. The ground-water basin storage reduction during these 21 months amounted to 950 million gallons. Some stream flow continued although at rates significantly lower than "average" for this basin. Total pumpage and stream base flow (ground-water output) during the 21-month drought was .693 MGD/mi^2; as much as twice that which might be expected under natural ground-water runoff conditions in a dry year (see Table 1).

3. Marble area ground-water basin specific yield is calculated to be 6.5%. This value is less than the specific yield determined for the Wissahickon schist—8-10% (by others). Consequently, it is likely that the specific yield of the marble was reduced prior to the period studied. Further long-term reductions are unlikely (under "normal" conditions) in that ground-water recharge equals or exceeds ground-water pumpage on an average annual basis.

4. The Second National Water Assessment by the U.S. Water Resources Council has said, "Even the humid East has experienced drought, although long-term droughts of several years' duration are rare. Usually the East experiences very short-term seasonal periods of drought. The Northeast drought of 1962 to 1966 was an event expected on the average only once every 150 years" (page 6, part II). Consequently, it appears that storage within the Hockessin basin ought to remain sufficient to withstand from one to two years of drastically reduced recharge without reduction of the current pumpage rates. The actual return period of ground-water shortages cannot be assessed until additional work on drought prediction is completed.

5. Favorable geohydrologic conditions in less than one-half of the topographic limits of the Hockessin basin have allowed the development of the resource to a limit approaching the long-term average recharge rate of the whole basin. The geologic contact of the schist and marble acts as a boundary on the effective *manageable* storage area of the basin, but *not* as a boundary on the effective recharge area.

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