WATER AVAILABILITY IN DIABASE REGIONS OF A WATER MANAGEMENT AREA

By Amleto A. Pucci, Jr.*

ABSTRACT: Ground-water availability concerns led the Delaware River Basin Commission to devise a management approach in a 1,683 mi^2 urban-suburban area to the northeast and west of Philadelphia, Pennsylvania called the Southeastern Pennsylvania Ground Water Protected Area (SEPAGWPA). The DRBC water management model assumes that ground-water availability is proportionate to mean annualized baseflow in sub-basins, and that characteristic annualized baseflow rates for four geologic sub-crop types are sufficient to predict mean annual baseflow in all 85 sub-basins in the SEPAGWPA. This investigation suggests an improvement to the management approach, especially as applied to Bucks County, most of which is within the boundary of the SEPAGWPA. Diabase is added as a fifth sub-crop type because it occurs extensively in areas of Bucks County where ground-water resources are undergoing increased development pressure and because it is believed the DRBC estimates for water availability from this geologic material are too high.

Baseflow separations of stream flow data for 5 streams in Southeastern Pennsylvania were analyzed to compute mean annual base flow for various return periods. 1^{st}–order equations were set up which accounted for characteristic contributions from each of 5 geologic sub-crop areas to mean annualized base flow for each sub-basin, and mean annual baseflow for diabase was computed. Mean annualized baseflow from diabase is, in units of MGD/mi^2/yr; 0.181 for 2-yr. return period, and 0.073 for a 25-yr. return period. The result was applied to calculate water availability for a 6 sub-basins covering a 97.6 mi^2 area, of which 32% was underlain by diabase. The calculated water availability for the 6 sub-basins using the DRBC water management model was 20.0% higher than computed using the modified DRBC water management model.

KEY TERMS: Water Management Model; Delaware River Basin Comm.; Bucks Co., PA; Low Flow Management; diabase; Southeastern Pennsylvania Groundwater Protected Area

INTRODUCTION

Major ground-water allocations and management issues in Bucks County, PA are regulated by the Delaware River Basin Commission (DRBC), a compact between four states and the United States Government that was formed in 1961. To give special focus in the rapid development area around Philadelphia, PA, in 1980 DRBC created the Southeastern Pennsylvania Ground-Water Management Area (SEPAGWMA) (Figure 1). Most of Bucks County is within the area. Initially DRBC management was mainly permitting and monitoring. In 1999, ground-water management regulations were made for this area that included withdrawal limits (DRBC, 1999). While this investigation supports these regulations, it is intended to show that the management model upon which these regulations are based should be flexible and adaptable for maximum effectiveness.

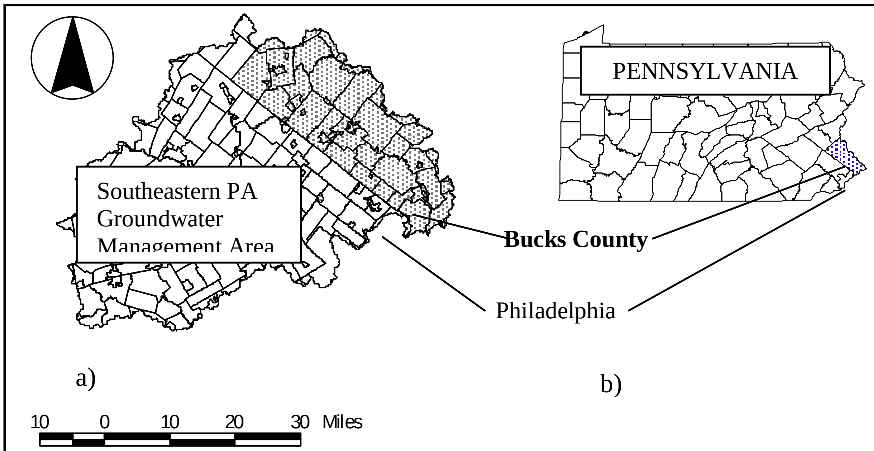

Figure 1.—Location of Bucks County a) within the Southeastern PA Groundwater Management Area, and b) within the Commonwealth of Pennsylvania, U.S.A.

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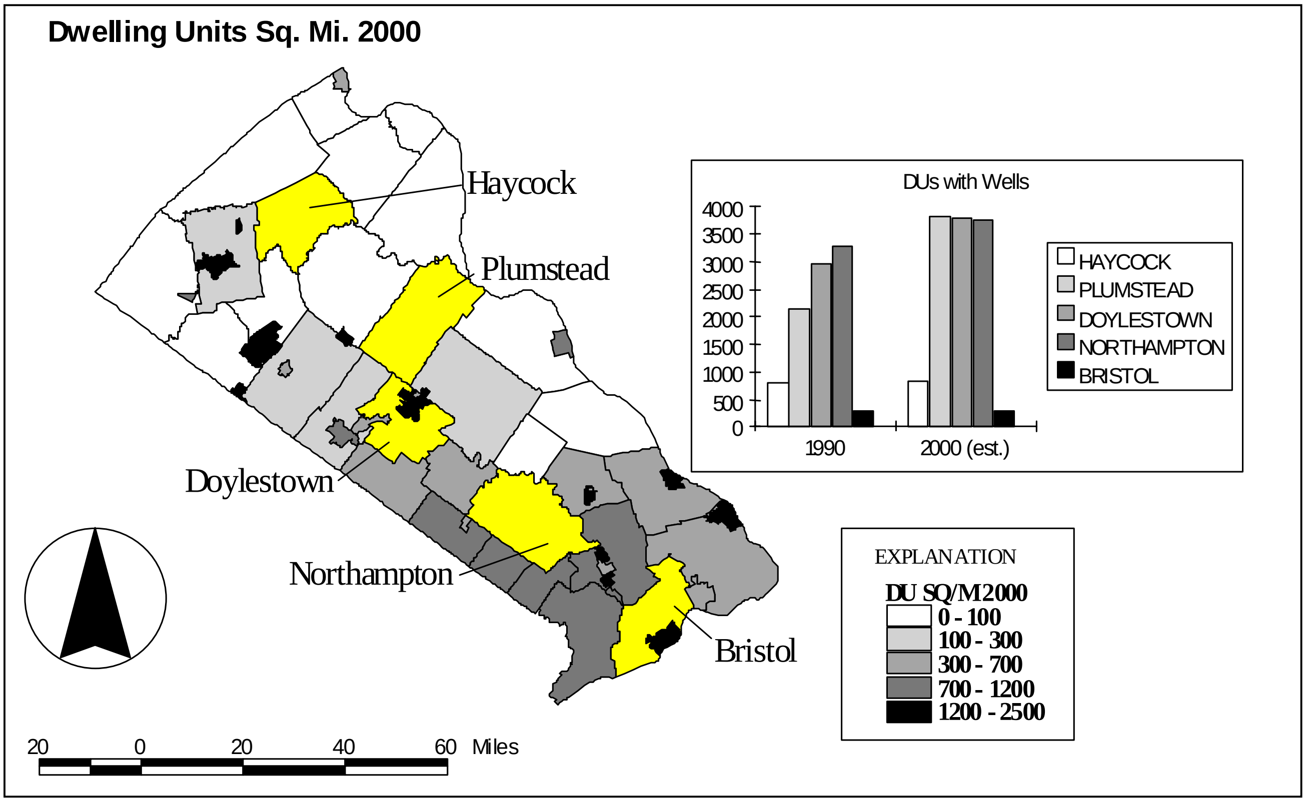
Location and Extent

The general project area coincides with the SEPAGWMA (1,683 mi^2) and the gaged drainage area of the Little Lehigh River, which is north of this area. The area is most densely populated in the immediate proximity of Philadelphia and becomes less populated with distance from the city. In the distant parts of the region the surrounding residential communities become increasingly interspersed with agricultural and wooded areas, which still dominate the landscape. Bucks County (623 mi^2 area) is the primary project area for this report, and 72.3 % of its area is within the SEPAGWMA.

Historically the soil conditions and prevalence of diabase hindered agricultural settlement in much of the northern part of the County. Unyielding sub-urban development has made water availability questions in diabase problematic. Figure 2 shows the relative density of the dwelling units in Bucks County for the year 2000. It also contains a chart that compares the changes in the number of dwelling units with individual wells in five municipalities between 1990 and 2000. In Bristol Township, nearest to Philadelphia, there is the highest density of dwelling units but lowest number of wells because of the availability of public water supply. The largest numbers of dwelling units with wells are in the Northampton, Doylestown, and Plumstead in the center of the county where the largest increases in dwellings over the ten-yr period are an indication of sprawl from Philadelphia. The chart shows migration of the population is clearly towards the northern part of the county.



Geologic Setting

The general project area lies within the Triassic Lowlands Physiographic Province and is within a structural-depositional feature known as the Newark-Gettysburg Basin. The topography consists of ridges and broad valleys. Within the primary project area, relief is greatest in the north where there is rocky terrain, especially along the north and northeast of the county where there are steep cliffs of the Palisades along the Delaware River and along the stream corridors.

The rocks within the basin belong to a geologic classification known as the Newark Supergroup of Late Triassic and Early Jurassic age (Lyttle and Epstein, 1987). For the purposes of this paper, and consistent with the DRBC model (Schreffler, 1996), this geology is simplified into major hydrogeologic units in accordance with the varying porosity and permeability of the different rocks. These units include crystalline rocks comprised of mixed granites and gneisses (Cc), which are weathered to a depth of 100 feet below land surface and which have mainly secondary permeability. There are also carbonate rocks (Clp), which may have significant flow through enlarged dissolution fractures. The next three characteristic rocks are sedimentary rocks of the Lockatong Formation, the Brunswick Formation, and the Stockton Formation. Most generally, the Lockatong Formation (Trl) consists of gray to black argillite and shale with interbedded red siltstones. The Brunswick Formation (Trb) is comprised of interbedded red sandstones and is more productive than the Lockatong (Slotto and Schreffler, 1994). (The DRBC model assumes Lockatong and Brunswick have the same hydrgeologic characteristics). The most productive rocks are in the Stockton Formation (Trs) which is comprised of interbedded sandstone, small amounts of shale, and coarser grained beds (Willard, 1950). In geologic time Jurassic-age diabase rocks (Jd) intruded the Triassic sedimentary formations. The diabase is a dark-gray to black, fine- to coarse-grained, very hard, fracture-resistant metamorphic rock with very low permeability or porosity (Schreffler, 1996). (The DRBC management model assumes the hydrogeologic properties for diabase are the same as for the Lockatong and Brunswick Formations.)

Diabase intrusions are extensive in the upper part of the primary project area in northern Bucks County (Figure 3) (Lyttle and Epstein, 1987). Sloto and Schreffler (1994) also report geophysical gamma logs of the diabase that reveal the diabase exists as sheets which can vary in thickness between 80 and 570 feet.

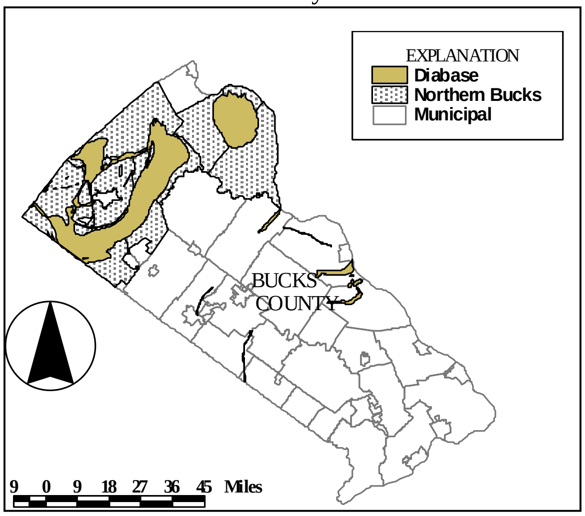


Figure 3.—Bucks County municipalities highlighting nine municipalities where diabase is most extensive (at left).

Figure 3 focuses attention on the importance of the assumption made in the DRBC model that the hydrogeologic properties of diabase intrusions is the same as for surrounding Lockatong and Brunswick Formations. Of course the significance of the assumption is based on the focus area of an investigation in the SEPAGWMA. Whereas diabase represents 5.3 % of the total SEPAGWMA, it represents 10.4% of the Bucks County area within SEPAGWMA. Within the area of the nine municipalities shown in the figure at left, diabase represents more than 35% of the combined area. For purposes of the local interest of Bucks County water resources managers, the assumption that the DRBC water management model in this part of the county is sufficiently accurate merits attention.

Surface Water Bodies and Watersheds

The entire project area is within the Delaware River Basin. DRBC manages withdrawals within 85 sub-basins within the SEPAGWMA. For the purposes of understanding the DRBC model, there are four “baseline” monitored watersheds. These watersheds are listed in Table 1, and shown in Figure 4, as a) Neshaminy Creek, b) the West Branch Brandywine Creek, c) Skippack Creek, and d) the Little Lehigh River. (Where it is monitored the Skippack Creek watershed is actually the cumulative flow from three sub-basins, and the flow of the Neshaminy Creek is the cumulative flow of 14 sub-basins.) As will be explained, e) Tohickon Creek is added in this investigation using only data for the precontrol period. (Where it is monitored, Tohickon Creek flow receives discharges from all or part of 6 subbasins.)

Table 1.—Characteristics of Select Watersheds from Southeastern Pennsylvania

Watershed	Drainage Area (mi^2)	U.S.G.S. Gage No.	Flow Record (dates)	Mean Annual Baseflow (Mgal/d/sq.mi.)	Baseflow (% annual flow)
Neshaminy Creek	210	01465500	10/1/34-9/30/94	- - *	- -
W. Branch Brandywine Cr.	18.7	01480300	6/1/60-9/30/97	0.5195	58.3
Skippack Creek	53.7	01473120	5/1/66-9/30/94	0.313	36.5
Little Lehigh R.	80.8	01451500	10/1/45-9/30/97	0.633	81.7
Tohickon Cr.**	97.4	01459500	10/1/35-9/30/73	0.2635	31.3

* Values for the period of record analyzed by Schreffler (1996), reported 2-yr return value is 0.411 Mgal/d/sq.mi.

* *Only precontrol period of flow

Table 1 presents the period of record that was used for the analysis of flow records for each watershed. Calculation of baseflow for the periods shown, “base-flow separation”, was done for streamflow-gaging stations listed in Table 1 using a hydrograph-separation program (Sloto, R.A., and Crouse, M.Y., 1996). The local-minimum method of hydrograph separation was used to separate baseflow from direct runoff for the total record period of all the gaging stations. Figure 4 shows the drainage areas for the subject watersheds and the locations of the gaging stations. Note that the Little Lehigh River is located as an abstract watershed shape and not drawn to scale. The most densely populated and developed of all five of the watersheds is the Neshaminy watershed, which also has flood control dams on several of its tributary sub-basins.

Figure 4 also shows the extent and types of the underlying geology, which has been simplified in a manner consistent with the DRBC model as previously described (Schreffler, 1996). The four DRBC “baseline” watersheds have long periods of record and to derive characteristic hydrologic properties for four distinct geologic subcrop areas. Figure 5 shows the relative subcrop composition of the watershed drainage areas. The figure shows the W. Branch of the Brandywine is underlain by more than 95% crystalline rocks (Cc), Little Lehigh by more than 90% carbonate (Cl), and Skippack Creek is totally underlain by Brunswick (Tbr) and Lockatong (Trl). The Stockton Formation is the largest subcrop area underlying the sub-basins which flow into Neshaminy Creek, the fourth DRBC "baseline" watershed. Tohickon watershed is predominantly underlain by Brunswick Formation and has the largest diabase component of the select watersheds.

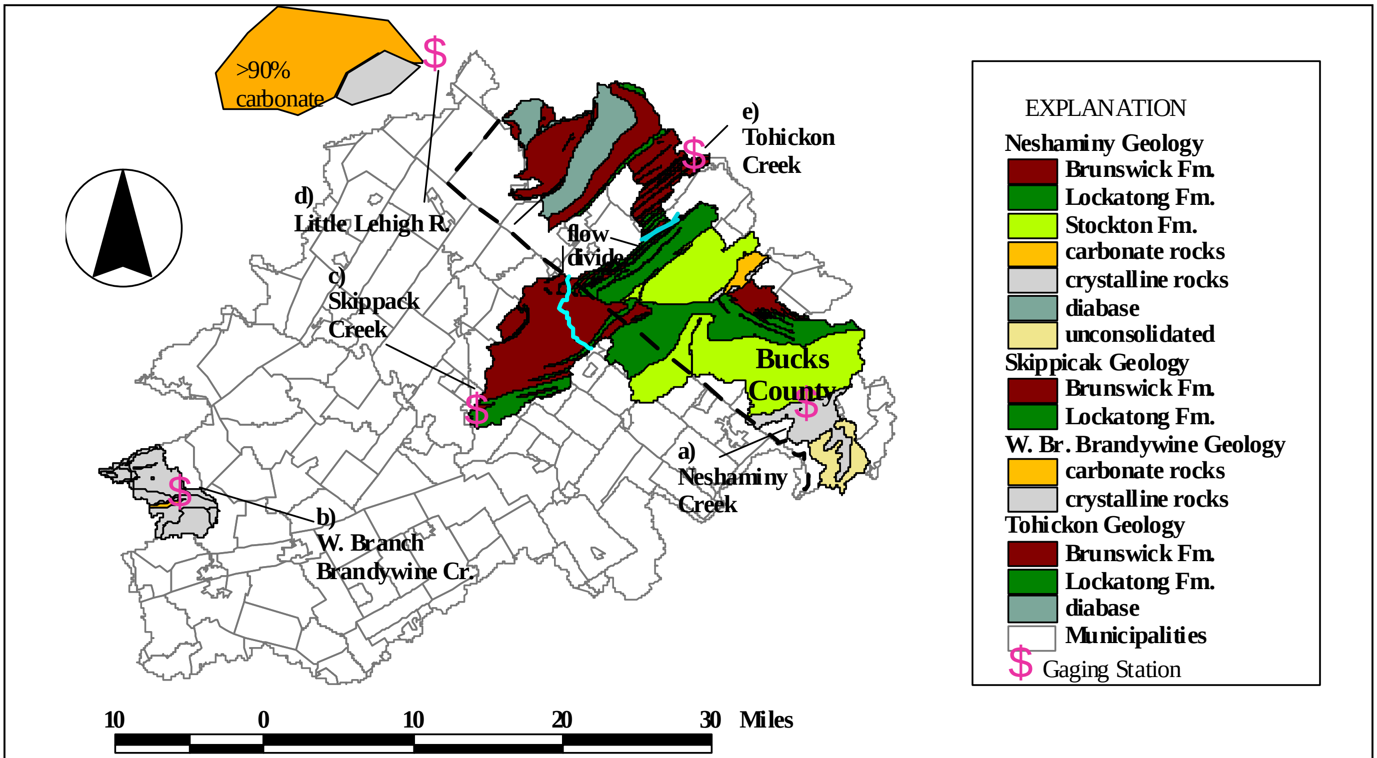


Figure 4.—The Southeastern Pennsylvania Groundwater Management Area and locations of four monitored baseline watersheds used by the DRBC for analysis showing subcrop geology, including a) Neshaminy Creek, b) W. Branch Brandywine Creek, c0 Skippack Creek, and d) Little Lehigh River. Additional watershed used for this analysis is shown as e) Tohickon Creek. (Note-outline of Little Lehigh is as type and not accurate.)

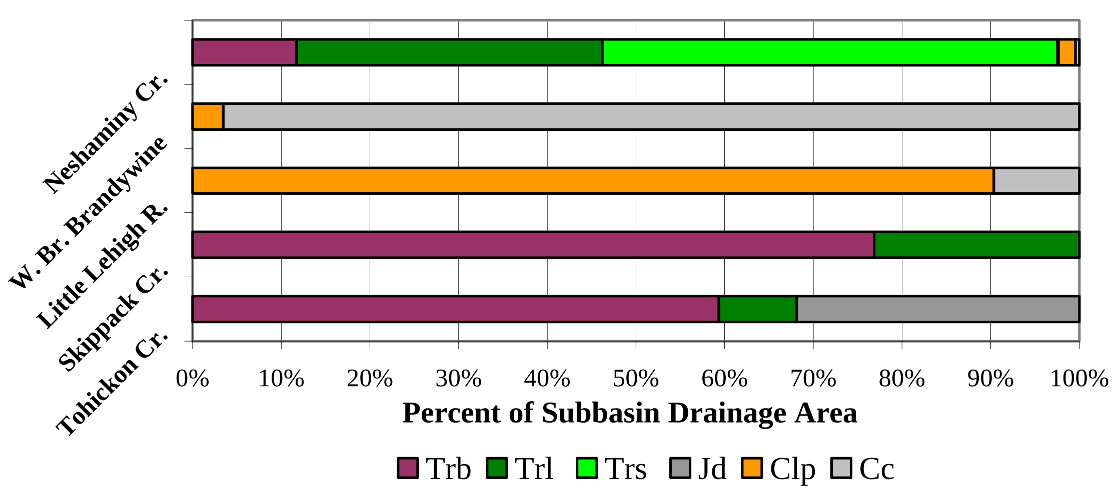


Figure 5.—Relative Hydrogeologic Subcrop Composition for Four Streams used by the DRBC for determining Mean Annual Baseflow from: a) Stockton Formation (Trs) (Neshaminy Cr.); b) crystalline rock (Cc) and diabase (Jd) (W. Br. Brandywine); c) Brunswick Formation (Trb) and Lockatong Formation (Trl) (Skippack Cr.); d) carbonate (Clp) (Little Lehigh R.) in Southeastern Pennsylvania. Additional Hydrogeologic Subcrop used in this analysis is from e)Tohickon Cr.

THE GROUND WATER MANAGEMENT MODEL

The DRBC water management model is a modification of low flow management model (LFMM). In this model, the water allocation guideline for a watershed can be no larger than some chosen low-flow level for the sub-basin, such as the flow volume represented by a statistical occurrence of low flow (Cahill and others, 1998). The selection of mean annual baseflow for a long-return period as a withdrawal limit makes hydrologic sense. It is a hedge that when full water allocation is reached in a sub-basin, in most years withdrawals should not cease permanence of streamflow. The DRBC model selects the 1-in-25 year return period low flow as the maximum permitted withdrawals in each sub-basin.

Ideally, the DRBC water management model could measure a 1-in-25 year low flow if each sub-basin had a continuous stream gage but that is impractical. Instead, the DRBC water management model applies a predictive LFMM in order to use it in unmonitored watersheds (Schreffler, 1996). The predictive model hypothesis is that contributions to baseflow in a watershed are proportionate to the contributing areas of various hydrogeologic sub-crops and that their contribution is characteristic of that hydrogeologic sub-crop. (As an example this says, if a watershed were underlain 40% by geologic material A, and 60% by geologic material B, the resultant baseflow is equal to the discharge comprised of 40% of the characteristic discharge from material A and 60% of the characteristic discharge from material B, weighted by area.) Applying this to the Neshaminy Creek for 1-in-25 year return period, the mean annual baseflow from the Neshaminy Creek is represented as a composite from its 4 main geologic sub-crop areas.

$$(1)\quad (Q_{\text{Neshaminy}})_{1/25} = [\text{Area}_{\text{ Neshaminy}}]_{\text{ crystalline rocks}} * (Q_{\text{ W.Br.Brandywine}})_{1/25} + [\text{Area}_{\text{ Neshaminy}}]_{\text{Bruswick/Lockatong}} * (Q_{\text{Skippack}})_{1/25} + [\text{Area}_{\text{ Neshaminy}}]_{\text{ Carbonate}} * (Q_{\text{LittleLehigh}})_{1/25} + [\text{Area}_{\text{ Neshaminy}}]_{\text{ Stockton}} * (Q_{\text{Stockton}})_{1/25}\,,$$

where Q_i = flow in stream “i”, except Q_{Stockton} which represents the characteristic baseflow from the Stockton Formation,
$[\text{Area}_i]_j$ = area of watershed “i” with geologic subcrop “j”.

Or, more generally,

$$(2)\qquad (Q) = Q_i * [\text{Area}_{\,i}\,]_{\,j}$$

Each of the four addends in equation (1) is the product of the area of each subcrop type and the characteristic flow per unit area for each type of geologic material.

The area coefficients in equation (1) can be solved by GIS planimetry (U.S. Geological Survey, 1998). Schreffler (1996) used the flow records to compute the characteristic “Q_i“ values in the DRBC model for three of the “baseline” streams, including the West Branch of the Brandywine, the Skippack Creek, and the Little Lehigh River. In each case he assumed the hydrogeologic properties of these watersheds were uniform (Figure 5). The Q_{Stockton} can be computed by difference from these three values and the measured records for the 1-in-25 year baseflow on the Neshaminy.

The DRBC management model predicts the mean annual baseflow for return periods for any sub-basin within the SEPAGWMA by assuming that the mean annual discharge for stream "i", $Q_{i,}$ is a linear function of the mean annual baseflow for that return period from any of the four characteristic geologic subcrop areas within its drainage area. Withdrawal limits are made for unmonitored sub-basins within its area based on their geologic sub-crop areas.

Using analysis of baseflow recession as an indication of aquifer yield and hydrogeologic properties in a watershed is fairly well established in the literature. The method of “transferring” a characteristic “mean annual baseflow for a given return period per unit area” for a hydrogeologic subcrop seems reasonable in that the properties are integrated on a large scale. Also, first order approximations are traditionally made in water resources management because of the uncertainty associated with baseflow. Other current investigators are using approaches that show similarities in watersheds using streamflow analyses (Bachman and others, 1998; and Amit and others 2002). However, the DRBC, as the author of the management model, must recognize that it may take years to determine the sufficient accuracy of such a “low order” model, while the decisions that affect long term conditions are constantly changing.

Management of the Ground Water Management Model

Flexibility of the model is critical. Aside from the technical merit of the DRBC water management model, which this paper supports, the regulations that established the management model led to a guideline for modifying them (DRBC, 2002). The guidelines, as a tool for managing, and the DRBC water management model need to reflect that evaluation and modification is an ongoing process (Lyle Raymond, 94). As an example, the selection of the 1-in-25 year return period as an upper limit for ground-water development in a sub-basin is an important datum. Why? It is because that datum is also a goal for the managers and should help to focus public support. Focusing on the goal will help change public perceptions and gain support for water management. The public should be aware that the goal, the computed number, is not carved in stone, it is not an absolute, that it is an approximation, but a reasonable scientific one. People will support the goal if they know it is the result of a policy objective. Therefore most people should support the goal because it minimizes the chance that streams could dry up.

The 2002 DRBC water management guidelines need to be careful not to be overly proscriptive, unrealistic in expectations, and based on unsound management practice, such that people may turn away from supporting policy. As an example, the 2002 DRBC regulations require that in order to change water allocations within a sub-basin within the SEPAGWMA, all municipalities containing any part of the watershed area must collaborate in an integrated resource plan (IRP). This could be a stumbling block. Then, if changes in the existing water management model are anticipated, the DRBC requires that they must participate in an IRP from the beginning. Regulations need to encourage and facilitate all sources of information and interaction. DRBC should use all this information, some of which may lead to revisions that improve the water management model (Meredith and others, 1993). Towards illustrating that end, the remainder of this paper will demonstrate the potential impact that an unmodified management model could have in northern Bucks Co.

A Modified Ground Water Management Model

As discussed, the trend in the demographic pressure into the semi-rural and sub-urban areas of upper Bucks County coincides with the area of extensive diabase. The DRBC management model does not distinguish hydrogeologic differences for diabase rocks in upper Bucks County and for the Lockatong and Brunswick Formations (Figure 3). There are no gaging stations with records of sufficiently long duration in southeastern Pennsylvania that primarily measures runoff from diabase subcrop areas. There is a long record of flow for the Tohickon Creek watershed that is underlain by more than 30% diabase (Figure 5), however the gaging station is downstream from a reservoir. This analysis used the flow from the Tohickon Creek from the precontrol flow period (Table 1). The extent of Tohickon Creek is shown in Figure 4. Figure 6 shows the mean annual baseflow from all four of the DRBC “baseline” watersheds and Tohickon Creek.

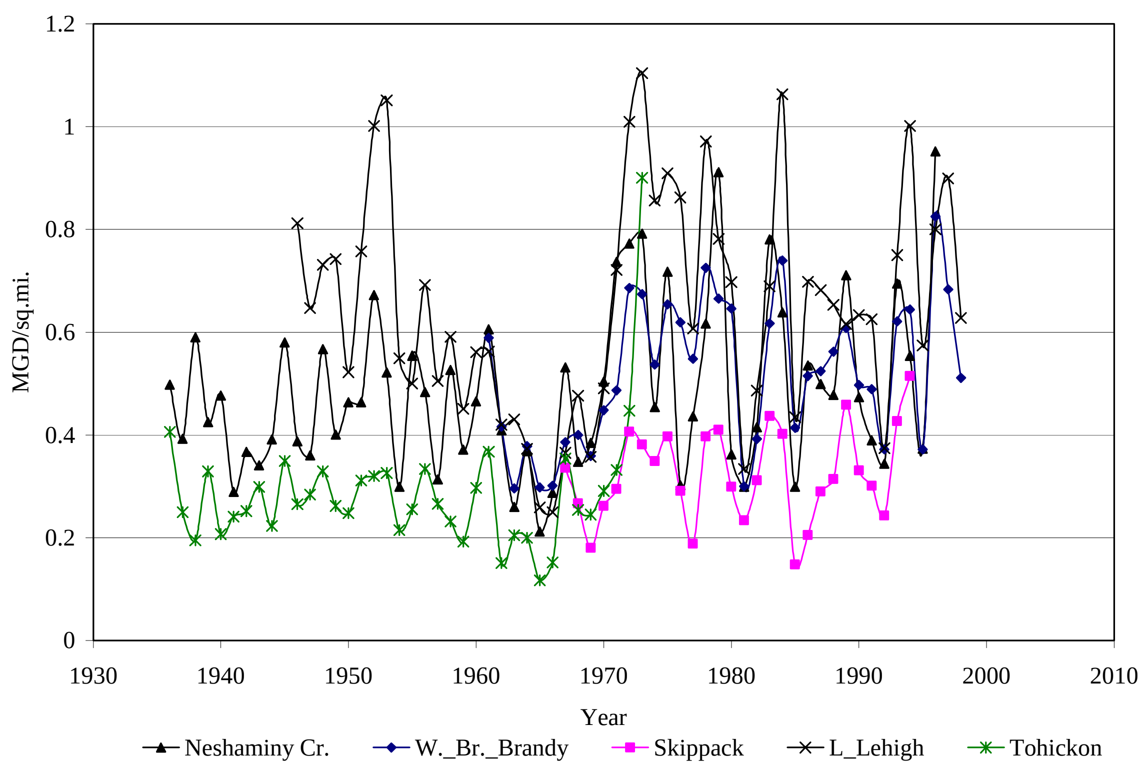


Figure 6.--Annual Mean Baseflow for Four Streams used by the DRBC for determining Mean Annual Baseflow from a) Stockton Formation (Neshaminy), b) crystalline rock and diabase (W. Br. Brandywine), c) Brunswick Formation and Lockatong Formation (Skippack), and d) carbonate (Little Lehigh R.) in Southeastern Pennsylvania. Additional data used in this analysis is from pre-control flow on e) Tohickon Creek.

Among the hydrologic features of Figure 6, the data show that the two streams that tend to have the lowest mean annual baseflow over their period of record are the Skippack Creek and Tohickon Creek. The baseflow in the two streams is the most susceptible of all the subject streams to extreme dry periods. Their range of mean annual baseflow is somewhat similar although the data period for the Tohickon is earlier in years than for the Skippack. The peak flows for the Skippack Creek are slightly higher than for the Tohickon (Figure 6) which suggests that the difference is mainly due to the occurrence of diabase in the Tohickon watershed. Diabase does not underlie the Skippack watershed. Examination of about three years of streamflow data from a stream in northern Bucks County (Slotto and Schreffler, 1994) which was underlain mainly by diabase, indicated the flows from the diabase were very flashy and did not permit much infiltration.

To determine if the occurrence of diabase contributed a statistical difference between the mean annual baseflow from the two creeks, a two-sample t-Test assuming unequal variances was done (Table 2). Log transforms are used for the test. The t value falls in critical range, therefore the means are not equal. Equation 2 was then applied to determine the mean annual baseflow from diabase areas. The equations can be solved either by difference or by simultaneous equations given data for the same return period and the appropriate area coefficients.

Table 2.—Statistical test of the difference in Mean Annual Flow (Q) for Tohickon Creek and Skippack Creek.

$H_0: :_1 = :_2$ Mean of Log values of Mean Annual Runoff is same

$H_1: :_1 \neq :_2$ Mean of Log values of Mean Annual Runoff is not the same

t-Test: Two-Sample Assuming Unequal Variances

	Tohickon	Skippack
Mean of Log Q Values	-1.344742217	-1.168555405
Variance	0.0797705675	0.0928062811
Observations	37	28
Pearson Correlation	NA	
Pooled Variance	0.0853573019	
df	56	
t	-2.382105678	
P(T<=t) one-tail	0.0103176298	
t Critical one-tail	1.6725223041	
P(T<=t) two-tail	0.0206352597	
t Critical two-tail	2.0032407147	

The computed mean annual baseflow values for the Diabase, along with DRBC values for Lockatong and Brunswick Formations, and Crystalline Rocks are presented for comparison in Table 3.

Table 3.—Mean Annual Baseflow in Mgal/d/sq.mi. for return periods in select geologic subcrop areas in Southeastern Pennsylvania

	Return Period				
Formation	2-yr	5-yr	10-yr	25-yr	50-yr
Diabase	0.181	0.119	0.094	0.073	0.062
Lockatong and Brunswick*	0.314	0.241	0.189	0.154	0.144
Crystalline Rocks*	0.524	0.381	0.302	0.299	0.206

* Values reported by Schreffler (1996)

An Application of the Modified Model

The results in Table 3 show there is a significant difference between the characteristic mean annual baseflow for the diabase and the Lockatong and Brunswick Formations. Baseflow from the diabase is almost half that of the Lockatong and Brunswick Formations. The baseflow from the crystalline rocks is more than three times as great, reflecting the descriptive lithology that reported weathering in crystalline rocks down to 100 feet below land surface.

The results of Table 3 were applied to predict the mean annual baseflow for various low flow periods for the Tohickon Creek Watershed in northern Bucks County using the original model and the modified model for comparison. Table 4 shows the results.

Table 4.— Mean Annual Baseflow for Tohickon Creek in Mgal/d for Various Return periods using the DRBC Model and the Modified DRBC Model.

	Return Period				
Management Model	2-yr	5-yr	10-yr	25-yr	50-yr
DRBC	30.6	23.5	18.5	15.0	14.1
Modified DRBC	26.5	19.7	15.5	12.5	11.5

CONCLUSION

The results of the calculations show that there is a significant overestimate in water availability by the DRBC in the area of northern Bucks County compared to the modified DRBC model. This overestimate could lead to failure on the part of water managers to sustain permanence of streamflow. The discrepancy ranges from 4.1 Mgal/d for the 2-yr return period to 2.5 Mgal/d for the 25-yr return period. The modified model estimates that the current DRBC water management allocation level in the Tohickon Creek watershed area is 20% too high. Results of this type, presented from the scientific and professional community, should always be considered for the concern and benefit of the management of resources in the community, whether they are expected or not. Suggestions for modification of the model and public interest are important ways of focusing on the goal of water resources management.

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